Production bolting using water hydraulic bolters in bord-and-pillar mines

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Production bolting using water hydraulic bolters has been successfully used alongside trackless mechanised mining machines (TM3 – oil electrohydraulic drill rigs and load haul dumpers) in bord-and-pilar mines for several years. The water hydraulic bolters have been shown to reduce cycle times by as much as 50% compared with traditional compressed air bolters, thus offering significant productivity benefits, while at the same time reducing both water and energy used for production bolting. This is supported by daily measurements taken over a period of 20 months. This paper describes the system layout, power and water connections, dirty water handling and reports the results based on the experiences at two Eastern Limb platinum mines.

Keywords: Water hydraulic, bolting, bolter, bord and pillar mining

INTRODUCTION

Bord-and-pillar mines, with stoping widths greater than 2 m, and where dips are less than 10°, are generally developed and mined with low-profile trackless mechanised mining machines (TM3). However, due to the complexity and high cost of dedicated TM3 bolters, support roof bolting in production areas is usually carried out with manual compressed air powered bolters under the cover of nets and temporary support props, despite TM3 bolters being able to maintain a remote/stand-off distance of 3 m between the bolt hole and the operator. The drive to improve safety and rock mechanics considerations have seen an increase in the support hole drilling task - both the pattern density and length of support holes increasing – thus necessitating the need for faster and more efficient production bolters. HPE were approached by two different mining companies, to develop a better production bolting solution, based on modern water hydraulics. This paper will show how water hydraulic technology delivers safer and faster bolting, with less water and energy per hole, reduced noise exposure, zero unhealthy oil or grease mist in the air and no reduction in visibility due to fogging. All this with good economics, in a manner that is aligned with the needs of South Africa, local communities, carbon emission reduction and long-term strategic sustainability. This is relevant to mining companies who need to attract investment, both by delivering attractive economic performance, as well as demonstrating responsible management of environmental, social and governance (ESG) goals.

Water hydraulic support hole drilling system

The system is made up of a plunger pump power pack (PP) mounted in a Utility Vehicle (UV) cassette connected to 3x Maxi Bolters via NW20 x 20 m quick-connect *Staplelok* hydraulic hoses allowing a range of up to 120 m from the power pack. This serves a production section with about 12 bords and allows six bords to be bolted by three crews in a single shift. The cassette PP has a 3 l/s x 55 kW pump and is plugged in to a standard TM3 type 550VAC gully box electrical supply and connected to standard Mine Service Water (MSW) pipe with a 50NB hose. It is positioned near the middle of the section and the cassette is re-located closer to the face when the strike conveyor is extended. A second UV cassette is used to transport and store Maxi Roof Bolters and drilling consumables next to the power pack cassette. The Maxi Roof Bolter is a roof bolter designed to operate in excavations varying from ~1,8 up to 2.5 m high (extendable to ~3.7 m in exceptional circumstances) and is designed to clamp between the hanging and footwall. Remote controls, connected via 5 m umbilical hoses, allow the operator to be remote from the rig while the drill is drilling roof bolt holes under permanent support. All bolting is done under the cover of nets and temporary support props. The Maxi Bolter sting and thrust functions are 100% water hydraulically powered and uses a short water powered drill. About a third of the drill water is used to flush the holes. Various lengths of 'stepped' and extension drill steels are used to drill the different lengths of support and camera inspection holes required. Drill exhaust and flushing water from the drilled hole, both gravitate to a low point where, like the cooling water from TM3 face drill rigs, the dirty water is pumped into a drainpipe to the mine de-watering pumps. The mining layout and equipment are shown in Figures 1 and 2.

