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Research Needs in Regard to Design, Performance Criteria, Construction, Maintenance Assessment and Repair of Coal Mine Seals

R Gallagher[1]

ABSTRACT

Legislation introduced for Queensland and New South Wales Coal mines provides different levels of prescription regarding specification of mine seals – generally in relation to capacity to withstand overpressure.

In Queensland, the *Coal Mining Safety and Health Regulation (2001)*, Section 341 (d) places a further onus on the statutory ventilation officer to 'ensure all ventilation control devices at the mine are properly constructed and maintained' and that the ventilation officer 'must ensure a ventilation control device mentioned in the regulation … and installed at the mine meets the design criteria stated' for the 'type of device'.

There is limited or no prescription in regard to:

- standards and methods for design;
- standards and methods for testing of seals in the 'lab' and relating results to field conditions (albeit limited recognised standard test facilities exist);
- standards and methods for testing of seals in the field;
- requirement to consider specific product types in light of the particular application and specific locational environment;
- site selection for the seal;
- consideration of the operational environment of the seal;
- consideration of potential water head applied to the seal;
- control and state of the ground surrounding the seal;
- testing/acceptance criteria for a given seal, identification of defects in installation eg filling voids, etc (other than generic product tests in regard to overpressure/leakage, which may or may not bear relevance to the specific coal mine application, environment and service duty);
- seal leakage limits (although NSW uses the term 'airtight');
- requirement for and systems to maintain the seal, whether at design rating or otherwise;
- guidance in regard to criteria for decisions to repair or identify the need to replace seals;
- acceptable and effective methods to complete repair of seals; and
- need for methods to assess effectiveness of repair in regard to both leakage and overpressure rating.

Based on the experience of the author, it appears that risk management and life cycle approach to seals has not been adopted to the same extent as for other aspects of operations. Further, because of the number of disciplines and personnel involved that may influence various factors affecting seal integrity, the opportunity for oversight or unclear allocation of responsibility is considerable.

While suppliers can provide explosion or design rated seals, this should only be a starting point for application of the product in a coal mine. Application is often considered by mine planning staff (taking into consideration mine environment parameters such as water, control of gas, spontaneous combustion risk, etc) in conjunction with the colliery ventilation officer, and then construction completed by contractors under supervision of operational staff. After construction, seals often are managed by operational personnel with input from the ventilation officer. Input of the geotechnical engineer into pillar design, roadway opening size, ground support specification and most stable seal location is also required. The need for a customised design approach for each seal site is proposed in order to take into account the many and variable factors that may influence a site so that improved seal performance reliability and predictability can be developed.

A program of quantitative as well as qualitative monitoring of performance and triggers for rectification or maintenance action is required, and would provide support to the aforementioned proposal. Many mines rely on visual/audible inspection and periodic bag sampling as the primary means of assessment. Other significant factors such as seal material properties, rib degradation, convergence, floor heave, effects of water on both structural integrity of the seal as well as the air tightness of the seal do not generally receive the same level of attention.

Based on the above observations, the author has compiled a reference checklist in regard to the above matters, including aspects of and approaches to mine and pillar design, geotechnical modelling and data collection, civil engineering design, site evaluation and practical options available.

It is apparent that while some research has in isolation examined issues such as overpressure resistance, leakage performance, seal materials, rib sealing, effects of longwall mining and assessment of seal construction and integrity, further research may be required to deliver answers to many of the issues identified above to assist the industry and service providers develop and improve standards.

INTRODUCTION

Based on considerable operational experience and more recent completion of work as a consultant, it has observed that the level of effort, understanding and sophistication in design, installation and management of goaf seals is largely limited in focus to development of written management plans and procedures, and is often reactionary to development of alarm level conditions. Significant benefit may be gained through full life cycle consideration of seals on a panel by panel basis, and on both the planning/evaluation of likely service duty and customised selection of the most appropriate type of seal on location by location (ie individual) basis.

There exists much of the data and information required for such analysis for most mine sites (particularly for mine environment/conditions and mine design issues). For improved risk management, there is a need to develop a comprehensive data set on each type of seal available in the market. Such seal related data should include information on associated material properties (both at component and fully constructed scales), limitations or risks in use and engineering design calculations and supporting test certificates. Some, but not all of the relevant geotechnical data (such as loading and convergence experienced by seals, rib softening, geological and geotechnical immediate roof and floor strata unit models, etc) required for analysis of seal integrity may not yet be routinely collected at all sites.

