2003 SME Annual Meeting
Feb. 24-26, Cincinnati, Ohio

Preprint 03-140

FRAGMENTATION METHOD: A GROUND CONTROL TOOL

J. Girard-Dwyer
J. Johnson
J. Whyatt
B. White
Natl. Inst. for Occuptnl. Sfty. & Health
Spokane, WA

ABSTRACT

The choice of fragmentation method is one of the most fundamental aspects of mine design, and often has a major impact on the safety and economic viability of an operation. Almost exclusively, underground mining operations rely on either mechanical excavation or drill and blast techniques to extract rock. Each of these fragmentation methods has distinct advantages and disadvantages, and each is appropriate, and economic, for different mining conditions. However, the choice of fragmentation method can have a pronounced effect on the amount of damage created in the rock mass surrounding the opening. This paper reviews a number of case studies where both mechanical excavation and traditional drill and blast were used in underground mines. Ground support requirements in the mechanically excavated areas are compared to the support requirements in the blasted sections in order to demonstrate the potential safety and cost benefits of the various fragmentation methods.

INTRODUCTION

Falls of ground are one of the most hazardous conditions underground miners face. In the six year period from 1996-2001, there were 53 fatalities caused by falls of ground in underground mines (MSHA, 2002). Non-fatal injuries related to ground control are also very common. For example, in the three year period from 1996 to 1998, there were 3061 non-fatal injuries reported, 65% of which resulted in permanent disability or days off work (Mark and Iannacchione, 2001). Although the majority of these injuries occur in underground coal mines, ground falls in underground metal and non-metal hardrock operations also warrant close examination.

Obviously, the method used to excavate the underground openings will contribute to the amount of damage and thus, the amount of loose ground that needs to be supported or scaled down. While the majority of metal and non-metal mines use conventional drill and blast to excavate underground openings, an increasing number of mines have successfully implemented mechanical excavation at their operations. This paper presents case studies from operations that have used both traditional blasting techniques and mechanical excavation. The effects that the fragmentation method has on the overall ground control system and other operational considerations are discussed.

BACKGROUND

Of the 53 ground control fatalties from 1996-2001, nearly one-third (17 of 53) occurred in underground metal and non-metal mines (Table I). As can be seen from this data, failure to remove or support loose ground accounts for a majority of the incidents. Loose rock can be dangerous and is problematic at many operations. In fact, the Mine Safety and Health Administration (MSHA) reports that the most frequent citation in 2001 for both underground metal and underground stone mines was violation of the *Code of Federal Regulations* -- CFR § 57.3200 which states:

> *“Ground conditions that create a hazard to persons shall be taken down or supported before other work or travel is permitted in the affected area…”*

In most underground mines, loose ground on the back/roof and ribs is removed by hand scaling or mechanical scaling. However, while scaling ultimately reduces the risks of rock fall injury to the mine workers, the personnel responsible for scaling are at risk for injury when performing this task. In one study of accidents in underground stone mines, nearly one-third of all ground control injuries involved scaling (Grau and Prosser, 1997). Approximately two-thirds of those accidents were caused by a direct hit from falling rocks, but loss of balance, injuries to limbs, extremities, and backs, and other ergonomic issues were also problematic.

Many injuries also occur while installing supports such as bolts, mats, or mesh to control loose ground caused by blast damage. Blast design parameters such as geologic setting, number of drill holes, drilling accuracy, type and amount of explosives used, delay sequences, and many other factors affect the size and shape of the final opening. Poor blast designs, poor quality control, or in some cases, the presence of unknown geologic structures, can lead to excessive overbreak, ore dilution, and damage to adjacent ground that has already been supported. Blast-induced rock mass damage is a significant problem with respect to both mining efficiency and safety (Scoble, *et. al.*, 1997). Clearly, the longer it takes to scale and support damaged openings, the higher the potential risks are to the workers. One way to minimize risks associated with loose rock is to use a fragmentation method that will not create excessive overbreak.

Table I. Summary of underground metal/non-metal ground control fatalities 1996-2001.

