The Next Level: Why Deeper Is Better for TBMs in Mining

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ABSTRACT: Diminishing surficial mineral deposits, increasing environmental regulation and advanced geological exploration techniques are ushering in a new era of mining. Unconventional technology must be adopted to ensure that safe, efficient and responsible access to minerals is possible as prospecting continues to push the mining industry deeper. This paper discusses why competitive mining operations will become increasingly dependent on Tunnel Boring machines (TBMs) for mine development and expansion, and explores the implications of TBMs in a drill and blast dominated industry.

INTRODUCTION

Like all industries, mining is constantly changing or evolving. The quality and types of materials being mined, the methods to extract those materials, the geographical location of the materials, the manner in which materials are accessed, and the social and political climate in which mines operate are all changing at a rapid pace. Narrowing the focus to mining minerals in ore bodies, the changes are no less significant. Current trends include a global reduction of surface deposits and continued increased awareness of environmental impact from mining.

GEOLOGICAL EXPLORATION

Ore Genesis

Ore genesis in its broadest sense determines how mineral deposits form within the earth's crust. Locating and classifying these ore bodies is a complex endeavor. Geologic exploration techniques range from conventional prospecting to the use of airborne and satellite imagery. Once a prospective site is identified, geophysical prospecting allows for surveying and mapping the ore deposit. Ore bodies are formed by a variety of geological processes and therefore can be found in a range of formations. Methods to survey and map the formation include remote sensing, aeromagnetic surveying, regional gravity surveying, and airborne radiometric methods.

Ore Evaluation

After an ore body is located, it must be evaluated to determine the content and concentration of the ore mineral in order to assess the economic viability of extraction. As demand for minerals found in ore deposits continues to rise, and as environmental concerns continue to grow, mining operations are forced to extract minerals from more complex locations and with less environmental impact. As surface ore deposits are being depleted and environmental concerns over surface displacement grow, underground mining operations will continue to become more prevalent. For subsurface mines, core drilling provides mineral samples and helps narrow the specific boundaries between materials.

The time and financial investment required to locate, identify, map and evaluate the ore, all critical components to successful mining operations, also contribute to the cost of mining. Yet, when well executed, these significant investments can help reduce cost to access and harvest minerals.

ACCESSING MINERAL DEPOSITS

Surface Versus Subsurface Ore Deposits

Underground mines will continue to be the primary mining method in the future—this fact is evidenced by the global reduction of available surface ore beds, the cost and environmental implications of overburden removal, the environmental impact and the public relation implications of large surface mining operations, and the increased global demand for minerals and metals.

Access Methods

Subsurface ore bodies are accessed by shafts and declines. The primary methods of accessing subsurface ore bodies are drill and blast—by far the most common—shaft boring machines and tunnel boring machines. In this paper we are discussing only decline access tunnels and are discussing TBM and drill and blast methods. As previously mentioned, ore deposits are found in a variety of formations. The depth and type of formation, as well as the type and quality of the material to be mined determine the

Table 1. Comparison of TBM and drill and blast methods

Factor	Drill and Blast	Tunnel Boring Machine
Site prep time	Requires less start up time	Requires 3 to 12 months
Equipment storage	Requires explosive storage permits	Requires slightly larger foot print
Length of the tunnel	Slower excavation rate (typically 3 to 9 meters per day averaging 180m/month with three shifts)	Significantly faster excavation rates from 15 meters to 50 meters per day, 450+/month)
Shape of the tunnel	Typically horseshoe-shaped but can be other shapes	Uniformly round
Length and depth of required tunnel	Difficult in low overburden settings Substantially slower in longer access tunnels (over 2 km)	Not comparable to drill and blast for short tunnels (less than 2 km) Minimum 30 m turn radius Faster for long, straight tunnels Can be used in low or high overburden
Ore body orientation/mining method used	Can be used with any ore body orientation	Best for use with deep or long ore bodies
Removal, disposal or reuse of spoils	Can be reused but spoil size and consistency is highly variable. Removal due to variable size of rocks can be difficult.	Can be reused; uniformly sized muck chips. Uniform rock also makes for easier removal by continuous conveyor
Means for removing mined material	Continuous conveyor; muck cars	Continuous conveyor; muck cars
Ground vibration	High	Low
Existence of explosive and/or hazardous gases	Mitigation possible	Mitigation Possible
Populated or unpopulated area	Typically unpopulated, or in populated areas with restrictions	Populated or unpopulated
Access to skilled labor	Requires unique skill sets and certification	Primarily mechanics