Issues are discussed in relation to the elements which may be considered in improving the system of seal life cycle management. Additionally, factors expected to further drive the need for improvement and related research are outlined.

LEGISLATIVE ENVIRONMENT – QUEENSLAND AND NEW SOUTH WALES

The relevant legislation in regard to seals in underground coal mines varies between the Queensland and New South Wales. In both states, the coal mining legislation holds specific requirements with the onus for compliance primarily resting with the operators.

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In Queensland, the *Coal Mining Safety and Health Act, 2001* places requirements on parties other than the operator through Section 43, *'Obligations of contractors',* Section 44, 'Obligations of designers, manufactures, importers and suppliers of plant, etc for use at coal mines', and Section 45, 'Obligations of erectors and installers of plant'. In New South Wales, the *Occupational Health and Safety Act 2000* holds precedence over subordinate and related coal mining legislation. Section 11 of the *Occupational Health and Safety Act 2000,* ('Duties of designers, manufacturers and suppliers of plant and substances for use at work') provides for similar obligations as in Queensland.

Section 325 of *the Coal Mines Safety and Health Regulation, 2001*, 'Types of seals for particular circumstances and parts of mines', states:

> 1. *The underground mine manager must ensure a seal installed other than at the surface, at the mine is of a following type:*
>   a. *if the level of naturally occurring flammable gas at the mine is insufficient to reach the lower explosive limit for the gas under any circumstance – type B;*
>   b. *if persons remain underground when an explosive atmosphere exists and there is the possibility of spontaneous combustion or incendive spark or other ignition source – type D;*
>   c. *for an underground mine, or part of an underground mine, not mentioned in paragraph (a) or (b) – type C.*
> 2. *The underground mine manager must ensure a type E seal is used for sealing the entrance to the mine mentioned in section 156(2)(b).*

Section 350(1) of the Coal Mines Safety and Health Regulation, 2001, 'Installing ventilation control devices', states:

> 1. *The ventilation officer must ensure a ventilation control device mentioned in schedule four, column one, and installed at the mine meets the design criteria in schedule four, column two, opposite the type of device.*

Table 1 sets out *Schedule 4* of the regulation.

Significant obligation is assigned to the ventilation officer in meeting compliance.

The only specific legislative requirement for seals in NSW underground coalmines is Section 99(3) of the *Coal Mines (Underground) Regulation 1999*, which states that:

> *A stopping constructed for the purpose of sealing off a part of a mine must be substantial in structure, airtight and designed to resist damage in the event of an explosion. Provision to allow sampling of the atmosphere in the sealed off area must be made.*

It is apparent that the legislation is far less prescriptive and far more open to interpretation.

SEAL LIFE CYCLE

The generic life cycle of a seal may be summarised as follows:

- consideration of impacts of mining environment and mine design on seal application, including geology, geotechnical, hydrogeological and goaf/pillar loading impacts;
- specification of operating environment, overpressure and permissible seal leakage;
- consideration of alternative materials and construction methods that may meet requirements;
- assessment of potential failure mechanism of seal in given location and likely repair and/or replacement strategy;
- selection of contractor to install preferred seal type, specific site selection, construction;
- inspection/approval of construction as in accordance with design, documentation/records of construction;
- installation of monitoring instrumentation and commencement of inspection and monitoring regime and reporting;
- completion of service in main-gate of panel providing first side abutment loading;
- service in tailgate of panel providing second front abutment loading;
- repair and/or replacement as indicated by monitoring/ inspection;
- service in goaf of panel providing second side abutment loading/double goaf loading until failure or seal well inside deep goaf; and
- review of seal performance, identification of design, construction, monitoring and/or repair improvement.

TABLE 1

Ventilation control devices and design criteria.

Column 1	**Column 2**
Ventilation control device	**Design criteria**
Brattice line or temporary stopping	Antistatic and fire resistant
Mine entry airlock	Capable of withstanding an overpressure of 70 kPa while it is open
Separation stopping for a primary escapeway	Antistatic, fire resistant and of substantial construction providing for minimal leakage
Stopping, overcast or regulator installed as part of the main ventilation system	Capable of withstanding an overpressure of 35 kPa
Stopping, overcast or regulator installed as part of the ventilation system for a panel	Capable of withstanding an overpressure of 14 kPa during the life of the panel
Type B seal	Capable of withstanding an overpressure of 35 kPa
Type C seal	Capable of withstanding an overpressure of 140 kPa
Type D seal	Capable of withstanding an overpressure of 345 kPa
Type E seal	Capable of withstanding an overpressure of 70 kPa
Ventilation ducting	Antistatic and fire resistant

The level of detail and depth of investigation and analysis of these steps generally varies widely between sites in different aspects.