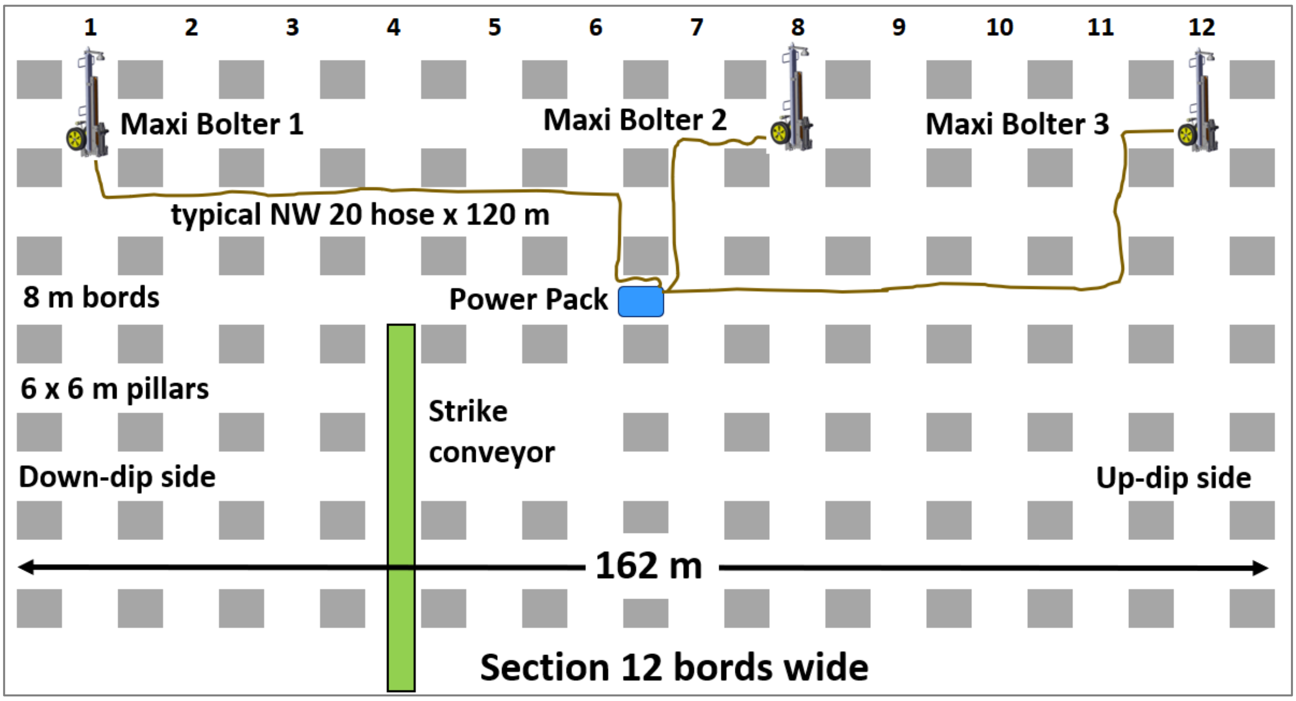

Figure 1. Mining and equipment layout.