Date, Location	Mine Type	Causative Factors	Type of Fall	Victim Activity
Jun. 2001, NV	Metal	Failure to examine, support, or remove loose ground	Roof	Blasting Crew
Mar. 2001, MT	Metal	Failure to examine, support, or remove loose ground	Rib	Installing Support
Jan. 2000, AZ	Metal	Failure to examine, support, or remove loose ground	Rib	Blasting Crew
Nov. 1999, NV	Metal	Inadequate support/working alone in unsafe area	Roof/Rib	Mine Owner
Oct. 1999, KS	Stone	Failure to scale ground from a safe location	Rib	Scaling
Oct. 1999, NV	Metal	Failure to support or remove loose ground/unsafe location	Bottom of drop raise	Driller
Oct. 1999, NV*	Metal	Inadequate support	Roof	Installing Support
Nov. 1998, CO	Metal	Failure to examine, support, or remove loose ground	Rib	Driller
Mar. 1998, AZ	Metal	Failure to examine, support, or remove loose ground	Roof	Installing Support
Jan. 1998, MO	Metal	Failure to support or remove loose ground	Roof	Surveying
Apr. 1997, TN	Stone	Failure to examine, support, or remove loose ground	Rib	Driller
Feb. 1997, NV	Metal	Unsafe location	Roof	Scaling
Feb. 1997, TN	Metal	Large span/geology	Roof	Driller
Jul. 1996, NV	Metal	Failure to examine, support, or remove loose ground	Rib	Driller
May 1996, MO*	Stone	Failure to examine, support, or remove loose ground	Roof	Blasters

*double fatality

Note: (Data in table was compiled from www.msha.gov and does not include fatalities related to rockbursts).

FRAGMENTATION METHOD

Specific criteria for assessing how the choice of fragmentation method will ultimately affect ground control requirements and safety are sparse, but a number of case studies have been published that show substantial advantages can be gained by altering the fragmentation method at an operation. Often, these changes are made by way of changing the blast design or implementing a controlled blasting program. Another less common, yet potentially viable option for reducing the amount of damage around underground mine openings is the use of mechanical excavation.

The most common mechanical excavation equipment includes roadheaders, tunnel boring machines (TBM's), continuous miners, mini- or mobile-miners, and shaft borers. Each system consists of cutters, discs, rollers, or drag picks that shear the face to produce broken rock that is subsequently transported away from the working face by conveyor or other means.

Today, mechanical excavation is primarily used by the heavy civil construction industry. Despite the well-documented success stories in hard rock tunneling, and the many advances that have been made with respect to equipment capabilities, mechanical excavation has not had a "serious impact on mining" (Robbins, 2001). The fact that mechanical excavation techniques have not been significantly adopted by the mining industry is a combination of the machine capabilities, economic feasibility, and the mining industry production approach. Because of the high capital cost of equipment, some mining companies are hesitant to change current operating practices unless the technology is "well-proven" at other mine sites.

Depending on the shape and size of the orebody, mechanical excavation is not always feasible. Nonetheless, there are a growing number of success stories related to mechanical excavation in underground mines. The following case studies are presented to show that appropriate implementation of mechanical excavation techniques may allow for more selective mining, reduced ground support, increased production, and increased safety.

Roadheaders in Mining

Although mechanical excavation has been successfully applied in coal mines for over 50 years, these techniques have only sporadically been implemented in the hard rock sector of the mining industry. There are many reasons for this – primarily, the capabilities of the machines to operate in hard rock were limited by rock strengths. A few trials have demonstrated successful roadheader excavations in rock with unconfined compressive strengths (UCS) above 20,000- psi [138-MPa]. However, the majority of successful cases of excavation have been in softer materials (UCS ranges up to 17,400-psi [120 MPa]) using light-duty and medium-duty roadheaders. Figure 1 shows the progression of rock cutting capability of various roadheaders versus unconfined compressive strengths from a variety of case studies.

Research advances in composites for drag picks, mini-disc cutter technology, water-jet assistance, or other cutter-head technology may drive the operating range even higher in the near future. Until this happens, roadheaders probably will not be common in underground hard rock mining. However, there are many advantages to using roadheaders as illustrated by the following case studies.