From observations in the working environment, seal performance between successive cut-throughs may vary considerably despite almost identical use of materials, means of construction and dimension. Often a contract is let for one type of seal for each longwall panel cut-through location, however this may not always be an appropriate approach.

An alternative approach might consider the mine environment and design, seal design, specification, seal type, site selection, construction and monitoring where construction may be varied on a seal by seal basis (ie customised) if performance is to improve and become more reliable. This would require consideration of a number of interacting factors that relate to the mining environment and the mine design.

MINING ENVIRONMENT

Depth of cover

Depth of cover will influence conditions of potential for rib spall, roof-floor convergence and/or floor heave. As stress increases with depth, effects of convergence and rib expansion and spall may become more pronounced.

Water

Wet conditions may impact floor conditions, the ability to prepare the site for seal installation, and the specifications of the seal (eg as a bulkhead and/or inclusion of a water trap).

Seam thickness

Seam thickness will influence the height of the seal, the risk of buckling and possibly method of construction.

Seam floor structure contours

Seam floor structure contours will indicate the likely grades and potential additional precaution required in provision of seal roof/floor frictional contact such as additional bolts, etc. Floor structure will also indicate potential areas where steeper gradients may require significant modification of design of the seal or supplementary measures to ensure stability and performance. Steep grades also raise the possibility of shear failure of pillars.

Seam gas

The gas content and composition will influence the risk and level of control that seal performance will be required to service.

Seam propensity to spontaneous combustion

Seam propensity to spontaneous combustion will influence the emphasis on both the explosion resistance and air tightness required of the seal and surrounding ribs, and possibly modify approaches to rib support and/or grouting.

Geological structure

Detailed exploration and underground mapping during development operations will identify potential areas where abnormal ground behaviour or other conditions may eventuate on longwall extraction that can impact on seal performance.

Stratigraphy/immediate roof and floor

Detailed modelling of geological and geotechnical roof and floor units will assist in anticipation of problem areas such as seam splitting or the presence of rider seams, as well as identify potential zones for poorer roof or floor conditions and potential horizons of shear failure in future longwall mining pass bys. Such information may significantly impact the type of seal selected for a site and influence the ground support strategies applied in these areas.

The majority of the required information is collected in the course of typical exploration, geological modelling and resource assessment processes for underground coal mine evaluation. It appears that there is limited further information regarding the resource that may be gathered and usefully assessed in regard to design, selection and installation of seals.

MINE DESIGN

Pillar and roadway size

The level of conservatism in pillar design (for a given roadway size, pillar size, depth and geomechanical properties) will significantly impact on assessment of required primary and secondary ground support, and in turn on supported roadway deformation and integrity. A number of pillar design methods will typically be applied to develop confidence in pillar stability. Ideally, this is verified by monitoring strata movements. Numerical modelling can provide insights not only to anticipated roadway deformation and support requirements but also as to aspects that may influence duty conditions for seals such as convergence, likely roadway failure modes and failure locations, etc. Experience in numerical modelling of stress conditions for successive longwall panels with the inclusion of criteria of limiting stress values aids selection of the location of seals as a factor in pillar size assessment. The limiting values may be derived through actual seal performance assessment and completion of modelling in the same package to derive the threshold. Indication of preferred location of the seal in the cut-through should also be possible.

Ground support and timing

Typically seals are installed after secondary support has already been installed. On initial development mining, the mining method (eg in place versus place change mining) and timing of primary support installation may impact levels of immediate roof delamination which can significantly impact the secondary support requirements and performance as well as ultimate roof behaviour. Data such as convergence (eg tell tale readings or roof extensometry) is typically taken at intersections and is relevant in considering variations in supported ground behaviour at different cut-throughs. Ongoing review and specification of ground support requirements, particularly in poorer ground can significantly impact on subsequent seal performance.

