Simtars

Report
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Mine Emergency Response System

For Coal Services Health and Safety Trust

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Client Reference	*20640*
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Report Date	*5 July 2018*

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1 Executive summary

The Health and Safety Trust engaged Simtars to investigate the feasibility and test components of a mine communication network that would enable real time information to be transmitted in and out of an underground mine environment. The communication network is to provide information that would be useful to the above ground rescue units after a mine explosion occurred and to aid in better equipping miners during self-rescue.

The project focused on four key areas: post explosion atmosphere monitoring, ultra-resilient communication system, blast protection (or blast resilience) and navigational aid.

Simtars engaged a consultant to investigate and produce a feasibility study outlining current technologies that would ultimately provide the construction of a prototype beacon. The prototype beacon were to incorporate the post explosion atmosphere monitoring, ultra-resilient communication system and electronics required to enable the system to be used as a navigational aid. The study enabled Simtars to identify shortcomings of such technologies. Simtars was able to test and develop an enclosure shell prototype in its dust chamber for use as a navigational aid and secondly in its propagation tube to ensure its blast resilience. In addition, a variety of hollow enclosure shapes were constructed from varying materials and tested for their blast resilience in order to identify potential enclosure design alternatives.

Despite the current technologies available nationally and internationally, a holistic solution was not found that could be readily assembled and developed as a working prototype beacon. There are devices that have been produced that accommodate one or more of the above key areas. However, the research indicated that all four key areas have not been accomplished yet for products that are commercially available. This project has identified areas of further investigation and short comings in the lack of power source longevity or the ability to re-energise devices in situ. Furthermore, communication switching between radio frequencies, Low Frequency (LF) and Ultra High Frequency (UHF) to produce an ‘Ultra-resilient communication system’, was identified as a critical element. Finally the lack of commercially available atmospheric sensors that comply with the intrinsic safety requirements for sensors to monitor the environment will need to be further investigated in future research.

2 Background

A core mines rescue activity is that of entering or re-entering a mine as part of an emergency response. Whilst there are many aspects of mine emergency management, the emergency mine entry / re-entry is a crucial and far-reaching aspect of mines rescue operations. It has significant interrelationships with how operations manage their principal hazards and emergency response. Successfully addressing this issue requires a risk based approach to mine re-entry based on explosibility assessment and to give miners more tools to self-rescue.

The project evaluated technologies that can address information deficiencies following major mine incidents. Information during emergencies is increasingly seen as a critical issue and requirement for emergency response, both in terms of safely committing mines rescuers in high risk situations and the self-rescue expectation of miners.

A series of interconnecting ‘beacons’ was proposed, that integrated the primary function of this project and allows data to be collected ‘in situ’ in an underground mine. This data is then transmitted from the underground environment to the surface and finally to a predetermined

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receiving location. At the receiver location the data can be accessed for use in line monitoring and emergencies situations.

3 Main Objectives

There were four (4), objectives identified for this project. They were;

- *Post explosion atmosphere monitoring* – Develop and test sensor systems that 'initiate' following an emergency event and capable of monitoring critical information to aid in a rescue and / or recovery operation.
- *Ultra-resilient communication system* – Develop a robust wireless mesh communications network that is capable of establishing a 2-way communications link both 'in' and 'out' of the mine following an emergency event.
- *Blast protection or blast resilient* – Examine, test and develop concepts to enhance the blast protection or blast resilience of devices needed to house the sensing and communications systems.
- *Navigational aid* – Examine and test different concepts of achieving navigational assistance including: time-of-flight (ToF) guidance, and vision enhancement, e.g. visible and near IR technology.

4 Methodology

4.1 Post explosion atmosphere monitoring

Explosibility assessment is a crucial activity following any mine emergency event, from both the viewpoint of time-critical emergency response decision making in assessing the safety for mine entry / re-entry and for longer term recovery / restoration activities. Sensing technology devices that could be installed as part of the mine infrastructure were examined. The devices must be capable of being 'rapidly engaged' and fully operational following a mine incident. This would require the devices to remain in standby-mode prior to an emergency event or engage a 'change of mode' where the system is also installed as part of the mine operational infrastructure. Sensing technologies for temperature, pressure and particularly gas (carbon monoxide, carbon dioxide, methane and oxygen), have seen significant developments in recent years in the development of semiconductor electronics (such as metal-oxide semiconductor in gas measurement) allowing sensors to be miniaturised and be low-powered.

To address this, Simtars consulted with two of Australia's largest air monitoring instrument providers, Airmet and Gastech, which deal heavily with the Asian and US markets. Both contacted their suppliers to obtain commercially available products that could be incorporated into the beacons for use in an underground coal mine. Their response indicated that they could not provide such a sensor and comply with the intrinsic safety requirements for underground coal mines. This result prompted Simtars to research and engage a specialist communication and electronics development company in the UK to search the European markets for suitable products.

Simtars conducted an energy harvesting literature survey to ascertain if there would be suitable charging technologies that were commercially available and could be incorporated into the beacon design. This would prolong the beacons ability to maintain atmosphere monitoring.

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4.2 'Ultra-resilient' communication system

One of the key requirements of this system is to ensure a reliable means of communication could be established. This involved research into developing a highly resilient wireless mesh communications network. Both high frequency and low frequency transmission were evaluated. A mesh-based wireless approach allows the system to be adaptable and for redundancy to be incorporated. For example, should the network loose communications with the surface, it could be re-established via introducing a node-gateway via a borehole or another mine entry. Means of powering the devices were also evaluated, such as permanently 'trickle charging' the devices in normal operation and then designing the 'nodes' to provide several days of independent operation following an event.

Simtars researched and engaged a specialist communication and electronics development company in the UK. They undertook a feasibility study on the beacons communication protocols and performed a literature review into current commercially available underground products.

4.3 Blast protection

Mine explosion scenarios, such as that which took place at the US Upper Big Branch Mine on April 5th 2010, confirm that explosion overpressures (particularly due to pressure piling and reflections) can reach 0.7 MPa with flame front propagation velocities of 500 ms^{-1} or more. Designing any atmospheric monitoring system to survive these conditions, or which can be remotely activated after an explosion is a major challenge. However, there is a significant justification in undertaking research to examine what options are available for rapidly implementing mine atmosphere monitoring after major mine incidents. Tests were carried out to trial different mechanical enclosures using Simtars' 30 m blast propagation tube.

Test Equipment

The Simtars explosion propagation tube is approximately 0.5 m diameter and 26.6 m in length. Fitted to the open end is a section that tapers up to 1.5 m in diameter and measures 3 m in length. The total length of the tube is approximately 30 m.

The tube is divided into 8 sections. The first two sections are separated from the open end of the tube (by inflating a 60 cm latex balloon) and are filled with an ignitable gas mixture. The gas mixture is ignited by an electric fuse head to produce an explosion. A schematic of the mixing section is presented in Figure 4.3.1.

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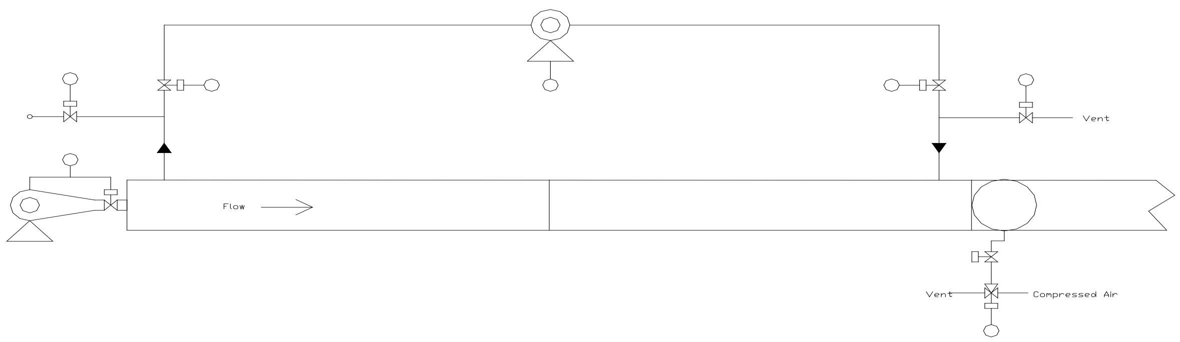

Figure 4.3.1: Mixing Section.

Test Procedure

At the closed end of the propagation tube a methane / air mixture of approximately 1.2 m^3 was ignited to produce an explosion.

An enclosure shape was fastened at the open end of the tube by using a M10 treaded bar that ran through the middle of the enclosure structure and fastened at both ends. This locked the enclosure into its testing position, as shown in Figure 4.3.2. All enclosures were fastened this way and at the same location for consistency during testing.

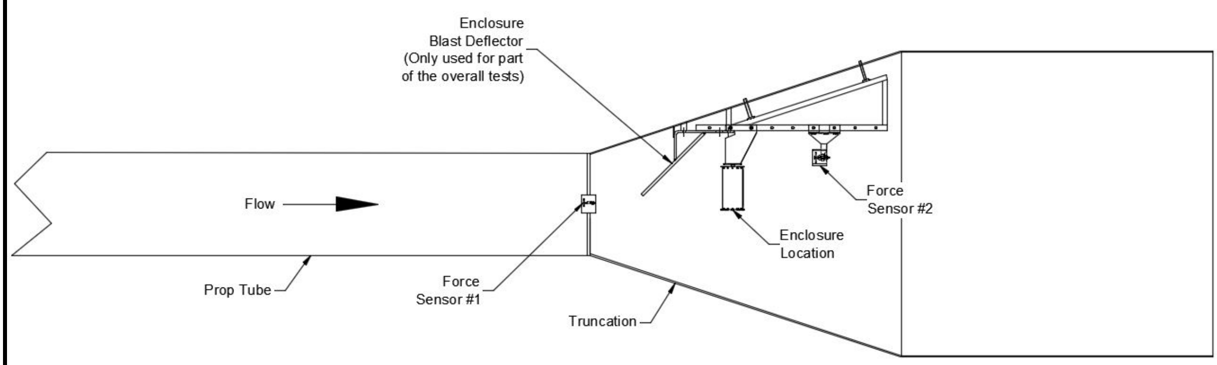

Figure 4.3.2: Tapered Section of Propagation Tube.

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Testing was conducted with the following enclosures;

1. Metal cylinder with 1.8 mm thick side wall and 2 mm thick end caps.
2. Metal cone with 2 mm thick side wall and 2 mm thick end cap.
3. Metal pyramid with 2 mm thick side walls and 2 mm thick end cap.
4. ABS plastic cylinder with 5 mm thick side wall and 8 mm thick flange.
5. ABS plastic cone with 5 mm thick side wall and 8 mm thick flange.
6. ABS plastic pyramid with 5 mm thick side walls and 8 mm thick flange.
7. Polycarbonate dome with 3 mm thick side wall and 3 mm thick flange and 2 mm thick aluminium end cap.
8. Polycarbonate prototype cylinder enclosure with 4 mm thick side walls with internal glass bead potted mix.

A total quantity of 5 of each of the above enclosure shapes / materials was tested. Each enclosure was subjected to only one test using the propagation tube. This prevented any fatigue or prestressing the enclosure before testing. A total of 2 of each enclosure shapes and material types were subjected to pressure produced by the explosion with an Enclosure Blast Deflector, located 380 mm in front of the enclosure, installed. The purpose of the Enclosure Blast Deflector was to provide protection to the enclosure positioned directly behind the device. The Enclosure Blast Deflector had been successfully used by Simtars in previous research, as documented in ACARP project number C198010[1]. Each of the protected enclosures were assessed for damage and their physical characteristics were evaluated. The enclosure test results are recorded in Table 5.3.1, section 5. The remaining 3 of each enclosure shapes and material type was subjected to the full pressure produced by the explosion and also assessed for physical characteristics damage.

4.4 Navigational aid beacon

The added functionality of using the system as a navigational aid were evaluated. The devices themselves can be used to house an LED array in order to give a simple exit route indication to assist as a self-rescue navigation guide. For example in using a different colour to give a clear indication of the correct direction of travel. Furthermore, in using a wireless sensor network with ‘nodes’ installed in known locations, it is possible to include a positioning and location capability with mobile devices (e.g. personnel or vehicle location). Simtars is currently conducting research into the use of wireless sensor networks for location and tracking applications, which could be modified and incorporated into the design. To evaluate the navigational effectiveness of the beacon, Simtars simulated the visibility affects that would be typical after a underground coal mine explosion. The simulation was conducted in Simtars’ dust testing chamber.

Test Equipment

The Simtars dust testing chamber is approximately 11.7 m long, 2.64 m high and 2.2 m wide, resulting in a testing chamber volume of approximately 67.9 m^3. Fitted within the chamber is a roof mounted monorail with guide wire that allows a test rig to be mounted and moved horizontally from the front to the rear of the chamber. This allows the tested item to move further away from the front of the chamber viewing window while the chamber environment is engulfed in dust.

Manual tape measuring was used to record the distance the test rig was from the camera location to ascertain the visibility distance of the beacon.

The dust testing chamber was fitted with a dust injection system to allow accurate quantities of dust to be dispersed into the chamber. To measure the dust concentration per volume within the chamber Simtars uses an Opacity meter called a ‘Dust Hunter’ that accurately measure the

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light dimming effect caused by the dust particles. The more dust particles in the environment the greater the dimming effect on the Opacity meter.

Test Procedure

The polycarbonate prototype cylinder enclosure was mounted to the test rig with white Light Emitting Diode (LED) navigation lights facing in the vertical direction. A reflective cone, installed in the enclosure, distributed the navigational light from the vertical plane into the horizontal plane, as shown in Figure 4.4.1. The navigation lights were then switch on ready for testing.

A Short Wave Infra-Red camera, Long Wave Infra-Red camera and normal vision camera were positioned at the front of the dust testing chamber, as shown in Figures 4.4.2 and 4.4.3.

