EXPLOSION TESTING OF TECRETE MINE SEALS

Verne S Mutton
Mining Engineer
Tecrete Industries Pty Ltd

Michael D. Downs
Principal Development Engineer for UG Mining
BHP Coal Pty Ltd

SYNOPSIS

The paper describes the background circumstances that led to the implementation of a series of explosion (overpressure) tests on seal and stopping structures at the Lake Lynn Experimental Mine facility near Pittsburgh, Pennsylvania, USA. Methods of seal and stopping construction, test instrumentation and test methodology are described, with the results for each test discussed.

The results obtained indicate the completion of a successful programme which has clarified the practical requirements entailed in recent Regulatory requirements introduced in Queensland, Australia, as that relates to ventilation devices utilised in underground coal mines. Inherent in the results is the demonstrated ability to design and build seals and stoppings that can meet overpressure ratings in the range of 14 kPa (2 psi) to 455 kPa (66 psi).

INTRODUCTION

During the normal course of underground coal mining, it sometimes becomes necessary to install permanent seals to isolate abandoned or worked out areas of the mine. This practice eliminates the need to ventilate those areas. Seals may also be used to isolate fire zones or areas susceptible to spontaneous combustion . To effectively isolate areas within a mine, a seal should:

- control the gas/air exchanges between the sealed and open areas to prevent toxic and / or flammable gases from entering active workings and oxygen from entering the sealed areas;
- be capable of preventing an explosion of designated intensity initiated on one side from propagating to the other side; and
- continue its intended function when subjected to fire test incorporating a specific (A.S 1530.4 - 1990) time- temperature heat input(1)

Previous research(2) indicates that it would be unlikely for overpressures exceeding 138 kPa to occur very far from the explosion origin provided that the area on either side of the seal contained sufficient incombustible matter and minimal coal dust accumulations. The provision of incombustible matter through the medium of stonedust mixed through coal dust on the roof, ribs and floor and recognising the need to include the dilution of coal "float dust", is an essential caveat in limiting explosion overpressures to 138 kPa.

This pressure rating basically relates to the intensity likely due to a "methane gas only" explosion, ie an explosion that does not include a coal dust fuel source, as such additional fuel can create explosions of significantly greater intensity than 138 kPa.

On August 11th, 1994 11 miners and 1 contractor were killed when a methane-air mixture ignited behind an area that had been sealed for 22 hours(5) at BHP Australia Coal Pty Ltd. Moura No. 2 coal mine located in Queensland. Spontaneous combustion within the sealed area has been determined as the cause of the ignition.

A potential hazard can eventuate when sealing a section of workings in underground coal mines that have a presence of methane gas and an incidence of spontaneous combustion . In this situation there is a possibility that in a period typically up to and within 48 hours from sealing, the atmosphere behind the seals could pass through the lower explosive range for methane-air mixtures, with potentially catastrophic effect if there is an ignition source such as spontaneous combustion.

As a result of this incident, BHP Coal and Tecrete Industries Pty Ltd jointly funded a research effort to investigate the explosion resistance of four seals and two stopping designs. A particular requirement by BHP Coal for this test program was to test a seal design within 24 hours of construction, designed to withstand an explosion producing a horizontal overpressure of 138 kPa [20 psi].

In parallel with this undertaking, the Coal Industry formed a number of Task Groups as recommended by the Warden's Inquiry report on the Moura Mine explosion. Task Group 5 was formed from Industry personnel representing the Queensland Mining Council (Mining Companies), the mining unions (CFMEU representative) and the Department of Minerals and Energy (Inspectorate), and was charged with investigating the issues of mine inertisation and reassessing the regulatory provisions for explosion resistant seals.

Each seal and stopping design for the test programme was ultimately targeted to meet the overpressure ratings being developed for underground ventilation devices by Task Group 5. These ratings became the Queensland Department of Mines and Energy " Approved Standard for Ventilation Control Devices" published in December, 1996. This standard does not address the structural design or material requirements for seals and stoppings.

In 1993, Tecrete Industries introduced a new system of seal construction, namely Meshblock (see later discussion for a description of this concept for construction), which made it possible to construct a monolithic structure on a continuous basis in Australian underground coal mines. In 1994, an explosion seal made with Meshblocks of 250 mm thickness was constructed at the Workcover Authority Explosion gallery, west of Sydney. This seal was constructed within a 2.7 metre diameter concrete tunnel and withstood eight methane gas explosions in the overpressure range 85 to 500 kPa(3). Previous research(4) has shown that the stiffness of the immediate surrounding roadway material and the fixation of the seal at this interface are the most important influences in the ability to resist horizontal overpressures. This seal was fully instrumented with time related pressure and displacement transducers, enabling a predictive design tool to be developed using Finite Element Analysis.

The research work at Workcover Authority provided the model for the designs for construction, instrumentation and explosion testing of Tecrete ventilation seal designs at the Lake Lynn Experimental Mine, Pittsburgh Research Centre (PRC), Pennsylvania (PA), starting in February, 1997.

Seal evaluation worldwide using controlled explosions has been based on visual observations of damage and leakage across the seal over a range of air pressure differentials. The tests performed by Tecrete at Lake Lynn where of a significantly different approach, in that each seal was fully instrumented with electrical transducers to measure the pressure and displacement effect of the explosion on the seal. The rationale behind the instrumentation used is based on the premise that the resistance of a seal to horizontal overpressures can be predicted from the time related measurements of displacement, static pressure and acceleration. The dynamic response of each structure during this test program, was measured by electrical transducers mounted on the seals on the non explosion side.

