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THE CASE FOR DEVELOPING AN AUSTRALIAN TECHNICAL SPECIFICATION FOR STRUCTURAL DESIGN OF VENTILATION CONTROL DEVICES

Michael Salu[1] and Verne Mutton[2]

ABSTRACT: Ventilation management and control plays an essential part in underground coal mining. Failure of the ventilation system or failure of underground seals can lead to multiple fatalities and closure of a mine. Examples include: Moura No.2 (Qld, 1994); Sago (USA, 2006) and Pike River (NZ, 2010).

Following the Moura No.2 disaster, the Qld Dept. of Mines put new regulations in place specifying pressure ratings for various classes of Ventilation Control Devices (VCDs). They also initially specified that only VCD's that had been subject to "full scale testing" would be accepted for use in Qld mines. No guidance was provided on how the full scale test results were to be applied to the design of VCDs in the field. It is considered that an Australian Standard for VCDs should be developed to address commonly observed issues including:

- Factors of safety
- Design methodologies and designer qualifications
- Material properties, testing and verification
- Dual ratings for overpressure and water head
- Provision for inclusions such as access hatches, doors and pipes.

Australian Standards are extensively researched, peer reviewed and subject to public comment. The entire process typically can take from two to four years. An Australian Technical Specification is a one-tier lower document than an Australian Standard, produced by an expert committee on the basis of consensus. Although peer reviewed, it is not subject to public comment and could be completed within 12 months.

It is suggested in light of the critical importance of VCDs and the lack of any Governmental or Regulatory technical progress since 2001, that the Coal Mining Industry should pro-actively assemble an expert committee and prepare a business case to Standards Australia for development of an Australian Technical Specification for VCDs with a target completion date of June 2018.

INTRODUCTION

The mining of coal underground has historically (Department of Labour) been recognised as one of the more hazardous occupations in the world. It is a universally recognized principle of underground coal mine safety that there must be proper ventilation of the mine. Indeed, no aspect of safety in underground coal mining is more fundamental than proper ventilation.

Before developing an argument for supporting the development of a design standard for Ventilation Control Devices (VCDs) it is pertinent to suggest a definition for seals and stoppings. It could be argued that the following 100 year old definition for a seal is still relevant today and literature provides many similar definitions.

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Old Definition (Herbert Bucksch, 1998)*: "a tight seal partition or barrier of wood, rock, mud or concrete in mines for the protection against gas, fire and water."*

Seals are used extensively in mining to isolate worked-out areas and active fire zones. Stoppings separate the air streams in intake and return airways. It is worthwhile examining how VCD designs have evolved by examining in greater detail the milestones globally that have driven design changes in the last one hundred years. Explosions (Mutton and Remennikov, 2010) of gases and of coal dust have always been a basic hazard in coal mines and to this day continue to be the cause of disasters in coal mines where ventilation control is inadequate. The investigations and advancement of knowledge in VCD design and construction has tended to be driven by these disasters. There has been no significant review of VCD design in Australia since the Task Group 5 investigations after the 1994 Moura disaster. Following the Moura No.2 disaster, the Qld Dept. of Mines put new regulations in place specifying pressure ratings for various classes of VCDs. This prescriptive legislation requiring the construction of designed VCDs provides some level of insurance against an explosion breaching seals and stoppings. The damage incurred on a VCD by an explosion will be influenced by the magnitude and shape of the pressure-time curve. This is recognised by the coal industry in the United States following the enactment of the 2006 Miner Act and MSHA's issuance of the Emergency Temporary Standard (ETS) after the 2006 Sago disaster. There is now a set of guidelines, the "final rule" issued in 2008 for mine seal design (MSHA, 1996). During this period extensive research investigating various mine geometries and a range of fuel loadings showed that an increase in seal design load capacity was necessary to adequately protect mine workings against explosions.

Today the designer has much greater access to a variety of construction materials, live testing and numerical design methods. Mine operations provide the designer with the required overpressure ratings for any VCD based on legislation. Unless the designer has an understanding of the duty requirements of the VCDs and of the construction materials and methods then ventilation controls may become ineffective during their life-cycle. However there are still VCD design challenges due to many variables such as a requirement for dual design loads, barometric changes, transient loads and the changing condition of the incumbent strata. Despite the ability to live test VCDs and provide numerical design modelling there will always be a statutory requirement to systematically inspect VCDs in the mine operation and make provision for repair. There are many design challenges including: at what condition does the VCD no longer comply with its design rating and what repairs are necessary to reinstate the rating.

It is left to the individual mine operations to determine whether these over pressure ratings are sufficient to protect the mine workings. Gas monitoring and inertisation practises in Australian longwall coal mines minimise the possibility of the goaf passing into the explosive range. This paper will not investigate the level of protection that is required. An Australian technical specification for structural design of ventilation control devices would provide a design guideline regardless of the duty required of the VCD.