Figure 4.4.1: Test rig with blast protection enclosure on picture left and 'Dust Hunter' picture right side.

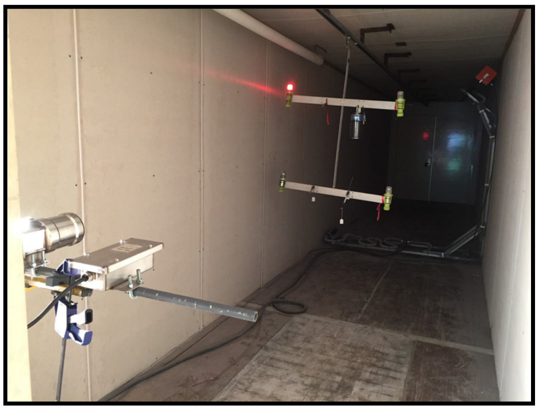

Figure 4.4.2: Test rig and cameras.

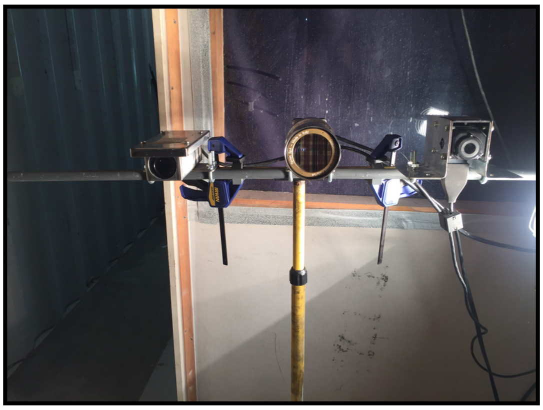

Figure 4.4.3: Testing cameras setup.

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The camera's images were viewed using a visual display unit, (VDU), with split screen capability, as shown in Figure 4.4.4. It was positioned outside the chamber and in the control room for operators use.

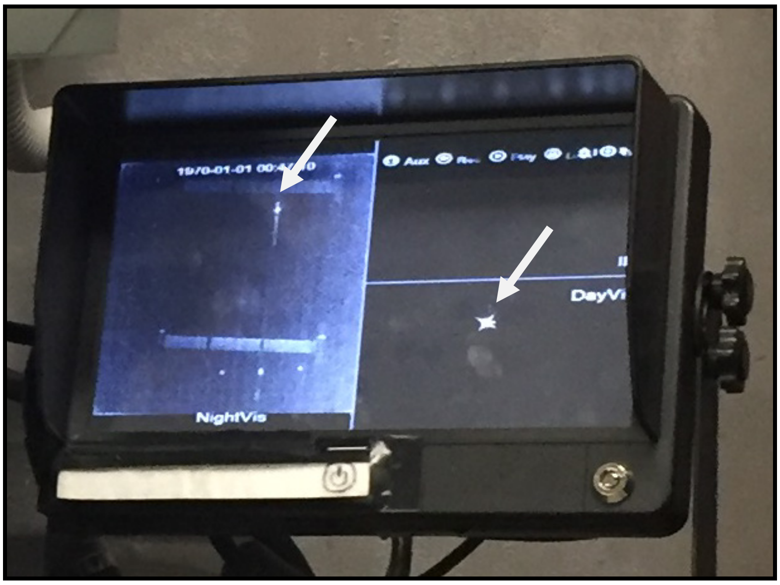

Figure 4.4.4: Visual Display Unit (VDU).

The three segregated screens on the VDU, Figure 4.4.4, can be seen with the beacon's light, (star like), visible in the left and bottom right screens. Once the light on the VDU were not easily distinguishable within the chamber, the dust was exhausted and the test rigs distance from the camera location was measured.

The 'Dust Hunter' was positioned midway down the length of the chamber to enable a mean value for dust distribution to be recorded. Different quantities of stonedust was weighed and injected into the chamber. This concentration value was measured by the optic 'Dust Hunter' with the values being documented in Table 5.4.1 'Opacity' column.

The test rig's position was recorded by manually measuring its position with reference to the front wall of the chamber by tape measure. The test rig was moved along the monorail during the test until the navigation lights were no longer visible on the respective cameras. A black out screen was used on the window between the control room and test chamber to block out any external light, leaving the chamber in darkness, except for the light emitted by the beacon.

The test rig's start position was nominated as 3.5 m from the front wall with the cameras set at 0.4 m in front of the wall leaving the actual visual start position to be 3.1 m. The maximum distance from the cameras that could be recorded in this test chamber was 11.3 m.

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5 Results

5.1 Post explosion atmosphere monitoring

Simtars engaged a consultant to investigate and report on the current technology in industry for atmosphere monitoring of Carbon Monoxide, Carbon Dioxide, Methane and Oxygen, and identify key commercially available sensors for the beacon design. Different atmosphere monitoring technologies, commercially available, to incorporate into the beacons design were investigated. Table 5.1.1 shows the different commercially available sensor technologies identified.

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Table 5.1.1 – Commercially available sensors technologies.

Sensor Type	Suitability
Catalytic (Pellet Resistor or Pellistor)	High power consumption, (225 mW typical), not intrinsically save, requires oxygen to be present to work, requiring frequent calibration and typical maximum operating life 3-5 years.
Infrared (Non-Dispersive Infra-Red)	Lower power consumption, (Less than 100 mW for incandescent type sensor and less than 5 mW for photodiode type). Operating life 10 years typical.
Electrochemical Cell	Very low power consumption, (0.5 mW). Not straightforward in use, minimum gas flow rates across the sensor can be required, cell may require to be short-circuited when not measuring , otherwise there can be a long start-up delay of several hours. Operating life, typically 5 to 7 years.
Semiconductor (Solid State) Metal Oxide Film	High power consumption, (300 mW typical), easy to use, robust. Operating life 10 years or more.
Fibre Optic	Requires the installation of a fibre optic network, does not lend itself to use in discrete sensors.
Laser (Tuneable Laser Adsorption Spectroscopy)	Not available as a discrete sensor. Suitable for analytic type gas measurements.
Flame Ionization	Not available as a discrete sensor. Suitable for analytic type gas measurements and not intrinsically safe.
Photo Ionization	Not available as a discrete sensor. Suitable for analytic type gas measurements.
Thermal Conductivity	Similar to Catalytic Pellistor sensing but less selective and less sensitive.
Nanotechnology (MEMS – Micro-Electro Mechanical Systems, SAW etc.)	This technology has much potential for realising sensors close to the ideal, but commercially available devices have yet to be realised. Some specialist sensors for this type are available for detecting nerve gas agents.

* taken from TestWorks report, Appendix A

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The investigation focused on gas sensors that measure for Carbon Monoxide levels of 50ppm and above, Carbon Dioxide at 2% and above, Methane at 5% and above and Oxygen up to 25%. Table 5.1.2 identifies some sensors of interest that was identified from a supplier called SGS Sensortech in Switzerland.

Table 5.1.2 – SGS Sensortech products.

Sensor Model Number	Gas & Range	Notes
DS-0229-INIR	Methane (CH_4) 4% - 100% volume Carbon Dioxide (CO_2) 0% - 5% volume	Integrated Infra-red (IR) sensor Power consumption: 32mA @ 3.3V Can be used in wake-up-sleep applications but there is a 45s warm-up time. Lifetime, typically 10 years.
DS-0138-SGX-4CO-V2	Carbon Monoxide (CO) 0 – 1000 ppm	Electrochemical sensor Power consumption of the sensor itself is negligible. A small bias voltage is required but the interface circuit will consume more power than the sensor, estimated to be less than 10mA. Lifetime, typically 5 years
DS-0141-SGX-4DT-V3	Carbon Monoxide (CO) 0 – 500 ppm Hydrogen Sulphide (H_2S) 0 – 200 ppm	Electrochemical sensor Power consumption of the sensor itself is negligible. A small bias voltage is required but the interface circuit will consume more power than the sensor, estimated to be less than 10mA. Lifetime, typically 5 years
A1A-EC410	Oxygen (O_2) 0 – 30%	Electrochemical sensor Power consumption of the sensor itself is negligible. A small bias voltage is required but the interface circuit will consume more power than the sensor, estimated to be less than 10mA. Lifetime, typically 5 years

* taken from TestWorks report, Appendix A

The literature survey into alternate energy harvesting brought to light some technologies that may be useful in some sections of the mine for powering the beacons. These have not been vetted against current underground coal mining regulations and may not comply but rather, add thought to the possibility of further research into this area once a beacon prototype is developed and its energy requirements are determined.

There is vast amounts of alternative technologies currently used on surface, these are wind, solar and thermal to name a few. However, the review identified some alternative energy harvesters that could be better suited for an underground environment. One such technology that is being developed uses carbon dioxide and oxygen / aluminium to produce an electrochemical reaction through anodic protection with, the outcome of producing an electric charge[2]. It is reported that a working prototype of this technology produced, "*13 ampere hours per gram of porous carbon with a discharge potential of around 1.4 volts*"[2]. This technology was developed to combat greenhouse gasses and convert them to an alternate energy source.

Another source that is becoming readily available is energy harvesting via Radio Frequency (RF). This technology uses radio waves which produce an electromagnetic wave that can

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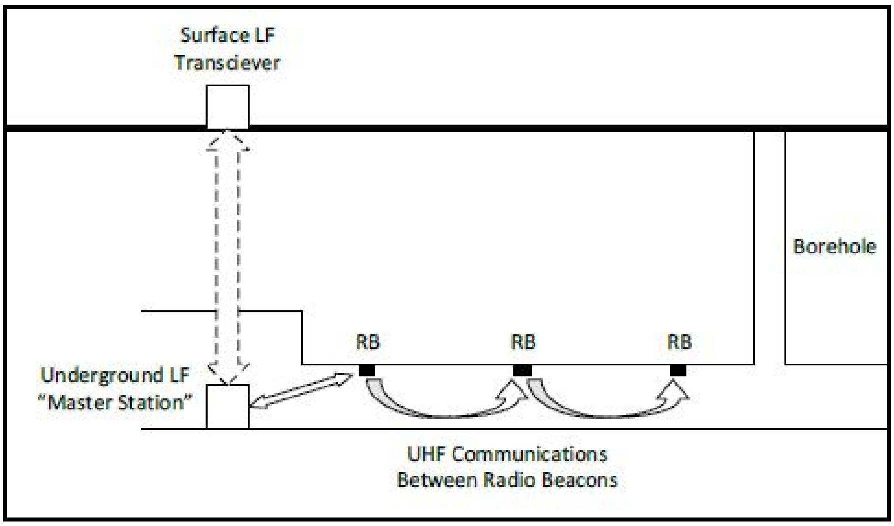
wirelessly charge a device through its receiver and then converted into an electrical charge that can be stored in the devices power source[3]. Radio Frequency charging is currently in use by many devices, including smart phones, wireless sensor networks, contactless smart cards and Radio Frequency Identification Tags, (RFID tags). It is stated that this technology can, "*currently only produce charging in close proximity to the transmission source but could be used to trickle charge rechargeable batteries in devices stored for long periods between use*"[3]. Also stated in the article is, "*the current charger rate from RF energy is very low, (typically measured in microwatts)"*[3].

Electrostatic vibration energy harvesting uses mechanical vibration between two plates that create a static charge and can then be amplified to create electrical charge[4]. This is stated in the text as, "*The use of a variable capacitor structure to generate charges from a relative motion between two plates*"[4]. The vibration is created when one plate, (a mobile mass), is free to move over the other which is fixed. This motion cause a static charge potential and produces an electric charge.

Research is being performed at the Wageningen University in the Netherlands on harvesting electrical energy from plants. This uses the potential energy of organic matter that is excreted by plants into the surrounding soil[5]. This excrete is broken down by bacteria and in the process it is said that electrons are released. The developers use inert electrodes that they insert within 30 cm of the plant roots to harvest the electrons. Lab trials have generated approximately one watt per square meter, of plant organic extcrete, but current expectations is to achieve approximately three watts.

5.2 'Ultra-resilient' communication system

Simtars engaged a consultant to deliver a feasibility study report, (see Appendix A), which provided recommendations on the setup of a robust communication network and radio frequency protocol for use in an underground coal mine. Two communication network approaches were delivered, as shown in Figures 5.2.1 and 5.2.2. A further recovery communication approach in the event of underground beacon signal disruption or loss of communication to the surface is shown in Figure 5.2.3.



* taken from TestWorks report, Appendix A

Figure 5.2.1: Communication network version #1.