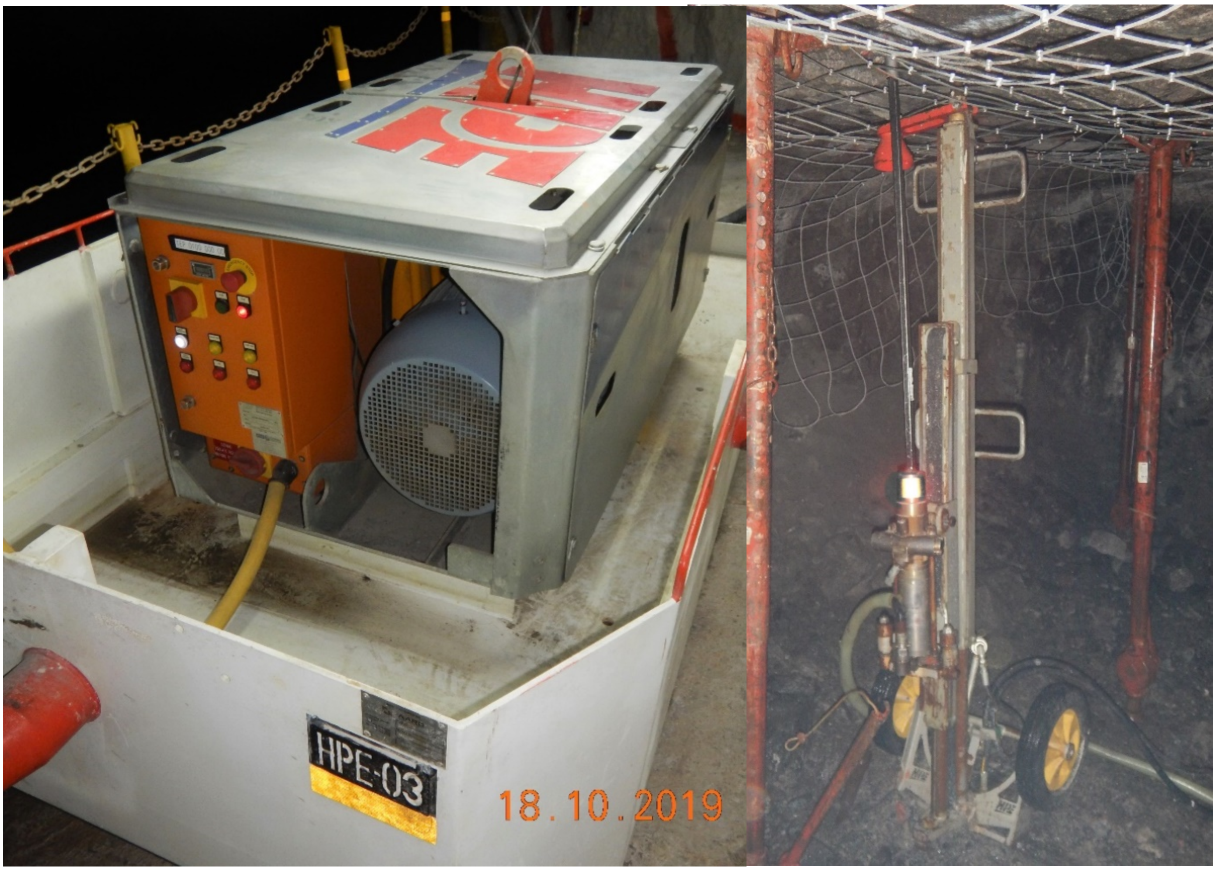

Figure 2. Power pack in UV cassette and Maxi Bolter

Mine site facts and equipment specifications
These are listed in Table I.

Table I. Site facts and equipment specifications

Site facts	Mine A	Mine B
Location and type of mine	Both Eastern Limb bord-and-pillar (B&P) mines chrome and platinum	
Reef and geology	Chromite reefs, triplet hanging wall parting planes in places, varying degrees of oxidation and inter-strata cohesion	
Bord and pillars sizes	Typical 8 m bords x 6 m pillar; ~12 bords per section	
Stepped drill steels and bit	22 mm hex drill steels with male-female hex socket couplings; Stepped steel lengths 0.9 m & 1.8 m; 38 or 41 mm bit	
Support and camera holes drilling task	Support bolt and cable anchor hole lengths varied; typically a mix of 1.5, 1.8, and 3.0 to 5.0 m holes	
Support patterns	4 holes x 3 m anchors + 6 holes x 1.5 m bolts + camera hole x 4 m (not every bord)	12 bolts x 1.75 m per bord for a 3 m advance; 1.5 m spacing; 0.5 from sidewall; 41 mm camera bolt x 4 m, one per strike face
Type of bolts used	EG 'Resin bolt' (1.5 m), 'Flexibolt' (3 m)	1.8 m plate bolt with mechanical end anchor; 5 m anchors as required by rock engineering