Roadheader Case Study #1: In 1995 Newmont Gold borrowed a Voest-Alpine AM75 roadheader from the Nevada Test Site to determine whether mechanical excavation was feasible at the Carlin East Mine. The tests were conducted primarily in siltstones with unconfined compressive strengths ranging from 3,000-psi to 10,000-psi [21-MPa to 69-MPa] and an average Laubscher rock mass rating (RMR) of 41 (fair rock). Additional tests were also run in a harder limestone rock (UCS range = 18,000 to 25,000 psi [124-MPa to 172-MPa]), but the roadheader did not perform as well. While the roadheader still cut the rock in this harder section, the bit consumption went from an average 20 tons per pick in the siltstone, down to 5 tons per pick in the limestone. Based on the preliminary results from the roadheader tests, Newmont decided to purchase a their own roadheader – an AC-Eickhoff ET-210.

The ET-210, a 50-ton class machine with a transverse head and tungsten carbide picks, was set up to convey cut rock into waiting haul trucks. Overall production rates using the roadheader were

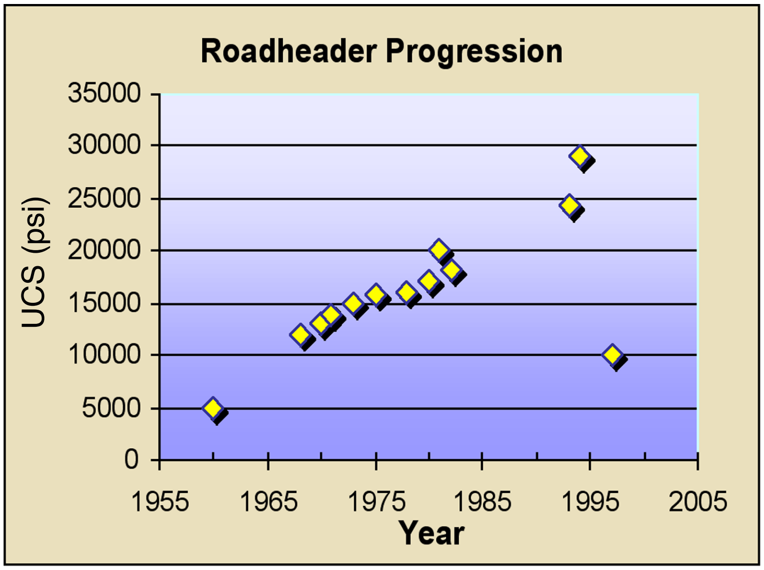

Figure 1. Progression of Roadheader Cutting Ability vs. Unconfined Compressive Strength (adapted from Morris (1985)).

approximately 45 tons [40 tonnes] and 2.1 feet [0.6 m] per man-shift which is slightly higher, or equivalent to, the average production rates using traditional drill and blast techniques (Sobering, 2001). Cutting rates of over 180 tph (200 stph) were experienced and could have been increased even more with additional truck haulage capacity (Driscoll, 1997; Breitrick, 1998). The roadheader production was executed at $60 USD per ton as compared to $65 USD per ton for drill and blast (Sobering, 2001). The roadheader costs could have been significantly lower than the drill and blast costs at the operation, but the full potential of the machine was not realized due to multiple cutting cycles and down-time while waiting for the installation of ground support and backfill. The machine could cut three times as fast as the ground support could be installed. In order to optimize the roadheader production, a large drift-and-fill area with multiple headings and short tram times between headings would be required. This case study proved a number of points:

- less ground support was needed because overbreak from blasting was eliminated;
- less ore dilution occurred; and,
- if the geologic setting and mine planning sequence allow for the roadheaders to be utilized efficiently, production costs have the potential to be significantly lower than production costs using traditional drill and blast methods.