Figure 5.2.1 displays a 'Parent' to 'Child' communication configuration where the RB beacons, (Child), transmit data along the chain until the information arrives at the 'Master Station', (Parent), and can be transmitted to the surface

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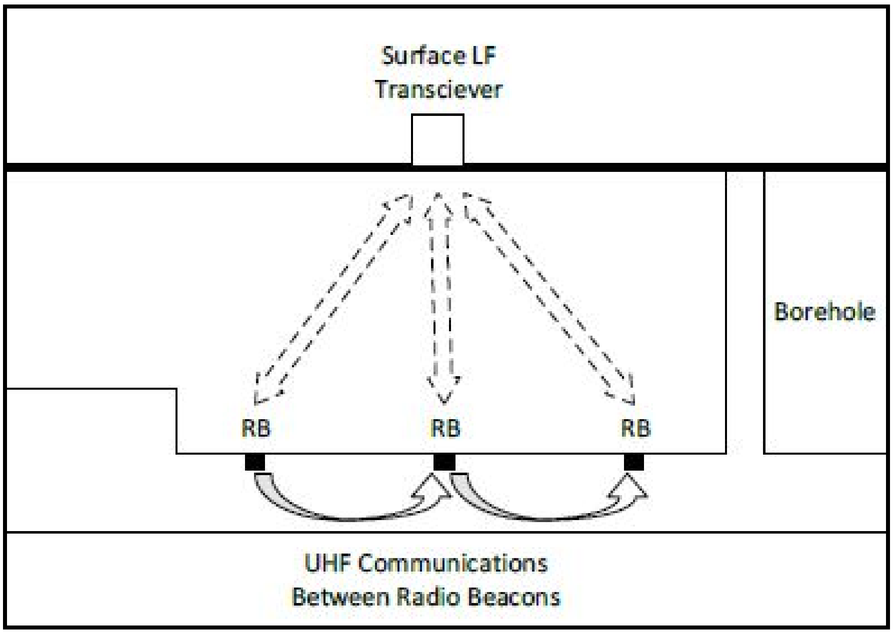
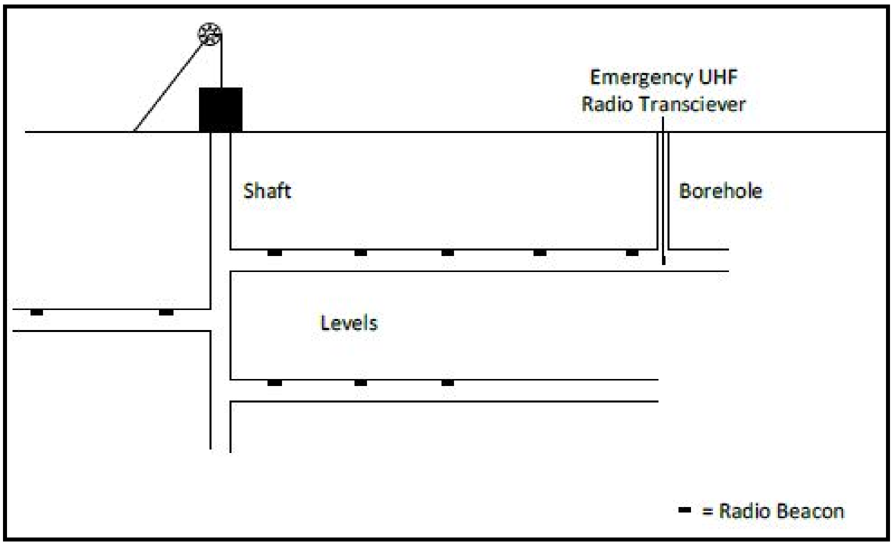


* taken from TestWorks report, Appendix A

Figure 5.2.2: Communication network version #2.

Figure 5.2.2 displays each individual beacon being a 'Parent' style beacon that communicates out of the mine, while at the same time, communicate underground with the other beacons. This is to establish communication out of the mine, in the case where one beacon can't establish contact with the surface transceiver. The beacon would transmit its data to another beacon, which would then transmit its own data and that of the second beacon back to the surface.



* taken from TestWorks report, Appendix A

Figure 5.2.3: Recovery to communication if underground beacon signal is disrupted or lost.

Figure 5.2.3 displays the use of a bore hole to lower a radio transceiver to re-establish surface communication with underground beacons.

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5.3 Blast protection - Propagation tube enclosures shape test results

There were 35 tests in total for all the enclosure shapes and materials. Table 5.3.1 displays the results of all 35 tests. The enclosures were subjected to an indicative, single point in time, pressure range of up to 53 kPa, using the propagation tube.

Table 5.3.1 – Results from propagation tube testing.

Test Number	Date	Enclosure Shape and Material	Enclosure Blast Deflector	Description: Enclosure and Anchor Physical Condition After Propagation Test
T1	13/06/2018	Cylinder/ABS Plastic	Installed	No damage to enclosures anchor and no damage to the enclosure
T2	14/06/2018	Cylinder/ABS Plastic	Installed	No damage to enclosures anchor and no damage to the enclosure
T3	14/06/2018	Cone/ABS Plastic	Installed	No damage to enclosures anchor and no damage to the enclosure
T4	14/06/2018	Cone/ABS Plastic	Installed	No damage to enclosures anchor and no damage to the enclosure
T5	14/06/2018	Pyramid/ABS Plastic	Installed	No damage to enclosures anchor and no damage to the enclosure
T6	14/06/2018	Pyramid/ABS Plastic	Installed	No damage to enclosures anchor and no damage to the enclosure
T7	14/06/2018	Dome/Polycarbonate Plastic	Installed	No damage to enclosures anchor and no damage to the enclosure
T8	14/06/2018	Dome/Polycarbonate Plastic	Installed	No damage to enclosures anchor and no damage to the enclosure
T9	14/06/2018	Cylinder/Mild Steel	Installed	No damage to enclosures anchor and no damage to the enclosure
T10	14/06/2018	Cylinder/Mild Steel	Installed	No damage to enclosures anchor and no damage to the enclosure
T11	14/06/2018	Cone/Mild Steel	Installed	No damage to enclosures anchor and no damage to the enclosure
T12	14/06/2018	Cone/Mild Steel	Installed	No damage to enclosures anchor and no damage to the enclosure
T13	14/06/2018	Pyramid/Mild Steel	Installed	No damage to enclosures anchor and no damage to the enclosure
T14	14/06/2018	Pyramid/Mild Steel	Installed	No damage to enclosures anchor and no damage to the enclosure
T15	15/06/2018	Cylinder/ABS Plastic	Uninstalled	No damage to enclosures anchor and no damage to the enclosure
T16	15/06/2018	Cylinder/ABS Plastic	Uninstalled	No damage to enclosures anchor and no damage to the enclosure

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Test Number	Date	Enclosure Shape and Material	Enclosure Blast Deflector	Description: Enclosure and Anchor Physical Condition After Propagation Test
T17	15/06/2018	Cylinder/ABS Plastic	Uninstalled	No damage to enclosures anchor and no damage to the enclosure
T18	15/06/2018	Cone/ABS Plastic	Uninstalled	No damage to enclosures anchor and no damage to the enclosure
T19	15/06/2018	Cone/ABS Plastic	Uninstalled	No damage to enclosures anchor and no damage to the enclosure
T20	15/06/2018	Cone/ABS Plastic	Uninstalled	No damage to enclosures anchor and no damage to the enclosure
T21	15/06/2018	Pyramid/ABS Plastic	Uninstalled	No damage to enclosures anchor and no damage to the enclosure
T22	15/06/2018	Pyramid/ABS Plastic	Uninstalled	No damage to enclosures anchor and no damage to the enclosure
T23	15/06/2018	Pyramid/ABS Plastic	Uninstalled	No damage to enclosures anchor and no damage to the enclosure
T24	15/06/2018	Dome/Polycarbonate	Uninstalled	Slight damage to enclosures anchor plate and no damage to the enclosure
T25	15/06/2018	Dome/Polycarbonate	Uninstalled	Slight damage to enclosures anchor plate and no damage to the enclosure
T26	18/06/2018	Cylinder/Mild Steel	Uninstalled	No damage to enclosures anchor and no damage to the enclosure
T27	18/06/2018	Cylinder/Mild Steel	Uninstalled	No damage to enclosures anchor and no damage to the enclosure
T28	18/06/2018	Cylinder/Mild Steel	Uninstalled	Slight damage to enclosures anchor and slight damage to the enclosure
T29	18/06/2018	Cone/Mild Steel	Uninstalled	No damage to enclosures anchor and no damage to the enclosure
T30	18/06/2018	Cone/Mild Steel	Uninstalled	No damage to enclosures anchor and no damage to the enclosure
T31	18/06/2018	Cone/Mild Steel	Uninstalled	No damage to enclosures anchor and no damage to the enclosure
T32	18/06/2018	Pyramid/Mild Steel	Uninstalled	No damage to enclosures anchor and no damage to the enclosure
T33	18/06/2018	Pyramid/Mild Steel	Uninstalled	No damage to enclosures anchor and no damage to the enclosure
T34	18/06/2018	Pyramid/Mild Steel	Uninstalled	No damage to enclosures anchor and no damage to the enclosure
T35	18/06/2018	Cylinder/ Polycarbonate	Uninstalled	No damage to enclosures anchor and no damage to the enclosure

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The enclosure photos shown in Figure 5.3.2 are of the different enclosure shapes. The prototype polycarbonate enclosure is shown in Figure 5.3.3. These shapes were all tested in the Simtars' propagation tube with the results recorded in Table 5.3.1.

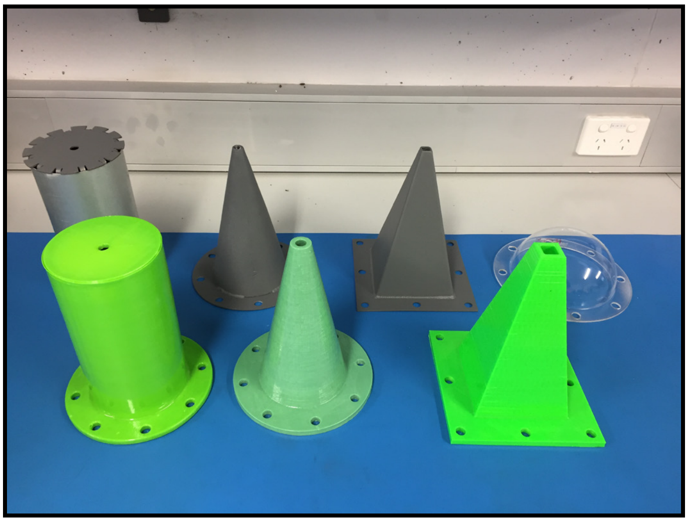

Figure 5.3.2: Enclosure shapes tested.

Figure 5.3.2 shows three different enclosure materials, the grey colours being made from laser cut and folded mild steel with the flange being stitch welded to the base of the shape. The cylinder shape had two endcaps that cradle the inside edge by the use of folded tabs on the endplates. This central aligns and holds the cylinder in place during the test. The green coloured shapes were printed from ABS plastic with an acetone wash to slightly harden the outside surface. The printing technique was the generic standard setting for the printer with the internal, 'infill', algorithm being the standard setting for the printer as well. The clear dome was constructed of 150 mm diameter polycarbonate material and is a commercially available item. Testing these enclosures and using different materials also brought forward some interesting results. It was surprising to note that the ABS plastic printed enclosures withstood the same rigorous testing as the mild steel sheet enclosures.

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Figure 5.3.3: Prototype polycarbonate enclosure.

Figure 5.3.3 shows the polycarbonate enclosure prototype that was also used in the dust testing chamber for the navigational aid component of the project. Figure 5.3.3 also shows the enclosures mounting configuration with the Enclosure Blast Protector removed.

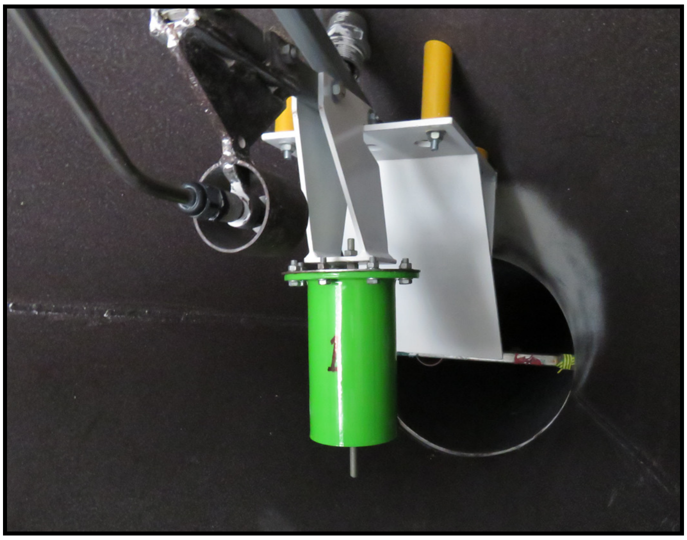

Figure 5.3.4: Printed enclosure mounted in propagation tube

Figure 5.3.4 shows the first ABS printed plastic enclosure in place for testing with the Enclosure Blast Protector installed. This protector was removed after the first round of enclosure testing had been completed in order to subject the remaining enclosures to the full blast of the explosion.