A series of controlled explosions, each increasing in magnitude, provided data that will enable the building of a predictive design tool for explosion rated seals and stoppings. Because one of the seal sites was mined out to about three metres of height, this test program has provided information on seal designs installed in roadway sizes that would be typically found in Australia.

This paper outlines installation methods, leakage test results, explosion test results and some of the time related measurements of seal response that provide input to further structural analysis being undertaken by Dr. F. Barzegar of the University of New South Wales (Department of Civil Engineering). Some initial considerations of structural behaviour are briefly discussed in Appendix 1.

EXPERIMENTAL PROCEDURES

Mine Explosion Tests

Explosion and air leakage tests were conducted on all stopping and seal designs at the Lake Lynn Laboratory near Fairchance, 80 kilometres south-east of Pittsburgh. One of the world's foremost facilities, Lake Lynn was chosen because of the ability to simultaneously test and monitor several seal designs in either a Longwall or Room and Pillar multi-entry mine layout.

Figure 1 (6) shows the immediate layout of the three drifts A,B and C which are connected by seven cross-cuts. E drift is isolated from the other drifts by a 100 psi rated explosion proof bulkhead which is hydraulically operated, altering the mine layout. The dimensions of the drifts and cross- cuts range from 5.6 to 6.0 metres wide and 2 to 2.25 metre high with the exception of cross-cut 3 between C and B drifts which was mined at 2.8 metre height to more closely resemble an Australian coal mine roadway of cross-sectional area 16.2 m^2.

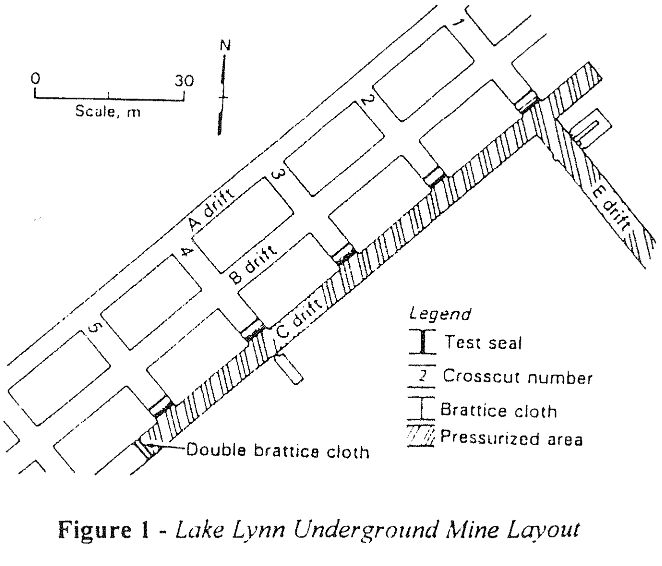

Figure 1 - *Lake Lynn Underground Mine Layout*

For the first of three main explosions, nearly 19 m^3 of natural gas was pumped into the closed end of C drift, with a flameproof electric fan used to circulate the gas-air mixture. The mixture is contained by a plastic diaphragm within the first 14.3 metres of the entry. The desired concentration of 9 % methane was sampled and measured by an on line infra-red analyser, and also checked by additional samples drawn through a tube-bundle system for later analysis at Pittsburgh Research Centre. Three electric matches located at the closed end of the entry ignited the gas-air mixture, initiated from the surface control room. Barrels filled with water located behind the plastic diaphragm acted as turbulence generators when impacted by the explosion pulse.

The first explosion to test the seal designs was a standard LLEM test generating a 138 kPa overpressure pulse. This is a standard test for gaining Mines Safety and Health Administration approval (MSHA) for any seal design in the United States. The first test had to be conducted at 138 kPa in order to meet the test 24 hour requirement on the rapid setting 2.8 metre high seal. The second and third explosions were enhanced by a loading of 80 and 160 kg of coal dust respectively, representing a dust concentration of 100 and 200 mg/L within a 64 metre length of C drift. (For explosions generating greater overpressure than 138 kPa, coal dust was located outbye the ignition zone on suspended polystyrene shelves located at three metre intervals from rib to rib.)

The second and third explosion gas and dust loadings were designed to generate overpressures of approximately 240 kPa (35 psi) and over 345 kPa (50 psi) respectively. It was accepted that during the successive and increased strength explosions, some seal designs would not survive.

Evaluation of the lower-strength stopping design required explosions with pressure pulses of less than 70 kPa (10 psi). Two further explosions, tests # 4 and 5 (LLEM # 350 and 351), were conducted on a second, light-duty stopping design installed in cross-cut 3. The natural gas length was reduced to 8.2 metres from the closed end of C drift creating a gas ignition zone of 115 m^3. Test #4 with 8.2 m^3 of natural gas, generated an overpressure at the cross-cut 3 stopping of approximately 21 kPa (3 psi). Test #5, with 9 m^3 of natural gas produced an overpressure of approximately 35 kPa (5 psi). Note that the stopping in cross-cut 3 was located in a 2.1 metre high section and not in the 3 metre zone.

INSTRUMENTATION

Successful instrumentation and measurement of the dynamic response of the explosion seal tested at Work Cover Authority, NSW, provided the expertise to design and install an instrumentation program for LLEM. The resulting test program was considered to provide the minimum number of electrical transducers per seal/stopping design necessary for building a reliable structural response model. Of particular interest was the mode of failure and ultimate capacity of each design. All measurements taken were time related. Some instrumentation was sacrificed to record stopping/seal failures.