Rib control

Mines typically collect rib extensometry data to verify design and optimise rib support. Rib control in the cut-through locations where seals are to be installed can be critical, particularly at depth. Where softening depth is difficult or uneconomic to control, there may be little option other than to grout or inject the ribs. From experience, typically a distance of 10 - 15 m either side of the centreline of the seal (approximately twice depth of softening) may be required to circumvent leakage. In extreme cases, reinforcement, shuttering and pouring of artificial rib followed by pressure grouting through the artificial rib may be required. As an example, measured rib softening in excess of 7 m has been found. Following change to rib strapping rather than spot bolting (providing greater confinement), rib softening was reduced to 0.5 m. Such improvements can have a large impact on rib leakage around seals and overall integrity of the seal/rib contact and cut-through in general.

Mining height

Where mining height is less than seam height, an indication of the amount of roof and/or floor coal that will need to be dug out or cut down during development can be made on a localised scale and also included as part tender specification in provision of services for installation of seals by contractors.

Seam dip and cross-grade

Cross grade will determine whether water will tend to pool in roadways, against the inspected side of seals (with the seal on the downdip side of operations) or against the goaf side of the seal (with the seal on the uphill side of operations).

Panel grade

A long section profile with exaggerated vertical scale should be generated to identify those locations planned for seals which will act as collection points for water (swillies) and to enable estimation of maximum head of water that the seal may be subjected to before water will flow to a lower elevation.

Gas drainage

Where gas drainage is applied, there will be associated dewatering and potential coal shrinkage which may impact local strata conditions. Care should be taken to ensure that both surface and in-seam boreholes are sealed so that they do not represent potential leakage paths. Particularly where holes pass within 10 - 15 m of seal locations, rib grout injections should be used to minimise risk of leakage. Where coal shrinkage/delamination has occurred (also identified from tell tale or extensometry data), grouting the roof may also be required.

Other than in the area of modelling/assessing seal stress and roadway deformation criteria as part of pillar design, there appear to be limited opportunities for additional research likely to provide significant impact on seal performance.

SEAL DESIGN

Modelling

Pearson *et al* (2000) discuss at length the application of thick plate theory and numerical modelling in assessment of seal design and in determining critical factors influencing performance when subjected to overpressure. Factors such as seal height and the frictional resistance at roof and floor contacts are determined as the key drivers. Further refinement to customise the approach for the specific or generic panel roof and floor units is a potentially useful extension of the application. Modelling however appears an unlikely predictive tool for leakage modelling following an overpressure event as a number of other factors including ground conditions and seal/rib/roof/floor defects will also play a role.

Some stress monitoring has been undertaken in thick seam mining with partial (lower section) seam extraction to show stress magnitude and orientation in the longwall main-gate area. The general movement of immediate roof strata towards and then away from goaf, as well as variations in stresses at shear horizons in coal and stone were quantified. These lateral movements may be expected to significantly impact the integrity of seals, especially where the floor remains relatively static and the roof horizons move. This behaviour is in addition to any effect of loading on the pillars which will cause lateral rib expansion against the sides of the seals. Oyler *et al* (2001) completed a quantitative study of convergence experienced by longwall lightweight block dry stack stoppings and resultant lateral movements of the face of the stoppings during both first and second goaf loading from longwall operations in a three heading gateroad system. Load on the stoppings was also measured through a set of four flat jacks incorporated in the construction of one stopping. Physical properties of the blocks were tested and quantified. The findings generally confirm with the authors observations in thick seam conditions, however quantify the levels of movement and loading. It is only through acquisition and analysis of this type of data that more informed seal design and specification will be enabled.

A number of other important observations made in the Oyler *et al* study include:

- that minor structure played a significant role in influencing strata behaviour and loading of the stopping and that anisotropic loading may lead to premature failure;
- lateral movement up to ~30 mm for this type of stopping is possible without apparent substantial damage;
- that the stoppings could resist vertical loads of 2700 - 3000 kN (which was almost three times the maximum load able to be carried by an individual lightweight block);
- that insertion of a phenolic foam yield layer in the stopping allowed for initial convergence but also allowed some block rotation that reduced the capacity of the stopping to cope with convergence;
- that wedging of rows of lightweight blocks (ie providing lateral confinement/loading) plays a substantial role in the ability of the stopping to resist lateral and vertical loads.

The collection of this level of detail of data from an industry survey would be a positive step in provision of data upon which an empirical or mathematical modelling tool could be developed. A survey by Oyler *et al* regarding the perception of validity of this modelling by mining companies indicated that nine out of 14 are supportive.

