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Mine Emergency Support Technologies

(Emtech)

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1 Final Summary

1.1 WP1 – RESILIENT RESPONSE CAPABILITY FROM INFRASTRUCTURE

Task 1.1: Assessment of current mine communications infrastructure

An assessment of mine communications infrastructure in terms of its resilience has been appraised from an EU and international perspective. A questionnaire was issued to mining companies to investigate the current status of their underground speech and data communication systems. The results confirmed that none of the installed systems involving traditional point-to-point cabling would be able to fulfil demands on survivability, resilience and functional safety. The work on reviewing national practice also identified a range of good practices. In the case of UK Coal, for example, their SCADA (supervisory, control and data acquisition systems) framework specification encourages measures to enhance resilience, including the use of a fibre-optic ring main for backbone communications.

The approaches considered to offer the greatest potential in terms of system survivability involve...

- Engineering multiple pathways and system integration.
- Engineering systems that will adapt and use whatever transmission path survives.
- Hardening of system components (especially cables), and
- Incorporating redundancy; power supplies, connectivity and increased radio coverage.

The further stage of work within Task 1.1 concerned a fundamental review of the role of formal assessment methods for evaluating the survivability of mine communications infrastructure. As far as can be ascertained, there are no formal methodologies employed in the EU mining industry (or indeed in mining industries elsewhere) at the present time to quantitatively assess the safety and resilience of critical mining communications infrastructure. The majority of studies to date have concerned the functional safety assessment of programmable electronic mining systems (PES). There remain fundamental questions as to how well suited IEC 61508 and other formal safety standards are to assessing of the survivability and resilience of systems to various major incident scenarios. For this reason, the partners assessed hybrid approaches involving SIL, FMEA, 'what if' scenario analysis and standard risk assessment tools.

Task 1.2: Re-engineering of mine infrastructure to achieve resilience

Specific technology studies have focussed on Ethernet technology, which was considered a primary candidate for engineering high resilience systems. An analysis of resilient communications technology use in other hazardous industries and applications was undertaken. This confirmed that Ethernet technology is increasingly being deployed in safety related applications. A systems analysis of functional safety and design requirements of underground data communications systems was carried out. Subsequent development work concentrated on high resilience Ethernet-based underground communication infrastructures. One particular research topic was the use of meshed structures and topologies within underground networks. Various candidate meshing functions and protocols were researched for possible application. The preferred topology consists of ring structures conforming to a main backbone with interconnections between the rings used to provide redundant pathways.

Related network functions were researched regarding the survivability of the network in the event of multiple network interruptions or complete loss of the communication to above-ground servers. The operational mode switching in response to failure functions was analysed and designed. To meet a worst case situation, it is essential that the network underground is able to replace the functions of the central (surface) servers as far as emergency support functionality is concerned. To implement such functions, the high resilience network requires 'intelligent' electronics to be used in each network node. Such a network node has been developed, a so-called 'Mining Infrastructure Computer' (MIC). The safety functions run as software applications using the MIC's microprocessor.

Task 1.3: Power supply infrastructure to ensure post-incident availability

This task was associated with the design, development and certification of an ATEX M1 Uninterruptible Power Supply Unit (UPSU). It is necessary to equip critical network sub-systems with a standby power source capability. This unit provides battery backup for when the mine power network is either damaged or manually isolated. The partners evolved an equipment specification to meet industry requirements for a UPSU that was compatible with existing underground controls and cabling systems. These requirements covered powering existing Fieldbus-based distributed control equipment and mixed application, high power, standalone equipment including access points, media converters, and so on. An analysis showed that it was possible to design a family of UPSU sharing enclosure and circuit arrangements, which would allow the respective requirements to be met. The required autonomous operating period was between two and four hours.

Safety controls and certification requirements (protection modes, energy limiting techniques and battery technology) were examined at length prior to submitting the design to a Notified Body for ATEX testing and certification. Further work involved the mechanical design of the enclosures, together with thermal analysis and tests. The lithium ($LiFePO_4$) cell technology selected initially was rejected due to short-circuit test failure. The development of the battery pack continued using lower capacity 2.2 Ah cells, with a subsequent design using two battery packs connected in parallel to meet the required operating duration.

1.2 WP2 – Incident Status and Decision Making Support

Task 2.1: Pre-and post-incident status information

This task addressed two related aims; firstly, to input data on gas and temperature conditions associated with fires, which were used subsequently in computational fire and evacuation modelling studies and, secondly, to develop environmental sensor interfaces and related data processing within the mining infrastructure computers (MICs). A study was undertaken of post-incident gas and temperature conditions associated with mine fires, and how these may be measured. The review included consideration of the complex vertical disposition of workings in Spanish mines and various Member State approaches to the determination and measurement of fire conditions.

The second area of work involved an analysis and design of the system for safety enabled network infrastructure. These network nodes provide functionality that includes automatic identification of all tracking devices in their proximity. This information is forwarded continuously to a central server above ground. However, the MICs do not require the assistance of central systems for this purpose, as these systems may not be accessible in an emergency situation. This is a key system attribute. Information on emergency egress options and information to guide the workforce to central meeting points is computed by the MICs. Geo-spatial and facility information relating to the local roadways is also used by the MICs, including the length/gradients of the roadways, location of emergency shelters, fire extinguishers and other emergency equipment. In an emergency, a so-called 'lighthouse' function provides guidance and information to personnel about the current situation. This includes unusual operating conditions, alarms and evacuation instructions. As an associated aspect, workforce deployment information plays a crucial role in the early stage of a rescue operation. A compact real time location capability was successfully integrated into a cap-lamp (equipment developed in task T4.2), which has been considered together with mine-wide personnel tracking systems.

Task 2.2: Modelling and prediction of products of combustion transport

This work concerned modelling of smoke transport. The objective was to develop a model that simulated an underground fire in order to predict smoke movement and interaction with the mine ventilation system. The smoke transport data was then inputted to an evacuation simulation model. The CFD modelling inputs were validated using the results obtained from full-scale fire tests. To reduce computational complexity, the simulation scenario was limited to critical zones of interest. Various fire characteristics and ventilation flow conditions were measured from tests performed in the fire test gallery at Santa Barbara, located at Leon, Spain. The fire test gallery is comparable in scale to the underground tunnels of Hunosa's coalmines. Three fire tests were carried out, differentiated by airflow introduced into the tunnel, which provided data on concentrations of gases and temperature profiles within the test tunnel. A supporting activity focused on the analysis of the ventilation network at Pozo Carrio Colliery, where the refuge prototype was to be installed. The information obtained concerning the smoke transport was then inputted directly into Task 2.4 'Evacuation modelling and safe egress routes'.

From an analysis of the simulation results it was determined that smoke products are transported to all areas covered by the mine fire scenario within ten minutes of the fire initiation. The results show the possibility of high temperatures (greater than 80°C) in the zone of the refuge location, although this was considered a worst case scenario. High temperatures were not observed throughout the adjacent drift, which is the main air intake. High temperatures were however observed downstream of the simulated fire. The modelling was supported by extensive analysis of case studies of previous fire incidents, which broadly suggested slower rates of fire growth, although rapid fire growth and ensuing effects on the ventilation circuit are clearly possible under some circumstances. The studies have demonstrated that a simulation model, based on commercial CFD code, can be used to predict smoke movement at least locally in a mine fire situation. The modelling approach of using a fire source represented by a heat release rate (HRR) fixed inside a volume leads to realistic temperatures except very near to the fire, around 5–10 m from the fire seat. In this zone the analysis requires a more sophisticated treatment.

Task 2.3: Psychrometric impacts of mine fires

The main objective here was to estimate the thermodynamic conditions anticipated underground in the case of the test and simulated fire conditions, and compare them with tenability criteria for humans. A further objective was to analyse, from a multistressor perspective, the consequences of the local conditions for evacuation. These studies included both assessing tenability criteria under radiant heat conditions, together with potential body core temperature rise associated with evacuation under severe heat and humidity conditions.

Dialogue was held with a wide range of institutes and research departments linked to the mining industry, including INSHT (Spain), HSE (UK) and NIOSH (US). Possible strategies identified to deal with heat during evacuation were examined. This included evaluating the impacts of dehydration, self-pacing, heat acclimatisation, pre-cooling, hyper-hydration, and smoke impacts, together with the role of heat index and mine regulations. This included consideration of the physiological benefits of cooling and rehydration within a staged evacuation process. A number of critical issues were identified including the roles of dehydration, self-pacing and eye protection.

Task 2.4: Evacuation modelling and safe egress routes

The studies investigated the simulation of the evacuation process within Pozo Carrio coal mine under fire conditions, taking into account the source data from the CFD simulations and ventilation impacts modelling. The evacuation times were calculated using an advanced Simulation Programme, STEPS conveniently adjusted with real displacement velocities and taking into account boundary conditions of temperature and smoke. The main achievement of this task has been to establish a very high correlation between the observations from evacuation drills and the simulation models, particularly where the evacuation simulations were repeated to incorporate precise mine survey data. The evacuation simulations were validated using data from evacuation drills conducted by the coal mine operators. Refinements made to the evacuation simulation model would permit other arbitrary mine layouts to be analysed without having to carry out corresponding evacuation drills.

The evacuation modelling pointed to improvements in evacuation times, which could be achieved by implementing additional fire detection systems, especially in the areas of greatest fire risk. Additionally, enhanced ways to raise the alarm with mineworkers could further improve these times. It was considered that these two aspects together could reduce total evacuation times by 2–3 minutes. In order to address worst case fire scenarios, it was also considered advisable to include an additional SCSR donning station in the sub-level.

1.3 WP3 – Systems and Procedures to Enable Self-escape

Task 3.1: Refuge and self-rescuer changeover station design and specification

The first aspect of this work was to examine the use of underground refuges (otherwise known as safe havens or emergency shelters) as part of escape strategy and planning activities. Underground refuges offer a place where the mine workforce can gather, exchange respiratory protective devices, rest and continue their evacuation or, if necessary, await rescue. Emergency preparedness strategies were contrasted for refuges in metalliferous mining (where they are more commonly used) against possible roles in coalmines. Generally, the primary response within the EU has been to evaluate the application of underground refuges as part of a staged evacuation strategy. However, the refuge must also be designed to serve, if required, as a place to shelter until rescued.

An extensive programme was undertaken to assimilate and assess relevant international guidance, regulatory matters and research relating to the use of underground refuges. Significant collaborative effort was devoted to the subject of underground refuge design and specification. The difficulty that faced all partners is that there are no national regulations relating to underground refuge design and application (although guidance has been issued by the UK Mines Inspectorate). The studies within Task 3.1 also examined the options for primary breathable air supplies and standby air delivery arrangements. Each option was carefully considered, including undertaking generic risk assessments. Hunosa and UK Coal examined the general guidance available and then developed specific refuge designs appropriate to their respective trial sites at Pozo Carrio and Daw Mill mines. Both coal mine operators selected compressed air as the primary breathable air source.

Task 3.2: Establishment and assessment of comfortable thermal conditions inside the refuge

One key issue was whether a tenable thermal environment could be maintained within generic underground refuges, particularly in hot, deep mines and where there is a high occupancy level in the refuge. Compressed air, as the primary means of providing breathable air and refuge cooling has key advantages of familiarity, simplicity, large volume flow rate, high cooling capacity, dilution of CO_2, and ensuring a refuge over-pressure hence preventing the ingress of products of combustion into the refuge. However it may be necessary for mine operators to seek secondary or even tertiary back-up air supply options. For these alternative air supply options, some form of refuge air conditioning will generally be required. The requirement for refuge air conditioning is based on a number of reported tests supported by numerical modelling thermal entrapment studies. One parameter difficult to enumerate is the figure that should be used for mean metabolic rate for individuals under emergency entrapment conditions. A figure of 180 W or more may be appropriate in high stress emergency conditions.

The experimental programme within Task 3.2 involved two aspects; firstly evaluating the air delivery scheme of the underground refuge at Pozo Carrio mine, and secondly measures to maximise the cooling capacity of compressed air delivered to an underground refuge. Essentially for compressed air supplied refuges, the refuge thermal environment and cooling requirement is dependent on air flow, the wet-bulb temperature, the occupant's clothing ensemble, metabolic level, and the total number of occupants. This directed that the research be focused on investigating the benefits in increasing the local air velocity within a compressed air supplied refuge. A number of schemes for air delivery were analysed and supporting practical tests undertaken within a simulated underground refuge environment. The use of air amplifiers was shown to be a highly effective approach to increasing air movement within compressed air supplied refuges and therefore of achieving maximum cooling.

Task 3.3: Development and testing of prototype refuges

The work in Task 3.3 was organised into three components – (i) Spanish refuge construction and testing, (ii) UK refuge construction and testing, and (iii) supporting environmental chamber test work by Polish partners. In this regard the refuge at Pozo Carrio mine is of a 'fixed infrastructure' design, employing a dedicated excavation which was shotcreted and provided with an airlock entry arrangement. The refuge is also a changeover station for self-rescuers. The refuge has a large capacity, sufficient for the underground district workforce. The breathable air supply to the refuge uses two independent sources of compressed air with high capacity in-line filters to ensure cleanliness of the air supply. The explosion and fire protection of vital services is an issue here. This suggests the protection of pipes in trenches and engineering redundancy in their distribution and routing as a possible consideration. Within the UK deep mining industry, a number of potential locations for fixed refuges were identified. As with the approach undertaken by Spanish partners, particular attention was given to ensuring the compressed air supply lines were either protected or routed in a manner to prevent fire damage. Given that roadway dimensions are generally somewhat larger in UK mines than Spanish mines, this offered increased flexibility in respect of the size and form of the refuge. UK Coal completed the implementation and testing of a sectional fabricated refuge ('safe haven' in the UK) and commenced work on a second strata refuge installed in a mine cross cut. A third commercially sourced transportable 'inflatable tent' type of refuge was also installed.

The third work component concerned tests of prototype instruments used for monitoring health and psychometric parameters. This was intended for use in monitoring rescue workers or occupants during refuge chamber residence tests. The tests employed CSRG's large climatic chamber facility. The measurements consisted of a wireless heart rate sensor, a prototype wireless relative humidity, temperature and carbon dioxide multi-sensor as well as a PC-based data logging station. The results indicated that the heart rate, relative humidity and temperature sensors all worked to specification.

Task 3.4: Evacuation support; wayfinding through smoke

The research concerning guidance through smoke first studied related issues and practices in the building, tunnel and fire research fields. The second aspect involved training initiatives in the use of lifelines and in the third aspect, practical technologies were evaluated which could provide guidance and location information, including cap-lamp and wrist-worn devices. The impact of smoke in terms of impairment of escape is often grossly underestimated. All fire atmospheres produce eye irritant effects, which can be severe even in the early stages of fire development. This directs that reliable eye protection is made available, and which is ideally attached to the escape respiratory protective device. Evacuation trials in low or zero visibility conditions confirm that the speed of travel can be reduced to less than a quarter of that possible under normal visibility conditions. Where self-contained self-rescuers (SCSRs) are used as the escape respiratory protective device, then this has direct implications for the oxygen cost of escape and the placement of SCSR caches. Studies confirm that lifelines equipped with suitable tactile ferrules can provide unambiguous directional cues and increase evacuation speed by a factor of up to three times that compared to the speed observed without lifelines in zero visibility conditions. A further innovation was the development of an emergency guidance and navigation system based on a wrist-worn wearable display device. The wireless wayfinding system relies on distance measurement to a wireless base station and was tested successfully in surface and underground tests.

Task 3.5: Enhancement to rescue and evacuation strategies

The findings from the programme were appraised regularly with industry personnel to help ensure early adoption. It was acknowledged that underground refuges had a central role for mustering, emergency decision-making, replacement of self-rescuers from cached stores and, if absolutely necessary, for taking shelter and awaiting rescue. The coal mine operators considered the provision of refuges an important component of self-escape, particularly in deep, hot mines with significant travelling distances to safety. UK Coal and Hunosa each implemented underground refuge/muster station installations. Staff from other mine operators visited UK Coal to view and adapt the design of the refuge. The studies also showed that if effective methods can be made available to guide miners through dense smoke, this could contribute greatly to saving lives during mine fires. A number of respiratory and thermal physiological management issues can arise both during evacuation and within refuges. These have been taken into account in evaluating evacuation strategies and developing training needs.

The partners conducted supporting emergency exercises against representative scenarios that required mineworkers to be evacuated from the work area and the Mines Inspectorate and colliery management were fully involved in the exercises. The research included an evaluation of the deployment of the mines rescue services to fight simulated fires and as required to assist in rescue from the refuge stations. The coal mine operators commissioned and completed dedicated training media and invested in a training model for a transportable refuge. Underground visits were arranged for European Commission staff at both Daw Mill and Pozo Carrio mines to view the escape support facilities.

1.4 WP4 – SEARCH AND ASSISTED RESCUE

Task 4.1: Basic research on through-the-Earth technologies

The basic research entailed (i) theoretical studies on through-the-earth propagation and radiolocation, (ii) background noise measurements in mines, and (iii) analysis of the options for an emergency location system. The initial research involved a technical review of VLF-ELF communication techniques, propagation, and location finding. There is a physical requirement to use very low frequencies in any system requiring a transmission and location capability at significant distances through strata. Given that there is generally a concentration of electrical interference at low frequencies, it was therefore essential to understand the mine electromagnetic noise environment. Sensitive noise measurements were carried out in two Polish mines; Guido and Ziemowit. After the preliminary theoretical studies, it was concluded that major improvements could be achieved to the currently-used Polish mining emergency location solution (GLON-GLOP), by implementation of an on-demand arrangement for the cap-lamp transmitter. Further supporting theoretical studies included an appraisal of grounded dipole antennas, quantifying strata effects and expected values of underground noise, together with the use of compact ferrite rod antennas for reception purposes. A study was also undertaken on the possible use of exploiting existing commercial high power surface AM transmitters in order to transmit emergency paging messages underground.

Task 4.2: Development of emergency location and tracking system

Development involved three areas (i) work on the location and direction finding receiver as an onward development of the Polish industry GLON-GLOP system, (ii) work to adopt appropriate standardised tracking protocols in the Mine Infrastructure Computer (MIC), and (iii) the evaluation and certification of sub-system components to accomplish physiological monitoring of rescue staff. Whilst the GLON-GLOP system for locating miners, including those entrapped by falls of ground, is highly regarded, the system demands a high level of skill from the operator in order to make a precise location determination. Furthermore, only one location transmitter can be examined at any one time. The use of a dual mode, dual frequency location transmitter in conjunction with a highly advanced range and direction finding receiver was an enhancement both in terms of simplicity of operation and the ability to monitor multiple transmitters. The system also provides for a legacy mode that is compatible with the existing emergency GLON location devices. The functionality and performance of this scheme has been proven.

The tracking and location software function was developed for the Mining Infrastructure Computer (MIC) nodes and central systems. The software can be used to track any generic type of WLAN device. The protocol development was completed and laboratory tests performed with five network nodes. Suitable interfaces to third party visualisation systems were also made available. These interfaces use open standardised protocols and thereby conform to the IREDES (International Rock Excavation Data Exchange Standard) tracking standard. Studies and experiments were carried out regarding the options available for determining ‘vital signs’ physiological status data. The system adopted uses a chest belt sensor configuration, which is very rugged and is used principally by military and emergency service personnel. The technology provides wireless transmission of human physiological status information together with movement data using an integral tri-axial accelerometer.

Task 4.3: Development of independent rescue team to surface communications

The studies lead to the development of rescue team communication systems from two independent approaches. Each was essentially tailored to the specific local requirements of the German and Polish mining industries respectively. The research approach has been for the German partners to develop a wide area wireless trunked radio, with Polish partners researching a rapid-deployment fibre-optic cable-based system. The German system development employed a new innovation in coal mining – TETRA (TErrestrial Trunked RAdio) systems, operating in the 400–800 MHz spectrum. TETRA technology is widely used by emergency services and in surface hazardous industries. Significant effort was expended on technical developments and discussions with a Notified Body to achieve M1 certification standard. For testing and evaluation purposes, the training mine TBW of RAG in Recklinghausen was used. A concept was developed which permits the operational range to be extended using an optical fibre in conjunction with TETRA radio expanders. The system meets all operational requirements, including providing full coalface radio coverage. The basic concept of the Polish system comprises the use of emergency-deployable battery-operated wireless modules that provide connection into a fibre-optical ‘back-bone’ link ensuring radio coverage along the entire route. The fibre, used primarily by the military, can withstand exposure to severe mechanical conditions. The core wireless technologies provide communication and location means as well as transmission of a rescuer’s physiological monitoring sensor set. The system uses bone conducting microphones to enable operation with a full face breathing apparatus.

Task 4.4: Construction and testing of prototype digital group communication system

One advantage of a TETRA system approach was that it could unite all required features and functionality; these include digital radio, analogue radio, mobile data transmission and mobile telephony possibilities. Furthermore, all conceivable radio structures are supported under TETRA. One significant drawback was encountered; namely that hazardous area TETRA devices were certified only for Group II (surface petrochemical industry), which inferred only ATEX M2 equivalence. However, rescue equipment in general requires ATEX M1 certification. Therefore significant effort was required on technical investigations, related equipment development and technical discussions with a Notified Body towards achieving M1 certification standard. Associated work was also done to appraise the options for providing an un-interruptible power supply capability. The network communications concepts identified under Task 4.3 have been shown to offer a solution that addresses both the requirements of rescue teams, together with meeting the day to day requirements in the production zone. In addition to the integrated networked communication system, based on TETRA technology, the parallel development took place of a dedicated rescue communications link using a rapid-deployment lightweight fibre-optic cable. Successful field trials on this system were carried out by CSRG.

1.5 WP5 – CENTRAL SAFETY MANAGEMENT

Task 5.1: Development of a localisation and visualisation support system

The development work reflects a tiered approach. At the upper tier, the system integrates with various mine databases and sources of real-time information to provide a standard visualisation environment with selectable intelligent filtering of represented data. Technical reviews were held with RAG and the rescue services to define the limitations of current visualisation software and how the applications could be enhanced. An implementation plan was devised to define the tasks required to develop the software tools and upgrade the 3D visualisation system. The required localisation and visualisation support then utilises directly the capabilities of the resilient networked mine-wide, multi-centre approach articulated in WP1. The system in concept is based around the use of central server systems. These systems perform central configuration support and interact with the underground infrastructure during regular operation and emergency support activities. A 'NetCenter' is used for network administration and supervision of the underground network structure. This also supplies the basic data to the 'SafeCenter' enabling this unit to determine hazard locations by evaluating the network failure location. A 'TracCenter' is used for tracking of people, materials and assets, whilst a 'SafeCenter' is used for mine safety applications such as dynamic evacuation guidance and localisation. Additional software tools were developed which can monitor and check the operation of several local mine networks using Zigbee location tags and provide the location data generated by these tags in a form which is accessible to third party monitoring systems. The visualisation support adopts a resilient networking approach with a capacity to provide information both above ground and underground. These studies provided a coherent framework for examining location and visualisation approaches suitable for emergency purposes.

Task 5.2: Implementation of 'intelligent' information processing infrastructure

The work undertaken covered the development and implementation of a Central Safety Management structure with supporting work on the development of person-worn wireless guidance system infrastructure. In order to meet redundancy and resilience objectives, the Central Safety Management infrastructure was engineered to provide autonomous operation, essentially an adaptive behaviour that is able to respond to a range of network failure modes. In this respect, the system has been engineered with several powerful attributes – (i) it can communicate either wirelessly or by wire with the control centre, field elements and tracking devices, (ii) it adapts to any network configuration, (iii) it knows its relative position within the network, (iv) it can decide which field element data should be collected, and (v) it prioritises key information and knows what to do with the information. Once this network was developed, integration of data concerning the mining operational processes, maintenance works, and tracking support for location tags was assimilated under the same platform. The associated software and algorithms have been subjected to extensive stress testing, initially in a laboratory setting and subsequently in an underground deployment. All of the above features and functions have been submitted as a patent application during the project work.

Further work concerned assessing the feasibility of implementing an intelligent guidance scheme to assist evacuation and identification of escape routes. The automatic guidance scheme relies on relative position finding and movement direction analysis. This is accomplished both by the mobile node and the base station. The information on valid escape routes can be sent from the central command centre providing the associated cable infrastructure survives. In the event that the wired infrastructure is damaged, the nodes can still send pre-programmed information such as the route to the nearest refuge. A patent application for the wireless emergency wayfinding system has been filed.

1.6 WP6 – FIELD TRIALS AND TECHNOLOGY TRANSFER

Task 6.1: Human factors and ergonomic appraisal of emergency technologies

These activities were carried out as required throughout all phases of the equipment development and test activities. This has included 'pit-worthiness' and 'fitness for purpose' assessments.

Task 6.2: Demonstration of systems and equipment at selected mines

The partners invested substantial resources in order to implement the various technologies that were researched and developed within RFCS EMTECH. In this regard, major initiatives included the refuge development and testing at Hunosa's Pozo Carrio colliery and UK Coal's Daw Mill colliery. A further major equipment trial was conducted at RAG Ibbenbüren mine where the resilient networking technology was installed and tested successfully. In addition to these demonstration activities, there were several short-term proving tests arranged between the Polish working partnerships, primarily at Guido and Ziemowit mines. It is noted that where significant elapsed time to obtain ATEX certification of systems was entailed, then alternative testing arrangements were made. In the case of DMT and RAG, the demonstration and tests of the TETRA trunked radio system was arranged at RAG's training mine 'Trainingsbergwerk TBW' in Recklinghausen.

Task 6.3: Post-trial critical review and equipment appraisal

Throughout the RFCS EMTECH research contract there was regular discussion and exchange of views between the research partners, various mine operators and the national Mines Inspectorates. The issues relating to self-escape were considered on several occasions by mining industry working groups. In addition, there was frequent international contact maintained with other experts. Each of these activities provided an opportunity for a critical appraisal of the research conducted, together with identifying additional measures that should be considered. The post-trial review represents one phase of these regular activities.

Task 6.4: Conclusions and recommendations

Emergency preparedness and emergency management are core safety concerns. The outcomes of the trials and related tests, together with the identification of training needs and the proposed approach to the implementation of new technologies were incorporated as a keystone within the programme's review of conclusions and recommendations (lessons learned). This included detailed appraisal of required dissemination activities.

Task 6.5: Preparation of training materials and training on the application of new technologies

This matter was given a high priority as the research was delivered. Various training initiatives were developed by the coalmine operators and rescue services. This includes expectations training for evacuation and wayfinding through smoke, induction training on the circumstances for seeking refuge and how the refuge technology should be initiated and used. Further technology or system-specific training has been devised to support the new networking, communications, personnel location and guidance technologies. The manufacturing partners have also provided technical manuals and installation/user instructions for their products.

Task 6.6: Dissemination of results

Dissemination activities included the publication of several scientific papers, patents and discussions with mining company system and technology specialists. These were progressed as required. The studies were also supported by a regular exchange of views with international experts. A further dissemination and information exchange mechanism was in attending key conferences, including the biennial International Mines Rescue Conferences. A co-objective here has been to strengthen the reputation of the RFCS programme and disseminate information on the research activities and achievements.

2 Scientific and Technical Description of the Results

2.1 Objectives of the Project

The objectives of the project are summarised here in terms of key innovation objectives, together with identifying the principal research aims and expected outcomes for each Work Package.

Key Innovation Objectives

- 'Safety capable' underground network infrastructure with adaptive behaviour and high survivability prospects.
- Evacuation modelling and real-time support – e.g. self-escape routes, escape time prognosis, affected mine areas, environmental conditions, tenability.
- Resilient messaging over entire mine, selected areas or to specific personnel.
- Fit-for-purpose mustering station and refuge designs with secure air supplies, managed thermal environment, contaminant removal.
- Wayfinding and navigation support through dense smoke.
- Advanced emergency location and communication systems with long range strata penetration capabilities.
- Provision of a high-resilience infrastructure for rescue team communications.

WP1 – Resilient Response Capability from Infrastructure

WP1 Research Focus	Expected Outcomes
• System assessment of resilience ('survivability'). • Development of 'safety capable' Ethernet-based infrastructure. • Provision of independent UPS power sources.	• Appraisal of 'survivability' of current communications systems. • A methodology for analysing and optimising system resilience. • Self-healing, automatically reconfigurable underground network infrastructure. • M1 ATEX UPS power sources.

WP2 – Incident Status and Decision Making Support

WP2 Research Focus	Expected Outcomes
• Evacuation modelling and decision support. • Integration of multi-sensor information into underground mine safety network.	• Knowledge of POCs and fire characteristics, tenability criteria. • Evacuation route modelling and decision impacts against various scenarios. • Information on emergency situation (fire location, zone endangered, viability of escape routes, personnel location etc.).

WP3 – Systems and Procedures to Enable Self-escape

WP3 Research Focus	Expected Outcomes
• Staged evacuation – refuges and mustering stations, refuge internal support systems. • Problems of reduced visibility, thermal issues.	• Specifications and guidance for use of refuges in coal mines. • Development of refuge support technologies. • Implementation of prototype refuges. • Escape route protection. Evacuation support in low or nil visibility.

WP4 – Search and Assisted Rescue

WP4 Research Focus	Expected Outcomes
• Long range, emergency through-the-strata location and communications system (inc. trapped/buried persons). • Wide area rescue team communications.	• Accurate earth penetrating location and messaging systems (incorporated within cap-lamp). • Independent high resilience, lightweight rescue team communications.

WP5 – Central Safety Management

WP5 Research Focus	Expected Outcomes
• Management of incident information to provide best available decision making support. • Dynamic and situation-dependent messages for the workforce/ rescue workers.	• Ability to broadcast messages over entire mine, selected areas or to specific personnel (e.g. rescue team leaders, entry controllers etc.). • Visualisation support for incident response teams including mineworkers' locations (or last valid location).

WP6 – Field Trials and Technology Transfer

WP6 Research Focus	Expected Outcomes
• Systems field testing in several different locations and various conditions.	• Confirmation that systems operate and demonstrate 'fitness for purpose'. • Promotion of linked dissemination and training activities.

2.2 COMPARISON OF INITIALLY PLANNED ACTIVITIES AND WORK ACCOMPLISHED

There were two developments that impacted on the delivery of the planned activities.

1. The project start was delayed by four months. This delay was recovered with minor extensions to some tasks. The timing of the deliverables substantially followed the contract.
2. Partner Embigence GmbH withdrew from the project and had to be replaced. Embigence input ceased effectively at January 2009. The withdrawal was a strategic decision of the parent company, Becker Mining Systems AG. No monetary or IPR claims were made by Becker. A new partner company Minetronics GmbH was proposed by the Consortium. Subsequent to demonstrating compliance with the Commission's financial guarantees and financial risk appraisal criteria, the core Embigence work was transferred to Minetronics, and the non-core work to Aitemin and DMT. An amended contract was issued. The transitional arrangements to the new partner were considered to be effective.

2.3 DESCRIPTION OF ACTIVITIES AND DISCUSSION

2.3.1 WP1 – Resilient Response Capability from Infrastructure

2.3.1.1 Assessment of current mine communications infrastructure (Task 1.1)

The assessment of mine communications infrastructure in terms of its resilience to failure modes and system availability after an emergency incident has been appraised from both an EU and international perspective. The work reported against this task has been split into three components.

- A review of international studies on mining system resilience and related initiatives.
- Scoping studies of current EU mining industry communications practices, statutory requirements, review of systems in place, their resilience, limitations and scope for improvement.
- General studies on the methodology and application of system resilience assessment techniques.

International studies to assess post-accident communication system survivability

Studies undertaken in the US by CDC NIOSH (National Institute for Occupational Safety and Health) and MSHA (Mine Safety and Health Administration) have been assessed comparatively along with earlier studies in Australia, Canada, Japan, South Africa and elsewhere. Overall conclusions suggest...

- Interoperability between systems is limited
- Solutions are often site-specific
- Further development of technologies is required.

The approaches considered to offer the greatest potential in terms of system survivability involve...

- Engineering multiple pathways
- Engineering system integration
- Engineering systems that will adapt and use whatever transmission path survives.

The current focus is on telecommunications systems, which can achieve their survivability through design. This primarily involves...

- Hardening of system components, and
- Incorporating redundancy – power supplies, connectivity and increased radio coverage.

Extensive communications studies are also being conducted on self-healing networks which exploit true physical route diversity to provide maximum system survivability. It is noted that significant research has been undertaken in this field within ECSC project PR-133, and RFCS projects IAMTECH and RAINOW. This work has been taken into full consideration.

Industry questionnaire across the mining industries of the European Union

A questionnaire was set up and issued via the project partners to mining companies in order to investigate the current status quo of their underground communication systems. The questionnaire raised dedicated questions about the current status of underground phone communications, 'leaky feeder' communications, public address intercom systems and SCADA data communication for ventilation and environmental monitoring and control. The results confirm that none of the systems involving traditional point-to-point cabling would be able to fulfil demands on survivability, resilience and functional safety. In the case of bus lines, analogue phone systems or leaky feeder installations, the limitation is a use of single ended or star topology point-to-point cabling. If a backbone cable is destroyed, then all the subsequent parts of the mine supplied from the critical node lose communications. The work on reviewing national practice, guidance and standards has also identified a range of good practices. In the case of UK Coal, for example, their SCADA (supervisory, control and data acquisition systems) framework document explicitly recognises various measures to enhance resilience, including the use of a fibre-optic ring main for backbone communications. The overall position from the survey can be gauged from the table below.

Criterion	Telephone	Leaky Feeder	Intercom	SCADA	Ethernet
Statutory requirement	Yes	No	Partly	Yes	No
Power supply robustness (UPS)	Good	Good	Good	Good	Good
Cabling robustness	Poor	Poor	Poor	Poor	Good
Local accessibility	Poor	Poor	Poor	Poor	Good

Table 2.3.1-1: Overview of EU mining communications system practice and resilience

The questionnaire also surveyed cabling and power supply resilience. Whilst redundancy in power supply arrangements can be engineered, cabling resilience is in general very poor. In most cases, star topology point-to-point cabling is used providing no redundancy at all. In the case of a single line component arterial trunk cable being cut, all associated safety related data and voice communications are disabled. Furthermore, current safety-related data communication systems are generally not designed to establish local access to safety related data acquired using the systems. A reason for this is that the functional system design often involves the logical data processing being performed in a central above ground location.

The questionnaire approach was also extended to review resilient communications practices in surface tunnels and how the national transpositions of European Directive 2004/54/EC on minimum safety requirements for tunnels in the trans-European road network are being implemented. This Directive establishes mandatory means of communication within tunnels, depending on their length. Taking the most restrictive case of a tunnel, say 1 km long, then a radio communication system, a public-address system, and intercom system must be installed in order to achieve compliance. In addition, fire detection, ventilation, CCTV and traffic information systems are required, and the equipment installed inside tunnels must be fire resistant up to 90 minutes, flame retardant, halogen-free and have low smoke emissions. As a general observation surface tunnels, largely because of their fixed infrastructure, now implement a range of relevant design and installation measure to enhance resilience. These measures have been noted.

Formal safety assessment methods for mining (communication) systems

The further stage of work within Task 1.1 has concerned a fundamental review of the role of formal assessment methods for evaluating the survivability of mine communications infrastructure. The intention here has been to evolve a straightforward, practical methodology with generic application potential. This can then be used to provide a representative EU overview of the resilience of currently installed systems, together with identifying key areas requiring attention. This work has inputted directly into subsequent tasks within WP1 and WP5.

As far as can be ascertained, there are no formal methodologies employed in the EU mining industry (or indeed in mining industries elsewhere) at the present time to quantitatively assess the safety and resilience of critical mining communications infrastructure. The majority of studies to date have concerned the functional safety assessment of programmable electronic mining systems (PES). There remain fundamental questions as to how well suited IEC 61508 and other formal safety standards are to assessing of the survivability and resilience of systems to various major incident scenarios. For this reason, the partners have assessed hybrid approaches involving SIL, FMEA, 'what if' scenario analysis and standard risk assessment tools. Specific technology studies have focussed on Ethernet technology, which is considered a primary candidate for engineering high resilience systems.

2.3.1.2 Re-engineering of mine infrastructure to achieve resilience (Task 1.2)

As part of the work programme, an analysis of resilient communications technology use in other industries was undertaken. This confirmed that Ethernet technology is increasingly being deployed in safety related applications. Ethernet-based systems are employed in safety critical applications such as naval ships, where the entire communications between the bridge and the engine room is performed via Ethernet designed as two fully redundant rings routed via different cable ways. Ethernet-based communication is also used for dynamic evacuation guidance in big residential buildings, administrative buildings and hospitals.

Further work has involved a systems analysis of functional safety related demands and the design of underground Ethernet communications. A study was completed; the results of which can be summarised as follows.

- Ethernet is considered suitable for use in safety related underground communication systems.
- There is sufficient experience in other industries regarding safety related Ethernet communications to suggest that this approach may be adopted with relatively low technical risk.
- Due to the special infrastructure demands and hazards in the underground mine environment, the use of ring structures alone may not be sufficient for a high resilience network and fully meshed structures may be required.
- Automatic error recognition and recovery is a prerequisite system capability.