Each drift at the Lake Lynn facility has ten environmentally controlled data-gathering stations which individually house a static pressure transducer and an optical sensor to detect the extent of flame travel from the explosion. Generally, the first explosion test generated static pressures ranging from 152 kPa at cross-cut 1 to 138 kPa at the stopping in cross-cut 5, some 150 metres from the ignition source. The pressure exerted on each seal is calculated by interpolation of the data from transducers located on both the inbye and outbye side in C drift. The seal in the first cross-cut also had a pressure transducer on the seal face, which indicated less than 7 kPa correlation difference with readings from transducers on either side.

The seal evaluation program used two additional types of transducer; linear variable transducers (LVDT) and accelerometers to measure dynamic response.

An LVDT is an electromechanical transducer that produces an electrical output proportional to the displacement of a separate movable core. It consists of a primary coil and two secondary coils symmetrically spaced on a cylindrical form. A free moving rod-shaped magnetic core inside the coil assembly provides a path for the magnetic flux linking the coils. The LVDT is calibrated by varying the position of the core and measuring corresponding output voltages, thus providing a calibration constant. These DC energised LVDT's provide reliable and highly accurate seal displacement measurements. The body of each LVDT was held by an aluminium block attached to a vertical 100 mm square plate contacting the face of the seal, all located by an RHS steel section bolted to the roof and floor behind the seal. The LVDT's and accelerometers were attached to the seal with epoxy putty.

Seals subject to a dynamic loads such as an explosion which imparts energy to the structure, will oscillate. To measure this movement, accelerometers with battery-powered preamplifiers were used. Piezoelectric crystals within the accelerometer produce an induced charge when a force is induced in the seismic mass under some acceleration. The magnitude of the electric charge is proportional to the acceleration of the seal.

For the first explosion test, LLEM # 347, the four seals in cross-cuts 1 to 4 and one stopping located in cross-cut 5 were instrumented with 3 LVDT's and 2 accelerometers on the B drift side. Accelerometers and LVDT's were installed on the seal/stopping centre and at the quarter point outbye at mid-height. In addition, LVDT's were also located at the ¾ - height and mid-width point of each seal.

Anticipation of a seal failure caused the removal of all the accelerometers and one LVDT before the next test was carried out. Seal/stopping failure times were thus determined from the failure time of the remaining LVDTs, enabling the pressure impulse to be calculated.

The pressure impulse is the summation of the area under the pressure - time profile before the time of failure. It gives a measure of the energy imparted to the structure up until failure. The concepts of peak explosion overpressure and impulse give further definition to the effects of dynamic loads on seals and stoppings.

DETERMINATION OF AIR LEAKAGE

An important factor to be considered for any seal design is its air impermeability, ie its ability to minimise leakage from one side of the seal to the other. Measurements of the air leakages across the seals were conducted before and after each of the explosion tests. In order to establish a ventilation pressure across the seals, a double brattice curtain was first erected in C drift, effectively sealing it off. On the B drift side of each of the seals and stopping a brattice curtain was installed with a 465 cm^2 opening.

Thus a controlled, pressurised area on the C drift side of the seals was created by the LLEM main ventilation fan. The fan pressure was varied in four increments from 0.25 kPa (1-in H_2O) to 0.75 kPa (3-in H_2O), as defined in the MSHA guidelines of Table 1.

A vane anemometer was used to measure the air flow through this opening for each fan differential pressure. A copper tube had been cast into each seal/stopping so that the air pressure exerted by the fan on each seal could be measured from the B drift side using a Magnahelic pressure gauge. Hence, from the air velocity and the area of the opening in the brattice curtain behind each seal, the air leakage volume could be calculated.

Differential pressure, kPa	**Maximum Leakage M^{3}5^{-1}**
Up to 0.25	<0.05
Up to 0.50	≤0.07
Up to 0.75	≤0.10
More than 0.75	≤0.12

Table 1. Guidelines for leakage through a seal

DESIGN AND CONSTRUCTION OF SEALS AND STOPPINGS

Six seal and stopping designs were tested at LLEM. There were two parts to the testing program, the first part involved constructing and testing four seal designs and one stopping design at explosion overpressures of 138 kPa [20 psi] and above. The second part of the program was the testing of a low pressure rated Gunmesh stopping. All test overpressures were targeted to investigate the ratings nominated by " Approved Standard For Ventilation Control Devices".

A seal has been defined in part as any structure that would withstand an explosion overpressure of at least 20 psi. The seals were all built using the Meshblock formwork system except for the 1200 mm wide plug seal which had Gunmesh and shotcrete walls to contain the wet-mix core, and the Gunmesh stopping designs which used Gunmesh formwork and sprayed shotcrete

As has been noted, the Meshblock concept was developed in 1993 by Tecrete Industries for Australian underground mines. At the LLEM, the shotcrete was applied within the formwork by a dry mix process using a Reed Lova 215 pneumatically operated gunnite machine. (This recently developed shotcrete machine supplied by Reed, CA was used in all seal and stopping construction utilising the dry shotcrete process.) A 40 metre length of 38 mm (1.5 inch) inside diameter shotcrete hose was attached to a trunk and a water ring suitable for casting shotcrete into the formwork. The shotcrete hose delivered the pre-bagged dry mix through a nozzle at which mixing water was added before entering the delivery hose. The minus 5 mm aggregate dry mix is designed to be cast into the Meshblock formwork and is also suitable for spraying as a shotcrete onto Gunmesh formwork. 40 metres of 38 mm shotcrete hose was attached to a trunk and water ring suitable for casting shotcrete into formwork.