Testing authority certification: what does it really mean?

There are differences in results derived from different testing authorities based on the physical geometry/dimensions of the authority, as well ad the resultant explosion. Oberholzer and Lyne (2002) describes this aspect in some detail. All facilities currently utilise physical explosion tests, although Sapko *et al* (2003) provides details of a hydrostatic test method which has recently been trialled.

It is worthwhile briefly revisiting the origins of overpressure specification of seals and assumptions made in conjunction with the values derived.

The National Institute for Occupational Health and Safety (NIOSH, 2001) report a brief summary of goaf gas explosions which occurred in US coal mines, resulting in destruction of goaf seals. Lightning strikes were identified as the likely energy source, with transmission to the goaf area postulated as steel cased boreholes. Stopping material fragments were strength tested to provide a guide as to the seal strength that may be required to avoid destruction. It was concluded that:

- seal strength of minimum 20 psi for mines without explosive mixtures of flammable gas and 50 psi for mines with explosive mixtures of flammable gas are appropriate;
- pressure balancing of the goaf to reduce oxygen ingress and size/opportunity of accumulations of flammable gas in the explosive range is required;
- deep steel casing connecting the surface to the goaf, particularly in the vicinity of locations where explosive mixtures of flammable gas may accumulate should not be used; and
- a high standard of stonedusting on the inside and outside of location of the seals prior to installation is required.

Relating each of these recommendations in turn to observed industry practice:

- Queensland has adopted specific overpressure standards, whereas New South Wales has adopted a less prescriptive standard;
- in regard to the necessity of pressure balancing, Pearson *et al* (2000) received a very mixed response to this as an essential requirement in a survey of Australian mines;
- in regard to steel cased boreholes in proximity to explosive gas risk zones, many Australian mines use goaf drainage and/or have fully cased surface boreholes adjacent to these areas; and
- observation suggests that industry typically does not follow this recommendation religiously, and that in many mines, rib spall may quickly negate the effect of once off stonedusting of ribs.

It appears that a majority of industry focus has been on the overpressure and leakage testing of seals based on the above recommendations; however, the recommendations are not generally implemented by the Australian industry. The industry might consider questioning the value of certification particularly in relation to the following:

- Various modifications (eg sampling pipes, bleed pipes, water traps, etc) being added to the seal certified by laboratory testing without additional test work. Note that doors are reportedly not considered by most suppliers as impacting integrity (Pearson *et al,* 2000), however no test results were made available to that survey.
- Procedures are not in place to ensure that seals are adequately constructed and maintained. The act of construction is not generally backed up with quantitative means of testing the seal or other means for confirming that a defect is not present. Ongoing compliance seems to be a significant issue that is largely without guidelines, somewhat overlooked and without sound controls.

Stephan (1990a and 1990b) reported in the United States Mines Safety and Health Administration – Ventilation Division, seal test work and the original mine explosion assessment and research work regarding the recognised standard for assessing damage to seals and identification of suitable means for repair and methods for recertification following repair.

Stephan (2004) indicated that:

> *Arbitrary decisions are made based on the visual observations of the seal's condition. Seals are to be maintained in a condition where they remain able to withstand 20 psi overpressure. The pass/fail nature of seal construction is based on the seal's ability to resist air leakage after impacted by such an overpressure. Small cracks may be okay but loose or missing blocks would cause the seal to be considered out of compliance. There is no damage assessment standard for seals. Suitable means for repair are not specifically identified.*

In response to the enquired as to whether Mr Stephan was aware of any work completed either as research or in the field in regard to relationships between load or convergence monitoring, damage to seals and assessment of ongoing explosion rating and or leakage, Stephan responded that:

> *A 'recertification' of repaired seals is not in place. If excessive leakage occurs, for any reason, repair or replacement of the seal will become necessary. There are no guidelines for how to accomplish this task and no specific definitions as to when repair or replacement is necessary.*

Site selection

Ideally, site selection within the cut-through is aided by analysis of data including stratigraphy (preferably derived from roof and floor core) and geological mapping (at detailed level). Floor grade, cross grade and water conditions require consideration and may influence the type of seal built at low points. Suitability of roof, floor and rib conditions and preferably a point of reduced width is useful. The flatness of floor and roof surfaces will also impact the ease of constructing and sealing the seal.

