ACARP

Australian Coal Association Research Program

Australian Roadway Development Improvement Project

REVIEW OF THE CIVIL TUNNELLING AND UNDERGROUND METALLIFEROUS SECTORS

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1. EXECUTIVE SUMMARY

1.1 Background

The report was commissioned in May 2006 by Australian Coal Association Research Program (ACARP) as part of a series of initiatives aimed at improving roadway development performance. The report is specifically targeted at identifying what technology, equipment, systems and practices being utilised in the underground metalliferous and civil tunnelling sectors could potentially be applied to improve roadway development performance in Australian longwall mines.

1.2 Key Observations

Key observations in respect to the potential application of underground metalliferous and civil tunnelling sector technology, equipment, systems and practices in Australian longwall mines are:

1.2.1 Underground Metalliferous Sector

- In 2003/04, it was estimated that approximately 600 km of roadway development was undertaken in Australian underground metalliferous mines, with drill and blast being used almost exclusively. Approximately 200 km of that development was completed by mining contractors.
- Typical development rates achieved by mine operators were 30 m/week/jumbo (range 20-40 m/week) in single entry drivages, with mining contractors achieving 40-55 m/week/jumbo (up to 50% higher rates were achieved in multiple entry drivages). Such rates are unlikely to encourage coal mine operators to seriously consider drill and blast as a viable alternative to existing longwall gateroad development practices, unless other factors such as a high propensity for outburst precludes utilisation of continuous miners.
- Roadway development costs of $4,000/m were the norm in 2003/04, with costs reportedly increasing by 50% since that time due to increases in labour, material, fuel and capital costs. Again, these costs are unlikely to encourage serious consideration of drill and blast as a viable alternative to existing longwall gateroad development practices.
- Roadways are typically mined 5-6 m wide and 5-6 m high in Australian underground metalliferous mines to allow large, high capacity equipment to be applied across all facets of the process, particularly high capacity (>50 t) haul trucks. Further, the nature of the orebodies being mined and the bulk extraction processes being adopted typically results in spiral access declines and levels being mined in surrounding waste rock at depths of up to 1,000 m.
- The adoption of larger profile roadways potentially creates space in the immediate working environment to facilitate the application of other technologies, or higher capacity systems (including larger diameter, higher capacity ventilation ducting).
- Metalliferous mines typically excavate arched roadways to form a stable roadway profile, thereby minimising roof control issues that would otherwise result if flat backs (roofs) were mined.
- Metalliferous sector original equipment manufacturers (OEMs) produce a range of equipment that could, subject to addressing compliance issues, be readily adapted and applied in the coal sector in the event that drill and blast mining methods were employed. However, greater potential probably exists to apply discrete automation and remote control technologies that are routinely used on metalliferous equipment to coal sector equipment and processes.
- Cycle times for drill and blast operations allow in-cycle shotcreting to be utilised as a skin reinforcement technique in lieu of steel mesh, while initial trials of thin skin liners showed considerable promise in reducing in-cycle curing time and may also offer improved application methods as compared to shotcrete and/or fibrecrete.

- Flexible ducting and forcing ventilation systems are used almost exclusively, with 1.4-1.6 m diameter 32-25 m^3/s variable pitch axial flow fans typically being utilised, with 1.4-1.6 m diameter fire resistant anti static (FRAS) ducting being readily available.

1.2.2 Civil Tunnelling Sector

- In 2003/04 it was estimated that approximately 25 km per annum of tunnelling would be completed in the Australian civil tunnelling sector for the period 2004-08 inclusive, with tunnels of greater than 2.0 m diameter averaging 14 km per annum over that period. It was also estimated at that time that typical excavation costs of a two lane civil (roadway) tunnel was averaging $20,000/m.
- Current projections are that with a subsequent 50% increase in labour, consumable, and equipment costs since then, that the “all-up” costs of a two lane civil tunnel were now typically $100,000/m, including capital, excavation and support/lining costs. While the installation of permanent ventilation, traffic control and remote monitoring systems in such tunnels makes direct cost comparisons with coal and metalliferous mines difficult, it is noted that rates currently being quoted for 27m^2 cross section main access drifts in the coal sector are of the order of $21,000-$28,000/metre.
- Civil tunnels are typically constructed in and around urban areas to extend or ease congestion on major infrastructure such as roads, railways and subways, water supply and sewage systems, power distribution and communication networks, with such infrastructure being designed for a 50-100 year service life. This necessitates that appropriate safety factors be applied in design to ensure that construction of tunnels does not adversely impact on existing urban facilities (eg; Lane Cove Tunnel), and that tunnels remain serviceable with minimal maintenance requirements throughout their service life.
- Although considered to be inflexible and require major infrastructure for mobilisation and disassembly, tunnel boring machines (TBM) are considered to be the “equipment of choice” for civil tunnels greater than 500 m length, unless highly variable ground conditions are likely to impact their effective utilisation, or the proposed tunnel cross section is not compatible with available TBM configurations. This inflexibility includes limited ability to reconfigure entry dimensions once design and manufacture of the TBM has proceeded.
- TBMs are individually manufactured in accordance with site specific geological conditions and tunnel design parameters. Each TBM is in effect a prototype, with extensive modifications sometimes being necessary to address design issues and/or optimise performance. Refurbishment of used TBMs is sometimes preferred as a means of shortening lead times and to capitalise on earlier modifications and enhancements to the TBM.
- TBMs are particularly favoured where there is only single portal access to a proposed tunnel, as multiple portals or entries (eg; shafts) will allow multiple roadheaders to be deployed to offset the higher advance rates of TBMs (eg; Cross City Tunnel, Sydney).
- TBMs now achieve sustained production rates of up to 1,200 m/month over the life of a project (eg; Blue Mountains Sewer Tunnels), with an experienced Australian TBM contractor proposing that sustained rates of 400 m/week were achievable in coal roadway development. It was also considered that achievement of higher development rates would be limited by the overall availability of TBMs.
- TBMs are not self-powered and cannot retreat, and require disassembly chambers to be pre-constructed in order to facilitate their disassembly and potential redeployment. Strategies would need to be developed to facilitate their rapid redeployment on completion of gateroad development, otherwise any benefits achieved from higher advance rates may be quickly lost.
- Civil tunnelling contractors and OEMs generally consider that there are no technologies, equipment or systems that the coal sector may wish to develop and apply for improving roadway development performance that had not already being developed and applied in the civil tunnelling sector.

- It is likely that technology available today would allow roadheaders to be more effectively utilised for longwall gateroad development than in past attempts, particularly technologies that enable operation of the roadheader to be fully automated and operated remotely, coupled with boom mounted automated bolting rigs. While roadheaders may be less productive than continuous miners, the level of sophistication of remote control technologies on roadheaders is was reportedly far more advanced than that of continuous miners.
- As is the case with underground metalliferous mining, it is unlikely that drill and blast technology and practices currently utilised in the civil tunnelling sector could be seriously considered as an alternative for existing continuous miner based roadway development systems, unless some other factor necessitated adoption of drill and blast, ie; a mine's inability to operate continuous miners due to the mine's outburst propensity.
- Civil tunnelling projects apply higher levels of technical resources throughout the tunnelling process, from project design and tender preparation through mobilisation and establishment, excavation, support, lining, and fit-out, with few matters being left to chance, particularly in respect to defining the geological/geotechnical environment and managing the associated risks.

1.2.3 Civil Construction and Surface Mining Sectors

- Like the mining sector, the civil construction sector is faced with severe shortages of skilled operators, however it is embracing technology as a means of combating those shortages.
- Contractors in the surface mining sector are utilising minesite training simulators to train new operators to work safely and productively with large expensive equipment and overcome severe shortages of skilled operators.

1.2.4 High Capacity Longwall Mines of the Future

The L15 project currently being undertaken by CSIRO on behalf of ACARP is studying the strategic implications of high capacity longwall mining in Australia. It is anticipated that the study will identify that the number and size of gateroad entries required to ventilate high capacity (>10Mtpa) longwalls will be key determinants in respect to any "new technology" roadway development system.

Longer, wider and higher longwall blocks are expected to generate significant emissions and will require high ventilation quantities, even if predrainage of seam gas is routinely adopted. High velocities and significant pressure losses are likely if existing twin entry, 3-3.5 m high roadways continue to be adopted, with high pressure differentials across pillars separating intake and return roadways potentially exacerbating spontaneous combustion risks.

An alternate to the more widespread adoption of three entry gateroads is to excavate higher and/or wider twin entry gateroads. Ventilation efficiencies are available if larger, circular or arched roadways are excavated, while maintenance of a two entry gateroad system minimises the sterilisation of reserves in chain pillars.

The adoption of a single entry system utilising say a standard "metro" size TBM (6.9 m diameter) would also result in significant improvements in ventilation efficiencies, as would a 6.2 m high, semi-circular arched (roadheader) roadway 6.9 m wide.

Potential options for technology development in a single entry roadway development system could include:

- enhancement of the existing continuous miner platform with an integrated and automated bolting and support system, combined with a continuous haulage/extensible conveyor system;
- enhancement of the existing borer miners as utilised in Canadian potash mines with an integrated bolting and support system, combined with the enhancement of existing continuous haulage/extensible conveyor systems as utilised in those (potash) mines;
- a purpose designed TBM with an integrated bolting and support system, combined with enhancement of existing continuous haulage/extensible conveyor systems as utilised in the civil tunnelling sector;

Considerable attention will be required in all such systems to adequately and effectively ventilate the advancing roadway, with multiple, in-series, high pressure fans likely to be used, potentially with some form of dust scrubbing incorporated therein.

In addition to the above technological developments, a multiple entry system would most likely require development of a system to more effectively interconnect roadways for ventilation, coal clearance, communication and egress, by either:

- introducing some form of articulation into the CM to allow it to break away the cut through more effectively;
- modifying the cutter head and/or chassis configuration and/or roadway width to improve the geometry of the break away process;
- in the event of higher roadways being mined, increasing the machine height and reducing its length/chassis configuration to improve the geometry of the break away process;
- introduction of a specialist cut through machine ie; narrow head continuous miner or augering system;
- integrating current “state of the art” machine guidance and remote control systems to remove operators from the break away process entirely.

Operators of older, lower capacity longwall mines are likely to face significant challenges to remain competitive with higher capacity, lower cost mines, and are also likely to be constrained by infrastructure limitations coupled with deeper, gassier reserves. Therefore they are likely to face equally as significant ventilation challenges, albeit at lower production levels.

It is therefore anticipated that they are equally likely to pursue similar technology based solutions to such challenges, although infrastructure limitations may obviate the utilisation of say large diameter TBMs. Hence their focus is likely to be on optimisation and enhancement of continuous miner based systems, or even on introduction of borer miner systems should it be possible to incorporate automated bolting systems into that platform.They are also equally likely pursue systems that will enable them to more effectively interconnect roadways for ventilation, coal clearance, communication and egress.

1.3 Conclusions

- The underground metalliferous, civil tunnelling, civil construction, and surface mining sectors all utilise enabling technologies that could be applied in the underground coal sector to improve roadway development performance. Potential technologies and applications include:
  - integration of current state-of-the-art machine guidance and control systems to enable continuous miner operating functions to be automated during the break-away process to ensure consistency, repeatability and reliability of breakaways without the need for highly skilled operators;
  - similarly, integration of current state-of-the-art machine guidance, sensing and control systems to enable continuous miners to be operated remotely from a non-hazardous environment, and/or to be operated free of delays due to the operator’s inability to sight the position of the cutter head and machine body relative to the roof, floor and sides, or other persons;
  - utilisation of extensible conveyor systems to facilitate the continuous operation of continuous miners, TBMs and roadheaders;
  - incorporation of carousel bolting systems to continuous miner mounted drill rigs (as is reportedly being progressed by Joy Mining Machinery), as a precursor to the potential development of other automated bolting systems;
  - the application of drill control systems for remote, semi automated operation of miner mounted drill rigs;
  - the adaptation of carousel drilling systems for continuous miner mounted cable bolting systems, potentially including cable storage and insertion systems;
  - application of remote control technology to enable shuttle cars and continuous haulage systems to be operated remotely from a non-hazardous environment;

  - application of immersion technologies to train operators in the safe and productive operation of roadway development equipment.

- Benefits that are likely to result from the application of such technologies include:
  - a reduction in equipment damage, and hence increased machine uptime and lower maintenance costs;
  - higher consistency and repeatability of automated operating functions, without the need to employ highly skilled operators;
  - the removal of operators from the immediate, unsupported face area, resulting in fewer injuries and fatalities at the face area;
  - reduced exposure to and incidence of manual handling injuries associated with handling of drills and ground control consumables;
  - potential improvements in operating rates.

- There could be significant benefit from driving larger dimension roadways in all phases of mine development including:
  - lower ventilation pressures and hence lower mine ventilation costs, and reduced risk of spontaneous combustion in mines so prone;
  - avoiding the development of a third entry in longwall gateroads and subsequent formation of a second row of chain pillars;
  - ability to utilise larger diameter and less resistant ventilation ducting;
  - potential to restructure the continuous miner and enable the fitment of automated bolting and material handling systems;
  - potential application of higher capacity coal haulage and material distribution systems.

- TBMs could provide an integrated roadway development system, particularly in punch longwall applications. However indicative costs ($21-22M) may limit there immediate and widespread application in the underground coal sector unless it can be demonstrated that significantly improved development rates can be achieved.

- The application of TBMs in gateroad development will pose a number of regulatory challenges, particularly in relation to equipment certification and approvals of flameproof and intrinsically safe apparatus, the use of high voltage sub-stations and motors in the hazardous/ explosion risk zone, and single entry drivage and the provision of emergency escape;

- Ishikawajima-Harima Heavy Industries (IHI) and Pacific Tunnelling have both developed engineering concept designs for application of TBM tunnelling technology to underground coal mines, while other OEMs (eg; Herrenknecht, Lovat, Robbins, Wirth) are also likely to pursue any such initiative. Experienced civil and mining contractors also expressed interest in participating in any such initiative (eg; John Holland, Leighton, McConnell Dowell, Walter).

- Application of TBMs (and other integrated high capacity development systems) will require a major reconsideration of how the roadway development process is managed, with the current level of management resources being applied at most mines being insufficient to ensure the technology is both utilised at, and performs to a level that could sustain the high capital cost;

- Utilisation of TBM-experienced mining and/or tunnelling contractors will be necessary to ensure that the technology, equipment, systems, expertise and skills that are available can be transferred to and developed within the coal sector in an effective, efficient and sustainable manner.

- Existing borer miners and continuous haulage/extensible conveyor systems as utilised in Canadian potash mines could, with integration of on-board bolting and support systems be utilised as the basis of an integrated, high capacity roadway development system in Australian coal mines.

- Conventional widehead continuous miners could, with further enhancement, similarly be utilised as the basis of an integrated, high capacity roadway development system.

1.4 Recommendations

1.4.1 What ACARP should do to facilitate the transfer of relevant metalliferous and tunnelling technology and practices to improve roadway development in Australian longwall mines:

- Establish a roadway development technology work group to further identify how relevant "enabling technologies" from the underground metalliferous and civil tunnelling sectors could be applied to improve roadway development performance.
- Conduct economic and technical evaluations of various entry configurations including two entry/high (partially out-of-seam) roadways and three entry/low (in-seam) roadways to determine which configuration of roadways is likely to address ventilation and gas management issues associated with future high capacity longwalls (>10Mtpa).
- Commission an appropriate organisation (eg; Parsons Brinckerhoff, or Terratec) to conduct a feasibility study on the potential application of TBMs for punch longwall gateroad development, such study to also assess the performance capability of TBMs utilising "temporary" support systems such as rock bolts and mesh as typically utilised in coal mines (as opposed to permanent lining systems such as shotcrete and mesh or concrete segments).

1.4.2 What mine operators and mine managers should do to improve development performance, particularly in relation to the potential transfer of relevant metalliferous and tunnelling technologies and practices:

- Continue to embrace and expand the application of process control and continuous improvement principles and practices as a means of developing management capabilities that can effectively capitalise on the development of alternate, high capacity roadway development technologies, equipment and systems.
- Adequately resource the management of roadway development functions and adopt a proactive management philosophy that leaves little to chance.
- Personnel interested in rapid excavation and tunnelling practice should consider attendance at the biannual Rapid Excavation and Tunnelling Conference being held in Toronto, Ontario, Canada, 10-13 June 2007, or alternatively, visit the website (www.retc.org) to obtain copies of past conference proceedings.
- Monitor the progress of Tunconstruct, a four year A$42.5M study recently implemented by the European Commission to develop innovative underground construction technologies, to identify any technological innovations in underground construction that may be transferred to the underground coal sector.

2. INTRODUCTION

2.1 Background to the Report

This report was commissioned in May 2006 by Australian Coal Association Research Program (ACARP) as part of a multi-faceted Australian Roadway Development Improvement Project which was developed as an extension to an earlier ACARP project to address various recommendations contained within that project report[1]. In particular, this report specifically addresses recommendation 7.10 regarding the identification of technology, equipment, systems and practices being utilised in the civil tunnelling and underground metalliferous sectors that could potentially be applied to improve roadway development performance in Australian longwall mines.

In 2004 ACARP's Underground Committee recognised that current development rates were failing to keep up with advances in longwall production, and that the introduction of a systems approach to roadway development initiated in 1995 had not delivered the promised doubling of development rates. Further, the industry was then (2004) envisioning 15 Mtpa mines within the next decade. A roadmap based on the research and development of new roadway development equipment and technology was formulated and, based on strong support from relevant senior corporate executives, the ACARP Roadway Development Task Group (RDTG) was formed.

Focussing on the key elements of roadway development, namely coal cutting, roadway support, coal clearance and logistics, the RDTG structured the initial phase of the project to:

- identify where past wins had been achieved and what lessons had been learnt;
- identify opportunities for research and development of new technologies, equipment and associated systems; and
- gain support and commitment for a targeted 7 year research and development program.

GaryGibson&ASSOCIATES was selected by the RDTG to conduct the initial phase of the project, with work commencing July 2005. The initial scope was subsequently extended to include the current Australian Roadway Development Improvement Project, which includes the following initiatives:

- Conduct Roadway Development Benchmarking studies on a six monthly basis as a means of engendering improved roadway development performance across the industry (recommendation 7.1).
- Conduct a Roadway Development Operators' Workshops on a six monthly basis, culminating in a Roadway Development Operators' Conference early 2008, to provide a forum where development practitioners share successes and failures, and learn of new practices, developments in R&D, and emerging best practice (recommendation 5.3).
- Conduct a Roadway Development Strategy (New Technology) Workshop aimed at developing a high capacity, integrated mining system capable of sustained continuous production at a level of 10 or more metres per operating hour (MPOH) for greater than 20 hours per day (recommendation 8.2).
- Conduct and report on a Review of Metalliferous Mining and Civil Tunnelling Sectors, as above.

Each of the above elements is to be separately reported, as appropriate.

2.2 The Approach Adopted

Due to the extensive nature of both the civil tunnelling and underground metalliferous sectors in Australia and overseas it was determined that desktop investigations would initially be conducted to identify if there were technologies, equipment, systems and practices being utilised in the tunnelling and underground metalliferous sectors that could potentially be applied to improve gateroad

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[1] Gibson GA, GaryGibson&ASSOCIATES, *Australian Roadway Development – Current Practices, 17 October 2005,* Australian Coal Association Research Project, Project C15005, Brisbane, 2006

development, with further investigations by way of site inspections being undertaken in the event that relevant technologies, equipment, systems and practices were identified.

The approach to the study comprised three main components as outlined below:

- An extensive literature review of civil tunnelling projects and underground metalliferous mine operations in Australia and overseas, including relevant conference proceedings and industry publications, coupled with limited interviews and discussions with Australian tunnelling and underground metalliferous contractors and mine operators.
- An extensive literature review of civil tunnelling and underground metalliferous original equipment manufacturers' (OEMs) product information in Australia and overseas, coupled with limited interviews and discussions with OEMs.
- Attendance at the 2006 Goldfields Mining Exposition in Kalgoorlie to view and inspect relevant technology and equipment, and to meet with metalliferous sector research co-ordinators and researchers at the Minerals and Energy Research Institute of Western Australia (MERIWA) and the Kalgoorlie School of Mines (Curtin University).