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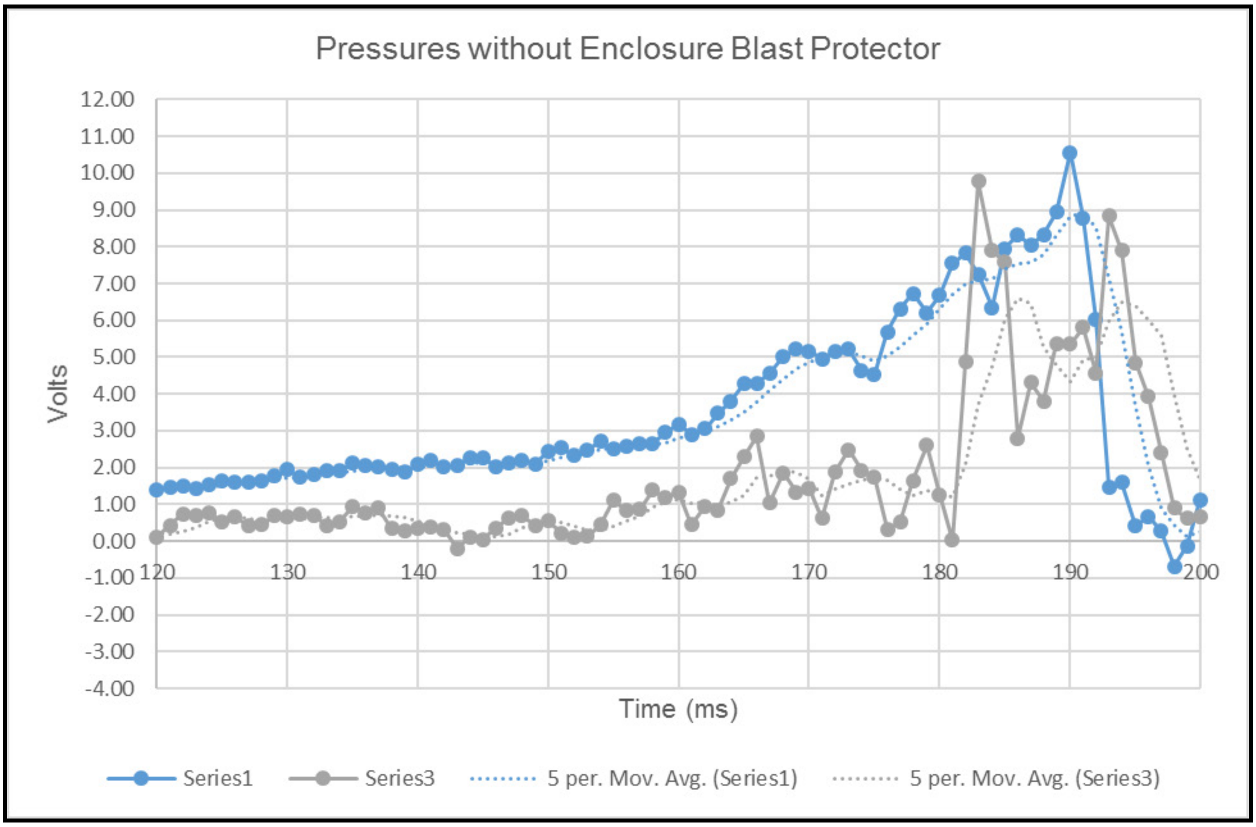

Figure 5.3.5: Pressure wave graph with Enclosure Blast Protector uninstalled

The pressure wave graph in Figure 5.3.5 shows the output voltage profiles of two force sensors (Figure 4.3.2), (Blue – Series 1 and Grey – Series 3), used to record the blast, during one of the enclosures testing. The sensor providing the blue pressure trace was mounted directly in line with the blast. The sensor providing the grey pressure trace was mounted at a position which would be behind the Enclosure Blast Protector. The sensors remained in their respective positions throughout all 35 tests. This graph shows what the blast profile with the Enclosure Blast Protector removed. The Series 1 and 3 lines are raw data from the blast and displays a certain amount of system resonance / vibration created by the blast. To accommodate this a trend line was used, (5 point moving average). It is the blue and grey faint dotted trend lines shown in Figure 5.3.5. This provided a more accurate blast profile voltage output from the sensors. From the Series 1 graph, the maximum voltage output was approximately 8.8 V. The total pressure was then calculated with the indicative pressure value of 53 kPa as stated in section 5.3.

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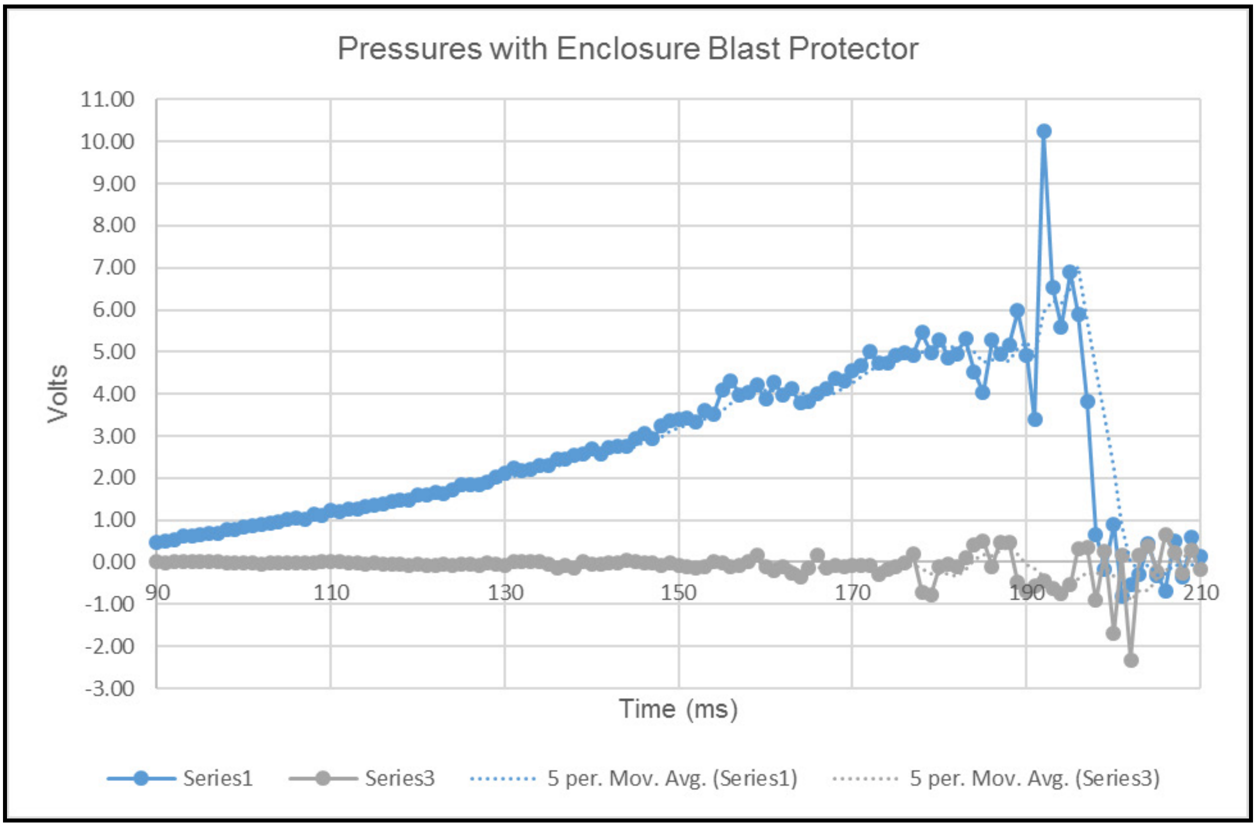

Figure 5.3.6: Pressure wave graph with Enclosure Blast Protector installed

In Figure 5.3.6 the voltage profiles of two force sensors, (Blue – Series 1 and Grey – Series 3), used to record the blast, during one of the enclosures testing. This graph shows what the maximum blast profile was with the Enclosure Blast Protector installed. Trend lines were again added in the Figure. The blue trend line provided the blast magnitude before the protector and the grey trend line of what the enclosure was subjected to. Unlike Figure 5.3.5, there is a vast difference between the blue and grey profiles. This demonstrated that the protector dramatically reduced the blast impact on the enclosure. It is possible, by installing an Enclosure Blast Protector, the enclosure would stand a better chance at surviving a blast.

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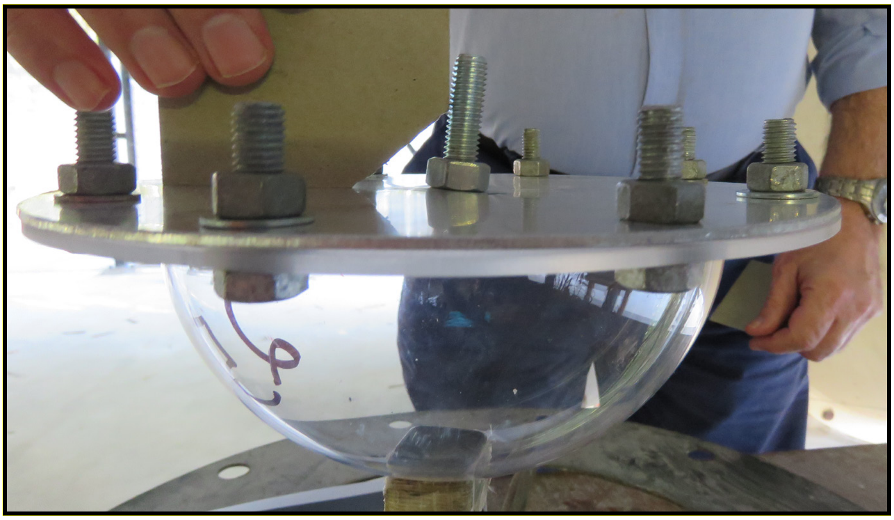

Figure 5.3.7: Enclosure 25 with physical damage to the anchor plate

Figure 5.3.7 shows Enclosure 25 with physical damage to the anchor plate. The anchor bolt can be seen on a slight angle due to localised deformation of the anchor plate around the head of the bolt. This was also noticed on Enclosure 24 which was the other polycarbonate dome that was subjected to the full blast of the propagation tube. This was not observed in the other shapes and may be due to the anchor plate being 2 mm aluminium instead of the 2 mm mild steel, as used on all other enclosures. The aluminium was used to trial different anchor materials and was selected for use on the dome shapes due to their low surface profile compared to the other shapes.

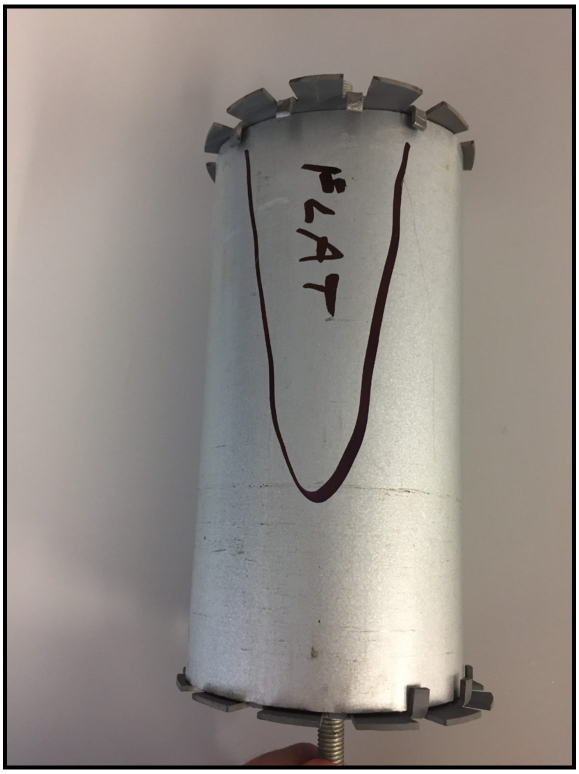

Figure 5.3.8a: Enclosure 28 with side wall Damage – Front View

Figure 5.3.8b: Enclosure 28 – Side View

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Figure 5.3.8 ‘a’ and ‘b’ shows Enclosure 28 with physical damage to side wall. The damage is identified by the ‘V’ shaped marking on the cylinder to indicate the extent of the damage. This section of the enclosure faced the oncoming path of the blast. It is interesting to note that the only section of the enclosure not supported by the fastening tabs on the end plate was also the only portion to sustain damage. The other enclosures of this style were not affected in this way and an assumption could be formed that this may not have occurred if the side wall had the mechanical support of the tabs, as given in the other tests on this type of enclosure.

5.4 Navigational aid beacon - Dust testing chamber / visualisation test results

A total of 11 tests were conducted in the dust testing chamber. Only the prototype polycarbonate enclosure was utilised during these tests, as it was the only enclosure setup with navigational aid componentry. Table 5.4.1 presents the results of all 11 tests.

Table 5.4.1 – Results from dust testing chamber.

Test Number	Date	Dust Weight (g)	Opacity (%)	Visible Distance (m)	Comments
T1	03/11/2017	100	52	11.7	Visible spectrum light was still easily seen when at the end of the container.
T2	03/11/2017	200	73	11.7	Visible spectrum light was still easily seen when at the end of the container.
T3	03/11/2017	300	89	11.7	Visible spectrum light was still easily seen when at the end of the container.
T4	03/11/2017	400	89	11.7	Visible spectrum light was still easily seen when at the end of the container.
T5	03/11/2017	500	88	11.7	Visible spectrum light was still easily seen when at the end of the container.
T6	03/11/2017	600	94	11.7	Visible spectrum light was still easily seen when at the end of the container.
T7	03/11/2017	700	95	11.7	Visible spectrum light was still easily seen when at the end of the container.
T8	03/11/2017	800	95	11.7	Visible spectrum light was still easily seen when at the end of the container.
T9	03/11/2017	900	97	11.7	Visible spectrum light was still easily seen when at the end of the container.
T10	03/11/2017	1000	98	11.7	Visible spectrum light was still easily seen when at the end of the container.
T11	03/11/2017	2000	100	4.3	Visible spectrum light was only slightly seen at the 4.3m distance. All visibility was lost after this distance.

The comments column of Table 5.4.1 refers to the ability of the operator to distinguish the beacons visible light through the cameras on the VDU.

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The above results indicate that in this environment the visible light spectrum was able to be seen by its camera up to 98% opacity with no other light present in the chamber. This means the light can be seen by its camera with approximately 67.9 g/m^3 of stonedust in the environment. Above 67.9 g/m^3 the visible distance of the light in the camera reduced to 3.9 m once the environment reached 100% opacity with 135.8 g/m^3 of stonedust.

During the test no external light was present in the chamber which may have aided in the results, as there was no extra light reflecting off the dust particles in between the cameras and the beacons light reflector. This extra light condition could produce a ‘white out’ blanket visual affect with the dust and make the beacons light harder to distinguish on the VDU. The beacon’s LED was lined up in such a way as to focus its light directly at the camera. In the test T11 the beacon was turned so that the LED’s were offset 45 degrees in the reflector to give worst case scenario. This was to investigate how the system would perform with the lights 45 degrees offset to the viewers direct field of vision which made the beacon’s LED’s brightness less intense in the reflector.

6 Discussion

6.1 Post explosion atmosphere monitoring

The feasibility report in Appendix A, indicated that power consumption of the sensors is of great importance for these devices and only focused on sensors that operate within specific size and power requirement. From this recommendation, Simtars conducted a review of current alternate energy harvesting devices that might be applicable or adapted for underground coal mine usage. There are many different energy harvesting technologies currently on the market along with research into unique theories. In a coal mine there are many sources of energy that could be harvested but there is not one type that could be used throughout the entire mine. Commonly in use above ground are solar panels, wind turbines, thermal energy, hydraulic turbines etc. but many of these are not suitable underground.