Ground and seal material properties

Coal mine strata are not always 'stiff' (eg coal, laminites and clays versus sandstones or conglomerates). Usually, the floor in a coal mine is more stiff than the immediate roof.

In civil engineering design, combined stiff and yielding systems rarely provide an appropriate solution for a given support problem. This leads seal material property specification into difficult choices, as most solutions are actually a combination of stiff and yielding systems. The yielding elements of the systems are usually limited in capacity and provided to allow absorption of a certain degree ground movement. The ultimate ideal balance is dictated by the service duty requirements of the individual mine.

To illustrate some of the advantages and disadvantages of seal material combinations, a brief summary description of US tested seal types follows.

TYPES OF SEALS TESTED IN THE LITERATURE

Solid block (stiff system) – Greinger *et al* (1991), Weiss *et al* (1993)

- 6 × 8 × 16' solid block;
- keyed to roof and floor with timber, wedged to the roof with timber to provide confinement; and
- use of central pilaster for span protection – critical in seal strength.

Cementicious foam seals – Greinger *et al* (1991), Weiss *et al* (1993)

Requires framing construction (typically props, battens, ply).

- Strength is subject to mixing, curing time and conditions during curing. Density/strength control is critical, and samples of the mixed foam should be taken and tested to verify strength.
- Can mix and pump some distance to use one location setup.
- Effects of water build up (especially acidic water) behind this type of seal should be avoided.
- Can increase friction between rib and cement plug by placing protruding rib bolts.
- Formwork and foam retention materials need to be removed to enable inspection of seal.

Lightweight (Omega 384 – glass fibre reinforced) and/or hollow block seals – Stephan (1990), Weiss *et al* (1993)

- Blocks are impervious to water and air leakage,
- cure time if bonding material is applied to blocks, and
- require hitching similar to that used for solid blocks

Wood block seals – Weiss *et al* (1993)

- Application in US in deeper operations where experience roof, floor or rib convergence (concrete block seals typically fail due to stiffness);
- typically only wedged into place row by row – require hitching;
- thick stonedust layer used to assist in rib sealing;
- stacked in direction of CT;
- sealant applied on goaf side of seal; and
- require additional retention to prevent *en masse* movement in event of overpressure.

Polyurethane foam/foam and sized aggregate with block walls (Micon) seals – Weiss *et al* (1996)

- Composite system between stiff outer walls, moderately yielding aggregate fill and fairly flexible polyurethane foam binder;
- only structural element of the arrangement appear to be the block walls – once destroyed only the friction of the core against the roof/floor/rib will prevent *en masse* movement;
- mixing in 1:1 ratio required of the polyurethane components needs to be accurate to meet density;
- it is critical to obtain correct aggregate/foam ratios – dry bagged/sized aggregate is used;
- surfaces need to be free of debris and duct between pours;
- foam may cause bulging of block walls during filling;
- need to wait for set between pouring subsequent courses;
- moisture/humidity is an issue in regard to bonding between polyurethane layers and/or roof/rib/floor surfaces;
- polyurethane is a fire hazard – more emphasis on fire resistance/requirement for external coating; and
- core thickness (related to seal height) is a key design issue.

Cellular (aerated) concrete – Weiss *et al* (2002)

- Density control an issue,
- ensuring fill to mine roof can be difficult,
- strength subject to curing time and conditions during curing,
- cold joints effectively a defect at higher overpressures,
- sensitive to method of poor, and
- woven steel reinforcement can provide significant integrity improvement.

Gunmesh and shotcrete walls with cementicious foam core fill – Mutton and Downs (1997), Weiss *et al* (1999)

- As per cementicious foam seals but with additional strength/confinement provided by the walls; and
- increased cost of seal.

Meshblock and shotcrete – Mutton and Downs (1997), Weiss *et al* (1999)

- Meshblocks are secured to the ground through perimeter bolting with protrusions into the middle of the block;
- the meshblocks reinforce the shotcrete; and
- cost is reduced in comparison to the previous seal type.

Significant experience and data gaps exist in regard to publicly available industry experience databases regarding conditions to which seals are exposed, in particular regarding load, convergence and rib expansion/spall. Some of this data may be available from geotechnical design verification/confirmation. There appears to be a paucity of good quality data regarding seal performance, as well as definition of tolerance limits for aspects of convergence, buckling and material properties of complete seals. The variations which exist in seal design (including crush blocks or timber, location of various pipes, doors and water traps) makes performance comparison difficult, and it also appears significant attention needs to be paid to geological variation.