2.2.1 Literature Review

Major literature sources are detailed in Section 8. It is noted that extensive use has been made of the internet to identify relevant articles and publications, with these sources being directly referenced throughout the report, as appropriate.

Industry newsletters such as Mining News and Construction Industry News have also been extensively reviewed, together with industry journals such as Mining Monthly and Contractor. Aspermont Ltd is acknowledged for their support in making the above sources readily available.

The Australian Tunnelling Society is also acknowledged for their extensive listing of Australian tunnelling projects and for the direct participation by a number of its members in the study process.

2.2.2 Review Participation

In all, some 60 persons participated in the review process by way of face-to-face or telephone interviews, including representatives from the following organisations:

- Mining and tunnelling consultants; Coffey Mining, Parsons Brinckerhoff Australia, SRK Consulting, Terratec.
- Mining equipment OEMs; Atlas Copco, Prairie Machine Parts (Saskatoon, Canada), Sandvik.
- Mining hardware and consumables suppliers; Dywidag, Elliot Ventilation Services, Jennmar, Protan Ventiflex, Stratacrete.
- Mining industry regulators; Department of Natural Resources, Mines and Water (Qld), Department of Primary Industries - Mineral Resources (NSW).
- Research organisations; CSIRO Queensland Centre for Advanced Technologies, Minerals and Energy Research Institute of Western Australia (MERIWA), Kalgoorlie School of Mines (Curtin University).
- TBM OEMs/developers; Herrenknecht AG, Ishikawajima-Harima Heavy Industries (IHI), Pacific Tunnelling, Terratec.
- Technology suppliers; Nautilus International, Remote Control Technologies.
- Tunnelling and mining contractors; John Holland Tunnelling and Underground Mining, Leighton Contracting, Leighton Contractors and Baulderstone Hornibrook Belfinger Berger Joint Venture (North-South Bypass Tunnel, Brisbane), MacMahon, McConnell Dowell, Roche Mining, Walter Diversified Services.

An alphabetical listing of review participants by surname is detailed in Section 9. Each of those participants is acknowledged for their contribution to the process.

2.3.2 Observations

During the interviews practices were observed or commented upon which are felt to be of real value to this report, however these observations may reflect cultural and experiential attitudes, opinions and actions rather than verifiable facts. An apology is offered if any party or individual considers that they have been incorrectly or inappropriately reported.

2.3 Report Structure

The remainder of this report is structured as follows:

- Key observations made during the review are detailed in Section 3;
- Overall conclusions are detailed in Section 4;
- Recommendations for further investigations and research are detailed in Section 5;
- Detailed observations and findings in relation to the civil tunnelling and underground metalliferous sectors are contained in Section 6;
- Observations in relation to the potential application of underground metalliferous and civil tunnelling technology, equipment, systems and practices in relation to future high capacity longwall mines are contained in Section 7;
- A bibliography is detailed in Section 8;
- A list of participants is included at Section 9.

3. KEY OBSERVATIONS

3.1 Underground Metalliferous Sector

3.1.1 In 2003/04, it was estimated that approximately 600 km of roadway development was undertaken in Australian underground metalliferous mines, with drill and blast being used almost exclusively. Of that development approximately 200 km was completed by contractors.

Underground metalliferous mines in Australia mine a variety of ores including copper, diamonds, gold, lead-zinc-silver, nickel, and tin, either in discrete or massive orebodies. In 2003/04 there were some 78 underground mines in operation throughout Australia, with one third (25) of those mines being operated in conjunction with or as an extension of an open cut mine (current statistics indicates an increase in the number of underground mines in WA, from 41 to 44 since 2003/04, with the number of solely underground mines increasing from 21 to 28 over that period)

In 2003/04, 21 mines reported a processing plant capacity of greater than 2 Mtpa, of which only 9 mines were solely underground mines, while 36 mines reported a processing plant capacity of less than 1 Mtpa, of which 27 mines were solely underground mines.

In comparison to the relatively flat, extensive, two dimensional coal seams typically experienced in Australian coal mines, metalliferous ore bodies are generally highly variable, discontinuous and geologically complex, and require a three dimensional mining strategy to exploit the resource. Underground metalliferous mines are typically accessed via 1:7 to 1:9 spiral declines for ore haulage and men and material access, with the declines being excavated in the country rock, rather than within the ore body. Levels are then excavated to provide lateral access to and throughout the ore body, with stopes being formed between levels to extract the ore.

3.1.2 Development rates of 30 m/week/jumbo (range 20-40 m/week) were typically being achieved by mine operators in single entry drivages and up to 40-55 m/week/jumbo by contractors. 50% higher development rates were being achieved in multiple entry drivages driven in close proximity, or the in development of declines from the surface which resulted in fewer operational constraints. Development rates were reported to be particularly impacted by shotfiring limitations such as end of shift firing.

A contractor noted that in a large scale mining operation utilising 3-5 drill jumbos on development, overall development rates of 1 km/month were being achieved.

Given the level of productivity achieved with drill and blast in metalliferous mines, and further limitations placed on the use of explosives in coal mines, it is unlikely that drill and blast would be considered as a roadway development option in coal mines, unless an alternate development system was required for mining in areas highly prone to outbursting (eg; grunching).

3.1.3 Roadway development costs of $4,000/m were the norm in 2003/04, with costs reportedly increasing by 50% since that time due to increases in labour, material, fuel and capital costs.

Again, these costs are unlikely to encourage serious consideration of drill and blast as a viable alternative to existing longwall gateroad development practices.

3.1.4 Roadways are typically mined 5-6 m wide by 5-6 m high in Australian underground metalliferous mines to allow large, high capacity equipment to be applied across all facets of the process. Further, the nature of the orebodies being mined and the bulk extraction processes being adopted typically results in access declines and levels being mined in surrounding waste rock, at depths of up to 1,000m.

Compare this with the underground coal sector where the industry is perhaps constrained by long held paradigms to limit roadway height to seam height or less in order to minimise dilution, or to say a height of 3-3.5 m in thicker (>4 m) coal seams.

Recognising the limitations imposed by such roadway heights, some mines are now mining three entry gateroads in order to improve ventilation characteristics associated with longer, wider longwall faces. Mining two-entry, 5-6 m high roadways (partially out-of-seam or even in-seam roadways in thicker seams) significantly improves ventilation characteristics in comparison to low height, dual intake, and single return gateroad panels, as illustrated in Table 1 below.

Table 1: Evaluation of Ventilation Efficiencies in Two and Three Entry Gateroads[2]

Assumptions
Pillars 100 m X 40 m centres
K factor belt return = 0.012 Ns^2/m^4
K factor travel road intake = 0.007 Ns^2/m^4
Stopping resistance with man doors every pillar = 500 Ns^2/m^8
Negligible shock losses
Minimum air requirement of air at last line of C/Ts at panel completion = 45 m^3/sec

Panel Configuration	**Twin gateroads**	**Twin intakes, single return**	**Twin gateroads**
Roadway Dimensions (m)	**5.2 X 3.0**	**5.2 X 3.0**	**5.2 X 5.0**
Panel Length (m)	4,000	4,000	4,000
Quantity Last C/T (m^3/s)	45	45	45
Quantity Panel Entry (m^3/s)	80	75	63
Pressure at 1C/T (Pa)	1,200	800	250
Panel Efficiency (%)	56	60	71
Panel Air Power (kW)	96	60	16
Panel Length (m)	3,000	3,000	3,000
Quantity Last C/T (m^3/s)	45	45	45
Quantity Panel Entry (m^3/s)	67	63	56
Pressure at 1C/T (Pa)	740	500	170
Panel Efficiency (%)	67	71	80
Panel Air Power (kW)	50	31.5	9.5
Panel Length (m)	2,000	2,000	2,000
Quantity Last C/T (m^3/s)	45	45	45
Quantity Panel Entry (m^3/s)	57	54	51
Pressure at 1C/T (Pa)	450	290	110
Panel Efficiency (%)	79	83	88
Panel Air Power (kW)	26	13	5.6

Proper economic analysis is warranted to evaluate the relative cost benefit of twin-entry, 5-6m high gateroads as opposed to low, in-seam three entry gateroads, including any economic benefits that arise from higher levels of recovery of reserves associated with a single chain pillar (two entry system), as compared to multiple chain pillars (three entry system).

3.1.5 The adoption of larger profile roadways could potentially create space in the immediate working environment to facilitate the application of other technologies, or higher capacity systems (including larger diameter, higher capacity ventilation ducting).

As noted above, mining 5-6 m high roadways potentially creates space in the immediate working environment to facilitate the application of other technologies by enabling the body of the machine to be extended in height, thereby potentially reducing the spread of components along the machine chassis within the existing machine envelope, thus freeing up space between the cutter head and machine body to improve roof and rib bolting ergonomics and/or allow the application of automated bolting systems (eg; carousel bolters).

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[2] Rowland JR, Dallas Mining Services, Personal Communication, November 2006

3.1.6 Metalliferous mines typically excavate arched roadways to form a stable roadway profile, thereby minimising roof control issues that would otherwise result if flat backs (roofs) were mined.

Consideration of arched profiles may also be warranted in coal mines, particularly if out-of-seam, large profile roadways were to be considered, as above. Such a profile replicates the arched section typically formed after a fall of laminated roof material in many coal mines, a profile that generally remains stable over time.

3.1.7 Metalliferous sector OEMs produce a range of equipment that could, subject to addressing compliance issues, be readily adapted and applied in the coal sector in the event that drill and blast mining methods were employed. However, greater potential probably exists for the application of discrete automation and remote technologies that are routinely used on such equipment, to coal sector equipment and processes.

The metalliferous sector has advanced the automation and remote operation of underground equipment to the extent that LHD units can be operated from the surface, or multi-boom jumbos can drill out a full face free of any human intervention, once the machine's initial alignment is established. Further, roadways can be bolted with a wide range of roof control products, including cable bolts, with the operator only leaving the air conditioned operator's cab to recharge the 8–10 bolt bolting carousel. Extension of drill control technology to the bolting rigs may ultimately allow bolts and cables to be installed to a pre-determined design with minimal human intervention.

Potential opportunities for applying discrete, metalliferous sector automation and remote technologies to coal sector equipment and processes include:

- integration of current state-of-the-art machine guidance and control systems to enable continuous miner operating functions to be automated during the break-away process to ensure consistency, repeatability and reliability of breakaways without the need for highly skilled operators;
- to similarly apply current state-of-the-art machine guidance, sensing and control systems to enable continuous miners to be operated remotely from a non-hazardous environment, and/or to be operated free of delays due to the operator's inability to sight the position of the cutter head and machine body relative to the roof, floor and sides, or other persons;
- application of remote control technology to enable shuttle cars and continuous haulage systems to be operated remotely from a non-hazardous environment.
- incorporation of carousel bolting systems to continuous miner mounted drill rigs (as is reportedly being progressed by Joy Mining Machinery);
- the application drill control systems for remote, semi automatic operation of miner mounted drill rigs;
- the adaptation of carousel drilling systems for continuous miner mounted cable bolting systems, potentially including cable storage and insertion systems;

Adaptation and integration of these latter, bolting related technologies may pose challenges whilst coal mines continue to be constrained by current mining height paradigms.

A further equipment design philosophy utilised in metalliferous mines worthy of potential consideration in the coal sector is the dual diesel/electric drive system used on face drills, roof bolters and cable bolters. Equipment is fitted with a diesel drive system for high speed, flexible access throughout the mine, with the drilling and bolting systems being power off an electrical system reticulated throughout the immediate face workings.

3.1.8 While improved operating rates (MPOH) did not necessarily result from the application of automation and remote control technologies, significant benefits were realised.

Specific benefits realised by mine operator and contractors include:

- a reduction in equipment damage, and hence increased machine uptime and lower maintenance costs;
- higher consistency and repeatability of automated operating functions, without the need to employ highly skilled operators;
- the removal of operators from the immediate, unsupported face area, resulting in fewer injuries and fatalities at the face area, and;
- reduced exposure to and incidence of manual handling injuries associated with handling of both drills and ground control consumables.

3.1.9 Cycle times for drill and blast operations allow in-cycle shotcreting to be utilised as a skin reinforcement technique in lieu of steel mesh, while initial trials of thin skin liners showed considerable promise in reducing in-cycle curing time and may also offer improved application methods as compared to shotcrete and/or fibrecrete.

Cycle times for continuous miner based roadway development systems would disallow adoption of in-cycle shotcreting in the coal sector, even if such a technology was considered appropriate.

Thin skin liners (TSL) trialled in the metalliferous sector[3] showed considerable promise as an alternative skin reinforcement technique, however vapours generated during application and curing have limited their adoption. Further development of this technology would be necessary to enable TSL to be utilised as an alternative skin reinforcement technique in both the metalliferous and coal sectors.

3.1.10 Flexible ducting and forcing ventilation systems are used almost exclusively, with 1.4-1.6 m diameter 32-25 m^3/s variable pitch axial flow fans typically being utilised, with 1.4-1.6 m diameter FRAS ducting being readily available.

Continuous mining in coal results in the generation of dust throughout the entire cutting and loading cycle as opposed to drill and blast operations which generate high quantities of shotfiring fumes and dust instantaneously during an unmanned phase of operations, with ongoing generation of dust being controlled by wetting of muck piles prior to and during the mucking cycle. Further, typical metalliferous advance rates of one 3-4 m round per shift and a lack of seam gas may not necessitate such a close attention to face ventilation as is necessary in continuous mining.

The fitment of dust scrubbers to continuous miners, in addition to fitment of on-board bolting rigs, could enable a forcing ventilation system to be utilised together with flexible ducting, potentially improving the cooling effect of intake ventilation on workers in the immediate face area. The alternate option of utilising a continuous miner mounted forcing fan with flexible ducting extending to the return is perhaps not practical, unless all face operations were remotely operated or “silent” fans were developed, and measures were devised to ventilate places in the event of power outages or maintenance activities.

3.2 Civil Tunnelling Sector

3.2.1 In 2003/04 it was estimated that approximately 25 km per annum of tunnelling would be completed in the Australian civil tunnelling sector for the period 2004-08 inclusive, with tunnels of greater than 2.0 m diameter averaging 14 km per annum over that period.

It was also estimated at that time that typical excavation costs of a two lane civil (roadway) tunnel was averaging $20,000/m, while current projections are that with a subsequent 50% increase in labour, consumable, and equipment costs since that time, that the “all-up” costs of a two lane civil tunnel were now typically $100,000/m, including capital, excavation and support/lining costs.

The installation of permanent ventilation, traffic control and remote monitoring systems in such tunnels makes direct cost comparisons with coal and metalliferous mines difficult, whilst rates currently being

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[3] Nowotny R, John Holland Tunnelling and Underground Mining, Personal Communication, November 2006

quoted in the coal sector for main access drifts are widely variable, ranging from $8,000/metre (24m^2 cross section, flameproof roadheader) to $21,000-$28,000/metre (27m^2 cross section, roadheader or TBM).

3.2.2 Civil tunnels are typically constructed in and around urban areas to extend or ease congestion on major infrastructure such as roads, railways and subways, water supply and sewage systems, power distribution and communication networks, with such infrastructure being designed for a 50-100 year service life.

Such requirements necessitate that appropriate safety factors be applied in design to ensure that the construction of tunnels does not impact on existing urban facilities (eg; Lane Cove Tunnel), and that tunnels remain serviceable with minimal maintenance requirements throughout their service life.

As a result high capital cost equipment can be expensed over relatively short tunnels (eg; 2 km), long project lead times allow for equipment to be purpose-built and preliminary site preparation to be completed prior to erection of equipment on site, and for the adoption of extremely robust ground support measures to ensure the long term availability and security of civil tunnels.

3.2.3 TBMs are particularly favoured where there is only single portal access to a proposed tunnel, as multiple portals or entries (eg; shafts) will allow multiple roadheaders to be deployed (eg; Cross City Tunnel, Sydney) to offset the higher advance rates of TBMs.

Other factors favouring application of TBMs include uniformity of rock throughout the drive, low to moderate water inflow expectations, portal access to facilitate construction of the TBM, long tunnels to offset the high initial capital cost, and the availability of adequate power resources (a TBM can require 5 MVA, or even higher in large diameter tunnels). Factors not favouring application of TBMs include inadequate or unconvincing geology, heavily faulted and/or wide fault zones, swelling ground conditions, or ground with a short stand-up time.

3.2.4 TBMs now achieve sustained production rates of up to 1,200 m/month over the life of a project (eg; Blue Mountains Sewer Tunnels), while an experienced Australian TBM contractor proposed that sustained rates of 400 m/week were achievable in coal roadway development. It was also considered that achievement of higher development rates would be limited by the overall availability of TBMs.

These high performance levels result from the close matching of boring capability, muck removal, and support installation systems on TBMs, whilst their design allows supports to be installed concurrently with and independently from boring and mucking, providing the stroke of the borer matches the support cycle.

Sustained rates of 400 m/week are at the current threshold of best practice gateroad development performance typically associated with punch longwall mines, although such mines are typically removing less than half the material per metre advance than a standard 6.9 m diameter metro tunnel. Even so, significantly higher TBM performance rates would need to be demonstrable before serious consideration is likely to be given to the potential introduction of TBMs at such mines.

Better performers in adverse conditions may however be encouraged to consider the potential application of TBMs as a means of leveraging quantum improvements in performance, providing ground conditions favour application of TBMs. However, TBMs are not self-powered and cannot retreat and require disassembly chambers to be pre-constructed in order to facilitate their disassembly and potential redeployment. Strategies would need to be developed to facilitate their rapid redeployment on completion of gateroads development, otherwise any benefits achieved from higher advance rates may be quickly lost.

3.2.5 Although considered to be inflexible and require major infrastructure for mobilisation and disassembly, TBMs are considered to be the "equipment of choice" for civil tunnels greater than 500 m length, unless highly variable ground conditions are likely to impact their effective utilisation or the proposed tunnel cross section is not compatible with available TBM configurations.

Ground conditions that are typically experienced in Australian gateroad development is expected to be eminently suitable for utilisation of TBM technology, and both IHI and Pacific Tunnelling have developed design concepts for the application of TBMs in longwall gateroad development, including measures to facilitate their rapid re-deployment following completion of a gateroad. Other TBM manufacturers have similarly expressed strong interest in applying their technology and equipment to coal mine and longwall gateroad development, while major civil contractors experienced in TBM tunnelling have also expressed strong interest in participating in such projects. Questions remain however in respect to the potential economic benefit of employing such technology in coal mine and gateroad development, particularly where the capacity of existing development systems are not being fully realised.

It was also noted that TBMs are individually manufactured in accordance with site specific geological conditions and tunnel design parameters, and that there is limited ability to reconfigure entry dimensions once design and manufacture of the TBM has proceeded. Each TBM is in effect a prototype, with extensive modifications sometimes being necessary to address design issues and/or optimise performance. Refurbishment of used TBMs is sometimes preferred as a means of shortening lead times and capitalise on an earlier modifications and enhancements to a TBM.

3.2.6 The civil tunnelling sector generally considers that there are no technologies, equipment or systems that the coal sector may wish to develop and apply for improving roadway development performance that has not already being developed and applied in the civil tunnelling sector.

No exhaustive listing of current tunnelling projects was able to be sourced, however it is likely that on a world wide basis the extent of tunnelling being conducted probably matches or exceeds the extent of gateroad development being conducted, with perhaps a greater variety of technology, equipment and systems being applied across a fairly diverse range of projects in the tunnelling sector. TBMs are used extensively throughout the world to construct tunnels of varying dimensions (2.0-15.2 m) in a wide variety of ground conditions, and are manufactured in a number of countries. Terratec, a Tasmanian based company provides an extensive range of services to the tunnelling sector, including overhaul of TBMs, cutting technology, and extensible conveyor systems.

Enabling technologies utilised in civil tunnelling practice include, for example:

- widespread automation of support installation functions, including rockbolting, shotcreting and concrete module erection, albeit that such support installation functions may not necessarily be conducted immediately behind the cutter head;
- application of machine guidance and control systems to enable TBMs to be steered through three dimensional space as a means of excavating complex compound curves;
- utilisation of extensible conveyor systems to facilitate the continuous operation of TBMs, with advance rates approaching that typically achieved in best practice gateroad development;
- application of machine guidance and control systems together with automation of operating functions to enable roadheaders to be operated remotely.