Subsequent work within this task has concentrated of high resilience Ethernet-based underground communication infrastructures. One particular research topic was the use of meshed structures and topologies within underground networks. More specifically, if an underground tunnel is regarded a vector and an underground tunnel crossing a node, a vectorised mathematical model of the mine can be created. If at each crossing an active network component is installed, supported by a cable originating from this crossing running through each tunnel, then the network layout will completely match the vectorised physical tunnel layout of the mine. This is the essential concept for the meshed network structures that have been researched. In an analogous fashion to the underground tunnel labyrinth leading to two or more different exits, the data packets are equally able to follow different paths and can automatically search and route a path under a range of situations. A network layout with high redundancy is set up by this means.

Various candidate meshing functions and protocols have been researched for use within the experimental network infrastructure, and which have addressed different prerequisites including data rates, availability, network security, usability in wireless and wired infrastructure and so on. The resulting preferred layout consists of ring structures conforming to a main backbone with interconnections between the rings mainly used to provide redundant pathways. If the ring now fails in one point, the data packets can be routed in the other ring direction. If there is a second failure in the ring, the data packets from devices completely disconnected from the ring can be routed via the backup mesh links to another ring. The principles of meshed redundancy are shown below in the figure below.

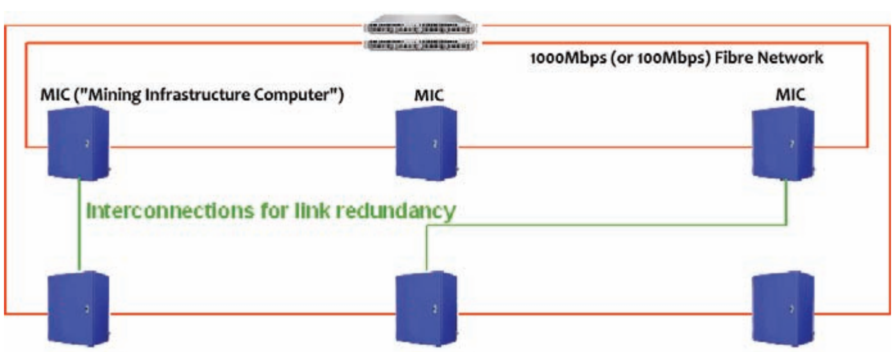

Figure 2.3.1-1: Principle of meshed redundancy

If all tunnels are equipped with network links, this infrastructure set-up provides the highest possible physical link redundancy in a mine and is therefore suitable for use with safety related applications.

Other safety related network functions have also been researched and designed. This work relates to the survivability of the network in case of multiple network interruptions and in case of a complete loss of the communication to above-ground servers. The operation modes and the operation mode switching for all the failover functions were analysed and designed. To meet a worst case situation, it is of vital importance that the network underground is able to replace the functions of the central (surface) servers as far as emergency support functionality is concerned. To implement such functions, the high resilience network requires 'intelligent' electronics to be used in each network node. Such a network node has been developed and has been named a 'Mining Infrastructure Computer' (MIC). The first prototype was commissioned underground in February 2010 and deployed in regular field trials from August 2010. From the prototyping experience, several improvements have been incorporated into the design, including an LCD display for status messages, which can also be used to provide safety information to mineworkers in the event of an emergency.

Figure 2.3.1-2: Mining Infrastructure Computer in enclosure with electronic modules

The MIC unit combines a highly energy-efficient embedded microcomputer (important for ATEX equipment), a fibre-optic Ethernet switch and up to three wireless LAN transceivers. The safety functions run as software applications using the system's microcomputer. The system design also introduces the first intrinsically safe certified fibre-optic Gigabit LAN connection. The modules and the system have been certified to ATEX intrinsically safe standards, permitting the device to be used in coal mining operations throughout all EC Member States. Arrangements have been made for commercial product manufacturing companies to take on larger scale product manufacture.

2.3.1.3 Power supply infrastructure to ensure post-incident availability (Task 1.3)

This task was associated with the design, development and certification of an ATEX M1 Uninterruptible Power Supply Unit (UPSU). Securing resilient response from the mine communications infrastructure requires the transmission infrastructure and power supplies to be engineered for automatic recovery in case of partial network breakdowns or damage and mains power loss. To secure this, the network needs to be provided with multiple redundancy features. Hardware redundancy and dynamic packet re-routing are two key approaches here, and it is also necessary to equip critical sub-systems with a standby power source capability. This unit is a key component in that any measures to increase networked data transmission resilience must generally include some means of providing battery back-up for when the mine power network is either damaged or manually isolated.

The specification adopted for the product was considered challenging in design terms. In addition to Minetronics' specification meeting German industry requirements, Aitemin also evolved an equipment specification to meet Spanish industry requirements to provide a UPSU compatible with existing underground controls and cabling systems. These requirements are summarised in the tables below.

Parameter	V_{nom}	I_{nom}	Capacity	Cable length	L_o/R_o
AITEMIN	14 V	1 A	2 h	> 300 m	> 30µH/Ω
MINETRONICS	12 V	1.8 A	4 h	< 100 m	Not relevant

Table 2.3.1-2: Generic power supply specification
Minetronics generic specification and Spanish legacy equipment specification

V_{nom} (V)	I_{nom} (A)	U_o (V)	I_o (A)	L_o (µH)	L_o/R_o (µH/Ω)	Overall Efficiency	Duration (h) 1 pack / 2 pack	
14.0	1.000	14.4	1.184	330	30.5	80.6%	4.9	9.7
12.5	1.750	13.0	1.928	125	n/a	83.9%	3.2	6.5
12.5	2.000	13.0	2.232	90	n/a	84.9%	2.9	5.7

Table 2.3.1-3: PSU performance parameters
(design values, operating from battery)

In the above table, line one corresponds to a UPSU suited for powering existing Fieldbus-based distributed control equipment. The second line refers to mixed applications; Fieldbus systems using Zener limiters in the cabling system and also high power standalone equipment. The third line corresponds to a UPSU suited for powering high power single devices, e.g. access points, media converters.

Whilst the two sets of industry requirements were not directly compatible, an analysis showed that it was possible to design a family of UPSU sharing enclosure and circuit arrangements, in which the change of a few components would allow the respective designs to be realised. Moreover, it was decided that the most convenient approach would be to split the UPSU into two functional modules; the main ATEX M1 Power Supply Unit (PSU) and the battery pack, each powered from 240 V mains, and which included their own monitoring circuits (with a galvanically isolated intrinsically safe serial interface). This is a relatively efficient solution, with each UPSU variant comprising a PSU module and one or more battery packs, whose number is dependent on the application (i.e. autonomous operating period) requirements.

Safety and certification-related aspects (protection modes, energy limiting techniques and battery technology) were discussed with the Notified Body before committing the critical aspects of the design, and battery cells were submitted for ATEX testing. Further work involved the mechanical design of the enclosures, together with thermal analysis and tests which were carried out in order to assess maximum temperature under normal operating conditions and under internal failure conditions as required by certification standards. Specific development issues are discussed below.

Main Block (Power Supply Unit): Some issues were identified with the first design of the PCB regarding switching regulator efficiency and overheating in transistors involved in the power stages. The revised circuitry demonstrated much better performance, both in terms of power efficiency and thermal behaviour. (The temperature of transistors when working at 80% of the maximum load of the PSU is less than 50°C, which is consistent with high reliability requirements).

From the point of view of the product certification, some additional improvements were also incorporated. The most important of these was the limitation of the let-through energy (essentially the maximum amount of energy over the nominal output limits capable of being provided by the PSU in the event of failure). According to the ATEX standards, this energy should always be less than 260µJ and the analysis must account for the transient behaviour of the circuitry. Basically the factors involved are (i) the maximum voltage, (ii) the maximum current and (iii) the time period during which these two parameters limits are exceeded.

The employment of high power switching regulators within the design obligates the use of high capacitance energy storage elements (electrolytic capacitors). These elements could discharge additional stored energy through the output terminal, in the event of short circuit in the cable line for example. This could exceed the permitted let-through limits. After performing an in-depth analysis and several supporting laboratory tests using different protective circuit topologies, a triple crow-bar circuit was employed to keep energy values under specified limits (the triple unit redundancy is established practice to meet a two fault failure analysis required as part of the system certification process). The integration of ultra-fast comparators and ultra-fast thyristors resulted in a power supply that can limit overcurrent in less than 4 µs and overvoltage in less than 500 ns. The figure below shows the limitation of transient energy release under short circuit conditions and the final prototype of the main PSU circuitry.

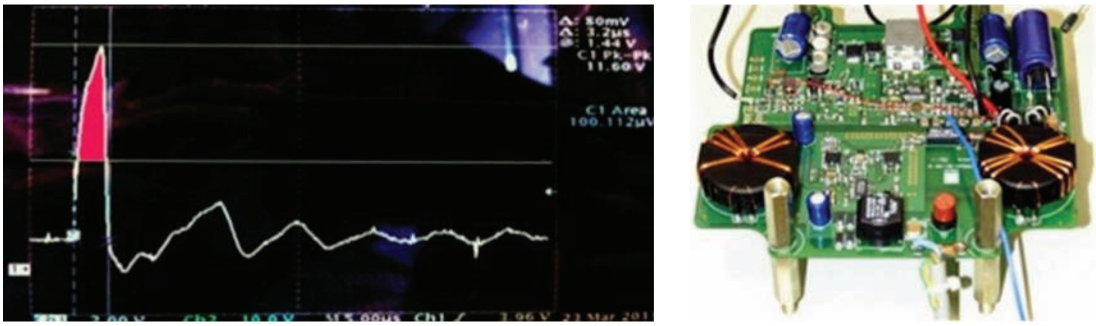

Figure 2.3.1-3: Power supply detail

Left: Short circuit energy release (< 260 µJ, shaded pink). Right: Final prototype of main PSU PCB

Battery Pack: After unfavourable results from the initial tests performed by the Spanish Notified Body (LOM) using $LiFePO_4$ cells, additional experiments were carried out using conventional lithium cells with a nominal capacity of 4 Ah. These tests were performed according to the procedures described in ATEX standards; however the results also showed that the battery type, as tested, cannot be certified. The figure below shows the effect of short-circuiting the 4 Ah test cells. The open flames, incandescent sparks and excessively high cell temperatures are not permitted.

Figure 2.3.1-4: 4 Ah lithium cells during tests performed at AITEMIN laboratories

Although the $LiFePO_4$ cell technology was not rejected unequivocally, the development of the battery pack continued using lower capacity 2.2 Ah cells in order to reduce the time to market of the product and to finish the development within the EMTECH project timescale. However, the use of lower capacity cells resulted in the UPSU autonomous operating duration not matching the target specification of 4 hours. One solution evaluated was the use of two packs connected in parallel and assembled under the same enclosure. The first UPSU prototypes were delivered in April 2011, with ATEX certification scheduled for completion in 2012.

2.3.2 WP2 – Incident Status and Decision Making Support

2.3.2.1 Pre-and post-incident status information (Task 2.1)

The work within Task 2.1 addressed two related aims,

(i) to input data on gas and temperature conditions associated with fires, which was used subsequently in computational fire and evacuation modelling studies, and

(ii) to develop sensor interfaces and assimilate and process available information, both pre-incident and post incident within the high network resilience mining infrastructure computers (MICs).

Regarding the first of these, a study was undertaken of post-incident gas and temperature conditions associated with fires, and how these are measured. Two types of effects can be differentiated. The first type is that of effects produced in the fire areas such as high temperatures and intense production of flame and smoke. The second is the rapid propagation of highly toxic smoke and combustion products through the ventilation circuit, which produces further consequences. Due to heat layering and buoyancy effects, critical ventilation velocities can be reached where air reversal and recirculation can take place. An aspect of the work concerned a review of the complex vertical disposition of workings in Spanish mines and what specific issues arise from this. Various approaches to measurement were reviewed, primarily covering Spanish practice. However, this was augmented by taking into account approaches offered by other Member States, which involved inputs from the Polish, German and UK project partners. Practice in the Czech Republic was also taken into account, where information was available. The studies included a survey of actual conditions and equipment installed in representative mines.

The second area of work involved an analysis and design of the system for safety enabled network infrastructure. This included the specification of safety-related functionality and their consideration in the design of the network node components. In order to combine such information and to create a local situation overview, software development was undertaken relating to a so called ‘Topology Application’ as a central function to enable each MIC to create a comprehensive and independent picture of the safety situation. The network nodes provide functionality that includes automatic tracking of all devices in the proximity using the wireless LAN client identification and radio signal characteristic. This information is forwarded continuously to a central server above ground (the ‘Tracking Centre’, see Task 5.2). Furthermore, the tracking information is stored on the network node for a certain amount of time so the information of ‘who is where’ is available within isolated network islands underground in the event that the above ground communications links are lost. This provides a complete record of tracking and location information, at least up to the point of a major incident.

The generation of pre- and post-incident status information is performed by the network nodes in a stand-alone mode, which does not require any contact with above ground computer systems. The MICs do not require the assistance of central systems for this purpose, as these systems may not be accessible via the network in an emergency situation. This is a powerful system attribute. Information on emergency egress options is computed by the MICs premised on the availability of data from the network links. In order to enable each node and inform the workforce of evacuation options or to guide them to central meeting points, the network topology must be known to each MIC. As each network cable is explicitly associated with the corresponding local underground tunnels, the network cabling infrastructure matches a subset of the physical infrastructure of the mine and the tunnel layout. The process of associating the raw network topology data with the geo-spatial information concerning the mine layout involves the MICs using a mine layout data set, which is downloaded from central systems upon regular boot-up or upon changes and which is stored in non-volatile memory on the MICs.

This geo-spatial information contains information on the roadways between the MICs; including the length/grade of the roadways, location of emergency shelters, fire extinguishers and other equipment needed in emergencies (see under ‘Central Systems’ in Task 5.1). The Topology Application is also required to communicate with neighbouring nodes in order to derive a complete picture of the mine, rather than situational knowledge limited to the surroundings of the particular unit. The critical algorithms for this were verified and subjected to full scale mine testing.

A key benefit of the generic interface design employed is that additional protocols (even proprietary protocols) may be connected in a simple manner without affecting functions already running. Multiple interfaces can be simultaneously connected to the Topology Application. Further interfaces for the network nodes include serial lines to gas sensors and ventilation control equipment. This takes into account the design and implementation of logic interfaces, which are highly application dependent. To inform people underground regarding the safety and environmental situation in their working district, part of the network node specification includes a so called 'lighthouse' function, which for practical reason has been implemented using the LCD display on the MIC network node computers. In an emergency, this provides simple signals or text messages to inform the local mine workforce about the current situation. A further means provided to inform the underground workforce (individually or broadcast) is via texting and voice messaging services issued to personal devices including handheld phones or PDAs. This is used to inform them about unusual operating conditions, alarms or evacuation instructions.

Work was also undertaken on incorporating and evaluating modifications to the location system concept originally developed for monorail tracking purpose in the RFCS MINTOS project. The aim of these modifications was to increase significantly the number of serviced mobile nodes and to reduce the system response time. By this means, personnel and asset tracking, even in congested conditions, is made possible. The target performance was to service dozens of mobile nodes in the coverage area of a single base station. The improvements demanded a migration from a 16-bit to a 32-bit platform together with the introduction of advanced power management schemes. This in turn made possible more computationally extensive processing within the communication protocol. Additionally, a compact real-time location engine, based on VHF time-of-arrival, was successfully integrated into a cap-lamp design (developed as part of task 4.2). The transmitter engineered into the cap-lamp can provide a real time location capability and information on pre-incident personnel deployment.

2.3.2.2 Modelling and prediction of products of combustion transport (Task 2.2)

The work reported in Task 2.2 concerns the modelling work on smoke transport. The objective was to simulate a fire model underground in Pozo Carrio Colliery, Spain in order to obtain a prediction of the smoke movement and its interaction with the ventilation system of the mine. The information obtained concerning smoke transport was then integrated with the evacuation simulation. The CFD model inputs were predicated on the results obtained from various real-scale fire tests. This enabled the simulation solver to be verified and optimised. The simulation scenario was reduced to critical zones of interest; the fire zone, the area where mineworkers are normally working, the zone where the refuge will be located and the galleries from the work areas to the refuge station or onward to exit from the mine. To develop the simulation model in computationally complex zones (including the fire zone, the refuge and the intersections between galleries where the air flow changes its direction abruptly) it was necessary to generate a homogeneous mesh based on 0.15 m cubes.

It was recognised that various combustion-related parameters, such as fire characteristics and real flow conditions inside a mine would need to be studied before the CFD modelling could be developed. In order to adjust and validate the fire modelling to be used, different tests were performed in the fire test gallery at Santa Barbara, located at Leon, Spain. The mine where the fire test gallery is located is also similar to the typical structure of Hunosa's current coal mines, with working levels divided into sub-levels, with a main entrance and exits to the surface via the upper levels.

As a first step, resources were concentrated on commissioning the test facility to run the tests. The necessary instrumentation and sensors were acquired and located in different points of the ventilation circuit of the main test drift and surrounding workings. As part of this process, any necessary computers, electronic I/O modules, cables, transducers were upgraded. In the fire test gallery, nine sections were available for fire experimentation, four sections of which are located ahead of the burning pool, and five after the pool. In each section, three thermocouples are placed to measure temperature. In section 9, there is one gas analysis station, properly constructed and protected from the high temperatures of the flue gases. The station equipment included a flue gas analysing system, O_2, CO, NO_2, NO, SO_2 gas sensors and temperature measurement.

Three tests were carried out, differentiated by airflow introduced into the tunnel. As a result of these tests, concentrations of gases and temperature profiles within the test tunnel were obtained. These provided an essential input into the CFD model to verify the outputs and give feedback to improve the model. A second activity focused on the analysis of the ventilation network at Pozo Carrio Colliery, where the refuge prototype was to be installed. The objective here was to simulate a fire model inside the coal mine in order to obtain a prediction of the smoke movement and its interaction with the ventilation system of the mine. The information obtained concerning the smoke transport would then input directly into Task 2.4 'Evacuation modelling and safe egress routes'.

The airflow Q (m^3/s), dry bulb temperature (T_{DB}), wet bulb temperature (T_{WB}), pressure P (Pa) were measured at a number of places in the mine ventilation circuit. With these data, the ventilation network was analysed with dedicated software, 'VENTILA'. Additionally, information related to the equipment in galleries was obtained in order to calculate the amount of material that could be involved in a fire, which sections and the placement of communication equipment (e.g. phones, intercoms). These data were taken into account in the CFD modelling. Another key point was to determine the influence of fire source location within the model. Several places were considered; the most probable and the most dangerous, leading to a location that fulfilled both conditions, near the end of the conveyor belt run and next to a ventilation shaft.

As points of detail, the simulation model incorporated the following features and assumptions.

- The simulation used a reduced scenario set of the Pozo Carrio mine, which is very large.
- The simulation used an estimated heat release rate (HRR) of 6 MW.
- The fire was located in sub-plant 4, which is 55 metres from the refuge. This location is coincident with one motor of the conveyor belt, which transports mineral out of the mine.
- The ventilation air had a flow value of 1.8 m/s.
- The ventilation door, located near the refuge, was closed in its normal position.
- The fire was simulated as a source of energy and mass, with the fire source represented by a heat release rate fixed inside a given volume. This value is not influenced by the ventilation.
- A reduction of 30% in the HRR has been applied in order to consider the energy lost by radiation near the fire.
- A 20 minute long simulation was employed.

The essential physical aspects of the simulation scenario are shown in the two figures below, including the available escape route options.

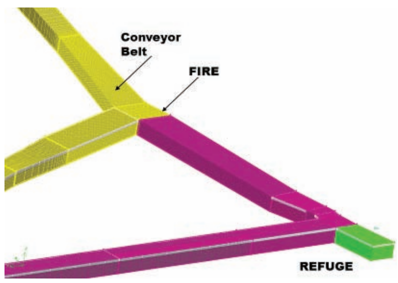

Figure 2.3.2-1: CFD simulation of mine fire, essential features

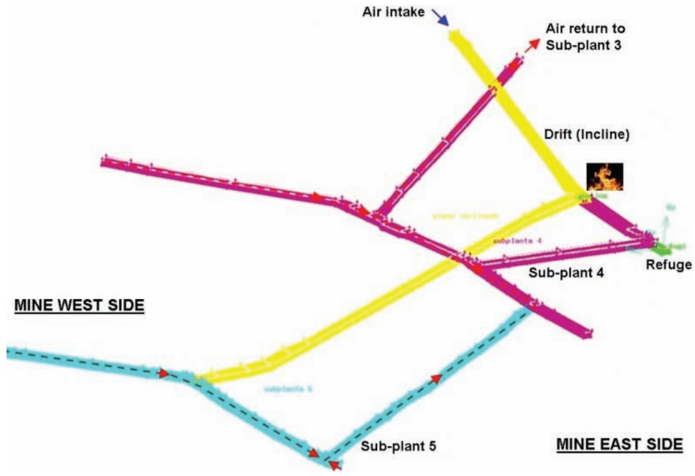

Figure 2.3.2-2: CFD simulation of mine fire, mine gallery relationship, evacuation route options

The geometry of the model includes sub-plant 4 and sub-plant 5 with their connecting galleries and the drift (inclined plane) which is a clean air ventilation gallery. The geometry and the mesh were simplified to reduce the required solver power of the software for modelling less important volumes of mine roadway. The lower 300 m of the drift was represented in the model. The created geometry does not include the vault shape of the gallery since this would generate an overly complex mesh. However the cross-section value used matches the mine value since this feature combined with the air velocity is the basis of the ventilation system analysis and of the smoke movement within the model. Consequently the generated mesh is homogeneous. The fire was analysed against three important parameters – temperature, visibility and toxicity.

Discussion of Modelling Results

In evacuation situations there are two factors that have critical influence on the oxygen cost and available wearing duration of the self-rescuer equipment – physical demands of evacuation and the mine thermal environment. From the point of view of the safety of the evacuating mineworkers, the minimum duration available from the self-rescue devices was assumed to be 20 minutes, which was assigned as the simulation time. The temperature limit was assigned to be 80°C, this value indicated by NFPA and PIARC recommendations. The analysis of the smoke movement illustrates how the hot smoke affects the tenability of moving along specific evacuation routes. Discussions with Hunosa specialists confirm that this is a worst-case analysis, since the build-up rate of previous underground fire incidents has been somewhat slower in practice, allowing more time to escape via various routes. Within the analysis, after about three minutes from the fire starting, the smoke has not arrived within the sub-plant 5 zone; the sub-plant 4 and its intersection with the gallery that ascend to the sub plant 3 also remain free of smoke. However, five minutes from the start of the fire it is not possible to traverse from the east side of sub-plant 5 to the refuge or the exit of the mine. If the door located near the refuge were to remain closed, it would be possible to exit from the west zone of the sub-plant 5 to the sub-plant 4 and then to the gallery which goes to the sub-plant 3 during the entire 20 minutes of this fire simulation.

For the last ten minutes of the simulation the temperature conditions remain relatively steady. The temperature conditions which are needed to reach the refuge through the door, which is located near to it, or the exit mine, through the gallery that ascends to the sub-plant 3, are tenable throughout the 20 minutes of simulation. The inaccessible zones due to high ambient temperatures are the zones near the fire, the area in the intersection between the drift and sub-plant 4 and the zone located between the refuge and the fire. It is not possible to evacuate to the exit through sub-plant 4, the only access to the exterior then being through sub-plant 3. Analysis of the temperature contours shows a short back layering, where the critical velocity of the smoke is lower than the air velocity in the ventilation gallery. The distribution of the smoke takes the same path as the clean air through the ventilation system down to the deeper sub-plants (levels) of the mine. Ten minutes after the beginning of the fire, the smoke has filled all the geometry of the model, there is not smoke stratification and the visibility is zero.

Conclusions of Analysis

The principal objective of this work has been to realise a simulation model, based on commercial CFD code that can be used to predict smoke movement in the mine. With the analysis of the results of the simulation it was determined that smoke products are transported to all areas covered by the mine fire scenario within ten minutes of the fire beginning. The results show the possibility of high temperatures (greater than 80°C) in the zone of the refuge, although this is considered a worst case scenario. High temperatures are not observed throughout the drift, which is the main air intake. At distances greater than 40 m from the fire up the drift, the temperature values are close to ambient values. Only near the seat of the fire are temperatures observed to be higher than 80°C.

High temperatures are however observed downstream of the simulated fire. In sub-plant 4 the temperatures are higher than 80°C and it would quickly become impossible to use this route to leave the mine. On the other hand, in sub-plant 5 and between sub-plant 4 and the gallery that ascends to the sub-plant 3, temperature values are no higher than 30°C providing a tenable route (at least in thermal environment terms) to leave the mine. However, it is recognised that the ability of evacuees to think clearly when exposed to smoke decreases with increasing smoke density and the heat associated with hot smoke.

The modelling and fire simulation carried out for Pozo Carrio mine confirm that the research approach of using a fire source represented by a HRR fixed inside a volume, leads to realistic temperatures except very near to the fire, around 5–10 m from the fire seat. In this zone the analysis requires a more sophisticated treatment. It is also observed that smoke is transported throughout the mine, which loses buoyancy and descends when in contact with cooler air and cold walls. In this case visibility is often close to zero and only the miners training and their knowledge of the environment can allow them to reach a place of safety.

However, in terms of emergency planning, there are only two zones which would be cut off due to the high temperatures of the smoke; one of them being the ‘cul-de-sac’ at the easterly part of sub-plant 5. To evacuate from this district, the mineworkers should cross the intersection between sub-plant 5 and the gallery that ascends to sub-plant 4. This zone reaches a temperature value of 80°C five minutes after the fire commences. The other zone that is cut off is the refuge external area, which fills quickly with hot smoke with a temperature greater than 80°C some five minutes after the fire commences. Under the specific fire conditions this would not allow the miners to approach the refuge.

The modelling has been supported by extensive analysis of case studies of previous fire incidents, which generally suggest slower rates of fire growth. It is also recognised that the model scenario of a developed fire in an intake represents a worst case. However, all emergency planning and risk assessment activities must account for such scenarios.

2.3.2.3 Psychrometric impacts of mine fires (Task 2.3)

The main objective of this task was to assess the expected thermodynamic conditions inside a mine in case of fire, and compare them with tenability criteria for humans. Another objective in this task was to analyse from a multistressor perspective the consequences on the conditions for evacuation of various factors including thermal physiology, psychological stress, ocular irritation, disorientation and lack of information. This work also provided support to activities in WP3, primarily in Task 3.2. Studies undertaken within RFCS EDAFFIC on safe working duration for firefighters were also taken into account. In terms of delivery of the work, Geocontrol, Aitemin and Hunosa concentrated on assessing tenability criteria, primarily under radiant heat conditions, whilst MRSL, UK Coal, CSRG and RAG focussed on uncompensated (uncontrolled) body core temperature rise associated with evacuation under severe heat and humidity conditions. Sectoral information was collected from dialogue with a wide range of institutes and research departments linked to the mining industry, including INSHT (Spain), HSE (UK) and NIOSH (US). Possible strategies identified to deal with heat during evacuation were examined. This included evaluating the impacts of dehydration, self-pacing, heat acclimatisation, pre-cooling, hyper-hydration, and smoke impacts, together with the role of heat index and mine regulations. This work identified a number of critical issues regarding, in particular, the roles of dehydration, self-pacing and eye protection.

In order to understand and interpret the objectives of fire regulations and fire safety it was necessary to have knowledge of fire physics and the tenability limits for escaping personnel and firefighters. The work on simulating the evacuation of mineworkers from a mine required key data, including mean walking speed and the time between the fire initiation and the commencement of evacuation, which consists of time for detection, alerting, reacting and leaving the mine/reaching a refuge. Fire produces high temperatures and thermal radiation, lowers atmospheric oxygen concentration, lowers visibility and produces a lethal complex of toxic and corrosive products of combustion. All these physical phenomena, some of which can be calculated with some degree of accuracy, have required assessment. In this respect the following key observations and findings have been made.

Exposure to heat can lead to a life threat in three basic ways, (i) hyperthermia, (ii) body surface burns, and (iii) respiratory tract burns. For use in the modelling of life threat due to heat exposure in fires, it is necessary to consider only two criteria; the threshold of burning of the skin and the exposure at which hyperthermia is sufficient to cause deterioration in physical and mental abilities and thereby threaten survival. Thermal burns to the respiratory tract from inhalation of air containing less than 10% by volume of water vapour do not occur in the absence of burns to the skin or the face. Thus, tenability limits with regard to skin burns are normally lower than for burns to the respiratory tract. However, thermal burns to the respiratory tract can occur upon inhalation of air above 60°C that is saturated with water vapour. Furthermore, the limit of tolerability for breathing water-saturated hot air (in the short term) has been empirically determined to be around 53°C.

The tenability limit for skin exposure to radiant heat is approximately 2.5 kW/m^2. Below this incident heat flux level, exposure can be tolerated for 30 minutes or longer without significantly affecting the time available for escape. Above this threshold value, the time to burning of skin due to radiant heat decreases rapidly according to the following equation

$$t = 4q^{-1,35}$$

where t is the time in minutes and q is the thermal radiation in kWm. Radiant heat tends to be directional, producing localised heating of particular areas of skin even though the air temperature in contact with other parts of the body might be relatively low. Skin temperature depends on the balance between the rate of heat applied to the skin surface and the removal of heat subcutaneously by peripheral blood circulation. Thus, there is a threshold radiant flux below which significant heating of the skin is prevented but above which rapid heating occurs. Thermal tolerance data for unprotected human skin suggests a limit of about 120°C for convection heat, above which there is, within minutes, onset of considerable pain along with the production of burns. Depending on the length of exposure, convective heat below this temperature can also cause hyperthermia.

Thermal physiology is the most widely researched field of the above factors. Progressive heat strain effects include; *heat cramps*, *heat exhaustion*, *heat syncope* and *heat stroke*. Under the most extreme conditions, the body temperature regulation fails. The studies included assessing the impact of factors related to heat during evacuation including breathing hot air when using an escape respiratory protective device. This work also included consideration of the physiological benefits of cooling and rehydration within a staged evacuation process. The key observations from the investigation of the psychrometric and related impacts from mine fires are given in an appendix to this report. This includes consideration of each of the following...

- Heat exhaustion presentation and risks
- Impact of dehydration
- Impact of self-pacing
- Impact of acclimatisation (heat acclimation)
- Impact of heat index used
- Impact of mine regulations
- Impact of pre-cooling
- Impact of fluid ingestion
- Impact of eye irritation
- Impact of lack of information
- Psychological issues

2.3.2.4 Evacuation modelling and safe egress routes (Task 2.4)

In Task 2.4, the main objective was to simulate the evacuation process within Pozo Carrio coal mine under fire conditions, taking into account the CFD simulations carried out. The evacuation times were calculated using an advanced Simulation Programme, STEPS conveniently adjusted with real displacement velocities and considering the boundary conditions of temperature and smoke. Details of the numerical code are given in an appendix to this report. Once the simulations were undertaken, it could be established whether nominal places of safety of underground were suitably sited, or whether they could be relocated to improve the overall security of the mine. After analysis of the results, improvements in evacuation times were identified by implementing better fire detection systems, especially in the areas of greatest fire risk. Additionally, enhanced ways to raise the alarm with mineworkers could further improve these times. It was considered that these two aspects together could reduce total evacuation times by two to three minutes. In order to address worst case fire scenarios, it was also considered advisable to include an additional SCSR donning station in the sub-level.

The main achievement of this task has been to establish a very high correlation between the observations from evacuation drills and the simulation models, particularly where the evacuation simulations were repeated to incorporate very precise geometrical data. Refinements made to the evacuation simulation model permitted other arbitrary mine layouts to be analysed without having to carry out corresponding evacuation drills. The process to calculate the evacuation times involves the following stages.

1. Mine selection
2. Establish evacuation routes
3. Selection of simulation software
4. Mineworker characterisation
5. Incorporation of CFD output data
6. Analysis of the evacuation process

It was found that smoke was a key factor influencing the evacuation time. Practical studies confirm that evacuation speed can be reduced to around one third of its nominal value when the visibility distance is three metres or less. In order to adequately account for this speed reduction in the evacuation simulations, a dedicated analysis was carried out for sections of the mine where smoke was considered to be present whilst mineworkers evacuated the mine. One modelling issue that arose in the study of the evacuation process was how to best maximise the zonal coverage of the supporting CFD output data. The process of mesh generation can act as a constraint on the analysis process due to limitations of solver automatic mesh generation algorithms. Developments in solver techniques have resulted in enhanced mesh elements and mesh connectivity. However further work is required to increase the scope of the modelling in order to examine efficiently a number of scenarios and cases underground. An alternative approach could involve the use of simplified fire studies with CFD simulation employed for the principal evacuation route.

One of the key aspects of Task 2.4 was to determine evacuation times under different boundary conditions of a real mine, where there are shafts and tunnels at different levels, so that the calculations performed in the simulations can be validated, if necessary with evacuation drills. Pozo Carrio Colliery, in Asturias was selected since it provides a physical arrangement with different levels, ventilation shafts, mustering points and other elements that influence an evacuation to a point of safety. In order to develop the evacuation modelling, the evacuation routes established in the Pozo Carrio Colliery Emergency Plan were analysed, taking the times estimated for different starting points from the workplaces and passing via the refuge location. The escape times and escape speed in each stretch were measured under normal conditions with two mineworkers with good cardio-vascular fitness walking together at the same time noting that...

- In case of an emergency the time taken to walk through the galleries in the mine may be different from the range of times measured.
- The evacuation time can be considerably extended due to possible confusion, reduced visibility, stress and eye irritation.

The above points are a central requirement to determine the realistic evacuation rates that permit correct evacuation model calculations. The method must also consider average worker physical qualities, the 'difficulty' of the escape route (height, clearances and obstacles, slope, requirement for climbing) and any impairment to visibility. The evacuation rate parameter is fundamental towards setting the distance between self-rescuer changeover stations against known characteristics of the self-rescue apparatus, where for example SCSRs are tested with a ventilation demand of 35 l/min.

The main problem determined here was that mine conditions exceed the standards considered realistic within commercial software, such that it is necessary to adjust (or calibrate) evacuation speed according to real values observed in a variety of evacuation exercises. Towards meeting this requirement of determining a representative and realistic evacuation speed function for the mine workforce, several dedicated exercises were conducted by Hunosa, UK Coal and CSRG (the latter undertaking a large set of measurements). In terms of the specific outcomes and observations regarding the evacuation modelling, the following points are noted.

1. Commercial software runs obey NFPA standards. In this standard, evacuation speed is set between certain values with regard to criteria such as slope or visibility, however none of these parameters matches the real conditions inside a mine (with gradients of up to 14% in Spain, for example).
2. Assumptions regarding mean speed during evacuation and climbing slopes has been predicated on information provided by the coal operators. This is considered reasonable.
3. Another key requirement is to comprehend the procedure of evacuation from a mine, since the routine may introduce periods of time that are not foreseen in the evacuation model. By way of example, the first stage in response to a fire is to try and extinguish the fire if the workforce is near enough and have the means to safely do so.
4. Mustering at a meeting point or refuge and communication with key decision-makers may also need to be carried out, prior to initiating a district or general evacuation.

The first simulation considered evacuation speed as a constant. Subsequent model runs employed a model with variable speed related to the mine gradients present together with data from the mine evacuation exercises. As a further enhancement, the model was amended to account better for the interaction between mineworkers and their respiratory protective devices. The time taken to don their devices and the placement of these devices was taken into account in order to make the evacuation simulation as realistic as possible. This also incorporated an estimate for mean fire detection times.

The evacuation simulations were validated using data from evacuation drills conducted by the coal mine operators. Pre-incident workforce deployment information also needs to be incorporated, since this is critical information in the early stages of a rescue operation.

After adjusting the evacuation speeds for the simulation software application STEPS with correspondence to data derived from real evacuations and other specific studies, all the simulations were carried out using high accuracy reference source data. However, one of the more important aspects to permit comparison between the results of the CFD fire simulation and the evacuation simulation is to determine how the sequence of events develops from the beginning of the fire to the beginning of the evacuation process. Sometimes, especially in slowly developing fires, the fire start time cannot be readily defined as, for example, on a conveyor belt in which friction is occurring. In fast developing fires, this time is self-evident as it matches the rapid appearance of flames. In the CFD simulation, the fire commences within the simulation when a constant Heat Release Rate of 6 MW over a surface of 6.5 m^2 is achieved, which takes five minutes to fully develop in terms of power and smoke release. As a final element of the simulation studies, further consideration was given as to how movement through smoke during evacuation affects the overall speed of evacuation. This is clearly an important parameter, and which has a close relationship with the studies conducted within Task 2.3 and Task 3.4.