<table>
<tr><td rowspan="2">Power pack (PP) specification</td><td colspan="2">18 MPa positive displacement triplex plunger pump with capacity control system</td></tr>
<tr><td>2.4 nominal l/s x 45 kW motor supporting TWO bolters with an early generation capacity control system</td><td>3.0 nominal l/s x 55 kW motor supporting THREE bolters with new generation PLC capacity control system with</td></tr>
<tr><td>PP Industry 4.0 data logging and connectivity</td><td>No data logging capability</td><td>Wi-Fi or network connectivity capability data logging</td></tr>
<tr><td>Bolter drill specification</td><td colspan="2">HPE HHH2 bolter drill ~4.5 kW percussive power
~0.90 l/s when percussing`</td></tr>
<tr><td>Maxi Bolter specification</td><td colspan="2">Closed height 1.61 m
Extended height 2.50 m
Stinger extension length 0.64 m (max. 2 allowed)
Thrust Stroke (1.8 m stope) 1.05 m with collar guide
Thrust Stroke (2.5 m stope) 1.89 m without collar guide
Mass 91 kg (excluding drill and controls)
Fitted with two wheels 0.28 m diameter</td></tr>
<tr><td>Remote controls</td><td colspan="2">5 m umbilical hoses allow the operator to be 5 m from the bolter</td></tr>
<tr><td>Replacement of air bolters</td><td>50% of older sections and all new sections use new generation PP3 power packs</td><td>Mine wide, all portal sections use new generation PP3 power packs and Maxi Roof Bolters</td></tr>
<tr><td>Technology evaluation</td><td>Mine measured water using a mechanical totalising flow meter and power with a 3-phase power meter and managed the trial process</td><td>Independent mine engineering consultants verified estimates and advised mine client regarding technology and equipment selection</td></tr>
</table>

Measured results from Mine A

Table II. Measured results from Mine A (20 months: March 2018 to October 2019)

Measured data TWO bolters only supplied by ONE 2.4 nominal l/s power pack - AVERAGES	Unit	Average
Bolter related safety incidents during trial	No. of incidents	0
3 m holes (from daily log sheet count)	holes/mth	238
1.5 m holes (from daily log sheet count)	holes/mth	445
Metres drilled and bolted per month	mb/mth	1 381
Minutes per metre drilled and bolted (from log sheet)	min/mb	3.38 (1)
Average drill and bolt time per bord	h/bord	1.2 (1)
Water used per month (from flow meter)	m^3/mth	186
Water used per metre drilled and bolted	l/mb	135 (2), 91 (3)
Energy used per month (from power meter)	kwh/mth	633
Energy used per metre drilled and bolted	kWh/mb	0.57
Standard bord pattern - metres drilled and bolted (4 holes x 3 m + 6 holes x 1.5m)	mb/bord	21
Standard bord bolted per month by TWO crews (4)	bord/mth	65.8
Std bords drilled and bolted per crew per MONTH (4)	bord/crew/mth	~33

Std bords drilled and bolted per crew per DAY assuming 21 shifts per month [4]	bord/crew/day	~1.6[5]
Note (1): Excludes set-up, installation of prop and net, pack-up and bord-to-bord move time. Includes drilling, bolt installation, moving to the next hole, stinging and any delays in bolt drill and install cycle and was recorded on the daily log sheet. Temporary prop and net installation took ~20 minutes. Note (2): Measured by flow meter including low-pressure water used before pump. Note (3): Estimated water pumped based on power meter measurements. Note (4): The bolt drilling and installation crew comprised two persons: an operator & assistant. Typically, 3 or 4 additional persons were used before and after drilling to install props and nets. The LHD was used to transport equipment between workplaces. Note (5): Crews could easily complete two full bords every shift, but for various reasons eg LHD availability, planning, did not. This was not due to bolting speed or bolting & support cycle times. The hole count, hole length and readings from the power meter are all expected to be accurate within 5% or less. Log sheet hole drilling times were measured to the nearest 15 minutes in one to two hours but are averaged over several thousand holes.		