The question remains as to whether the technologies can be directly transferred to existing gateroad development machinery platforms such as continuous miners, or whether tunnelling platforms such as TBMs need to be transferred to the coal sector together with their relevant technologies.

3.2.7 It is likely that technology available today would allow roadheaders to be more effectively utilised for longwall gateroad development than in past attempts, particularly technologies that enable operation of the roadheader to be fully automated and operated remotely, and include the use of boom mounted automated bolting rigs.

Roadheaders have been utilised on a limited basis in underground coal mines, usually in association with penetration of geological structures or for excavation of major infrastructure such as cross measure drifts, driveheads, and overcasts. They have not been widely used for roadway development in coal, probably because of the ready availability of continuous miners, together with the roadheaders typically low cutting rates and limited support capability, and hence limited rates of advance.

However, application of state-of-the-art roadheader technology could result in a machine that may alleviate many of the issues associated with formation of breakaways, and also allow a longwall-preferred flat roof profile to be mined where conditions allowed, or for arched section roadways to be mined if conditions deteriorated. While such a machine is unlikely to seriously challenge a continuous miner's potential cutting rate, the continuous miner's cutting rate is itself compromised by installation of roof and rib support, and its ability to breakaway cut throughs. An effectively utilised roadheader may therefore prove to be as effective as many of the currently under-utilised continuous miner/roof bolter configurations. The question remains in this instance as to whether improved levels of utilisation could be achieved with such equipment in existing "under-utilised" environments.

3.2.8 As is the case in respect to underground metalliferous mining, it is unlikely that drill and blast technology and practices currently utilised in the civil tunnelling sector could be seriously considered as an alternate for existing continuous miner based roadway development systems, unless some other factor necessitated adoption of drill and blast, ie; a mine's inability to operate continuous miners due to the mine's outburst propensity.

3.2.9 Civil tunnelling projects apply higher levels of technical resources throughout the tunnelling process, from project design and tender preparation, through mobilisation and establishment, excavation, support, lining, and fit-out, with few matters being left to chance, particularly in respect to defining the geological/geotechnical environment and managing the associated risks.

Civil tunnelling projects are often undertaken to supplement or relieve congested civil infrastructure such as roadways, railways, water and sewerage in areas of high population density, with tunnel developers being faced with significant challenges to construct and integrate the new works in an already congested environment. Added to this are requirements regarding the design life of the tunnel, the necessity to maintain tunnel alignment within close tolerances, and the need to install an effective, low maintenance tunnel support and lining system. Extensive design, project management, supervisory and specialist (eg; geological/ geotechnical) resources are utilised to ensure that tunnel design standards and specifications are achieved, that performance meets contracted rates, and that resulting costs are contained within budget levels. It was also reported that contractors typically expend 1.5% of overall project costs up-front for geological and geotechnical investigations to ensure that ground conditions are fully understood, and that design of tunnelling equipment and support systems is appropriate to the likely ground conditions.

3.3 Civil Construction and Surface Mining Sectors

3.3.1 Like the mining sector, the civil construction sector is faced with severe shortages of skilled operators, however it is embracing technology as a means of combating those shortages.

Automatic machine control is considered as being universal on major construction and highway projects within the next five years, and it was projected[4] that application of automatic machine control in the construction sector would emulate that of the manufacturing sector where the industry had progressed from skilled operators at milling machines or lathes to systems that transmit the design directly to computer operated machines. The construction sector utilises bulldozers, motor graders and excavators to shape the earth, and with the application of remote control and sensing technologies it was projected that the operation of multiple machines could be automated as precise machine tools from a single design. Further, it was noted that the application of these technologies to fine grading on an earthmoving project was likely to improve productivity by more than 100%, whilst enabling unskilled operators to be turned into fine-grade machine operators very quickly.

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[4] O'Connor R, Topcon Positioning Systems, *Construction Industry Opens its Doors to Automation*, Construction Industry News, 9 October 2006

3.3.2 A contractor in the surface mining sector is utilising minesite simulator training to train new operators to work safely and productively with large expensive equipment and overcome severe shortages of skilled operators.

The contractor also attributed significant reductions in maintenance and repair of surface mining plant to the adoption of simulator training as it allowed operators to be trained to be more familiar with, and responsive to, alarms and information displays in the event of the equipment being operated outside its design parameters[5]. The utilisation of state-of-the-art simulators for development of new dragline operators at Anglo Coal's Callide coal mine in Queensland is expected to remove the threat of damage to the mine's $A150 million draglines and to halve the time it normally takes to bring trainee operators up to 75% or more of the skill level of experienced operators[6].

Immersive Technologies, an Australian mining equipment simulator developer has supplied about 80 units to Phelps Dodge, Rio Tinto, Anglo American, Newmont Mining, BHP Billiton, Tata Steel and Thiess, and now has exclusive technical alliances with five of the world's biggest manufacturers of mining machines, including the two biggest, Caterpillar and Komatsu. The exchange of proprietary machine information has allowed Immersive Technologies to produce simulator training modules that are said to be the most advanced in the industry today.

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[5] Baker P, Thiess, *Immersive Unearths Value at Thiess*, Construction Industry News, 6 October 2006

[6] Roberts R, *Simulators Deliver Real Benefits*, Mining News, Aspermont Publications, 7 December 2006

4.0 CONCLUSIONS

4.1 The underground metalliferous, civil tunnelling, civil construction, and surface mining sectors all utilise enabling technologies that could be applied in the underground coal sector to improve roadway development performance. Potential applications of such technologies include:

- integration of current state-of-the-art machine guidance and control systems to enable continuous miner operating functions to be automated during the break-away process to ensure consistency, repeatability and reliability of breakaways without the need for highly skilled operators;
- to similarly apply current state-of-the-art machine guidance, sensing and control systems to enable continuous miners to be operated remotely from a non-hazardous environment, and/or to be operated free of delays due to the operator's inability to sight the position of the cutter head and machine body relative to the roof, floor and sides (or other persons);
- utilisation of extensible conveyor systems to facilitate the continuous operation of continuous miners, TBMs and roadheaders;
- incorporation of carousel bolting systems to continuous miner mounted drill rigs (as is reportedly being progressed by Joy Mining Machinery), as a precursor to the potential development of other automated bolting systems;
- the application drill control systems for remote, semi automated operation of miner mounted drill rigs;
- the adaptation of carousel drilling systems for continuous miner mounted cable bolting systems, potentially including cable storage and insertion systems;
- application of remote control technology to enable shuttle cars and continuous haulage systems to be operated remotely from a non-hazardous environment
- application of immersion technologies to train operators in the safe and productive operation of roadway development equipment.

4.2 Benefits that are likely to result from the application of such technologies include:

- a reduction in equipment damage, and hence increased machine uptime and lower maintenance costs;
- higher consistency and repeatability of automated operating functions, without the need to employ highly skilled operators;
- the removal of operators from the immediate, unsupported face area, resulting in fewer injuries and fatalities the face area;
- reduced exposure to and incidence of manual handling injuries associated with handling of both drills and ground control consumables;
- potential improvement in operating rates.

4.3 There could be significant benefit from driving larger dimension roadways in all phases of mine development in regard to:

- Lower ventilation pressures and hence lower mine ventilation costs, coupled with lower risks of spontaneous combustion in mines so prone;
- Avoiding the development of a third entry in longwall gateroads, together with the formation of a second row of chain pillars and the associated lower level of recovery of reserves;
- Ability to utilise larger diameter and less resistant ventilation ducting;
- Potential to restructure the continuous miner and enable the fitment of automated bolting and material handling systems;

- Potential application of higher capacity coal haulage and material distribution systems.

4.4 TBMs could provide an integrated roadway development system, particularly in punch longwall applications. However indicative costs ($21-22M) coupled with performance levels that may only be marginally better than best practice gateroad development rates may limit there immediate and widespread application in the underground coal sector.

- The application of TBMs in gateroad development would pose a number of regulatory challenges for the mine operator, OEM, and/or contractor, including equipment certification and approvals, provision of flameproof and intrinsically safe apparatus, use of high voltage sub-stations (33 kV) and motors (3.3 kV) in the hazardous/explosion risk zone, and issues in relation to single entry drivage including provision of emergency escape;
- As noted in the earlier report, *Australian Roadway Development – Current Status*, both IHI and Pacific Tunnelling have developed engineering concept designs for the application of conventional TBM tunnelling technology to underground coal mines, and both are of the view that equipment could be on site in 18 – 24 months. Both machines are designed to achieve rapid advance rates (10MPOH) and would necessitate a substantial commitment in associated infrastructure to sustain such development rates;
- Other OEMs (eg; Herrenknecht, Lovat, Robbins, Wirth) would also be likely to pursue any initiative to introduce TBMs into the coal sector, while a number of contractors have also expressed interest in participating in any such initiative (eg, John Holland, Leighton, McConnell Dowell, Walter);
- Application of TBMs (and other integrated high capacity development systems) will require a major reconsideration of how the roadway development process is managed, with the current level of management resources being applied at most mines being insufficient to ensure the technology is both utilised at, and performs to, a level that could sustain the high capital cost;
- Utilisation of a TBM-experienced mining and/or tunnelling contractor will be necessary to ensure that the technology, equipment, systems, expertise and skills that are available can be transferred to and developed within the coal sector in an effective, efficient and sustainable manner.

4.5 Borer miner and continuous haulage system technology currently being utilised in Canadian potash mines could be utilised as the basis of an alternate, integrated, high capacity roadway development system, subject to measures being incorporated on the borer miner to install immediate face support.

- Such a system appears likely to provide a lower cost first step towards an integrated development system than would be achieved with a TBM, with the modular components being able to be demonstrated independently before final integration as a combined development system;
- Magatar Mining are currently modifying and developing the “Flexiveyor” continuous haulage system, as used in Canada, for use in a South African coal mine. The refinements will be of direct benefit to any potential Australian coal mine application;
- Borer miners face challenges in breaking away cut throughs, similar to that experienced with conventional widehead continuous miners. Their adoption in a multiple entry system would most likely require development of a system to more effectively interconnect roadways for ventilation, coal clearance, communication and egress, either by way of a specialist cut through machine (ie; narrow head continuous miner or augering system) or the integration of current state-of-the-art machine guidance and remote control systems to remove operators from the break away process.

4.6 Conventional widehead continuous miners could, with further enhancement, be utilised as the basis of an integrated, high capacity roadway development system. Potential enhancements would include:

- Integration of an automated bolting and support system, combined with a continuous haulage/extensible conveyor system;
- Improve the machines ability to break away cut throughs by either incorporating some form of articulation into the CM, or modifying the cutter head and/or chassis configuration and/or roadway width to improve the machines geometry relative to the breakaway, or increase the machine height and reduce the length of configuration on the chassis configuration to similarly improve the machines geometry relative to the break away in the event that higher roadways are mined, and/or integrate state-of-the-art machine guidance and remote control systems to remove operators from the break away process.

5.0 RECOMMENDATIONS

5.1 What ACARP Should Do

5.1.1 Establish a roadway development technology work group to further identify how relevant "enabling technologies" from the underground metalliferous and civil tunnelling sectors could be applied to improve roadway development performance.

- This group should include experienced and innovative mine personnel, including mechanical, electrical, and mining engineers, together with limited representation from the OEM and remote sensing and control technology sectors.
- The study to include the potential application of technologies identified at section 4.1 (metalliferous and tunnelling "enabling technologies"), 4.5 (application of borer miners and continuous haulage systems), and 4.6 (enhancement of conventional continuous miner platforms), including site visits and inspections as appropriate.
- The study should also consider whether existing roadway height limitations constrain the potential application of such technologies in any way, and identify whether there are any minimum height limitations for effective application of such technologies.
- The group to carry out the study and report to the proposed Roadway Development Strategy (New Technology) Workshop (with such Workshop potentially being rescheduled to end second quarter 2007 to facilitate reporting of the study).

5.1.2 Conduct economic and technical evaluations of various entry configurations including two entry/high (partially out-of-seam) roadways and three entry/low (in-seam) roadways to determine which configuration of roadways is likely to address ventilation and gas management issues associated with future high capacity longwalls (>10Mtpa).

- The evaluation to include an assessment of the benefits and costs of mining two entry/high (partially out-of-seam) roadways versus three entry/low (in-seam) roadways (including the effect on overall recovery levels), together with assessing operational and engineering issues associated with integrating such high roadways with longwall gate-end and face equipment.
- Findings of the study to be reported at the proposed Roadway Development Strategy (New Technology) Workshop, as above.

5.1.3 Commission an appropriate organisations (eg; Parsons Brinckerhoff or Terratec) to conduct a feasibility study on the potential application of TBMs for punch longwall gateroad development.

- The study to evaluate the issues identified in Section 4.4 (application of TBMs), particularly in respect to the statutory and regulatory issues, the relative practicalities and economics of the existing IHI and Pacific Tunnelling concept designs (and any other concept proposals received from other OEMs), and the level of expertise and skills available within the contracting sector to sustain the successful introduction, demonstration and ongoing utilisation of such a system.
- The study should recommend potential design profiles in respect to tunnel dimensions and support systems, and advise on measures to both reduce the overall machine length to be more compatible with potential highwall applications, and to facilitate its rapid redeployment for subsequent gateroad development.
- The study should also assess the performance capability of TBMs utilising "temporary" support systems such as rock bolts and mesh as typically utilised in coal mines, as opposed to more permanent lining systems utilised in civil tunnels such as shotcrete and mesh or concrete segments.
- The study should also evaluate likely development rates achievable and the resulting development costs, and systems required to achieve and sustain such rates and costs,

including the disassembly, relocation, refurbishment, and reassembly of the TBM on subsequent gateroads. The study should also consider and advise on the nature and extent of management practices and resources necessary to ensure the technology is both utilised at and performs to planned levels.

- The study may also propose alternative mechanisms for funding the initial design, construction and commissioning costs, including the potential involvement of contracting companies in bi-partite or tri-partite funding arrangements. It may also propose contract structures that will facilitate successful outcomes for all participants.
- Findings of the study to be reported at the proposed Roadway Development Strategy (New Technology) Workshop, as above.

5.2 What Mine Operators and Mine Managers Should Do

5.2.1 Continue to embrace and expand the application of process control and continuous improvement principles and practices as a means of developing management capabilities that can effectively capitalise on the development of alternate, high capacity roadway development technologies, equipment and systems.

- As noted in the earlier report, *Australian Roadway Development – Current Status*, it became evident during the initial review process that there was often a significant difference in roadway development rates between mines operating in similar mining conditions and utilising similar mining equipment. Clearly, other factors were at play, and a number of factors considered to differentiate between best practice, high performance mines and others were proposed.
- The introduction of alternate, high capacity roadway development technologies, equipment and systems is unlikely to realise the full potential of those technologies, unless the principles and practices of process control and continuous improvement are part of the mine's routine management systems and culture.

5.2.2 Adequately resource management of roadway development functions and adopt a proactive management philosophy that leaves little to chance.

- A presentation on the development function at Beltana and the management processes adopted and performance levels achieved, as presented at the recent ACARP Roadway Development Operators' Workshop, demonstrated the performance capability of a "current technology" roadway development system. Clearly, good ground conditions are experienced at the mine and the mine has minimal outbye infrastructure to constrain performance. In the context of the recent Roadway Development report, and the key factors differentiating best practice operations identified therein, it is evident that leadership and management of the roadway development process is a significant factor underpinning the performance levels achieved.
- From a financial perspective it is estimated that the mine applies some $0.5-0.6M per annum in direct management costs to manage and optimise performance from a single development unit which has an annual labour cost of approximately $7.8M. Compare this with other mines that are potentially applying similar or lower levels of management resources to manage *multiple* units, each with an annual labour cost of approximately $5.0-6.0M. It appears to be good business sense to increase management resources to optimise development performance, and to then be able to reduce the number of units being applied.
- Management resources are leverage by the involvement of employees in the improvement process. This ultimately leads to a freeing up of management resources to develop better operating strategies and to focus on other improvement initiatives, thus developing a self-sustaining continuous improvement culture, rather than being dissipated in ongoing command, control and rectification issues.
- With capital cost for a development unit approaching $8-9M and annualized operating costs almost of a similar level, there appears to be significant upside from improved development

performance, either by reducing the level of development assets employed in the event of stable longwall performance, or at least not increasing the level of development assets employed in the event of improved longwall performance. Management's challenge is to visualise what improved development performance could mean in a specific environment, and to develop and execute change strategies that will lead to achievement of the vision.

- As shown in the civil tunnelling sector (and at Beltana), the introduction of integrated, high capacity roadway development systems will require greater levels of management resources than that typically employed in gateroad development to ensure that the full potential of the new system is realised.

5.2.3 Personnel interested in rapid excavation and tunnelling practice should consider attendance at the biannual Rapid Excavation and Tunnelling Conference being held in Toronto, Ontario, Canada, 10-13 June 2007, or alternatively, visit the website to obtain copies of past conference proceedings.

The conference is regarded as the premier international tunnelling forum with over 100 papers on current developments in tunnelling practice being presented. Further details can be obtained from the Rapid Excavation and Tunnelling Conference website (www.retc.org).

5.2.4 Progress of Tunconstruct is monitored to identify any technological innovations in underground construction that result from a four year, A$42.5M study recently implemented by the European Commission[7].

The Tunconstruct project is based at the Graz University of Technology in Austria and was established with the objective developing innovative underground construction technologies such as new TBMs with larger diameters and suitable for any ground condition, the use of robotics in construction, and automated shotcreting machines and roadheaders. Research and development will also focus on developing efficient and durable materials for lining and ground treatment.

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[7] Tunconstruct, www.tunconstruct.org, accessed 5 October 2006.

6.0 THE AUSTRALIAN METALLIFEROUS AND TUNNELLING SECTORS

6.1 Introduction

In September 2004 it was estimated[8] that the total amount of roadway development then being undertaken in the civil tunnelling and underground metalliferous sectors in Australia was 625 km per annum, with the vast majority of this development (600 km or 96%) being excavated in the 80 or so underground metalliferous mines then in operation[9]. Of the total 600 kms of metalliferous roadway development, it was estimated that some 200 km was mined by contractors, with nearly all roadways being driven by drill and blast. Roadways were typically driven 5-6 m high by 5-6 m wide to allow 50 tonne (or more) capacity trucks to be used for ore and waste removal.

Of the 25 km estimated to be completed in the civil tunnelling sector, it was projected[10] that the development of tunnels of greater than 2.0m diameter would average 14 km per annum for the period 2004 to 2008 inclusive. Excavation methods comprise a mix of roadheader, TBM, drill and blast, and cut and cover, with the majority being completed by roadheader or TBMs. It was also projected that an average 4.8 km per annum of tunnels would be completed by TBMs during the period 2004 to 2008, across a variety of projects in Brisbane, Melbourne, Perth and Sydney.

It was also estimated at that time that the average cost of roadway advance in the underground metalliferous sector was then $4,000/m, with typical excavation costs of a two lane civil (roadway) tunnel then typically averaging $20,000/m. It was subsequently reported that roadway excavation costs had typically increased 50% since 2004, due to increases in labour, consumable, and equipment costs, while “all-up” costs of a two lane civil tunnel were now typically $100,000/m, including capital, excavation and support/lining costs.

While civil tunnelling excavations are typically completed for road, rail, sewerage, water and power distribution applications, the development and utilisation of “commercial space” in underground voids is now being more readily considered (eg; Elgas LPG Storage Caverns, Sydney), particularly where underground quarrying is required for industrial materials (eg; sandstone dimension stone, road base). Improved sustainability is achieved by establishing suitable end-uses for such underground voids (eg; underground storage and offices, waste disposal). It is also noted that underground processing plants have now been constructed in the Australian underground metalliferous sector in response to environmental issues.

6.2 Roadway Development in Australian Metalliferous Mines

Underground metalliferous mines in Australia mine a variety of ores including copper, diamonds, gold, lead-zinc-silver, nickel, and tin, either in discrete or massive orebodies. Data from the Register of Australian Mining indicates that there were some 78 underground mines in operation throughout Australia in 2003/04, with one third (25) of those mines being operated in conjunction with or as an extension of an open cut mine. 21 mines reported a processing plant capacity of greater than 2 Mtpa, of which only 9 mines were solely underground mines. 36 mines reported a processing plant capacity of less than 1 Mtpa, of which 27 mines were solely underground mines.