Various empirical tests confirm that the speed of locomotion when visibility is zero can be reduced to less than one third of the speed which can be developed under conditions of normal visibility. Studies of the impacts of irritating and non-irritating smoke were examined. As to be expected, there is a strong influence concerning the ocular irritation level experienced from the smoke and its impact on overall progress. Given the cross section of the mine, it is anticipated that smoke products will in a worst case scenario be transported in a fully de-layered form without significant stratification, greatly impairing visibility.

2.3.3 WP3 – Systems and Procedures to Enable Self-escape

2.3.3.1 Refuge and self-rescuer changeover station design and specification (Task 3.1)

The first component of work within WP3 was to examine the strategy for using underground refuges (otherwise known as safe havens or emergency shelters) as part of escape strategy and planning activities. Underground refuges are a central component of mustering and emergency decision making actions, and offer a place where the mine workforce can gather, exchange respiratory protective devices, rest and continue their evacuation, or if necessary await rescue. Emergency preparedness strategies were contrasted for refuges in metalliferous mining (where they are more commonly used) and possible uses in coalmines. Generally, the primary response within the EU has been to evaluate the application of underground refuges as part of a staged evacuation strategy. However the refuge must also be designed to serve if required as a place to shelter until rescued.

An extensive programme was undertaken to assimilate and assess relevant international guidance, regulatory matters and research relating to the use of underground refuges. This work included discussions between partners on their respective member state national arrangements and needs, together with examining experience in Canada, South Africa, United States and Australia. Significant collaborative effort was devoted to the subject of underground refuge design and specification. The difficulty that faced all partners is that there are no national regulations relating to underground refuge design and application (although guidance has been issued by the UK Mines Inspectorate). On this basis, the relevance and insight from US Federal Regulations published on this issue has been scrutinised at length (the regulation referred to originated with the US Department of Labor, Mine Safety and Health Administration: Federal Regulation 30 CFR Parts 7 and 75 (RIN 1219–AB58), *Refuge Alternatives for Underground Coal Mines*, issued Federal Register, Vol. 73, No. 251, December 31 2008, Rules and Regulations pp 80656 – 80700). The US regulations are however limited insofar as they do not necessarily proscribe or detail how the various parameters pertaining to an underground refuge should be implemented.

There are a number of technical differences between the respective positions taken by US Authorities and mine operators and national Mines Inspectorate bodies in the European Union. Of particular note is the US requirement for an explosive overpressure withstand of greater than 15 psi (0.1 MPa) for 200 ms. This parameter has not (yet) been assimilated into any design standards or guidance used in the EU mining industry. Furthermore, the fire resistance, the minimum distance to the working face and the use of apparent temperature climate index limits have also not been adopted, although these parameters have been carefully considered. There is however substantial agreement with the US regulations specified for breathable air supplies. Technical discussions were also held concerning the draft standard developed for Chinese coal mines (*General Technical Specifications of Portable Refuge Chambers for Coal Mines* issued by China State Administration of Work Safety, 2011). Annexes B and C within this document set out explosion proof performance and test criteria, which suggests an even higher explosive overpressure strength standard of 1 MPa.

It is noted that Hunosa and UK Coal have each examined the general guidance available and then developed specific refuge designs appropriate to their respective trial sites at Pozo Carrio and Daw Mill mines. Both coal mine operators selected compressed air as the primary air-oxygen source. This option provides significant benefits, as follows.

- The compressed air provides a high volume flow rate and maintains an overpressure inside the refuge.
- The arrangement is reliable, requires no special maintenance and is the simplest system option. Mineworkers are also very familiar with operating compressed air systems.
- The required plant is already installed in most mines. The cost is therefore potentially low.
- There is no requirement to have dedicated systems to produce oxygen or scrub out carbon dioxide (unless this is part of a secondary air supply arrangement).
- The air is cooled if adiabatic expansion takes place on discharge from the compressed air network.

The studies within Task 3.1 have also examined the options for standby air-delivery arrangements. Essentially the options include (i) banks of large compressed air cylinders fitted with facemasks, hoods, or outlets (ii) oxygen cylinders or chlorate candles (oxygen producing canisters) together with suitable carbon dioxide scrubbing arrangements, and (iii) spare sets of long duration self-contained self-rescuers. Pressurised borehole air supply schemes have also been considered, although for deep mines with intervening water-bearing strata there are considerable engineering and installation issues to address. Each option has been carefully considered, including undertaking generic risk assessments. By example, the explosion and two deaths resulting from self-contained chlorate candle oxygen generators aboard submarine HMS Tireless, 20 March 2008 were analysed to determine if any issues apply to mining use of chlorate candles. In this regard, transportation, storage and maintenance of oxygen generators were identified to be important issues. It is noted that refuge design and specification was kept under continuous review throughout the EMTECH project.

2.3.3.2 Establishment and assessment of comfortable thermal conditions inside the refuge (Task 3.2)

The work within Task 3.2 addressed the issue of whether a tenable thermal environment can be maintained within generic underground refuges, particularly in hot, deep mines and where there is a high occupancy level in the refuge. As noted, compressed air has key advantages of simplicity, large volume flow rate, high cooling capacity, dilution of CO_2, and ensuring a refuge over-pressure hence preventing the ingress of products of combustion into the refuge. However, suitable compressed breathable air sources are not available in all mines and so it may be necessary for mine operators to seek secondary or even tertiary back-up air supply options. For these alternative air supply options, some form of air conditioning will generally be required. With adequate compressed air flow characteristics, the thermal environment should be assured for compressed air supplied refuges. There is also reasonable agreement between UK and US minimum compressed air flow rate guidance figures, with 12.5 cfm/person (0.35 m^3/min/person) cited in US legislation.

The requirement for air conditioning is based on a number of reported tests conducted on sealed inflatable and steel enclosure refuges, which have shown rapid heat build-up when occupied. These tests are supported by numerical modelling thermal entrapment studies. This problem has an international dimension, with most refuge manufacturers recognising the requirement to address hazardous atmosphere refuge cooling. Discussions with staff at NIOSH Pittsburgh Research Laboratory confirm that research is being conducted to determine refuge chamber heat build-up and develop general occupancy de-rating factors, time of occupancy reduction criteria and cooling requirements. The outcomes and observations from the occupancy tests conducted by UK Coal (reported in Task 3.3) are also noted. Here, a definite threshold effect was noted for the compressed air delivery rate where, at the lower flow rate used, the refuge environment was considered just tolerable by the volunteer subjects, who were sitting quietly throughout the trial. Whilst the air supplies to refuges are often site- or manufacturer-specific, a number of broad observations can be drawn, as outlined in the table below.

One parameter difficult to enumerate was the figure that should be used for mean metabolic rate for individuals under emergency entrapment conditions. A number of refuge manufacturers, as part of the relevant US State approval process, cite a metabolic rate of approximately 120 W per person in their supporting engineering calculations. There is a case for considering a higher figure than 120 W. Whilst this figure is accepted for sedentary, low stress conditions, it may not be appropriate to that observed in an emergency situation, despite the emergency preparedness training given to the workforce. Spanish work (in collaboration with the National Institute of Silicosis) proposed a higher figure of 250 W. Research in South Africa and Australia on metabolic rate associated with entrapment in an underground refuge suggests a figure of 180 W, which could increase further in high stress emergency conditions. This parameter is important in that it sets the minimum level of cooling that must be provided to maintain a tenable refuge chamber thermal environment.

Type of Refuge	Description	Thermal Environment?
Sealed underground area	Large 'residual air' sealed underground voids with emergency bottled air/O_2 back-up supply. Suitable for salt/ other mines with very large, stable, void areas.	Probably acceptable, particularly in shallow mines
Borehole air supply	Borehole(s) supplying fresh air via a compressor directly from surface. Suited to relatively shallow mines.	Probably acceptable. High air delivery rates anticipated.
Compressed air fed static	Compressed air feed to cement-block enclosure, shipping container or prefabricated structure. Generally static arrangements, in-house design.	Acceptable only providing compressed air supply delivery rate sufficient and has moderate temperature and humidity
Compressed air fed inflatable	Inflatable purged fabric refuges or canopies supplied by compressed air.	Acceptable only providing compressed air supply delivery rate sufficient and has moderate temperature and humidity
Transportable, oxygen supplied	Sealed transportable steel enclosure providing life-support via bottled O_2 supply, chlorate candles and CO_2 scrubbers. Suitable for large mines where transportation feasible.	Will require supplementary air conditioning of enclosure
Other standby arrangements	Other standby arrangements – compressed air cylinder banks with facemasks/hoods, long duration SCSRs.	Will require supplementary air conditioning if enclosed

Table 2.3.3-1: Overview of refuge types
showing air supplies and the need for supplementary air conditioning

The experimental programme within Task 3.2 involved two aspects; firstly measures to analyse and exploit, to maximum extent, the cooling capacity of compressed air delivered to a fixed infrastructure-based underground refuge. The second aspect involved evaluating the air delivery scheme of the underground refuge at Pozo Carrio mine using thermal imaging and other assessment methods. Further information on both areas of work is provided in appendices to this report. In respect of the first of these, the cooling/air conditioning approaches examined involved the following options.

- Internal air movers (compressed air venturi diffuser, or 'air amplifier')
- Carbon dioxide 'dry ice' sublimation cooling
- Electrical (ATEX) air conditioning units; Carnot, Peltier
- Evaporative cooling to build up chamber coolth prior to use.

Whilst there would appear to be electrical (ATEX) air conditioning units available to meet Zone 2 and possibly Zone 1 hazardous area requirements, no suitable apparatus was identified which met Zone 0 (ATEX M1) requirements, where the risk of secondary explosion is high. However, each of the other cooling techniques appears to meet Zone 0 cooling requirements. Carbon dioxide sublimation cooling can provide useful levels of cooling and is being considered for use in 'sealed' transportable refuges supplied by chemical or bottled oxygen air supplies. However the number of carbon dioxide cylinders for cooling involves an appreciable weight and volume space to meet extended duration refuge occupancy requirements. In addition, a supplementary air mover is required to ensure air is passed through the heat exchanger in which the carbon dioxide is released and sublimated. Carbon dioxide cooling schemes are now being evaluated by a limited number of commercial refuge suppliers.

Of the above options, compressed air supplied by an 'air amplifier' to increase local air recirculation demonstrated considerable promise. This essentially addressed the research issue "*How do we keep the refuge cool if the compressed air supply cannot be delivered at an acceptable flow rate and/or acceptable temperature and humidity?*" It is recognised that suitable compressed breathable air sources may not be available in all required locations within a mine. The compressors can be sited on both the surface and underground. The delivered air characteristics can vary considerably. A limited survey, illustrated in the table below, shows the variation in delivered flow rate and temperature/humidity recorded at specific underground locations. If it is considered that the compressed air supply is marginal in terms of delivery, the mine operator must consider investing in additional supply capacity or consider alternative cooling options.

Location	‘A’	‘B’	‘C’	‘D’	‘E’
Compressor siting	underground	on surface	on surface	on surface	underground
Compressed air flow available	1700 m^3/h	6500 m^3/h	6500 m^3/h	6500 m^3/h	500 m^3/h
Dry bulb/wet bulb temperature of compressed air	26.5°C/19°C RH 64%	25°C/18°C RH 64%	28.5°C/20.5°C RH 62%	26°C/18°C RH 46%	34°C/27°C RH 56%

Table 2.3.3-2: Mine survey of compressed air delivery rates and psychrometric characteristics

Essentially for compressed air supplied refuges, the refuge thermal environment and cooling requirement is dependent on air flow, the wet-bulb temperature, the occupant’s clothing ensemble, metabolic level, and importantly the total number of occupants. For refuges with air supply options involving either bottled oxygen/air or chlorate candles, some form of air conditioning will generally be required in hot mines. Inspection of the ACP and ACPM scales for air cooling power confirm three requirements; firstly, that the subjects within the refuge must remain as inactive and unstressed as possible, otherwise their metabolic rate increases, secondly they should be very lightly clothed if long duration occupancy is envisaged, and thirdly there is an imperative that the local air velocity is maximised to prevent stagnant micro-climates and impaired cooling in the boundary layers surrounding the skin.

This directed that the research investigate the benefits in increasing the local air velocity within a compressed air supplied refuge. It is noted that total delivered compressed air flow rate into the refuge remains unchanged here. The key to increasing the cooling effectiveness of the compressed air supply is to significantly increase its velocity around the refuge occupants and thereby exploit fully its cooling capacity. There are various possibilities to increase air movement and local air recirculation. The approach advocated was to use the compressed air source to power air movers referred to as ‘air amplifiers’ or ‘transvectors’. The compressed air venturi diffuser, shown below, exploits Bernoulli’s theorem and the Coanda effect. The action entrains the surrounding air and induces large volumes of low velocity air to move through the air diffuser. A number of schemes have been analysed and theoretical air delivery characteristics derived. This work was extended to include psychrometric modelling in conjunction with practical testing and evaluation within a simulated underground refuge environment. This is reported in an appendix to this report. The use of air amplifiers has been shown to be a feasible approach to increasing air movement within compressed air supplied refuges and therefore achieving maximum cooling.

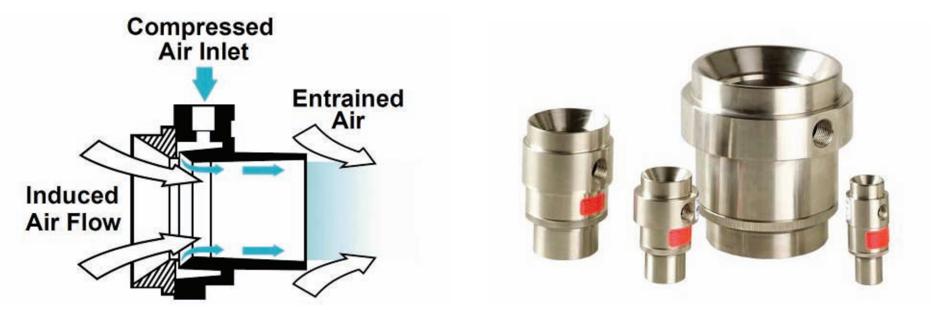

Figure 2.3.3-1: Compressed air supplied venturi diffuser or ‘air amplifier’

2.3.3.3 Development and testing of prototype refuges (Task 3.3)

It is reported that excellent progress was made towards completing case studies of prototype refuges. Indeed, such was the recognised importance of this work that UK Coal and Hunosa each implemented designs and installations for their underground refuges. These refuges were completed on schedule. A variety of field tests and exercises were also conducted to test and confirm the operational characteristics of the prototype refuges and to establish whether they met essential fitness for purpose criteria. This work reflects the importance of emergency refuge (safe haven) technology to European mining companies, particularly those whose mines are deep, laterally extensive and characterised by elevated heat and humidity levels. The report for Task 3.3 is organised into three components, covering collectively...

i. Spanish refuge construction and testing

ii. UK refuge construction and testing, and

iii. Supporting tests work by Polish partners.

(i) Spanish refuge construction and testing

Following consideration of the general requirements and air supply options for the prototype refuge, the design of the installation proceeded. This included defining the equipment and components to be installed in the refuge. The breathable air supply to the refuge uses two independent sources of compressed air. In each compressed air supply line a filter is installed to ensure cleanliness of the air supply. The outline design of the installation is shown in the figure below.

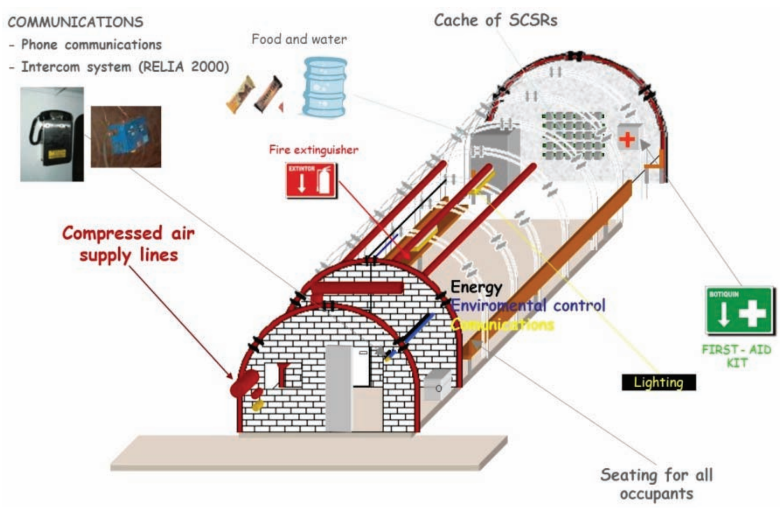

Figure 2.3.3-2: Outline design of the strata refuge at Pozo Carrio Mine

The air supply to the refuge is fed through a single valve located inside the refuge, in the airlock zone. Outside of the refuge there are two valves that allow an interchange of air supply. This would be used if there were an incident involving the active airline. The refuge is also a changeover station for SCSRs. The reserve SCSRs (MSA model Savox, 30 minutes duration according to standard EN-13794) were acquired and incorporated in the refuge. The SCSRs are installed on a purpose-designed frame device. In terms of communications facilities, the refuge is equipped with two independent means of communication; a PABX telephone and a line amplifier/intercom connection via the environmental control system. A RELIA environmental monitoring system is installed in the refuge. The concentration of CO_2, CO and O_2 are monitored inside the refuge, whilst outside the refuge CO and O_2 are monitored. The air quality sensors for the various gases have been installed at different height, according to rules for mine gases monitoring and control. In order to detect if the refuge is occupied, sensors show the door status (open/close). These sensors are connected into an alarm near the refuge and also into the mine monitoring system.

Following the general requirements established for the prototype refuge, and in accordance with the planned maximum number of occupants, additional equipment and components were installed; comprising first aid, extinguishers, water, seating, food, lighting, chemical toilet, and so on. The refuge was completed with appropriate signs and user information. Reflective signs were installed outside the refuge to help provide location from the mine roadways. After completion and commissioning of the refuge, various verification and residence tests were conducted. In all cases the refuge met the primary life support requirement specifications. The collective work to specify, design, build and test the strata refuge was considerable. Further information is given in an appendix to this report.

(ii) UK refuge construction and testing

Within the UK deep mining industry, a number of potential locations for fixed refuges were identified. As part of this, psychrometric surveys were conducted to measure the flow and dry and wet bulb temperatures of the compressed air available at the various locations. This data was entered into design and emergency planning studies on refuge capacity. As with the approach undertaken by Spanish partners, particular attention was given to ensuring the compressed air supply lines were either protected or routed in a manner to prevent fire damage. Given that roadway dimensions are generally somewhat larger in UK mines than Spanish mines, this offered increased flexibility in respect of the size and form of the refuge. Equal attention was given to ensuring effective means of communication and environmental monitoring would be available within the underground refuge. The communication arrangement again involves two independent communication means; mine telephone and roadway amplifier unit.

Figure 2.3.3-3: UK Coal refuge
(a) Sectional construction, (b) Completed refuge assembled in-situ, (c) Seating area

Figure 2.3.3-4: Refuge safety features
(a) Communication and environmental monitoring (b): Colour-tactile coded lifeline installed in escapeway

UK Coal completed the implementation and testing of a sectional fabricated refuge ('safe haven' in the UK) during the project period, as planned, and commenced work on a second strata refuge installed in a mine cross cut. The figures above show the essential elements of the sectional fabricated refuge. It can be seen that the refuge is constructed from pre-fabricated modules, complete with seating and windows, and which are subsequently assembled into the required refuge structure underground.

(iii) Supporting instrumentation development and test work by Polish partners

The third phase of work reported concerns tests of prototype instruments used for monitoring health and psychometric parameters. This could be used for either monitoring rescue workers in incident situations or during refuge chamber residence tests, as reported here. The monitoring tests employing the prototype sensors were carried out via collaboration between CSRG and EMAG. The tests took place in CSRG's headquarters facilities in a large climatic chamber (see figure below).

Figure 2.3.3-5: Views of the climatic chamber
(a), the test set-up inside (b), and data logging stand (c)

The measurement set-up consisted of two wireless heart rate sensors type HRM-1, a prototype wireless relative humidity, temperature and carbon dioxide multi-sensor as well as a PC-based data logging station. A magnetically braked cycle ergometer was used to set precisely the metabolic load conditions. Two volunteers took part in the exercise. Their heart rates were monitored and logged with timestamps together with corresponding temperature, humidity and carbon dioxide levels. Temperature was increased up to 30°C and humidity was increased progressively up to 90%RH. Different load conditions were simulated – from resting through 25 W workload up to 100 W workload. Whilst one of the volunteers was exercising the other, the 'control group', was resting in a sitting position. The chamber was closed with limited access to fresh air supplies – therefore conditions similar to inside a refuge were simulated. In the course of these tests carbon dioxide levels were continuously monitored. The results indicated that the HRM-1 heart rate sensors operated flawlessly. The relative humidity and temperature sensor also worked to specification – the results were comparable with a psychometrically calibrated measurement system being used as part of the climate chamber controller. The only deficiencies detected were in the operation of the prototype CO_2 sensor, where its output periodically saturated (which required a design change). The tests were regarded as preliminary tests prior to scheduling longer duration proving trials with the use of breathing apparatus.

2.3.3.4 Evacuation support; wayfinding through smoke (Task 3.4)

The research concerning wayfinding and guidance support through smoke has approached the issue from a number of directions. Firstly, a study of the related issues and practices in building and fire research was undertaken. Secondly, assessment and training initiatives have been implemented in the use of lifelines. Thirdly, practical technologies have been evaluated which can provide guidance and location information, including cap-lamp and wrist-worn devices.

(i) Examination of wayfinding and guidance issues

As noted in the linked studies on evacuation modelling in Task 2.4, the impact of smoke in terms of impairment of escape is often grossly underestimated. The degree of eye irritation, as an immediate effect, is dependent only on the concentration of the irritant. *In extremis*, affected individuals are forced to shut their eyes to alleviate the irritant effects, impairing any escape attempt. Irritant effects are produced by all fire atmospheres and can be severe even in the early stages of fire development. Limited research suggests that severe impacts from mine tunnel smoke irritation can occur before critical carbon monoxide levels are reached. This directs that reliable eye protection is made available.

The studies examined international practice and related supporting research, including that appropriate to building, ship and tunnel evacuation. This includes, for example, European Commission Framework Research concerned with upgrading of tunnel safety features (e.g. *UPTUN – UPgrading of existing TUNnels*, Project GRD1-2001-40739). These studies have mainly investigated lighting devices, such as LED or photo-luminescent panels. Unfortunately, none of these systems appear adequate for mining purposes; the performance of these products being generally poor in smoke with a high obscuration/low transmissivity factor.

(ii) Practical assessment of the utility of passive lifeline technologies

Evacuation trials conducted in South Africa under conditions of low or zero visibility confirm that speed of travel can be reduced to less than a quarter of that possible under normal visibility conditions. Where self-contained self-rescuers (SCSRs) are used as the primary respiratory protective device, then this has direct implications for the oxygen cost of escape and the placement of SCSR caches and changeover points, which was considered as part of a broader assessment of escape strategy.

Methods to guide miners through dense smoke could contribute greatly to saving lives during mine fires. Studies confirm that one practical and effective approach is to deploy a lifeline, particularly if it equipped with suitable tactile ferrules to provide unambiguous directional cues (essentially cones placed around the line with their vertex pointing to the egress direction). This device has been proven to help to increase evacuation speed by a factor of up to three times that compared to the speed observed without them in cases of zero visibility. Lifelines are prescribed by US Federal legislation within the MINER Act. A second useful finding from interviewing evacuees is that sound can help during evacuation, which could be the ambient sound of machines or conveyor belts, or sirens.

Figure 2.3.3-6: Training of mineworkers to use passive lifelines

UK Coal undertook practical studies involving the installation of tactile and colour-coded lifelines at Daw Mill mine. An alternative lifeline design at Aberpergwm Mine, Wales was also evaluated. These studies assessed how the visual and tactile feedback provided by the lifeline can be altered to provide further useful feedback and information. UK Coal then arranged training for wayfinding through smoke, which involved preparing mineworkers to deal with reduced or nil visibility wayfinding. To ensure that personnel have a representative environment for training, subjects are provided with heavily obscured special goggles, which are a reasonable analogue of the visibility presented in smoke-filled conditions. The figure above shows mineworkers being trained to follow a lifeline using the special obscuring goggles.

A simple and robust lifeline device for rescue teams was also evaluated by CSRG. This employs a dedicated fluorescent type of communication wire for the PTR-3 rescue communication system. The cable specification and sample cable sections have been supplied for manufacture. Related activities were also undertaken to investigate the possible use of thermal imaging cameras as a mean for finding the way in zero visibility conditions. Visibility depends on the smoke type, with the size of smoke particulate having a significant influence. For rescue situations it is also important to maintain 'hands-free' operation. On this basis, a combination of a miniaturised thermal imaging camera and an associated lightweight display device would be required. An adaptation of related 'augmented reality' apparatus within RFCS EMIMSAR is being considered for this purpose.

(iii) Developing the messaging capability of cap-lamp and roadway-based indication equipment

This work involved assessing the requirements of emergency guidance-navigation systems and developing and testing a dedicated wearable display device of high versatility. The prototype device (see figure below) type UPD-1 (Universal Personal Display 1) is suitable for presentation of emergency related information. The UPD-1 device is of a wristwatch configuration and is equipped with a high brightness 'view at any angle' OLED display which has high readability in smoke conditions. The display permits information to be presented on possible escape routes, constraints, warnings as well as status from vital sensors in either numerical form or as pictograms or progress bars. The unit also provides carefully chosen sound tones to reinforce the visual information on whether the wearer of the device is following the correct escape route heading.

The device is equipped with personal area network communications to receive information from various sensors (health, environment, breathing apparatus), including the heart rate monitor developed in the course of RAINOW project. The UPD-1 device is equipped with an embedded 3-axis accelerometer and 3-axis magnetometer (compass) for providing 3D orientation. The power supply is based on rechargeable battery technology enabling three days of continuous operation. The device is outlined in the figure below.

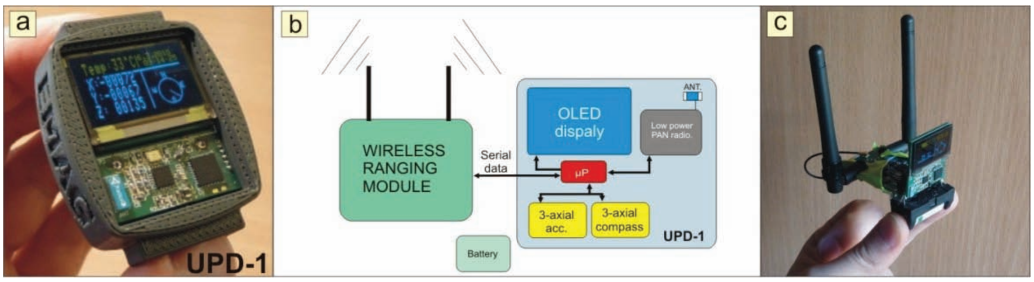

Figure 2.3.3-7: UPD-1 way-finding device

The principle of operation of the wireless wayfinding system relies on distance measurement to a wireless base station from its two displaced antennas. The mobile node is able to determine which antenna is closer and therefore its relationship to the base station. In the event of a fire or emergency, the wireless base station sends information regarding the desired direction of evacuation (i.e. the valid evacuation route is to the left or right direction). To test this principle a series of tests were carried out with the mobile device prototype and a dual output base station, identified in the figure below. During the tests, the ability of the mobile node to determine its position with reference to the base station was successfully tested in an 'open-space' (free field) environment. The distance to both antennas was correctly displayed when mutual separation of the base station antennas was greater or equal to 2 m. Further confirmatory tests were then carried out at Guido Mine.

Figure 2.3.3-8: Surface tests of wayfinding system

2.3.3.5 Enhancement to rescue and evacuation strategies (Task 3.5)

The status of the work was appraised regularly in order that any key findings or recommendations were circulated and discussed with industry personnel at the earliest opportunity. It is clear that underground refuges have a central role in mustering and emergency decision making actions, and offer a place where the mine workforce can gather, exchange respiratory protective devices, rest and continue their evacuation, or if necessary await rescue. The coal mine operators consider the provision of refuges as an important component of self-escape, particularly in very long drivages in deep, hot mines. UK Coal and Hunosa have each implemented in-house designs and prototype installations of underground refuges. These refuges were completed ahead of schedule and the coal mine operators have collectively undertaken considerable work to implement the research and subsequent training measures within their mines. The extensive integrated work programme of Spanish partners on fire and evacuation modelling and emergency refuge development is discussed further in appendices to this report. An underground visit to the underground refuge facility at Hunosa's Pozo Carrio mine by TGC1 members was made in May 2011. Related UK work has also included the following items.

Implementation of further refuges and escapeways

Following on from the installation and commissioning of mine refuges in Spain and the UK, consideration has been given to the requirements and possible siting of additional refuges. With support from the UK Mines Inspectorate and the mining industry unions, active consideration has also been given to refuge requirements at other mines. UK Coal has supported visits from other coal operators wishing to consider implementing mine refuges/muster stations. In this regard, staff from Maltby Colliery (operated by Hargreaves Services plc) have visited Daw Mill to view and possibly adapt the design of the muster station.

It is noted that the mine emergency plan and considerations for the location of refuges is a significant issue in its own right. Considerable attention was given to this by the EMTECH project partners. In the case of Daw Mill colliery, the principal mustering station is strategically located close to the man-riding terminus, and it also provides access to the production face together with the various development headings and laterals of the new horizon. In this regard the mustering station is well matched to the forward reserve exploitation plans for the mine. However, operationally it was considered that an additional refuge facility was required in the long roadways serving the initial phase of a retreat face. In this respect, a transportable refuge was then located approximately 1 km along one of the roadways serving 32's face. This employed a commercial Strata Products refuge, which is 0.9 m high, accommodates 16 personnel and provides an air supply for at least 48 hours.

The installation of a further refuge was completed at UK Coal's Kellingley colliery. This again was strategically located, sited in a cross slit at the outbye end of a main road within the Beeston seam. This refuge, again intended primarily for mustering purposes, is matched to the production plans for the mine to about 2020. The refuge is located some 7 km inbye from pit bottom and 2 km from the production face and development headings. A nominal travelling speed of 3.6 km/h was assumed in the planning process in terms of accessing the refuge from the production areas. The associated travelling time was considered well within the capacity of the filter self-rescuer type used. In summary, it can be seen from the UK and Spanish initiatives that the coal industry has actively pursued the introduction of refuges and that considerable progress was made here.

Drills used to test and evaluate the mine emergency plan

UK Coal carried out a mock emergency exercise. The scenario involved a fire outbye of the working area. This required mineworkers to be evacuated from the work area and into the muster station. Mines Inspectors from the UK Health and Safety Executive and Colliery management were involved fully in the exercise. The research included an evaluation of the deployment of the rescue services to fight the mock fire and as required to assist in rescue from the muster station. The emergency exercise provided useful feedback on the following items.

- Testing and updating the mine emergency plan.
- Assessment of real travelling times to the muster station and safe haven and ascent from the furthest extremities of the mine to the surface.
- The opportunities for management to enhance their knowledge and skill base, if they have to deal with a major mine incident.
- Identifying any further requirements to promote discussion on emergency planning and preparedness.

Training support related to muster stations/safe havens

UK Coal commissioned and completed dedicated training media for consideration in weekly training days on the deployment and use of the safe havens installed underground. To add to this, investment was made in a full-scale training model of the safe haven installed in 32's district.

Additional work

An underground visit was hosted for Mr Alan Haigh and Mr Lionel Boillot of the European Commission at Daw Mill Colliery. This provided an opportunity to view the safe haven, muster station and the cone and rope lifeline system.

2.3.4 WP4 – Search and Assisted Rescue

2.3.4.1 Basic research on Through-the-Earth technologies (Task 4.1)

Under this task, the following three topics were considered.

- Theoretical studies on through-the-earth propagation and radiolocation
- Background noise measurements in mines, and
- Analysis of the options for an emergency location system under development.

Through the strata propagation/location – theoretical studies

All aspects of through the strata communication were studied in order to select the most suitable scheme for the emergency location system to be developed. This research included a broad review of VLF/ELF communication techniques, including theoretical studies on VLF/ELF propagation, range finding and geo-surveying. As a result of these studies it was clear that significant improvements could be made in terms of location and range finding by implementing a method which relied less on transmitter magnetic moment determination and its spatial orientation (i.e. gradient type methods). The adopted method uses sophisticated power management techniques.

Background noise measurement

The natural and man-made noise background measurements characteristic to the mining environment such as those carried out by the U.S. Bureau of Standards in the 1980 s do not reflect the actual situation present in contemporary European coal mines. This is due to the different geological strata, the depth and the presence of switched power supply electronics (e.g. motor drive inverters). It was considered imperative that background noise measurements were made in representative mine noise environments. Measurements were carried out in two Polish mines – Guido and Ziemowit. The results of those tests indicated clearly that the background noise in Guido mine has a dominant natural character (as was expected for a non-operating mine) whereas measurements taken in Ziemowit were characterised by the high level contribution of electrical mining equipment originated noise. Sample spectral plots taken in both mines are compared in the figures below.

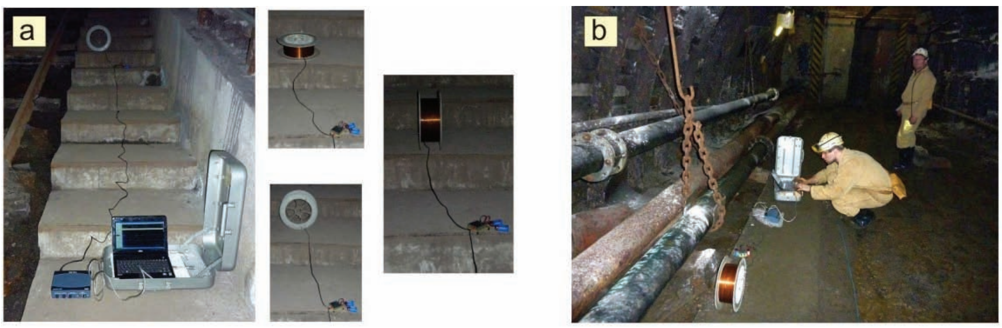

Figure 2.3.4-1: On-site noise measurements
Background noise measurements in (a) Guido, (b) Ziemowit mine

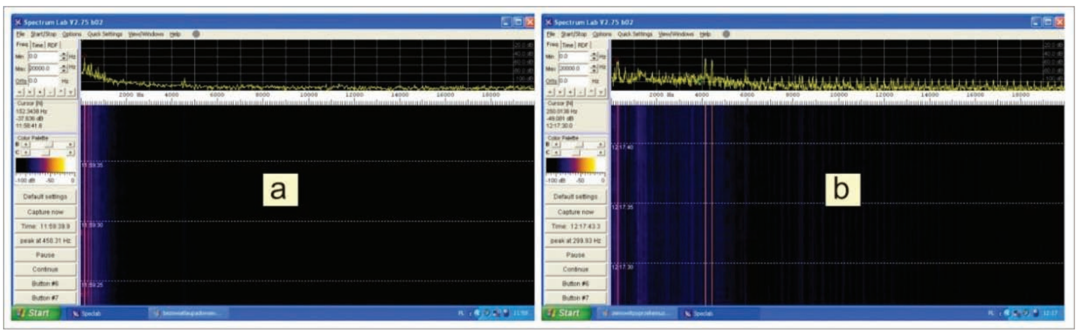

Figure 2.3.4-2: Noise floor levels. (a) Guido, (b) Ziemowit mine

In the case of Ziemowit mine there are spectral spikes visible which relate to mains harmonics. This indicates the criticality of selecting optimum centre frequencies for the transmission channel(s) in order to operate at a sufficient signal to noise ratio. These studies were expanded to provide a statistical description of the noise, together with redesigning the low noise preamplifier to improve the rejection of mains harmonics in the noise measurement apparatus.

Analysis of target emergency location scheme

After the various preliminary theoretical studies it was concluded that a major improvement to the currently-used Polish mining emergency location system (GLON-GLOP) could be achieved by implementation of an on-demand arrangement for the cap-lamp transmitter. This would result in a significant extension in battery life, together with a greater range by increasing peak current in the transmitter antenna. A low power 'system activation' receiver would however be required using three orthogonal antennas to minimise the susceptibility to field nulls, which are a significant disadvantage of single-axis arrangements. The conceptual arrangement is given in the figure below.

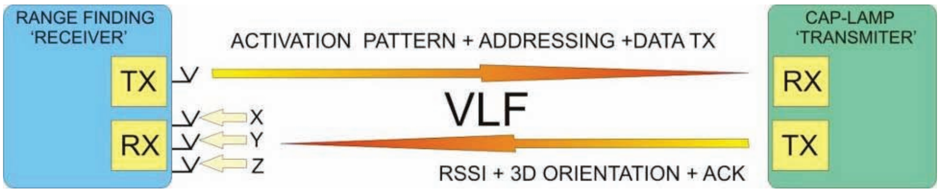

Figure 2.3.4-3: The enhanced location scheme

One potential legislative problem identified was that current Polish mining regulations require 'continuous operation of the cap-lamp transmitter'. However CSRG was of the opinion that if the low power 'wake-up' method was proven to be reliable, then it was feasible that the legislation could be revised. The other advantage of the proposed arrangement is that it uses a single frequency channel and addressable 'wake-up' receivers in the cap-lamp instead of using multiple channels. This greatly simplifies tuning and stability issues, which the current solution (GLON) suffers from. Another improvement impacting on location accuracy can be achieved by transmitting the received signal strength and spatial orientation data back to the range finding receiver. The final location scheme, reported in Task 4.2, was subjected to extensive practical verification.