GROUND PREPARATION

Key issues include aspects related to achieving appropriate keying in (including depth required) and/or setting of additional support as required for frictional resistance. Removal of loose floor and rib debris, as well as cutting into coal/stone to refusal (preferably removing all roof/floor coal) is critical for overpressure resistance and leakage reduction.

A formalised system of permitting of construction sites as described by Humphries (1999) is sensible, provides hardcopy records, adds control and can include a checklist for guidance. The permit also provides guidance in relation to seal specification, installation and inspection/approval following construction.

CONSTRUCTION METHOD

Construction method is normally in accordance with the supplier's procedure, which is typically based on engineering calculations, consideration of the material properties of the seal components and risk management approaches.

RECOVERY MEASURES

Consideration of recovery measures in the event that seal leakage and/or failure occurs in a given location requires consideration at planning stage and not after construction commences. Ideally, a strategy for each individual cut-through will be developed and when required, preparatory work completed as a part of seal construction. Examples of such works may include installation of rib reinforcement, excavation of keying in channels, construction of a containment wall on the goaf side of the seal so that the void between can be filled at a later date to create a plug seal.

Adequate space should be left for construction of another seal should the need arise.

In order to assist in dealing with leakage repair and/or development of a heating, controlled leakage measures (eg inclusion of pipe with a valve) may be used. This approach will allow for preferential leakage through the pipe, avoiding fractured coal zones and allowing completion of rib sealing.

CONSTRUCTION

Materials ease of use, logistics and handling for use underground and time for construction will be important. Control of material properties can be a critical factor, particularly where mixing grouts with water, two part resins, or needing control of placed density to ensure rating or integrity.

Particular consideration is required to be given to seals with materials that have a curing time prior to achieving full strength and/or rating. Control of conditions/environment in the seal installation location may be required (eg temperature, water, etc)

Identification of possible forms of construction defects (strength, voids, anchors, etc) needs to be completed prior to award and should be considered in the checklist and methods for reviewing construction activities and completion.

Again, use of a permit system to provide documentation, guidance in regard to critical factors influencing construction and resultant seal compliance with test certification and acceptance criteria/inspection records is essential. Humphries (1999) also indicates that a calculation of likely load on the seal from longwall abutment loading is also required. While of interest, unless the effective strength of a seal is known, as well as the impact of other factors, the factor of safety (and failure risk) for a seal cannot be estimated.

The mine typically remains responsible for evaluating, specifying and installing additional ground support required to protect the seal once installed. In particular, secondary support requirements will need to consider effects of longwall mining and opening stability, protection of the seal against convergence, protection of the ribs in vicinity of the seal and protection of mine personnel from seal failure/toppling should such and event occur.

Where poor rib conditions develop, additional increment/s of rib sealing may be required through grouting, application of polyurethane foam, or rib shuttering and forming with subsequent drilling and pressure grouting.

There may be an issue with timing of damage to the ground from development to first longwall abutment loading to side abutment loading to goaf reconsolidation to second abutment loading, requiring successive ground support review and response.

OPERATIONAL

Stonedusting

As noted previously, an important element of the US approach to limiting risk of overpressure from goaf explosion propagation into the gate-road via the seals is the application of incombustible dust.

Control of goaf gas composition and proximity of explosive mixture to seal

Control of goaf gas composition and proximity of explosive mixture to seal is dictated by a combination of the mine ventilation system, goaf gas drainage system and standards of seals.

Rate of seal completion

The ability to complete construction rapidly to match longwall retreat rate is important to avoid oxygen ingress to the goaf. It is noted however that construction of seals in the maingate up to hundreds of metres in arrear of the face will experience ongoing loading as the goaf reconsolidates. This behaviour has been clearly demonstrated by microseismic monitoring (Hatherly *et al*, 2003) at a number of sites and explains why damage can continue to occur to seals until the longwall face passes in excess of 500 - 600 m outbye.

Impacts of successive goaf loading

Impacts of successive goaf loading include response of installed secondary support and in particular the lateral movement towards and then away from the goaf as the second face passes the location of the seal.

MONITORING

Seals

Monitoring procedures include visual (dependent on type of seal), audible (leakage), air flow (ventilation reading, smoke tube), gas sampling – general body in the seal cut-through and from behind the seal, seal buckling/movement (from displacement of the face of the seal), load cell monitoring, convergence monitoring and rib softening monitoring.