method in which the ore is extracted. These and other factors also play an important role in determining the most cost effective and efficient way to access the ore body itself.

Factors Affecting Sub-Surface Access Methods

Table 1 provides a partial list of factors that affect the type of access method employed.

COMPARISON OF MINING METHODS FOR A DEEP ORE BODY

For the purposes of this paper we will use an example that is likely to become more and more prevalent in the future—that of a deep ore body. To extend the life of a hypothetical mine, an access bore must be excavated to a depth of 750 m below the surface (see Figure 1). Assuming a 15% grade, the bore will need to be approximately 5km in length. Because this is an existing mine, there is minimal site prep, logistics and permitting and therefore excavation can begin in six months.

Surface Mining

Surface mining for such a deep ore body, while possible, is unlikely. Removing hundreds of meters of overburden would probably not be financially viable, and would definitely have negative environmental implications. The PR implications associated with surface mining to such a depth are also likely to be negative.

Drill and Blast

While Drill and Blast (D&B) is likely to be favorable over surface mining at such a depth, the method has advantages and disadvantages. No overburden must be removed and the method is considered much better for the environment than surface mining. The D&B method can be mobilized fairly quickly, starting immediately after the site prep is complete and can excavate short radius turns in tunnels. However, the 5-km tunnel length exposes the drill and blast method's major weakness—advance rate. The excavation rate of a drill and blast operation may average out to 6 m per day (Tarkoy & Byram, 1991). At this rate, and assuming 6 months for site prep, logistics and permitting, it will take about 2¾ years to finish the access tunnel.

TBM Tunneling

Through decades of experience in tunnels around the world, it has been observed that in tunnels over 2 km in length, TBMs are the most effective tunneling method (see Figure 2).

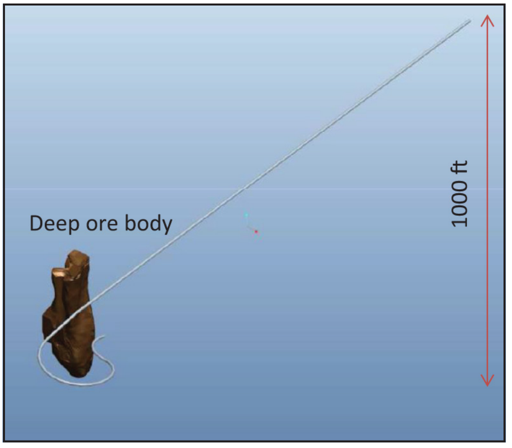

Figure 1. Deep ore body with access tunnel (OZ Minerals, 2013)

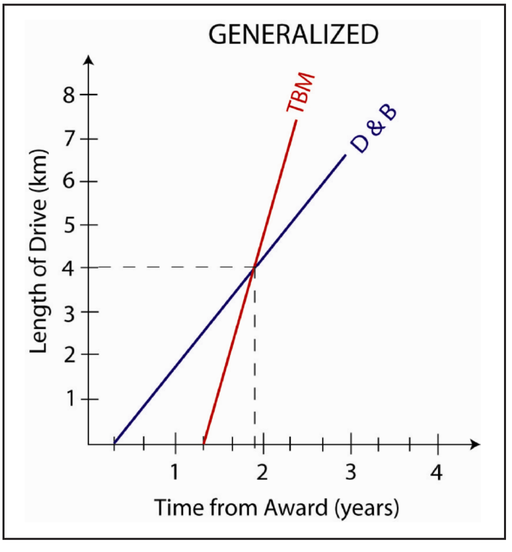

Figure 2. Generalized graph comparing advantages and disadvantages of TBMs vs. D&B