Further supporting theoretical studies

Whilst Task 4.1 *Basic research* was scheduled for completion by the end of year 2, it was of considerable benefit to continue a low level of activity to address on-going basic research issues and opportunities as they arose. This included a theoretical appraisal of the relative merits of grounded dipole antennas, including link budget calculations, strata effects and expected values of underground noise. Comparative studies were also undertaken on the design and use of compact ferrite rod antennas for reception purposes.

An analysis of a large immobile surface antenna (LISA) concluded that a surface-based loop antenna should be large in relation to a skin depth. This raised the question of whether an electric dipole would be a better antenna to use in this situation. A further conclusion was that a short grounded electric dipole can perform significantly better than a similar sized loop, but that a large loop (e.g. the LISA device described above) would perform better than a grounded horizontal electric dipole (G-HED) antenna. The analysis of the G-HED antenna was considered to be of significant scientific relevance and a paper is under preparation for submission to the IEEE Transactions on Geoscience. One further type of receiver antenna that was considered was a compact ferrite rod antenna for portable apparatus applications. The performance of ferrite rod antennas was analysed and a useful result was obtained with regard to the design of such antennas. Essentially there may be some advantage in re-arranging the magnetic material into a bobbin shape. A bobbin design was simulated using magnetic field visualisation software to confirm that it behaved as predicted.

The theoretical studies also generated further opportunities for consideration. A primary example here was an analysis of the feasibility of establishing an emergency broadcast pager to underground mine workings using existing AM broadcast transmitters equipped with messaging capabilities (known as AMSS systems). This idea exploits the fact that long wave radio transmissions are known to penetrate underground and that broadcast transmitters have very high transmission power. Discussions were held with the BBC in the UK on the feasibility of leasing data packets on 198 kHz Radio 4 broadcasts. For shallower mines the principle of using high power terrestrial transmitters and 'piggy-backing' emergency messages may have merit. In part, the propagation will be assisted by the continuous metallic infrastructure present in many mines, for example power network cables.

2.3.4.2 Development of emergency location and tracking system (Task 4.2)

Development under Task 4.2 involved three areas. Firstly, the evaluation and certification of sub-system components to accomplish basic physiological status monitoring of rescue staff was undertaken. Secondly, work was undertaken to adopt appropriate standardised tracking protocols in the Mine Infrastructure Computer (MIC). Thirdly, work on the location and direction-finding receiver was completed as an onward development of the Polish industry GLON-GLOP system. Work on all areas was progressed to certification and underground trials.

Tracking and location functions within the resilient network scheme

The tracking related software functionality was developed for the Mining Infrastructure Computer (MIC) nodes and central systems (see Task 5.1). This software employs open protocols using *WebServices* as the technological basis. It is noted that any type of WLAN device can be tracked with this technology. For simple and low accuracy tracking the wireless 'tag' devices do not need any application-related functionality. A candidate device was identified which was integrated into a small enclosure, together with a battery and certified as a simple and cost efficient WLAN-based tag for use in coal mining. The protocol development was completed and laboratory tests performed with five network nodes. However given that large-scale testing is required to verify various infrastructure scenarios, it was arranged for extensive underground testing to take place, which would continue beyond the end of the project. Suitable interfaces to third party visualisation systems were also made available. These interfaces use open standardised protocols and thereby conform to the IREDES (International Rock Excavation Data Exchange Standard) tracking standard.

VLF-based through strata location capability

Development of the cap-lamp transmitter – the initial scheme developed used an 'on demand' activation approach for the cap-lamp transmitter in order to achieve significant gains in terms of power consumption. In this regard the activation receiver needed to be powered continuously and particular attention was given to ensuring low power consumption of this stage. A 3-channel receiver was developed, based on a highly power efficient ASIC (application-specific integrated circuit). However, in the course of intensive testing it was observed that the location system was subject to false triggering which affected battery life. Various alternative approaches were investigated and an elegantly simple and reliable alternative location scheme was devised.

The revised cap-lamp location scheme uses a VLF (very low frequency) transmitter to provide a long range penetration and location capability through strata, together with a VHF (very high frequency) transceiver. The VLF location mode does not depend on any supporting mine infrastructure and allows an accurate position determination to be made through tens of metres of strata. The VHF mode provides a secondary location capability together with a data messaging facility, but requires a supporting mine infrastructure and has relatively limited strata penetration capabilities. The VHF transceiver provides a precise location capability for normal day to day operations. Here the VHF transceiver communicates with the reference nodes of the infrastructure and employs a time of flight positioning method to calculate its precise location within the mine. In the event of an emergency, if there is no signal from the VHF location infrastructure the device switches automatically to the VLF transmission mode. To enable concurrent monitoring of multiple devices an innovative scheme of synchronisation was developed using a unique identifier within the data frame sent from the transmitter. The VLF scheme uses OOK modulation with a bit rate of 40 b/s. An advanced forward error correction scheme was implemented to improve the probability of reception at the extremities of range. The cap-lamp device is equipped with a small OLED display on which text messages sent from the infrastructure system can be displayed. The device also has a personal alarm push button and a sounder that provides additional guidance cues in low visibility conditions. The final cap-lamp prototype is shown in the figure below.

Figure 2.3.4-4: The cap-lamp location transmitter with built-in information and guidance display

Development of the range and direction finding receiver – work focused on the development of a proof of concept prototype location receiver. The range and direction finding receiver takes advantage of software defined radio technology. Processing of the 3D magnetic field components, steep slope signal filtering and demodulation is implemented entirely in the digital domain. It was anticipated that digital signal processing would permit significant performance gains relative to the currently used analogue electronics solution (GLOP system). In order to achieve this high performance it was however critical that the noise figure for the preamplifier and antenna was engineered to be as low as possible. Various circuit topologies were tested extensively, first in laboratory and then in underground trials at Guido and Ziemowit mines with the DSP-based receiver prototype.

Based on the experience gained from the early prototypes a number of improvements were introduced. The active 3-axis antenna was equipped with improved preamplifiers. The modifications were related to further improvements in noise characteristics and the introduction of band-pass filtering instead of notch filtering. An active filter of 4–9 kHz pass band characteristic was built as a cascade of high-pass and low pass filters using a multiple-feedback topology. As a consequence of these design improvements, the attenuation of (troublesome) mains frequency harmonics was greatly improved compared to the initial version. The analogue section preceding the ADC (analogue to digital converter) buffering amplifiers was equipped with an antenna selector based on an analogue multiplexer. This change was to permit the concurrent use of two antenna sets to implement a field gradient determination method. Further to these changes, the entire mechanical construction was redesigned in order to achieve compactness and robustness. The electronic modules and the battery power supply of the final revision of the receiver were housed within a lightweight carrying case (see figure 'a' below). The DSP (digital signal processing) board and application processor /display module were internally provided with a suitable magnetic metal shield. Additionally the internal walls of the enclosure were covered with EMI shielding paint.

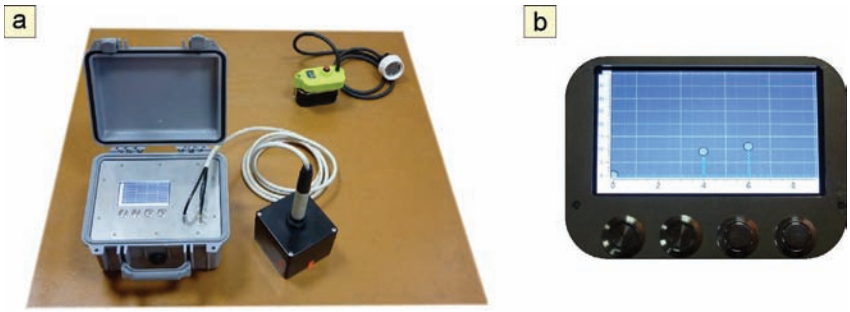

Figure 2.3.4-5: Final prototype of range and direction finding receiver

The software of the receiver operates in two basic modes – legacy and extended. The legacy mode is required for backward compatibility with the existing emergency GLON-GLOP location scheme employed in Polish mines. The functionality in the legacy mode is similar to that of the GLOP receiver but has a key advantage in that signals from multiple GLON transmitters can be visualised simultaneously on the receiver screen and the corresponding calculated distances displayed in a convenient graphical form (see figure 'b' above). The basic functionality of the receiver was proven initially in laboratory and then in underground trials. The underground trials of the equipment were carried out with the assistance of specialist personnel from CSRG, who are highly experienced in the practical deployment and use of the GLON-GLOP location system. The trial outputs and technology transfer issues are discussed in WP6.

Subsystems to accomplish 'vital signs' physiological monitoring

Studies and experiments were carried out regarding the options available for determining 'vital signs' physiological status data, both to monitor personal health and local environmental conditions. Regarding the selection of the physiological measurement approaches, use was made of previous RFCS project findings, including RAINOW. The figure below shows the chest belt configuration physiological Sensor Electronic Module (SEM), which is also used by military and emergency service personnel.

Figure 2.3.4-6: Physiological monitoring system

This physiological monitoring system incorporates proprietary patented algorithms and delivers noise-free, real-time physiological data. The technology used in the system combines the measurement and wireless transmission of human physiological status information together with movement data using an integrated tri-axial accelerometer. After extensive usability testing of the hardware and software, the versatility and fitness for purpose of this system was confirmed. Concerning the data connection with the TETRA radio devices (described in Task 4.3), the data interface can accommodate data transmission speeds up to 28.8 kb/s. Clearly, physiological data such as heart rate, skin and core temperature, galvanic skin response or body inclination/position can take place with a relatively long measurement interval and so the bandwidth available for transmitting this data via a TETRA radio link was certainly sufficient.

2.3.4.3 Development of independent rescue team to surface communications (Task 4.3)

As a preface to this section, it is necessary to highlight the differing historical positions that have arisen in regard to mines rescue and indeed the generality of emergency support instruments and communications equipment. It is noted that whilst there has been a progressive convergence in terms of adopting common closed circuit breathing apparatus, this has not yet taken place with respect to emergency communications equipment. In part this reflects the differing system philosophies and implementations within Member State mining industries. By way of example, the German coal mining industry has made significant investments in ATEX certified wireless technology and underground PC stations. German engineers, craftsmen and rescue specialists are therefore relatively familiar with these technologies. However, the application of these technologies in UK, Poland, Czech Republic, Spain and Slovenia has been more evolutionary and selective. To add to this, there has been a tendency for critical rescue equipment to be sourced from national suppliers. The net outcome is that, for the present, it is not feasible to develop a common 'one size fits all' approach to rescue communications between the Member State rescue services.

Work within Task 4.3 has therefore examined the provision of dedicated rescue team communication systems from two independent approaches. Each is essentially tailored to the specific requirements of the German and Polish mining industries respectively and good individual progress was made, with some significant communications innovations emerging. The research approach has been for the German partners to develop a wireless trunked radio, as planned, with further research undertaken by Polish partners, which addresses their local system requirements.

German studies on a TETRA trunked radio rescue/emergency communications infrastructure

A comparison of market offerings and communication system capabilities was made against the requirements of the underground mining environment. The development of the rescue team emergency radio equipment was the first priority. Candidate equipment was purchased and initial benchmarking assessments of analogue and digital radio equipment carried out. The results confirmed the superior intelligibility of digital systems, together with a generally greater range and wider communication options available. A significant task was then to make the correct choice between the available digital radio systems, in terms of systems designed for the spectrum at 400–800 MHz or 2.4 MHz ISM band technology. In this regard ISM band (WLAN) technology was initially favoured since RAG has wide experience of this technology and already had an installed base of wireless access points, routers and switches in RAG mines. The system requirements for the equipment included the transfer of data from mobile devices including VoIP speech technology. The speech communication concept was developed further with an objective of providing coverage for the coalface area.

There were specific approval requirements for apparatus to be used in hazardous atmospheres in emergency incident situations. Here all electrical equipment is subject to the regulations of zone 0 and must be approved to ATEX M1 ia. This in turn directs that the entire system (access points, routers, switches, power supplies and radio handsets) would have to comply with this level of certification. This in itself was not however a limiting factor, since it was anticipated that emergency-enabled wireless access points and un-interruptible power supplies would become available during the course of the studies. The crucial point for discarding WLAN concepts was premised on the fact that the manufacturers at the time could not offer adaptive additional transmission capabilities for the mobile nodes if the local access point became disabled or disconnected. This was not acceptable in an emergency situation. The radio handset manufacturers also raised doubts concerning the feasibility of ATEX M1 certification of their products. TETRA radio devices have an advantage, since they can employ a direct mode (DMO) of communications. The operational loss of a base station would not necessarily mean that rescue team members would be unable to communicate with each other. Providing team members were located within 100 m of each other, they could maintain communications in the event of a power failure. The other approach examined was to engineer resilience into the power supplies of critical equipment, addressed under Task 1.3. For these reasons TETRA digital radio equipment was considered a robust and practical option. As operational background, TETRA (TErrestrial Trunked RAdio) systems, operating in the 400–800 MHz spectrum, are manufactured and used worldwide. A TETRA system approach could unite all required features and functionality; these include digital radio, analogue radio, mobile data transmission and mobile telephony possibilities. Furthermore all conceivable radio structures are supported under TETRA – whether this involves group broadcasting of alarms or confidential telephone conversations. Discussions therefore were resumed with manufacturers and distributors of TETRA communication equipment. There was however one significant initial drawback, namely that hazardous area TETRA devices were certified only for Group II (surface petrochemical industry), which inferred only ATEX M2 equivalence. Therefore significant effort was expended on investigations and technical discussions with a Notified Body on the feasibility of achieving M1 certification standard.

For testing and evaluation purposes, the training mine TBW of RAG in Recklinghausen was used. The initial tests served the purpose of providing familiarity with TETRA components in a mine environment. This included testing various certified accessories (i.e. microphones, speakers, headsets and data communication equipment) with regard to their suitability for working within emergency teams. Further tasks involved validating the radio range and coverage of the 400–800 MHz TETRA components in representative mine surroundings, involving assessing both radio and leaky feeder assisted transmission range. Here different forms of antennas as well as different types and lengths of leaky feeder cable were installed and tested. For the evaluation a special Windows-based field strength measuring programme for TETRA components was employed with dedicated field strength measuring electronics.

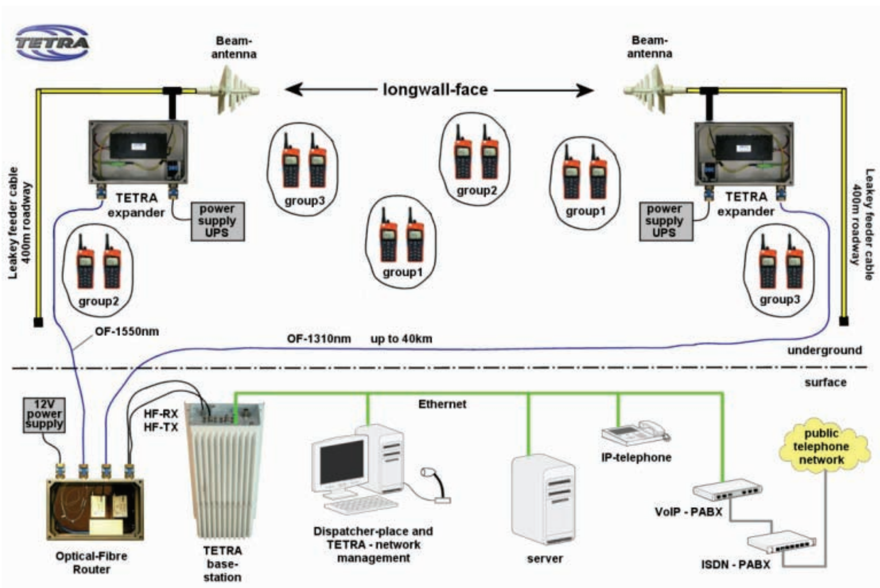

Figure 2.3.4-7: Concept of using two TETRA expanders with a base station

In parallel a further development was advanced. After an extensive system review, it was proposed that the scheme could be enhanced. The aim was to create a 1000 m radio zone from a single TETRA base station supported by a UPS rated at four hours, and based on M1 certification. The concept involved each member of a rescue team being equipped with radio, whilst the officer-in-charge (possibly located several hundred metres from the team) could issue orders by radio. The solution proposed was to use a HF to OF (high frequency to optical fibre) converter to permit the radio coverage zone to be greatly expanded by the use of a field-deployable optical fibre communication link. After an intensive study of all the system components and sequential tests of several modular prototypes, a concept was evaluated which permits the operational range to be extended up to 40 km via an optical fibre used in conjunction with TETRA radio expanders. In mine incidents the rescue team simply unwinds the optical fibre from lightweight cable drums, which are used in conjunction with a lightweight TETRA expander unit. Furthermore, the system is designed to use two independent fibres in conjunction with directional antennas to provide full coalface radio coverage. The system concept is shown in the figure above.

Polish studies on a rapid deployment fibre-optic rescue communications system
As result of co-operative activities with CSRG, the detailed requirements for a new rescue communication system of extended functionality were defined. The main objective was to take advantage of current field proven technologies, including low power wireless communications, high efficiency fibre-optic WDM (wavelength division multiplexed) transmission as well as low power sensor technologies. The basic concept of the system comprises the use of emergency-deployable battery operated wireless modules which provide connection into a fibre-optical 'back-bone' link (see figure below) ensuring radio coverage along the entire route.

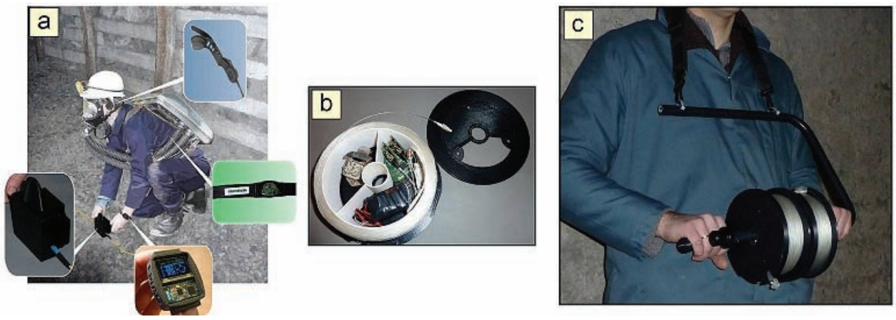

Figure 2.3.4-8: Rescue communication system with 250 m of optical fibre

For the fibre-optic link a thin (0.9 mm diameter) lightweight armoured optical fibre was selected. The fibre, used primarily by the military, can withstand exposure to severe mechanical conditions including repeated bending, torsional twisting and crushing. The core wireless technologies provide communication and location means as well as transmission of vital parameters from a rescuer's physiological sensor set (health and status monitoring). To permit group communications, a modified voice communication transceiver was developed. Field trials were arranged with the involvement of CSRG to verify the design and obtain feedback on any necessary improvements. The prototype system uses bone conducting microphones to enable operation with a full face breathing apparatus. The main electronic module was developed which contains multimode wavelength division multiplex fibre-optic interfaces and a communications processor. The first successful transmission trials were carried out in the laboratory. The available transmission bandwidth for user data was measured to be about 50 Mb/s.

A purpose-designed dispensing reel was prototyped (see figure above) with external diameter 170 mm, width 80 mm, and which featured a foldable recessed handle to facilitate the winding action. A dedicated compartment located in the central part of the reel houses the communication modules and battery power supply. There is also provision for an IP68 electrical connector to provide an intrinsically safe serial interface (for optional connections with multi-sensor gas measurement units or a video camera). Despite the large capacity of the reel it is anticipated that the optical fibre length on each reel will be limited to 300 m in order to ensure a radio link between sequential units (coverage of each radio transceiver is approximately 450 m in line of sight tunnel conditions). The high capacity of the reel can however be exploited in situations when a long distance point to point link is required (without interim stations). Point to point communication (limited by the physical capacity of the reel) can be established for a distance of 1000 m.

2.3.4.4 Construction & testing of prototype digital group communication system (Task 4.4)

Further information on the construction, certification and testing of the TETRA-based rescue communications system is reported here. One area that initially presented a development issue was associated with certification of two TETRA components for mining ATEX application. Specifically; integration of the TETRA base station with an un-interruptible power supply arrangement within a flameproof enclosure and certification of the handsets to ATEX M1 ia presented both technical and commercial supply issues to be resolved. The technical issues were resolved by critically appraising the zoning requirements of the system components whilst the supply issues relating to the certification and supply of ATEX M1 equipment required assurances on minimum sale volumes to industry. In co-operation with TETRA component suppliers and manufacturers of flameproof enclosures, discussions were held on the possible ways for constructing a TETRA base station that could be operated under M1 conditions for up to four hours. Associated work was also done to appraise the options for providing an un-interruptible power supply capability. The figure below shows various mechanical details of the prototypes, including the flameproof enclosure that was assessed for use.

Figure 2.3.4-9: TETRA base station and prototype flameproof enclosure

This arrangement was to involve location of the components of the base station (shown in the left photograph above) within the hazardous area enclosure (shown in the right photographs). The internal batteries would require additional enclosure sealing together with a fail-safe arrangement to ensure the power supply could not be connected when the enclosure was opened. However after discussions with RAG and Mines Inspectorate, decisions were reached on where the various system components could be located (in hazardous atmosphere terms) when deployed underground. It was determined that certain equipment could be located in fresh air areas or above ground, with the disposition shown in the figure below. This helped resolve the adaptation of a flameproof enclosure for a TETRA base station.

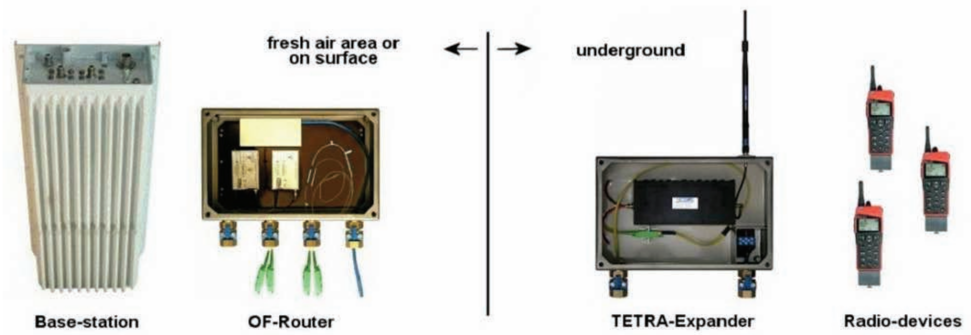

Figure 2.3.4-10: Hazardous area disposition of communication system components

Development was focussed on the two devices to facilitate radio expansion of the base station – the OF (optical fibre) router, together with the TETRA expander. Radio-to-fibre converters were procured, which were tested extensively to prove the base station and receiver/transmitter fibre converter functionality. Similar work was performed with the TETRA expander. In this case, matters such as the attenuation of the intervening diplexer filter also had to be accounted for. The radio network was then tested intensively at the TBW facility in Recklinghausen (see Task 6.2).

Given the OF routers would remain exclusively in fresh area or on the surface, and given the inherent isolation offered by optical fibre with Ex areas underground, it follows that no special demands arose in regard to the associated electrical design. For convenience the first router was assembled in a similar case to that of the TETRA expander. Since the power requirement of the expander is moderate, an IS certification of M2 and M1 was feasible without having to resort to using flameproof equipment. All necessary power requirements are combined within a single power supply module, which is encapsulated along with industrial (non-intrinsically safe) modules within an appropriate mining housing.

As other points of detail, the omni-directional antenna can be exchanged for a directional antenna. For the external power supply, any approved 12 V/1 A supply can be utilised for general mining use. However with regard to the intended M1 certification only a power supply with M1 UPS functionality could be considered. The development of such a unit is considered in Task 1.3. Both TETRA expander versions (fixed and mobile) share the same development base concerning their radio and optical fibre equipment and so the respective power consumption requirements are identical. However, for the mobile version of the TETRA expander a reduction in weight and dimensions was required in order to make the units more manageable for rescue teams during emergency operations (who already must carry significant support equipment). To accomplish this, a TETRA expander was fitted with a specially developed diplexer filter of reduced dimensions and weight.

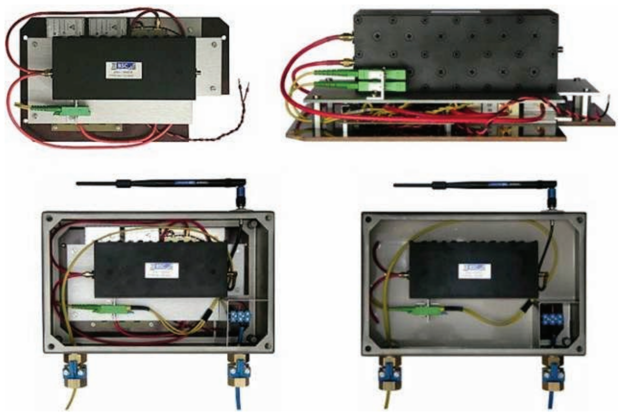

Figure 2.3.4-11: Different stages of construction of the TETRA expander

The upper two photographs above show the assembled internal modules in plan and profile view. The two lower photographs show the completed expander prior to and after the partial encapsulation of the modules (to comply with ATEX certification requirements). For ATEX M1 certification, additional work was carried out in the area of the power input circuitry. Here, three series wired diodes were implemented to block the unspecified capacitance in the electronic modules. Since the diodes caused a reduction of the available input voltage it was necessary to re-evaluate the functionality of all modules within the system again.

Further measures included incorporating thermal fuses to prevent over-temperature stress of the protective potting compound in the event of a thermal overload. The certification and associated documentation work for the TETRA expander was completed on time. The development and construction of the OF router was not subject to the restrictions of ATEX conformity. Nevertheless, the OF router is a critical component within the communications system, with important functions of distributing (splitting) the transmitted data and combining (multiplexing) the received signals of different wavelength from the two decentralised TETRA expanders. The router was fitted with revised components in the OF splitter and the OF multiplexer in order to ensure three-way TETRA communication.

The network communications concepts identified under Task 4.3 have been shown to offer a solution that addresses both the requirements of rescue teams, together with meeting the day to day requirements in the production zone. In addition to the integrated networked communication system based on TETRA technology, the parallel development took place of a dedicated rescue communications link using a rapid-deployment lightweight fibre-optic cable. This system, whilst technically simpler, offers the prospect of a further independent communications option for mines rescue use.

2.3.5 WP5 – Central Safety Management

2.3.5.1 Development of a localisation and visualisation support system (Task 5.1)

The work reported reflects a tiered approach. At the highest level, the system integrates with various mine databases and sources of real-time information to provide a standard visualisation environment with selectable intelligent filtering of represented data. The required localisation and visualisation support then utilises directly the capabilities of the resilient networked mine-wide, multi-centre approach articulated in WP1. Additional software tools were developed which can monitor and check the operation of several local mine networks using Zigbee location tags and provide the location data generated by these tags in a form which is accessible to third party monitoring systems. The visualisation support adopts a resilient networking approach with a capacity to provide information both above ground and underground. Whilst the central safety management and visualisation infrastructure described essentially reflects German industry practice, these systems and the underlying techniques can certainly be replicated elsewhere.

Further development of existing industry 3D visualisation tools

The development of 3D visualisation systems at RAG came into technical maturity with the development of the ProGrube and subsequently ProNet software applications. The expanded capabilities of the ProNet software facilitated access and input of geographical databases from mine surveyors and other mine technical departments, as well as process data and sensor data. A further software package, ProScape added planning and calculation of escape route parameters. Technical reviews were held with RAG and the rescue services to define the limitations of current visualisation software and how the applications could be enhanced. It became clear during the studies that these applications could not meet the technological requirements described in Tasks 5.1 and 5.2. ProNet and ProScape were undoubtedly useful for simple tasks of representation and perhaps even for individual decisions regarding operational processes, however they would be greatly overwhelmed in the event of a connection to the emergency processes described.

Discussions were advanced with suppliers on a design variant of the ProNet 3D visualisation software. The revised scheme would incorporate direct data requests from the mine geotechnical database to provide current information on the mining structure, together with the use of CAD-based software to input the position and identity of all relevant underground services and infrastructure. To exploit such a system in an emergency situation it was recognised that appropriate software tools would need to be developed to facilitate the decision-making processes and support the emergency management team. Studies were undertaken to examine the incorporation of static/historical data from the various ‘mining observatory’ supervisory processes used to control coal production together with the dynamic data arising from the SafeCenter, TracCenter and NetCenter services. An implementation plan was devised to define the tasks required to develop the software tools and upgrade the 3D visualisation system. On analysis the required development programme would require extensive resources and the implementation would have to be phased and completed as a future work programme. A revised structure for the emergency networks with substantially higher load capacities and resources is depicted in the figure below.

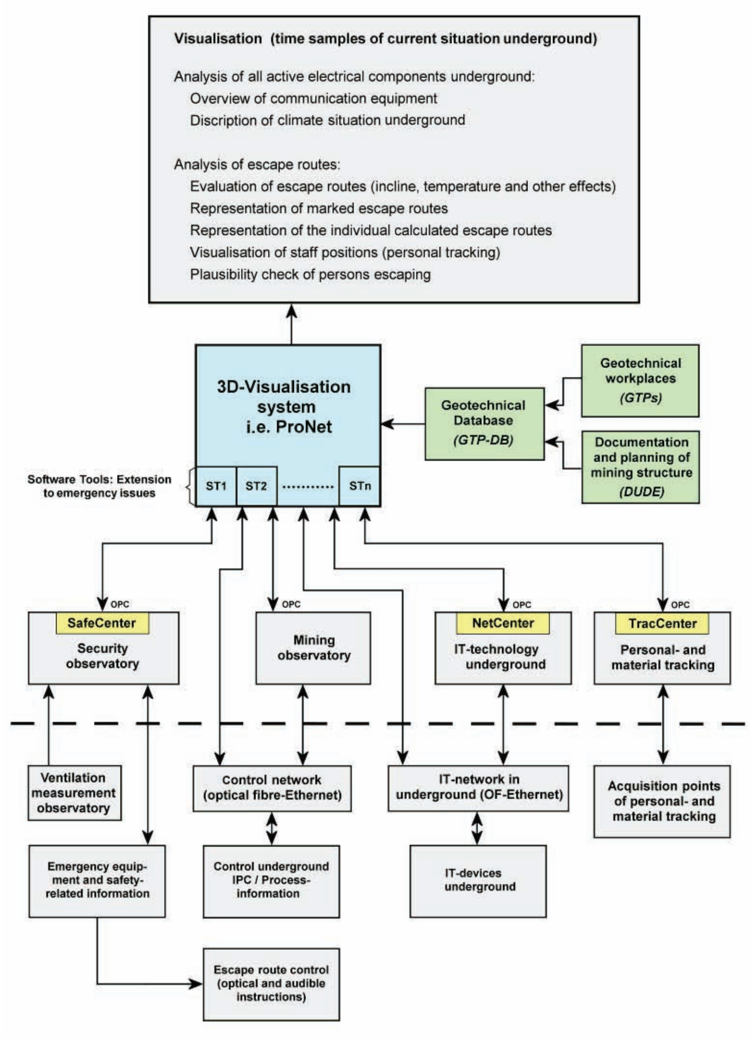

Figure 2.3.5-1: 3D visualisation system with resilient network support

The results of the location determination would be stored in an Oracle database. OPC interfaces would be used to collect data and, in particular, ventilation information via optical fibre links from the respective mine control networks (mining observatories). A specification for the necessary software tools was drawn up in conjunction with associated partners including CSRG who has extensive experience of using fire visualisation tools, as follows.

- Tools for assessing underground areas (accessibility, presence of gas, POCs, temperature, ventilation).
- Tools to simulate the progression of the fire situation and ventilation impacts.
- Tools to visualise the availability and condition of underground communications and environmental monitors.
- Tools for the assessment of escape routes (e.g. physical description, tenability, and availability of transport).
- Tools to direct the most useful means of escape for employees affected underground.
- Tools for determining individual escape routes for underground staff.
- Tools for marking of escape routes underground.
- Tools for evaluating the time requirements along still usable escape routes.

An extensive co-review was undertaken of the existing functionality of ProNet and ProScape visualisation capabilities and the feasibility of implementing an advanced visualisation subsystem. This included consideration of base functionality, alternative volume representations and the means to enhance image quality. The developments arising from RFCS EMIMSAR were also considered here. One critical requirement identified was the need for more effective display filtering and selection within the different object families. As many objects are brought into display the overall picture can quickly become cluttered and lose its clarity. Various schemes for graphical representation of objects in the mine structure were examined, including tabulations. The above studies provided a coherent framework for examining location and visualisation approaches suitable for emergency purposes, and which were matched to the lower tier elements as follows.

Resilient networked mine-wide, multi-centre approach

The system in concept is based around the use of central server systems. These systems perform central configuration support and interact with the underground infrastructure during regular operation of the network. It is noted that specific clustered server systems are used to separate applications and functionality as follows.

- A 'NetCenter' is used for network administration and supervision of the underground network structure. This also supplies the basic data to the 'SafeCenter' enabling this unit to determine hazard locations by evaluating the network failure location.
- A 'TracCenter' used for tracking of people, material and assets.
- A 'SafeCenter' used for mine safety applications such as dynamic evacuation guidance, emergency localisation.
- A Remote Access Client provides remote network administration services via the system supplier/manufacturer.

Within Task 5.1 an initial discussion document 'Dynamic Evacuation Procedures' was produced which outlined functions and design options for supporting situation dependent self-escape procedures. These procedures are based on the detection of emergency locations via the real time network status in combination with environmental sensors connected within the network. A precondition for these networking functions is to implement a system design that ensures the network remains functional when, in a worst case situation, all connections to the central system servers are lost. In such cases, the 'mining infrastructure computers' (MICs, described in WP1) will start automatically in an emergency mode, with all the central network and application functions of emergency relevance performed independently by the MICs underground. As the location of an emergency cannot be predicted, this functionality has been implemented in a way such that every single MIC is able to start any central service or application required. This relates in the first instance to the dynamic assignment of network (IP) addresses using a Dynamic Host Configuration Protocol (DHCP) service and to provide Voice-over-IP audio communications using a Session Initiation Protocol (SIP) server. Further information on the assignment process is given in Task 5.2.

Additional intelligent infrastructure functions were implemented in the MIC software covering the local storage of tracking information in the MICs. In traditional (and all previous) tracking systems, the tracking information is sent to central servers above ground. This information is generally not accessible to personnel underground. Within the multi-centre approach, all tracking information remains stored in the MIC up to the point where personnel tags were last detected. Furthermore, the tracking remains fully functional in order to be able to inform mineworkers and rescuers underground how many colleagues are located in specific areas and also to facilitate initial mustering actions. This intelligent infrastructure requires central systems to store configuration and application data, which is distributed to the underground network nodes during normal operation. Such data covers the following points.

- A simplified mathematical model of the underground tunnel infrastructure in order to allow the network nodes to compute escape routes.
- An overlay of the network infrastructure and the normal operational layout in order to enable the intelligent network to detect the location of network interruptions which can be potential locations of hazards.
- The location of emergency exits, refuges, fire fighting equipment and other safety relevant items underground.

As outlined, the MICs acquire information from the central computer systems during regular operation. When connections to the underground network are lost, all information concerning the location of the workforce and machines can be retrieved in order to conduct and optimise rescue operations and for subsequent emergency guidance work. This hand-over is an important aspect of achieving continuity of operations and ensuring high system resilience. All this information is downloaded to all MICs underground upon any change and when a MIC is restarted or newly added to the network. This information is used by the MIC-based intelligent infrastructure to support personnel underground in an emergency case when the MICs are working in emergency mode. The real-time information on location of personnel involves a complex distributed functionality performed by the MICs that are communicating with each other. The location information can be displayed locally on the unit's display.

Route guidance information is provided by sending the routing information to the handheld devices used by the mineworkers or by illustrating simple symbols (e.g. arrows) on the MIC LCD displays. Using this function, a controlled mustering of personnel from different areas of the mine can be performed by assigning a meeting point at one of the MICs, which invokes all other MICs to transmit this information to the mineworkers. The system can also provide routing information in order to locate the mustering point using the shortest or safest route. This intelligent technology can also help ensure that all staff are accounted for and that all persons who were reported in this area have actively evacuated the area. This in turn enables the SAR teams to perform their work in a more targeted way, hopefully avoiding speculative searching of areas. This will save effort on the part of the SAR team and will allow them to concentrate on those areas where mine personnel are suspected to be.