The Qld Dept. of Mines (Mutton and Salu, 2013) initially after the Moura disaster in 1994 also specified that only VCD's that had been subject to "full scale testing" would be accepted for use in Qld mines. No guidance[4] was provided on how the full scale test results were to be applied to the design of VCDs in the field. It is now accepted practise by regulators and some structural engineers that VCDs can be designed and rated using numerical methods. Development of numerical models for VCD design from the results of explosion testing can be quite different to design using structural analysis that uses inputs from seal and stopping material characterisation testing. A variety of structural design questions that have arisen during VCD design and certification would be addressed by a working group developing a technical design standard. Dual load ratings, factors of safety and numerical modelling will be expanded upon as a portion of the relevant questions to be addressed. Due to longwall mining retreating to the rise and impoundment of water, many goaf seals must be simultaneously rated for water loads up to 30 metres of water and explosion ratings up to 345 kPa (50 psi). The distinct differences in duty between water bulkheads and explosion rated seals will be discussed with the requirements for a dual rating.

For (Muttonb and Salu, 2013) the purposes of structural design, the loads are considered to be "ultimate" loads using terminology from Australian Standards and the design thicknesses derived from live test results are said to have a "safety factor" *greater* than 1. There are many design variables that will influence the safety factor adopted for VCD designs, with some of these listed below:

1. The condition of the roadway in contact with the VCD
2. The changing loads due to adjacent extraction that are difficult to define numerically
3. Whether the load is transient (explosion) or long-term e.g. water impoundment.

It will be argued that by using the framework provided by Australian Standards a universal standard for the provision of VCD design can be developed for Australian underground mines, overcoming a situation now where consistency of design guidance is uncertain. This would also assist operators to provide clearer definition of designs in commercial tenders. There are many types of standards and it must be decided which is more suitable for providing design guidance. Whatever is developed will require industry acceptance and needs to be completed in a suitable timeframe with the available resources, a challenge where people resources have been depleted in an industry wide downturn.

The challenge provided within this paper is to persuade the mining industry that a VCD design standard is required. Once this is accepted, funding and a motivated team will be required to make it a reality.

HISTORICAL BACKGROUND: THE LAST 100 YEARS OF VCD DESIGN

This discourse is a brief summary of events shaping VCD design that have led to the technology we use today to safely and economically control ventilation flow in underground mines. The Laurium silver mines of Greece, operating in 600 BC (Mutton and Remennikov, 2010), had layouts which reveal that the Greek miners were conscious of the need for a connected ventilating circuit. At least two airways served each major section of the mine and there is evidence that divided shafts were used to provide separate air intake and return connections to the surface. The first great textbook on mining, De Re Metallica, was published in 1556 in Latin by Georgius Agricola, a physician in a thriving iron ore mining and smelting community of Bohemia in Central Europe. A number of the prints show ventilating methods and controls that include diverting surface winds into the mouths of shafts, wooden centrifugal fans powered by men and horses, bellows for auxiliary ventilation and air doors.

Much historical literature on coal mining concentrates on the effects of the poisonous and explosives gases found in coal mines. From the seventeenth century onwards, papers began to be presented to the Royal Society of the United Kingdom on the explosive and poisonous nature of mine atmospheres. The onset of the industrial revolution and a rapid rise in the demand for coal had precipitated many disastrous explosions from methane and coal dust due to lack of understanding of the necessary ventilation controls and the nature of the combustible materials. In metalliferous mines many miners succumbed to the effects of "gas" i.e. carbon dioxide generated from oxidation of minerals and accumulated spoil in the workings. John Buddle (1773-1843), a mining engineer in northern England developed improved methods of ventilation control including providing layouts for discrete panels and separate intake and returns i.e. the first parallel circuits (McPherson, 1993). Decades later Atkinson in 1854 proved mathematically the improved airflow and reduced concentrations of methane from these circuits and modern ventilation theory was born.

In response (Mutton and Remennikov, 2010) to the alarming number of fatal explosions and fires in U.S underground coal mines the Bureau of Mines was set up on July 1st, 1910 (Tuchman and Brinkley, 1990). Likewise in Poland, from 1925 Experimental Mine Barbara conducted live tests on mine seal designs typically constructed in coal mines. Various other experimental mine facilities around the world e.g. Buxton (Great Britain) and Tremonia (Germany) also conducted live explosion tests in the absence of mathematical models that could adequately describe seal response to such explosions. Mine disasters in 1933 and 1960 prompted UK Commissions which reported it desirable that explosion proof stoppings be designed to withstand explosion pressures of 20 to 50 psig (140-345 kPa).

In 1980s Europe monolithic seal designs were being developed using pumpable (Underground coal mining safety research materials) such as concrete, Gypsum, anhydrite, Flyash and Bentonite replacing the rocks, bricks, timbers, sand, dust, and cement which had been commonly used for seals. During this time, gypsum based products were preferred by British, Czechoslovakian, and German coal miners who believed them to be the most effective, easiest to use, and least costly. In1981 the National Coal Board developed a two component high yield grout that was used for gate-side packs on advancing longwalls and for seals.