The Reed Lova 215 was operated at casting rates of up to 4 tonnes per hour during seal construction, which is at the lower end of the machines capability. The dust catching system on this machine virtually eliminated dust apart from that dust generated by bag handling. Air was supplied via a 50 mm bull-hose providing the 165 litres/s [350 cfm] necessary to run this machine when utilising a 38 mm shotcrete hose. When handling these cementitious products all safety data sheet instructions were adhered to by the operators.

The average air temperature of 10.5 degrees C (51 degrees F) (ranged from 9 - 15 degrees C or 48 - 59 degrees F) and an average relative humidity of 59 % (ranged from 50 -74 %) were recorded during the two week construction period. Previously, other test programs at Lake Lynn had been conducted during summer months where temperature and humidity levels were higher.

MESHBLOCK SEAL CONSTRUCTION

Three Meshblock and shotcrete seals constructed in the crosscuts between B and C drift ranged in thickness from 175 mm to 325 mm. Cross- cut No 3 was mined to a 2.8 metre height to simulate the height of a roadway in a typical Australian coal mine. Seals were constructed in the LLEM under conditions analogous to those that may be encountered during seal construction in an Australian underground coal mine.

As in the installation of any seal design all loose material has to be removed from the seal construction site, exposing competent strata. There is a 150 mm thick concrete slab within each crosscut at the LLEM which is laid on gravel. As the stiffness of this slab will influence the ability of each seal design to resist horizontal loads, the floor was drilled at 600 mm centres across the centre line of the intended seal and injected with a grout to increase floor stiffness. Roof, rib and floor bolts were installed at 600 mm centres forming a vertical plane at the centre line of the seal. These 24 mm diameter steel bolts were 1.2 metres in length and fully encapsulated to a depth of 600 mm with 16 second set polyester resin capsules. The bolt holes were of 30 mm diameter. The bolts provide a rigid attachment of the seal to the rock strata which is important if the seal is to resist horizontal loads.

The concrete floor was scabbled to a depth of approximately 20 mm, providing a key and a level footing for each seal.

The Meshblock formwork or building block consists of a U-shaped frame formed as a folded grid of 4 mm diameter steel wire. A 3 mm aperture steel mesh encloses the sides of and is an integral part of this building block enabling the shotcrete nozzleman to examine the shotcrete material flowing into the formwork. The Meshblocks are laid horizontally in rows in which the ends are butted to each other and secured by plastic or wire ties. Normally two rows of Meshblocks are erected and cast with shotcrete and the cycle repeated until seal completion. There is a 45 mm overlap built on each successive layer of Meshblocks. The sides of each Meshblock are secured by five steel clips which are attached to the wire grid to keep the seal width consistent. Care must be taken to prevent a cold joint forming, such that the interval between casting successive layers does not exceed half an hour. All Meshblock seals were constructed in a continuous manner until completion using Quikrete MB500 shotcrete (formulation by Tecrete).

Steel roof, rib and floor bolts anchor the seal to the surrounding strata and provide edge restraint for the seal when explosion overpressures are applied. They perform the same purpose as keying. (Normal practice at LLEM when testing block seals is to provide edge restraint by bolting a 6- by 6- by ½ inch steel angle to the floor and ribs using 24 inch long, 1-in-diam case- hardened steel bolts (embedded 18 inches), on 18 inch spacings.)

As the structure on a Mesh block seal is built upwards, the floor steel bolts are extended vertically towards the roof. The overlap is 600 mm for vertically extended reinforcing. (Normally the roof bolts are installed first so that the lower floor bolt holes can be aligned by string -line and drilled so that the vertical steel reinforcing forms straight lines.) Once all the steel reinforcing is tied together, it forms a vertical plane which is central to the completed Meshblock seal. For the 138 kPa [20 psi] and higher rated seals, all peripheral roof and floor bolts are installed at 600 mm centres. Table 2 below, summarises the Meshblock designs that were constructed for these explosion tests using the Meshblock formwork system. The seal mass was calculated from the total weight of shotcrete, Meshblocks and steel bolts used.

Cross-cut Location	Thickness [mm]	Road size [m]	Shotcrete in seal [kg]	Seal mass [kg]
B	325	5.76x2.24	9225	9408
C	325	5.82x2.80	11063	11291
D	175	5.97x2.26	5316	5510

Table 2 Gunmesh Stopping Construction

Two stopping designs were constructed in the cross-cuts between B and C drift at the LLEM, one being of 40 mm thickness and the other of 75 mm thickness. These stoppings were constructed using Tecrete MB500 minus 5 mm aggregate shotcrete supplied in a 25 kg bag, based on Gunmesh formwork erected and in-filled with sprayed shotcrete. In the stopping erected in cross-cut 5 this product was applied with the Reed 215 gunnite machine. As with the seals, the roof, ribs and floor are cleaned of loose debris back to solid material. The concrete floor was keyed 20 mm to form a level base for the foot. The bolt pattern in

Gunmesh stoppings requires 24 x 1200 mm bolts in roof, ribs and floor spaced at one metre centres. All bolts supporting the formwork are fully encapsulated 600 mm into solid ground forming a vertical plane.

The Gunmesh formwork consists of a 4 mm galvanised wire framework (square grid pattern on 150 mm centres), with a sheet of size 1.2 by 3.0 metre in-filled with a 3 mm aperture galvanised steel mesh. This flat sheet has attached to it a square grid pattern of welded 4 mm galvanised wire bars held apart from the sheet by cross braces of the same material, thus forming a lattice formwork of 40 mm thickness open at one side. The open side is installed with the long side of each sheet vertical and tied into the roof and floor bolts. The Gunmesh sheet edges are overlapped 100 mm and tied together with plastic cable ties. Once the formwork is in place and attached to the peripheral bolts, it can be in-filled from the open side with the shotcrete, building from the bottom up. Vertical roof and floor bolts are linked by attaching like steel bolts with plastic cable ties with an overlap of 0.5 metres to 0.6 metres. Care must be taken that there is total coverage of the steel bolts with no shadows of dry or over-spray shotcrete material and that the Gunmesh cage is attached to and envelopes the steel bolts. The Gunmesh stopping is spray shotcreted with no delays until the nominated thickness is achieved.