Roadheader case study #2: (Navin, *et. al.*, 1985): In the early 1970's, the White River Shale Oil Corporation designed a decline that called for 5000-ft [1525-m] of development through sandstone with average compressive strengths of approximately 7,000-psi [48-MPa], sporadic bands of shale with compressive strengths up to 20,000-psi [138-MPa], and massive formations of dolomitic marlstone with compressive strengths as high as 30,000-psi [207-MPa]. Geotechnical data on Bieniawski's Rock Mass Rating (RMR) system and Barton's Q-system indicated that the majority of the rockmass was rated as good to very good, and the beds were self-supporting over the maximum excavated width of 28.5-ft [8.69-m]. Table II lists the support classes for the White River Shale Project's anticipated ground support requirements.

An E182, 70-T Paurat roadheader with a conveyor muck-handling system was used for production. Average advance rates varied from 85-ft [36-m] per week in the sandstones up to 104-ft [32-m] in the oil shales. Bit wear and breakage were extensive in the marlstones, and mining rates (as compared on a volumetric basis) were 20% slower than the mining rates in other areas. Blasting had to be used in conjunction with mechanical excavation in some of these areas. Several difficulties were encountered trying to remove muck when the slope was 17-degrees or more, and areas with high water inflow caused problems with conveying materials. This is an older case study, but is included to show that in spite of the many difficulties encountered, the use of a roadheader ended up being successful at the White River Project. Namely:

- the project was completed in 90% of the scheduled time and 1.7% under budget;
- ground support went from Class II in blasted areas to Class I in roadheader-mined areas – an estimated reduction of 40%; and,
- overall, roadheader advance rates were 150% higher than advance rates using drill and blast.

Table II. Ground support classes at White River Shale

Ground Support Class	Typical Bolt Spacing*+ (ft)	Typical Shotcrete Application*#
Class I	5	2-in plain shotcrete on back
Class II	4	2-in shotcrete with welded wire mesh on back and down 4-ft on rib
Class III	3	2-in shotcrete with welded wire mesh on back and down 4-ft on rib
Class IV	2.5	2-in shotcrete with welded wire mesh on back and down 4-ft on rib

* Additional support installed as needed
\+ 1-in diameter, 8-ft fully resin-grouted reinforcing bar
\# 4,000-psi Type V cement, over optional 4-in by 4-in welded wire mesh

Tunnel Boring Machines in Mining

Tunnel boring machines (TBMs) have been successfully used in numerous heavy civil construction projects and were first tested in hard rock mines beginning in the 1960's (Bullock, 1994). Because TBMs are best used for long, straight openings they are generally not suitable for many mining applications. High capital costs and long turn-around times for assembly, transport, and launch are also disadvantages. Despite this, there have been successful applications of TBMs in mining.

TBM Case study #1: (Tilley, 1989; Bullock, 1994). In the late 1980's, the Stillwater Mining Company started using a TBM in their platinum- palladium mine in south central Montana. Host rock UCS ranged from 12,500-psi to 24,000-psi [86-MPa to 165-MPa]. Compared to drilling and blasting at the operation, the TBM tunnels resulted in a one-third cost reduction and higher production rates. The significant savings in development time brought the mine into more rapid production, which was a very important financial benefit. From a ground control standpoint, the roof-bolting requirement was only 10-20% of the normal usage as compared with the drill and blast areas at that time. However, there were some drawbacks to the first TBM system: the turning radius was too large and made alignment difficult; a single-speed cutterhead was inadequate for startup; and operation in highly broken or changing ground conditions was problematic.

For the Stillwater mine the advantages of using TBMs for development work far outweighed the disadvantages. In August 1998, a custom-built TBM began boring an access tunnel over 3.5-miles [5650-m] in length at the company's East Boulder operation (Strickland & Einarson, 1999; Alexander, 1999). The new TBM was purchased from Construction and Tunneling Services (CTS) and included many advanced features such as: more maneuverability with a 225-ft [70-m] short turning radius; a computer-controlled laser guidance system; backloading for changing bits; a two-speed electric drive with hard rock thrust capability; and, modular sections for portability (Burkhart, 1998; CTS, 1998). A second TBM was acquired by the mine and was used to accelerate the project schedule by driving an adit parallel to the CTS machine. This machine was purchased from BHP (Magma Copper's Lower Kalamazoo Project (see next case study)) and was reconditioned for use by Stillwater. Reports from the mine indicate that work progressed smoothly with both machines and that the TBMs crossed the mineralized reef in July 2000 (McCullough, 2001).