In comparison with D&B methods, TBMs have many advantages. TBMs are a more automated form of construction, requiring fewer workers. It has been shown that less ground support is needed in comparison with drill and blast. This can be attributed to the smooth excavation profile. The type of ground support is also more widely varying for TBMs—from wire mesh to ring beams, rock bolts, and steel slats using the McNally Support System. Installation of these types of ground support from within the machine shield, paired with the absence of explosive materials for excavation, also makes TBM tunneling safer in general than Drill and Blast.

Time is both the main advantage and disadvantage of TBMs. The advantage comes in the form of advance rate whereas the disadvantage is due to delivery/setup time. TBMs average speeds of 20 m per day which means it will take a TBM only 250 days to excavate the access tunnel, as opposed to the 830 days needed for D&B. However delivery and setup for a new, custom TBM is about 1 year. This means that the TBM will start six months after the D&B operations would. Despite the six month latency, using a TBM will still beat D&B to the finish by nearly a year. Furthermore, a TBM can be reused, so if a mining operation were to own one then the lead time for startup could be reduced from one year to a couple of months.

The addition of a continuous conveyor for muck removal can further increase TBM advance rates over long distances, with typical conveyor system availability rates of 90% or higher observed. Ventilation is also much better in TBM tunnels using conveyors, as there is a substantial reduction in exhaust from locomotives. Continuous conveyors could also be used with drill and blast operations, with the same effect of speeding up advance rates over rail car haulage.

Chosen Method

Given the advantages offered by a TBM in a longer access tunnel scenario, paired with modern TBMs' unique abilities to excavate in conditions such as decline tunnels, make this the obvious choice. Modern TBMs can be designed with shorter main beams to bore in reduced radii curves, be outfitted with core drills and other ancillary equipment for ore body exploration, and can be specially designed for muck haulage on a decline.

MAJOR MINING PROJECTS

Stillwater Mine, Montana, USA

Examples of successful mining projects using TBMs are available worldwide. The Stillwater mine is perhaps the best example of TBMs being used over a significant period of time to extend the life of a mine and access a longitudinal ore body.

The Stillwater Mining Company (SMC) is the largest producer of platinum group metals (PGMs) in North America and the only producer in the United States. Its J-M Reef lies under southern Montana's Stillwater, Sweet Grass and Park Counties and is located approximately 30 miles north of Yellowstone National Park. Discovered in the early 1970s, the 28-mile-long J-M Reef is part of the Stillwater Complex, a layered succession of ultramafic to mafic rocks in the earth's crust. Its uniform layers of mineral concentrations and proximity to the earth's surface make the J-M Reef a world-class ore body for Platinum Group Metals.

SMC has selected TBMs for mine development because of the benefits they offer over conventional mining methods. The mine has found that TBMs have increased advance rates over traditional mining methods. While the capital cost for TBMs is approximately 1.5 times that of conventional mining fleets, they only have 33% of the operating costs. SMC has used four TBMs for mining in the past, with the first TBM used at the Stillwater mine in 1988. Table 2 shows a list of TBM drives completed or started at SMC since 1988.

SMC's latest TBM bore is the Blitz Tunnel, a 7.1 km (4.4 mi) mine development tunnel, which will map the location of the reef in the Eastern portion of the mine where there is limited drilling data. SMC ordered a 5.5 m (18.0 ft) Main Beam TBM manufactured by The Robbins Company for the job (see Figures 3 and 4).

In order to detect the reef in relation to the TBM, careful analysis is required during drilling. Diamond core drills on the TBM, in addition to probe drills, take samples above, ahead, and alongside the machine every 150 m (500 ft). The cores are logged and interpreted on the spot, concurrent with boring. Based on the data, the TBM is then readjusted so that it stays on the correct bore path—near but not intersecting the reef.