It was in 1930 that experimental work involving measurement of seal response to explosions was carried out by the U.S Bureau of Mines. This was the beginning of understanding structurally what influenced the performance of ventilation seals when subjected to an explosion overpressure. There was also no means to physically measure and define seal response to real time explosion impulses. In the USA sealing unused and abandoned areas was a common practice in coal mines prior to World War II. The few seals (bulkheads) since built were principally in areas having a potential for spontaneous combustion. Historically, “explosion proof" has been a consensus interpretation. For example, the 1921 regulation for sealing connections between coal mines on U.S. Government-owned lands required that stoppings withstand a pressure of 345 kPa (50 psig). This was the earliest known standard for seals in the United States and the main concern during this period was that sealed areas needed protection from ignition of gases that emanated from working areas. In the USA the Federal Coal Mine Health and Safety Act of 1969 required that such areas be ventilated or sealed with explosion-proof bulkheads. Later research at the United States Bureau of Mines (USBM) showed that seldom, however, do pressures 200 feet and more from the origin of an explosion exceed 140 kPa (20 psig) unless coal dust accumulations are excessive and the incombustible content of the dust is less than required by law.

In the United States, since 1971, statute 39 CFR 75.335 (Mine Safety and Health Administration – Title 30 Code of Federal Regulations, 1997) had required a seal to “withstand a static horizontal overpressure of 20 psi (140 kPa). Since 1986 there had been 12 known explosions within the sealed areas of active United States coal operations where seals were destroyed. In some of these explosions lightning was suspected as the ignition source. Later events in 2006 would put the 1971 statute into question. It was also recognised by 1990 explosive mixtures could form behind the seal because of leaking air from the working areas. There was potential for explosion pressures greater than 20 psi (140 kPa) with ignition sources from falls of roof or spontaneous combustion in the goaf. The Mine Improvement and New Emergency Response Act (“MINER Act”) required the Mine Safety and Health Administration (MSHA) to increase this design standard by the end of 2007 due to tragic accidents at Sago, WV and Darby, KY Mines in 2006 caused by methane explosions behind sealed off areas (Mutton and Salu, 2013). Following the enactment of the 2006 Miner Act and MSHA’s issuance of the Emergency Temporary Standard (ETS) more stringent performance standards have been adopted for mine ventilation seals (Mutton and Remennikov, 2010). There is now a minimum standard of 345 kPa (50 psi) (designed, constructed and maintained) for a specific pressure-time curve, when the atmosphere inside the sealed volume is monitored and maintained inert. In the United States more commonly pressure rated seals have a capacity for 827 kPa (120 psi) in line with the findings of the NIOSH study entitled, “Explosion Pressure Design Criteria for New Seals in U.S Coal Mines” (Zipf, Sapco and Brune, 2007). The findings of this report have challenged globally established beliefs in seal design and explosion propagation. The research that followed these disasters provides guidance on the scenarios that will generate explosion pressure/time impulses.

Extensive use of computer aided numerical analysis provided a range of designs for use in the USA using a variety of materials over a wide range of explosion pressures.

Many seals and stoppings, although designed as explosion rated, often unintentionally impound heads of water. Seals expected to withstand a hydraulic head (bulkheads) have unique design characteristics. The loads are often long term (not transient) and the condition of the strata holding the seal is critical and deterioration and leakage can occur over time. Much emphasis is put on designing strata injection programs to seal the surrounding strata. Care must be taken that when adjacent mining increases vertical abutment load, these loads do not severely impact the bulkheads stability. Designs must have the ability to impound water where subsidence breaches surface aquifers. With longwalls extracting to the rise the use of water holding bulkheads is increasing.

After the Moura No 2 Mine explosion in 1994 (Mutton and Remennikov, 2010) there were changes to mining legislation in Queensland that required all VCDs to have been tested in an internationally recognised laboratory. In 1997 at Lake Lynn Experimental Mine, Tecrete Industries (designed an explosion seal and stopping test program in which instrumentation was introduced for the first time for measuring the structural response of VCDs when subject to transient loads (Weiss, Cashdollar, Mutton, Kohli and Slivensky 1999). Using linear variable transducers, accelerometers and carefully situated overpressure monitoring, live test data was captured that would be useful to enable the design of VCDs in a wide range of roadway sizes and pressures ratings ranging from 14 kPa (2 psi) to 345 kPa (50 psi). Using this data, numerical models were developed to facilitate the design of a wide range of VCDs. There have been various live test programs since 1997, which provided measurements of structural response that could be used to develop engineering design tools for a range of VCD designs. Design is now undertaken with sophisticated computer based numerical analysis. However building representative numerical models (meshes) with suitable material properties and interpreting the results of analysis requires considerable experience and structural knowledge. Although most VCDs in Australia are now designed by professional engineers, there is a variation in design practises and outcomes with no design methodology common to the coal industry in Australia.