OPC Server-Zigbee device tracking approach

This sub-task involved primarily the development and testing of software tools for checking the operation of location tags and providing location data generated by these tags in a form accessible to third part monitoring systems, such as mine SCADA systems. It is noted that the physical wireless technology exploits Zigbee technology, developed elsewhere under RFCS RAINOW. The work within EMTECH has used the Zigbee wireless technology as a commodity enabling technology without further development. The technical approach uses an OPC Server (OPC – Object Linking and Embedding, OLE for Process Control) to provide communication with a number of mine sub-networks, each of which can monitor a large number of Zigbee devices.

The tracking approach essentially involved the development of a software application that acts as an API (Application Programming Interface) and a protocol converter with appropriate graphical user interface services. A tool set was developed for monitoring the tags, reading and interpreting the messages coming from them, as well as providing a position determination. This tool set comprises three principal building blocks, namely...

- A software driver, which talks and listens to the tags.
- A location engine, which interprets and tracks messages and estimates the position of each tag.
- A graphical user interface (GUI) for monitoring data generated by the above engine. This GUI has provisions for showing tag information, tag location and network structure information.

Regarding the development process, the GUI was replaced by an OPC server interface to capture selected variables for each tag. The OPC server runs on PC machines and employs three core executable files – *runtime*, *configuration* and *administrator*. External libraries are used to communicate with client applications including SCADA systems, e.g. Siemens *WinCC*, *Wonderware InTouch*, GE-Fanuc *iFix*, which are all OPC-capable. The OPC server permits the integration of a location subsystem into mine-wide supervisory systems, providing location display information in a variety of advanced ways (e.g. within 3D, virtual reality and augmented reality subsystems).

The OPC server was developed further in order to communicate concurrently with several ZigBee networks. The purpose of having several co-ordinators was to permit deployment of several independent sub-networks in a mine, allowing coverage of the different working areas without having to establish direct connections between the respective sub-networks. In this arrangement, each ZigBee network has a unique co-ordinator and it communicates to the driver through a virtual serial port assigned during the configuration of the system, with the general schema shown below.

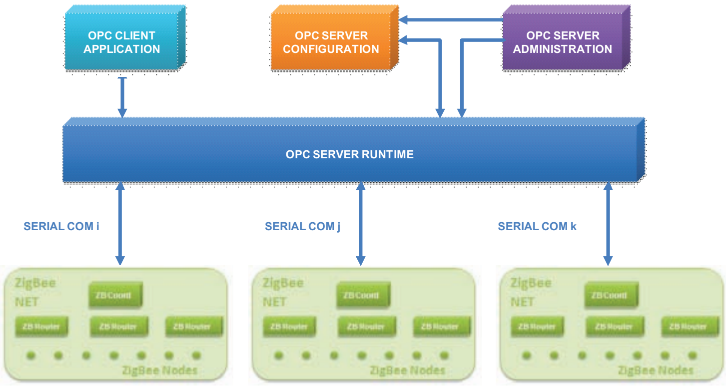

Figure 2.3.5-2: Multiple Zigbee networks, general communication schema

The initial tests were completed with three networks (three co-ordinators) and 25 nodes (either routers or mobile end devices). In order to accomplish stress testing of system behaviour under heavy loads, the client-server connection was linked up to 25,000 virtual tags (or items), using a simple OPC client for test purposes, with all the variables read asynchronously. The OPC server approach was demonstrated to offer a feasible, standards compliant platform for interrogating a complex underground network to provide location of Zigbee wireless tags. The integration with mine SCADA supervisory systems supports the remote display of information in a wide range of display sub-systems.

2.3.5.2 Implementation of 'intelligent' information processing infrastructure (Task 5.2)

The initial approach to Task 5.2 involved gathering information on current mine infrastructure, focusing initially on practice in Spain. Here, it is usual to find four different networks coexisting at a mine; telephone, intercoms, public address systems and environmental sensors, with all of them based on a wired non-redundant bus structure. The second step taken was to develop a Central Safety Management structure that unified these networks into a single network. In terms of meeting the overall project objectives of providing redundancy and resilience, such a system was identified to benefit from a ring topology. Once this network was developed, integration of data concerning the mining operational processes, maintenance works, and tracking support for location tags would be available under the same platform. In this respect a basic overview of how the system was implemented is provided here. Firstly, the system required 'intelligent nodes' with the following capabilities.

- Communicates either wirelessly or by wire with the control centre, field elements and tracking devices.
- Adapts to any network configuration.
- Knows its relative position within the network.
- Decides which field element data should be collected.
- Changes its relative position when a new node enters into the network.
- Prioritises key information and knows what to do with the information.

Again, aligned with system general objectives, the system employs wireless networks, WLAN as the basis of the mine communication network. A LAN network is required however from the surface control centre, connecting into the WLAN architecture. The intelligent nodes block, filter and prioritise information relevant to safety matters. This requires an intelligent infrastructure similar to a

CAN bus system, which appends a ‘dominant’ or ‘recessive’ bit to data. Related to this issue is how these nodes generate location and tracking information. The inputs from Task 5.1 concerning location and wireless tracking were integrated into Task 5.2 system development activities, the objective being to create a two-way WLAN communication between nodes and mineworkers that supports tracking consistent with efficient communication.

This task covered the implementation of safety and application level functions for the safety-related networks and, in particular, ...

- The ‘Application Launcher’ software used to activate the central network functions in a network island disconnected from central systems.
- The ‘Emergency Application’ providing the safety and rescue support functions in emergency cases.
- The ‘Application Launcher’ which uses the topology database generated by the topology application. The objective of this application is to maintain the network infrastructure under emergency conditions, e.g. when the contact with the NetCenter is lost, or the network becomes disrupted or fragmented in some way.

To support these measures, important services like the DHCP (Dynamic Host Configuration Protocol) identity/address leasing and the VoIP SIP (Voice over IP Session Initiation Protocol) server are replicated when the network nodes underground determine that a connection is lost to these services. The Application Launcher continually checks the connection to the NetCenter (above ground). Upon a connection loss, the Application Launcher associated with all network nodes in a network island commence working together as follows.

- Each node determines the new geographical centre of the network.
- The master node, which is the mathematical centre of the network (or assumed to be that), sends a message to all other nodes in the network, announcing itself as the new master node.
- If no other nodes claim to have this role (or contradict this by using special messages) within a certain time frame, the new master node launches the central services (e.g. DHCP, SIP).
- If the connection to the NetCenter (above ground) is re-established, the replication node shuts down its replicated services (e.g. DHCP, SIP).
- If two network islands are merged and there is still no connection to the NetCenter (above ground), one of the replication nodes shuts down its services.

This behaviour, whilst relatively sophisticated in network technology terms, offers a highly adaptive and resilient system response. It should be pointed out that this automatic reconfiguration of the basic network services will ensure a basic level of survivability of the underground network. It cannot assure a full operational network capability and reliability, particularly when repeated reconfigurations during an emergency lead to intermittent dropouts. However it is important to note that the essential functions for emergency guidance and location of the mine workforce will remain functional.

Emergency Application development – the Emergency Application is the software on the network nodes responsible for rescue support in emergency incidents. This includes the depiction of evacuation ways, shortest ways to special points (e.g. firefighting equipment, refuge chambers), location of personnel and their proximity, guidance support of personnel to muster stations and supporting communication related issues. The Emergency Application can be implemented in a differentiated manner in specific host programmes. By way of example, communication related applications are mainly related to voice communications and tracking. In an emergency situation, all audio devices in a network are connected in one single group using a half-duplex communication arrangement in order to maintain compatibility with roadway amplifier ‘Tannoy’ loudspeaker systems and line radios. This in turn means that everybody in reach of an audio device in a network island is able to hear anybody else speaking, via a shared broadcast. This offers unconditional, simple procedure-free communications, which is important in a highly stressful situation. Further tasks of the Emergency Application concern the communication of information associated with the individual locations of mineworkers underground. In such a situation it is clearly necessary to know ‘who is where’. The Emergency Application can provide this information to staff using handheld IT devices by means of web-based technology. When a mustering or meeting point has been fixed, another part of the Emergency Application will instruct all network nodes to direct people in the proximity to the agreed meeting point by using the lighthouse functions of the MIC.

Application Launcher development – A primary purpose of the application launcher is to keep the network infrastructure running under adverse conditions, e.g. when the contact with the above ground servers is lost (the ‘NetCenter’), or the network is fragmented in some other way. Therefore, key services such as DHCP (Dynamic Host Configuration Protocol), VoIP SIP (Voice over IP Session Initiation Protocol) and time information (Network Time Protocol, NTP server) are replicated when the application determines a connection loss to these services. The approach is triggered at connection loss to the NetCenter (using dedicated software above ground) and functions as follows.

The application launcher becomes active if the network communication to the NetCenter is interrupted and there is at least one more node active in the network. The first task of the Application Launcher is to compute its current view of the topology and to determine an order for the nodes, where the most central node stays as the first placed in the order and the least central node as the last placed. This is required since the remaining nodes in the network have to decide jointly, which of them will take over and perform the unique central tasks. The algorithm defines that the task of the new NetCenter or ‘Network Island Master’ will always will be performed by be the most central node, i.e. the virtual ‘middle’ of the network island. To decide which node is the centre node, every node in a specific interval transmits the first *n* places of the topology order via multicast or broadcast to every other member node. All received packets are evaluated from each node and a global ranking is calculated. The first node of the global ranking becomes the new ‘network centre’, running vital services. If the first node does not become the ‘network centre’ within a particular time, the second ranked node becomes the ‘network centre’. This process continues up to the end of the ranking list. The ‘network centre’ node multicasts or broadcasts periodically, with the message including the time since this role was established. If two network parts remerge, whilst there is still no connection to the network facility above ground, the node with least active lifetime shuts down and permits the older ‘network centre’ to continue to host this role.

After connection to the central systems is re-established, the devices switch from an emergency mode of operation back to the regular mode, after which the regular behaviour of the communication and networking systems can be re-asserted. The Application Launcher is the central application for the safety support networks. When the core structure of the network is running again, with a DHCP service and SIP service for VoIP, this then ensures that underground staff are able to communicate with each other via their PDA applications or via calls made over VoIP. The application launcher utilises complex software with functions essential to the safety support of the network. The software has been subjected to extensive stress testing and any necessary software revisions implemented. Testing however by nature is limited to the number of nodes available at a laboratory scale or with additional simulation; hence the final testing and verification was only completed when a larger underground installation became available.

All of the above features and functions have been submitted as a patent application during the project work.

Development of person-worn wireless guidance system infrastructure

A further work area concerned assessing the feasibility of adapting the GIS/SCADA software developed originally for monitoring of underground vehicles (via the RFCS MINTOS project) for use with the personal mobile guidance units developed in Task 3.4. The objective here was to investigate the possibilities for implementing an intelligent guidance scheme to assist evacuation and identification of escape routes. It was concluded such functionality could be implemented in the embedded firmware of the location base station as an extension to its existing features. The automatic guidance scheme relies on relative position finding and movement direction analysis. This is accomplished both by the mobile node and the base station. The information on valid escape routes can be sent from the central command centre providing the associated cable infrastructure survives (see figure ‘a’ below). In the event that the wired infrastructure is damaged, the nodes run on battery back-up power supplies and are restricted to sending pre-programmed information such as the route to the nearest refuge (see figure ‘b’ below).

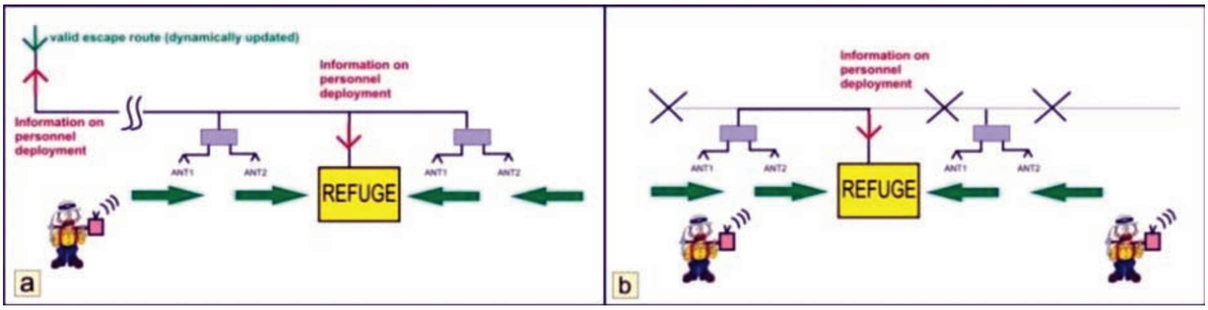

Figure 2.3.5-3: Automatic wireless escape route/refuge guidance scheme

The development work involved modifying the control firmware in the wireless base station LHU (LHU: Location Head Unit, a wireless ranging base station developed under the RFCS MINTOS project). This was required to establish the relevant functionality for carrying out initial underground proving trials of a prototype wireless guidance scheme. These trials, carried out in the underground workings of Guido mine, were assessed and reviewed by specialists from CSRG. Real time visualisation of the node position, direction of movement and text messaging was tested with positive results. The functionality of ‘latching’ the last known position and status of multiple nodes (identification, co-ordinates, accelerometer readouts, and timestamp) was implemented and tested, again with positive results. A patent application for the wireless emergency wayfinding system has been filed.

2.3.6 WP6 – Field Trials and Technology Transfer

2.3.6.1 Human factors and ergonomic appraisal of emergency technologies (Task 6.1)

These activities were carried out as required throughout all phases of the equipment development and test activities. This has included 'pit-worthiness' and 'fitness for purpose' assessments, primarily undertaken by the coal operators and mines rescue companies; with each having specialist skills and experience. By way of example, CSRG undertook a scoping review of the system requirements and associated human factors arising in the use of rescue communications apparatus deployed at the time of an incident. This was used to help formulate and direct overall functions and specification of systems. It is noted that related ATEX certification activities have also been associated with systematic engineering assessments of mechanical robustness.

2.3.6.2 Demonstration of systems and equipment at selected mines (Task 6.2)

The partners, and the mining company partners in particular, invested significant resources towards implementing the various technologies that were researched and developed within RFCS EMTECH. The practical implementation and demonstration initiatives are reported (in the relevant context) in the various Work Package report sections together with specific appendices. In this regard a significant appendix to this report is associated with the refuge development and testing at Hunosa's Pozo Carrio Colliery, Spain. In addition to these demonstration activities, there were several short-term proving tests arranged between the Polish working partnerships, primarily at Guido and Ziemowit mines. Brief additional information is provided here of specific demonstration and test work.

Demonstration work at RAG's training mine 'Trainingsbergwerk TBW'

DMT and RAG used the TBW facility to undertake tests on the communication system described within Task 4.3 and Task 4.4. Since ATEX certification of the system components was not anticipated to be granted until after the end of the contract period, it was not possible to deploy the developed prototypes in the intended underground mining applications, which include the coalface. In such cases, RAG has recourse to the training mine TBW at Recklinghausen, where all equipment can be tested in fully replicated mining conditions. Within the course of the EMTECH project, the training mine has been used many times. The training mine facility is particularly suited to radio communication system testing, since the geometrical conditions and installed metallic infrastructure are identical to that used in underground mines.

The plan below highlights where the various tests were conducted. Whilst initial tests were used to confirm the broad range of TETRA functionality and characteristics, later tests evaluated all the system aspects concerned with TETRA. For this, the base station together with the OF router was positioned at the point coloured blue above, point 'Tor 2' (one of the entrances to the training mine). This location also simulates a fresh air area underground. Transmissions were then sent to TETRA Expander1, some 100 m away and marked on the plan as a red coloured point. A second expander (Expander2) was located in a highly screened zone to check 'worst case' transmission behaviour. A further six radio handset devices were used, with which it was possible to establish three communication groups (two devices for each group). Tests were carried out by registering continuous communication between the radio devices whilst simultaneously observing the attainable radio range. With the support of a portable spectrum analyser the required attenuation and amplification settings were also established for the HF to OF converter and the antennas. The various tests confirmed that it is possible to relay TETRA radio signals with all supported TETRA functions from a surface centre up to 40 km from the underground mine location using fibre-optic transmission. It has also been verified that a TETRA expander can provide coverage up to distances of 150 m in rectilinear roadways with a simple orthogonal antenna and up to 400 m with leaky feeder cable support.

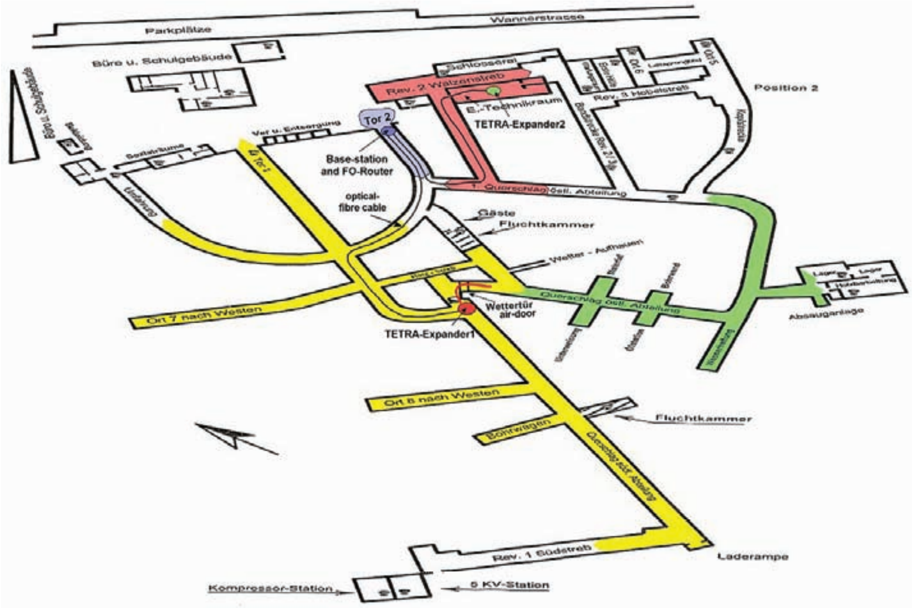

Figure 2.3.6-1: Plan of the RAG training-mine 'Trainingsbergwerk TBW'

High resilience adaptive networking system demonstration at Ibbenbüren mine

The Mine Infrastructure Computer (MIC) systems were subject to intensive laboratory stress testing and were then installed at the RAG anthracite mine in Ibbenbüren, Germany (see figure below).

Figure 2.3.6-2: Mine Infrastructure Computer (MIC) on test at Ibbenbüren mine

These phased tests commenced with laboratory testing of the hardware, which demonstrated robustness. The functions of the intelligent networks, the central system functions for network topology overlay and the mathematical model of the mine were tested intensively with excellent reliability. The tests were extended progressively to cover the network analysis and safety support functions. This especially related to the emergency mode switching and the generation and use of the network topology information. The stress testing and simulation was conducted at a laboratory scale since full underground testing of a full-scale underground application network would exceed the requirements and resources of the EMTECH project. However the algorithms and procedures for a large-scale application were prepared for implementation in the RFCS OPTIMINE demonstration project.

After the MICs were developed, they were tested successfully at the RAG Ibbenbüren mine. The underground demonstration and proving trials were completed satisfactorily in the final semester. Based on the experience gained from over 12 months field testing, the system has proven to be very reliable and functioned well in the mining environment. In the light of feedback from the underground trial, a LCD display was added to the outer door of the system. This was originally planned for a later stage of revision; however the mine requested this for local diagnostics and for the implementation of the safety-related functions of the intelligent infrastructure. During testing, the electricians and users of the system at RAG Ibbenbüren mine were trained and inducted in the application and use of the resilient network technology and its associated subsystems. These activities were progressively extended to all safety support functions as soon as commissioning was completed.

The prototype cap-lamp location transmitter and evacuation guidance device together with the rapid deployment rescue communications equipment were tested extensively by the Polish partners in the underground workings of Guido mine (located in Zabrze, Poland).

Tests of the emergency cap-lamp location system

The tests were conducted in two roadways leading from a junction with an included angle of approx. 40°. This arrangement allowed the system's through-strata capability to be investigated. Both the legacy mode (VLF) and the extended (VHF) mode of location were evaluated. The VLF tests confirmed that a through-strata location determination with acceptable accuracy to a range of 30 m could be achieved, whilst detection of the VLF transmitters was possible up to a separation distance of around 40 m. Correct transmitter identification and reception of uncorrupted data transmissions was possible to distances exceeding 35 m. This location determination performance was considered highly satisfactory. It is noted that the cap-lamp location transmitter power consumption is only 15% of that of the original devices. Hence there is significant scope to increase the peak magnetic moment, which would result in a marginally greater reception range.

Figure 2.3.6-3: Tests of the emergency location system prototype in Guido mine

Figure 2.3.6-4: Tests of the wireless wayfinding and guidance scheme

Tests of the cap-lamp wireless way-finding and guidance function

Tests of the prototype wayfinding and guidance function were conducted in both normal visibility and low visibility smoke conditions at Guido mine. A basic scenario was tested using two infrastructure nodes (LHU1 and LHU2, see figure above). During the tests it was possible to send text and character information on the escape route to the cap-lamps from a PC simulating a dispatcher. It was also possible to set the direction of the valid escape route and observe the automatic warning mechanism implemented in the cap-lamp. In the case of deliberately moving against the set 'escape route' direction, an alarm sounded and a warning message was displayed on the high brightness OLED display. The tests confirmed that the scheme operated in accordance with the system design requirements and assumptions.

Tests of the rapid deployment fibre-optic rescue communications system

A prototype of the rapid deployment rescue communication system was tested in various underground conditions in order to validate its practicality. The test set-up consisted of two reels of fibre-optic cable equipped with the relevant radio transceiver electronics and power supplies. Each reel contained 250 m of fibre-optic cable. Additionally tested were the wireless headsets, the heart rate monitor and the cap-lamp transceiver. A laptop PC with a wired headset was used at the simulated fresh air base. The system components can be seen in the figure below.

Figure 2.3.6-5: Tests of the rapid deployment fibre-optic rescue communication system

Tests were carried out on both the voice communication and data transmission (heart rate sensor and alarm trigger button) capabilities of the system. Simplex and intercom communication modes were successfully demonstrated.

2.3.6.3 Post-trial critical review and equipment appraisal (Task 6.3)

Emergency preparedness and emergency management are core safety concerns. Throughout the RFCS EMTECH research contract there was regular discussion and exchange of views between the research partners, various mine operators and the national Mines Inspectorates. The issues relating to self-escape in particular were consistently a major agenda item of mining industry working groups. In addition, there was frequent international contact maintained with other experts. Each of these activities provided an opportunity for a critical appraisal of the research conducted, together with identifying additional measures that should be considered. By way of example, the RFCS EMTECH consortium met in Spain (24–25 March 2011) at the Fundación Santa Bárbara, Leon where an extensive discussion took place between the partners on the outcomes and recommendations. The coal operators and rescue services, as end users of the delivered outputs of the EMTECH contract, considered the research to be of high relevance to industry.

2.3.6.4 Conclusions and recommendations (Task 6.4)

The conclusions and recommendations regarding mine emergency support technologies and associated tools are covered in §2.4, *Conclusions* on page 67.

2.3.6.5 Preparation of training materials and training on the application of new technologies (Task 6.5)

All parties – both suppliers and users – are aware of the critical need to provide induction training and support an effective programme of technology transfer. This matter was therefore accorded increased priority as the research was delivered. A related discussion is given in §2.5, *Exploitation and Impact of the Research Results* on page 73. Reference is also made to Task 3.5, *Enhancement to rescue and* *evacuation strategies*, which includes consideration of various coal operator training initiatives which have been developed. A number of further initiatives have been maintained under consideration by the coal mine operators and rescue services. This includes expectations training for evacuation and wayfinding through smoke, induction training on the circumstances for seeking refuge and how the refuge technology should be initiated and used. Further technology or system-specific training has been devised to support the new communications, personnel location and guidance technologies. Much of this training involves initial familiarisation and induction courses supported by regular exercises and drills to develop familiarity and ultimately expertise in the use of these support systems. The manufacturing partners have also had to provide technical manuals and installation/user instructions for their ATEX-certificated products, which in itself represents a significant element of this task.

2.3.6.6 Dissemination of results (Task 6.6)

As mentioned above, during the course of the EMTECH contract there has been regular exchange of views with international experts, including Federal and State Authorities in the United States responsible for supporting the consultation and research activities associated with, *inter alia*, the US *Mine Improvement and New Emergency Response Act* of 2006. Consideration was also given as to whether an international workshop could be arranged, although the resources for this lead to the research partners advancing dissemination initiatives largely at a local or national level. One effective dissemination and information exchange mechanism was in attending the biennial *International Mines Rescue Conferences* which provided opportunities for extended discussions with experts on specific incidents, associated emergency actions, consideration of 'what-if' incident scenarios and how these should be managed.

A further 'indirect' aspect of dissemination activities concerned scientific publications, patents and discussions with mining company system and technology specialists. These were progressed as required. Information on published papers is given in §2.5.4, *Publications / Conference Presentations* on page 74.

2.4 CONCLUSIONS

2.4.1 Summary

EMTECH is a three-year project, which has the aim of ensuring that European standards and procedures to be used in the event of a mine emergency incident continue to be at the forefront of world best practice. The major objectives of the project have been to provide an integrated network infrastructure for the optimisation of mine processes and to introduce a range of new support technologies for mine evacuation and rescue. The results of the research, in the form of products, applications and systems are summarised as a listing of key achievements. A discussion is then provided of the principal conclusions. Rather than address this on a Work Package by Work Package basis, the discussion is presented in the form of key thematic areas. This approach provides a strategic analysis and context for the issues and gains from the research. The key achievements may be summarised as follows.

WP1: Resilient response capability from the mine communications infrastructure

- ✓ An industry-wide appraisal of the 'survivability' of current underground speech and data communication systems.
- ✓ A methodology for analysing and optimising system resilience, primarily based on risk assessment tools and 'what if' scenario analysis.
- ✓ The development of a resilient, self-healing, automatically reconfigurable underground network infrastructure.
- ✓ The development of an ATEX M1 certificated un-interruptible mine power supply.

WP2: Incident status and decision making support

- ✓ Knowledge of POCs and fire characteristics and their relationship to human tenability criteria, based on validated CFD and ventilation modelling.
- ✓ The development of validated evacuation route modelling and decision impact assessment tools suitable for various incident scenarios.
- ✓ Information on various aspects of the emergency situation (fire location, zone endangered, viability of escape routes, personnel location).
- ✓ Integration of environmental and personal tracking information into the management information network.
- ✓ Dynamic real-time guidance support via the local and distributed network infrastructure.

WP3: Systems and procedures to enable self-escape

- ✓ Application knowledge relevant to the EU mining industry on the design and use of refuges in coal mines.
- ✓ A physiological appreciation of refuge thermal and respiratory demands.
- ✓ The development of a key refuge support technologies.
- ✓ The implementation of completed underground refuges using both fixed and transportable types.
- ✓ Evacuation support technologies for use in smoke with low or nil visibility conditions.

WP4: Search and assisted rescue

- ✓ Basic research knowledge on electromagnetic propagation and its optimisation.
- ✓ Accurate earth penetrating location (to distances greater than 30 m) and messaging systems.
- ✓ Development of vital life signs status physiological monitors.
- ✓ Provision of independent rapid deployment, lightweight rescue team communications set.
- ✓ Implementation of an advanced independent TETRA communication network serving emergency and production needs.

WP5: Central safety management

- ✓ Automatic switching of the data network to implement dedicated 'emergency mode' support features.
- ✓ Intelligent infrastructure status detection which automatically exploits path redundancy and meshing.
- ✓ Visualisation support for incident response teams including mineworkers' locations (or last valid location).
- ✓ The ability to broadcast messages over entire mine, selected areas or to specific personnel.

WP6: Field trials and technology transfer

- ✓ Systems field-tested in several different locations and various conditions.
- ✓ Post-trials review, recommendations, training and dissemination involving coal companies and rescue organisations.
- ✓ Confirmation that demonstration systems meet operational 'fitness for purpose' demands.
- ✓ Promotion of industry dissemination and training activities.

2.4.2 Resilient networks

It is clear that the organisation of current underground speech and data communication systems offers little in the way of resilience. The traditional network approaches in mining employ a philosophy where most, if not all, data and system connections are linked into surface infrastructure via arterial roadway backbone communication links. In the event of infrastructure damage, which could result from a major fire, explosion, ground failure or inrush, the communications infrastructure is often completely disabled. This is a general observation throughout underground mining.

What has therefore been required is a self-recovering network capability that is engineered for automatic network recovery in the event of partial network breakdowns, infrastructure damage and mains power loss. To implement such functions requires that each critical network switch is provided with 'intelligent' electronics and a backup power supply of sufficient duration. At a strategic level there is also a requirement for a fibre-optic ring main for the backbone communications.

In the event of multiple network interruptions and possibly even complete loss of communications with the above ground servers, the systems which have been developed will automatically reconfigure themselves to maintain a maximum level of functionality within the system. This is maintained even when the infrastructure damage is extensive. The intelligent network nodes will still attempt to maintain local or district level communications and system functions. This is a very powerful system attribute and indeed the system patent applications confirm that it is a decisive innovation.

Consistent with providing a network with an ability to at least partially recover after disruptions from a major mine incident, the system can then continue to provide a number of critical emergency functions to assist self-escape. This includes incident location and status information, evacuation and mustering instruction, wayfinding and guidance support, and warning of untenable environmental conditions. Conversely for rescuers, information on the location of personnel, and whether an area has been evacuated can help considerably in focusing the efforts of the rescue teams. Collectively the intelligent network infrastructure helps address one of the principal issues of emergency management; namely the problems of information deficiency.

It is noted that the network infrastructure that has been developed makes use of open standards protocols and can interface with a variety of third party SCADA software applications. The research studies have also confirmed that it is entirely feasible to monitor a multiple number of district networks that are in turn monitoring multiple numbers of Zigbee tracking devices. Low power Zigbee wireless technology is a rapidly maturing technology in underground mining, which can support personnel, vehicle or materials identification and tracking.

It can be seen that real progress has been made towards an objective of imparting resilience and adaptive behaviour in the underground communications infrastructure. It can also be seen that progress has been made in ensuring the underground network subsystems can 'talk' with one another. A related requirement is that mine emergency incident managers have access to all required information but that they should not be simply inundated and overwhelmed with information. This requires careful consideration of the 3D visualisation and data filtering that should be applied to the data. Here again, valuable progress has been made in defining how data should be managed and presented to assist critical decisions in the initial phase of a mine emergency.

2.4.3 Evacuation modelling support

There is an increasing international awareness and responsibility to reduce the likelihood and severity of major mine incidents and ensure that self-escape and assisted escape has a high probability of success. The first priority in coalmines is always to attempt to evacuate the mine. As part of this process it is acknowledged that underground refuges/muster stations have a key role in offering a place of relative safety where the workforce can be briefed, exchange their self-rescuer, or rest and recover as part of a staged evacuation process. The latter role is of particular importance where the evacuating mineworkers must travel a long way on foot to reach safety, possibly in hot humid conditions.

The siting of refuges must be very carefully considered against a wide-ranging scenario analysis, which constitutes part of a rigorous risk assessment and hazard analysis process. Estimations have traditionally had to be made on fire growth rate, the transport of toxic and irritant smoke products in the ventilation system, possible back-layering and other ventilation impacts in order to ensure the escapeways provide a feasible means of withdrawing staff from the mine. As part of these considerations, estimates have to be made on evacuation speed/time, oxygen cost of escape and whether mineworkers can successfully negotiate a way through smoke-filled tunnels.

In response, the research has greatly advanced the science of evacuation modelling and decision making support. The initial phase involved full-scale fire testing and evaluation of the resultant heat release characteristic, with downstream gas and temperature conditions associated with the fire measured. This data was used to validate a CFD model for the local mine geometry and ventilation conditions. It is however recognised that CFD modelling is situation-specific and that a combinatorial approach using CFD in conjunction with conventional ventilation models and simplified analyses could offer a broader application potential.

The fire and smoke transport modelling provides a reference framework to judge potential siting options for refuges and limiting factors arising from heat tenability criteria. In the case of the Pozo Carrio mine there was an extensive associated study since there is a relatively complex arrangement of levels, drifts/inclines and workings that are served by the refuge. This work allowed a critical appraisal of the fire conditions that could compromise the ability of the workforce to follow primary/secondary or tertiary escapeways.

The foregoing fire ventilation modelling was used directly to help develop an advanced evacuation simulation model. The evacuation simulation was partly validated from data derived from realistic evacuation exercises conducted by the mine operators and rescue services. After appropriate testing, it has been shown that the simulated evacuation times have an impressive correspondence with the data derived from the evacuation drills. Indeed, there is a high degree of confidence that the evacuation simulation tools can now be applied against a wide range of other mine and tunnel plans to predict the likely evacuation time characteristics. Importantly, there is reasonable evidence to support a conclusion that only limited further validation is required of the evacuation simulation model.

2.4.4 Underground refuges

As aforementioned, there is an increasing recognition of the role of refuges (safe havens in the UK) as a critical component of supporting initial mustering activities and the subsequent evacuation. The requirement for refuges in underground coalmines is not mandated in EU member states. Refuges are however prescribed in Federal law in the United States (MINER Act 2006) and will be mandated in China.

Whilst there is now a well-established supplier base for mobile and transportable mine refuges, there are no commercial suppliers (that could be identified) for large capacity strata or multi-section refuges. In this case the mine operator must assume the role of design authority in the specification and commissioning of fixed infrastructure refuges. This dictates a requirement for a full understanding of the various refuge support technologies and in particular respiratory and thermal safety issues arising in refuge design. This can pose significant design challenges, particularly in hot and humid mines and where the refuge must be designed for a potentially large number of occupants.

The implementation of the prototype refuges was preceded by an in-depth appraisal of international practice, including US Federal regulations and UK Mines Inspectorate guidance. Particular attention was paid to the breathable air supply arrangements and ensuring the refuge thermal environment would remain acceptable even after long periods of occupation. Achieving this required careful design and verification testing. The associated research has resulted in a fundamental understanding being obtained of refuge breathable air and cooling requirements. Associated studies were undertaken to examine how the cooling capacity of a given compressed air delivery rate to a refuge could be maximised. The use of air amplifier technology was shown here to be an effective means of increasing local air velocities in the refuge chamber and therefore of achieving an acceptable microclimate for the occupants.

2.4.5 Guidance through smoke

Escape planning must take into consideration the impacts of irritant smoke and low or zero visibility conditions. One immediate recommendation is to ensure that suitable goggles are supplied with escape respiratory protective devices (filter self-rescuers or self-contained self-rescuers). The irritant effects of smoke can be severely disabling. Without goggles it may be necessary to keep the eyes closed in order to reduce the irritation.

In low or zero visibility conditions the speed of travel can be reduced to less than a quarter of that under normal visibility conditions. Therefore a related recommendation is that, where feasible, mines install evacuation lifelines. If the lifeline is equipped with conical ferrules then this imparts directional information, with the user’s hand coming up against the back face of the cone if an attempt is made to travel in the wrong direction. The studies confirm that lifelines provide a very simple but effective means of guidance. In order to prepare the mine workforce in the use of lifelines, special obscuring goggles can be used to simulate low visibility conditions. Experience in UK coalmines confirms that training with special goggles can provide realistic lifeline expectations training.

The research also resulted in highly effective wayfinding support technologies that exploit the resilient network infrastructure. One variant uses a 'lighthouse' function in the resilient mining infrastructure computers (MICs) to provide evacuation and guidance instruction (for example initial mustering instructions). A second development uses either a wrist-worn or cap-lamp information display to provide dynamic guidance information. Both techniques are effective and arrangements are being made to commercialise these technologies. In each technology the systems provide dynamically updated information. However if the network infrastructure is heavily damaged they can continue to provide predetermined (default) escape route information.

2.4.6 Emergency location and tracking

In a mine emergency, an imperative requirement is to determine the location and status of all personnel underground. This can then help direct both self-escape and assisted escape activities. In the event that rescue teams must commence searching the mine workings to locate the mine workforce, then accurate location knowledge is vital, even if this is available only up to the time of the incident. A further requirement is to be able to rapidly determine location in cases of entrapment, possibly through many metres of falls of ground.

The research has addressed directly all of these issues. An innovative dual-mode cap-lamp location transmitter with a built-in messaging capability has been developed which is regarded as a natural successor to the 100,000 GLON cap-lamp transmitter units in current use. This system can provide an accurate position determination of multiple transmitters at a distance of up to 30 metres, including transmission through any intervening strata. The device can also provide messaging to the cap-lamps, which are equipped with a special high visibility display.

The other critical aspect of emergency location support is providing a tracking function based on Zigbee or other tag devices. In this regard the developed network infrastructure is capable of performing tracking and concurrent monitoring of several mine districts, providing these are suitably equipped. The mining infrastructure computers are also designed to conform to the IREDES (International Rock Excavation Data Exchange Standard) tracking specification.

Studies and experimental tests were also carried out on assessing how individual vital signs physiological status could be determined. Wireless-based sensor technology to accomplish this has been shown to be entirely feasible.