Current statistics[11] from the West Australian Department of Industrial Relations indicates an increase in the number of underground mines in WA, from 41 to 44 since 2003/04, with the number of solely underground mines increasing from 21 to 28 over that period.

In comparison to the relatively flat, extensive, two dimensional coal seams typically experienced in Australian underground coal mines, metalliferous ore bodies are generally highly variable, discontinuous and geologically complex, and require a three dimensional mining strategy to exploit the resource, as illustrated in Figs 1 and 2. Underground metalliferous mines are typically accessed via 1:7 to 1:9 spiral declines for ore haulage and men and material access, with the declines being

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[8] Tennent Isokangus Partners, TIP’s Tips, September 2004

[9] Register of Australian Mining 2003/04

[10] Tennent Isokangus Partners, TIP – Tunnel to 2008 Update, September 2004

[11] West Australian Department of Industrial Relations (Minerals and Petroleum), *List of Operating Mine Sites*, Perth, 2006

excavated in the country rock, rather than within the ore body. Levels are then excavated to provide lateral access to and throughout the ore body, with stopes being formed between levels to extract the ore. Roadways are typically driven 5-6 m high by 5-6 m wide to allow 50 tonne (or more) capacity trucks to be used for ore and waste removal.

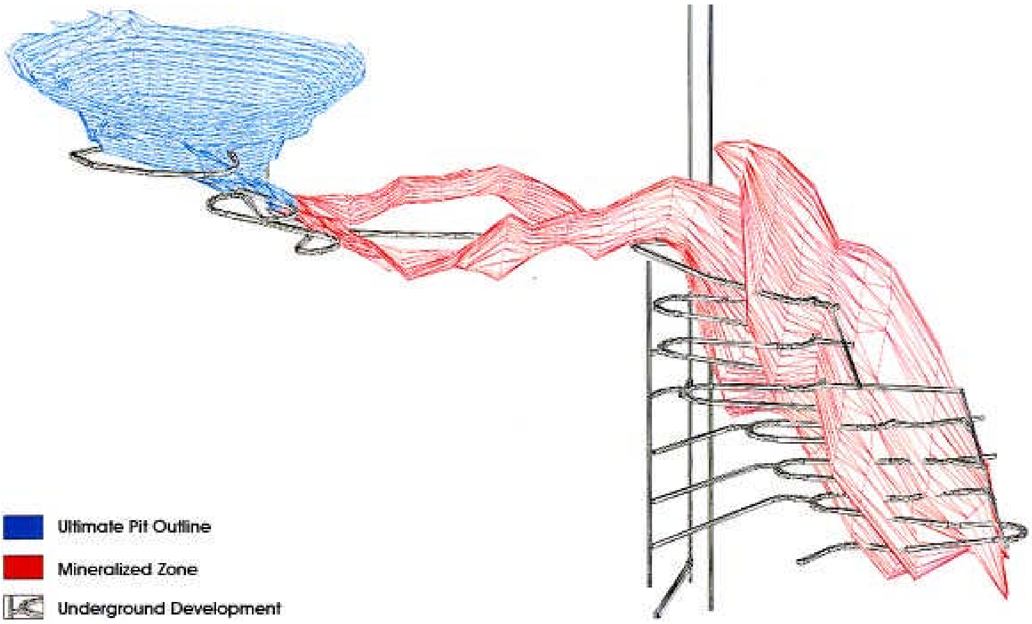

Fig 1: Resource Model and Development Osborne Copper-Gold Mine, Mt Isa, Qld (courtesy of www.mining–technology.com)

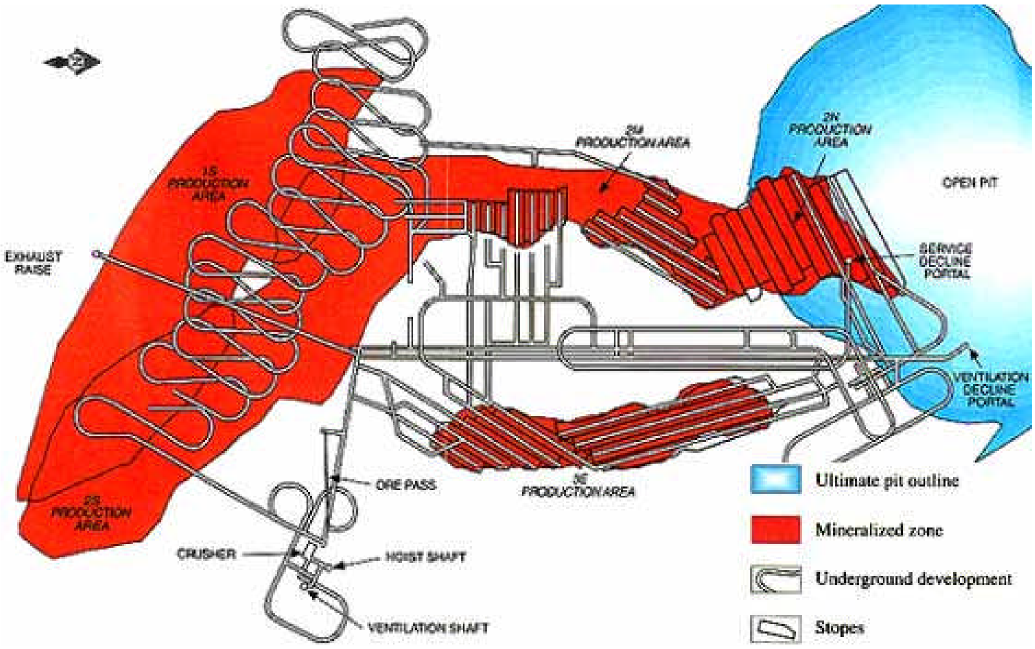

Fig 2: Diagram of Access Drives and Production Areas Osborne Copper-Gold Mine, Mt Isa, Qld (courtesy of www.mining–technology.com)

Truck haulage is typically utilised for haulage of ore from mines at depths of up to 500 m and for mine outputs of less than 2 Mtpa[12], where the low capital cost favours its application. Vertical hoisting is generally utilised at depths greater than 500 m and/or output levels higher than 2 Mtpa, where low operating costs favour its application. The development of stronger conveyor belting and variable speed drives has also led to the introduction of inclined conveyor haulage systems for high capacity/

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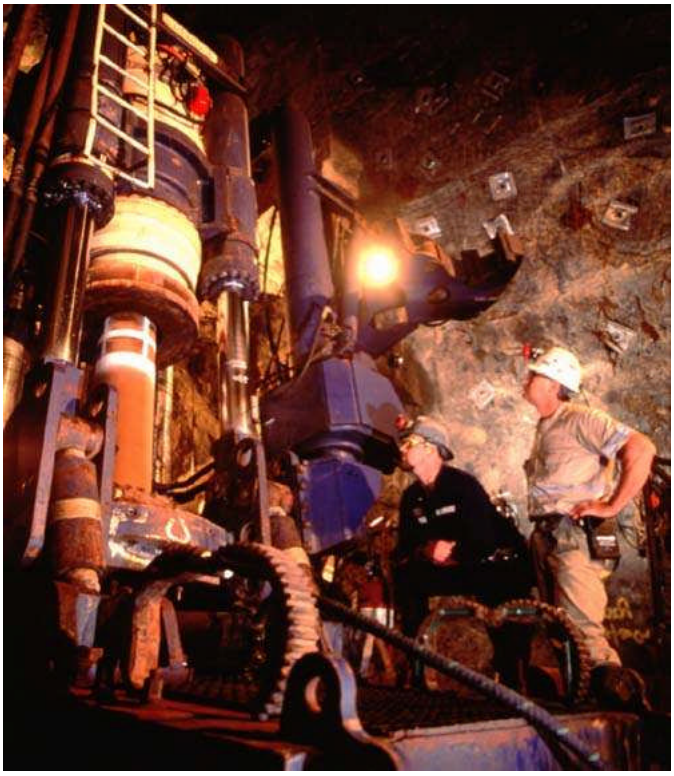
[12] Pratt AGL, *Application of Conveyors for Underground Haulage*, Ninth Underground Operators' Conference, AusIMM, Perth, 2005

deep mining applications, and reportedly result in lower overall life of mine operating costs than both truck haulage and shaft hoisting.

Vertical shafts are used for exhaust ventilation to the surface with raise bored shafts and stopes being utilised for underground ventilation between levels where required (Fig 3).

Fig 3: Raiseboring for Ventilation Shafts and Rock Passes, Kanowna Belle Gold Mine, Kalgoorlie, WA (photo courtesy of www.mining–technology.com).



No production data on roadway development in underground metalliferous mines was able to be sourced, however it was reported[13] that development rates in Australian underground metalliferous mines were typically 30 m/week (range 20-40 m/week) in single entry drivages, with development rates being particularly impacted by shotfiring limitations (eg; end of shift firing). Multiple entry drivages in close proximity enabled development rates to be improved by some 50%, as did the drivage of declines from the surface where there were fewer constraints on drivage. In comparison to these typical rates, a contractor[14] reported achieving rates of 40-55 m/week (single entries) and 75 m/week (multiple entries in close proximity) per drill jumbo in a large scale mining operation utilising 3-5 drill jumbos on development, with overall development rates of 1 km/month being achieved.

Fig 4: A Development Drive in the Enterprise Section, Mt Isa Copper Mine, Mt Isa, Qld (photo courtesy of www.mining–technology.com).

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[13] Robertson A, Coffey Mining, Personal Communication, October 2006

[14] Humphryson R, MacMahon Contractors, Personal Communication, October 2006

A typical drill and blast cycle in the underground metalliferous sector[15] consists of the following steps, with a complete cycle being typically completed in 12 hours:

- Drilling 3.4 m long rounds in the 5.5 m wide by 5.5 m high arched roadways (typically 2-2.5 hours);
- Charging and blasting the face (typically 45-60 mins);
- Loading out 250 t round (typically 3 hours);
- Mechanically scaling the roof and sides;
- Shotcreting the roof and sides (no mesh installed);
- Bolting the roof and sides (typically 7 bolts per 1.5 metres, with 5 on the roof and one bolt on each side wall) after waiting 60-90 minutes for the shotcrete to develop minimum strength requirements (typically 1 MPa);
- Scaling and preparing the face for drilling the next round.

An alternative, in-cycle shotcreting approach is to partially load out the face before scaling and shotcreting, with the balance of the load out being completed whilst the shotcrete cures.

Fig 5: Drilling Underground at George Fisher Lead-Silver-Zinc Mine, Mt Isa, Qld (photo courtesy of www.mining–technology.com).

Atlas Copco (Boomer), Boart Longyear (Face Master), Jama, and Sandvik (Axera, Quasar) all provide a range of drill jumbos and equipment to suit the variety of metalliferous mining conditions experienced, including narrow vein (≤2 m wide), low stopes (≤2 m high), and massive orebodies (stopes or drives to 18.5 m wide by 11.9 m high). Drill jumbos can be equipped for semi or full automatic drilling, and with up to 4 drill rigs depending upon the roadway profile. Drill jumbos are typically fitted with a diesel engine for rapid, flexible access through the mine, and then revert to an electrical power supply at the face (1,100 v) to power the hydraulic drill rigs and compressors, thus reducing contamination of the immediate face environment. Machine envelopes for a drill jumbo in a typical 5.5 m high by 5.5 m wide roadway are 2.3-3.2 m high by 2.2-3.3 m wide (first figure is tramming height/width, second is mining height/width with canopy and work platforms extended), with an overall length some 12.65 m and a weight of 22.5 t.

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[15] MacKenzie S, Roche Mining (Cracow Gold Mine Project), Personal Communication, October 2006

Fig 6: Tamrock Minimatic Two-Boom Jumbo in Development of Access Decline at Kanowna Belle Gold Mine, Kalgoorlie, WA (photo courtesy of www.mining–technology.com).

It was noted that many mines utilise the drill jumbo for both drilling and bolting operations, although in some instances specialist roof bolting rigs are utilised where the scale of operations conducted justifies the deployment of specialist bolting rigs (eg; Atlas Copco Boltec MC, Tamrock Robolt 7). Similarly, many mines also utilise drill jumbos for cable bolting while some mines utilise specialist cable bolting rigs (eg; Atlas Copco Bolter Cable L, Tamrock Cabolt 7). It was noted that cable bolting rigs are typically contractor owned and operated[14]. Specialist bolting rigs are typically fitted with a bolting carousel that allows up to 8-10 bolts to be manually inserted into the carousel (Fig 7), and can be equipped for semi or full automatic bolting. The bolting rigs are able to be fitted for cement, resin, mechanical expansion shell, or mechanical wedge type anchored bolts, or for split set or Swellex bolts, or a combination thereof.

Fig 7: 8 Bolt Robolt Bolting Carousel (photo courtesy of Sandvik).

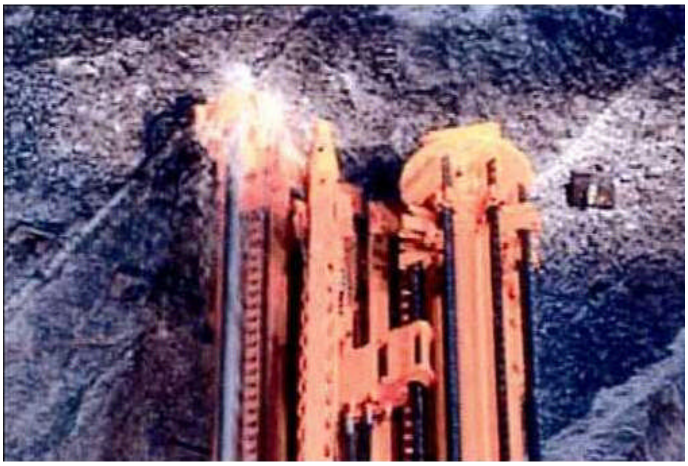

Fig 8: Tamrock Robolter.

Specialist cable bolting rigs allow up to 25 m long cement grouted tendons to be installed, and are fully mechanised, one-man operated electro-hydraulic units. Capacity of the plain or bulbed steel strand (tendon) reels is typically 800 m. The specialist bolting and cable bolting rigs are similarly dual powered (diesel tram/electric drilling), and have similar machine envelopes to the drill jumbos (Fig 9, 10, and 11).

Fig 9: Tamrock Cabolter With Cement Grout Injection

(Fig 8, 9, 10 and 11 courtesy of Sandvik).

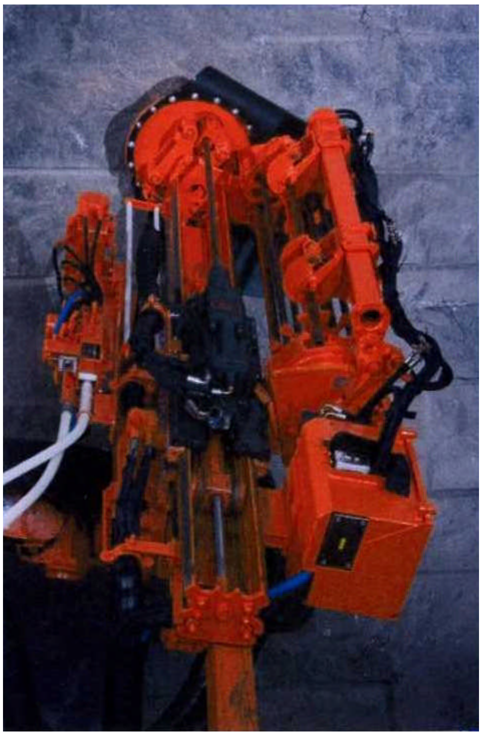

Fig 10: Robolter Drilling Carousel for Drilling and Insertion of Cables of up to 25 m in Length.

Fig 11: On-board Cementitous Grout Mixing and Pumping System.

Blasting utilises emulsion based explosives and electronic detonators, with blasting typically completed at end of shift. The development and application of electronic detonators coupled with long round firings (6.5 m) were reported to have significantly improved blasting efficiency, although stand-up time of long rounds could become an issue in some mines due to the time required to load out, shotcrete and bolt the working places.

The control of over-break resulting from blasting is also an issue in development, and it was reported[16] that for every 100 mm of over-break in a typical development round, an extra 30,000 t of rock (or 750 loads for a CAT AD40) would be generated in a mining operation completing a moderate 6 km of roadway per annum. The use of emulsion based explosives allows the density of explosives to be varied on a hole by hole basis, with high density, high strength “heavy” explosive product in the body of the round, progressively reducing to a “light” explosive product in the perimeter holes. As well as affecting the amount of blasted material to be handled, successful perimeter control blasting significantly reduces the time to scale places prior to installation of support.

Fig 12: LHD in Operation at Perilya’s Potosi Zinc-Lead Mine, Broken Hill, NSW (photo courtesy of Aspermont Publications).

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[16] Miller DK, Bottomley L, and Tucker AJ, *Perimeter Control in Development Mining*, Ninth Underground Operators’ Conference, AusIMM, Perth, 2005

Atlas Copco (Wagner), Caterpillar (Elphinstone), and Sandvik (Toro, EJC) all provide an extensive range of underground loaders and haulage trucks to suit specified mining conditions, with Hitachi Bell and Dux Machinery also providing a range of haulage trucks. The remote control operation of loaders in stopes is widespread, with systems utilised comprising line of sight (similar to continuous miner remote control systems) or tele-remote systems, with the latter being used to operate loaders from the surface in some instances (Fig 13). The adoption of 5-6 m wide, 5-6 m high roadways allows 50-55 tonne capacity haul trucks to be used, while dual and triple trailer configurations are also being utilised at some mines to haul ore from the mine (Fig 15).

Fig 13: A Remote-Controlled Load-Haul Dump Machine Moving Ore from Stopes to an Orepass, Olympic Dam Copper-Uranium Mine, Woomera, SA (photo courtesy of www.mining–technology.com).

Roof and sides are scaled down after places are mucked out, with either mechanical scaling (typically drill jumbos) or hydraulic scaling methods being utilised (Fig 14). In the latter, high pressure water (20 MPa) is utilised to both scale down scat and loose rocks, and to clean off the roadway surface. This reportedly improves shotcrete adhesion and reduces over-break in the roadway, while reducing damage to drill jumbos and hence reducing their maintenance requirements[17].

Fig 14: Hydroscaling in Progress[17].

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[17] Jenkins PA, Mitchell J, and Upton B, *Improved Ground Control Using Hydro Scaling and In-Cycle Shotcrete*, Ninth Underground Operators' Conference, AusIMM, Perth, 2005

Fig 15: Toro Haul Truck in Operation at Plutonic Mine, Meekatharra, WA (photo courtesy of Sandvik).

As noted by Davidson[18], ground support systems are continuing to evolve in the Australian metalliferous sector, from the mid-late seventies when rockbolting was not the norm, to the early 1990's when rockbolting was the norm, and to late 1990's when the installation of surface support in addition to rock bolts became the norm. While provision was then available to reduce requirements for surface support through a geotechnical risk assessment, mining companies in many instances found it simpler to add surface support for any new development rather than undertake a risk assessment that was considered to be non-definitive. Further, the provision of a surface support is a firm, undeniable barrier, whilst the risk assessment approach was considered to be open to interpretation. The simplest approach to meeting the emerging codes of practice was therefore to install some form of mesh, as meshing did not require the purchase of extra capital equipment or the employment of skilled operators (although the installation of mesh using jumbos is reported to have its own inherent risks).

Today, the majority of underground metalliferous mines reportedly use mesh although a further refinement in this evolution has been the application of shotcrete over the mesh to strengthen the surface support measures, while a more recent development has been the introduction of in-cycle shotcreting (ICS) as a primary ground support, in lieu of steel mesh. ICS is applied after roadways are scaled and before they are bolted, with bolting being initiated after the recently applied shotcrete (or fibrecrete) achieves minimum strength specifications (usually 1 MPa), which is typically achieved in 40-60 minutes. It was also reported[18] that following the application of boltless shotcrete in a number of overseas mines, trials have also been undertaken in Australian mines to utilise fibrecrete as a replacement for, and/or reduce the number of bolts being installed for primary support. While it was proposed that the scaling down and installation of fibrecrete prior to mucking out would increase the curing time and allow the strength of the fibrecrete to develop, it was suggested that there was a great amount of justifiable caution being exercised by mine operators in its implementation because of a lack of information in relation to the early strength of fibrecrete.