STANDARDISATION OF VCD DESIGNS AND WHY IT IS IMPORTANT

Standards generally go unnoticed (Gibbons, *et al*, 1992)

"*They are mostly quiet, unseen forces, such as specifications, regulations, and protocols that ensure that things work properly, interactively, and responsibly".*

Development of standards came about during global industrialisation at the end of the 19th century. Now standards govern the design, operation, manufacture, and use of nearly everything for products that are produced around the world. Construction of VCDs in the underground coal industry and metalliferous mines is typically either carried out by contractors or in-house workers. Design certification in Queensland and New South Wales coal mines is provided by Registered Professional Engineers Queensland (RPEQ). In-house development of VCD construction techniques and operating procedures results in a variety of outcomes for mining companies. As there is no agreed or available standard there are currently widely different design methodologies and design approaches used.

What is a standard?

The International organization (ISO/IEC GUIDE 2:2004) for Standardisation (ISO) and Electro-technical Commission (IEC) Standard (ISO/IEC) Guide 2 defines a Standard as a:

"document, established by consensus and approved by a recognised body, that provides, for common and repeated use, rules, guidelines or characteristics for activities or their results, aimed at the achievement of the optimum degree of order in a given context. Standards should be based on the

consolidated results of science, technology and experience, and aimed at the promotion of optimum community benefits."

Standardisation (according to Xie, *et al*, 2016) is the process of implementing and developing technical standards based on the consensus of different parties that include commercial organisations users, interest groups, standards organisations and governments. In a more general sense, standards help to codify best practices, methods and technical requirements, contributing to the community demand for a safe and sustainable environment, a point not lost on the coal mining community. Standards are intended to promote compatibility, interoperability, quality and safety. It is very important that VCDs consistently perform the way they were intended to over their life span.

For engineers and ventilation practitioners a standard would define quality and safety criteria in a common language setting achievable goals in a practical way. A Standard or Technical Specification would provide a platform for regular reviews which would be required to keep pace with technological advances. Use of design standards is common place in the building and construction industry with government, industry and the community as stakeholders. Of the VCD design research including live testing instigated after mine disasters the question must be asked; is this material reviewed and updated at regular intervals? The outcome from developing a "consensus" standard or design is that any design innovation has a platform for inclusion enabling the ideas to be used by the whole mining industry. The development of a standard is a rigorous, structured and formal process that can satisfy the requirements for:

1. Voluntary or mandatory applications (achieve as a minimum objectives of safety, quality and performance)
2. Regulatory compliance
3. Contracts
4. Guidance

Standards may provide guidance for: products' definition, materials, analysis and design, material testing, construction and maintenance. As an entity a standard has no legal status or requirement for compliance. It can be cited in legislation and commercial contracts. A recent example is the NSW code of practice: Strata control in underground coal mines, which is an approved code of practice under section 274 of the Work, Health and Safety Act 2011(NSW Government 2015).

STRUCTURAL DESIGN QUESTIONS FOR THE CODE COMMITTEE OR ITS WORKING GROUP

It is suggested that the following topics could provide a suitable starting point for issues to be addressed by a technical committee or working group:

a. Scope

The suggested scope for a Technical Specification (TS) is to cover structural design of VCDs, including VCDs that may also impound water (bulkheads). The VCDs will be limited to those constructed in underground drifts and roadways i.e. anchored all around by roof, ribs and floor strata. It is not intended to include underground dams, although they could be added later. Aspects such as inspection, construction and maintenance would only be addressed to the extent that assumptions required for design purposes, need to be specified.

b. Materials of construction

Traditionally, a wide variety of materials has been used for VCD construction underground. The purpose of a Technical Specification is not to limit materials or techniques but to provide scientific guidelines (known as performance specifications) that define the expected performance characteristics. For example, a VCD should be resistant to fire as well as to overpressures. Some materials are better suited for long-term durability or to withstand strata convergence and a TS will provide guidance and "best practice" as well as minimum structural requirements.

c. Types of underground structures

Initially, the TS should be limited to the more common and arguably most straightforward types of underground VCDs, including: stoppings, seals, overcasts and air locks. Dual-function VCDs, designed to impound water as well as resist blast pressures are also reasonably common and have many similarities with VCDs. Other, more exotic structures such as so-called "coffin seals", machine doors, water storage dams and high-head bulkheads are seen as being outside the scope of the initial TS.

d. Use of material testing data and live testing data in numerical modelling

Full-scale live explosion testing performed both in Australia and overseas has demonstrated that the structural behaviour of VCDs subjected to a short burst of high pressure while being fully confined by the surrounding strata is complex and does not follow any simple structural rules. A combination of complex structural behaviour and varying material properties when subjected to shock loading means that it is difficult to extrapolate the usual small scale test results (for example from slowly crushing concrete test cylinders) to real VCD behaviour.