Magma Copper Mine, Arizona

The San Manuel Mine is one of the largest underground mines in the world, but projections before the tunnel was built estimated its reserves would be depleted by 1998. The tunnel allowed the

Table 2. List of TBM drives at SMC since 1988

Mine	Machine	Drive	Start Date	Finish Date	Length (m)
Stillwater	Robbins MB 146-193-1	5000 East FWL	March 1988	July 1988	975
Stillwater	Robbins MB 146-193-1	5900West FWL	May 1989	August 1990	3,390
Stillwater	Robbins MB 146-193-1	5700West FWL	October 1990	January 1991	1,405
Stillwater	Robbins MB 146-193-1	5500West FWL	February 1991	June 1991	7,500
East Boulder	CTS	Access #1	July 1998	July 2000	2,286
East Boulder	Robbins MB 156-275	Access #2	March 1999	September 2000	5,530
East Boulder	Robbins MB 156-275	West FWL	September 2000	September 2008	2,200
East Boulder	Robbins MB 156-275	Graham Creek	January 2011	2012	2,590
Stillwater	Robbins MB244-313-2	Blitz 5000 East	May 2012*		6,858*
			Total		**32,734**

* Indicates project in progress as of January 2014.

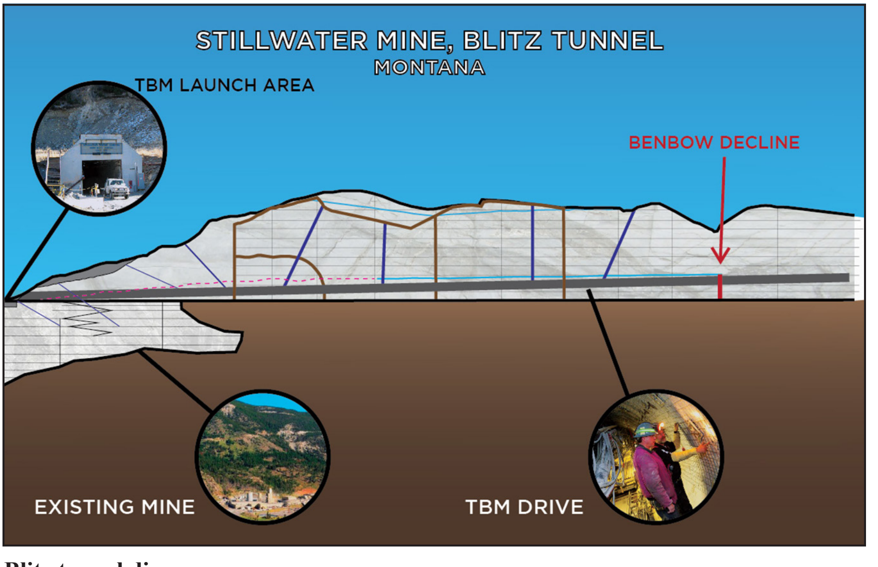

Figure 3. Blitz tunnel diagram

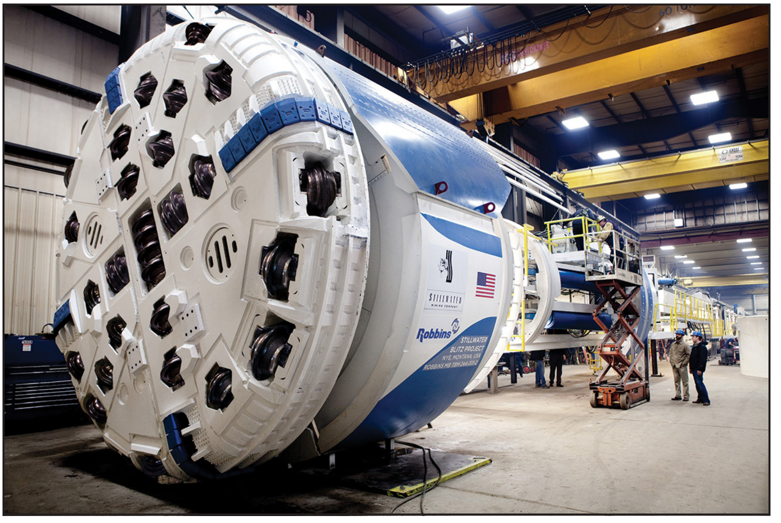

Figure 4. Main beam TBM for Stillwater Mine

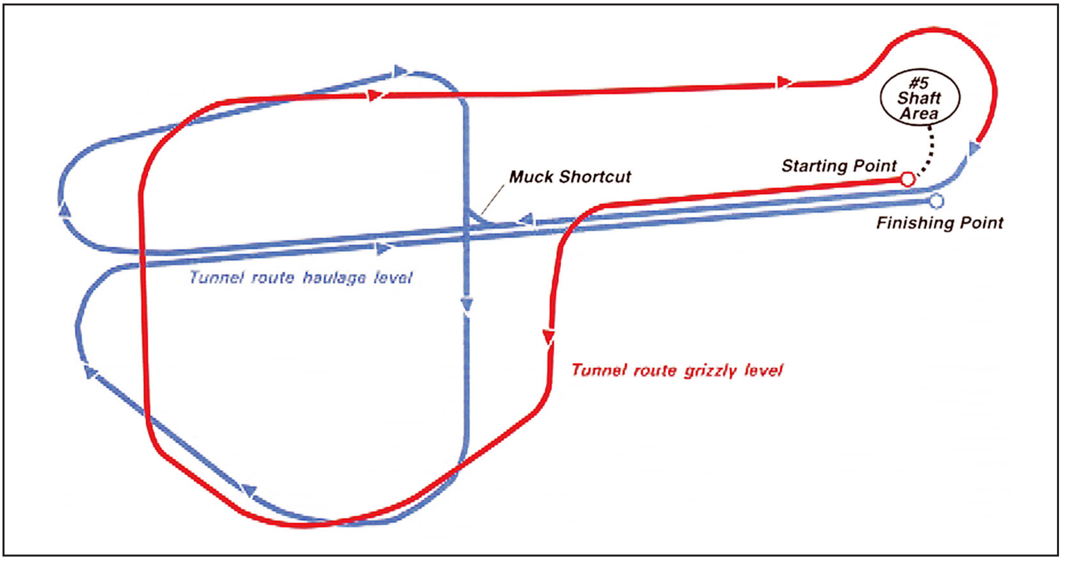

Figure 5. Route of Magma copper tunnel

development of the Lower Kalamazoo ore body, in the vicinity of dwindling ore bodies that had already been tapped. As a result the mine was able to stay open until 2003.