Table III. Approximate drill and bolt times and bolting rates based on Table II measured data

Type of anchor or bolt	Time to drill and install one	Number per hour
3 m anchors	~10.1 minutes per anchor	~6 anchors per hour
1.5 m bolts	~5.07 minutes per bolt	~12 bolts per hour
4 of x 3 m + 6 off x 1.5 m bolts	~71 min. per standard bord	~0.85 bords per hour

Table IV. Comparison of Mine A measured water and energy usage for bolting with results from narrow stope drilling in two other mines

Comparison with other sites	Unit	Mine A	Mine Pt[1]	Mine Au[1]
Rock type		Chromite	'Soft' UG2	'Very hard' basalt reef
Type of drilling and equipment		Bord bolting 2.1 m high: Bolting - Maxi Bolter	Stoping 1.25 m high: Face drilling off a Drill Guide & some bolting	Stoping 1.10 m panel: Hand-held face drilling using a thrust leg
Water usage per metre drilled	l/md	91 (134 includes lp water before the PP)	80	198[2]
Energy usage per metre drilled	kWh/md	0.57	0.55	2.66[2]
Note (1): From Fraser (2022) which describes water hydraulic drilling in narrow reef mines Note (2): Higher figures for Mine Au largely due to 'very hard' basalt reef				

Calculated water and energy usage

Following trial at Mine A, consultants appointed by Mine B together with the OEM, prepared a motivation for Mine B. This involved calculating bolting rates and the usage of water and energy as Mine B was concerned that water hydraulic drilling would use more water and energy than compressed air drilling. Table V shows water and energy usage for water hydraulic drilling (blue shading) and compressed air drilling (tan shading).

Table V. Mine B estimated water and energy usage

Calculated results based on method accepted by Consultant for Mine B	Unit	Water hydraulic	Compressed Air
Drilling time			
Average time to complete cycle per bolter	hrs	1.6	2.4
Water usage			
Hours air drills connected to water supply	hrs	NA	4.0
Water used per shift	m3	5.6	8.6
Water used per metre drilled	l/md	108	167
Water usage ratio relative to water drills	*%*	*100%*	*155%*
Energy usage			
Installed power (PP or compressor - note 1)	kW	55	81
Elec. energy used per shift (PP or compressor)	kWh	39	326
Elec. energy used per metre drilled & installed	kWh/md	0.76	6.3
Energy usage ratio relative to water drills	*%*	*100%*	*830%*

Table V shows the result based on the method reviewed and accepted by independent consultants for Mine B. The drilling task was adjusted to replicate that of the trial in Mine A. The results in the blue cells for the water hydraulic bolting are the conservative side of the results measured at Mine A:

- Calculated drilling time 1.6 hours (measured 1.2 hours at Mine A)
- Calculated water usage 108 l/m drilled and installed (measured 91 or 134 l/md at Mine A)
- Calculated energy usage 0.76 kWh/m drilled and installed (measured 0.57 kWh/md)

The calculations for the compressed air bolting show water usage about 1.55x higher than estimated for water hydraulic bolting. (The reason for this is explained in detail in the 'discussion' section below.) The compressor power was based on an installed screw compressor power of 2.2 MW estimated by the consultant to be needed for 18 compressed air bolting sections. It was conservatively assumed that bolting absorbed power for only four hours per day and that only 67% of the compressed air was used for bolting. The calculations for the compressed air bolting show energy usage 8.3x that estimated for water hydraulic bolting. This excludes leaks and Refuge Bays, both of which are notoriously difficult to quantify accurately. The main point from these Table V calculations is that even with conservative assumptions favouring compressed air, water hydraulic bolting uses either a comparable or lesser volume of water and significantly less energy … by almost an order of magnitude.

DISCUSSION

Bolting cycle times: The average drill-and-install time per bord averaged 1.2 hours for 4 x 3 m anchors and 6 x 1.5 m bolts. This was made possible by the following factors:

- Superior percussive power (~4.5 kW) and higher torque of the water hydraulic drill compared with about 1.7 kW for a S215 compressed air drill at 400 kPa
- Sufficient thrust and torque to insert the bolt, mix the resin and pre-tighten the nut
- Quick stepped drill steel changes
- Manoeuvrability and ease of use of the Maxi Bolter.

In a short side-by-side air versus water drill speed test at Mine A, each drill drilled 5 x 1.5 m holes and 5 x 3 m holes. The water hydraulic drilled at twice the average speed of the compressed air drill. At the same mine it was observed compressed air bolters took very much longer to drill holes, especially the longer 3 m holes, where air pressures were low.