A wide variety of approaches that have been applied to this issue over the years results in an equally wide variety of outcomes. Modern computer simulations are able to use limited live test data to produce useful predictive models. However, the approach is generally too time consuming and expensive for routine VCD design tasks. This is a difficult question to resolve, as it is also tied in with commercial interests of VCD suppliers who are understandably reluctant to provide access to privately funded research into this question.

e. Design loads

Currently in Australia where VCD design pressures are specified by State Mining Authorities, they are called up as uniform (and presumably static) pressures. Design pressures called up in Regulations are tabulated below:

Table 1: Statutory design pressures in native units

New South Wales (NSW)	20, 120psi
Queensland (QLD)	14, 35, 70, 140, 345 kPa

If the above design pressures are standardised to metric units, the following matrix provides the above information in another form:

Table 2: Statutory design pressures comparison

State	Statutory Design Pressure (kPa)					
	14	35	70	140	345	830
NSW	No	No	No	Yes	No	Yes
Qld	Yes	Yes	Yes	Yes	Yes	No

Note that neither dynamic factor nor pressure/time history is stipulated by either authority. Current industry practice appears to be to adopt the above specified pressures as nominal uniform static pressures. That is, they are not considered "explosion pressures" for design purposes. Recent research in the USA has shown that dynamic and confining effects can significantly amplify explosion pressures. Pressure/time curves have been produced for both gas and coal dust explosions, based on that research. The TS committee should consider how design loads are to be interpreted and then codify their findings to eliminate uncertainty. This process may, in turn, lead mining regulators to review VCD design overpressures in light of recent overseas research recommendations.

f. Factors of safety

Questions regarding Factors of Safety (FoS) to be applied when designing VCDs are one of the most common issues raised by Ventilation Officers and others responsible for VCD construction. This would be one of the most important issues to be addressed by a TS and a single clear set of guidelines would provide significant benefits to the underground mining industry. As an example, in late 2016 a major Australian coal mine released a tender for VCD and bulkhead design and construction covering a wide variety of roadway sizes and four (4) pressure ratings. Thicknesses (and costs) were requested for each combination, a total of some 30 different VCDs. However, there was no mention anywhere in the 20-page tender document of what factor of safety (if any) was required for any of the VCDs or bulkheads. In response to a query regarding the FoS for this tender, the mine initially didn't know and then appeared to hedge their bets by specifying a range of different FoS to be applied to all of the VCDs and bulkheads. This resulted in a tripling of the amount of work required to calculate all of the requested data, for each of the prospective tenderers. The selection of agreed FoS will be a challenging task for a TS committee but there is a wide range of literature available for guidance, including existing Australian Standard AS1170. Decisions on an appropriate FoS must be made based on a sound engineering basis, so that they can provide a balance between cost of implementation and risk of failure.

g. Design life and importance

The expected design life for a VCD will influence its cost, as a short-term structure can usually be more lightly constructed than a permanent structure with the same level of overall safety. There is no known information on any current design life guidelines or requirements for underground structures other than seals which are to be designed "for the life of the mine". In central Queensland, several mines were originally designed for a twenty year design life in the 1970s and 1980s. These mines are currently still operational due to improvements in mining technology over that period. They now face the challenge of infrastructure that is 40 years old as well as the question of what design life should be specified for new structures.

As previously described, there are a variety of VCDs in underground mines, performing various tasks. These can range from directing ventilation to permanently sealing off goafs or adjacent workings. An "Importance Factor" (IF) is one concept that structural engineers have used in other fields to help quantify these types of differences. The IF could include an allowance for the expected design life and would potentially form part of the calculation to determine the appropriate FoS for a VCD or underground structure.

h. Structural behaviour

As discussed briefly in Item "d" above, full-scale explosion testing of VCDs has shown that these devices exhibit complex structural behaviours. Depending on their configuration, VCDs can resist blast pressures using a variety of mechanisms (Pearson, *et al*, 2000):

- **Sail** Flexible so-called "sail" stoppings act purely in tension just like a sailboat sail (Figure 1). These are typically only suitable for low-pressure stopping applications.

- **Plate** VCDs constructed from thicker material will tend to flex slightly under load and carry blast loads by bending. (Figure 2). Such VCDs require significant flexural strength and/ or thickness to carry loads.

- **Flat Arch** as VCDs increase in thickness, the bending mechanism starts to give way to an arching mechanism (Figure 3) where the loads are carried primarily in compression rather than bending.

- **Plug** Relatively low compression strength materials can be used for VCD construction if they are thick enough. These form a plug, which resists loads through direct compression and internal shear strength as well as shear resistance along the roadway contact. (Figure 4)

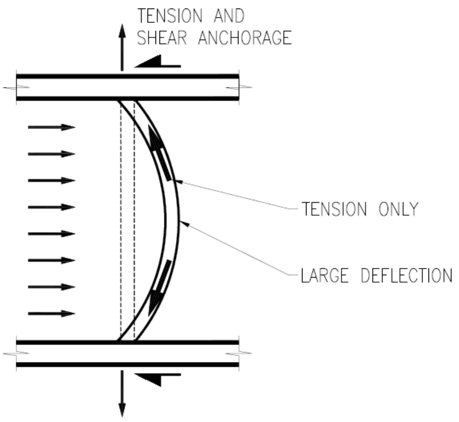

Figure 1: Sail mechanism

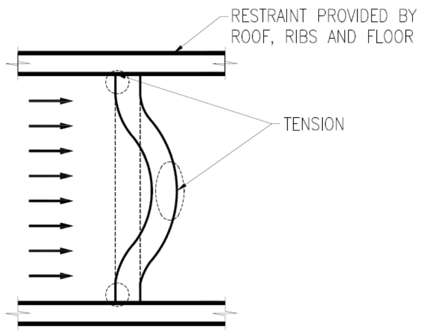

Figure 2: Plate mechanism (Pearson)