The first stopping to be constructed was a 75 mm thick Gunmesh stopping within No. 5 cross-cut. The Gunmesh formwork was cut with 14 inch bolt cutters to fit the contours of the entry as necessary. The edges of the roadway were spray sealed with shotcrete. The formwork used had a depth of 50 mm which meant that an additional 25 mm thickness of shotcrete was sprayed to provide the total stopping thickness. The entry size was 5.79 metres wide by 2.22 metres high.

As part of a low pressure explosion test program (3 to 10 psi), a second 40 mm thick Gunmesh stopping was erected in a 5.88 metre wide by 2.1 metre high entry, using 40 mm wide formwork. Generally, to satisfy the Queensland Mines Department "Approved Standard for Ventilation Control Devices", Gunmesh stoppings will be used in applications which require explosion overpressure ratings of 2, 5 and 10 psi. A total of 5239 kilograms and 1952 kilograms of shotcrete was sprayed on the 75 mm thickness and 40 mm thickness stoppings respectively.

PLUG SEAL CONSTRUCTION

The 1200 mm width plug seal was constructed in No 1 cross-cut and consisted of two Gunmesh and shotcrete stoppings with an injected Aquablend core, which achieved a 28 day compressive strength of 3.81 MPa. The entry size in No. 1 Cross-cut was 5.43 by 1.95 metres. The first Gunmesh stopping was constructed in the manner previously described, and required 1837 kilograms of MB500 shotcrete to provide an seal sufficient to prevent leakage of the wet mix core material when being injected.

A 600 mm square window provided the opportunity to clean shotcrete rebound from the interior floor of the plug seal, this window being closed up and sealed with shotcrete

The second Gunmesh stopping closest to C Drift and located 1150 mm from the first stopping was sprayed from the C drift side with 2317 kg of MB500 shotcrete. Steel spacers located approximately 130 centimetres off the floor and spaced across the entry at 600 mm centres, provided lateral support to the walls which were subjected to a hydraulic head by the Aquablend wet mix.

One day after completing the stoppings, contractor's from Alminco Pty Ltd injected 7400 kilograms of Aquablend into the void using an air driven Langley Placer with 61 metres of 32 mm diameter hose. Three, 32 mm injection ports were cast into the C drift Gunmesh stopping 400 mm from the mine roof. One port was located 900 mm from each rib and the third port equally spaced from both ribs at the centre of the stopping. Plastic extension pipes (air bleeders) were attached to the stopping wall and located 300 mm down from the mine roof. They were angled towards the mine roof at the highest cavities to ensure complete closure to the roof with injected Aquablend. The air ports were progressively closed from the outbye side of the seal and the last injection port pressurised until refusal of the placer at 1.38 MPa [200psi] slurry pressure. This ensured that the slurry level was in direct contact with the roof.

EXPLOSION TEST RESULTS

After the first four seals and one Gunmesh stopping were constructed in five working days as part of the high explosion pressure test program, preparations were made to test each structure for leakage. The seals and stoppings were between 11 and 14 days old when the 138 kPa explosion (LLEM # 347) was initiated. Previously at LLEM, seals using cementitious products has been cured for 28 days. The seal in cross-cut 3 had cured for 27 hours from the finish of construction on the previous day to the time of explosion test #347 initiation.

Results Of Test #347 (138 kPa Overpressure)

All structures passed pre and post explosion air leakage tests and survived the first explosion test intact. Table 3 below gives the results of these air leakage tests which compare favourably with all other seal systems reported [3], pp 7.

The seals and stoppings were subject to peak pressures (visual readings) ranging from 23 psi for the plug seal and 23.5 psi for the Meshblock seal in cross-cut 2, to 19 psi for the Gunmesh stopping in cross-cut 5. These peak pressures are calculated by interpolating data between the nearest sensors inbye and outbye of each seal.

(LLEM has recently acquired new software called LABVIEW which has enabled a closer interpretation of the data to within an accuracy of ± 0.5 psi or 5 kPa. This software has a smoothing function which enables single point data spikes from signal noise to be removed. The 10 millisecond, 15 point smoothed data more closely models the visually reported data from previous test programs.)

Seal Type	Cross-cut	Pre-explosion pressure differential		Post-explosion pressure differential		Outcome
		0.25 kPa	1.1 kPa	0.25 kPa	1.1 kPa	
Cementitious Plug	1	0	0	0	0	Pass
Shotcrete 325 mm/2m	2	0	0.014	0	0.0165	Pass
Shotcrete 325mm/ 3m	3	0	0	0	0.0165	Pass
Shotcrete 175mm/2 m	4	0	0	0	0.021	Pass
Shotcrete 75 mm/2m	5	0	0.03	<0.012	0.03	Pass

Table 3

Although the stopping in cross-cut 5 survived the leakage tests, it had two long horizontal hairline cracks on the C drift side, one across the entire top section of the stopping about 150 mm down from the roof and a second across the centre portion. A chipped out section of the centre, C drift side, wall indicates compression failure of the shotcrete, with the structure very close to failure.