TBM Case Study #2: In September of 1993, Magma Copper Company's San Manuel Mining Division began lowering the components of a Robbins Series 150 TBM underground to the Lower Kalamazoo portion of the mine. Mine plans called for 32,235-ft [9826-m] of tunnel driveage including eleven 360-ft [110-m] radius curves. Using a TBM was a serious decision on the part of the mine management because over 1300 jobs were at stake (VanDerPas & Alum, 1995). Furthermore, while many curved, TBM-bored drifts and tunnels had been completed in the civil industry, mine development plans for the Lower Kalamazoo included tight curves, at greater arc lengths, than had ever been driven before in a single TBM project (Chadwick, 1995).

The rock at the mine had been subjected to hydrothermal metamorphosis and ranged from very weak to very strong. The TBM's excavation route included a stable pre-Cambrian quartz-monzonite with a UCS of 21,750 to 26,100 psi [150-180 MPa]. The path also crossed a 6.5-ft [2-m] wide clay zone associated with the San Manuel Fault six times and crossed the steeply dipping Virgin Fault zone five times. Several weak zones associated with dyke contacts were also encountered.

There were several start-up problems associated with the project: clay frequently plugged the cutterhead; the cutterhead would not rotate in soft, collapsing ground; the side grippers gouged the walls in weak ground and contributed to sidewall collapses and steering problems. Subsequently, the TBM was modified to better suit the conditions in the mine. These modifications notably improved the TBM's performance and led to average daily advance rates of 74-ft [22.6-m] as compared to only 21-ft [6.5-m] per day previously (Cigla, et. al., 2001).

Magma Copper Company also tested a narrow-width DOSCO SL-120 roadheader in select portions of the Kalamazoo and San Manuel ore bodies. In certain sections of the mine, conventional blasting exposed an average or 30% more area than intended (Sandbak, 1985). This significantly increased the amount of ground control that was necessary to support the openings. The roadheader was able to cut the openings closer to the planned dimensions. In addition, the excavation using the roadheader was at least 38% faster than conventional drill and blast.

In spite of initial start-up problems, mechanical excavation at San Manuel was very successful, and allowed the mine to meet an accelerated schedule. In most cases, less ground support was needed and advance rates were considerably faster than conventional drill and blast.

Historically, the success of TBMs in mining has been spotty. Several attempts using inadequate machines under rather hostile conditions led to a number of failures. However, the science of underground excavation has come a long way since these earlier trials, and research continues to advance the capabilities of mechanical excavation equipment. In recent years, novel applications (e.g. novel for the mining industry) include projects that used TBMs to drive a tunnel between two open pits to minimize haulage distance (Chadwick, 1995), and driving water tunnels to divert a creek from flowing past environmentally susceptible waste piles (Yanagisawa, 2001). Whenever possible, the mining industry should also consider innovative uses as well as typical applications for mechanical excavation equipment.

DISCUSSION AND CONCLUSIONS

As can be seen from the preceding case studies, there are a number of potential advantages to using mechanical excavation equipment instead of traditional blasting. These advantages include (modified from Speight, 1997):

- Worker Safety: no explosives handling or fumes generation, less damage to the rock mass (typically 20% of that due to blasting), and less workers are required which in turn, decreases exposure to hazards.
- Debris Size: smaller, uniform muck is easier to handle and process.
- Selectivity: selective mining is possible and less ore dilution occurs.
- Equipment: a single machine replaces the multiple components of the drill-blast-muck cycle.