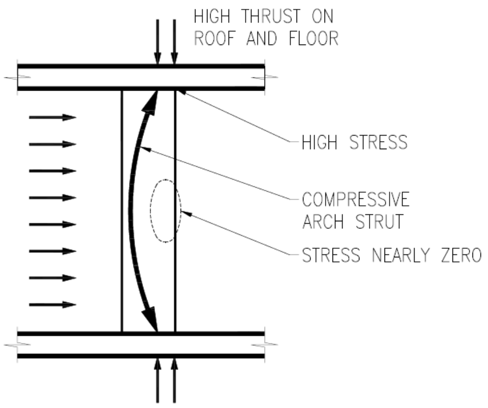

Figure 3: Arch mechanism (Pearson)

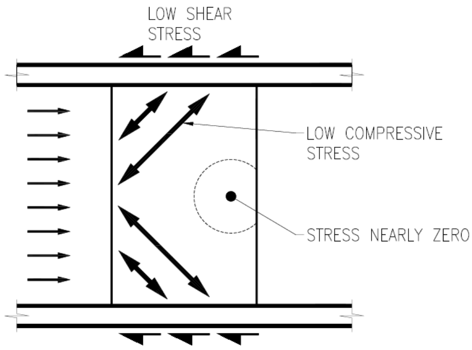

Figure 4: Plug mechanism

In practice the plate, arching and plug mechanisms form a continuum of varying structural behaviour, which makes simple modelling unreliable. However, through parametric studies, guidelines are available in the literature regarding the transition points between these systems. A TS committee could develop simplified rules using, for example, height to thickness ratio to provide guidance to engineers for structural modelling of VCDs. As mine drifts and roadways are typically limited to between 2.5 to 4.5 m high and 5 to 6 m wide, the work required to perform such a study would be well within the scope of an ACARP-sponsored report.

i. Design and analysis methods

Several Australian Standards (AS) covering structural designs provide for a “tiered” approach to structural analysis and design. In other words, there is allowance for simplified methods to be used to produce well understood routine designs. For more complex or unusual designs, guidelines are provided in those AS for more detailed methods of analysis.

A TS for structural design of VCDs could similarly provide a simplified design section, perhaps limited to stoppings or to short-life structures. Some design codes provide design charts and tables for routine design tasks and it may be possible to incorporate similar information into a TS for VCDs.

j. Designer qualifications and responsibility

Currently, Queensland Mining Regulations require that VCDs are designed and certified by a Registered Practicing Engineer, Queensland (RPEQ). In NSW, the requirement is for VCD’s to be designed “fit for purpose”, which is a vague term to use for something as important as a VCD. There is also a requirement in NSW15 for “Structural rating (of seals) to be to a standard acceptable to the Chief Inspector of Coal Mines”.

It is suggested that design responsibility for VCDs should rest with a suitably qualified and experienced structural, mechanical or mining engineer. The Institution of Engineers, Australia (I.E. Aust.) already provides suitable oversight of engineering qualifications and experience at a professional level, which provides the starting point for this section. A designer should be able to demonstrate a body of work, relevant to design of VCDs, which would provide a level of assurance to mines that the “experienced” part of the “qualified and experienced” requirement was achieved. It may be that Mining Schools could provide short courses in VCD and bulkhead design to meet potential demand for appropriately trained engineers? Another option could be to recommend that for critical life of mine VCDs with a pressure rating greater than say 300 kPa, an independent engineering design review should be performed prior to construction of the VCD.

k. Geological/Geotechnical issues

Geotechnical aspects of VCD design are very similar to geotechnical issues for footings of surface structures. Provision of geotechnical engineering advice for VCD design is generally provided by mining geologists. In some cases, their exposure to structural engineering has been limited and a TS could include a section outlining the geotechnical information that VCD designers require.

A working underground mine is a dynamic, changing environment and geotechnical factors will change over time even though the overall geology of a mine site is fixed. VCD and bulkhead effectiveness can be very heavily influenced by local, minor geological features and therefore a pre-construction site inspection by an experienced mine geologist is essential prior to construction of long-term or high-importance structures. Some of the issues requiring geotechnical/geological advice include:

- Overall site suitability for the proposed VCD
- Strength of floor, ribs and roof strata
- Likely degree and timing of roof convergence or floor heave
- Potential for gas or water leakage around the VCD (through the strata)
- Recommendations for strata injection, if required

l. Robustness and siting

Robustness is not a new concept in design. In the past it has formed a key part of rules of thumb that were widely used for structural design prior to modern physics-based methods. However, over-reliance on physics has led the Australian Loading Codes Committee to formally re-introduce in 2002 the concept of robustness into Australian/New Zealand Standard AS/NZS 1170.0. The best way to illustrate robustness is using an example of a plaster stopping for a 6 m wide roadway, 4.5 m high, which was reportedly designed (by a qualified engineer) to be 60 mm thick. Putting aside the question of suitability for ventilation pressures, a plaster stopping of that size and thickness has virtually no capacity to withstand accidental impacts from plant, light vehicles or even from loosely stacked materials falling onto it. Specification of minimum thicknesses for plaster, grout and concrete VCDs would be one method of incorporating robustness requirements into a TS. The influence of siting is very important but is sometimes overlooked even by experienced underground miners. The structural capacity of a VCD relies on it being solidly connected to the roof, ribs and floor. This assumption on the strength of the strata can be compromised by the proximity of adjacent workings. Although each situation is different, rules of thumb that are currently used by various mines to specify minimum distances to roadway intersections or niches could be reviewed, assessed and codified by a TS committee to provide a consistent set of guidelines to the industry.

m. Durability

Long-term durability of VCDs due to underground environmental effects is influenced by a number of factors:

- Underground hazards such as strata movement, spontaneous combustion, corrosive mine water, corrosive gasses and accidental impact
- The material properties of the VCD and its fixings (if applicable)
- The applied hydraulic loads in the case of water bulkheads. An explosion in the goaf although not breaching a seal could affect its durability.

As each mine will have a unique combination of durability hazards, these will need to be assessed on a case by case basis. A TS would provide guidance and recommendations based on the best available industry and research information, for each particular hazard.

n. Provision of inclusions such as doors and pipes

The interface between VCDs and access doors of hatches has been a “grey” area for some time, in terms of design responsibility. Typically, VCD hatches and doors are designed, fabricated and tested independently of the VCDs of which they are intended to be part. The VCD designer typically assumes at first that the VCD will be a uniform structure with no openings. In practice, doors and hatches are required in many VCDs, even if they are later intended to be permanently sealed. It may appear to be obvious that for a VCD to be rated to a particular overpressure, a door or hatch should be rated to the same or higher pressure. But there is a need for an appropriate FoS for doors and hatches and any limitations that should be placed on their use and positioning.

It is not uncommon for mines to request two doors to be placed in a VCD. Knowledge is available of an incident where a mines Inspector found a VCD with three doors installed with a subsequent engineering assessment reporting that the overall VCD strength had been significantly compromised. As a result of the engineering assessment, one of the openings was permanently and rigidly sealed in order for the VCD to achieve the required pressure rating.

Cast-in pipes for water or gas drainage and tube bundles for gas monitoring are also required to penetrate VCDs. These are typically a maximum of 150 – 200 mm diameter and do not have as dramatic an effect on VCD strength as doors or hatches. However, a concentration of pipes could create a weak spot in a VCD, potentially compromising its strength. The Qld Mines Inspectorate produced Mines Safety Bulletin No. 107 in 2011, which stipulated maximum pipe sizes and minimum spacing. This appeared to have the intention of minimising the risk of creating a weak point in a VCD through prescriptive means. That document would provide a useful starting point for a clause in a TS that could be expanded to include doors, hatches and potentially other built-in items.

o. Dual functionality VCD/bulkheads

When a roadway is constructed on a slope, there is always the potential for seepage water to collect on the uphill side of a VCD. Typically this is of minor concern unless the VCD has not been constructed from water-resistant material. Once a goaf is permanently sealed, there are limited options for inspecting the inbye side of a seal. Such seals often have U-tubes fitted to allow drainage of water from behind the seal without allowing gas transfer. The height of the U-tube above the floor will limit the water head behind the seal. However, sometimes valves are also fitted to the U-tubes to control water flows and in those cases water build up behind a seal can be significant in terms of structural loading on the VCD. The short, sharp pressure on a VCD from an overpressure event is quite different to the sustained pressure from impounded water. Water pressure will also be higher at the bottom of a VCD than at the top, compared with uniform blast pressure. Large bodies of impounded water behind seals will attenuate a shock wave from an explosion, however the momentum imparted to that body of water will still effect the rigid body of the seal. There is limited information available in technical or research literature regarding methods for designing VCDs to retain water. In the authors' experience in Australian practice, individual mines will request a variety of FoS for water-retaining VCDs ranging from 1.5 up to 4.Some mines request a dual rating i.e. an overpressure rating and a separate maximum water head rating. Other mines ask for the overpressure rating to be added to the water head pressure and then the total resultant pressure is required to have a FoS applied to it. This can lead to very high design pressures and consequently very substantial and expensive structures. The question of extending the TS work from dual-purpose VCDs to bulkheads intended purely for impounding water will be one to be decided by the committee, depending on available resources and expertise. The authors believe that in the interests of time, at this point standardisation of bulkhead design might be best left to a future update or perhaps a separate publication.

p. Construction requirements

When a VCD is designed, there are a number of assumptions regarding construction that are inherent in the design process. The purpose of specifying particular construction requirements in a TS is to highlight the critical factors that will affect the strength of a VCD. Some examples of these include:

- Use of depth gauges for sprayed VCDs
- Cylinder strength testing for concrete VCDs
- Manufacturers certificates for rated inclusions
- Geologist and mine undermanager or ventilation office sign-off on VCD location

q. Inspection, testing and maintenance

Once a VCD has been constructed in accordance with its design specifications including any drawings, responsibility for maintenance of the VCD passes to the mine. Without proper maintenance, the designed pressure rating of a VCD cannot be guaranteed indefinitely.