2.4.7 Independent rescue communications

Whilst mines rescue services will attempt to make use of mine communication and mine transport systems if available, these systems may however be non-functioning due to mine infrastructure damage. A critical requirement for effective mines rescue is to ensure an independent means of communication is always available if needed. Indeed, some legislatures restrict the rescue penetration distance of rescue teams to less than 1000 m if no supporting communications system is available.

Such systems must be lightweight, intuitive to operate and simple to deploy. Furthermore as with all specific rescue apparatus intended for use in hazardous atmospheres of indeterminate composition, the apparatus must be certified to ATEX M1 standard. Generally, speech communication is now widely facilitated with the use of modern facemasks with speech diaphragms.

Consistent with the above requirements, the communication system must also fit into the standard procedures and equipment used by national mines rescue services. It was determined during the studies that a standard 'one size fits all' approach to procuring rescue communications equipment is probably unrealistic at the current time. The research to develop rescue team communication systems was therefore progressed to meet the specific local requirements of the German and Polish industries respectively.

The German system development focused on an entirely new approach of adopting TETRA (terrestrial trunked radio) technology to coal mining. Whilst hazardous atmosphere TETRA equipment is available for the petrochemical industry this did not meet ATEX M1 requirements. Therefore significant development and certification work was required to secure appropriately certified equipment. The TETRA technology has been shown to offer excellent underground performance, including full coalface coverage when the system is deployed there. The system can also if required use a fibre-optic cable to provide an independent link up to a distance of 40 km.

As a complementary approach, the Polish partners developed a lightweight rapid-deployment fresh air base to rescue team communications set. This uses a hybrid fibre-optic/wireless approach that can provide a high bandwidth transmission capability if required. Both systems demonstrated their utility and value in simulated rescue scenarios.

2.4.8 Assimilation of new technologies

Mine emergency support technologies are by definition of potentially critical importance to the outcome of an emergency intervention. If the technologies are to be successfully assimilated into self-escape and rescue support practices, then the technologies must be fit for purpose, simple and intuitive in operation, and designed to meet any anticipated human factor issues arising. The technologies must then have high quality supporting training provided, including realistic expectations training, which may need to include the entire mine workforce.

Within RFCS EMTECH, all the partners and specifically the coal mine operators have shown an impressive degree of commitment in installing demonstration schemes and promoting effective training arrangements. Major initiatives include the refuge development and testing at Hunosa’s Pozo Carrio colliery and UK Coal’s Daw Mill colliery, and the trial of the resilient networking technology at RAG’s Ibbenbüren mine. Several in-depth test programmes were conducted at RAG’s training mine, Trainingsbergwerk TBW at Recklinghausen and at Guido and Ziemowit mines, located at Zabrze and Lędziny respectively. The partners have equally imparted significant resources to procure ATEX certification for a wide range of products. Collectively it can be seen that there has been a high level of application to achieving successful demonstrations of these critical technologies.

2.5 EXPLOITATION AND IMPACT OF THE RESEARCH RESULTS

2.5.1 Actual Applications

The actual mine applications can be considered broadly within two categories – ‘application knowledge’ and ‘developed/certified systems’. This includes the following points.

Application knowledge used in the trial mines...

- Design and specification knowledge on fixed infrastructure underground refuges.
- Specifier and application knowledge on transportable/mobile refuges.
- An appreciation of communications system survivability potential and how to ‘harden’ systems.
- A modelling methodology for assessing fire growth and ventilation impacts.
- A validated evacuation time simulation approach.

Developed/certified systems used in the trial mines...

- ATEX certified resilient, automatically reconfigurable underground network components (mining infrastructure computers) complete with Gigabit fibre-optic Ethernet links and wireless access provision.
- ATEX certified un-interruptible mine power supplies (with certification to be completed in 2012).
- Refuge sub-systems, including breathable air supply, cooling and communications support technologies.
- Evacuation and wayfinding support technologies for use in low or nil visibility conditions – (a) lifeline technologies and (b) active electronic support measures.
- ATEX certified vital signs status physiological monitors.
- ATEX certified independent, multi-role emergency communications infrastructure, based on TETRA wireless network technology.
- Provision of a rapid deployment, lightweight fresh air base to rescue team communications set.

The installed demonstration systems at Pozo Carrio, Daw Mill and Ibbenbüren are noted. Discussions with various mine operators confirm that additional installations are under active consideration.

2.5.2 Technical and Economic Potential

The technical improvements to mine operations from this work are essentially associated with increased safety and the implementation of networked systems which will provide a number of important additional day-to-day functions which include; flexible messaging systems, and tracking and location capabilities. Certain sub-systems such as physiological status monitoring and back-up communication and power supply facilities will also find operational roles beyond their primary emergency preparedness application. The economic potential from the manufacture or licensing of ATEX-certified products is difficult to estimate at this point, but the associated partners have commenced marketing initiatives and sales engineering discussions to procure sales in the EU and a number of other countries with major mining interests. Manufacturing arrangements for the resilient networking and TETRA system developments are also being progressed. The first batch of 26 ATEX un-interruptible power supply units has been produced for use at Hunosa’s St. Nicolás mine. General commercialisation is planned thereafter. A tracking system based on the OPC server approach is also being commissioned at the St. Nicolás mine. In the case of the cap-lamp-based location transmitter and messaging system, if the current 100,000 GLON units in use are replaced or upgraded, then the value of the product sales will be significant, although this would probably entail a staggered approach to replacement.

A further consideration is the reduction in insurance costs and uninsured losses associated with major mine accidents. There are two issues that accident law must address – who should be held responsible for accident costs, and how the costs should be evaluated. That said, all mine emergencies can lead ultimately to high costs. It is not an intention to comment further on the cost-benefit analysis between accident costs and accident avoidance costs, other than perhaps to cite the example of the North Sea Piper Alpha disaster (6 July 1988). Here the explosion and resulting fire destroyed the production facility, killing 167 men with only 61 survivors. The total insured loss was about €2 billion.

2.5.3 Patents

Minetronics filed a German patent application under official reference number DE 10 2009 030 910.1 and title '*Sicherheits-gerichtetes Verfahren und -system für untertägige Bergwerke*'. The application covers the procedures and systems required for the implementation of mining-related safety functions using a network-based underground communication system.

Based on the initial German patent application, Minetronics filed an international patent, application number PCT/EP 2010/056825 to secure the Intellectual Property related to the developments.

2.5.4 Publications / Conference Presentations

Brenkley D and Jozefowicz R (2011), Thermal issues in evacuation and rescue, *Presentation to 5th International Mine Rescue Conference*, 22-26 October 2011, Beijing, China.

Müller C, Noack A, Szekely I (2010) Ethernet communication for detection of emergency locations and dynamic evacuation in underground infrastructures, *Proceedings of IEEE 12th International Conference on Optimisation of Electrical and Electronic Equipment (OPTIM),* 20-22 May 2010, Brasov, Romania

Müller C and Noack A (2011) Network-based communication for mine and tunnel constructions, *17th Colloquium "Bohr- und Sprengtechnik*, 21-22 January 2011, Clausthal, Germany.

Müller C and Noack A (2011) Safety support functions for underground network communications, *Proceedings 35th APCOM Conference*, 27-29 September 2011, Wollongong, Australia.

Wiszniowski P and Babecki D (2010), Nowoczesne technologie wspierające prowadzenie akcji ratowniczych" (tranls.: New emergency support technologies), *Industry seminar hosted by EMAG Scientific & Industrial Centre*, 23 November 2010, Katowice, Poland.

A co-objective was to strengthen the reputation of the RFCS programme and disseminate information on related research activities and achievements.

2.5.5 Other Aspects Concerning the Dissemination of Results

Minetronics MIC development: EC type approval number IBExU10ATEX1125

DMT-RAG TETRA development

TETRA Expander:	EC type approval number BVS 11 ATEX E 095
Vital Signs Measuring System:	EC type approval number BVS 11 ATEX E 099
Wireless Push-to-talk Unit:	EC type approval number BVS 11 ATEX E 100

3 Reference Material

3.1 List of Figures

3.2 LIST OF TABLES

3.3 ACRONYMS AND ABBREVIATIONS

ACP	Air cooling power
ACPM	Air cooling power (M scale)
ADC	Analogue to digital converter
Aitemin	EMTECH project partner: Asociación para la Investigación y Desarrollo Industrial de los Recursos Naturales
AM	Amplitude modulation
AMSS	Amplitude modulation signalling system
API	Application programming interface
ASIC	Application-specific integrated circuit
ATEX	Appareils destinés à être utilisés en ATmosphères EXplosives
BBC	British Broadcasting Corporation
BET	Basic effective temperature
BMI	Body mass index
CAD	Computer aided design
CAN	Controller area network
CCTV	Closed circuit television
CDC	Centers for Disease Control and Prevention
CFD	Computational fluid dynamics
cfm	Cubic feet per minute, ft^3/min
CO	Carbon monoxide
CO_2	Carbon dioxide
CSRG	EMTECH project partner: CSRG; Centralna Stacja Ratownictwa Górniczego SA
dB(A)	Sound pressure level, dB A-weighted
DHCP	Dynamic host configuration protocol
DMO	Direct mode of communications (TETRA mobile to mobile)
DMT	EMTECH project partner: DMT GmbH & Co. AG
DSP	Digital signal processing
EDAFFIC	An RFCS project: Early Detection And Fighting of Fires in belt Conveyors
ELF	Extra low frequency
EMAG	EMTECH project partner: Centrum Elektryfikacji i Automatyzacji Gornictwa
EMI	Electromagnetic interference
EMIMSAR	An RFCS project: Enhanced Miner-Information Interaction to Improve Maintenance and Safety with Augmented Reality Technology and New Sensors
FMEA	Failure mode and effects analysis
FSR	Filter self-rescuer

Geocontrol	EMTECH project partner: Geocontrol SA
G-HED	Grounded horizontal electric dipole
GIS	Geographic information system
GLON	Type of VLF beacon transmitter
GLOP	Type of emergency location receiver
GUI	Graphical user interface
HF	High frequency
HF-OF	High frequency to optical fibre
HMS	Her Majesty's ship
HRR	Heat release rate
HSE	Health and Safety Executive
Hunosa	EMTECH project partner: Hunosa; Hulleras del Norte SA
I/O	Input –output
IAMTECH	An RFCS project: Increasing the Efficiency of Roadway Drivages through the Application of Advanced Information, Automation and Maintenance Technologies
IEC	International Electrotechnical Commission; a standards organisation
IEEE	Institute of Electrical and Electronics Engineers
INSHT	Instituto Nacional de Seguridad e Higiene en el Trabajo
IP	Internet protocol
IPR	Intellectual property rights
IREDES	International rock excavation data exchange standard
IS	Intrinsically safe
ISM	Industrial, scientific and medical (radio bands)
IT	Information technology
LAN	Local area network
LCD	Liquid crystal display
LED	Light-emitting diode
LHU	Location head unit; part of WLSS system.
$LiFePO_4$	Lithium iron phosphate
LISA	Large immobile surface antenna
LOM	Laboratorio Oficial Jose Maria de Madariaga
MIC	Mining infrastructure computer (Minetronics designation)
MINER Act	US Mine Improvement and New Emergency Response Act of 2006
Minetronics	EMTECH project partner: Minetronics GmbH
MINTOS	An RFCS project: Improving Mining Transport Reliability
MRSL	EMTECH project partner: Mines Rescue Service Ltd
MSHA	Mine Safety and Health Administration
MW	Medium wave
NFPA	National Fire Protection Association
NIOSH	National Institute for Occupational Safety and Health
NO	Nitric oxide
NO_2	Nitrogen dioxide
NTP	Network time protocol
O_2	Oxygen
OF	Optical fibre
OLE	Object Linking and Embedding
OLED	Organic light-emitting diode
OOK	On-off keying (modulation)
OPC	Object linking and embedding for process control
OPTIMINE	An RFCS project: Demonstration of process optimization for increasing the efficiency and safety by integrating leading edge electronic information and communication technologies (ICT) in coal mines

P	Pressure (Pa)
PABX	Private branch exchange
PC	Personal computer
PCB	Printed circuit board
PDA	Personal digital assistant
PES	Programmable electronic mining systems
PIARC	Permanent International Association of Road Congresses
POC	Products of combustion
PPE	Personal protective equipment
PR-133	An ECSC project: Extending the utility of underground data transmission networks and other data processing equipment
PSU	Power supply unit
Q	Airflow (m^3/s)
RAG	EMTECH project partner: RAG Deutsche Steinkohle AG
RAINOW	An RFCS project: Researching the applications of innovative open wireless technologies
RH	Relative humidity (%)
SAR	Search and rescue
SCADA	Supervisory, control and data acquisition systems
SCFM	Standard cubic feet per minute
SCSR	Self-contained self-rescuer
SEM	Sensor electronic module (proprietary name)
SIL	Safety integrity level
SIMRAC	Safety in Mines Research Advisory Council
SIP	Session initiation protocol
SLPM	Standard litres per minute
SO_2	Sulphur dioxide
STEPS	Mott MacDonald software simulation tool
TBW	RAG Trainingsbergwerk Recklinghausen
T_{DB}	Dry bulb temperature (°C)
TETRA	Terrestrial trunked radio
TGC1	Technical Group Coal 1
T_{WB}	Wet bulb temperature (°C)
UK Coal	EMTECH project partner: UK Coal Mining plc
UPS	Un-interruptible power supply
UPSU	Un-interruptible power supply unit
UPTUN	An EU Fifth Framework project: Upgrading of existing tunnels for fire safety
VHF	Very high frequency
VLF	Very low frequency
VoIP	Voice over internet protocol
WDM	Wavelength division multiplex
WLAN	Wireless local area network
WLSS	Wireless logistics support system
Zigbee	A low-power wireless mesh network standard

3.4 REFERENCES

For the convenience of the reader, references in this report are given at the end of each section to which they refer.

4 Appendices

4.1 Psychometric Impacts of Mine Fires

This appendix provides accompanying material for the report on Task 2.3.

Part of the objectives of Task 2.3 involved analysing from a multistressor perspective the consequences on the conditions for evacuation of the following factors.

- Thermal physiology
- Psychological stress
- Ocular irritation
- Disorientation
- Lack of information

Sectoral information was collected from a wide range of institutes and research departments linked to the mining industry, such as INSHT (Spain), HSE (UK), NIOSH (US) amongst others. The following summarises the information and key findings obtained in each field. This work also provided support to activities in WP3.

4.1.1 Thermal physiology

This is the most widely developed field of the above factors. It is well known that heat affects the performance of the individual in several ways. NFPA standards lay down a method of evaluating heat effects on a human body. Exposure to heat can lead to life threat in three basic ways, namely...

- Hyperthermia
- Body surface burns
- Respiratory tract burns

These modes of affecting the human body can cause the following effects.

Heat cramps: This occurs due to salt depletion from excessive sweating. These are the first signs that the body is having difficulty with increased temperature.

Heat exhaustion: This is more serious than heat cramps. It is due to salt and water depletion occurring from excessive sweating. This occurs when a person is exposed to high temperature for a longer period or the body may become dehydrated and temperature regulation may begin to fail. The symptoms include headache, nausea, exhaustion, weakness, dizziness, faintness, mental confusion.

Heat syncope: Due to vasodilation and excessive sweating there is circulatory and vasomotor instability.

Heat stroke: Under the most extreme conditions, the body temperature regulation fails. The subject may become mentally confused and aggressive. There is very little perspiration. There is a requirement for emergency medical attention. Without care, death will ensue in a matter of hours.

Related research publications by the UK HSE were taken into account (UK HSE 2003, UK HSE 2008). This work assessed the impact of factors related to heat during training of mineworkers to provide hot air breathing when using an escape respiratory protective device. The HSE study consisted of two phases...

Phase 1: The development of a hot air device which provided a simulation of the breathing behaviour of a W95 filter self-rescuer operating in a carbon monoxide contaminated atmosphere. This work involved thermo-chemical modelling of generic FSR behaviour in specific challenge atmospheres together with the construction and testing of suitable prototype hot air simulation devices for use in

Phase 2 of the study. Consideration was also given as to how the hot air simulation device could be used as the basis of an industry training device.

Phase 2: This involved undertaking a range of baseline and high temperature physiological endurance tests to examine how well mineworkers accommodate the hot air breathing effects of a filter self-rescuer whilst making a long duration evacuation. This, importantly, also included consideration of the physiological benefits of cooling and rehydration within a staged evacuation process. HSE Research Ethics Committee approval was granted for a programme of physiological tests to evaluate long duration wearing of a hot air FSR simulator device.

The conclusions of this investigation were as follows.

Heat exhaustion

- Risk of heat-related disorders increases significantly between 31°C and 35°C BET.
- Risk of heat stroke increases tenfold between 32°C and 35°C T_{WB}.
- Core temperature on presentation of heat exhaustion does not generally exceed 38.5°C.
- Few cases of heat exhaustion will occur if $T_{WB} < 25°C$, $T_{DB} < 34°C$, air speed >1.5 m/s, air cooling power > 250 W/m^2.
- Mental performance and judgement can be significantly affected by heat.

Impact of dehydration

- Water deficit (hypo-hydration) can range from ~1% to 8%.
- Dehydration magnifies the body core temperature response in hot environments.
- Effects are detectable for fluid deficits as small as 1%.
- Physical work is potential grossly impaired at > 4% dehydration.
- As water deficit increases, there is a progressive increase in core temperature (compared with euhydrated state) during exercise stress.
- The magnitude of additional core temperature elevation ranges from 0.1°C to 0.23°C per percent of body weight loss.
- Dehydration can negate the core temperature advantages conferred by acclimation.
- At a dehydration level of 5%, core temperature responses of un-acclimated and acclimated persons are similar.
- A maximum dehydration limit of 3% is suggested for industrial workers.
- Urine colour is a useful indicator of hydration status (with reservations).

Impact of self-pacing

- There is some evidence that central nervous system of athletes can moderate the rate of rise and maintain core temperature within critical limits.
- Experienced mineworkers generally employ self-pacing strategies to help cope with heat.
- However, severe climatic conditions that can occur underground may overwhelm any self-pacing strategy.
- Heat storage will generally occur if exercise is conducted at high wet bulb temperatures.
- Time to exhaustion is inversely related to the initial body core temperature and directly related to the rate of heat storage.

Impact of acclimation

- Heat acclimation is likely to confer one important advantage – a lowering of resting body core temperature of the order of 0.3–0.5°C.
- The use of acclimated subjects in the HSE exercise protocol may have presented, at least initially, a lower body core temperature response compared with non-acclimated subjects.
- The benefits of acclimation are rapidly negated by increasing levels of dehydration.

Impact of heat index used

- The effective temperature index has limitations, particularly in severe hot humid climates.
- On balance however, the continued use of effective temperature in the mining industry is recommended.

Impact of mine regulations

- German regulations and practice confer the highest degree of protection against heat-related illness.
- UK industry depends on voluntary guidance codes. The preventive measures contained in these codes are representative of good practice.

Impact of pre-cooling

- The current body of evidence suggests that pre-cooling allows a greater rate of heat storage. This is a decisive advantage.
- Conversely, any pre-warming will reduce the heat storage potential.
- Intermittent regional cooling can be as effective as constant microclimate cooling.
- Cooling rates of >60 W/m^2 are feasible.

Impact of fluid ingestion

- Under normal circumstances the gastro-intestinal tract can absorb fluid at a very high rate.
- However as the body reacts to prolonged heat stress and dehydration the gut-barrier function can be compromised.
- Moderate over-drinking (or hyper-hydration) confers limited value as a heat strain mitigation strategy.

4.1.2 Psychological issues

Relevant research findings on this subject have been systematically reviewed, but only limited quantitative data has been identified, with the literature essentially reflecting qualitative analyses. Research conducted at the University of Delaware (c1986) based on the psychological and social aspects of sheltering and evacuation in the event of an accident at a nuclear plant offers a number of insights. For example, responses to warning messages are heavily dependent on whether those warned find confirmation of the threat from those in their social setting; which is far more important in generating coping or adaptive behaviour than the actual content of the message. Those exposed to a warning will attempt to confirm that the threat is to be taken seriously, either by looking at what other people are doing, telephoning others, or turning to broadcast new sources. Effective planning has to ensure that the social confirmation that is sought is provided somehow. Otherwise the warning may be discounted and disregarded. Alerting naïve subjects in particular to a danger may not be enough. Warnings, to be effective, require reinforcement by other social actions that confirm the necessity to act.

All the evidence points to a strong probability that the weight of feeling would be substantially against the idea of sheltering rather than evacuating in the case of a nuclear power plant accident. The time frame that might be involved would not seem to make any difference in the probable attitude. Nonetheless, if people are ‘caught’ and must shelter, then planning can assume they will react relatively well despite the stresses of the situation. However, irrespective of whether sheltering/refuge or evacuation occurs, the results will only be positive if there has been appropriate prior planning and testing. In general, facility planning is usually not too well integrated with overall community disaster planning.

To understand disaster behaviour it is crucial to see it from the viewpoint of those reacting at the time of the emergency, not as it might be viewed from an outside perspective or in retrospect. Within that context, people do not act irrationally; they try to respond in terms of what makes sense to them in a sudden crisis. What will seem reasonable is that which people are accustomed to doing, and there will be reluctance to engage in unfamiliar or unusual behaviour patterns. In general, any attempt to have in-place sheltering in facilities in response to a nuclear power plant accident will be problematical. Such behaviour runs counter to a number of social psychological factors usually operative in crisis situations.

There are also some negative social psychological consequences. From a technical point of view there may be merit in asking people to remain in place in the face of danger. There may also be situations where in-place sheltering may be only one of a few options realistically available in an extremely rapid development of an emergency. This form of behavioural adjustment is fraught with a variety of potential human and social problems. However, in the one kind of emergency where such in-place sheltering has been the norm or at least one option suggested for endangered persons, that is, some kinds of fire emergencies, the results have been, at best, mixed. The philosophy has been that instead of attempting to flee through smoke and fire-filled halls or stairwells, persons in burning buildings should remain behind the closed doors of their hotel or dormitory rooms. The research literature on the topic is not extensive but it suggests that it is very difficult for human beings to remain behind doors in rooms where there is a fire outside or very nearby. There are cases where people initially behind closed doors, where it would have been safe for them to remain for hours, eventually attempted, with fatal results, to leave their relatively safe place of refuge.

It is quite understandable why in-place sheltering is difficult. The behaviour runs contrary to what human beings have been socialised to do in the face of an immediate threat, and that is to move away from the situation. In-place sheltering is also a passive rather than active form of response which also runs against the learned impulses of people of what to do in the face of danger and that is to take and continue to take actions until the peril is no longer facing the individual (the actions themselves may range from directly attacking the danger source such as by throwing water onto a fire to indirectly dealing with the threat by physically distancing oneself from the specific danger source). Finally, sheltering in-place runs against both common sense and familiar behaviour patterns, and thus can be seen as not being rational behaviour. Human beings under extreme stress act on the basis of what they perceive a situation to be at the time; they try to respond on the basis of what rationally makes sense to them, and they react as much as possible in terms of familiar and usual behavioural traits.

Remaining in place in an endangered locality is at variance with all of these matters, and is part of the reason why sheltering in-place, at best, can be characterised as atypical behaviour whether it is advocated or attempted. In conclusion, it should be noted that there is also a difference between disaster planning and disaster management. A parallel here can be drawn to the distinction the military draws between strategic and tactical principles. The latter tactics allow taking into account all the contingencies associated with a concrete situation, which cannot be done in the strategic approach. In a rough sense, disaster planning is, or should be, the strategy of preparing for disasters generally, whereas disaster management involves the carrying out of the specific steps which need to be done in a given actual emergency situation.

4.1.3 Ocular irritation and disorientation

Information concerning both topics was researched together due to its interrelation. It is obvious that in the presence of smoke and gases, eyes must suffer from irritation. It is also obvious that due to ethical reasons, limited research has been undertaken using human subjects. Nonetheless, there are some studies which have focused on determining the effect on walking speed in situations of low visibility. A critical issue affecting the success of escape is the irritant effects of smoke. Irritant effects are produced by all fire atmospheres and can be severe even in the early stages of fire development. The degree of eye irritation, as an immediate effect, is dependent only on the concentration of the irritant.

The ability of smoke to impair escape is often grossly underestimated. Chemically induced sensory irritation results from stimulation of the free nerve endings of the trigeminal nerve in the mucosa of the eye and the nose (Nielsen 1991). The nerve endings in the cornea are stimulated, which causes pain, reflex blinking and tearing. Severe irritation may lead to subsequent eye damage. In the extreme, affected individuals are forced to shut their eyes to alleviate the irritant effects, impairing any escape attempt. Kissell and Litton (1992) undertook conveyor belt fire tests and examined the subjective irritant response to smoke. The carbon monoxide (CO) concentration and subjective response to the smoke were noted as follows. The observations on sensory irritation were confirmed by Rasbash (1975) and Jin (1981).

CO concentration and related reactions

- Up to 40 ppm: Mild discomfort. Breathing laboured and eyes mildly irritated.
- 80 ppm: Hard to breathe. Eyes stung.
- 160 ppm: Very difficult to breathe. Severe eye irritation. Could barely see.

Under the specific test conditions it was observed that severe sensory irritation could take place at CO levels that did not represent an immediate carboxy-haemoglobin danger. The minimum acceptable smoke visibility was also reached before the critical maximum carbon monoxide value. Smoke is hence considered a key factor in escape from mine fires. In particular, if a fire is in the early growth stage, escaping miners will meet with visibility problems before any other. Methods to guide miners through dense smoke may contribute greatly to saving lives during mine fires. This also directs that reliable eye protection is made available. However, even if reliable eye protection can be provided, under conditions of low or zero visibility, speed of travel is materially impaired and may be less than 25% of that possible when visibility is normal (Kriel et al 1995). The SIMRAC project concerning problems associated with low visibility, undertaken in South Africa in 1995 is noteworthy (Kriel et al 1995). The methodology of this study comprised three distinct phases, namely....

(i) Conducting a literature review and interviewing survivors of a recent incident, as well as Rescue Brigadesmen, to ascertain the exact nature and extent of the problem,

(ii) Conducting simulated escapes to record experiences and reactions of escapees under conditions of limited visibility, and

(iii) Evaluating existing and novel guidance systems.

Early tests demonstrated that the speed of locomotion when visibility is zero is reduced to approximately one third of the speed which can be developed under conditions of normal visibility. All the escapees had difficulty in finding the refuge bay door despite the presence of a siren which was mounted on the hanging wall approximately 10 m from the refuge bay entrance. It was clear that the siren gives an indication of the general vicinity of the refuge bay but does not direct the escapee to the refuge bay door. Escapes from within the section were also performed and these proved to be reasonably effective. The two workers used for this purpose conceded that the sound of the running conveyor belt assisted them in finding the escape route. Obstacles in the section, however, proved to be problematical. The most important findings emanating from these investigations were...

a) The speed at which escape routes can be negotiated is reduced considerably – even under conditions where the sense of hearing could assist the escapee in locating familiar structures, such as when he is close to a transformer or is following the sound from an operating conveyor belt structure,

b) The slower speed at which escapees are forced to negotiate escape routes under low visibility conditions has a direct bearing on the distances that can be covered within a specified period of time; the implication is that distances between working places and back-up facilities should be considerably less than those currently recommended (Kielblock and van Rensburg, 1987) with respect to the use of SCSRs. Although the devices last longer due to the slower speed of locomotion and the resultant reduction in physiological demand, this does not necessarily compensate for the lower speed of locomotion in terms of distances covered. Moreover, the element of panic has not been taken into account in these observations,

c) A support structure, in agreement with comments made by survivors of the Black Diamond disaster, is required to enable escapees to maintain balance, especially when escapes are attempted over uneven terrain or where obstacles are present,

d) Directional guidance is of crucial importance. Means should thus be provided to ensure that escapees escape in the right direction along the designated escape route,

e) Dedicated escape routes clear of obstacles and/or hazards are essential. In this regard belt roads cannot be considered to be satisfactory as an escape route due to the many obstacles associated with the belt structure and the fact that conveyor belt structures are symmetrical in design,

f) Back-up facilities in the form of refuge bays form an integral part of escape strategies and should be recognised as such,

g) A guidance lifeline appears to be the only feasible solution to effect successful escapes under conditions of zero visibility, and

h) Sirens at refuge bays do not provide satisfactory guidance to locate refuge bay doors, particularly in collieries.

4.1.4 Lack of information

This subject is also closely related with the previous subject and the conclusions of the same research lead to some key points. The importance of effective communication has also been highlighted during incidents locally and internationally. Insufficient communication regarding the nature, location and magnitude of the problem appears to be a major problem, particularly with respect to the decision making process.

However, the complete lack of communication in many instances could be regarded as an even greater problem. It is generally accepted that a telephone system is impractical as a means of warning underground personnel and that other means of warning be investigated to alert personnel of impending danger.

4.1.5 References

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4.2 EVACUATION MODELLING: STEPS NUMERICAL CODE

This appendix provides further details of work carried out in Task 2.4 to develop a general-purpose numerical simulation model of a mine evacuation.

The calculation basis of the STEPS numerical code is NFPA 130 'Standard for fixed guideway transit and passenger rail systems', used in default mode but with appropriate modifications to account for mineworkers' behaviour during the evacuation process. Briefly, the modelling procedure includes the following steps.

4.2.1 Geometry definition

The first step to be taken when considering an evacuation analysis is to generate a geometric calculation model, generally attaching drawings. The next step is to introduce into the model evacuation routes and blockages, creating a realistic 3D model that may be used for calculations. Each item of the model, such as a door or slope, is assigned as an 'exit' in accordance with width and walking speed as regulated in NFPA 130. The infrastructure geometry is important, hence the requirement for correct definition.

4.2.2 Mine load definition

The mine load depends on the mine process which will be analysed. In this case, a load factor of 70 people was selected. This parameter needs to match the local deployment situation, noting the possibly of significant variance throughout the EU and North America.

4.2.3 Simulation parameter definition

Mine load placement, response time, form of emergency, visibility, mineworkers' skills, doors open/closed are the parameters set before running the model. The simulation will operate on a set of rules that define mineworkers' possible behaviours. The rules will cover classes of information necessary to create a realistic simulation. These classes of information will include, but are not limited to

- Human factors – e.g. physiology, psychology, level of training.
- Physical factors – e.g. mine location, ventilation systems.

Once the model is fully designed, data that should be stored for further analysis are determined, such as miners' load, number of people that use the different egress routes, the number of people that manage to exit from the model, and so on. Finally, redundant simulations are made to avoid, through mean and error analysis, typical fluctuations of a transitory, random simulation. The evacuation routes available at the mine consist of two 1.2 metre wide 'corridors' that lead to evacuation galleries. In a panic situation it is recognised that congestion could arise in a small clearance situation and that further scenarios with larger clearances (representative of larger mines) may be required.

Human behaviour modelling and fluid mechanics model

Fluid mechanic analogues are often used as a technical basis for predicting human behaviour in case of evacuation. The principles involve time estimated from several expressions that connect empirical data with fluid mechanics, as follows.

People trying to escape from an emergency area keep a free area between themselves and the walls and other unanimated objects whilst they pass near them. This is similar to fluid concept of boundary layer. The width of this layer may vary from 10 cm to 40 cm. Thus, effective width is the real width minus two times the width of the boundary layer. To enumerate the number of people present within the model, estimates were provided by partners for the number of mineworkers present inside the mine in the case of various incidents. As a first approach 70 people were allocated to the model.

The people density (as persons per square metre) may then be calculated. If this ratio is less than 0.54 persons/m^2, the mineworkers would escape at their own pace, independent of the others' speed. If however the density is greater than 3.8 persons/m^2, then personal interaction is such that individuals cannot evacuate until the crowd passes any bottleneck again reducing density. Between these two limits, evacuation speed can be considered as a lineal function,

$S = k - a \cdot k \cdot D$, where

S= Evacuation speed in m/s
D= People Density in persons/m^2
k= constant. In case of a slope, a door or a corridor, k=1.40
a= constant. If speed is in m/s and Density in persons/m^2, then a=0.266

These are general parameters used in building evacuation simulations. Given the special conditions under which evacuation in a mine take place, other factors need to be considered such as...

Positive factors

- Mineworkers usually know their way inside the mine to a high degree of familiarity.
- Mineworkers are well trained and know exactly how to behave in case of an emergency.
- Mineworkers' physical condition exceeds the standard of the general populace.

Negative factors.

- Visibility is reduced.
- Gradients are very steep.
- Psychrometric conditions can become very unfavourable.

The possible effects of all these factors were considered during the study. Once speed is determined, the next factor to calculate is specific flow, it being the ratio between people that passes through an area in a period of time. Thus,

$Fs = S \cdot D$, where

Fs= specific flow in persons/s•m^2
S= evacuation speed in m/s
D= density in persons/m^2

Joining the two previous equations,

$Fs = (1 - a \cdot D) \cdot k \cdot D$

Thus, maximum flow occurs when density is 1.9 persons/m^2. Real flow is the product of specific flow and effective width,

$Fc = Fs \cdot We$

Joining the two previous equations,

$Fc = (1 - a \cdot D) \cdot k \cdot D \cdot We$

Now, the time needed to pass through a certain point in an evacuation route can be evaluated as

$Tp = P/Fc$

Where Tp is the time needed to pass, and P the number of persons. Thus,

$Tp = P \cdot /((1 - a \cdot D) \cdot k \cdot D \cdot We)$

Transition Points

There are many transition points inside an evacuation route, such as narrowings, joinings, and critical points. Considering similarity with fluids, an alternative form of Bernoulli's principle can be used,

$\sum Fsi \bullet Wei = \sum Fsj \bullet Wej$, where,

i, j mean before and after a transition point, respectively.

4.2.4 Speed settings on STEPS

The Max Speed field is used to specify a maximum walking speed for the edited People Type. When one defines subsequent walking speeds in the list, this parameter is used as the basis for all of them. The maximum walking speed can also be defined directly in metres per second by entering it into the field, or it can be picked from a distribution. It is acknowledged that walking speed underground is also complex function of surface roughness. Walking conditions can be adversely affected where there is floor lift, wet conditions or walking on tracks. The distribution list enables the desired distribution to be selected. Each time a new person of the edited People Type is created in the simulation, its maximum walking speed will be randomly picked against the specified distribution. The first entries in the list come from the predefined distributions library section. The entries after the separator are the distributions defined in the model by the user. Once the maximum walking speed has been defined, several other parameters can be specified to model the effect of the environment on people's speed during the runs. The generic equation used in STEPS to model walking speed is as follows.

$V=\min(\alpha_{slope} \times \alpha_{proximity} \times \alpha_{density} \times \alpha_{local} \times V_{max} + V_{local} , V_{smoke})$

The Use slope calculation checkbox can be checked so that STEPS automatically takes into account the influence of slopes on walking speeds. When this option is activated, STEPS calculates the variable α_{slope} each time a person moves. It is necessary to specify the Up slope factor (β_{up}) and Down slope factor (β_{down}), which are used as follows.

- Assign θ as the angle of the slope for a specific move.
- When the person is going up: $\alpha_{slope} = \beta_{up} / \sin \theta$
- When the person is going down: $\alpha_{slope} = \beta_{slope} / \sin \theta$

The Use Speed/Distance Curve checkbox can be checked so that STEPS automatically takes into account the influence of person inter-distance on walking speeds. When this option is activated, STEPS calculates the variable $\alpha_{proximity}$ each time a person moves. It is needed to specify a Speed/Distance Curve in the list when this option is activated. This Curve gives $\alpha_{proximity}$ versus the distance to the closest person ahead. The first entries in the list come from the predefined speed distance curves library. The entries after the separator are the Curves defined in the model by the user.

The Use Speed/Density Curve checkbox can be checked so that STEPS automatically takes into account the influence of local density on walking speeds. When this option is activated, STEPS calculates the variable $\alpha_{density}$ each time a person moves. It is needed to specify a Speed/Density Curve in the list when this option is activated. This Curve gives $\alpha_{density}$ versus the local density around the person. The first entries in the list come from the predefined speed density curves library. The entries after the separator are the Curves defined in the model by the user.

The Use Smoke Data checkbox can be checked so that STEPS automatically takes into account the influence of smoke on walking speeds. When this option is activated, STEPS calculates the variable V_{smoke} each time a person moves. The concentration of smoke is set through sample planes. It is needed to specify a Speed/Smoke Curve in the list when this option is activated. This Curve gives V_{smoke} versus the smoke concentration in the person's cell. The first entries in the list come from the predefined speed smoke curves library. The entries after the separator are the Curves defined in the model by the user.

The Walking Speeds group of commands is used to specify various walking speeds for this People Type. These speeds will be used when defining Paths and Planes through their index. Each walking speed in the list is made of two numbers α_{local} and V_{local} defined in the equation above. The list of walking speeds shows all the speeds that have been defined for the edited People Type. The Local Factor field is used to specify α_{local}. The Local Speed field is used to specify V_{local}.