Each of these aspects can also decrease costs and increase productivity at a mine. However, there can also be complications and disadvantages associated with mechanical excavation equipment. Factors such as high capital costs, delivery and setup time, equipment maintenance requirements, high power requirements, heat and dust generation, ventilation capabilities, orebody dimensions, etc., must be considered when determining whether mechanical excavation is feasible at a mining operation. Accordingly, mine plans should be developed to maximize the benefits of using mechanical excavation equipment – faster advance rates are of little use if haulage systems or ground support installation cannot match the excavation pace. The properties of the rock mass are also a very important consideration. In rock masses that are highly fractured or too hard, drilling and blasting may be more appropriate from a production standpoint. On the other hand, if the rock mass falls in between those two extremes and is fairly consistent along the entire length of the opening, mechanical excavation advance rates far beyond the highest possible advance rates using drill and blast are possible and will increase worker safety (Sapigni, et. al., 2002; Barton, 2001; Barton, 2000).

Many authors have expressed the advantages of using mechanical excavation in mining: (Robbins (2001); Gertsch (2001); Alexander (1999); Strickland & Einarson (1999); Bullock (1995, 1994); Friant (1995); Carter (1996); Lovat, *et. al.*, (1993); Garrett (1985); Handewith (1980); and others). Many others are doing research to improve cutters, machine designs, guidance systems, electrical systems, dust suppression systems, and other mechanical excavation components. Clearly as technology continues to advance, an increasing number of mining companies may be able to incorporate mechanical excavation in an economical and efficient manner. Based on results from mines currently using mechanical excavation, this may also enhance safety in underground mines by minimizing damage to the rockmass and decreasing injuries and accidents associated with the installation of ground support. While both blasting and mechanical excavation have distinct advantages and disadvantages, the important concept to consider is the effect the fragmentation method has on the surrounding rock mass. The National Institute for Occupational Safety & Heath is currently investigating these effects in order to develop tools and procedures to reduce ground control accidents in underground mines. No matter what method is used for fragmentation, significant improvements in mine safety and production can be achieved by paying strict attention to variable site geology and by carefully designing the excavation method to match site conditions. If implemented properly, future advances in mechanical excavation equipment, drilling equipment, and blasting products will contribute to the reduction of damage around openings. Judicial use of appropriate methods and attention to detail will go a long way in reducing ground control accidents.

REFERENCES

Alexander, C. (1999). “Tunnel Boring at Stillwater’s East Boulder Project.” *Mining Engineering Magazine*, September. Publ. SME. pp.15-24.

Barton, N. (2000). “Rock mass classification for choosing between TBM and Drill-and-blast or a hybrid solution.” Keynote Lecture in Proceedings of the International Conference on Tunnels and Underground Structures (ICTUS), Singapore. Publ. Balkema.

Barton, N. (2001). “Are Long TBM Tunnels Faster by TBM?” In Proceedings of Rapid Excavation and Tunneling Conference, pp. 819-828. Publ. SME.

Brietrick, M. (1998). “Breaking the Mold: Using Roadheaders for Production in Hardrock Gold Mining.” SME Annual Meeting, Orlando, FL. Preprint 98-102.

Bullock, R.L. (1994). “Underground hard rock mechanical mining.” *Mining Engineering Magazine*, November. Publ. Society for Mining, Metallurgy, and Exploration.

Bullock, R.L. (1995). “The Gradual Evolution of Mechanized Hard Rock Mining.” SME Annual Meeting, Denver, CO.

Burkhart, D. (1998). “Beartooth mine ‘Beast’ will bore into mountains.” Billings Gazette, July 2nd.

Carter, R.A. (1996). “Magma Puts the Pedal to the Metal.” *Engineering and Mining Journal.* January.

Chadwick, J. (1995). “Mechanised Drivage.” Mining Magazine, Vol. 172, No. 4, April. pp. 227-236

Cigla, M., S. Yagiz, and L. Ozdemir (2001) “Application of Tunnel Boring Machines in Underground Mine Development." International Mining Congress, Ankara, Turkey.

CTS, Construction & Tunneling Services, Inc. (1998). http://www.ctstbm.com/joblist.htm#stillwater

Driscoll, J. (1997). “From Surface to Underground, Newmont Gold’s Carlin East Mine.” *Mining Engineering Magazine*, August. Publ. SME.