Drilling consumables: The 22 m hex steels with hex socket connectors were quick to change, more robust, less expensive, and lasted longer compared with rope threaded connections used elsewhere. They do however require the 38 mm diameter hole, whereas rope couplings are slightly more compact. While smaller holes are possible, the 38 mm diameter hole results in good flushing and longer bit life as more bit-gauge wear can be tolerated with the larger hole size.

Water usage: This was measured at 135 litres per metre drilled over the trial. This includes water for the bolter drill and cylinder or stinging and thrusting. When bolting, the need to extend and retract each time a stepped steel is changed and the fact that the drill is normally left percussing to aid retraction, increases the water usage. As a cross check, this result was compared with stoping trials in: (a) a 'soft' UG2 reef and (b) a 'very hard' basalt reef reported in Fraser 2022. The 135 litres per metre bolted lies midway between 82 and 198 litres per metre drilled respectively and is therefore broadly in line with these results.

Although not measured at the time of the trial, it was discovered later that other flow demands on the inlet side of the power pack must have consumed about a third of all water used. This was not productively used. From the power meter measurements, the power pack could only have pumped about 91 litres per metre drilled, being closer to the 82 l/md in the UG2 stoping trial.

Water flow rates: Water hydraulic drills have higher instantaneous flow rates, but this is largely mitigated by the diversity factor, ie not all water drills demand water at the same time.

These points become clearer in the illustrative calculations below:

- Water drill flow demand: 3 drills x 0.80 l/s per drill x 67% diversity = 1.6 l/s
- Air drill flow demand: 6* drills x 0.20** l/s per drill x 100% diversity = 1.2 l/s

(6 x compressed air drills required to drill at the same rate as 3 x water hydraulic drills; ** air drill flushing flow is between about 0.20 & 0.24 l/s depending on Mine Service Water pressure)*

- Water drill water usage: 1.6 l/s for 2 hours percussion time per shift → 10.5 m^3/shift
- Air drill water usage: 1.2 l/s for 5 hours connection time per shift → 21.6 m^3/shift

Even if the calculation is repeated for just three compressed air drills the water usage is comparable with water drills.

Energy usage: The long-term average energy usage per metre drilled and installed measured by the mine-installed power meter was 0.57 kWh/m drilled and installed. This compares with 0.55 kWh per metre drilled for a mix of face and bolt holes in a UG2 stope for Mine Pt as reported in Fraser 2022. Calculated results show that compressed air drilling uses an estimated 8x more energy excluding allowances for Refuge Bays, leaks, 24-hour compressor operation and de-watering pump energy. This ratio has been placed between 5 and 10x in previous studies over the last 30-years (Fraser 2010 and Harper 1993) and is widely accepted. However, it is notoriously difficult to separate compressed air for drilling from all other legitimate compressed air uses and waste due to leaks.

Power pack capacity control: The power pack incorporates an unloader valve capacity control system that ensures the pump is unloaded (drawing little power) when the demand is low. This system ensures that the pump supply matches the demand, and that minimizes energy usage.

The new generation capacity control system is controlled by a PLC which permits operational data to be logged and due to Wi-Fi or fibre connectivity, allows power pack water demand to be used as a proxy for production activity. The Industry 4.0 (4IR) capability allows for real-time monitoring and management of bolting operations if desired.

Noise: All water hydraulic drills are significantly quieter than compressed air drills as they do not emit the supersonic air exhaust shock wave. The noise levels of the bolter drills used have been measured by independent noise experts and found to comply with Mine Occupational Safety and Health legislated limits. This, combined with the 5 m separation distance between the drill and operators, the single-drill short drilling times, and the use of hearing protection devices means that the eight-hour noise exposure (Lex8hr) of 85 dB_A is not exceeded.

No oil/grease mist or fogging: As water hydraulic drills do not consume grease or oil no unhealthy grease or oil mist enters the air or is spilled on the footwall increasing the risk of slip-and-fall accidents. Furthermore, visibility is not impaired by exhaust fogging associated with compressed air drills and water is non-toxic and inexpensive.