4.2.5 Example results

Whilst a large ensemble of simulation runs is required to analyse any particular application, an indication of example results is provided below, which accounts for a subset of the test parameters.

$\alpha_{slope} = \beta_{up} / \sin \theta$, $V_{max} = 0.9$. So if $\theta = 16°$ then $\sin 16 = 0.2756$ and with $\beta = 0.146$, $\alpha = 0.53$, $V = 0.9 \times 0.53 = 0.477$ m/s

Mine Paths	**Measured**	**Constant v = 0.52 m/s**	**B = 0.146 v = 0.9 m/s**
1 to 5	06:00	07:00	07:05
5 to 6	06:00	06:30	06:36
6 to 7	09:00	07:30	08:35
7 to 8	08:00	06:30	07:25
TOTAL TIME	**29:00**	**27:30**	**29:41**

Table 4.2.5-1 : Comparison of walking simulations
Comparison between real simulation, constant speed virtual simulation and variable speed simulation

The combination of an ensemble of runs results in an example evacuation profile as given below. The evacuation modelling studies, as discussed, considered a wide variety of circumstances and parameter settings for Pozo Carrio mine. Whilst modelling requires high quality input data, supported by verification or validation, it was observed that the evacuation modelling approach showed good agreement with real data derived from evacuation exercises. Data on these exercises is given below. The use of numerical evacuation modelling tools shows considerable promise and potential as part of emergency planning activities.

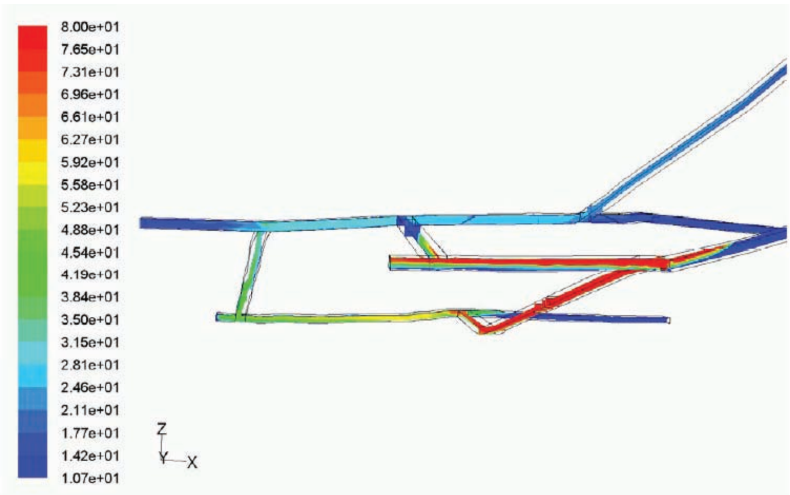


Figure 4.2.5-1: Modelled evacuation times in areas served by Pozo Carrio drift

4.2.6 Input data from evacuation exercises

There was requirement for determining a representative and realistic evacuation speed function for the mine workforce. Towards this objective, several dedicated exercises were conducted by Hunosa, UK Coal and CSRG. These are reported below, together with brief explanatory comments.

UK Coal Mining Ltd., Daw Mill Colliery

UK Coal staff undertook several egress exercises. The prevailing conditions were...

- No smoke or combustion products were present during the exercise.
- Effective Temperature was below 30°C.
- The walking speed was 55 m/min (~0.92 m/s).
- Mineworkers wore heavy footwear and an SCSR.

The results suggest that an average evacuation speed of 0.92 m/s is reasonable assignment in good conditions of temperature and visibility, and which can be maintained for a long period of time.

CSRG District Mining Rescue Station, Wodzislaw

CSRG's evacuation studies included a comparison of theoretical studies with a large number of mine exercises. The individuals were tested in mines in various circuits, with different slopes. Parameters such as age, height, weight and slope were analysed against a range of 52 tests, involving 97 individuals.

Analysis of successive age groups confirmed that different mean movement speeds are observed. For a range of test circuit inclines of between 7° – 10°, a slight deviation between groups is observed and an average speed value of 42.5 m/min was derived. In the range of inclination from 10° to 15°, the difference of mean speed of movement of the participants is reduced to 7 m/min, and then at 11 m/min in the range above 15°, the difference is 3.5 m/min.

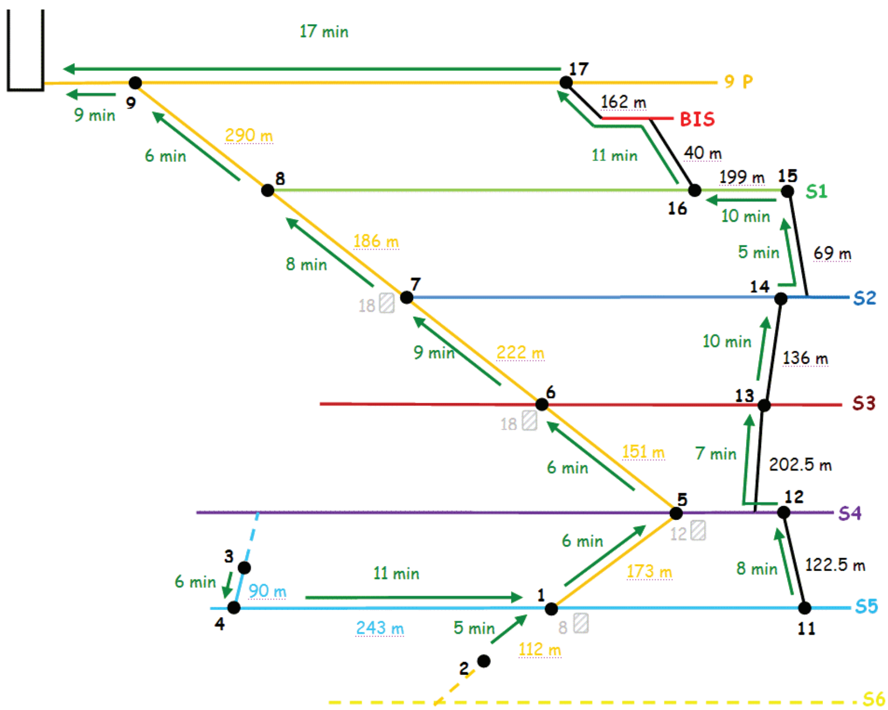


Figure 4.2.6-1 : Summary of evacuation exercise results at Hunosa's Pozo Carrio mine

Regarding BMI, it is observed that the speed for each of the groups declined with increasing slope, however there is a large divergence between the results; attributed to the number of exercises, which hampered proper interpretation of the test results. Further to this, measurements relative to short time segments with a transition of less than 100 metres also resulted in discrepancies. In order to reduce errors, it is proposed that the measurement of segments of transition less than 100 m length should be ignored. The test participants should also be varied in terms of age with a clear sub-division into groups to aid interpretation.

Hunosa Pozo Carrio Exercises

The mean speed obtained was 0.52 m/s (31.2 m/min), and is in broad agreement with the results obtained from CSRG (34 m/min for a 10° slope), largely because most of the Hunosa circuit had a high slope value, of more than 7°.

4.3 Refuge Design at Hunosa's Pozo Carrio Colliery

Emergency planning and supporting analysis at Pozo Carrio colliery lead to a decision that a large fixed infrastructure refuge should be installed. A decision was made that the refuge would be constructed in rock using part of the excavation as a wall. Its location was fixed in an arterial zone of the mine that would remain in long-term use. The following discusses specific design aspects of this refuge, together with summary test information.

4.3.1 General refuge requirements

a) Refuge size, volume and dimensions: the final dimensions of the refuge are determined by the maximum number of workers that may be present in an emergency. The prototype refuge followed the recommendations of the US Mine Safety and Health Administration, which cites minimum requirements of space per person in the refuge defining a surface and volume requirement per miner of 1.4 m^2/person and 2.4 m^3/person respectively. Testing of the prototype refuge confirmed that these values were sufficient.

b) Choice of constructional materials: the refuge has to be robust, fire and impact resistant. There are several possibilities – concrete blocks or walls, excavations in the rock, brick and steel sheet lining.

c) Pressure conditions and capacity of structure to prevent contaminant ingress: the refuge must function as a sealed enclosure to prevent gases from contaminating the atmosphere inside it. This can be achieved by two methods.

(i) Overpressure refuges. Here the pressure of the refuge atmosphere is maintained at a slight overpressure to the external atmosphere to prevent toxic gases from entering the refuge. Clearly a system is needed to create this pressure difference. There is no need for hermetic sealing if the refuge is overpressured. A single door or a full curtain is enough to maintain isolation from external pollutants. However, the overpressure does not guarantee a breathable atmosphere in the refuge since the CO_2 arising from breathing can reach dangerous concentrations if the flow that maintains the pressure differential is too low. In some mines there are overpressured refuges in which the fresh air is supplied by boreholes directly from surface; but this option is not suitable for deep European mines.

(ii) Refuges under normal pressure. Here the internal and external pressures are equal thus toxic gases can enter into the chamber by diffusion. In this case the refuge must be isolated by a hermetic sealing system.

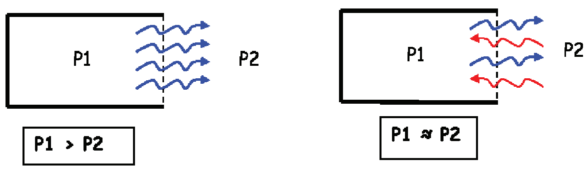


Figure 4.3.1-1: Overpressure refuge and refuge under normal pressure

d) Design of refuge entry (access doors). The design of the access needs to take into account the overpressure that may be developed inside the refuge. This is an important issue since injured personnel must be able to open the refuge door, but sealing should not be compromised. Doors, usually made of steel, should be wide enough for ready access. There are two different systems – single door and double door arrangements. The latter separates the refuge into two zones; the habitable zone and the airlock chamber.

e) Windows. These are important in that they permit outside conditions to be appraised and rescuers to check on the presence of personnel. Windows in the refuge need to be robust and meet general constructional and sealing requirements.

f) Breathable air systems. Maintenance of a fresh air supply system is an essential aspect. The air inside the refuge must be guaranteed to supply clean air, remove CO_2 produced by breathing, and at the same time there must be systems to prevent the contamination of the refuge's atmosphere by external toxic gases. The use of compressed air as the primary breathable air supply is favoured for the following reasons.

- The compressed air provides the oxygen and maintains an overpressure inside the refuge.
- The airflow is adjustable, and can be set to adequately dilute the CO_2 from respiration and to keep toxic gases from entering the refuge. Additional systems to purify the refuge's atmosphere are not required.
- The required plant is already installed in most mines hence there is no requirement to install additional equipment. The cost is therefore low. There is no need for sophisticated technology. Hence the arrangement is reliable, requires no special maintenance and is the simplest system. Mineworkers are very familiar with its use and operation. There are several cases of successful rescue operations assisted by local leakage in the compressed air network and exploited by mineworkers.
- There is no requirement to have autonomous equipment to produce oxygen, or to provide an airlock-isolated entrance. Hence the overall volume of the refuge can be lower along with commensurately lower building costs.
- The air is cooled whilst adiabatically expanded on discharge from the compressed air network. This can help to maintain the climatic conditions within the chamber within acceptable limits.

The delivered compressed air must sweep the entire chamber; hence the discharge point has to be at the remote end of the refuge, opposite the entrance. In practice there will be a multiplicity of discharge points for the compressed air in order that even air distribution, including into the chamber corners is ensured. The refuge also requires a valve or other system to shut off the refuge air supply in the event of failure of the compressed air. It is clear that the compressed air supply network pipes may be susceptible to damage by fire or explosion. The temperatures reached during fires can melt the plastic joints of the network, either disabling the air supply to the refuge or allowing contaminated air into the network. To reduce this risk an isolation valve is required to ensure the supply line to the refuge may be isolated. The figure below indicates the operation of a valve to prevent back-feed of contaminated air into the refuge in the event of a shunt pipe feed being compromised by fire.

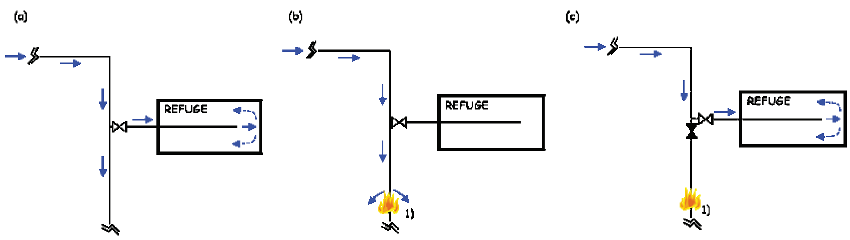


Figure 4.3.1-2: Airflow conditions
(a) Pipe shunt to refuge (b) Failure in the network beyond the pipe shunt
(c) Valve to recover the flow of air to the refuge

Compressed air discharge is inherently noisy and it is recommended that a silencer be fitted. As a practical observation, there can be water or solid deposits present in the compressed air pipe network due to lack of use. It is necessary therefore that a drain and filter arrangement is installed. Given that oil can carry over from the compressors it is recommended that an oil vapour filter be installed to improve the air quality. Where possible, it is recommended that two independent compressed air supply lines be routed through two different galleries. In each case the risk of failure of the compressed air supply must be appraised to decide whether or not to install a second supply line. The figure below indicates how redundancy may be used in the air supply network. The refuge may also need to be engineered to provide a second independent breathable air supply.

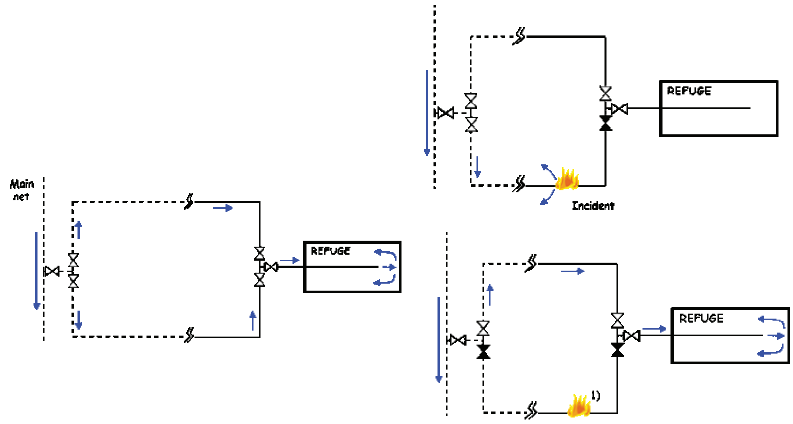


Figure 4.3.1-3: Redundancy approach to compressed air supply network

g) Communication system. A refuge should have two independent communication systems. The main communication system is typically the telephone system, which allows communication with other mine telephones, including the surface control room. Secondary communications may employ a roadway amplifier type system that provides broadcast intercom communications with other roadway amplifier units.

h) Environmental monitoring. The personnel within the refuge should be able to monitor the atmospheric conditions within the refuge, and particularly CO_2, CO and O_2. The equipment should be certified for underground coal mining use and equipped with a warning alarm for when the concentration falls outside of levels set by legislation.

i) Self-rescuer cache (changeover facility). The evacuation strategy in coalmines is always 'make your way to the surface as soon as possible'. Any decision to stay in the refuge would be taken only if all available evacuation routes are closed, representing an extreme case. Therefore the refuge should perform two objectives.

- As a rest and recovery facility within a staged evacuation process, where further instructions can be received.
- As a facility to exchange self-rescuers (changeover station). The refuges should therefore provide sufficient caches of self-rescuers.

4.3.2 Construction of prototype refuge

The purchase of mobile refuges is a favoured option for many mining companies. However in consideration of the feasibility of transporting and installing mobile refuges in underground mines operated by Hunosa, the following points can be made.

1. This type of refuge requires broad galleries for transportation and installation; however Hunosa galleries only have cross sections of 9 m2–12 m2. The excavation of wide chambers for mobile refuges would therefore be very expensive and technically redundant, since once a room is excavated this could be used as the basis of a fixed refuge.
2. The most suitable models are folding canopy type refuges, since they are readily transported along galleries. However they must offer a relatively narrow width (otherwise they would block passage along the gallery); therefore they will intrinsically have a low capacity, dictating a requirement for additional refuges. Their advantage is that they may be readily purchased, reused and they offer mobility.

The location of the refuge was considered against working requirements and future coal production plans. The prototype refuge was excavated directly in rock and adapted to the particular conditions and existing infrastructure of the mine. The support structure was formed with conventional steel arches, which determined the geometry and dimensions of the refuge. The chamber was excavated with the traditional method of drilling and blasting. The final chamber is 9 m long and 4.5 m wide with a section of 12 m^2 and surface area of 40 m^2. This size was calculated according to the maximum number of mineworkers working in the area, with a volume factor of >8 5 ft^3 (2.4 m^3) and floor space factor of > 15 ft^2 (1.4 m^2) per person. The breathable air supply to the refuge uses compressed air. The following figure shows the final scheme for the refuge.

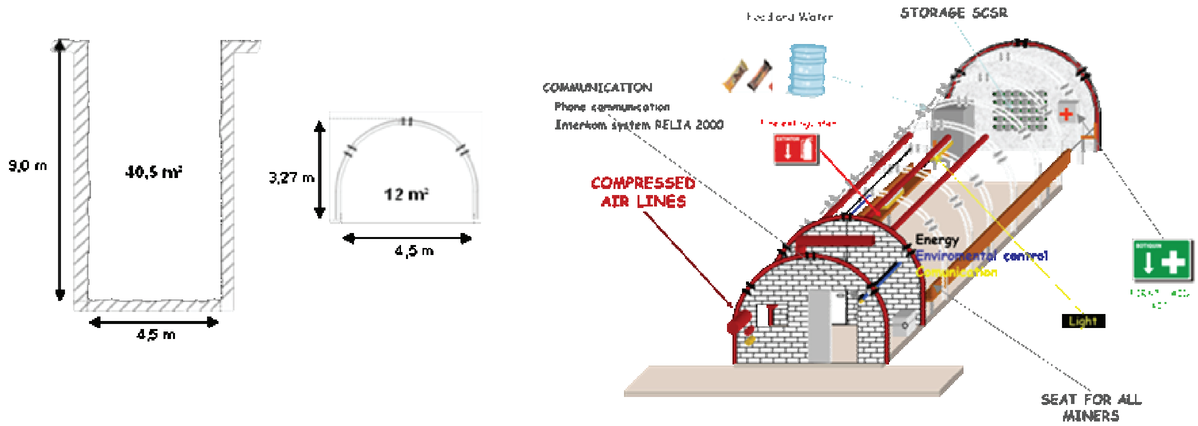


Figure 4.3.2-1: Refuge excavation dimensions and final prototype refuge design

The refuge was sealed with fireproof doors and foams to avoid inward leakage. The airlock walls were painted white, making it easier to locate the refuge from the mine roadways and also to increase the available illumination levels inside the refuge. The sequence of figures below shows successive phases of the construction of the refuge.

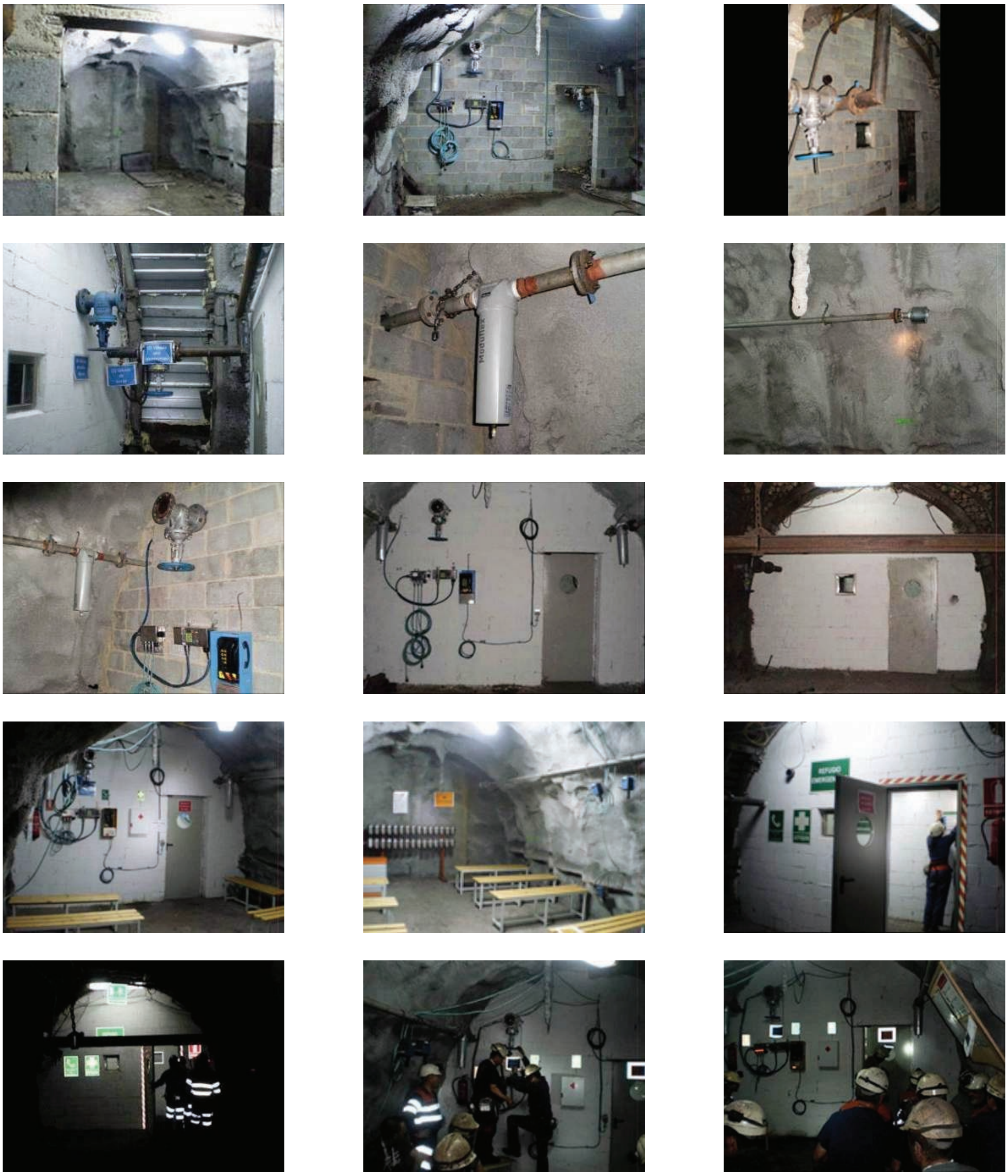


Figure 4.3.2-2: Sequence of images for refuge under construction and use

4.3.3 Refuge support systems and equipment

(a) Breathable air system: the air supply to the refuge is made through a single valve located inside the refuge, in the airlock area. Outside of the refuge there are two valves that allow the air source to be interchanged. The supply scheme is outlined in the figure below. Each air supply line is equipped with an in-line filter to ensure the cleanliness of the air supply.

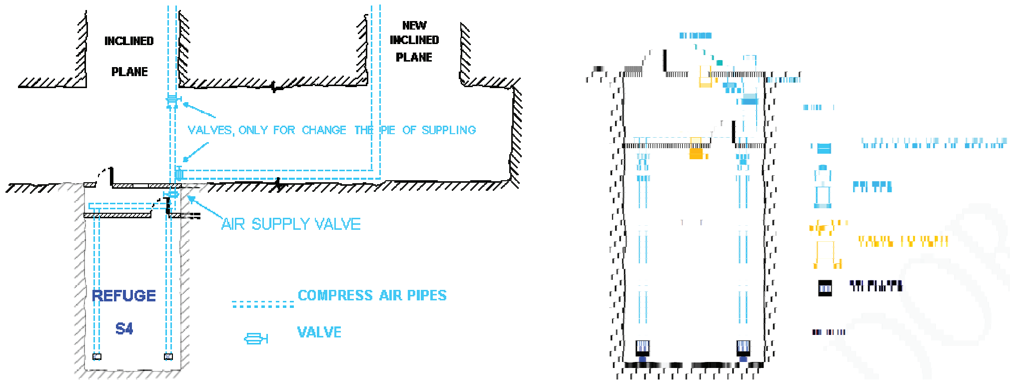


Figure 4.3.3-1: Air piping distribution (left). Scheme of compressed air supply (right)

The SCSR changeover facility is provided by a rack of MSA model Savox SCSRs, which provide 30-minute duration according to test standard EN-13794. Importantly, the escape respiratory protective device is also equipped with a built-in set of goggles.

Figure 4.3.3-2: Cache of MSA Savox SCSRs in refuge

(b) Environmental monitoring system: key environmental parameters are measured both inside (CO_2, CO and O_2) and outside the refuge (CO and O_2). The air quality sensors were installed at different heights, according to mine rules for the determination of mine gases. The disposition of the sensors may be gauged from the figure below.

Figure 4.3.3-3: Gas sensors: CO (1), O_2 (2) and CO_2 (3)

All environmental monitoring system outputs are transmitted to the surface control room.

(c) Communications: the refuge employs two independent communication systems – a telephone connection, and an intercom connection into the SCADA equipped RELIA 2000 system.

(d) Signage and information: the refuge was completed with appropriate signage and reflective materials to help locate the refuge from the mine roadways. Within the refuge, information posters and instructions are appropriately placed. These provide information on; operating instructions for the compressed air supplies and associated valves, the mine emergency plan with egress routes, the mine telephone list, and SCSR donning instructions (as a reminder).

Finally, a variety of other equipment and services were installed in the refuge which included; seating, first aid kits, fire extinguishers, lighting, food and water, toilet facilities and a thermometer / psychrometer.

4.3.4 Prototype refuge testing

On completion the refuge was subjected to various tests to confirm the tenability of the respiratory and thermal environments, together with the measurement of noise levels. The tests simulated an emergency situation, with the mineworkers donning their escape respiratory protective devices (SCSRs) and making their way to the refuge. Measurements of cardiac rate, aural canal temperature and SCSR oxygen run-out time were recorded for the mineworker test subjects. The recorded heart rate and body temperature data were observed to be well within normal medical limits.

Noise levels: the noise level in the main chamber was measured. The main source of noise in the refuge installation derives from the release of compressed air into the refuge.

Figure 4.3.4-1: Performing noise measurements under various occupancy conditions

Baseline noise measurements were made without external influences (i.e. without mineworkers present in the refuge). In practice, communication between the mineworkers and the compressed air valve (flow rate) setting had a measurable influence on the noise level. The figure below illustrates the influences on noise level.

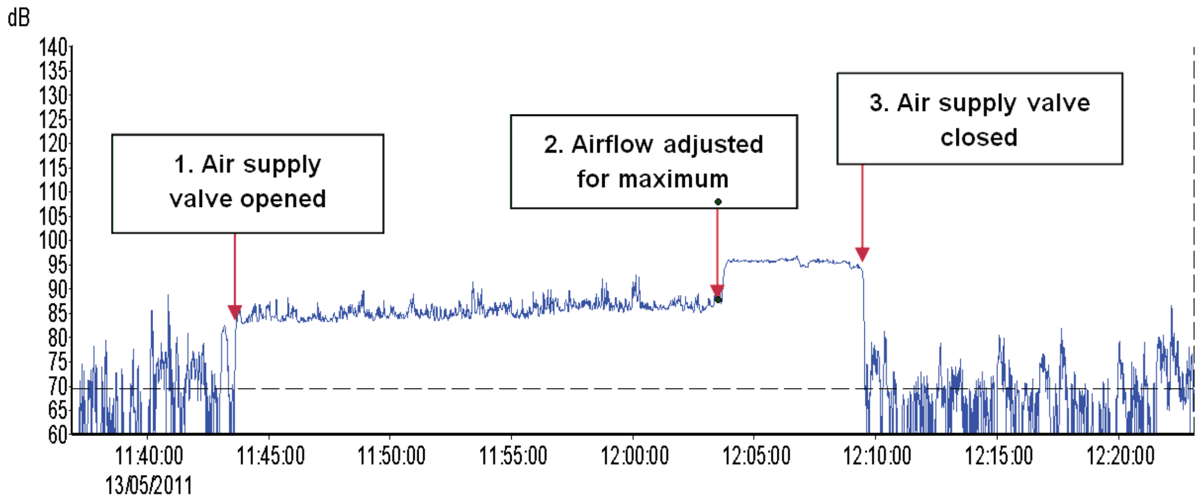


Figure 4.3.4-2: Noise level into the refuge during an evacuation drill

There are different zones in the graph, as are now noted.

1st phase, prior to point 1: here the air supply to the refuge was closed off and the doors left open. Mineworkers were instructed to enter the refuge. The noise levels are very irregular, with large fluctuations.

2nd phase, from point 1 to point 2: the air supply valve to the refuge was opened providing a nominal compressed air flow into the chamber. The doors were closed. The noise increased to 85–90 dB(A).

3rd phase, from point 2 to point 3: here the valve to the compressed air network was opened fully, increasing the noise level to 95 dB(A).

4th phase, from point 3 to the trial end: the air valve to the refuge was closed whilst the mineworkers remained in the chamber. The noise level was around 70 dB(A).

It is evident that for an extended period of occupancy of the refuge that earplugs would be required.

Refuge environmental conditions: the gas sensors installed inside and outside the refuge provided continuous measurements during the occupancy testing, with observations as follows.

- *Carbon dioxide (CO_2)*. At all times, with the supply of air compressed in operation, the CO_2 concentration was always less than 0.2%.
- *Oxygen (O_2)*. The O_2 concentration inside the refuge was maintained at around 21% and never dropped below 20%.
- *Carbon monoxide (CO)*. The CO concentration inside the refuge was maintained almost constant during the course of the exercise at a value below 4 ppm.
- *Temperature and humidity*. The temperature in the chamber was determined by a standard whirling psychrometer, which provided dry bulb and wet bulb temperatures. Relative humidity values were also determined. The graphical data below corresponds to these measurements. During the test, dry bulb temperature did not exceed 28°C.

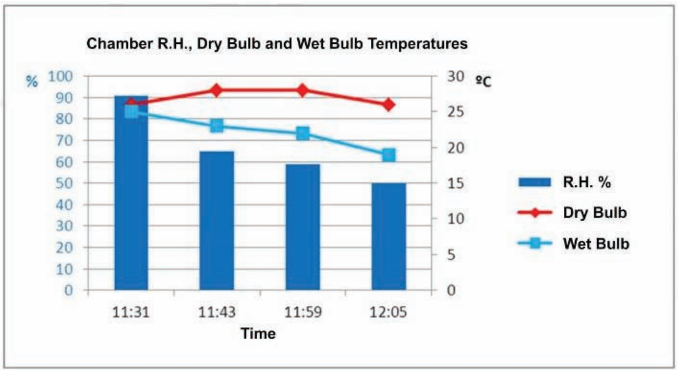


Figure 4.3.4-3: Temperatures and humidity inside the refuge during occupancy testing

To support the temperature measurements, a thermal imaging camera was used to provide an insight on the cooling behaviour observed after the mineworkers arrived at the refuge wearing their SCSRs. The images below also indicate the heat generated by the operating SCSRs.

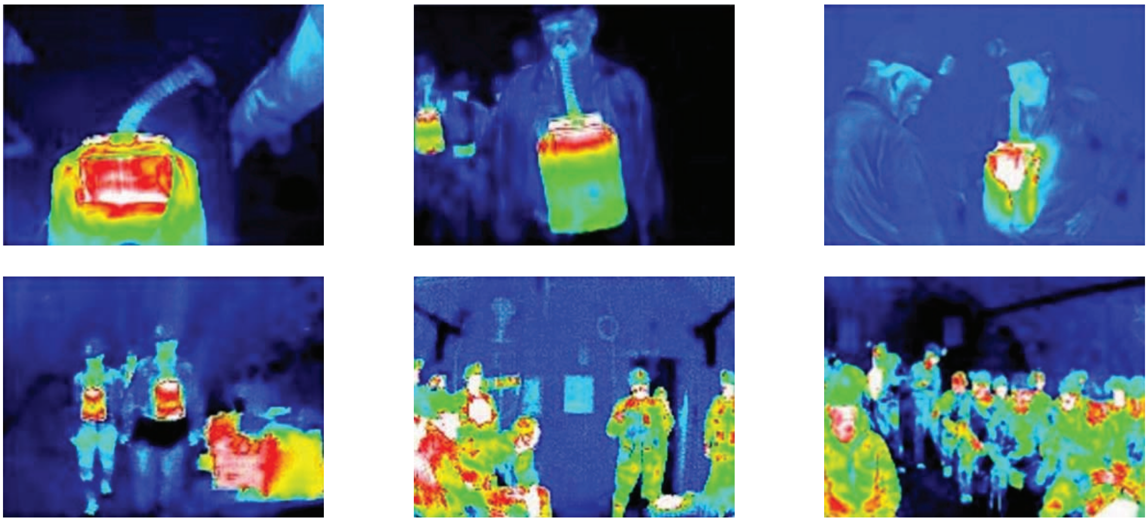


Figure 4.3.4-4: Thermal images of mineworkers outside and inside refuge

4.3.5 Summary of results of trial

The results of the trials confirm that the design of refuge maintains environmental parameters in conditions of safety and comfort (gases, humidity and temperature). The environmental conditions in a real situation would be an improvement on this since the refuge capacity was exceeded by 10% due to the presence of exercise observers and members of the Mines Rescue Brigade.

The air supply design is robust and has enough capacity to replace the chamber air and provide fresh air in the refuge within a few minutes.

The size of the refuge is enough to accommodate all workers comfortably.

In order that the escape respiratory protective devices (SCSRs) have a large safety margin in terms of duration, one recommendation would be to install a facility to exchange SCSRs at an intermediate point along the evacuation route to the refuge.

4.4 IMPLEMENTATION AND TESTING OF UK COAL REFUGES

The work described here summarises the work of UK Coal to test a prototype fixed infrastructure type refuge, together with evaluating transportable designs of refuge (in this case manufactured by Strata Products Limited). It is noted that underground mustering stations, emergency refuges and self-rescuer changeover facilities are collectively described as 'safe havens' in the UK.

The figures below show the essential elements of the Daw Mill fixed refuge described in Task 3.3, which is constructed from pre-fabricated modules, complete with seating and windows. The aspect ratio of the refuge can be seen to constitute an 'elongated corridor'.

Figure 4.3.5-1 : Daw Mill mustering station/refuge
(a) Completed refuge assembled in-situ (b) Internal view

4.4.1 Transportable refuge design

Evaluation of self-rescue and evacuation strategy confirmed that significant benefit could accrue if an effective transportable design of refuge could be sourced. Clearly, the design of such a refuge is generally beyond the scope of mine operators and several manufacturers now offer transportable refuges of varying sizes and capacities. Some designs employ substantial construction methods and are very heavy, but can be moved periodically to match changes in mine production (by way of example refer to the figure below). These refuges require substantial space requirements however and are not suited to many roadway settings in coalmines. The approach adopted by UK Coal was to employ refuge types that are transportable, but which are inflatable and only erected when required by means of a separate compressed air supply. It was considered that this approach could offer significant flexibility and a wider potential scope of deployment within current mines. An important consideration in the selection of a portable refuge was the ability to sectionalise the equipment and to ensure that it was capable of being transported in a mine cage. The dimensions were therefore restricted to a maximum of 3.95 m × 1.6 m × 1.3 m. The portable units had to be capable of providing refuge to 12 persons as a minimum. Taking into account the transportable nature of the refuge, the specification to the supplier also included a number of requirements to facilitate lifting and safe transportation.

The selected modular design employs a skid mounted air supply arrangement together with a closely coupled tent with maximum inflated dimensions of 11.4 m × 1.5 m × 1.1 m. The air supply module includes 300 bar breathable oxygen cylinders/compressed air cylinders and an air-driven CO_2 scrubbing arrangement. The assessment of the inflatable refuge first involved a surface workshop evaluation. The figures below show the sequence of events in erecting and evaluating the refuge.

Figure 4.4.1-1 : Example of a transportable refuge (MineArc)

Figure 4.4.1-2 : Deployment of inflatable refuge
(a) Base skid module containing air supply and purification sub-systems
(b) Inflatable refuge being evaluated in surface workshop environment
(c) Refuge partly inflated, (d) Refuge ready for deployment

4.4.2 Testing of Daw Mill muster station

On completion of the Daw Mill colliery fixed refuge (muster station) refuge, verification tests were undertaken to confirm the acceptability of the thermal environment using a group of mineworkers. Initially, it was hoped that the refuge verification tests could be conducted with a full shift of mineworkers. In the event, a smaller scale verification test was conducted, using 10 mineworkers. The test subjects were un-acclimatised young men, with two subjects over 50 years old. The internal refuge environment was instrumented with real-time humidity and dry bulb measurement using hazardous atmosphere approved data loggers. The cohort of test subjects arrived at the refuge directly after travelling from pit bottom. In this case, they arrived as they would at the commencement of the shift, in a normo-thermal euhydrated state wearing usual clothing, workwear and PPE.