The project owner, Magma Copper Company, awarded the construction contract to a joint venture of Frontier-Kemper Constructors Inc. and Deilmann-Haniel GmbH. The joint venture chose a 4.6 m Main Beam Robbins TBM to bore the 10.5 km mining tunnel (see Figure 5).

The Lower Kalamazoo geology is quite complex, consisting of porphyry, and granodiorite. The tunnel route includes numerous faults and dikes—it passes through the San Manuel fault six times and the Virgin Fault five times. Much of the rock has been weakened by hydrothermal metamorphosis.

The cutterhead of the 4.6 m diameter machine could reverse rotational direction to prevent jamming when it encountered fractured rock. The machine was designed with a shorter main beam, allowing it to excavate reduced radii curves in the tunnel. Boring

Figure 6. Breakthrough ceremony at Magma Copper Mine

began on November 11, 1993 in a specially prepared concrete chamber. There were no major problems crossing the San Manuel Fault, but wet clay at the Virgin Fault slowed boring. The TBM continued to encounter soft clay and crumbling ground.

Robbins and the contractors added several features to the machine to optimize performance. They increased muck flow through the cutterhead, increased cutterhead torque, and added additional rock support to the tunnel. After the initial modifications, TBM performance greatly improved. Daily advances tripled to 22.94 m per day for the first 15 months of boring and the machine averaged more than 30 m per day for the rest of the project. The TBM stayed on schedule and holed through on December 4, 1995 (see Figure 6).