Results of Tests # 348 and 349

In order to develop a numerically based design tool for explosion seals, successive and more intense explosions were required. With an additional loading of coal dust, the overpressure was next increased to 385 kPa (55.5 psi) in test #348 and ultimately to 595 kPa (86 psi) in test # 349. The following Table 4 summarises results of the first three tests using visually recorded and 10 millisecond, 15 point average, smoothed data.

Seal Distance	**P max #347**			**P max # 348**		**P max #349**	
feet metres	visual reading psi	10 msec psi	15point average kPa	10 msec psi	15point average kPa	10 msec psi	15point average kPa
Seal in cross-cut #1 *59 ft 18.0 m*	23	22	150	48	330	62.5	430
Seal in cross-cut #2 *156 ft 47.7 m*	23.5	23.5	160	45.5	315	66	455
Seal in cross-cut #3 *246 ft 75.0 m*	21.5	19.5	135	43	300	86 Destroyed	595
Seal in cross-cut #4 *355 ft 108.2 m*	20	17	120	55.5 Destroyed	385		
Stopping cross-cut 5 *452 ft 137.8 m*	19	17	115	53.5 Destroyed	370		

Table 4

In the second explosion, LLEM #348, the three metre high seal was subjected to an overpressure of 300 kPa without failure. The 175 mm thick seal in cross-cut 4 and the 75 mm thick stopping in cross-cut 5 were destroyed. The post explosion air leakage tests on the three remaining seals showed little or no change.

Minor tension cracking on the B drift side of the seal in cross-cut three showed a yield line mechanism where the seal is divided into a series of elastic plates forming a roof to floor arch. The resistance to bending loads from the explosion is provided by the stiff surrounding rock which provides a reaction to the arch formed in the wall.

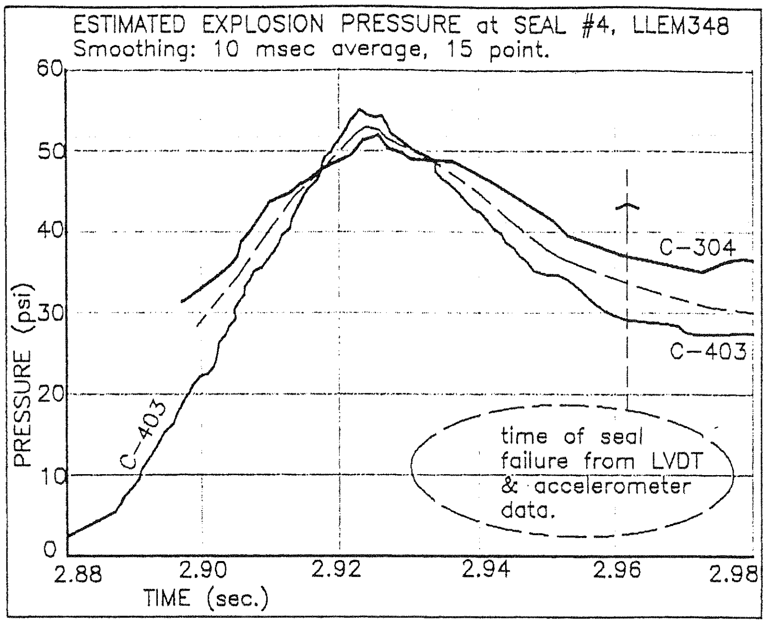

Figure 2

When the C drift central portion of the seal can no longer sustain the high compressive load and the shotcrete crushes, failure is by snap through of the seal. It is very important to determine the failure pressure of the seals to validate any future numerical design tool. The seal failure time is shown by the loss of electrical signal from the transducers. Figure 2 shows that the seal in cross-cut 4 failed at a pressure of between 210 and 250 kPa (30 and 36 psi) and that failure occurred after the peak pressure was reached.

Further structural analysis will provide an understanding of the failure mechanisms of the seals under dynamic loads where inertial effects and acceleration are important factors. Structural failure under static applied loads occurs when the peak pressure matches the structures ultimate strength.

Test # 349 saw the failure of the 2.8 metre height Meshblock seal with failure occurring well after the peak pressure of 595 kPa (86 psi) was achieved. The plug seal sustained some very minor cracking on the C drift shotcrete wall with no noticeable damage on the B drift side. A horizontal yield line crack on the B drift face of the cross-cut 2 seal occurred after test #347. Yield lines extended into the seal corners on 45 degree angles on the subsequent two tests.

An important consideration of the damaging potential of an explosion overpressure is the "pressure impulse". This is defined as the time integral of the pressure profile and is a measure of the energy that the seal is subjected to during the explosion. Destructive forces depend on the peak overpressure and the impulse, and can be expressed as $\int$ P A dt, up to seal failure time t. ([6] pp 16.)

Figure 3 below shows the explosion pressure-time profiles at measuring station C-304 (inbye cross-cut 3) for tests # 347,348 and 349. The magnitude of the last two explosions over the standard 138 kPa (20 psi) MSHA test for seals is evident. Impulse values are calculated as follows :

Cross-cut 3 seal	800,000 N-sec
Cross-cut 4 seal	321,000 N-sec
Cross-cut 5 stopping	116,000 N-sec
Cross-cut 3 stopping	75,000 N-sec