Mine-wide water recirculation system: Power pack-based water hydraulic drilling systems are analogous to oil electrohydraulic systems in that the hydraulic fluid is circulated in a loop and used many times over and pressure is generated near the point of use by an efficient positive displacement pump. However, oil and the water hydraulic systems differ in two fundamental ways:

- Water hydraulic systems are oil-free, open-loop systems (ie all water is returned via the mine de-watering systems and is recirculated in a mine-wide continuously recirculating system) and they are designed to be dirt-tolerant
- Conversely, oil hydraulic systems are sensitive to dirt and hence can only be a closed loop. They therefore require a separate cooling water flow which is dumped on the footwall to be handled along with flushing water in the 'open' mine service water and mine return (dirty) water systems.

Dirty water management: Dirty water management was not found to be problematic and was handled in the same manner as for TM3 drill rigs and legacy air bolters. This is not surprising as the water used by TM3 equipment for cooling and flushing is comparable with that of bolting:

- TM3 drill rig water usage: 0.5 l/s for 4 hours per shift → 7.2 m^3/shift
- Bolting water usage 3 bords x 21 m drilled and installed using 135 l/md → 8.5 m^3/shift or 5.7 m^3/shift if the usage is 91 litre per metre drilled and installed.

Equipment reliability: All equipment breakdowns were recorded and the life per metre drilled calculated. Drilling vertically upwards under a shower of flushing water and cuttings is demanding on chuck bushes etc. It was found that water hydraulic bolter drill life is comparable with that of compressed air bolter drills. The mean distance drilled between repairs was acceptable and in line with experience elsewhere.

Power pack and service exchange maintenance: The use of TM3 UV cassettes for both the power pack and transport of bolters etc. means that if required, power packs and other equipment can be easily brought to surface and then swapped with a service exchange unit. In this manner underground servicing can be minimised to daily checks, oil-level top up, etc. and maintenance simplified to managing a service exchange system.

Costs: Capital, operating, and maintenance costs are client confidential, but were found to be lower than compressed air unit costs, due to improvements in productivity and reductions in electricity costs make water hydraulic bolting economically attractive. The biggest contributor to monthly operating costs is bolter drill repair, but this is based on a fixed rate per metre drilled incentivising the OEM to improve reliability, rather than maximising the number of repairs.

Refuge chambers: Removal of compressed air bolters and removing compressed air pipes, (except for those supplying refuge chambers), can dramatically reduce the energy used by compressors. Refuge hambers need to be supplied with fresh air for ventilation, cooling, and pressurisation, but this can be done with air at lower pressure (eg 2 bar). Further savings are possible in rationalising the compressed air system, but this is outside the scope of this paper.

Implementation and change management: Finally, implementation, training and change management were achieved with support from the OEM who had the relevant experience and personnel. Given the reduced noise and superior performance of the water hydraulic equipment, operators acceptance was immediate, and they were productive within a few shifts and had mastered the necessary skills within a month.

CONCLUSIONS

Measured data for a water hydraulic bolting system over 20 months in one mine and experience in two bord-and-pillar mines has convincingly shown the benefits of water hydraulic production bolting. The long-term average of bolt-to-bolt, drill and install time of ~10 minutes for a 3 m anchor and ~5 minutes for 1.5 m bolt is significantly faster than the compressed air bolters they replaced. Water and energy usage per metre drilled and installed is also lower at 91 to 134 litres and 0.57 kWh than for compressed air bolters. These figures are in line with results from other trials and calculations. *By comparison, air bolters will consume up to 2x more water and use up to 8x more energy.*

These results confirm calculations and experience elsewhere that power pack-based water hydraulic bolting technology offers improved performance, environmental benefits and energy and carbon footprint reductions, thus making the wider adoption attractive from an ESG perspective. Being 100% local, easy to retrofit into existing operations, and offering productivity gains and energy savings makes this water hydraulic bolting solution economically sound. Furthermore, the technology is well aligned with modernisation, improves life-of-mine sustainability, and meets needs of communities for appropriate local employment and the provision of services.

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