Research is currently underway at the Kalgoorlie School of Mines[19] (Curtin University) to establish guidelines for expected energy absorption of various types of combined reinforcement and support

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[18] Davison GR, *Spraying the Surface or Just Scratching the Surface – What Are the Real Benefits of In-Cycle Fibrecrete?*, Ninth Underground Operators' Conference, AusIMM, Perth, 2005

[19] Villaescusa E, and Thompson A, *Dynamic Testing of Ground Control Systems*, Project No M349A, Minerals and Energy Research Institute of Western Australia, Perth, 2006

systems. Similarly, research is underway into the corrosion of rock reinforcement in underground excavations[20].

To facilitate the installation of mesh sheets at height, specialist mesh handling rigs can be supplied with bolting jumbos, with a separate jumbo arm being utilised to lift the mesh sheets into place and temporarily support it while bolting proceeds with the drill rig (Fig 16). It was noted that where mesh is utilised, it is installed in full sheets rather than as mesh modules as utilised in the coal sector.

Friction bolts ("split sets") were reported to comprise some 75% of the bolts used in rockbolting, primarily because of the ease of installation and low cost[21]. The use of drill jumbos for both face drilling and rockbolting operations in most metalliferous mines results in operators using a one size, 43-45 mm diameter drill bit, for both blast holes and rockbolts, which then requires a 47 mm diameter friction bolt to be utilised (which have a lower yield strength and ultimate tensile strength than the 33 mm and 39 mm diameter friction bolts). All metalliferous mines were reported to utilise friction bolts for securing side walls, with resin anchored bolts now gaining acceptance for securing the backs (roof), particularly among the larger producers. Systems utilised to install resin at extended working heights (5-6 m above floor level) remain fairly rudimentary and are likely to limit the penetration of resin anchored bolts into the metalliferous sector until effective resin insertion systems are developed. Dywidag noted that they were well advanced in developing a "one shot" resin anchored bolt, comprising a tubular bolt fitted internally with a resin cartridge that is injected into the bolt/rock annulus after the bolt is inserted into the hole, and then mixed conventionally by rotating the bolt[21].

Fig 16: Robolter with Mesh Handling Boom (photo courtesy of Sandvik).

Forcing ventilation systems with variable pitch axial flow fans of 1.4-1.6 m diameter (32-35 m^3/s) and flexible, lay flat ducting are typically used to ventilate developing faces and stopes. Fans sighted at the Goldfields Mining Expo were clearly less sophisticated than those utilised in the coal sector, no doubt due to the more rigorous safety controls required in the coal sector. A wide range of ducting is available to the metalliferous sector, with 1.6 m diameter FRAS ducting being manufactured by some suppliers.

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[20] Villaescusa E, *Corrosion of Rock Reinforcement in Underground Excavations*, Project No M333, Minerals and Energy Research Institute of Western Australia, Perth, 2006

[21] Rataj M, Dywidag-Systems International, Personal Communication, November 2006

It was reported that there had been some attempts to introduce roadheaders to underground metalliferous roadway development in Australia, however these trials had proved largely unsuccessful to date, generally due to the hardness of the materials being excavated[13]. The recent development of the ICUTROC technology by Sandvik and the incorporation of that technology on their current generation of roadheaders (eg; ATM105C, AHM105C), reportedly allows materials of greater than 120 MPa UCS to be mined. Terratec and CRC Mining have recently completed development of an alternative cutting mechanism (oscillating disc cutter) capable of cutting “hard rock” material typically found in underground metalliferous mines[22]. Commercialisation of the technology is now underway.

Most respondents considered that the underground metalliferous sector had little to offer the underground coal sector by way of roadway development practices, primarily due to the widespread adoption of drill and blast in the ”hard rock” metalliferous sector, as opposed to “soft rock” continuous miner based systems in the coal sector. In fact, most respondents considered that the underground coal sector had offer more to the underground metalliferous sector by way of roadway development technology, equipment and systems than the reverse.

An experienced contractor offered an alternate view, namely that the coal sector had a lot to learn from the metalliferous sector in respect to matching geology to ground control measures. It was suggested[3] that metalliferous mines typically adopt more rigorous geotechnical monitoring and mapping practices, and adapt ground control measures on a day by day basis depending upon the ground conditions being experienced, rather than relying on inflexible, mine-wide or panel-wide standards.

6.3 Observations on Australian Metalliferous Roadway Development Practice

A key observation in relation to Australian metalliferous roadway development is the sector’s practice of excavating large dimension (5-6m wide by 5-6m high) roadways which facilitate the application of large, high capacity equipment across all facets of the process. Compare this with the underground coal sector where the industry is perhaps constrained by long held paradigms to limit roadway height to seam height or less in order to minimise dilution, or to say a height of 3-3.5 m in thicker (>4 m) coal seams.

Recognising the limitations imposed by such roadway heights, some coal mines are now mining three entry gateroads in order to improve ventilation characteristics associated with longer, wider longwall faces. Mining twin-entry, 5-6 m high roadways (partially out of seam or even in-seam roadways in thicker seams) is likely to produce better ventilation characteristics than a low height, dual intake, single return gateroad panel (as illustrated in Table 1), and potentially create space in the immediate working environment to facilitate the application of other technologies, or higher capacity systems (including larger diameter, higher capacity ventilation ducting). Alternatively, the continuous miner chassis could be made higher and shorter within the existing machine envelope to free up space between the cutter head and chassis to improve roof and rib bolting ergonomics and/or allow the application of automated bolting systems (eg; carousel bolters).

Proper economic analysis is warranted to evaluate the relative cost benefit of two-entry, 5-6 m high gateroads as opposed to low, in-seam three entry gateroads, including any economic benefits that arise from higher levels of recovery of reserves associated with a single chain pillar (two entry system), as compared to dual chain pillars (three entry system).

Metalliferous mines also typically excavate arched roadways to form a stable roadway profile, thereby minimising roof control issues associated with the formation of flat backs (roofs). Consideration of arched profiles may also be warranted in coal mines, particularly if out of seam, large profile roadways are formed, as above. Such a profile replicates the arched section typically formed after the fall of roof laminated roof material in many coal mines, a profile that generally remains stable over time.

The metalliferous sector has advanced the automation and remote operation of underground equipment to the extent that LHD units can be operated from the surface, or multi-boom jumbos can drill out a full face free of any human intervention, once the machine’s initial alignment is established. Further, roadways can be bolted with a wide range of roof control products, including cable bolts, with

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[22] Sandvik, website:www.sandvik.com (accessed 14 November 2006)

the operator only leaving the air conditioned operator's cab to recharge the 8–10 bolt bolting carousel. Extension of the drill control technology to the bolting rigs may ultimately allow bolts and cables to be installed to a pre-determined design with minimal human intervention.

While improved operating rates (units/hour) did not necessarily result from the application of automation and remote control technologies, significant benefits that are realised include:

- a reduction in equipment damage, and hence increased machine uptime and lower maintenance costs;
- higher consistency and repeatability of automated operating functions, without the need to employ highly skilled operators;
- the removal of operators from the immediate, unsupported face area, resulting in fewer injuries and fatalities at the face area;
- reduced exposure to and incidence of manual handling injuries associated with handling of both drills and ground control consumables.

OEMs produce a range of equipment that could, subject to addressing compliance issues, be readily adapted and applied in the coal sector in the event that drill and blast mining methods were to be employed (eg; in grunching operations associated with potential outburst conditions), or metalliferous bolting and cable bolting equipment was employed for secondary bolting applications. However, greater potential probably exists for the application of discrete automation and remote technologies to coal sector equipment and processes, including for example:

- integration of current "state of the art" machine guidance and control systems to enable continuous miner operating functions to be automated during the break-away process to ensure consistency, repeatability and reliability of breakaways without the need for highly skilled operators;
- to similarly apply current "state of the art" machine guidance and control systems to enable continuous miners to be operated remotely from a non-hazardous environment, and/or to be operated free of delays due to the operator's inability to sight the position of the cutter head and machine body relative to the roof, floor and sides, or other persons;
- application of remote control technology to enable shuttle cars and continuous haulage systems to be operated remotely from a non-hazardous environment.
- incorporation of carousel bolting systems to continuous miner mounted drill rigs (as is reportedly being progressed by Joy Mining Machinery);
- the application of drill control systems for remote, semi automatic operation of miner mounted drill rigs;
- the adaptation of carousel drilling systems for continuous miner mounted cable bolting systems, potentially including cable storage and insertion systems;

Adaptation and integration of these latter bolting related technologies may pose challenges whilst coal mines continue to be constrained by current mining height paradigms.

Cycle times for drill and blast operations allow in-cycle shotcreting to be utilised as a skin reinforcement technique in lieu of steel mesh in the metalliferous sector. On the contrary, cycle times for continuous miner based roadway development systems would disallow adoption of in-cycle shotcreting in the coal sector, even if such a technology was considered appropriate. Thin skin liners (TSL) trialled in the metalliferous sector[3] showed considerable promise as an alternative skin reinforcement technique, however vapours generated during application and curing have limited their adoption. Further development of this technology would be necessary to enable TSL to be utilised as an alternative skin reinforcement technique in both the metalliferous and coal sectors.

The widespread adoption of drill and blast operations allows flexible ducting and forcing ventilation systems to be used almost without exception in the metalliferous sector, as limited dust is raised during drilling, mucking out and support phases of the roadway advance cycle. Installation and maintenance of ventilation ducting is considered to be far easier than installation of rigid duct as used in coal mines, with the flexible ducting reportedly suffering lower quantity and pressure losses. Application of flexible ducting in gateroad development would require either improved dust capture and suppression at the cutting face (with a positive intake system as used in cut and flit operations), or forcing fans installed at the face with the exhaust ducted to a return outbye, or the application of remote control technologies to all facets of the process to enable equipment (including cutting, bolting and coal clearance) to be operated remotely from a dust free environment. Installation of dust scrubbers on continuous miners fitted with on-board bolters could be practical solution, if additional space could be made available on the continuous miner to install the scrubber.

6.4 Tunnelling Practice in Australia

As noted above the civil tunnelling sector in Australia is expected to complete approximately 14 km per annum of tunnels greater than 2.0 m diameter during the period 2004 to 2008 inclusive. Excavation methods comprise a mix of roadheader, TBM, drill and blast, and cut and cover, with the majority being completed by roadheaders or TBMs. Examples of tunnelling projects undertaken during this period include:

- ***North-South Bypass Tunnel Project, Brisbane***

  The project comprises the development of twin two lane 4.8 km long tunnels and ancillary roadworks to connect Woolloongabba, Kangaroo Point and Bowen Hills to allow motorists to avoid the CBD when travelling north-south or vice versa.

  The $1.6B project was recently awarded to the Leighton Contractors Baulderstone Hornibrook Bilfinger Berger Joint Venture by the Brisbane City Council, and tunnelling is expected to commence early 2007 following delivery of the first of the two 12.4 m diameter TBMs.

- ***Lane Cove Tunnel, Sydney***

  The project comprises the development of twin 3.6 km long tunnels and ancillary roadworks connecting the Gore Hill Freeway with the M2, with three lanes provided in longer sections to improve safety and traffic flow for tunnel users. The $1.5B project is being constructed by Thiess and John Holland, and will be subsequently operated by Transfield Services (Fig 17 and 18).

  Seven roadheaders were used during construction, including 3 Voest Alpine ATM105-IC roadheaders and two Mitsui SLB300 roadheaders. The ATM105-IC machines have an extended field of operation for mechanised tunnelling in hard and abrasive rock formations and can cut up to 9.1 m wide by 6.6 m high excavations, and are fitted with Voest Alpine's ICUTROC cutting system. This system utilises half the specific energy of earlier systems because of its reduced cutting speed and more effective cutting concept, and is reportedly capable of cutting rock of up to 120 MPa UCS.

Fig 17: Lane Cove Tunnel, Sydney - Roadheader in Operation (photo courtesy of Australian Tunnelling Society).

Fig 18: Lane Cove Tunnel, Sydney - Waste Removal, Ventilation Ducting and Services (photo courtesy of Australian Tunnelling Society)

650,000 m^3 of Hawkesbury sandstone will be excavated during the project, with the project being due for completion in May 2007 (although it is now expected to be completed some months ahead of schedule).

- ***EastLink (formerly Mitcham-Frankston Freeway), Melbourne***

  EastLink comprises a 45 km long freeway project connecting Melbourne's eastern and south-eastern suburbs between the existing Eastern Freeway at Donvale and the Frankston Freeway on the Mornington Peninsular. The $2.5B project is being constructed by Thiess and John Holland on behalf of the Southern and Eastern Integrated Transport Authority.

  The project includes twin 1,510m long triple carriageway tunnels, 16 m wide and 12.5 m high. Each of the tunnels is being excavated from either end with a Voest Alpine ATM105 roadheader, with each tunnel being advanced in two stages with top most section (header) being completed prior to the floor section being excavated and the road surface formed. The tunnels will be fully concrete lined on completion, with shotcrete being utilised as a temporary support during excavation (Fig 19). The tunnels are up to 40 m below ground and at least 450,000 m^3 of material will be excavated from the tunnels.

  Tunnel construction commenced in the last quarter of 2005 with the first hole through of the header section completed in October 2006. Excellent progress has been reported despite rock strengths of up to 200 MPa being encountered, and it is projected that EastLink will be completed 6-12 months prior to its scheduled completion date, late 2008.

Fig 19: EastLink Tunnel, Melbourne (photo courtesy of Australian Tunnelling Society).

- ***New MetroRail City Project, Perth***

  The City Project is part of the 72 km long Perth to Mandurah South West Metropolitan Project, linking the rapidly growing Perth South-West Corridor with the Perth CBD and the existing electrified rail network. The total length of the project through Perth's CBD is 2.2 km and includes 700 m of twin 7 m diameter TBM bored tunnels, 700 m of cut and cover tunnel, and two 135 m long underground stations (Fig 20). The $1.52B New MetroRail Project is being completed by Leighton-Kumagai.

  The first of the two 7.0 m diameter tunnels commenced in October 2005 and was completed in June 2006. The second tunnel was then commenced late July 2006 and the first 470 m section of the second tunnel was completed on 31 August, at an average rate of over 10 m per day. Tunnelling was completed end October 2006.

Fig 20: NewMetroRail City Project, Perth WA - 7.0 m diameter TBM Shield (Sandgroper) (photo courtesy of Australian Tunnelling Society).

- ***Epping to Chatswood Railway***

  The project will deliver a new underground rail service connecting Epping in the northwest to Chatswood in the north and provide three new, fully mined railway stations along the route. The Thiess Hochtief Joint Venture (THJV) is the major contractor responsible for the excavation, lining, and track laying through their sub-contractor United. THJV is also responsible for the complete mechanical and electrical equipment necessary to operate the trains.

  Twin 12.5 km long, 7.2 m diameter tunnels were each bored with a Robbins TBM, with each TBM being 210 m long and weighing 1,060 t each (Figs 21 and 22) . Excavation of a 100 m box cut and 150 m long tunnel decline was necessary at the M2 worksite at Macquarie Park for access and egress to the tunnel. The first TBM commenced from this site in September 2003, with the second commencing one month later, and both headed westbound to complete the 6.7 km first stage to Epping mid 2004. They were then disassembled and taken back to the M2 site by road for reassembly before completing the remaining section to Chatswood. After tunnelling for 5.2 km and crossing the 170 m long cut-and-cover section of tunnel constructed under the Lane Cove River, the TBMs holed through at Chatswood in June and July 2005 respectively, before being moved forward to a previously excavated disassembly tunnel at the Chatswood site.

  The TBMs were reported to have performed suitably well during the life of the project, and even though the conveyor system caused unexpected delays the combined average performance of both TBMs throughout the project was 33 m/day, with a combined availability of the TBM and conveyor system exceeding 80%[23]. Best performance was 92 m in 24 hours, which was a world record for TBM daily excavation rate in its diameter class, while best weekly performance was 368 m which was only 4 m less than the then current world record.

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[23] Australian Tunnelling Society, Current Projects, website: www.ats.org.au

Concrete lining of the tunnels was carried out with a total of six 15 m long lining forms, with concrete lining commencing in October 2004 and continuing through to July 2006 at rates in excess of 400 m per week.

It is expected that following fit out of railway tracks and electronic signalling the Chatswood-Epping rail line should be ready for use in 2008.

Fig 21: (above) Epping to Chatswood Railway – TBM and Associated Structure

Fig 22: (right) Epping to Chatswood Railway – 7.2 m Diameter TBM Cutterhead

(photos courtesy of Australian Tunnelling Society)

- ***Cross City Tunnel, Sydney***

  The 2.1 km long Cross City Tunnel was designed to improve east/west travel across the Sydney CBD, and runs under the city between Darling Harbour and Rushcutters Bay, linking the Western Distributor to New South Head Road and connecting to the Eastern Distributor and Domain Tunnel. The $1.0B project was completed by Baulderstone Hornibrook Belfinger Berger.

  Eastbound and westbound traffic travel in separate two lane tunnels, each 2.1 km long, while a total 8.5km of tunnelling was completed to both interconnect and to ventilate the network of roads. Seven roadheaders were utilised on the project, including five Mitsui S300 and one S200 machines (Fig 23). A 42 m deep, 14 m long and 8 m wide shaft was excavated at the corner of Bourke and William Streets to allow one of the roadheaders to be lowered down for excavation of the main westbound tunnel. The 8.6 m wide by 7.8 m wide tunnels were advanced an average 6 linear metres per day per roadheader through the Sydney sandstone, with about 400 m^3 of material being excavated per day per roadheader. The tunnel was supported with rockbolts and steel reinforced fibrecrete, with fibrecrete being sprayed on in two 50 mm passes.

Fig 23: Cross City Tunnel, Sydney - Roadheader in Operation (photo courtesy of Australian Tunnelling Society)

- ***Tugun Bypass, Gold Coast Airport***
  A 7 km motorway is being constructed from Currumbin in Queensland passing to the west of the Gold Coast Airport main runway to join the Tweed Heads Bypass in NSW. The motorway requires the construction of a 350 m long tunnel to avoid interfering with airport operations, and with runway extensions that are scheduled to commence end 2006. The tunnel will be 27 m wide by 8 m high, and be built 2 m below the existing ground level, with 300 m long approach ramps at either end. The tunnel will initially provide for 4 lanes of traffic, with provision to adapt it to 6 lanes in the future if required. North and south carriageways will be separated by a central wall. The tunnel will be built in several stages, including the installation of piles, construction of external walls, roof construction, soil excavation works and approach ramps.

Other recent tunnelling projects which illustrate the diversity of tunnelling practice in Australia include[24]:

- ***Sydney Airport Rail Link***
  The single 10 km long, 11 m diameter tunnel consisted of a 4 km long rock tunnel, a 6 km long soft rock tunnel, four underground stations and an interchange station. The rock tunnel section was excavated with two roadheaders, one used in sandstone and the other in soft shale, while the soft rock section was excavated with a slurry TBM through complex geology consisting of soft alluvial soils and marine deposits to 30 m depth. The project was valued at over $650M and was completed over 5 years in time for the Sydney Olympics by Transfield Bouygues Joint Venture.

- ***Northside Storage Tunnel, Sydney***
  The primary aim of the $450M project was to improve the waters of Sydney Harbour by substantially removing diluted sewage overflows from entering the Harbour during periods of heavy rain. The project involved 21 km of TBM driven tunnel, 2 km of declines, 7 major caverns and 1,050 m of vertical shafts, and two underground pumping stations, linking sewage systems at Lane Cove West, Scotts Creek, Tunks Park, Quakers Hill, and Little Manly Point with the North Head Sewage Treatment Plant. Four Wirth TBMs were employed, ranging from 3.8 m to 6.6 m diameter, with three being used concurrently from the Tunks Park portal. The four TBMs achieved a best week's advance of 1,093 m, with performance of the largest and smallest machines being as follows:

	6.6 m Ø	3.8 m Ø
Best Shift (12 hours)	47 m	57 m
Best Day (24 hours)	70 m	80 m
Best Week (7 days)	328 m	377 m

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[24] Australian Tunnelling Society, Historical Projects, website: www.ats.org.au

1.8 Mt of excavated material was removed from the TBMs with continuous conveyors through a combination of inclined, vertical and horizontal conveyors to two barge loading points on the Harbour, where material was barged to a railhead at Whites Bay for transport to the western outskirts of Sydney and subsequent reuse in industrial development earthworks.