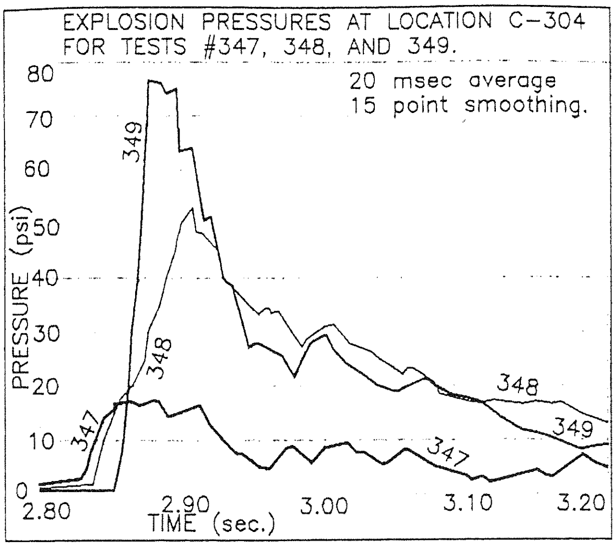

Figure 3

Results of Tests # 350 and 351

A 40 mm thick Gunmesh stopping was constructed in cross-cut 3 at a roadway height of 2.1 metres and tested to provide useful data on a design which could provide explosion overpressures in the range 14 kPa to 35 kPa (2 to 5 psi). This stopping was instrumented with two LVDT's and because of time constraints to the program, no leakage testing was performed. The stopping survived the Test #350 at a peak pressure (read visually) of 27.5 kPa (4psi) and 23 kPa (3.4 psi) with 10 msec, 15 point smoothing. Test # 351 produced a peak pressure (smoothed) of 39 kPa (5.6 psi). The stopping was destroyed at an overpressure of 31 kPa (4.5 psi).

Results of LVDT Measurements of Seals and Stoppings

The LVDT measurements for each seal and stopping design for successive explosions will be used to develop *validated numerical models* for structures over a wide range of opening sizes, pressure ratings and strata conditions characterised by rock stiffness. In cases where the seal did not fail it is important to develop a model that determines its ultimate capacity and the mode of failure. The data in Table 5 below is important in that it will be compared with the simulated responses from numerical modelling. Values are displacements in mm.

INSTRUMENT	LVDT	Test #347	Test #348	Test # 349	Test #350	Test #351
Seal in cross-cut 1	U X-1	0.3	0.5	0.7		
	R X-1	0.3	0.5	0.5		
	M X-1	0.2	0.5	0.5		
Seal in cross-cut 2	U X-2	1.8	1.8	3		
	R X-2	1.8	2.4	6.8		
	M X-2	1.7	1.8	11.1		
	M X-2	1.7	1.8	11.1		
	R X-3	2.3	4.5			
	M X-3	2.7	7.2	13.0		
Seal in cross-cut 4	U X-4	5.7	>15			
	R X-4	7.2	>15			
	M X-4	8.1	>15			
Stopping cross-cut 5	U X-5	26.6				
	M X-5	26.6	>60			
Stopping cross-cut 3	U X-3				10.9	25.6
	M X-3				13.2	28.2

Table 5

CONCLUSIONS

The Tecrete designs tested at the LLEM proved successful in meeting the desired levels of resistance to explosion overpressures and provided sufficient data to enable a mathematical model to be developed as an aid to overall design.

The seals and stopping built at the test facility have been shown to meet specified criteria as defined by the newly promulgated "Approved Standard for Ventilation Control Devices".

The Meshblock seal designs and the plug seal all satisfied the air leakage and explosion resistance requirement for a seal subject to a 138 kPa (20 psi) pressure pulse. Test pressures ranged from 21 kPa (3 psi) to 592 kPa (86 psi), with the 1200 mm plug seal and the 325 mm Meshblock seal sustaining overpressures up to 455 kPa (66 psi).

The special requirement to demonstrate the ability to construct a seal capable of withstanding a 138 kPa (20 psi) overpressure 24 hours after completion has been satisfied, with the 2.8 m high seal achieving a resistance of at least 300 kPa (43 psi) without failure.

Results from testing the 40 mm and the 75 mm Gunmesh stoppings show that designs can be provided for structures that can resist overpressures in the range from 14 kPa (2 psi) to 69 kPa (10 psi).

The development of high explosion resistance in the seal designs can be attributed to the lateral restraint provided by the surrounding rock and the high strength of the shotcrete materials used. An important aspect demonstrated by these tests is that the height of the seal is of major importance to the seal's ability to resist overpressure.

This is clearly shown by the observations that the 2.8 m high seal was close to failure at 296 kPa (43 psi), whereas the 2 metre high, 325 mm thick seal survived 455 kPa (66 psi) with only minor yield line cracking apparent.

Keying of the seals and stopping was minimal, with fully encapsulated steel bolts providing restraint at the seal to rock interface.

Failure of the seal and stopping designs was due to a flexural mode of collapse, as there was sufficient strength available to prevent shear failure without substantial keying. It must be stressed that the test environment is one of solid, non-yielding strata.

The data provided by the LVDT's and the accelerometers will enable numerical models to be developed to assist with seal designs to meet current requirements and enable future improvements to be made to these structures. It is recognised however, that further study is needed in design techniques for seals that can resist roadway convergence loadings, and to address the impact on seal integrity of man-doors and other cast in fittings such as water-traps and pipework.

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APPENDIX 1

Consideration of Structural Behaviour

A preliminary analysis of the test results indicates a number of interesting characteristics. The seals and stoppings are practically unreinforced when compared to, for example, concrete slabs which normally require a mesh of reinforcement on the tension side. The vertical and horizontal bolts were installed at mid-section of each seal, hence not contributing to its flexural strength significantly. In spite of such arrangements, the obtained capacities are many times larger than those obtainable in reinforced concrete slabs designed in accordance with modern codes of practice (eg AS 3600 - 1994).