The electrochemical reaction alternative of the carbon dioxide and oxygen / aluminium device, would prove beneficial if the beacons were located in an area containing high amounts of carbon dioxide. Before this device could be used, further data would be required around the materials used in the device’s construction, to make sure they meet all mining regulations, i.e. material used is aluminium.

Wireless charging has its benefits as this would be the best form of charging due to its ability to use existing mine electrical infrastructure to charge the beacons power source. Unfortunately current technology only allows low power charging of devices up to 10 m from the radio wave source. If beacons were trickle charged using this energy source, they would need to be within the charging range. As many beacons would be required to monitor the mine atmosphere along with the communication component, only a select few would have the capability to utilise this source.

Electrostatic vibration energy harvesting requires a vibration to create an electric charge. Unless there was a vibration source around the beacon using this technology, the charging system would not work. This may have potential in working longwalls where the vibration would be created by the mining process but after this event the charging system could be rendered redundant.

Using the potential energy from organic plant excrete also has its flaws. This technology was created for a surface installation with the researches looking to progress from the lab to a working model in the future [5]. They anticipate this technology working in a wetland or wet area

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environment like a rice paddy or mangrove. The organic environment underground may not be suitable for the same theoretical organic matter and bacteria electron conversion.

Through the research undertaken by the consultant it was identified that multiple sensors would be need. This is required to satisfactorily monitor the environment around the individual beacon as not one individual sensor can measure all 4 gasses within the specific ranges as specified above and low power requirements. It is also apparent that even though there are a multitude of commercially available sensor technologies, only a select few can be used that fit within the confines of this project objectives. Identified as possible solutions were infrared sensors to measure explosive gasses and electrochemical to detect and measure the poisonous gas and oxygen levels. Out of the sensors indicated by the consultant as viable options, a caveat was stated that the sensors have the possibility of lasting 5-10 years if they only operate and take a sample every 2 hours. This may be acceptable in normal operation but in the case of a mine disaster, sampling the environment and for data dissemination every 2 hours would be far too long. This would give the surface operations a large window of error when formulating their risk assessments and may hinder rescue operations.

The consultant displays a vast amount of research into sensor technologies and provides a variety of possible options. However, they state, “To date, very little has found its way into commercially available mainstream products, largely due to market sensors based on new technologies, compared to their demand and cost”. This statement on the assessment of commercially viable sensors to be incorporated into this project may hinder the progression or the economic viability of the beacons development and industry acceptance.

6.2 ‘Ultra-resilient’ communication system

Some of the existing commercially available products that were identified have been proven in underground use, including, the “Hey-Phone”, developed by John Hey, “Rescue Dog”, a product by mine ARC systems and the existing PED system from Mine Site Technologies.

Low frequency communication requires a long antenna in order to transmit signals from underground to the mine surface. The report identifies this as an issue and gives two antenna solutions. The first antenna was identified as a ‘loop’ configuration. In order to achieve the optimum communication from this antenna configuration, it is stated, there are a few key parameters that need to be addressed. The communication improves with the largest antenna diameter achievable along with the number of turns. This in addition with the largest possible current flowing through the antenna allows for the communication to be transmitted to the surface. Depending on the location of this antenna, the loop antenna option may not be a viable solution due to power, and spatial constraints. It also may create other unforeseen problems with mining personnel and day to day operations.

The second solution was an Earth antenna. This is where, *“antennas are formed by inserting metal rods into the ground”*, as described in the consultant’s report. It is stated that this configuration achieves better communication than that of loop antennas. The optimum commination from this antenna is achieved by the distance between each antenna. The report states that, *“good success has been noted in experiments with large antenna separation distances of 1500 mm”*. It is also stated that, “*if more than one rod is inserted at each endpoint, connected radially this can also increase the effect of the transmission*”. Further adding to the communication, the report states that, *“if the soil surrounding the rods is dampened with a salt water solution, this has increased the effect of the transmission”*. Since there is an abundance of metal structure that is attached to or into the earth in an underground mine, using the Earth antenna configuration may be the preferred solution for the beacons communication network. This is further supported by the moist nature of the underground environment which may aid in a better transmission.

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To create the "Ultra-resilient' communication system, the report identifies the use of multiple communication beacons underground. The beacons would be configured in a 'Parent-Child' configuration where the 'Parent' beacon would be capable of Low Frequency (LF) communication to the surface, with several 'Child' beacons surrounding the 'Parent'. The 'Child' beacons would house the instrumentation that would provide atmospheric monitoring and transmit the data back to the 'Parent' beacon for broadcast out of the mine. The report suggests that the 'Child' beacons would use Ultra High Frequency (UHF) primary communication, as they would be within a short distance from the 'Parent' and within the UHF range. This may vary dependant on signal strength between the 'Parent' and the 'Child' beacons in individual mines. If a 'Parent' beacon's antenna is damaged in a mine blast, the report suggests that re-establishing the communication link could be achieved by using a bore hole and lowering a transmitter / receiver device into the mine. An alternative is also discussed where the damaged beacons automatically realign their communication links to another 'Parent' beacon to transmit information from underground to the surface.

The report indicated that to use LF or ULF communication transmission, the 'Parent' beacon would require significantly more power than the UHF system of the 'Child' beacon. Simtars conducted a review of commercially available energy harvesting technology. To date there is not one charging system that will suit every aspect of an underground mine environment to charge the beacons. Further work is required, however, it is likely that only some beacons can be recharged using this method. Another alternative is that the beacons must rely purely on the capacity of its power source before maintenance / replacement is required.

6.3 Blast protection or blast resilience

Installation of the Enclosure Blast Deflector showed that no physically noticeable damage occurred to the enclosures tested. With no protection, three enclosures showed noticeable damage. A small portion of the enclosures, (approximately 80 mm), was exposed to the full blast while using the Enclosure Blast Deflector. It is unknown if the deflector also protected this exposed portion and leads to the possibility of exposing the navigational aid light section of the beacon while, maintaining structural integrity of the remaining protected unit. Positioning a deflector may be difficult in a mine unless the theoretical direction of an explosion could be ascertained. This possibility also opens up to the ability of mounting the beacon into the roof or walls of a mine. This may also provide protection to the enclosure while exposing only a small portion of the beacon to the full mine explosion. Further testing is required to verify these assumptions and considering this approach as a scenario on a final design test could be advantageous. Also there were not any notable advantages of each individual shape tested over the other shapes for these pressures. This may be due to the size of the enclosures tested or other factors from the dynamics of the propagation tube pressure wave.

Figure 6.3.1 shows a cut through of one of the cone shaped enclosures. It shows the internal printing technique of the plastic enclosures. The internal 'infill' mesh structure of the enclosure theoretically makes the components stronger for less overall component weight and may have aided in their blast resilience. This may be why the printed enclosures' were comparable to the steel enclosures, with in the 53 kPa indicative pressure range. Further testing with plastic enclosures are needed to verify them as a viable alternative to other materials like steel.

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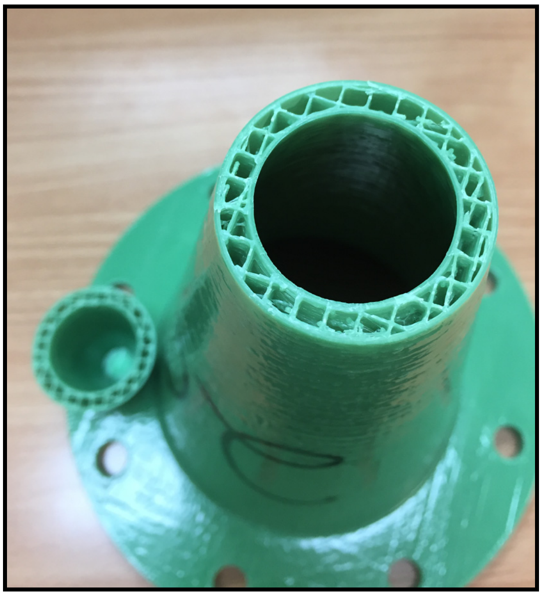

Figure 6.3.1: ABS plastic enclosure with Internal ‘infill’ mesh structure shown.

6.4 Navigational Aid

During the evolution of the dust testing chamber tests, the beacon was turned so that the LED’s were offset 45 degrees in the reflector to give worst case scenario. Even with the lights being offset in this way, the light was visibly distinguishable on the VDU. It is apparent that navigation in a completely dusty environment may be possible when using visible light produced from the selected LED’s. The outcome from the worst case test also indicates that by using the installed prototype reflector, orientation of the beacon is not critical. However, aligning the LED to focus light in the direction of the approaching miner would conceivably be the optimum solution. Only a white LED’s were used in the testing. It would be pertinent to identify that this may not be the most acceptable colour of light, depending on the miners sight ability. Further investigations and alterations may need to be evaluated to better suit the end users.

7 Conclusion

Achieving a working underground communication system linked to above-ground communication beacons that can also provide full-duplex transmission, would be highly advantageous in everyday operations and even more important in the unfortunate event of a underground mine disaster.

Through international research and local testing, Simtars has identified that there are some major compromises or barriers that need to be addressed in order to achieve such a valuable device.

The external consultant’s report indicated that there are various options when it comes to assembling the communication devices but each has its advantages and disadvantages. One of the major obstacle outlined was overcoming the power requirements to run each of the communication beacons. The report indicated that for the communication section of the beacons, Low Frequency transmitting should be used to communicate between the surface and underground environment. It also indicated that Ultra High Frequency transmitting should be used as the main communication between clusters of beacons back to the ‘Parent’ low frequency transmitting beacon. The switching between these two frequencies, (LF and UHF), is a technology which is thought to be the critical key to the success of this type of installation,

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which needs to be created and developed. It is believed that this will make the underground communication system robust in the event of a mine disaster. To use these frequencies for communication would require the device to have a substantial power source. Otherwise a compromise of a shortened power source life and maintenance schedule for replacing the power source would need to be considered. These intervals may require weeks, months or years to achieve. The possibility of using various hybrid charging devices across the mine to maintain or prolong the power sources should also be considered. The alternative energy sources identified by Simtars' literature review indicates some trickle charging concepts that may work for a selection of the beacons. Further research into this area would be needed to ascertain a viable charging solution for the beacons that could adhere to underground mining regulations.

Further development is required in the atmospheric sensor section of the beacon. There are commercially available sensors that, in operation, use low amounts of power but none could be found that are classified as intrinsically safe for underground coal mines use at present.

It is believed that once the above issues are resolved, a blast enclosure could be developed to suit either a maintenance free or low maintenance beacon that is more robust and likely to better withstand a mine disaster. Further testing is required to ascertain protection of the complete system in specific scenarios, typical of an underground mine disaster condition.

The navigation possibility of using visible light from white LED's was demonstrated by testing conducted in the Simtars' dust testing chamber. This navigation ability would depend on the location and configuration of the beacons underground in relation to other lights or equipment with lights. Also the interval distances of the beacons would need to be assessed, in terms of their ability to work effectively in its other operations, (communication distances and cluster requirements for communication network.). Short or long wave infrared LED's could be added in the case of using personal equipment to pick up the emitted light. Further testing would be required to ascertain the intensity and colour of the LED's required for the beacons. This would be to ascertain the appropriate amount of visible light from either visible or infra-red technologies, at distances of greater than 11 m as tested in the Simtars' dust testing chamber.

From the testing and the recommendations produced in the research, it is apparent that there is more investigation, innovating and testing required in order to produce a robust, safe and reliable communication, atmospheric and navigation aid for use after an incident underground. With current technology trends progressing forward at a rapid pace in sensors, power and electronics every day, the commercial items required to create this important device may be available within the near future. At present, the research indicates there are no commercially available products that could be used to develop a working prototype and comply with the intrinsic safety requirements in an underground coal mine. Until these items are commercially available, that accomplish all the original projects objectives, such a device could not be developed.

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8 References

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9 Appendices.

A. TestWorks Group Report 90161-46-01 Issue

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Appendix A – TestWorks Feasibility Report

Doc No. 90161-46-01 Issue: 0B

Feasibility Study Report

Project: SIMTARS Radio Beacon

Date: 17th Nov 2017

Issue: 0B

Prepared by	:	Nigel Dean
Authorised by	:	....
Checked by	:	
Customer Signature	:	....
Date	:	17th Nov 2017

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Document Modification Record			
Issue	**Date**	**Author**	**Comments**
0A	31/07/2017	Nigel Dean	Initial Version
0B	17/11/2017	Nigel Dean	Sensor review material added

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1 Introduction

This report is in response to a requirement by the Safety in Mines Testing and Research Station (SIMTARS), based in Queensland, Australia, to investigate the feasibility of developing an emergency communication system based on an array of radio beacons located underground in a mine, which will utilise both UHF and LF radio.

Underground wireless communications are well known to be problematic, with normal frequencies being greatly attenuated by the surrounding rock etc. resulting in very restricted range and generally poor performance. It has been known for some time (more than 100 years) that communications using the ground itself as a medium are possible when low frequencies, LF and VLF are employed, and a number of systems using this approach have been developed, both within the mining industry and also notably by cave rescue teams.

The proposal put forward by SIMTARS is to design and develop a radio beacon device which would be deployed in multiple numbers to form an underground communications network. Under normal conditions, communications between beacons could be via unlicensed UHF radio using readily available off-the-shelf radio modules designed for the ISM bands, but in an emergency when this link may be broken, e.g. by rock fall etc., the break in the link could be automatically re-established by low frequency, through the ground communications. It is the aspect of integrating low frequency radio into the beacon proposal that will be the primary focus of the feasibility study, exploring the trade-offs between beacon spacing, antenna design, power and communications protocol.

1.1 Scope

This report is a summary regarding the feasibility of using low frequency through the earth radio techniques as a communication method in a network of radio beacons, installed in a mining environment, both for short range links between beacons and for longer range links between underground and the surface.