Grosvenor Decline Tunnel, Australia

A unique tunnel has just begun excavation near Moranbah, Australia at the Anglo American Coal Mine. An access tunnel is required for deep coal drifts. Two decline tunnels, at grades of 1:6 and 1:8, will be used for the mine access to new coal seams. An 8.0 m hybrid EPB/rock machine was supplied for mixed ground conditions ranging from sand and clay to varying grades of hard rock up to 120 MPa UCS, as well as coal seams. Methane gas is expected to be present throughout the tunnel, so the machine has been designed as Explosion Proof Compliant to ERZ-1. The TBM was launched in December 2013 (see Figure 7).

Only about 300 m of ground are expected to require EPB mode, while the rest will be bored in hard rock mode. Thus, the design was optimized towards hard rock excavation. In EPB Mode, the machine utilizes a two-stage, center-mounted screw, with a replaceable inner liner and carbide bits for abrasion protection. A mixed ground cutterhead is fitted with interchangeable knife bits and Trimay abrasion resistant wear plates for abrasion protection. To keep the mixing chamber spark-safe in the presence of methane, the chamber is filled with water, foam, and other additives. To deal with the resulting watery muck, the first screw conveyor is run faster while the second screw conveyor is run slower, creating a muck plug in the beginning of screw conveyor #2, which keeps most of the water in front of the machine.

The machine essentially uses its EPB technology to deal with any methane gas safely. If any methane leakage is detected, an evacuation system called a “snuffer box” will draw methane out of the end of the screw conveyor and directly into the ventilation system.

To convert to hard rock mode, a hydraulically operated muck chute is deployed around the screw. The muck is then picked up by paddles in the muck chamber to load the screw. Interchangeable EPB knife bits must be replaced with disc cutters on the cutterhead, and the EPB scrapers on the cutterhead must be replaced with hard rock bucket lips.

A skew ring twists the thrust cylinders in order to react the torque of the machine in hard rock, allowing for more efficient single direction cutterhead excavation and muck pickup. Mini grippers on the rear shield allow the machine to bore 400 to 600 mm forward, then be retracted for cutter changes (see Figure 8).

A final unique aspect of the machine is a specially designed “Quick Removal System.” As no