Regular inspections must be performed on VCDs during their life, with the frequency depending on the use, life expectancy and importance of a VCD. Regular monitoring will ensure that any developing issues can be addressed as soon as they occur and will significantly reduce the risk of an unexpected, sudden failure. Visual inspections are expected to be the predominant form of regular VCD inspections, as they are at present (when implemented). Several Non-Destructive Test (NDT) methods have been used successfully on completed VCDs and bulkheads, to verify their construction and structural condition. NDT testing could be specified at longer intervals for less important VCDs, or more frequently for operationally critical VCDs.

r. Modification, strengthening and repairs

Any modification, strengthening or repair of a VCD should be carried out under engineering supervision and ideally with input from the original VCD designer. A TS could provide examples of minor modifications, strengthening or repairs that do not require a full engineering assessment. This could include, for example, repair of minor damage to a sail stopping resulting from accidental impact. For more extensive modifications, such as installation of machine doors or strengthening (up rating) a 5psi (35kPa) stopping to say a 20psi (140kPa) seal, these should always be subject to a full engineering assessment similar to that for a new structure.

DEVELOPMENT OF A DESIGN STANDARD

As previously discussed at the start of this paper, production of an Australian Standard is time-consuming, in part because of the stringent requirements for public consultation and peer review. A Technical Specification is also peer reviewed but does not require mandatory public comments and therefore can be brought to publication more quickly than a Standard. Using a recent (2015) example, the concrete fastener industry produced a 96-page TS within 12 months. They did have an expert committee already formed together with support from both the I.E. Aust. in Victoria and Swinburne University.

Another, lower-tier option is to develop a Mine Design Guideline (NSW) or Mine Safety Bulletin (Qld). These might be quicker and easier to put together but will not achieve the objective of preparing a single unified document that can eventually be used anywhere in Australia.

Developing a Code of Practice (CoP) is another possibility. A CoP is a practical guide to achieving the standards of health, safety and welfare required under various WHS and Mining Acts and Regulations. The NSW CoP for Strata control in underground coal mines runs to 102 pages and specifically addresses how to meet regulatory requirements (NSW Govt. 2015). The Australian CoP for Ventilation of Underground Mines was drafted in 2011 by Safe Work Australia but does not appear to have progressed since the draft stage. (Safe Work Australia 2011)

The first step in developing a TS must be to assemble a group of individuals with the desire to develop this project further. Ideally, the widest possible representation from industry, consulting, suppliers and academia should be sought with the aim of assembling an expert panel that has the knowledge and expertise to develop the proposed Technical Specification.

Standards committees are generally run on a voluntary basis, with only a part-time project manager assigned by Standards Australia to help manage the processes but not to contribute directly to production of the standard or TS. Under SA procedures, a TS is prepared by an expert Working Group, which is a sub-set of an existing Standards Technical Committee. Thus the underground coal mining industry would need to find a sponsor this particular TS and to overview the publication of the TS.

Ideally, some members of the initial interest group will have had previous experience on Code committees or contacts on existing committees that could be useful in finding a suitable structural committee to oversee production of a Technical Specification for Structural Design of VCDs.

The list of issues that should be addressed by a Code of Practice can be made as short or as long as the Committee decides it should be. In practice, structural design Standards vary from thick documents covering all aspects of detailed design through to slim manuals providing basic information to experienced practitioners. One of the first tasks for a Working Group will be to decide what level of detail will be included in the document to be produced.

CONCLUSION

It is critically important to maintain an effective, safe and efficient ventilation system in an underground coal mine and ventilation control devices (VCDs) play an essential role in mine operations and safety. It is therefore concerning that no agreed or accepted standard exists for the structural design of VCDs. With no required design standard in place, design of VCDs in Australia is currently performed in accordance with individual engineer's understandings and preferences. The result is that VCDs that are designed for identical applications can vary widely in their construction details. At best, this represents wasted resources where VCDs are over-designed and at worst under-designed VCDs will fail when they are exposed to explosion or water pressures. The effectiveness of a VCD to perform its function is dependent on a variety of factors, only one of which is design. These factors can be summarised as follows:

- Geology
- Siting
- Design
- Materials
- Construction
- Inspection and Testing
- Maintenance

It is proposed that a Technical Specification for Structural Design of VCDs should be developed by the industry to address all of the above issues. Future review of the Technical Specification can be undertaken so that new developments in technology can be shared within the industry. This will provide a higher level of safety to underground miners by minimising the risk of VCD failures.

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