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1.2 Glossary

SIMTARS Safety in Mines Testing and Research Station

LF Low Frequency (30 – 300 kHz)

VLF Very Low Frequency (3 – 30 kHz)

UHF Ultra High Frequency (300 – 3000 MHz)

ISM Industrial Scientific Medical (Radio Bands)

TTE Through The Earth (Communication System)

RB Radio Beacon

1.3 Applicable documents

1. TestWorks group quotation Ref: 21015_01
2. Outline Proposal for the Design Configuration of the Radio Beacon (RB) Enclosure, by S.M. Jenkins, SIM/SMJ 2 Revision D

1.4 Conventions

Text highlighted in red, identifies values or statements that require validation.

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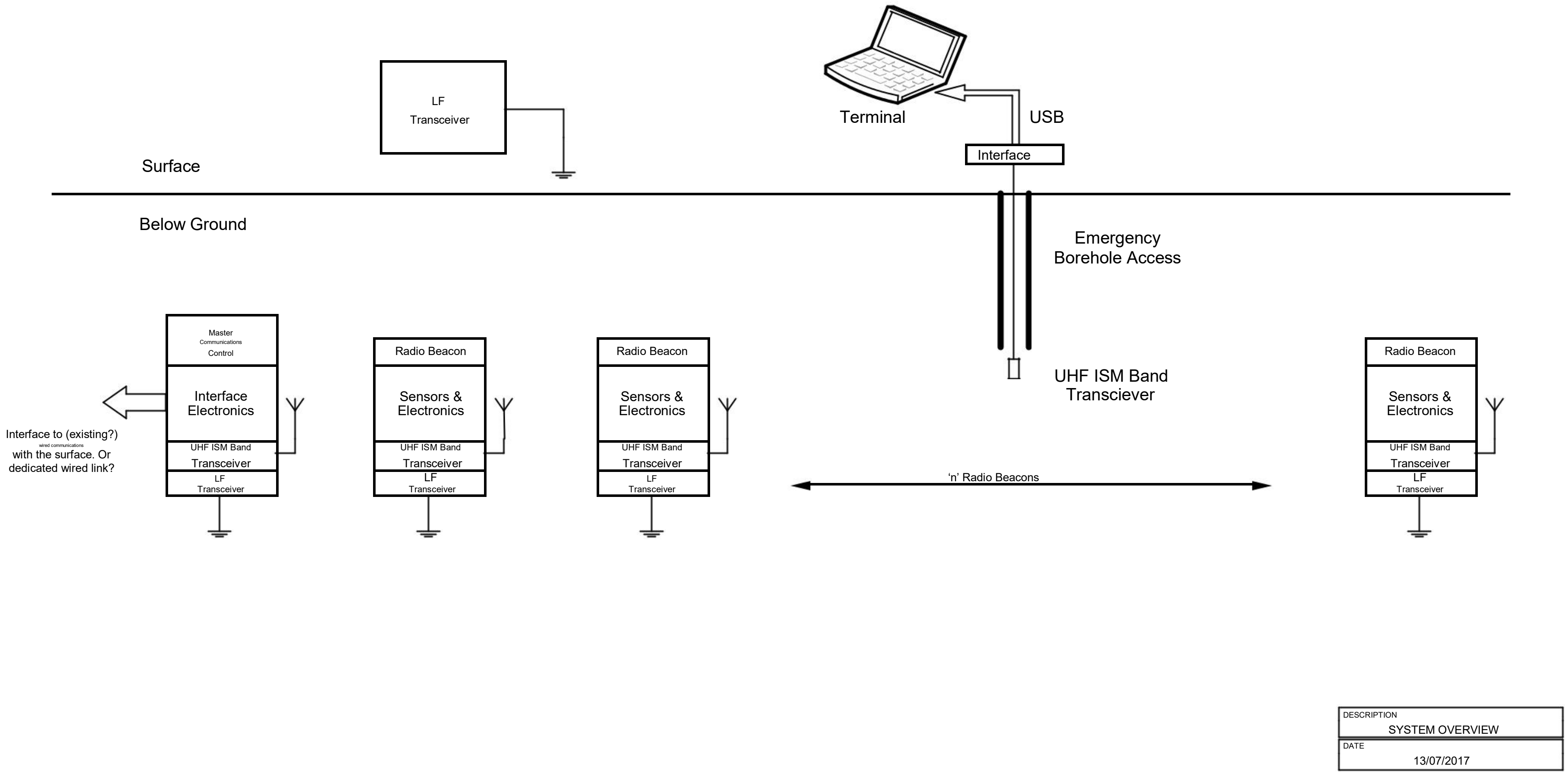

Figure 1. System overview

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2 Proposed System Concept

An overview of the system is presented in the figure above, underground it comprises a series of radio beacons which communicate normally using short range e.g. line of sight, UHF radio. It is proposed that the radio beacon design could include sensors: Carbon Monoxide, Carbon Dioxide, Methane and Oxygen being the most important, and that data from these sensors could be transmitted back to the surface via the UHF radio providing additional functionality to the system and value for the operator.

2.1 Radio Communications

It is proposed that the radio beacon design includes transceivers for both short range UHF as well as for low frequency through the earth communications. Other than to note it's inclusion

and discuss how it might be integrated into the communications protocol, the technical details of the UHF radio will not be examined in detail because the operation of such radio links are already well known, the key point being that underground, operation between transmitter and receiver is restricted to more or less line of sight.

Of particular interest are the aspects of LF through the earth communications and the technical feasibility of utilising this type of communications in the design of a radio beacon.

2.2 Low Frequency through the Earth Communications

Using low frequency as a method of radio propagation has been known and experimented with since at least 1900, it was used during the First World War and has more recently been developed as a means of communications for cave rescue applications (the "Hey-Phone" developed by John Hey).

The Hey Phone, which allows two-way voice communication between the surface and underground is an excellent starting point for any studies into LF TTE radio communications because all the deign information is in the public domain and is freely available on the internet. The information regarding the use of ground spikes as a means of coupling signals into the ground is particularly useful.

Low frequency communications are already being used in the mining industry, at least three companies are offering products, the PED system from Mine Site Technologies, and the Rescue Dog system from mineARC systems. The PED system offers only one-way communications between a surface station and any number of underground receiver devices and works by displaying text type messages on the receiving device, selected from a list of pre-defined messages. The Rescue Dog system offers two-way communications between a single surface station and up to sixteen underground transceivers, again using pre-defined messages. Neither of these two systems enable voice communications which is more difficult to achieve reliably, the range is maximised when messages consist of data only.

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Lockheed Martin have also developed a low frequency TTE communications system, "MagneLink", which can transmit both voice and data, although the range is reduced for voice communications to 450m compared to the range for data only which is 600m. Published information about this system mentions magnetic waves (i.e. induction) as the communications method rather than radio waves, and this is backed up by the antenna arrangements which are described as comprising a wire loop underground and an "inductor" on the surface.

Low frequency TTE communications is also being actively researched and experimented with worldwide by amateur radio enthusiasts and much useful information can be found on the internet regarding their work.

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2.3 Antenna Design for Low Frequency

Antenna design is an extremely important aspect of any radio system and low frequency radio communications are no exception. One of the problems presented by low frequencies is that theoretically ideal antennas that are fractions of a wavelength (e.g. half-wave, quarter-wave etc.) as is common at higher frequencies, would end up being inordinately long at low frequencies. Fortunately it has been shown by experiment that there are two more practical options: the loop antenna, and an antenna formed by inserting metal rods into the ground (earth antenna).

2.3.1 Loop Antenna

The approach to loop antenna design for low frequency has been very much experimental, but there are some general points common to most articles appearing in the literature, essentially that the larger the diameter, the higher the number of turns and the higher the current flowing through the antenna, the better. Following this, loop antennas can still be quite physically large, e.g. suggested loop antenna designs for the Hey Phone are approximately 1m square.

2.3.2 Earth Antenna

This type of antenna is simply formed by inserting metal rods into the ground and connecting them to the transceiver using lengths of wire, as shown below. In general, the range achievable in through the earth communications is increased with this type of antenna compared to the loop type, but there are several aspects that need to be considered to optimise performance. Firstly, the distance between the rods largely determines the achievable range, the greater the distance, the greater the range, some experimenters have had good success with large separation distances (e.g. 1500m) between the rods. Secondly, it is documented that more than one rod at each end point, connected radially, can also be beneficial. Thirdly, if the soil surrounding the rods is dampened with a salt water solution, this can also enhance performance, the important point being that the resistance, or impedance between the rods is reduced.

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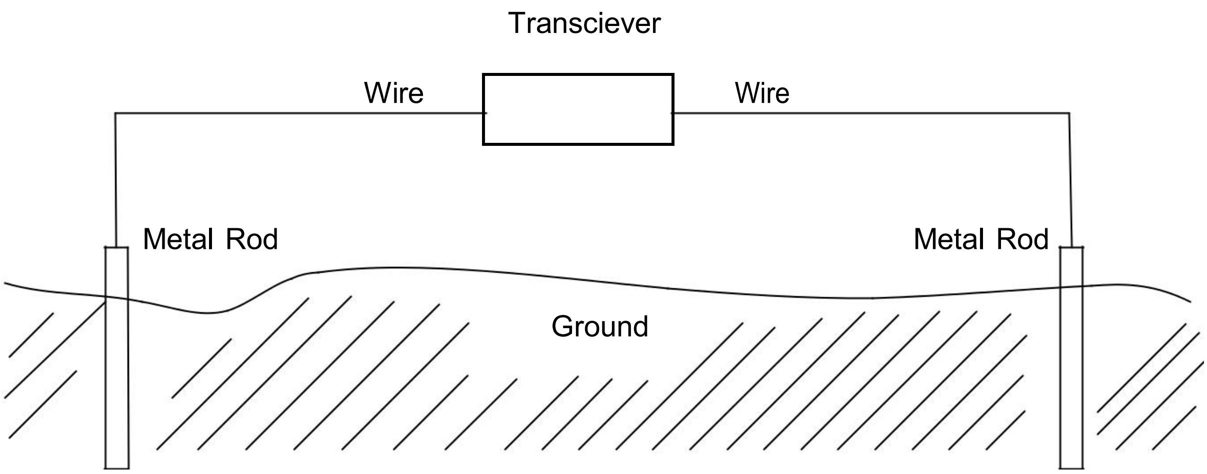

Figure 2. General earth antenna arrangement

2.4 Underground-Surface Link

The focus of the discussion in this report has set out to address the key points of successfully achieving an underground network of radio beacons, but this would not be much use without a surface link. For normal operations when the beacons are being used for example to transmit sensor data, it would be relatively straightforward to arrange a link to the surface, perhaps by interfacing with existing wired communications links, or by installation of a dedicated wired link, this could be an option and would greatly simplify the development of the system.

If the link to the surface becomes inoperative due to an accident, explosion, rock fall etc. a possibility is to re-establish communications with the underground radio beacon network via a bore hole, by lowering a UHF transceiver into the underground workings and use a portable terminal (laptop plus interface) for communications. If either no bore holes existed or existing bore holes could not be used for some reason, one could be created.

Although it would certainly be feasible (and systems already exist) to enable the underground to surface link to be via low frequency TTE radio, the additional work to develop a transceiver system to provide this capability would be significant, due to the increased range that is likely to be required when compared to the radio beacons themselves, there are also implications for the design of the radio beacons if it is a requirement to implement the underground surface link using low frequency TTE radio, this is discussed in more detail in the conclusions section.

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2.5 Links between Tunnels or Levels

In a mine with multiple levels, links between lower levels may be better achieved using low frequency TTE communications rather than wired links, as accidental damage to wired links here, might not be bypassed as easily as they can be on an upper level with potential access to the surface via bore holes. This situation, showing a shaft-based mine is illustrated in the figure below. Providing robust links between levels, or linking between different tunnels and hence to the surface is perhaps the most challenging aspect of a wider network comprising radio beacons.