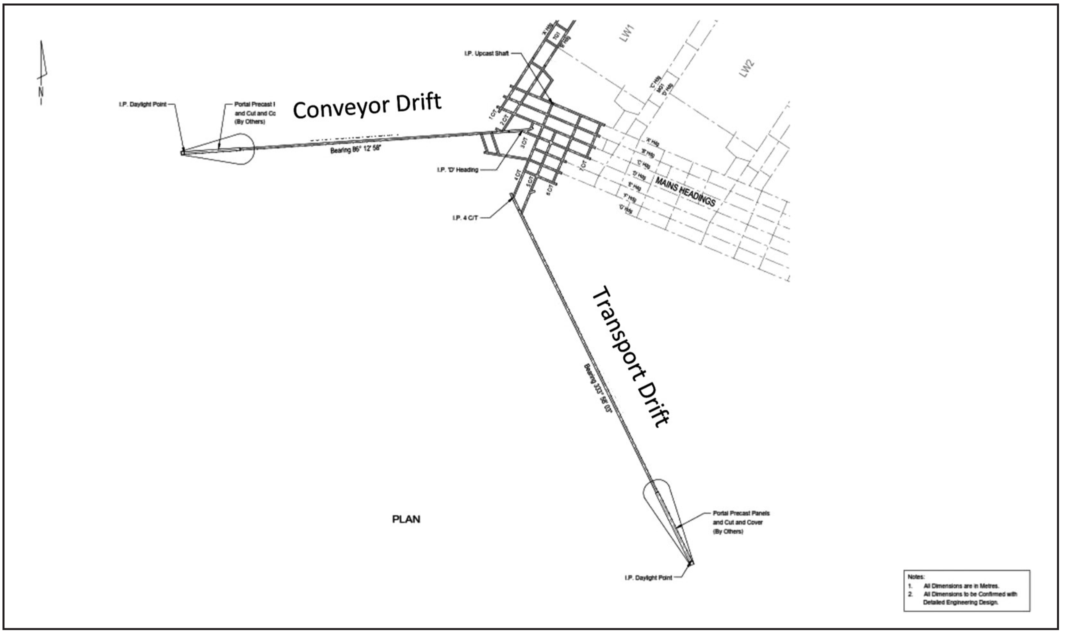

Figure 7. Layout of tunneling at Anglo American Coal Mine

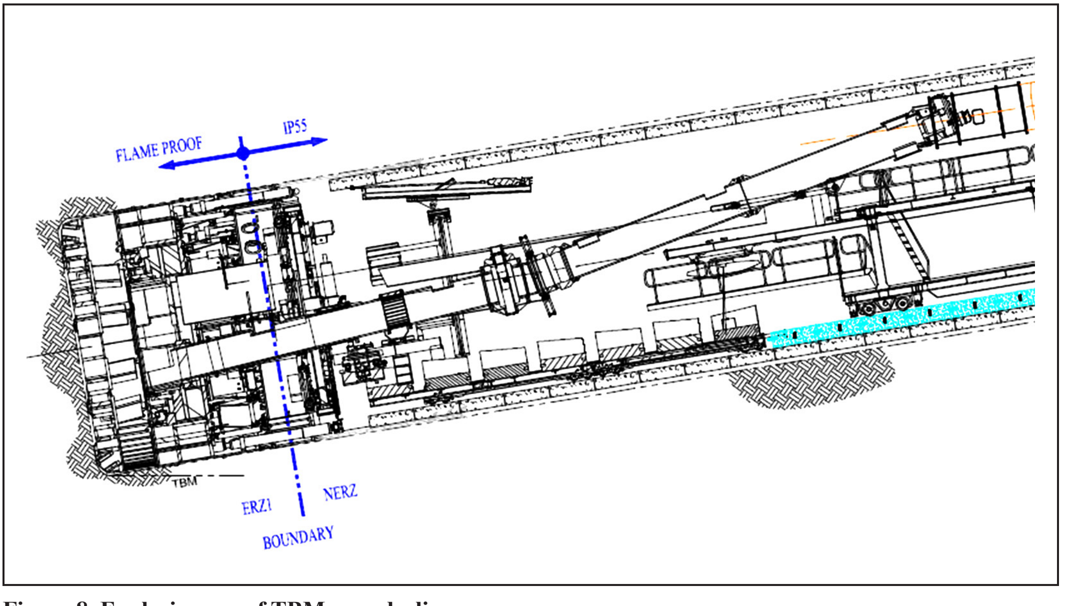

Figure 8. Explosion-proof TBM on a decline

ground in Australia can be left unsupported and the machine is boring a blind tunnel, it is designed to be retracted in one piece from its shield, leaving the shield in place. The core of the machine is a bolted design and separates from the shield, in a process that does not require a cutting torch. The machine will then be walked up the decline tunnel on a set of specially designed transport dollys and sent by rail to the second decline tunnel, where another shield will be waiting for machine assembly prior to launch.

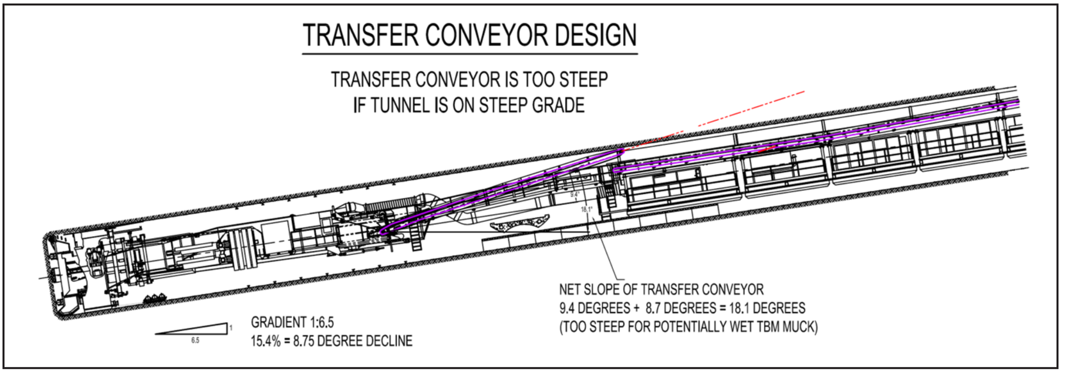

Figure 9. Typical conveyor design does not provide correct angle for muck removal