Friant, J.E. (1995). “Full Face TBM’s in Mine Applications.” Mechanical Mining Technology for Hardrock Short Course, Colorado School of Mines, Golden, CO.

Garrett, C.R. (1985). “Development of a Roadheader Mining System at American Borate Company.” In Proceedings of Rapid Excavation and Tunneling Conference, Vol. 2. pp. 886-901.

Gertsch, R. and L. Gertsch (2001). “Mechanical Mining: The State of the Art.” SME Annual Meeting, Denver, CO. Preprint 01-22.

Grau, R.J. III, and L.J. Prosser (1997). Scaling accidents in underground stone mines. *Rock Products* 1:39-41.

Handewith, H. (1980). “Mine Applications of Tunnel Boring Machines.” Bulletin of the Canadian Institute of Mines and Metallurgy. Volume 73, No. 823, November.

Lovat, R.P., et al. (1993). “TBM Use in Mine Development.” VIII Australian Tunneling Conference.

Mark, C. and A. Iannacchione (2001). “Ground Control Issues for Safety Professionals.” Chapter 32 in Mine Health and Safety Management, M. Karmis ed., Society for Mining Metallurgy, and Exploration, pp. 347-367.

McCullough, R. (2001). “Annual Review 2000: State and Provincial Activities – Montana.” *Mining Engineering Magazine*, June. Publ. Society for Mining, Metallurgy, and Exploration, pp. 80-82.

Morris, A.J. and W. Harrison (1985). “Significant Advances in Cutting Ability – Roadheaders,” in Proceedings of Rapid Excavation and Tunneling Conference, Vol. 1. pp. 317-340.

MSHA (2002). Mine Safety and Health Administration Fatal Accident Investigations. http://www.msha.gov

Navin, S.J., J.S. Goff, and W.W. Moulton (1985). “Roadheader Decline Development.” In Proceedings of Rapid Excavation and Tunneling Conference, Vol. 2. pp. 847-866.

Robbins, R. (2001). “Mechanical Mining in Hard Rock: A Glimpse into the Future.” SME Annual Meeting, Denver, CO. Preprint 01-35.

Sandbak, L.A. (1985). “Drift Excavation at San Manuel.” In Proceedings of Rapid Excavation and Tunneling Conference, Vol. 2. pp. 902-916.

Sapigni, M. M. Berti, E. Bethaz, A. Busillo, and G. Cardone (2002). TBM performance estimation using rock mass classifications. *International Journal of Rock Mechanics and Mining Sciences*, Vol. 39, Issue 6, pp. 771-788.

Scoble, M.J., Y.C. Lizotte, M. Paventi, and B.B. Mohanty (1997). “Measurement of blast damage.” *Mining Engineering Magazine*, June. Publ. Society for Mining, Metallurgy, and Exploration, pp. 103-108.

Sobering, J.G. (2001). “The Carlin Underground Mine.” Chapter 39 in Underground Mining Methods: Engineering Fundamentals and International Case Studies, W. Hustrulid and R. Bullock, eds., Society for Mining Metallurgy, and Exploration, pp. 339-343.

Speight, H.E. (1997). “Observations on drag tool excavation and the consequent performance of roadheaders in strong rock.” In Proceedings of Australian Institute of Mining and Metallurgy (AusIMM), Vol. 1. pp. 17-32.

Strickland, B. and D. Einarson (1999). “Design of Stillwater Mining Company’s East Boulder Mine.” SME Annual Meeting, Denver, CO. Preprint 99-43.

Tilley, Cherie M. (1989). “ Tunnel Boring at the Stillwater Mine Nye, Montana.” In Proceedings Rapid Excavation and Tunneling Conference (RETC). pp. 449-460.

VanDerPas, E. and R. Allum (1995). "TBM Technology in a Deep Underground Copper Mine." In Proceedings Rapid Excavation and Tunneling Conference (RETC). pp. 129-143.

Yanagisawa, S. (2001) "Asarco Mineral Creek Tunnel." In Proceedings Rapid Excavation and Tunneling Conference (RETC). pp. 567-577.