In terms of procedure, the thermal environment tests comprised two components – (i) a period of occupancy where the refuge was supplied with a very low compressed air flow rate, and (ii) subsequent operation of the refuge at the nominal compressed air flow rate. Regarding the two flow conditions, these were as follows.

Low Flow Condition: 0.06 m/s air speed (0.31 m^3/s air flow)
Normal Flow Condition: 0.25 m/s air speed (1.28 m^3/s air flow)

The refuge was fully instrumented throughout both periods, and the test subjects were asked to provide written observations and comments periodically during the tests in terms of thermal comfort, noise and air-quality. The total residence period was 2.5 hours. However, there was every indication that the thermal environment could be comfortably maintained, once the compressed air supply was established.

The summary results of the refuge station test are given in the table below. In this case, three measurement location points refer to positions immediately downstream of the compressed air supply point (after the filter silencer), the middle of the refuge, and the furthest point in the refuge downstream from the compressed air supply (adjacent to the airlock and entrance to the refuge) respectively. These locations may be related directly to internal and external images of the refuge shown collectively in the figures below. The test subjects were positioned in the furthest downstream location ('3') and were sitting throughout the test. The first phase of the test, which ran for 90 minutes, involved supplying the refuge with a very low compressed air flow rate. The pressure gauge registered 25–27 Pa overpressure within the refuge, with 20.7% oxygen concentration measured. The airflow within the refuge was considered to be relatively stagnant, estimated at 0.06 m/s drift velocity. The second phase of the test, conducted from 90 minutes elapsed time onwards, involved opening the compressed air supply valve fully and delivering the nominal design airflow to the refuge. The pressure gauge registered 100 Pa overpressure within the refuge with 20.7% oxygen concentration. The mean air speed within the refuge was estimated at 0.25 m/s (1.28 m^3/s air delivery and around 5 m^2 cross-sectional area). This represents a fourfold increase in airflow against the initial baseline test. The noise level within the refuge was also noted along with air-quality.

Comments on the thermal environment are assimilated in the table. It is clear that the baseline (low airflow) thermal environment was considered unacceptable. Indeed, at full occupancy, the refuge would have become increasingly hot and humid to the occupants. Equally, it is evident that the introduction of adequate compressed air as a fresh air source immediately improved the thermal environment. There was unanimous agreement that the refuge environment with the given compressed air supply was comfortable, and that extended occupancy would have been possible for the subject group. Facilities were not available to monitor the carbon dioxide levels within the refuge during the tests. However, reference to a standard Canadian mining industry nomogram for determining refuge carbon dioxide build-up suggests that critical levels of carbon dioxide would not have built up for 80 persons within the refuge, even at the lower baseline flow rate (with a volume of around 350 ft^3 per person being available within the refuge, supplemented by 8 cfm fresh air per person).

The noise level in the vicinity of the compressed air filter-silencer was measured to exceed 90 dB(A). In all compressed air supplied refuges, this is recognised as a significant issue. It is possible that the compressed air supply would need to be periodically switched off in order to facilitate effective telephone communications. Alternatively, a noise cancelling adaptation to the telephone and Tannoy speaker unit would be recommended. However, given the communications apparatus must be approved for hazardous atmosphere use, a sound insulating booth might be a feasible alternative.

OCCUPANCY TEST OF UK COAL DAW MILL MUSTER STATION – PHASE 1, NO (LOW) COMPRESSED AIR FLOW													
TIME min.	INTAKE T_{DB} / T_{WB}	MIDDLE T_{DB} / T_{WB}	EXHAUST T_{DB} / T_{WB}	SUBJECT OBSERVATIONS (10 SUBJECTS)									
Start	35 / 27	36 / 29	36 / 29	Hot and sweaty	Warm and sweaty	Much warmer, notable humidity	Warm, slightly uncomfortable	Soon deteriorated	Cooler at first	Warm	Warm	Normal at first	Slightly warm
15	36 / 27	35 / 29	36 / 30										
30	36 / 28	37 / 29	36 / 29	Hotter, sweaty	No change	Slowly deteriorating	No change	Stuffy, no air	Hot and sweaty	Hot, sweaty	Hot, sweaty, lack of air	Hot, sweaty	Very sweaty
45	36 / 27	36 / 29	36 / 29										
60	36 / 27	36 / 29	36 / 29										
75	36 / 28	36 / 29	36 / 30	Hot, headache	Hot, more uncomfortable	Hotter, a little tired	No change	Feel better	Feel worse	Hotter, more sweaty	More sweaty	Hot, sweaty, restless	Same
OCCUPANCY TEST OF UK COAL DAW MILL MUSTER STATION – PHASE 2, NOMINAL COMPRESSED AIR FLOW													
TIME min.	INTAKE T_{DB} / T_{WB}	MIDDLE T_{DB} / T_{WB}	EXHAUST T_{DB} / T_{WB}	SUBJECT OBSERVATIONS (10 SUBJECTS)									
90	35 / 20	36 / 22	35 / 23	Instantly cooler, stopped sweating, dust an issue	Fine, no sweating, dust an issue	Environment much better	Environment cooler, dust noted	Fine, dust noted	Fine	Fine, dust noted	Cooler, dust noted	Fine apart from dust	Fine, dust noted
120	36 / 18	35 / 25	35 / 22										
135	36 / 21	36 / 25	35 / 25										
150	36 / 23	36 / 23	36 / 24										

Table 4.4.2-1: Summary of Daw Mill refuge residence test results and subject observations

A further issue arose which had not been anticipated. This related to the scouring and clearance of scale from the compressed air supply line, which then passed out into the supply feed to the refuge when the supply valve was opened fully. This resulted in the refuge atmosphere becoming quite dusty, with visibility down to less than 1 m. Efforts were made to reduce the dust levels by opening the refuge doors; however this measure was generally unsuccessful and ultimately two men had to be withdrawn from the refuge on account of the dust. This directs two important measures be introduced; firstly, that adequate air filtration be incorporated in the supply line, and secondly, that the compressed air line is operated and purged periodically. Collectively these measures should ensure the dust level in the supplied air is acceptable. Consideration was also given to measures to achieve an increase the local airflow velocity within the refuge. As identified in the following appendix, the use of 'air amplifiers' can result in a useful increase in air movement and circulation, offering a commensurate increase in air cooling power. Inspection of the standard indices for air cooling power shows a significant sensitivity to air speed and moderate improvements here would offer increased cooling capacity, making the best possible use of the cooling air supply.

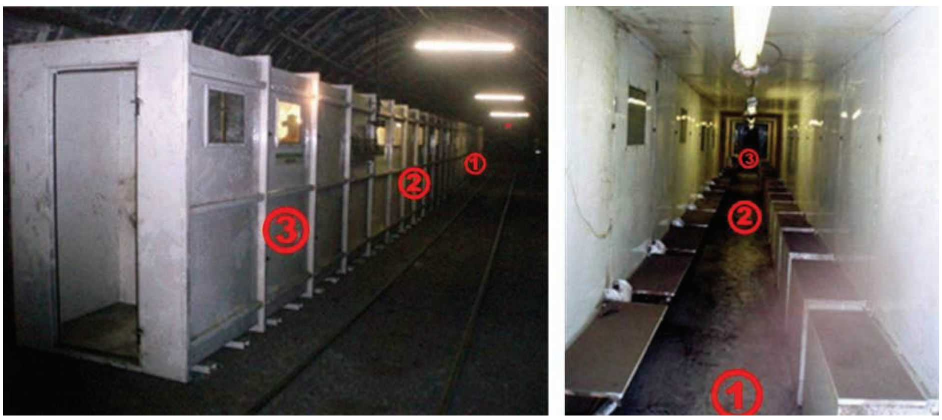


Figure 4.4.2-1 : Measurement locations within Daw Mill refuge occupancy tests

4.5 REFUGE COOLING AND EVALUATION OF AIR AMPLIFIERS

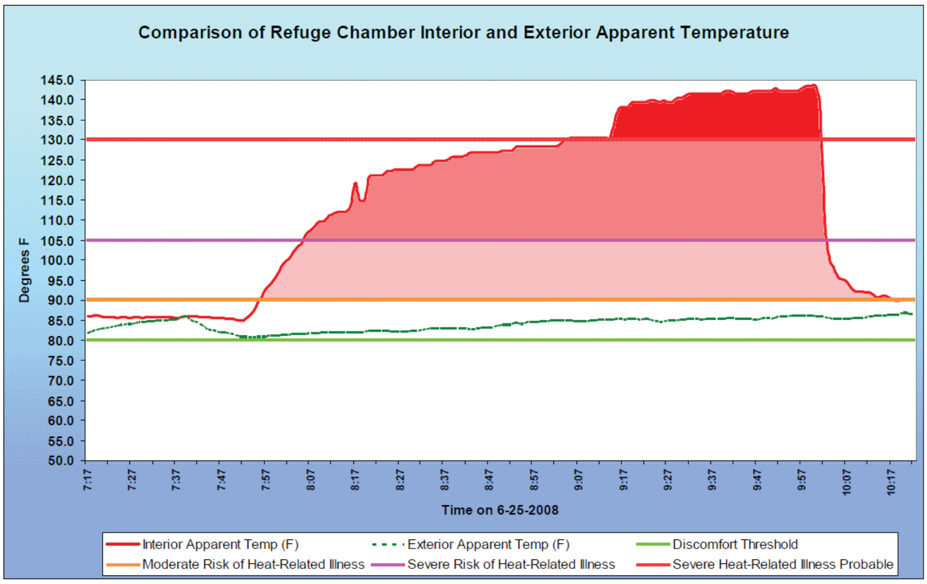
This appendix summarises experimental work to examine how the cooling effect of compressed air fed into a refuge may be maximised, in this case by significantly increasing local air movement from the judicious use of 'air amplifier' technology. The approach is shown to be a practical and low cost approach to improving refuge climate control, particularly where compressed air supplies are considered marginal in terms of air delivery rate or wet bulb/dry bulb temperatures.

Various sources confirm that body core temperatures of subjects within a refuge chamber could exceed medical guidelines unless adequate cooling provisions are made. Candidate cooling/air conditioning approaches include; electrical powered air conditioning units, compressed air venturi diffuser air movers (air amplifiers), carbon dioxide 'dry ice' sublimation cooling, personal cooling systems and measures to build up chamber coolth prior to use.

4.5.1 Thermal safety concerns in underground refuges

The issues of respiratory and thermal safety of underground refuges, together with noise control pose significant design challenges, particularly in hot and humid mines.

Background evidence supporting thermal safety concerns – analysis together with a variety of anecdotal evidence confirm that thermal management within underground refuges is a significant issue if insufficient cooling is available. As part of a consultation exercise relating to developing US regulations for underground refuges, MineArc Systems America, a refuge manufacturer, submitted evidence to MSHA on the risks of hyperthermia which could result in a refuge chamber without adequate cooling provision. The results shown in the figure below identify a rapid build-up of heat within the test refuge. In regard to tests of inflatable underground emergency shelters with independent oxygen supplies, tests conducted by Mines Rescue Service Pty in South Africa confirm a similar heat build-up characteristic. The related figures identify the chamber environmental temperatures, and importantly, evidence that body core temperatures of subjects within the chamber could exceed medical guidelines. These findings corroborate earlier studies by Kielblock et al [1988] and Venter et al [1998].



MineARC Systems America, LLC
Assessment of Thermal Environment of Mine Refuge Chamber
IHST Project Number 18050 July 11, 2008

Figure 4.5.1-1: Results of refuge chamber residence tests conducted by MineArc Systems

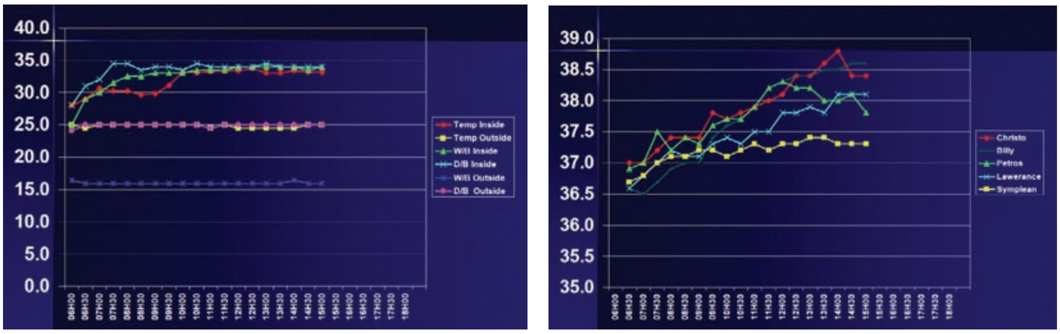


Figure 4.5.1-2: Refuge chamber test data
Left: residence test environment data (from De Klerk 2007)
Right: residence test body temperature data (from De Klerk 2007)

Thermal modelling of refuge environment – computational fluid dynamic (CFD) and finite difference models (providing an approximate solution to the differential equations in thermal modelling) have been used to model entrapment thermal conditions [Gilbey 2006]. However the complexity and computational overhead of the CFD model constrain its practical application. The finite difference model is simpler in terms of application, but the results are more limited in scope. Crosschecking of the outputs from the CFD and finite difference models has confirmed that the latter has the potential of providing a descriptive model of sufficient accuracy for determining the refuge thermal environment. However, a finite difference model would require a number of representative parameters from each refuge design and situation. This would need to include the following items.

- The total number of occupants and crowding density if greater than 1 person/m2.
- Mean figures for metabolic rate, clothing insulation characteristic, skin area, and body preheating criteria.
- The thermal properties of the refuge walls and enclosure, together with accounting for any radiative heat sources.
- The mean air velocity, ventilation air inflow rate and air cooling capacity.
- The ambient conditions at commencement of use of the refuge.

If representative figures could be determined for the above, then a prediction of the psychrometric conditions versus period of occupancy could, in principle, be determined by modelling. The approach adopted by the mining industry is rather more likely to be based on empirical verification. This would have to be done on a site by site basis.

4.5.2 Air-conditioning options in underground refuges

The central issue here is "*How do you make the most efficient use of the compressed air supply to cool the refuge occupants?*" This is important where the compressed air delivery rate is considered marginal. However with adequate compressed air flow rate, the thermal environment should be assured. The cooling effect of compressed air is associated with high velocities in the discharge and low humidity levels in the compressed air. Candidate cooling/air conditioning approaches include...

- Internal air movers (compressed air supplied venturi diffuser, or 'air amplifier')
- Carbon dioxide 'dry ice' sublimation cooling
- Electrical (ATEX) air conditioning units; Carnot, Peltier.

Venturi air diffuser (air amplifier) – this option is proposed where compressed air delivery rates are shown to be marginal. The central premise is that the compressed air source is used in a manner that creates a large volume air recirculation characteristic within the refuge. Clearly this does not introduce any additional fresh air, however, it does ensure that the air cooling power value of the chamber air is utilised to the maximum extent. Inspection of the ACP and ACPM scales for cooling power shown below confirms three requirements; firstly, that the subjects within the refuge must remain as inactive and unstressed as possible, otherwise their metabolic rate increases, secondly they should be very lightly clothed if long duration occupancy is envisaged, and thirdly there is an imperative that the local air velocity is maximised to prevent stagnant micro-climates and impaired cooling in the boundary layers surrounding the skin. It is not feasible to specify minimum air velocity specifications here. However at high wet bulb temperatures, a large relative increase in air velocity is required to achieve a comparable increase in cooling effect.

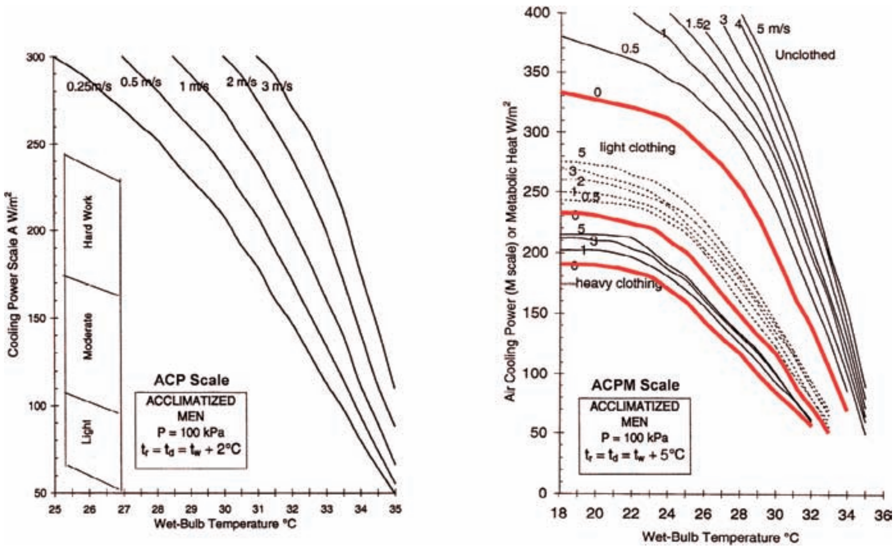


Figure 4.5.2-1: Influence of clothing ensemble and air velocity on Air Cooling Power

Compressed air is the power source for these air movers, often referred to as ‘air amplifiers’ or ‘transvectors’. The compressed air venturi diffuser exploits Bernoulli’s Theorem and the Coanda Effect. The action entrains the surrounding air and induces large volumes of low velocity air to move through the air diffuser (with an ‘amplification factor’ of up to 25x the compressed air delivery rate). There are disadvantages; a potentially high (nuisance) noise level, the units must be earthed to reduce any static electricity hazard, and the compressed air supply must be filtered.

Non-cyclic refrigeration – CO_2 sublimation – this option is considered most relevant to transportable refuges that use O2 generators and CO_2 scrubbers (which generate significant waste heat). The concept is that external cylinders of CO_2 are discharged through an air-air heat exchanger matrix. Dry ice is created by adiabatically expanding the CO_2 from the cylinders into the heat exchanger matrix, with significant associated cooling capacity. Below –56.4°C and 5.2 bar (the triple point) solid CO_2 changes directly to a gas (sublimation). The enthalpy of sublimation is 571 kJ/kg (25.2 kJ/mol) which may be compared with ice melt enthalpy of 333.55 kJ/kg. This approach can potentially provide a simple, effective air conditioning arrangement without electrical power requirement. However there are issues of static electricity creation, which are inherently associated with the rapid discharge of CO_2 cylinders. Cooling-based on CO_2 sublimation is used in commercial MineArc refuges. Sublimated gas can also be used to drive pneumatic fans to create forced airflow through a CO_2 scrubber bed. Both piston and diaphragm pneumatic fan arrangements are feasible. The benefit of non-cyclic refrigeration using CO_2 sublimation is that it does not require electricity supplies, and therefore electrical hazardous atmosphere approvals. A significant disadvantage is the large number of cylinders required for extended periods of refuge operation.

Electrically powered refrigeration options – this option would be recommended for refuges located in non-gassy mines, or where the refuge is located in a fresh air zone. Several commercial examples of conventional cyclic and non-cyclic refrigeration equipment for ATEX Zone 2 and also Zone 1 have been identified. However, no electrical refrigeration apparatus has been identified that is approved (or is at the development stage) for Zone 0 applications. Battery powered thermoelectric coolers use relatively low voltage (24 V dc) but have modest unit cooling capacities. The possibility of installing banks of coolers is also noted.

Build up chamber or personal coolth – this option is described as 'unconventional/speculative refrigeration concepts'. One concept here is to develop a refuge, best described as an 'inverse' of a storage radiator. This would be a very simple structure exploiting existing underground booster fan capacity. In concept, air from a local booster fan is ducted over a refuge structure that is clad with wetted granular material. Significant local evaporation takes place around the structure. Coolth then builds up, which should maintain the refuge in a cooled condition. The disadvantage would be the requirement for water management and some deterioration in the air quality released downstream. Brake and Bates [1999] cite a number of other cooling options including; 'cold guns' of the vortex tube type, chilled service water, cold vests and stored ice.

4.5.3 Experimental studies on air amplifiers

The experimental studies involved the selection of air amplifiers, their installation and testing in a representative simulated refuge environment, together with an assessment of the resulting air flow and noise characteristics. Finally a chamber cooling test was conducted with 10 rescue brigadesmen at the end of a 'hot and humid' training exercise. The test environment selected to simulate an underground refuge was one of the 'hot and humid' training chambers operated by MRSL. This chamber has a floor plan dimension of approximately 9.5 m x 3 m. The chamber is equipped with a heating and humidification unit which permits a range of dry bulb and wet bulb chamber temperatures to be established. The chamber therefore allowed a variety of underground environmental conditions for a refuge to be replicated. The test chamber can be seen in the figure below.

The intended action of the air amplifier is to induce large volumes of low velocity air moving through the air diffuser. Two units were installed as shown (Exair Type 120024). Two electronic handheld psychrometer instruments, Type 3500 and 4000 from Nielsen Kellerman were also used alongside a conventional Casella whirling hygrometer instrument to determine local wet and dry bulb temperatures. Calibration checks indicated a close correspondence (+0.5°C) between the electronic instruments and the Casella hygrometer. The air supply to each air amplifiers was delivered via an adjustable pressure setting valve and in-line filter. Further elements of the instrumentation included a sound level meter and specialised software to undertake frequency domain and time domain signal analysis of the acoustic signatures.

The range of tests undertaken comprised the following...

- Heating and cooling cycles, and observation of cooling behaviour
- Local chamber air speed characterisation, and
- Noise level measurements and assessment on speech communications.

Figure 4.5.3-1: Simulated refuge test environment (left) and air amplifier (right)

Heating and cooling cycles, and observation of cooling behaviour – the simulated refuge environment was set on a heating cycle which achieved a dry bulb temperature of 40°C and a wet bulb temperature of 24°C. The heating phase of the cycle can be gauged from the figure below. The electronic psychrometer instruments were located at a height of 1.1 m in the centre of the chamber. The heating and humidification supply was then shut down and compressed air admitted to the chamber at a delivery pressure of 5 bar. This corresponded to a total air consumption supplied to the chamber of ~53 SCFM (1500 SLPM). The air volume at the outlet of each air amplifier was estimated to be ~660 SCFM (18700 SLPM). This corresponded to an air amplification ratio of 25. It can be seen that the chamber cooled to comfortable temperatures relatively quickly (within 15 minutes). The rapid rate of initial cooling probably resulted from the fact that there was some temperature stratification in the chamber during the heating phase, and that the subsequent air mixing produced an even vertical temperature distribution. The local air speed in the centre of the chamber was ~2 m/s. After one hour the chamber compressed air supply was reduced to a 'maintenance flow rate' with 2 bar supply pressure. The air speed at the centre of the chamber then reduced to ~1 m/s.

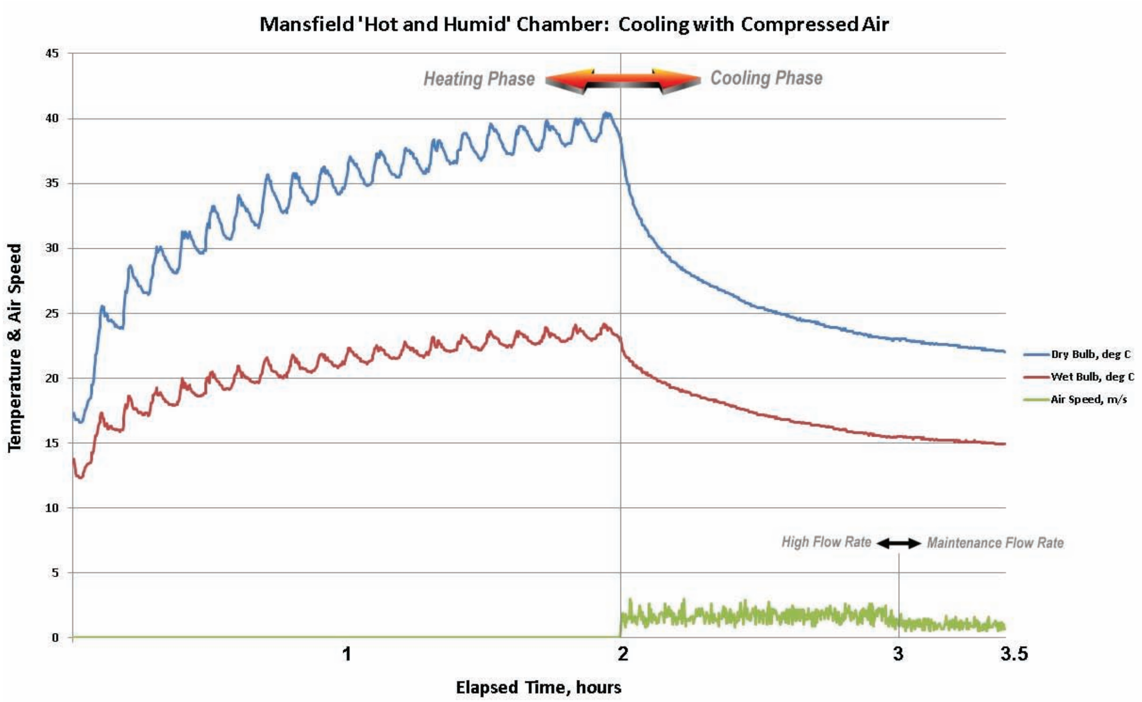


Figure 4.5.3-2: Chamber heating cycle and cooling cycle using air amplifiers

A second more challenging test involved assessing the cooling impacts of the compressed air supply after a 'hot and humid' training exercise had been conducted with 10 fully equipped brigadesmen together with two observers within the chamber. The chamber wet bulb temperature was ~30°C. After removing the heater supply, the chamber commenced cooling with dry bulb temperature falling by 6°C and wet bulb temperature by 5°C over a period of approximately 30 minutes. The observed chamber cooling characteristic is given below. Positive comments were received regarding the substantial local airflow in the chamber.

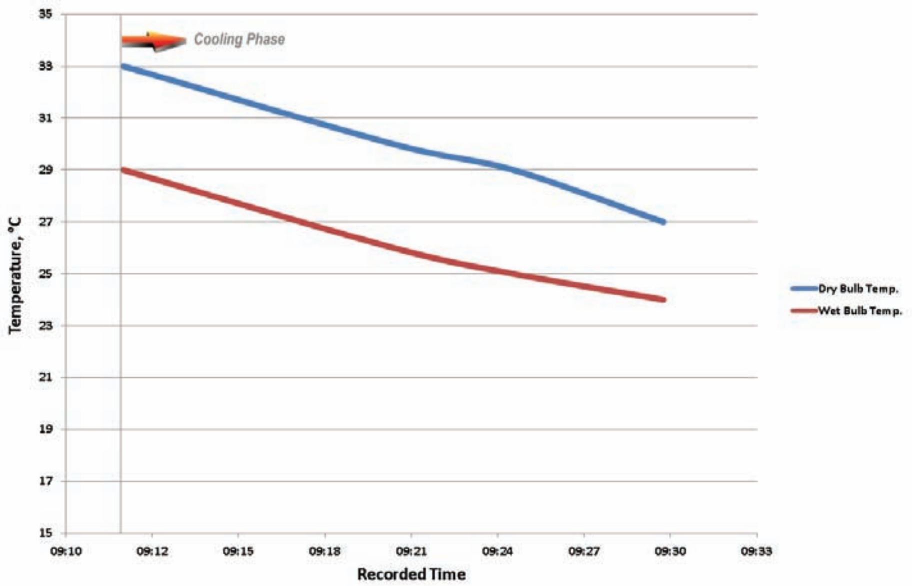


Figure 4.5.3-3: Cooling observed in refuge with 12 persons present

Chamber air speed mapping – various permutations for the placement of the air amplifiers were examined. These tests were conducted with smoke tubes and streamers to identify zones of stagnant air and flow streams. The optimum arrangement was considered to be where the amplifiers were symmetrically located at each end of the chamber with their air flows directed slightly downwards towards the centre of the chamber. This produced a narrow zone of stagnant air (< 10 cm wide) where the two streams of horizontally opposed air met, together with some stagnant pockets in the corners of the chamber. However neither of these presented any practical problem or reduced the value of the additional air movement to the occupants of the chamber, who would nominally be seated along either wall.

Feedback from the chamber occupants was that the air movement could at times be judged to be excessive along the central longitudinal axis of the chamber, but that the air movement was quite comfortable in the seating positions along each wall. The subjective feedback was supported with an air speed profile determination. Here local air speed was measured at various chamber locations at a consistent height of 1.25 m above floor level. The latter was judged to correspond with the mean head height for seated occupants. The chamber compressed air supply was set for 5 bar throughout these measurements. The profile of air speeds can be gauged from the figure below.

It can be seen that significant local air speeds are produced in the chamber, and which are certainly much greater than would be observed without the use of the air amplifiers. In practice the central zone of the refuge could be employed for maximum cooling effect, probably where the occupants have just arrived at the refuge after travelling in hot, humid conditions. After the new entrants have cooled down sufficiently, they could then adopt a seated position with a lower but still significant local air movement present. Further research is required to determine if an array of directed small cooling jets or a limited number of large capacity air amplifiers provide the best cooling effect.

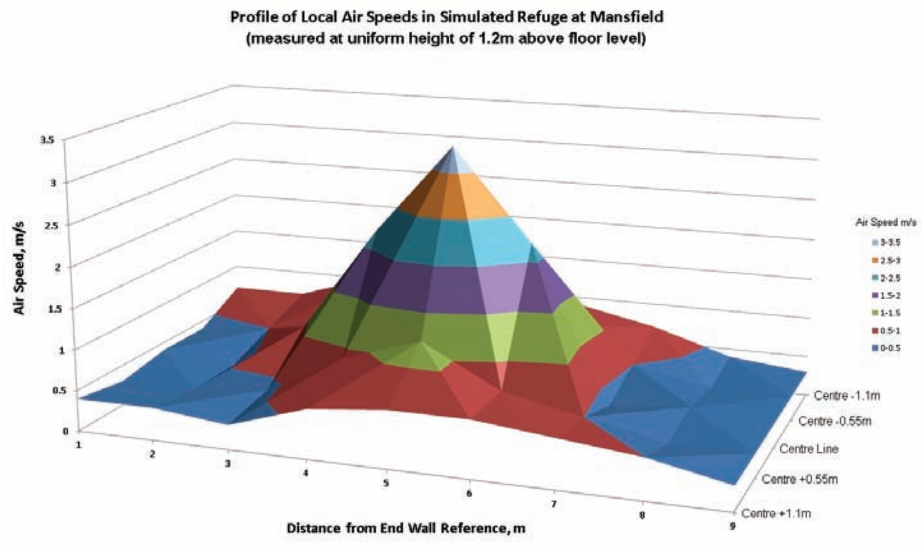


Figure 4.5.3-4: Air speed mapping in refuge

Noise levels and impact on speech communications – an important aspect of any refuge air supply arrangement is that the associated noise level should not be excessive. Ideally, those sheltering within the refuge should not be required to wear hearing protection and the air supply noise level and noise characteristic should not impact adversely on the use of telephone or other communication systems installed within the refuge. The use of any air jet technology needs to be assessed carefully here. The air amplifier type selected has a sophisticated shim and orifice design and is claimed to have one of the lowest sound levels available. To assess the impact of the air amplifier's delivery and recirculation scheme, two sets of noise measurement were conducted.

1. Sound level measurements were performed at end and central locations for compressed air supply delivery pressures of 1 to 5 bar, and
2. Speech recordings were made in the centre of the refuge, in a location of high relative air movement, using a standard omni-directional microphone and recording apparatus. These recordings were then analysed to gauge the frequency characteristics of the noise together with any impacts on speech intelligibility.

The noise level measurements were taken at three locations – L1, the geometric centre of the chamber, and L2 and L3, at a distance of 1 m vertically below each of the air amplifiers. The noise level measurements are summarised as follows.

Compressed Air Delivery Pressure, bar	Noise Level at L1, dB(A)	Noise Level at L2, dB(A)	Noise Level at L3, dB(A)
1	67	68	66
1.5	70	71	69
2	72	73	71
3	75	76.5	75
4	77	80	78
5	80	83	81

Table 4.5.3-1: Noise level measurements for various compressed air delivery pressures

It is evident that occupational noise exposure and noise dose for a realistic period of occupancy would not constitute an issue. The other aspect of noise control is essentially associated with noise nuisance and adverse impacts on speech communication. Here the tonal characteristics of the noise source are important, particularly since a jet ‘whistle’ must be avoided. The measurement approach adopted here was to record several short messages at the centre of the chamber, where there was a high level of wind buffeting noise present which could affect the microphone. A simple omni-directional microphone type representative of those used in mine roadway communication systems was employed with air delivery pressures from zero to 5 bar. A spectrum analysis software package (www.sigview.com) was used to undertake time domain and frequency domain analysis of the speech recordings.

The time domain recordings confirmed an increasing level of background noise with increasing air amplifier flow rate. However despite an increasing wind noise characteristic, in every case the speech recorded was highly intelligible. Further work was undertaken to analyse the frequency content and characteristics of the air amplifier noise source. The spectrograms reproduced in the figures below show two cases of (i) speech only, and (ii) speech + noise (@ 5 bar air delivery pressure). The tonal characteristics of the air amplifier noise can be seen to be relatively broadband without dominant narrow spectral components. This represents an almost ideal response, where a flat noise spectral energy density is sought. These results confirm that the specified air amplifier type under the conditions of use is associated with acceptable sound levels together with a spectral content that does not present a significant nuisance noise characteristic. Therefore noise as a physical agent would not require further specific controls within the refuge.

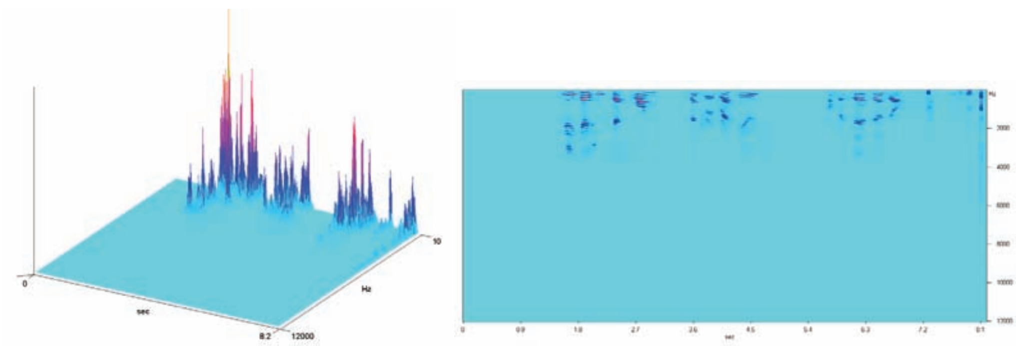


Figure 4.5.3-5: Spectrograms for 0 bar Delivery Pressure

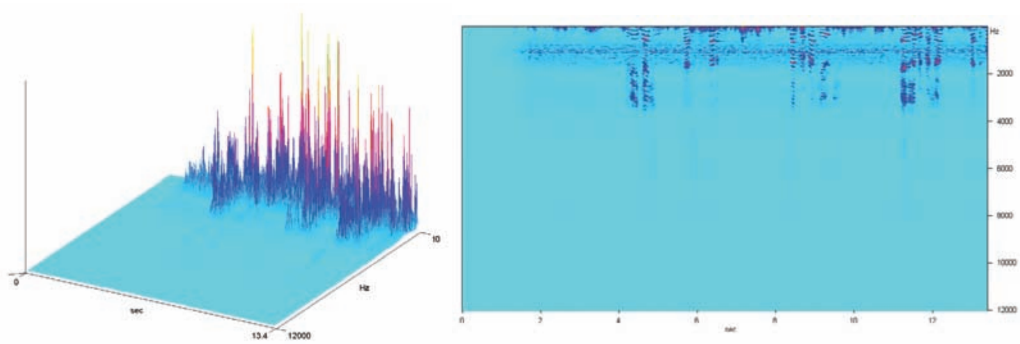


Figure 4.5.3-6: Spectrograms for 5 bar Delivery Pressure

4.5.4 References

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The major objectives of this project have been to provide a resilient network infrastructure which meets the dual requirements of operational day-to-day and emergency management needs, together with researching and introducing a range of new support technologies for mine evacuation and rescue. The research consortium involved three EU coal operators, two mine rescue services and five research institutes/manufacturers. The project was highly application focused and a number of innovations and prototypes have been produced; including resilient networked communications, emergency refuges, evacuation modelling tools, and evacuation support technologies together with knowledge on their application. It is considered that there are excellent prospects for a successful technology transfer process and subsequent take-up of the research outputs by industry.

The key innovation objectives of the research were as follows:

- Provision of a 'safety capable' underground network infrastructure with adaptive behaviour and high survivability prospects;
- Evacuation modelling and real-time support tools for self-escape routes, escape time prognosis, affected mine areas, environmental conditions, and tenability;
- Resilient messaging throughout the entire mine, selected areas or to specific personnel;
- Fit-for-purpose mustering station and refuge designs with secure air supplies and a managed thermal (psychrometric) environment;
- Effective wayfinding and navigation support through dense smoke;
- Advanced emergency location and communication systems with long range strata penetration capabilities;
- Provision of a high resilience rescue team communications infrastructure.

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