A one-shot chemically anchored and encapsulated GRP rock bolt system was used for support due to their compatibility with fast TBM drivage and their lower proneness to corrosion.

Construction of the project was completed in 24 months and successfully met all of its project objectives, despite many constraints and technical difficulties[25].

- ***Energy Australia Cable Tunnel***
  The 1.4 km long, 4.0 m wide by 3.6 m high tunnel was excavated by roadheader mostly within Sydney sandstone at depth ranging from 13-31 m below surface (average 20 m) depth, to reticulate 132 kV electricity cables for the Sydney CBD (Fig 24). The tunnel runs under the Eastern Suburbs Railway tunnels and also under the proposed MetroPitt and MetroWest railway tunnels. A forced ventilation system is installed in the tunnel with ventilation fans installed in a 70 m long, 8.0 m wide by 7.0 m high chamber within the tunnel.

  Primary support is provided by 2.1 m long GRP rockbolts for the standard excavation, with CT bolts used where the tunnel widens and for the ventilation chamber. The walls and crown of the tunnel were lined with a minimum 50 mm thickness of steel fibre reinforced shotcrete, with the invert being lined with polypropylene fibre reinforced concrete slabs.

Fig 24: Energy Australia Cable Tunnel, Sydney (photo courtesy of Australian Tunnelling Society)

- ***Transgrid MetroGrid Cable Tunnel, Sydney***
  The TransGrid Cable Tunnel is a 3.5 km long tunnel constructed for the installation of a new 330 kV cable from South Sydney Substation at Picnic Point, to a new high voltage substation at Ultimo. Construction of the tunnel commenced in 2002 and was undertaken in Hawkesbury Sandstone and Ashfield Shale at depths up to 30 m. The tunnel comprises two sections, a 3.0 km long 3.4 m diameter TBM driven tunnel and a 0.5 km long roadheader driven section 3.6 m wide by 4.0 m high. The tunnel was shotcrete lined and grouted to reduce water inflows to an acceptable level, and is force ventilated to reduce the build up of heat from power cables.
- ***Crafter Highway - Eagle on the Hill Tunnels, Adelaide***
  Twin 480 m long, 13.3 m wide by 9 m high tunnels were completed by Walters Construction as part of the 9 km long Crafters Highway Project in the Adelaide Hills. Tunnelling commenced with a Mitsui S200 roadheader and achieved satisfactory rates and minimal overbreak. However, at 50 m depth the rock hardened and a Montebert V-45 Rock Hammer mounted on a 30 t excavator was introduced, and lifted production by 25 percent.

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[25] International Tunnelling Society, Focus on Australia, website: www.ita-aites.org/cms/289.html

As tunnelling progressed further extremely hard quartzite was experienced, which necessitated the introduction of drill and blast techniques. Excavation techniques evolved rapidly to a combination of rock breaker and/or blasting to take out the rock to an intrados line some 1 m inside the final excavation line, with the roadheader then being used to trim the final metre and minimise overbreak. In time, the technique relied on drill and blast with roadheader trimming only.

Excavation and construction was guided by a computer based laser system to achieve the gently sloping, curved tunnel profile. The laser system was based on a Leica TCM1100 total station fitted with laser eyepiece, and located the position of blast holes on the face for rapid mark up and preparation for drilling.

Tunnel support was designed for an extremely long life and required 6 m long permanent rock bolts and shotcrete.

- ***Blue Mountains Tunnel, NSW***
  The $80M project required the completion of over 20 km of tunnels and nine 3.0 m by 1.5 m diameter blind drilled shafts of depths ranging between 60-115 m in 40-50 MPa sandstone through the Blue Mountains by the McConnell Dowell/Obayashi Joint Venture. The 3.4 m diameter tunnels were excavated by a Robbins Mk12 TBM, with spoil being removed with a continuously advancing Terratec conveyor system, up to 13.4 km long. Locomotives were used for transport of materials and personnel inside the tunnels. Rock bolts and shotcrete were used to support the tunnel roof and walls, with the invert being concrete lined. Several world records were established on the project, including 70.5 m in a single shift, 172.4 m in a single day, 703.3 m in a single week, and a best four week period of 2,166 m.

- ***LPG Cavern, Sydney***
  Four 230 m long, 14 m wide by 11 m high caverns were excavated by Walter Construction to form a 65,000 t (130,000 m^3) underground liquefied petroleum gas (LPG) storage facility, 135m below Port Botany in Sydney (Fig 25). The four caverns are interconnected by 5.5 m wide by 5.5 m high galleries with the storage facility being accessed by two 150 m deep shafts, 6 m and 4 m diameter respectively. Another series of 4 m wide by 3.5m high tunnels totalling 700 m in length were excavated 15 m above the storage caverns to form a water curtain gallery and saturate the rock above the caverns, thereby maintaining gas pressure within the caverns. All excavation was undertaken by drill and blast, with a total 160,000 m^3 of sandstone being excavated from the facility and compacted on the surface to raise the level of the site.

Fig 25: Elgas LPG Storage Caverns, Sydney (photo courtesy of Australian Tunnelling Society).

- ***West Cliff Colliery Access Drift***
  A 5.1 m diameter TBM was used to complete West Cliff Colliery's 1,600 m long, 1:3 gradient main access in 1978 after being modified to accommodate the 1:3 gradient and to comply with

electrical requirements of the Coal Mines Regulations Act (CMRA). Ingress of ground water from the overlying Hawkesbury sandstones caused problems during the initial drivage and necessitated alterations to the construction methods, while adverse geological conditions in the inter-bedded shale and sandstones beneath the Hawkesbury sandstone gave rise to unstable roof conditions which considerably slowed the advance. Notwithstanding the problems encountered on this project, experience showed that a tunnel boring machine could be successfully used on a 1:3 decline drift, however the high initial cost of providing and installing the equipment were then considered to limits its application to coal mines. It was subsequently reported that little maintenance of the drift has been necessary over the ensuing 28 years of operation of the mine.

6.5 An Historical Perspective on Tunnelling Practice

Tunnels were hand-dug by several ancient civilisations in the Indian and Mediterranean regions[26]. In addition to hand digging tools and copper rock saws, fire was sometimes used to heat rock obstructions before they were quenched with water to crack the rock apart. The cut and cover method which is a method used extensively today (eg; Tugun Bypass), and comprises the digging of a trench and construction of a roof at an appropriate height within the trench before covering over the trench, was used in Babylon over 4,000 years ago.

A qanat or kareez of Persia is a water management system comprising a tunnel accessed by a series of vertical shafts, and was used to provide a reliable supply of water to human settlements and for irrigation in hot, arid climates. The oldest and largest one was built over 2,700 years ago and still provides drinking and agricultural water to nearly 40,000 people in the Iranian city of Gonobad, with water being transported over a distance of 45 km. The Eupalinian aqueduct on the island Samos (Ionia) was built in 520 BC by the Ionian engineer Eupilinos, with the 1.5-1.8 m wide by 1.5-1.8 m high and 1,030 m long tunnel being constructed under a 250-300 m high mountain (limestone), from both ends simultaneously. Re-discovered in the 19th century, it has been found that a second tunnel had also been constructed some 12 m below the still accessible main tunnel, and was lined with ceramic pipes for carrying water.

The first advance beyond hand-digging was the use of gunpowder in France in 1681 to excavate a 160 m long canal tunnel, with dynamite (stabilised nitro-glycerine) being first used in the 1850's to replace black powder in tunnel blasting. Steam and compressed air powered drills were introduced during the 1850's to replace manual chiselling of 4.2 m long shot holes with sledge hammer and steels. The first drilling jumbos were built in 1931 to dig tunnels around the site of construction of the Hoover Dam, and consisted of 24-30 pneumatic drills mounted on a frame welded to the bed of a truck

Tunnelling shields, which are the forerunners to modern TBMs, were first developed by Sir Marc Isambard Brunel to excavate the Thames Tunnel beginning in 1825[27]. Brunel's original design, which was of rectangular cross section, was substantially modified by Peter W Barlow in the construction of the Tower Subway under the Thames River in Central London in 1870. Barlow's most crucial design innovation was the adoption of a circular cross section which at once made it simpler in construction and better able to support the weight of the surrounding soil. The Barlow design subsequently was enlarged and further improved by James Henry Greathead in 1894, for construction of the City & South London Railway (which today is part of the London Underground's Northern Line). Most tunnelling machines used today are still loosely based on the Greathead shield.

In 1873 American tunneller Clinton Haskins kept water from seeping into a railway tunnel being constructed below the Hudson River by pressurising it with compressed air. The method is still used today although it presents several dangers including a requirement to depressurise workers at the end of their shift (which also limits emergency escape), and risks of under or over pressurisation which results in either tunnel collapse or bursting (and hence flooding) respectively[26]. The development of measures to control soft ground has also included freezing of the ground with a circulating fluid being

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[26] How Products Are Made contributors, *Tunnel*, How Products are Made, January 2006 (accessed 18 November 2006)

[27] Wikipedia contributors, *Tunnelling Shield*, Wikipedia, the Free Encyclopedia; August 2006 (accessed 8 November 2006)

pumped through pipes imbedded in the ground at intervals surrounding the area (early 1900's), the injection of a liquid bonding agent or grout into the soil or fractured rock surrounding the tunnel route (1970's) and the spraying of liquid concrete (shotcrete) on the tunnel surfaces. Invented in 1907 shotcrete has been widely used as preliminary and final lining for tunnels since the 1920s, and now typically includes steel and/or polypropylene fibres (fibrecrete).

A number of attempts were made to mechanise the tunnelling process, with the first (unsuccessful) tunnelling machine being attributed to a Belgian engineer Henri-Joseph Maus in 1845-46[28]. The first, and almost the only successful rock machine of the period was designed by Colonel Fred Beaumont and Arthur English, two officers of the Royal Engineers, with a machine being put into service in 1882 on both sides of the English Channel to commence the first under-Channel tunnel[29]. The 2.1m diameter, pneumatically operated machines produced at a rate of 15 m/day over the last 53 days, with peak rates of 24 m/day being achieved in the soft chalk marl (the project was halted by the British Parliament due to political concerns after some 2,000m was bored at Shakespeare Cliff near Dover and around 1,600 m at Sangatte near Calais) The unlined tunnels were still standing when intersected by the new Channel Tunnel nearly 100 years later, while the machines were later used to bore tunnels in soft sandstone under the Mersey River.

In London in 1893, JJ Robbins patented a shield with full rotating head equipped with drag picks, hydraulic jacks thrusting against cast iron rings, and an endless chain haulage system for removing muck, although there is no record of the machine ever being built. The Price machine was also patented by J Price in 1896, and was put into commercial production in 1901 by Markham and Co Ltd in England after it was modified and further developed.

A new era in rock tunnelling began in the 1950's when James S Robbins, then of Chicago, developed a tunnel boring machine, "Mittry's Mole" (as it was called). The machine weighed 114 t, was 27 m long, 7.9 m diameter, with 300 kW at the cutterhead, and achieved rates of up to 49 m in 24 hours in the soft Pierre shale experienced in the water diversion tunnel then being constructed outside Pierre, South Dakota. Subsequent machines, similarly equipped with cutter picks as utilised in the mechanisation of early coal mines, were not as successful in anything but soft rock conditions and it was not until Robbins developed early "disc cutters" in the late 1950's that the technology was able to be more widely applied after Robbins first disc cutter machine drove a 3.3 m diameter tunnel in limestone, sandstone and shale with strengths ranging from 55-186 MPa. While the machines proved capable of advancing tunnels three times faster than drill and blast tunnelling techniques then employed, *when they were working*, low machine availability and unreliability reportedly limited their acceptance.

It was not until the late 1960's that the technology was accepted to the point that the City of Chicago specified that only TBMs would be employed on the Chicago Deep Tunnels Project. The project was designed to reduce sewage overflow entering Lake Michigan during rain events, and included 197 km of tunnelling to connect a vast system of holding tanks (68 Bl) that were constructed to hold run-off until treatment plants could catch up (the project commenced in the mid 1970's and is not expected to be completed until at least 2019). This project reportedly gave impetus to companies all across the world to develop TBM technology, with performance rapidly improving from the then hard rock tunnelling record of 180 m/month, to 450 m/month and then 600 m/month. Modern TBMs now achieve sustained production rates of up to 1,200 m/month.

Roadheaders were first developed in Hungary in 1949 and have evolved significantly to +100 t machines capable of excavating roadways up to 7.9 m height by 11.0 m width (Eickhoff ET480) in a single pass, with recent developments in cutting technology reportedly enabling rocks of more than 120 MPa to be excavated by roadheader (Sandvik ATM105C).

The excavation and support of tunnels by non-TBM methods has also evolved over time with for example, the New Austrian Tunnelling Method (NATM) being developed in Austria between 1957 and

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[28] Hapgood F, *The History of the Tunnel Boring Machine*, website: www.fhapgood.fastmail.fm/TBM.html (accessed 10 November 2006)

[29] Sutcliffe H, *Tunnel Boring Machines*, Tunnel Engineering Handbook 2nd Edition, Kluwer Academic Publishers, Norwell, Massachusetts, USA, 1996

1965. NATM was developed for tunnels that are excavated in a number of passes or headings (as illustrated in Fig 26), with NATM essentially comprising a philosophy of mobilising the strength of the ground around a tunnel by allowing controlled deformation of the ground in conjunction with installation of an initial primary support of appropriate load deformation characteristics to the ground conditions. Extensive monitoring of ground deformation and the initial support system is utilised to optimise the initial support design and the sequence of excavation of the tunnel.

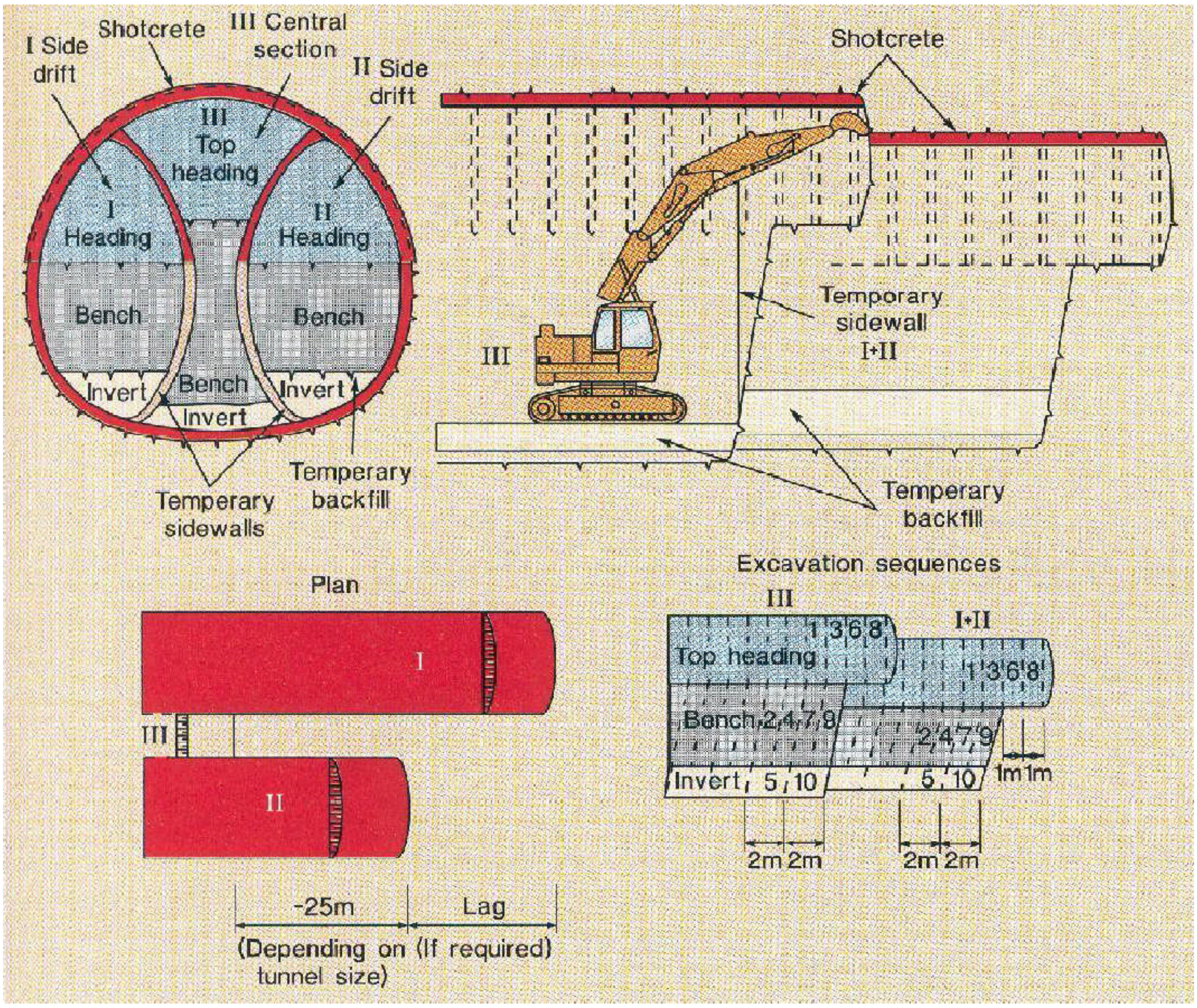

Fig 26:Typical Extraction Sequence for Tunnel Constructed Using NATM (from Soft Ground NATM[30])

A thin shotcrete skin is typically applied as the initial primary support and, depending upon ground conditions, may be supplemented by a flexible combination or rockbolts, mesh and steel ribs. Closure of the invert and creation of a load bearing ring is considered important, particularly in soft ground conditions. A permanent support is subsequently installed prior to fit-out of the tunnel. The method has been used extensively in North America for tunnelling in soft ground conditions, possibly even before the method was first described in European literature, hence the sometimes reference in North America to either soft ground tunnelling method, North American Tunnelling Method[31], sequential extraction method (SEM), or sprayed shotcrete lining (SCL).

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[30] Lees D, Soft Ground NATM, *Technical Papers, Tunnelling Systems*, Australian Tunnelling Society, 2006

[31] Field DP, Hawley J, and Phelps D, *The North American Tunnelling Method – Lessons Learnt*, Rapid Excavation and Tunnelling Conference, Society for Mining, Metallurgy, and Exploration, Inc., 2005

6.6 Application of Tunnel Boring Machines (TBMs) in the Tunnelling Sector

TBMs typically consist of one or two shields and trailing ancillary services, and are typically fitted with a rotating cutter disc at the front end of the machine. A chamber is located immediately behind the cutting wheel where the excavated material is either mixed with slurry (so-called *slurry* TBM) and pumped from the machine, or left as-is and discharged via an elevating conveyor onto the waste clearance system (typically another conveyor system). A set of gripper hydraulic jacks at the rear of the TBM are used to stabilise the rear section and enable the forward section, including the cutter wheel, to be pushed forward to excavate the face, with a stroke of up to 1.83 m. Once the forward section has been fully extended it is then stabilised with gripper hydraulic jacks before the rear section is moved forward, much like the process utilised to advance a longwall face.

Support systems are installed immediately behind the shield, and may comprise pre-cast concrete rings or segments, cast-in-place concrete, shotcrete, or more recently, rock bolting and straps (or in some cases, no support at all). Other ancillary systems are located in the finished part of the tunnel immediately behind the shield, and include control rooms, slurry pumps or conveyors (as appropriate), concrete ring or segment handling devices, and even refuge chambers. A high degree of automation is utilised on state-of-the-art TBMs, with machine guidance systems being used to steer and control the machine in three dimensional space.

Cutter and shield configuration depends upon the type of geology to be encountered and the speed of excavation required, with double shielded TBMs normally being used in unstable geology or where a high rate of advancement is required. Single shield TBMs are generally more suitable to hard rock geology.