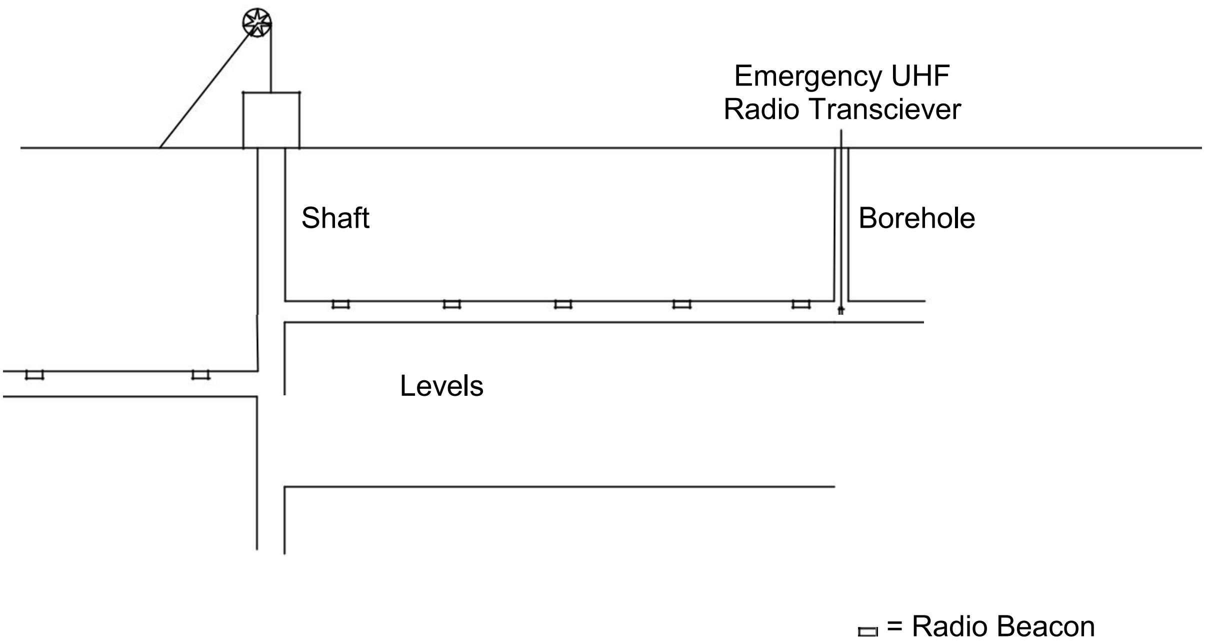

Figure 3. Mine requiring multi-level links

2.6 Wireless Protocol

One of the objectives of the radio beacon network is that communications from the surface to all remaining functioning beacons should not be interrupted if one or perhaps several are lost due to an accident etc. A fundamental requirement to enable this is that each beacon needs to have a unique identification code i.e. “address”, and ideally the addresses would be allocated in a sequential manner for each beacon position along a tunnel for example, as in the figure below:

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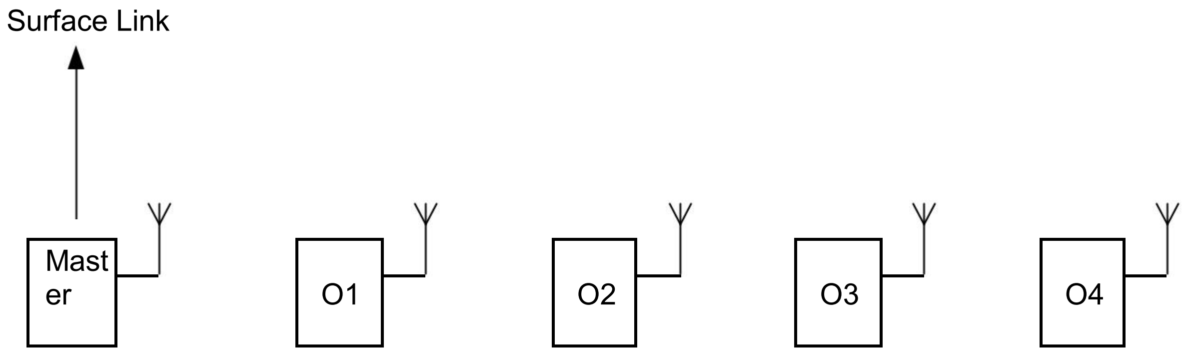

Figure 4. Sequential Addresses

In the topology illustrated, the communication strategy is operating as a chain due to the range limitation of UHF ISM band radio, the first beacon or unit in the chain, labelled "master" is only communicating directly with its nearest neighbour, address 01, and data from all other units is passed down the chain to it. The master would maintain a list of all unit addresses present in the system and could send a warning message to the surface if data from any of the addresses is not present. In order to receive and forward data, each beacon will need to know (initially learn) the addresses of its immediate neighbours, and in the event that a particular beacon is lost the beacons on either side can switch to low frequency mode and attempt to re-establish communications across the "gap".

The amount of data transmitted (data packet size) could be reduced if the network detects that particular beacons may be lost and the radio mode switches to low frequency. It could be that the sensor data that may be transmitted under normal conditions is not sent under these conditions to allow emergency messages instead, but the limiting factor will be the data rates achievable whilst maintaining reliable low frequency communications, which will need to be established by experimentation, given the antenna constraints etc.

2.7 Power Supply

It is yet to be confirmed whether a permanent power supply might be available for the beacon network underground. The beacons themselves will be fitted with a battery or batteries and a requirement has been established that they are to have a minimum service life of 5 years. If no permanent power supply is available, the batteries would either need to have a large capacity (and likely be physically of large size), or the proposal to include sensor data would need to be compromised in terms of update rate etc.

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3 Conclusion

Fundamentally, there is plenty of evidence that low frequency TTE communications works, and is in fact already being used in the mining environment. Given this, the viability of the proposed radio beacon and its use as a repeater in a wider underground communications network consisting of many such beacons hinges more on practical considerations.

The spacing of the beacons is a key consideration constrained on one hand by economics, i.e. more beacons are required if the spacing is short along with increased installation and maintenance costs, and on the other hand by the limitations in range imposed by maintaining reliable radio communications.

If the radio beacon, as proposed, is to use UHF low power radio to transmit sensor data back to the surface, the range that this would work over (nominal line of sight is anticipated) would become the limiting factor in determining the beacon separation distance, some experimental work is recommended to determine in reality what this would be. At present it is assumed that the range of the UHF radio underground will be significantly less that the range that can be achieved by the low frequency TTE radio.

Based on studies of the existing literature, it would appear that the best performance achievable for the low frequency radio would be obtained using the “Earth Antenna” type of approach, although in this case the rods will be inserted into rock rather than soil. Experimentation will need to be carried out to find the best arrangement of rods, whether multiple rods are better than single rods, the separation distances between rods that may be necessary to achieve reasonable communications range, and whether there’s a suitably conductive material that can be used to line the bore holes and act as a conductive medium between the rods and the rock. It is anticipated that the separation distance between rods is realistically going to need to be several metres, or even tens of meters in order to achieve sufficient range.

Testing will also need to be carried out to determine the best orientation of the rods relative to the axis of the tunnel, although it is anticipated that the best results between beacons are more likely to be achieved when the rods are arranged in an orthogonal orientation to the tunnel axis i.e. if the beacons are attached to the tunnel roof roughly on the centreline, the rods would be inserted horizontally into the tunnel walls on either side of the beacon. The disadvantage of this arrangement is that the separation between the rods is then dictated by the width of the tunnel, unless it was very wide (e.g. greater than 10m), in which case the rods could be inserted in the roof to either side, see fig below.

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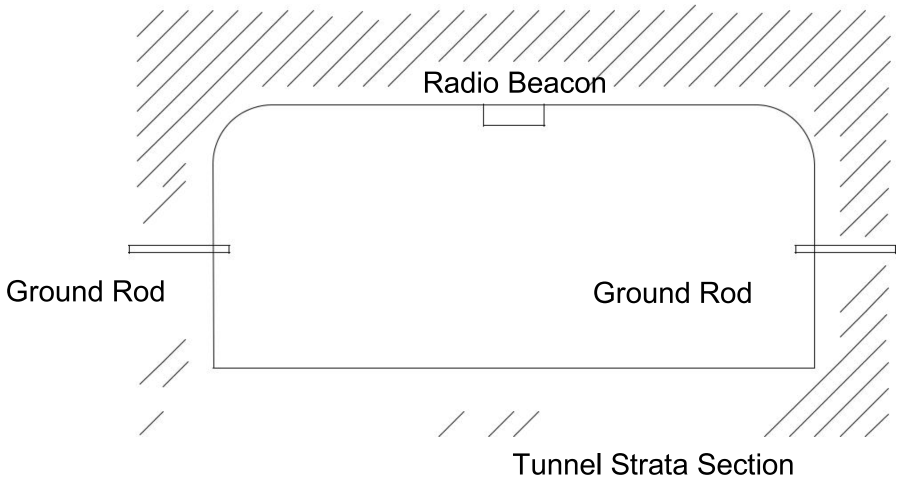

Figure 5. Earth antenna in a tunnel with horizontal ground rods

The object of the low frequency radio is to provide back-up communications between beacons when the UHF radio is not working, due to rock fall, or perhaps when one or more beacons might have been damaged by explosion etc., therefore, a sufficient range for the low frequency radio must be at least twice the distance between beacons, but the greater the range the better.

As mentioned in the section above regarding the underground to surface link, this could be achieved via low frequency TTE radio communications, but there are possible implications for the radio beacons themselves depending on the distance through-ground that the underground to surface link must penetrate.

Although space is not particularly limited in the environment where they will be used, the assumption has been made that the physical size of the radio beacons should not be overly large. The reason for this is that it is envisaged the radio beacons will most likely be mounted to the roof of the tunnel, therefore smaller and lighter is better, and also the associated intrinsically safe enclosure will be of lower cost if the unit is smaller in size.

Potentially there are two alternative approaches for realising an underground to surface link using low frequency TTE radio, one option would require the development of a high power surface based transceiver and a matching underground receiver which would also have the capability of acting as a “master station” for managing the communications to the radio beacon network. Although this approach is feasible, it is vulnerable in that the underground master unit is a critical component and any failure of that unit due to an accident, explosion etc. would sever the link between the surface and the radio beacon network, although communications could be re-established via a borehole as mentioned previously.

An alternative option is to use the surface transceiver as the master station capable of communicating directly with any of the underground radio beacons, the disadvantage with this approach is that the low frequency radio in every beacon, will then need to be sufficiently powerful and have sufficient antenna provision for direct communications with the surface, the size and cost implications of this could be prohibitive, also this would appear to make the requirement for the short range UHF radio unnecessary, because each beacon could transmit

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it's data to the surface in isolation. The two different approaches are illustrated in figure below:

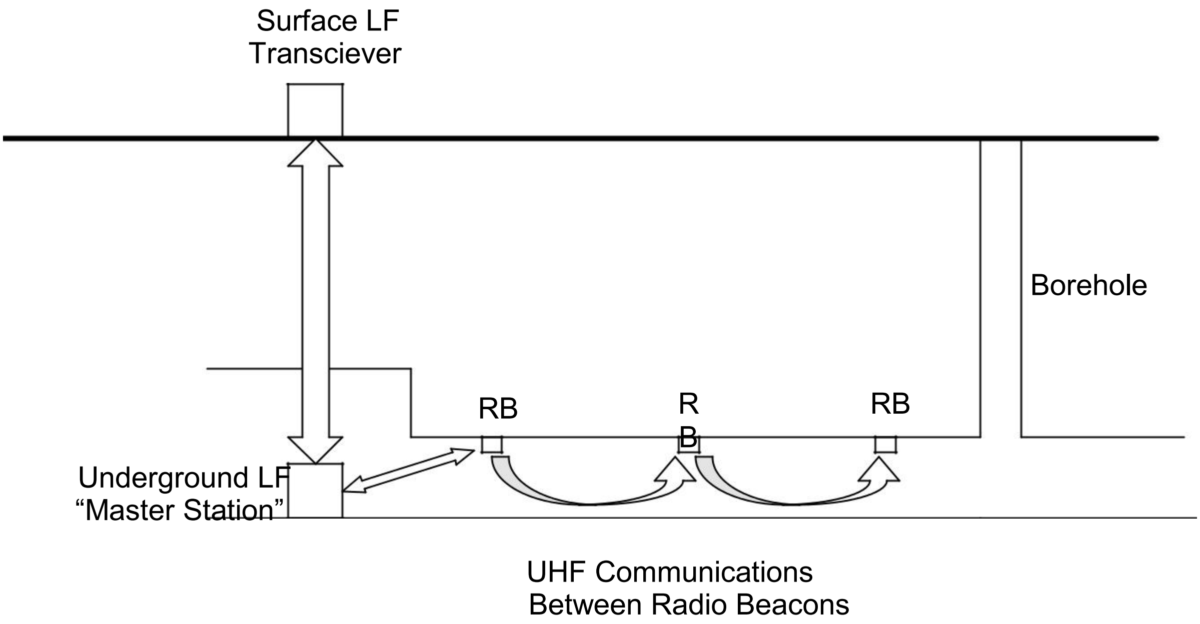

Figure 6. Master station topology with slave beacons

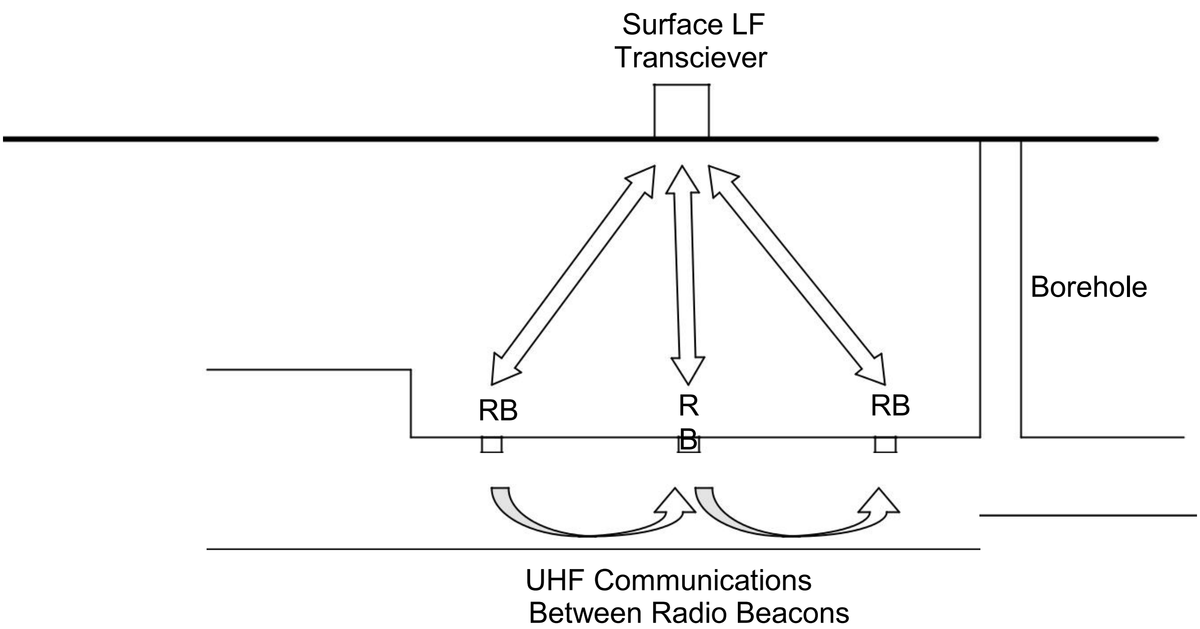

Figure 7. Surface transceiver communicating directly

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4 Recommendation for Further Work

Based on the findings in this initial feasibility study, we can make some recommendations about the likely stages required to develop a prototype radio beacon system.