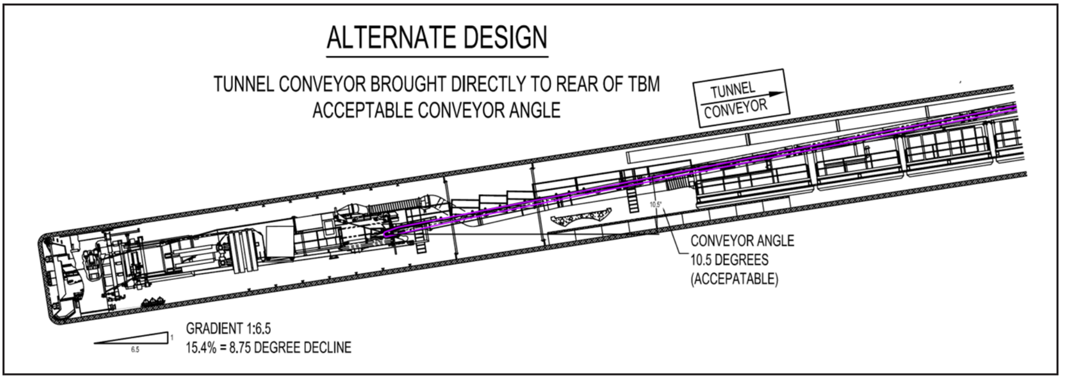

Figure 10. Alternate conveyor design brings tunnel conveyor directly to the rear of the TBM

Carrapateena Decline Tunnel, Australia

Another decline tunnel, yet to begin excavation is located at the OZ Minerals copper and gold mine in southern Australia. A high grade, cylindrical ore deposit has been identified 500 to 1,500 m below the ground. To excavate the ore body, a TBM access tunnel 1,000 m deep is required. A 5.8 m diameter Main Beam TBM was procured to excavate a 7 km access tunnel at 15.4% grade. The angle of decline requires the TBM and continuous conveyor to be uniquely designed to maintain an acceptable angle for conveyor muck removal (see Figures 9 and 10).

The TBM is currently being assembled at Robbins' manufacturing facility in Shanghai, China, and will be delivered in early 2014. The project is on hold and has an unknown start date.

CONCLUSIONS

Looking at only TBMs manufactured by Robbins, 29 have been used in mining applications over the years and mining use is accelerating. Given the various aspects that these projects have demonstrated—boring longitudinal ore bodies, curved tunnel drives, steep declines, and in gaseous conditions—modern TBMs have what it takes to make mine development rapid, efficient and economical. For deep ore bodies requiring drives over 2 km in length, TBMs should be seriously considered for their higher advance rates, improved range of ground support, and safety.

With the global demand for minerals increasing, mines can only be pushed in one direction—deeper. As the location of deposits change, the excavation must necessarily evolve with it. Those mines embracing mechanized tunneling, and more specifically TBMs, will experience a paradigm shift in their mining operations. Ore bodies which were once considered inaccessible will finally be within reach. Early adopters of the TBM method will be able to better meet the increased demand and/or extend the life of the mine—a result every miner hopes for.

REFERENCES

OZ Minerals 2013. Carrapateena Decline Excavation by TBM. Powerpoint presentation.

Tarkoy, P.J., Byram J.E. 1991. The advantages of tunnel boring: a qualitative/quantitative comparison of D&B and TBM excavation. Hong Kong Engineer, January 1991.