To control ground movement and subsidence in soft alluvium or sedimentary deposits often associated with urban tunnelling projects, positive face control machines are utilised, including earth pressure balance (EPB), bentonite slurry (BS), or compressed air (CA) systems. In contrast, open face machines are typically used in hard rock environments. One of the criticisms levelled at TBMs is that while they can be designed to excavate almost any type of ground, from soft, water logged strata to extremely hard rock (>250 MPa), they are typically unable to effectively excavate and support widely varying geological conditions across a single tunnel. A detailed understanding of the expected geology and ground conditions is necessary to ensure that machines are properly specified and designed for the specific site conditions likely to be experienced.

Fig 27: The largest TBM currently in operation is a Herrenknecht 15.2 m diameter, 4,364 t S-300 EPB machine being utilised on a 3.65 km long motorway tunnel in Madrid (photo courtesy of Herrenknecht AG).

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More recently, mixed face TBMs have been developed that can be employed in mixed ground conditions (Fig 28), however the design of such machines reportedly compromise key elements and capabilities of the respective core technologies[29].

Fig 28: Herrenknecht are currently commissioning a 15.43 m diameter S-317 mixshield in Shanghai where it will be used to construct one of two 7.2 km long three lane road tunnels (photo courtesy of Herrenknecht AG).

TBMs have now been developed that will excavate a wide variety of tunnel profiles, including:

- Double O Tube (DOT)[32] machines with two interlocking synchronously controlled cutters that similarly allow wide-low tunnels or high-narrow tunnel sections to be excavated (Fig 29);
- Multi-Circular Face Shield[33] machines with two or three overlapping offset cutters that allow wide-low tunnels or high-narrow tunnel sections to be excavated (Fig 30);
- JIYU-DAMMEN machines[34] fitted with planetary cutters that allow horseshoe, oval, ovoid, rectangular or arched profiles to be excavated (Fig 31), or Wagging Cutter[35] machines (see below) that similarly allow rectangular cross sections to be mined (Fig 32);
- DPLEX machines[36] with a cutter frame supported eccentrically at the end of multiple crank shafts which when rotated in the same direction causes the cutter to move in a circle along the inside perimeter of the tunnel face to create a cross section of similar shape to the cutter. An EPB method is typically used to ensure stability of the face (Fig 33).

Fig 29: Double O Tube (DOT) Shield

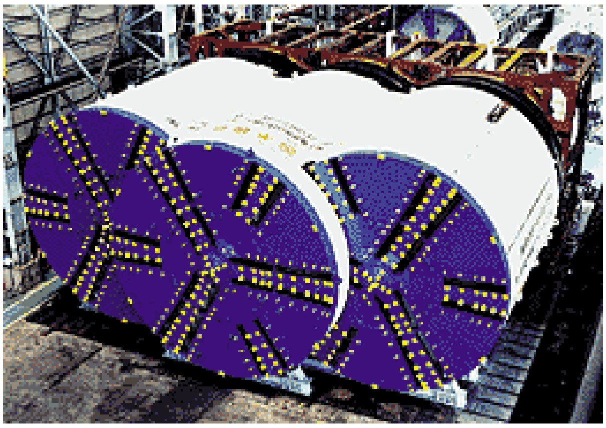

Fig 30: Multi-Circular Face Shield

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[32] Shield Tunnelling Association of Japan, website: www.shield-method.gr.jp/english/dot/index.html (accessed 29 September 2006)

[33] Shield Tunnelling Association of Japan, website: www.shield-method.gr.jp/english/mf/index.html (accessed 29 September 2006)

[34] Shield Tunnelling Association of Japan, website: www.shield-method.gr.jp/english/jiyu/index.html (accessed 29 September 2006)

[35] Shield Tunnelling Association of Japan, website: www.shield-method.gr.jp/english/wac/index.html (accessed 29 September 2006)

[36] Shield Tunnelling Association of Japan, website: www.shield-method.gr.jp/english/dplex/index.html (accessed 29 September 2006)

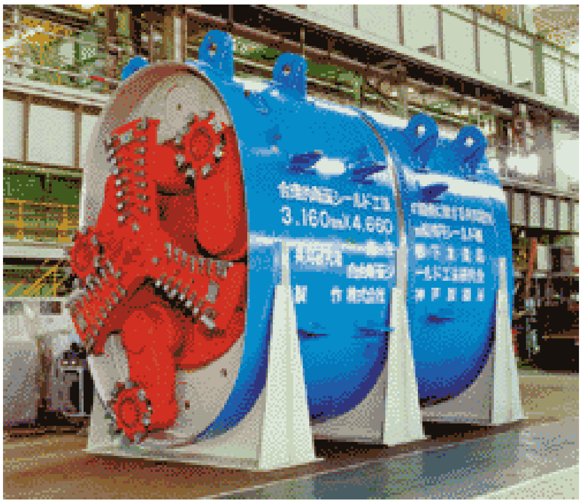
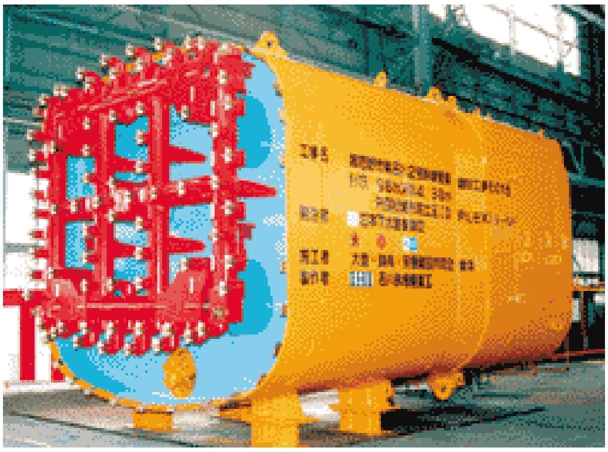


Fig 31:JIYU-DAMMEN Shield

Fig 32:Wagging Cutter Shield

Fig 33:(right) DPLEX Shield



(Fig 29-33 courtesy of Shield Tunnelling Association of Japan)

An exhaustive listing of current tunnelling projects was not able to be sourced however it is noted that TBMs are used extensively throughout the world to construct tunnels of varying dimensions. Herrenknecht reportedly have 18 TBMs operating in Spain alone, while the Shield Tunnelling Association of Japan reports that around 150 shield tunnelling projects are awarded each year, down from its peak of some 300 projects during the 1980's. On an international basis, TBMs are manufactured in a number of countries (as detailed below), while Terratec, a Tasmanian based company provides an extensive range of services to the tunnelling sector, including overhaul of TBMs, cutting technology, and extensible conveyor systems. TBM manufacturers include:

- Germany - Herrenknecht AG, Wirth Group
- Japan - Hitachi Construction Machinery, Ishikawajima-Harima Heavy Industries (IHI), Kawasaki Heavy Industries, Mitsubishi Heavy Industries;
- Italy - Seli Tecnologie
- North America – Construction and Tunnelling Services (recently acquired by Herrenknecht AG), Lovat (Canada), Robbins (USA)

While a TBM was successfully used for the development of the West Cliff drift in the mid 1970's, there have been no reports of TBMs being used in the Australian underground metalliferous sector. Overseas, Cigla et al report on the successful utilisation of TBM for mine development in two American metalliferous mines (San Manuel Copper Mine, Tucson, Arizona and Stillwater Mine East Boulder Project, Billings, Montana (Fig 34)) with rock strengths of 150-180 MPa and 60-190 MPa, respectively[37]. There are also reports of TBMs being used in underground development in coal mines

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[37] Cigla M, Yagiz S, and Ozdemir L, *Application of Tunnel Boring Machines in Underground Mine Development*, Colorado School of Mines, 2000

in both Germany (Lohberg Mine) and the UK (Dawdon Colliery, Selby Complex), although further details of these applications are yet to be sourced.

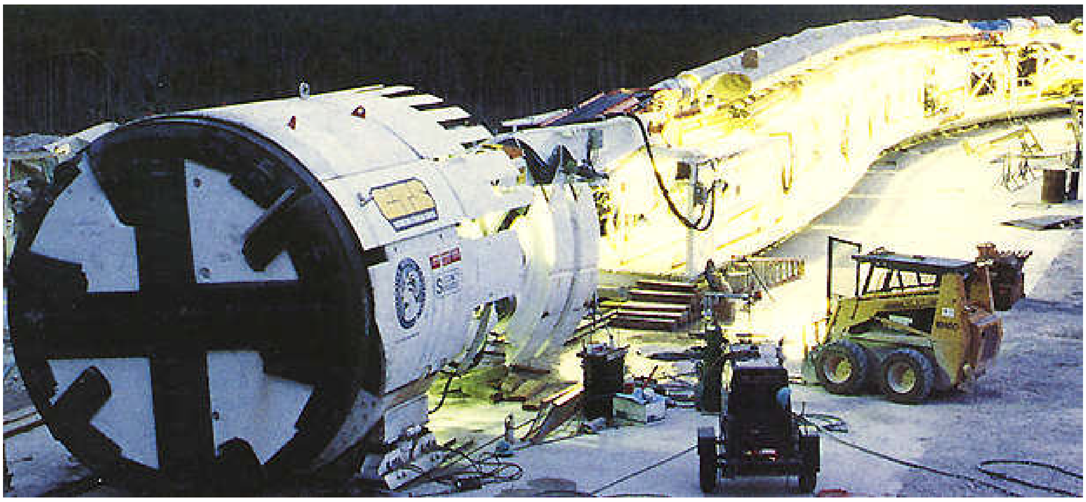

Fig 34: One of Two TBMs Used to Mine Access Drives at Stillwater Mine East Boulder Project, Billings, Montana, USA (photo courtesy of www.mining–technology.com).

In regard to the ability of TBMs to cut "hard" rock, a TBM manufacturer reported that TBMs were currently operating in tunnelling applications in Europe in material up to 260 MPa UCS[38], while Hutton et al report on the use of two hard rock TBMs for development of the 5.6 m diameter, 13.3 km long Nancy Creek Tunnel in Atlanta USA, in material ranging from 255 MPa to 540 MPa, with overall average advance rates of 23.2 m/day and 26.4 m/day respectively for the two machines[39].

As noted by Sutcliffe, a modern TBM is a complex system of interdependent parts that can occupy as much as 300 m of tunnel, and is made up of mechanisms for cutting, shoving, steering, gripping, exploratory drilling, ground control and support, lining erection, spoil removal, ventilation and power supply[29]. All of these parts must advance with the tunnel heading, with items such as trackwork, conveyors, power supply, ventilation ducting and other services being extended behind the TBM as it advances. All mechanisms must be able to function at a rate consistent with the advance of the cutterhead, with any deficiency in any part impacting the rate of development and the project schedule and costs.

Another feature of this interdependency and integration is the size and overall weight of TBMs, and the manufacturing and construction lead time typically required to construct a new machine. The two 7.2 m diameter TBMs utilised to bore two 12.5 km long parallel tunnels for the Epping-Chatswood railway each weighed 1,060 t and were 210 m long, while hard rock TBMs used on the San Manuel and Stillwater mine development projects (and therefore more likely to represent machines that would be used in a gateroad development application) were reported by Cigla et al as follows (refer Table 2):

For further comparison, the two 5.6 m diameter Robbins TBMs used to complete the Nancy Creek Tunnels in Atlanta USA, with rock strengths reported as ranging from 255 MPa to 540 MPa UCS, had 2,205 kW of power installed on the cutterhead and were capable of a thrust of 13,360 kN. The machines were equipped with roof/probe drills, and a ring steel erector for installing rock support. The machines each required excavation of 140 m long launch tunnels, 6.7 m high by 6.7 m wide to assemble the machines prior to commencement (Figs 35 and 36).

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[38] Parnell RJ, Herrenknecht AG Tunnelling Systems, Personal Communication, October 2006

[39] Hutton R, Bonner J, and Nonako T, *The Nancy Creek Tunnel: Hard Rock Tunnelling in Atlanta*, 2005 Rapid Excavation and Tunnelling Conference, Society for Mining, Metallurgy, and Exploration, Inc., 2005

Table 2: TBM Summary (adapted from Application of Tunnel Boring Machines in Underground Mine Development[37])

Project/TBM OEM	San Manuel - Robbins	Stillwater - CTS	Stillwater - Robbins
Boring Diameter	4.62 m	4.58 m	4.62 m
Cutterhead			
Installed Power	1,259 kW	1,345 kW	828 kW
RPM	4-12	3.8-11.6	4-12
Thrust	7,340 kN	8,545 kN	7,300 kN
Boring Stroke	1,575 mm	1,220 mm	1,550 mm
Minimum Turning Radius	105 m	61 m	105 m
Weight	225 t	275 t	225 t

Fig 35: Launch Chamber of 15.2 m Diameter EPB TBM Used to Construct 3.65 km Underground Freeway as Part of Madrid's Plan to Construct 124 km of Underground Metro System Between 1999 and 2007, Madrid, Spain (photo courtesy of Herrenknecht AG).

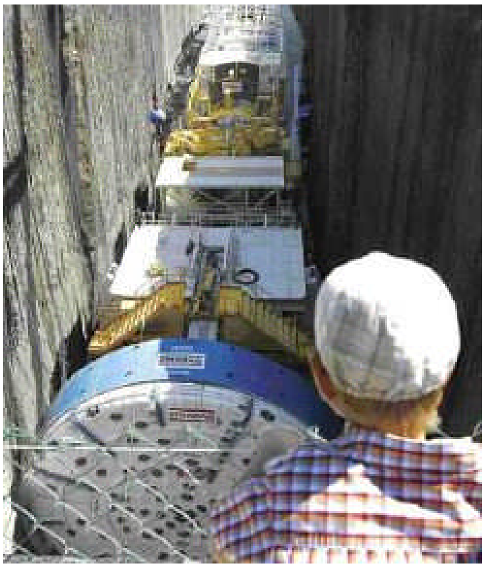

Fig 36: Launch Chamber of 14.4 m Diameter Open, Hard Rock, Floating Gripper TBM Used to Construct 10.4 km Long Water Tunnel for Hydro-Electricity Generation, Niagara City, Ontario, Canada.

Modern TBMs typically have high voltage power supplied to the machine (eg; 33 kV) and utilise on-board sub-stations to transform power to the main motors (typically 3.3 kV), with installed power requirements typically 5-8 MW, depending upon the TBM duty and rock hardness. It was noted that modifications were required to the West Cliff TBM to comply with CMRA requirements at that time, including when operating in the main drift section.

Even though it was reported that TBMs were economic in tunnels as short as 500 m, tunnel developers and contractors noted that an extensive learning curve was often experienced on TBM projects. Australian contractors reported that 1 km of tunnel was typically required to fine tune the TBM, a further 1 km of tunnel was required to fine tune the operating systems and develop skill levels to an appropriate level, with a further 1 km of "performance" tunnel being required to generate suitable overall returns. Even though Sutcliffe suggests that figures showing the learning curve of the six TBMs used on the undersea section of the Channel Tunnel (Table 3) are not typical of the industry, citing learning curves of 5 to 10 weeks for underland tunnels in the United States, he notes that the figures are consistent and suggests that other factors were at work, such as logistic and support systems peculiar to that project which also have their own learning curves[29].

Table 3: The Learning Curve – The Channel Tunnel (adapted from the Tunnel Engineering Handbook[29])

TBM	Total drive (km)	Total time (weeks)	Average advance rate (m/wk)	Learning Period		Weeks rest of drive	Average rate during learning (m/wk)	Average rate after learning (m/wk)	Ratio during/after learning	Maximum weekly progress
				Distance to reach average m/wk (km)	Time to reach average m/wk (wks)					
B1	22.3	151	147.7	2.6	42	109	61.9	180.7	2.91:1	293
B2	17.9	112	159.8	2.1	42	70	50.0	225.7	4.51:1	409
B3	19.0	101	188.1	3.0	40	61	75.0	262.3	3.50:1	426
F1	15.6	139	112.1	2.0	57	82	35.1	165.9	4.73:1	291
F2	20.0	128	156.2	2.8	45	83	62.2	207.2	3.33:1	295
F3	18.9	117	161.5	2.7	36	81	75.0	200.0	2.67:1	306

(Note: TBMs B1 and F1 respectively are the British and French TBMs that were utilised to complete the service tunnel between the two main running tunnels

TBMs B2 and B3, and F2 and F3 respectively are the TBMs used to complete the British and French sections of the two parallel running tunnels, with the two tunnels traversing similar ground to each other and to the service tunnel)

While a universal TBM may not available, the widespread adoption of TBMs across a variety of strata conditions and in a variety of end use applications and tunnel diameters facilitates an active market in the remanufacture or refurbishment of TBMs, a factor reportedly driven by the extensive lead time to design, manufacture and construct new TBMs[29]. The known performance and capability of existing TBMs is also a key factor, as a used TBM may have already been extensively modified to improve its performance (therefore obviating potential delays and under-performance that may result during commissioning and work-up of a new TBM).

6.6 Observations on Tunnelling Practice in Relation to Longwall Gateroad Development

A key observation in relation to civil tunnelling practice is the design life of civil tunnelling applications (eg; underground roadway and railway tunnels, often under bodies of water, water supply and sewage systems, high voltage power reticulation and communications networks). Such end use applications necessitate that appropriate safety factors be applied to ensure continuity and reliability of service over time, typically 50-100 years, hence the ability to expense high capital cost equipment over relatively short tunnels (eg; 2 kms), coupled with the extremely robust ground support measures employed to ensure long term availability and security of civil tunnels.

TBMs are not self-powered and rely upon thrust jacks and grippers to maintain pressure against the face and to advance. TBMs cannot retreat due to the installation of tunnel support and lining behind the cutter head, and on completion of a tunnel they require disassembly and removal or, as is the case in some projects, are bored into the surrounding rock and are sealed off and left intact (eg; Channel Tunnel). Consideration therefore needs to be given to disassembly and removal strategies in the event that a TBM was proposed for mine or gateroad development, including the preconstruction of assembly and disassembly chambers.

While TBMs are considered to be inflexible, and necessitate major infrastructure for mobilisation and disassembly, they are considered to be the equipment of choice for tunnels greater than 500 m length, unless highly variable ground conditions are likely to impact their effective utilisation, or the proposed tunnel cross section is not compatible with available TBM configurations. Ground conditions that are typically experienced in Australian gateroad development are expected to be eminently suitable for utilisation of TBM technology, and both IHI (Fig 37) and Pacific Tunnelling have developed design concepts for application of TBMs in gateroad development, including measures to facilitate their rapid re-deployment following completion of a gateroad.

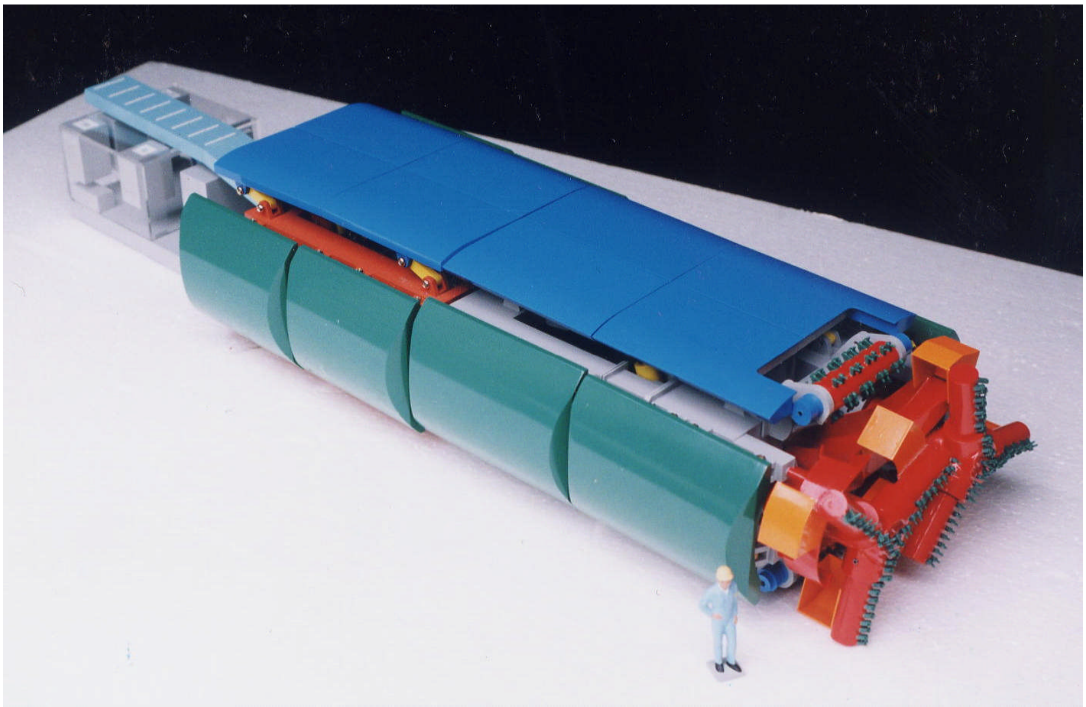

Fig 37: Concept Design for IHI's Double-O-Tube TBM for Coal Mine Roadway Development (courtesy of IHI Engineering)

Contractors noted that an open, hard rock gripper style TBM (similar to the Stillwater TBMs, Fig 34) would be an appropriate design for coal mine roadway development conditions, with current machine configurations allowing installation of ground support some 4 m from the face (although it is understood that the Pacific Tunnelling concept design allows rock bolts to be installed at less than 2 m from the face).