Figure 1a illustrates a schematic view of a typical seal. The smallest width D to height L ratio was around two (for seal 3) implying that the principal load-carrying mechanism is that of a one-way slab acting in the short (vertical) direction. For such (and larger) D/L ratios it is conservative to assume that the applied pressure is carried entirely by strips spanning in the vertical direction (Figure 1b). the attainment of large ultimate capacities for such strips can be attributed to development of significant lateral restraints H (Figure a) exerted by the mine strata as well as the stiff mine floor. The lateral forces develop in response to bending deformation of the strips under applied pressures. Such restraints resemble the external post-tensioning forces often applied to concrete beams and slabs through pre-stressed tendons to increase their flexural capacities. Figure 2b shows the lateral compressive force H on the cross-section at mid-span significantly reduced the tensile stresses caused by bending, hence delaying the initiation of cracking. The development of this strength-enhancing mechanism will depend on a number of parameters including the stiffness and strength of shotcrete material and mine strata, seal thickness, and the height of crosscuts.

The data also indicate that in some cases the recorded times at peak pressures do not match the times of seal failure; this signifies the need for dynamic analysis. Further examination of the pressure time histories reveals an impact-type input of energy to some seals when comparing their natural periods in bending response (computed in the pre-test round of analyses) with the times taken to reach the peak pressures. In such cases the dynamic response amplification (eg maximum seal displacements) will depend on the descending portion of the pressure versus time diagram. Development of simple response models is currently underway.

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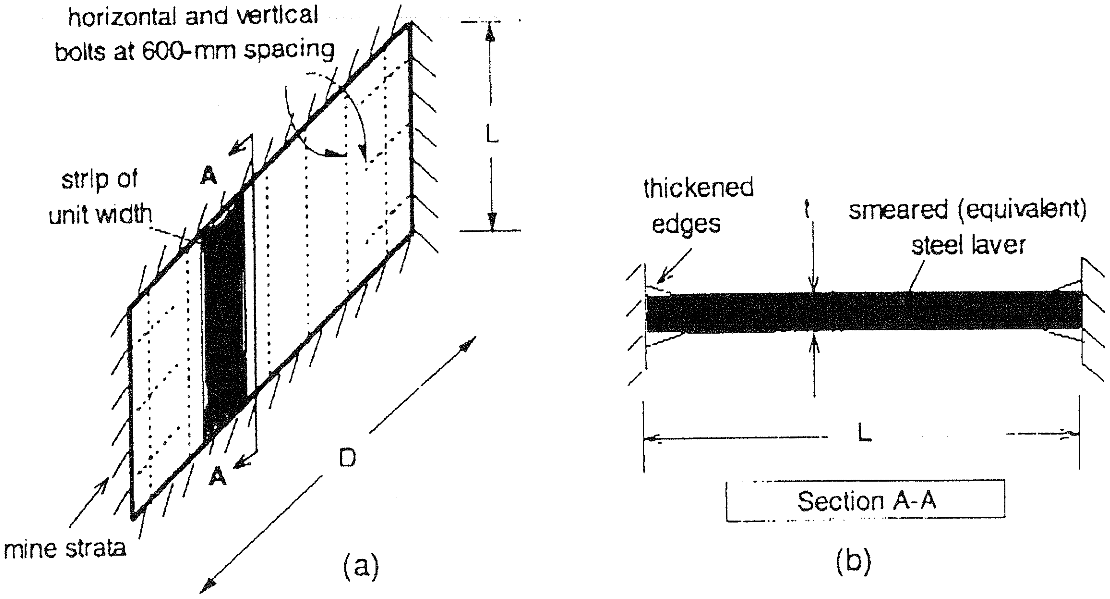
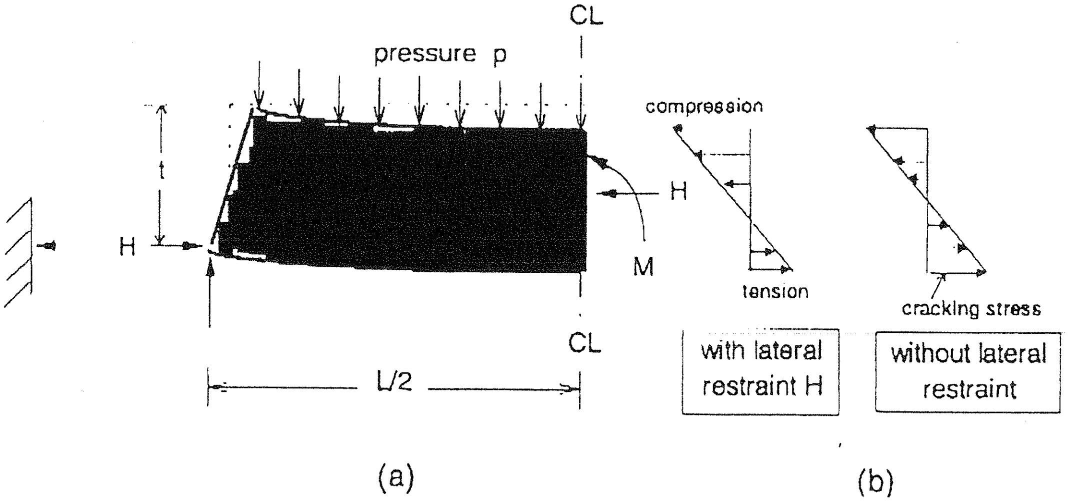


(a)

(b)

Appendix Figure 1a - *A Strip of Mine Seal for Structural Modeling*



(a)

(b)

Appendix Figure 2a - *Effect of Lateral Restraint H on Delaying of Crack Initiation*