4.1 UHF Radio Performance Underground

The range capability of low power ISM band radio modules using relatively compact antennas in underground tunnels needs to be determined, as this parameter dictates the maximum spacing between radio beacons. Readily available off-the-shelf modules or development kits can be used, and it should be straightforward to find a suitable site (tunnel or disused mine etc.) for such tests.

4.2 Initial Low Frequency Testing

Testing needs to be carried out on the earth antenna aspects of low frequency TTE radio communications. Although it is the antenna arrangements underground, in a tunnel, that are of interest, initially, some above-ground testing could be carried out because inserting the ground rods into soil on the surface represents the best scenario for maximising range, the assumption is that the range will be less underground, also such above ground testing is low cost, straightforward to arrange and will provide much useful information for the work that follows.

For these initial low frequency tests, the specific design of the transmitter/receiver apparatus, modulation scheme etc. is not of particular concern and can be relatively simple, the aim being to simply transfer low frequency energy into the antenna. If above ground testing can demonstrate that a reasonable range is achievable, ideally at least twice the distance of the UHF radio range, with earth antenna rods approximately 10m apart, underground testing can commence.

Once it is known that the range is achievable given the space and orientation constraints on the antenna, it would also be useful to carry out some tests regarding the ability of the low frequency radio to transmit/receive data, and what the achievable data rates might be.

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4.3 Underground Low Frequency Testing

Once an experimental low frequency transceiver apparatus has been constructed and tested above ground, underground testing can be conducted to determine the best range that can be achieved with different earth antenna arrangements. Because these tests necessitate the boring of holes into the surrounding rock for the placement of earth antenna rods, an underground test site where such equipment and qualified personnel to operate it are available is going to be required, ideally a disused mine used as a training or test facility where the tunnel width is not too narrow.

It is recommended that initial underground tests should start with earth antenna rods positioned either side of the tunnel at both the transmitter and receiver stations, as discussed elsewhere in this report. Testing could start with single rods at either side, but multiple rod arrangements should also be tested.

4.4 Radio Beacon Design and Development

Following the radio testing to determine the optimum antenna arrangement for the low frequency TTE communications, design work on a prototype radio beacon can commence which would include LF and UHF radio sections, control electronics, battery and basic sensor(s) e.g. gas. Although the design for a suitable enclosure (taking into account the requirements for robustness and intrinsic safety) for the radio beacon could be commenced in parallel with the electronics design work, the final housing design will not be required for prototype testing, which could use a readily available off-the-shelf enclosure, it is the functionality and performance of the radio aspects which are important at this stage.

A small number of prototype radio beacons can be constructed and tested, particularly the ability of the system to continue providing a communications link using the low frequency TTE facility if the UHF fails in one of the beacons (i.e. radio beacon is switched off). Again, initial tests of this functionality can be carried out above ground.

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5 Review of Gas Sensor Technology

Since the initial draft of this report was sent to SIMTARS for review, the significance of gas sensing has been highlighted, in fact the use of the radio networks discussed in the sections of the report above, for retrieving gas data is perhaps of more importance than messaging. One of the existing methods for obtaining data on the underground gas levels at the surface is by means of a “tube bundle” system where gas levels are sampled at points within the mine using fixed tubes which are connected to instrumentation on the surface. The sample points within such a system can be up to 12km from the surface instrumentation, so delays in obtaining samples are an inherent disadvantage with this technology.

Although the availability of reliable real time gas information during an emergency situation is of key interest, the ability of an underground radio network to provide this information at all times, not only during emergencies, would be a highly desirable feature for mining companies who would be more willing to invest in such a system.

To obtain gas data via the underground radio network, suitable gas sensors are required and SIMTARS have specified that the following gases are of primary interest:

Gas	Typical Range (Real Time)	Typical Range (Tube Bundle)
CO (Carbon Monoxide)	50 ppm	1000 ppm
CH4 (Methane)	5%	100%
CO2 (Carbon Dioxide)	2%	50%
O2 (Oxygen)	25%	25%

For integration in the radio networks being discussed in the first part of this report, the single most important sensor characteristic is low power consumption as the power source will be battery technology. Next in importance is ease of use in this particular (fixed) application and also a long service life is highly desirable to reduce the cost and frequency of ongoing maintenance. From a technical point of view the ideal sensor for the application in question would have very low power requirements, be highly accurate, easy to use and have a long service life, additionally from a commercial perspective low or lower cost is desirable as many sensors could potentially be deployed in a single installation. Unfortunately at this time of writing such a sensor does not commercially exist for any of the gases of concerned, or indeed for any gas.

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5.1 Commercially Available Sensor Technology

Major gas sensor technologies are listed in the table below along with comments regarding the suitability of a particular sensor technology in general terms for use in the type of sensor network being discussed in this report. Only the first four in the table can be considered realistic candidates, although as discussed below some modern technology e.g. MEM's is being utilized to enhance the characteristics of the older technology [7].

Sensor Type	Suitability
Catalytic (Pellet Resistor or Pellistor)	High power consumption (225mW typical), not intrinsically safe, requires oxygen to be present to work, requiring frequent calibration and typical maximum operating life 3-5 years.
Infrared (Non Dispersive Infra-Red)	Low power consumption (Less than 100mW for incandescent type sensor, less than 5mW for photodiode type). Operating life 10 years typical.
Electrochemical Cell	Very low power consumption (0.5mW). Not straightforward in use, minimum gas flow rates across the sensor can be required, cell may require to be short-circuited when not measuring, otherwise there can be a long start-up delay of several hours. Operating life, typically 5 to 7 years.
Semiconductor (Solid State) Metal Oxide Film	High power consumption (300mW typical), easy to use, robust Operating life 10 years or more.
Fibre Optic	Requires the installation of a fibre optic network, does not lend itself to use in discrete sensors.
Laser (Tuneable Laser Absorption Spectroscopy)	Not available as a discrete sensor. Suitable for analytic type gas measurements.
Flame Ionization	Not available as a discrete sensor. Suitable for analytic type gas measurements and not intrinsically safe.

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Photo Ionization	Not available as a discrete sensor. Suitable for analytic type gas measurements.
Thermal Conductivity	Similar to Catalytic Pellistor sensing but less selective and less sensitive.
Nanotechnology (MEMS – Micro-Electro Mechanical Systems, SAW etc.)	This technology has much potential for realising sensors close to the ideal, but commercially available devices have yet to be realised. Some specialist sensors of this type are available for detecting nerve gas agents [13].

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5.2 Sensor Technology

In terms of implementing an underground sensor network within a coal mine, the solid state semiconductor type sensor would initially appear to offer many advantages including robustness, ease of use and long service life, but the typically higher power consumption of these devices is a considerable disadvantage in a battery powered application making them a less than ideal candidate.

In general the same argument regarding power consumption can be applied to catalytic bead (pellistor) sensor types, although there are other disadvantages that could rule them out even if the power consumption was lower e.g. intrinsic safety [13].

One of the sensor technologies from the table above that appears to offer many of the characteristics being sought is infrared (NDIR), these have typically low power consumption, long service life and are straightforward to use [12], [22]. Cost may be a factor, but infrared type sensors are replacing the catalytic bead in many applications which is tending to drive the cost of this technology down. One of the common criticisms of infrared sensors compared to catalytic bead types is that there are some explosive gases that are not detected e.g. hydrogen, it is not clear yet if this is a concern for this application.

Electrochemical type sensors certainly offer very low power consumption, but in general their use is not straightforward, there could be flow-rate related problems, and the lifetime of these types of sensor would be typically be between 5 and 7 years, certainly less than NDIR types.

The comments in the preceding paragraphs and table above are a generalisation of the advantages and disadvantages of the different types that have been available to date, but technological advances are changing the situation. For example, an interesting sensor manufactured by SGX Sensortech uses MEM's technology to enhance the performance of the traditional catalytic (pellistor type) sensor, mitigating some of the disadvantages found with traditional types. The resulting device (VQ548MP) is marketed for mining applications, it is primarily a Methane sensor (up to 5% volume in air) but can also detect some other flammable gases [7]. The device has low power consumption (< 50mA at 3V) and can operate in a sampling type application where the sensor is powered periodically for a short time, but the majority of the time is in a low power shut-down mode.

It is important to note that there is no single sensor technology that can be used to detect all four of the gases in the list above [6], [8], [9] e.g. a catalytic bead sensor detects only flammable gases (because they burn on contact with the heated catalytic pellet), so cannot be used to detect carbon dioxide (CO_2) for example. From this brief review of the available sensor technologies it would appear that infrared (NDIR) sensors are commonly used for carbon dioxide while oxygen (O_2) sensors are commonly of the electrochemical type [14], [15], [19].

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5.3 Example Gas Sensor Specifications

Having identified that infrared type sensors offer advantages for explosive gas sensing, and that perhaps electrochemical is the best currently available type for poisonous gas & oxygen sensing in this application, it is useful to select some specific sensors that are commercially available and examine their specifications, particularly regarding power consumption as this will provide an indication of the battery capacity that may be required.

For the gases in question, SGX Sensortech have recommended the following sensors from their range:

Sensor	Gas & Range	Notes
DS-0229-INIR [16]	Methane (CH4) 4% - 100% volume Carbon Dioxide (CO2) 0% - 5% volume	Integrated Infra-red (IR) sensor Power consumption: 32mA @ 3.3V Can be used in wake-up-sleep applications but there is a 45s warm-up time. Lifetime, typically 10 years.
DS-0138-SGX-4CO-V2 [18], [20], [21]	Carbon Monoxide (CO) 0 – 1000 ppm	Electrochemical sensor Power consumption of the sensor itself is negligible. A small bias voltage is required but the interface circuit will consume more power than the sensor, estimated to be less than 10mA. Lifetime, typically 5 years.
DS-0141-SGX-4DT-V3 [17], [20], [21]	Carbon Monoxide (CO) 0 – 500 ppm Hydrogen Sulphide (H2S) 0 – 200 ppm	Electrochemical sensor Power consumption of the sensor itself is negligible. A small bias voltage is required but the interface circuit will consume more power than the sensor, estimated to be less than 10mA. Lifetime, typically 5 years.
A1A-EC410 [19], [20], [21]	Oxygen (O2) 0 – 30%	Electrochemical sensor Power consumption of the sensor itself is negligible. A small bias voltage is required but the interface circuit will consume more power than the sensor, estimated to be

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		less than 10mA. Lifetime, typically 5 years.

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5.4 Power Requirements & Estimated Battery Life

Viewing the performance data for the sensors in the table above, it would not seem unreasonable to estimate that all of the sensors for detecting the four specified gases together would not consume more than 50mA from a 3.3V power rail.

Taking the application as a whole, there will be power required for radio communications, power for the control electronics and power for the sensors. Additionally there may also be power needed to manage gas sampling and dust removal e.g. a small motor driven fan to draw an air sample into a chamber for dust removal prior to being passed over the sensors, but the necessity for this and how much power it may consume is not known at the present time.

For the radio communications, the high frequency short range ISM band radio used to communicate with other nodes in the network is likely to have very low power consumption (10 years battery life from a single CR2032 coin cell is not uncommon), as are the control electronics (microprocessor).

The low frequency through the earth communications are likely to require significant power but the assumption is that not every node in the network would have LF TTE capability.

An alkaline D cell has a capacity in the region of 15,000 mA/Hours, and there are buck/boost regulators available that are designed to work with 2 series connected D cells to generate a 3.3V voltage rail. A switching regulator of this type will be essential to extract as much power as possible from the batteries as their capacity declines.

Using the 50mA as a power consumption figure, a battery with a capacity of 15,000 mA/Hours results in a battery life of 300 hours, or 18,000 minutes of continuous use. If the sensing unit was only powered on for a total time of 10 minutes a day (e.g. unit would be powered on for a 1 minute period 10 times a day) this would equate to 3,650 minutes a year and a battery life of approximately 5 years.

These figures provide a starting point and an approximation of what might be achievable, four D cells instead of 2 theoretically would provide 10 years battery life, which is the shelf life of alkaline battery technology. Also there may be sensors from other manufacturers which have even lower power requirements, e.g. the MinIR CO2 sensor from GSS Gas Sensing Solutions [22], which although has a peak current requirement of 32mA at 3.3V, it's power on warm-up time is less than 10s, reducing the overall time the sensor needs to be on for.

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6 Gas Sensors Summary

Although there is much research being carried out into new and novel gas sensing technology, to date, very little has found its way into commercially available mainstream products, largely due to commercial reasons of the cost of bringing to market sensors based on new technologies, compared to the demand for them [11]. The basic sensing technologies as presented in the table above have been and remain the preferred methods for gas sensing, although these existing methods are being subjected to continual improvements which is negating some of the historical disadvantages [7].

The conclusion is that although there are no new sensor types that offer an ideal solution for the application in question, there are sensors available based on existing types that could be used, and that the aim of creating a battery powered wireless sensor node (beacon) with a battery life of between 5 and 10 years is achievable provided the gas sampling interval can be greater than an hour e.g. a sample every 2 hours. It may well be that this can be improved upon when the overall power requirements are more fully understood.

7 Modular System

In researching the material for this report and in discussions with colleagues regarding the best way to develop the hardware for the system being considered, it is our opinion that a modular approach would have many benefits, as it is clear that every mine installation is likely to be different. Also if service replaceable items such as batteries are manufactured as modules, replacement is easier and costs are minimised.

For example the system could comprise the following modules:

Sensor module (All Sensors) Sensor module (IR Sensors)*

Sensor module (Electrochemical Sensors)* Battery module

Control module (permanently installed) UHF (ISM Band) radio module

LF through the earth transceiver module

*Due to the different expected life times of these sensors it could be an advantage to house them in separate modules.

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