TBMs now achieve sustained production rates of nearly 1,200 m/month over the life of a project (as shown in Table 4), with these high performance levels resulting from the close matching of boring capability, muck removal, and support installation systems. The design of TBMs allows the supports to be installed concurrently with and independently from boring and mucking, providing the stroke of the borer matches the support cycle.

Table 4: World TBM Performance Records (adapted from Robbins[40])

Machine Diameter (m)	Best Day (m/day)	Best Week (m/week)	Best Month (m/month)	Monthly Average for Project (m/month)	Overall Tunnel Length (km)
3.01-4.00	172.4	703.3	2,066	1,189	
4.01-5.00	128.0	477.0	1,822	1,352	13.5
5.01-6.00	99.1	562.2	2,163	1,161	5.8
6.01-7.00	114.6	500.0	1,690	1,187	11.3
7.01-8.00	92.0	372.0	1,482	770	10.8
8.01-9.00	75.5	428.0	1,719	873	18.3
9.01-10.00	74.0	324 (5 days)	753	715.2	11.5

An experienced TBM contractor considers that sustained rates of 400 m/week are achievable in coal roadway development, while sustained rates of 400 m/week are at the current threshold of best practice gateroad development performance in Australia, and are typically associated with punch

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[40] The Robbins Company, www.robbinstbm.com/records/body_index.html, accessed 7 December 2006.

longwall mines (it should be noted that a standard 6.9 m diameter metro tunnel generates twice the volume of material per metre advance than a standard 5.2 m wide by 3.5 m high gateroad). Based on indicative costs of $21-22M for a roadway development TBM, significantly higher TBM performance rates would need to be both achievable and demonstrated before serious consideration could be given to the introduction of TBMs at these mines.

“Better performers in adverse conditions” may however be encouraged to consider the potential application of TBMs as a means of leveraging quantum improvements in performance, providing ground conditions favour application of TBMs and issues associated with the rapid construction, and redeployment of TBMs are addressed.

It is questionable whether mines that may currently be considered as “poorer performers in better conditions” could successfully apply such an integrated system for roadway development, unless a sustained organisational turnaround was achieved, one which perhaps reflected the attributes of best practice mines as previously reported[1]. Clearly, technical and economic evaluations are warranted to fully evaluate the overall benefit and risk/reward profile for employment of such technology in any gateroad development.

Roadheaders have been utilised on a limited basis in underground coal mines, usually in association with penetration of geological structures or for excavation of major infrastructure such as cross measure drifts, driveheads, and overcasts. They have not been widely used for roadway development in coal, probably because of the ready availability of continuous miners, together with the roadheaders typically low cutting rates and limited support capability, and hence their limited rates of advance. It is noted that an AM50 was used at Leichhardt Colliery for roadway development during the mid 1970’s, due to the roadheaders ability to excavate an ovoid profile (which replicated the shape of conventional rectangular roadways after regular falls of immediate roof) and to their less aggressive advance rates (in an endeavour to combat the risk of outburst that resulted from adoption of full face machines). Although trials of a boom mounted bolting rig were undertaken at the time, the technology then available did not prove effective and the AM50 was eventually redeployed for fault drivage at Cook Colliery, minus the bolting rig.

An AM75 was also utilised on a limited basis for roadway development at Stockton Borehole Colliery during the early 1980’s, mining a 2.1 m high roadway in a 1.35 m seam section and excavating a minimum of 0.75 m of tough sandstone to form the roadway. Operators did not readily accept the boom mounted cutter head over a conventional Jeffery Heliminer, which was then highly regarded as a stone cutting CM, with roadway development eventually reverting to Heliminers.

It is likely that technology available today would allow a roadheader to be more effectively utilised for longwall gateroad development, particular technologies that enable operation of the roadheader to be fully automated and operated remotely, and including the use of boom mounted automated bolting rigs. Such a machine would probably alleviate many of the issues associated with formation of breakaways, and would also allow a longwall-preferred flat roof profile to be mined where conditions allowed, or for arched section roadways to be mined if conditions deteriorated. While such a machine is unlikely to seriously challenge a continuous miner’s potential cutting rate, the continuous miner’s cutting rate is itself compromised by installation of roof and rib support, and its ability to breakaway cut throughs. An effectively utilised roadheader may therefore prove to be as effective as many of the currently under-utilised continuous miner/roof bolter configurations (however, the flaw in that argument is that it requires operators to improve the level of utilisation currently being achieved).

As is the case in respect to underground metalliferous mining, it is unlikely that drill and blast technology and practices utilised in the civil tunnelling sector could be seriously considered as an alternate for existing continuous miner based roadway development systems, unless some other factor necessitated adoption of drill and blast, ie; a mine’s inability to operate continuous miners due to its outburst propensity.

In regard to the enabling technologies utilised in civil tunnelling practice key observations are the:

- widespread automation of support installation functions, including rockbolting, shotcreting and concrete module erection, albeit that such support installation functions are not being conducted immediately behind the cutter head;

- application of machine guidance and control systems to enable TBMs to be steered through three dimensional space as a means of excavating complex compound curves;
- utilisation of extensible conveyor systems to facilitate the continuous operation of TBMs, albeit that overall advance rates may be less than that typically achieved by best practice gateroad development operations;
- automation of roadheader operating functions to enable the equipment to be operated remotely.

A key observation in regard to management of civil tunnelling projects is the level of technical resources applied throughout the tunnelling process, from project design and tender preparation through mobilisation and establishment, excavation, support, lining, and fit-out. Few matters appear to be left to chance, particularly in respect to defining the geological/geotechnical environment and managing the associated risks.

6.8 Observations on the Civil Construction and Surface Mining Sectors

The construction industry generally is similarly faced by a severe shortage of skilled operators and is embracing technology as a means of combating those shortages. Automatic machine control is considered as being universal on major construction and highway projects within the next five years, and it was projected[4] that application of automatic machine control in the construction sector would emulate that of the manufacturing sector where the industry had progressed from skilled operators at milling machines or lathes to systems that transmit the design directly to computer operated machines. The construction sector utilises bulldozers, motor graders and excavators to shape the earth, and with the application of remote control and sensing technologies it was projected that the operation of multiple machines could be automated as precise machine tools from a single design. Further, it was noted that the application of these technologies to fine grading on an earthmoving project was likely to improve productivity by more than 100%, whilst enabling unskilled operators to be turned into fine-grade machine operators very quickly.

The surface mining sector is also faced by a severe shortage of skilled operators, and one contractor has utilised minesite simulator training to train new operators to work safely and productively with large expensive equipment. The contractor also attributed significant reductions in maintenance and repair to surface mining plant to the adoption of simulator training as it allowed operators to be trained to be more familiar with, and responsive to, alarms and information displays in the event of the equipment being operated outside its design parameters[41].

The utilisation of state-of-the-art simulators for development of new dragline operators at Anlgo Coal's Callide coal mine in Queensland is expected to remove the threat of damage to the mine's $A150 million draglines and to halve the time it normally takes to bring trainee operators up to 75% or more of the skill level of experienced operators[42].

Immersive Technologies, an Australian mining equipment simulator developer has supplied about 80 units to Phelps Dodge, Rio Tinto, Anglo American, Newmont Mining, BHP Billiton, Tata Steel and Thiess, and now has exclusive technical alliances with five of the world's biggest manufacturers of mining machines, including the two biggest, Caterpillar and Komatsu. The exchange of proprietary machine information has allowed Immersive Technologies to produce simulator training modules that are said to be the most advanced in the industry today.

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[41] Baker P, Thiess, *Immersive Unearths Value at Thiess*, Construction Industry News, 6 October 2006

[42] Roberts R, *Simulators Deliver Real Benefits*, Mining News, Aspermont Publications, 7 December 2006

6.9 Application of Continuous Miner Technology in the Tunnelling and Metalliferous Sectors

Prairie Machine Parts[43] produce a range of borer miners (formerly Marietta borer miners) in Saskatoon, Canada that are being utilised to mine potash in a number of Canadian mines[44], with some mines operating at depths in excess of 1,000 m. The borer miners are used in either two or four rotor configurations, with mining widths ranging from 4.2 m to 5.6 m on the two rotor configuration, and 7.6 m wide on the four rotor configuration. Mining heights range from 2.5-3.4 m on the two rotor configuration and 2.7 m on the four rotor configuration.

Borer miners are reported to consistently produce at output rates of 1,200 tons per hour in conjunction with "Flexiveyor" continuous haulage systems (Figs 38, 39, and 40). At Lanigan[45], rooms 14.6 m wide by 4.8 m high and 1,200 m long are formed using a four-rotor borer miner with a multi-pass mining system, at a depth of approximately 1,100 m. Potash is reportedly of a similar unconfined compressive strength as that of coal.

Fig 38: Prairie Machine Parts Xcel-72 Two Rotor 700 hp Borer Miner (photo courtesy of Prairie Machine Parts).

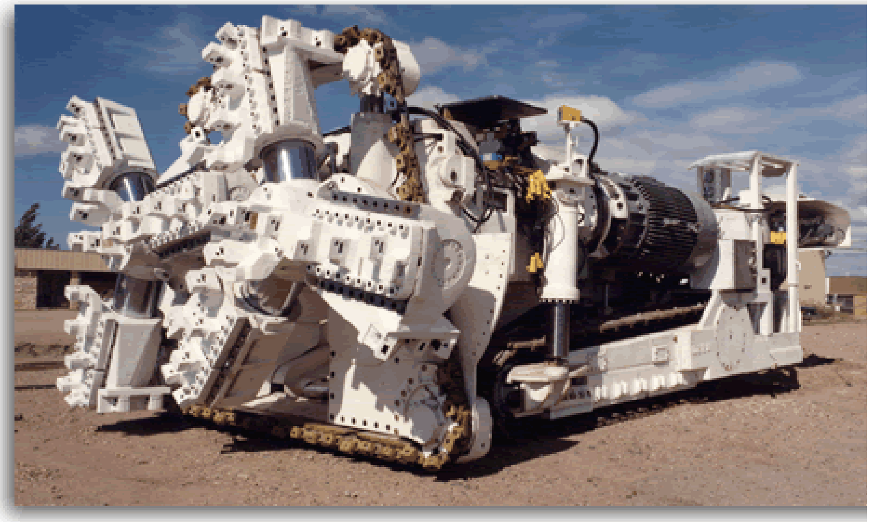

Fig 39: Prairie Machine Parts Xcel-44 Four Rotor 400 hp Borer Miner Underground at Saskatoon, Canada (photo courtesy of Prairie Machine Parts).

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[43] Prairie Machine Parts, website: www.pmparts.com (accessed 30 September 2006)
[44] Popplewell M, Prairie Machine Parts, Personal Communication, October 2006
[45] Fracchia M, PotashCorp Lanigan, Personal Communication, November 2006

Fig 40: Prairie Machine Parts Flexiveyor Continuous Haulage system (photo courtesy of Prairie Machine Parts).

Friant et al report on the development of mobile excavators for tunnelling applications, including the Robbins Ranging Arm Mobile Miner which has a tracked chassis and a short manoeuvrable ranging arm on which is mounted a vertical cutting wheel carrying disk cutters around the circumference[46]. The cutter wheel axis is at right angles to the tunnel axis, and the cutters face radially outward with axes parallel to the cutterhead. The cutters operate much as on a TBM except that there are fewer cutters in contact with the rock at anyone time. The Mobile Miner can cut similar profiles to that of a conventional roadheader, including a flat floor profile, but can cut harder rocks than a roadheader. The first Mobile Miner was built in the mid-1980s and tested at Mt Isa where it drove a 1,100 m long decline and 540 m long horizontal drift in rock ranging from 110-330 MPa, with production rates of 9.11 m/day and 28.5 m/week being achieved[47].

A second generation machine (MM130) was used at Pasminco's Broken Hill Mine in 1993 to drive a 300 m long horizontal drift 6.15 m wide by 4.1m high in rock ranging from 70-300 MPa (Fig 41). Robbins was also reported to be then developing a larger Mobile Miner to excavate cross sections of 50-80 m^2 in granites of 150 MPa UCS.

Friant et al also report on the then (1993) development of a number of other hard rock excavators including:

- a continuous miner being developed by Wirth and HDRK Mining Research (a research consortium of three Canadian metalliferous mining companies), which again utilises proven hard rock disk cutters for excavation and is crawler mounted for mobility. This machine appears to have evolved into Wirth's T4 series of continuous miners, as illustrated in Fig 42, capable of mining cross sections of 9.95 m wide by 6.0 m high in rock of >100 MPa UCS;
- Atlas Copco's development of a hard rock mobile excavator called the Disc Boom Miner which featured a rotating circular head fitted with disc cutters, with the cutter head mounted on a swinging boom. Again the miner was to be track mounted for mobility, and at that time was still in the conceptual development and design stage;
- Tamrock-Eimco was similarly reported to be developing a mobile hard rock excavator which featured a turrent-mounted boom with a large diameter in-line cutterhead fitted with drag cutter bits. The cutterhead featured a low speed, high torque drive system designed to allow deep bit penetration for efficient chipping of the rock, and the machine was firmly held in place with a series of roof and wall jacks to provide a rigid and stable platform for reacting to the high loads generated from the cutting cycle.

Blunt et al (2005) also note the development of new continuous, excavating machines including a narrow reef rock cutting machine then being developed by Voest-Alpine, the ARM 1100, using conventional disc cutting technology[48]. The rock is undercut to a depth of 50-60 mm, to minimise the power and cutting forces and maximise chip size. Voest-Alpine estimated an expected production rate

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[46] Friant JE, and Ozdemir L, *Tunnel Boring Technology – Present and Future*, Proceedings Rapid Excavation and Tunnelling Conference, 1993

[47] Robbins R, *Machine Tunnelling in the Twenty-First Century*, Approaching the XXIst Century, International Tunnelling Association Conference, Florence, 1987.

[48] Blunt J, Ganza P, and Moss D, *Specialised Equipment and Mining Techniques for Narrow Vein Mining,* Ninth Underground Operators' Conference, The Australasian Institute of Mining and Metallurgy, Perth, 2005

of 280 t per day, assuming stope dimensions of 4.25 m wide by 1.1 m high, with 60 mm slices being taken off the face.

Fig 41: Decline at Broken Hill Mine Driven by the Robbins Mobile Miner, MM130[49]

Fig 42: Wirth T4.31 Continuous Mining Machine, Designed for the Continuous Extraction of Minerals such as Salt, Potash, or Gypsum (photo courtesy of www.mining–technology.com)
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[49] Hood M, *Advances in Hard Rock Mining Technology*, Mineral Economics and Management Society Thirteenth Annual Conference, 2004.

7.0 HIGH CAPACITY LONGWALL MINES OF THE FUTURE

The L15 project, which is currently being undertaken by CSIRO on behalf of ACARP, is studying the strategic implications of high capacity longwall mining in Australia. It is anticipated that the study will identify the number and size of gateroad entries that are required to ventilate high capacity (>10 Mtpa) longwalls will be key determinants in respect to any "new technology" roadway development system. That is, it is likely that such longwalls will take advantage of the then available technologies to adopt wide faces (>300 m) and long blocks (> 4km), and potentially mine at full seam height rather than artificially limit the mining height. As a consequence rib emissions are likely to necessitate high ventilation quantities (>100 m^3/s), even if predrainage of seam gas is routinely adopted, which will result in high velocities and significant pressure losses if existing two entry, 3-3.5 m high roadways continue to be adopted. High pressure differentials will also be experienced across pillars separating intake and return roadways and are the likely to exacerbate the risk of spontaneous combustion in all but the most benign of seams.

Options to reduce such pressure losses are to increase the size or number of roadways, or a combination thereof (alternatively, the integration of booster fans into mine ventilation systems may become a more routine consideration). The adoption of a single entry system utilising say a standard "metro" size TBM (6.9 m diameter) would result in a cross sectional area of 37.4 m^2, as compared to 18.2 m^2 for a conventional 3.5 m high 5.2 m roadway. Alternatively, a 6.2 m high, semi-circular arched (roadheader) roadway 6.9 m wide would have a similar cross section to the 6.9 m circular roadway, as would a 7.2 m high by 5.2 m wide conventional (flat roofed) roadway. The resultant TBM mined roadway is likely to have a lower coefficient of friction than conventional continuous miner excavated roadways (or roadheader excavated roadways). It will also have significantly less rubbing surface than say two conventional 3.5 m high by 5.2 m roadways, and less than a single 7.2 m high by 5.2 m wide conventional roadway.

An alternative to adopting a three entry gateroad system is to excavate higher and/or wider two entry gateroads, with similar ventilation efficiencies being available if circular or arched roadways are excavated. The continued adoption of a two entry gateroad system as opposed to a three entry system also minimises the sterilisation of reserves in chain pillars.

Assessment of the various options is warranted to evaluate the economics of higher and/or wider two entry gateroads, including potentially partially out-of-seam roadways, as opposed to the costs of mining three entry systems and the subsequent loss of reserves in chain pillars.

Potential options for technology development in a single entry roadway development system could include:

- enhancement of the existing continuous miner platform with an integrated and automated bolting and support system, combined with a continuous haulage/extensible conveyor system;
- enhancement of the existing borer miner platform with an integrated bolting and support system, combined with enhancement of existing continuous haulage/extensible conveyor systems as utilised in potash mines;
- a purpose designed TBM with an integrated bolting and support system, combined with enhancement of existing continuous haulage/extensible conveyor systems as utilised in the civil tunnelling sector;

Considerable attention will be required in all such systems to adequately and effectively ventilate the advancing roadway, with multiple, in-series, high pressure fans likely to be used, potentially with some form of dust scrubbing incorporated therein.

In addition to the above, a multiple entry system would most likely require development of a system to more effectively interconnect roadways for ventilation, coal clearance, communication and egress by utilising one or more of the following:

- introducing some form of articulation into the continuous miner to allow it to break away the cut through more effectively;

- modifying the cutter head and/or chassis configuration and/or roadway width to improve the geometry of the break away process;
- in the event of higher roadways being mined, increase the machine height and reduce the length of the main body and reconfigure the machine to improve the geometry of the break away process;
- introduction of a specialist cut through machine ie; narrow head continuous miner or augering system;
- integrating current “state of the art” machine guidance and remote control systems to remove operators from the break away process.

While operators of lower capacity longwall mines may consider attainment of high capacity status (>10 Mtpa) as unlikely due to the age and extent of existing mine infrastructure, geological constraints, subsidence limitations, etc, they are likely to face significant challenges to remain competitive with higher capacity, lower cost mines. Further, mine age and infrastructure limitations coupled with increased depth and higher in-situ gas levels are likely to ensure that these lower capacity mines face equally as significant ventilation challenges, albeit at lower production levels.

It is therefore anticipated that they are equally likely to pursue similar technological solutions to these challenges, although infrastructure limitations may limit the potential utilisation of say large diameter TBMs for roadway development. Hence their focus is likely to be on optimisation and enhancement of continuous miner based systems, or even on introduction of borer miner systems should it be possible to incorporate automated bolting systems into that platform.They are also equally likely to be challenged in the development of systems that will enable them to more effectively interconnect roadways for ventilation, coal clearance, communication and egress.

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