Ribs, roof and floor

Visual indicators include spall, convergence/heave or water flow or bubbling from the floor. Open cracks may be observed, but deeper fracturing may be difficult t assess. Use of devices such as shear strips, etc may provide indictors of the progress and extend of rib damage. Convergence monitoring is also applicable. The mode of strata and seal failure needs to be carefully observed.

Inspection regime

Successful inspection regimes will include regular and appropriate frequency, and preferably use of the same personnel to complete inspections. Inspection without a specific checklist of matters to examine and record status will be far less effective than a well thought out and designed record sheet based one. Collection of goaf gas bag samples from behind seals is often included within the weekly seals inspection scope.

Ventilation, gas monitoring and spontaneous combustion

Aspects of routine monitoring of the mine ventilation and gas control systems including mine fan pressure and quantity, panel return pressure/quantity, panel return gas levels and various gas ratios and mass flow rates will all be useful in identifying changes in seal integrity. The reliability of gas monitoring systems also needs to be checked regularly.

An example of the effectiveness of a simple inspection system in a mine prone to spontaneous combustions and appropriate response is illustrated by Nicholls (2004) in the description of a minor heating which developed due to damage to a seal in the immediate goaf behind the longwall face.

MAINTENANCE

Consideration needs to be given to the type of maintenance that may be required and the materials and skills required to complete it.

There are a number of components to any seal, including; the seal wall (both overpressure rating and air tightness), devices and/or gauges fitted to the seal and pipes (including pressure gauges, level indicators or gas monitoring tubes/sensors), ground support around the seal, water traps, sampling tubes, inertisation pipes, the ribs, the roof, the floor, travel ways to/from the seal, pumping in access roadways and ventilation of the seal.

Many mines treat seal maintenance as an exercise in patching up cracks or recoating the external surface of the seal as a majority of the other matters form routine operational tasks.

The primary research need, as indicated earlier is in regard to the effectiveness of maintenance/repair and whether seal overpressure rating is retained. In this respect, there remains no clear guidance as to when a seal should be replaced.

In ACARP Report C10014, Oberholzer (2002) considers *in situ* test methods for ventilation structures. Initially consideration was focused on non-destructive tests, however it was broadly concluded that there was limited scope, and that destructive *in situ* testing (with portable test equipment) was preferred. Trevits *et al.* (2002) trialled application of ground penetrating radar (GPR) and Schmidt Hammer Tests (both non-destructive approaches) on cementicious seals. Some success was evident with both methods, and GPR in particular appeared to show promise. However, as Oberholzer concluded, the likely cost of equipment for approved use in assessment of *in situ* goaf seals is likely not prospective and the preferred approach is destructive testing in lower cost test galleries.

Significant further research is required to deliver means for assessment of seals in situ, for effective repair (outside of current practice) and means to be able to reassess seals as acceptable following repair. Further, means for assessing required replacement of a seal based on objective criteria is required.

INTEGRATION WITH OTHER MANAGEMENT PLANS

Consideration needs to be given to the integration with management plans that cover spontaneous combustion, gas monitoring, ventilation, gas drainage, strata management, longwall operations, mine inspection, extraction panel sealing and emergency response in order to streamline operational control and improve response and risk management. A particular example is means of provision of distribution of Tomlinson boiler gas for goaf inertisation. While the conversion and use of existing boreholes and pipelines is often proposed, the approach will not often be appropriate as the switch over/preparation time for unplanned incidents will often be so long as to allow the incident to escalate.

ISSUES FOR THE FUTURE

Australian underground coal mines are gradually becoming deeper and gassier. This requires greater care and emphasis in pillar, roadway and support design in combination with considerations for mine seals. At increased depths, floor heave and rib expansion/spall effects will also continue to increase in severity and increase risk.

Further, the industry appears to be embarking on the path of operating multi-seam longwall workings. Where the interburden between goaves is relatively thin (30 - 50 m), sealing the overlying goaf from the caved area of the undermining seam may be problematic, and new solutions will need to be found.

The push for productivity and cost reduction is driving a trend for longer and wider longwall panels, higher ventilation pressure differentials and a squeeze on both site based professional staff (in terms of both numbers and adequate time to appropriately complete all assigned tasks) as well as cost of seals and physical inspections.

A system design approach is essential for the future so that important issues are adequately considered at an early stage of planning to reduce reactional problem solving.

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