Investigation of factors influencing the determination of discount rate in the economic evaluation of mineral development projects

by S-J. Park* and I.I. Matunhire†

Journal Paper

Synopsis

When evaluating mining investment opportunities, one should consider the risks associated with mineral exploration and development. These are commonly classified as technical, economic, and political risks, and are accounted for in the investment decision by changing the discount rate. Thus, a company may use different discount rates associated with varying risks in order to compensate for the variability of success. The discount rate has a tremendous effect on the economic evaluation of mineral projects. Even when all other factors used as inputs for calculating the NPV (net present value) are equal, the project under consideration may be accepted or rejected depending upon the discount rate. Determining a realistic discount rate for a given project is therefore the most difficult and important aspect of cash flow analysis. It should be determined with the consideration of proper technical, economic, and political conditions surrounding the specific project undergoing economic evaluation. One key problem for determining the appropriate discount rate is that it typically depends more on subjective perception of the degree of risk or other experience factors than on a systematic approach. Thus, this study aims to identify, analyse, and document the type, role, and impact of risk factors influencing the determination of discount rates, and then to determine discount rate by using the aforementioned factors.

Keywords

discount rate, risk factors, economic evaluation, mine development.

Introduction

Mining is based on the minerals on or buried in the ground. Mining involves large risks, while requiring heavy capital investment with relatively long payback periods when compared with other business sectors. Thus careful assessment and decisions are required when investing in mining in order to reflect the distinctive characteristics of the sector. Investment decisions in mining projects are made after an economic evaluation, which is common in most business ventures. The construction of a realistic investment model is required in the evaluation of a proposed mine project. This investment model should include significant variables that are not fixed or known with certainty, such as the length of time and the cost not only to obtain the necessary permits, but also for the actual development of the mine and plant, and whether the ore deposit is economically viable. Owing to the fact that there is no comprehensive projection of the possible relevant variables, one is therefore obliged to estimate these in the decision-making process. To arrive at a solution to the project evaluation problem, one will need to determine the level of discount rate for each project within an acceptable margin of error. The discount rate for a given project is typically determined by using risk-free market rates plus a market risk premium adjusted in relation to the volatility of the investment compared to the market. In practice, however, the discount rate is still subjective and dependent on corporate or other experience factors. These factors are usually determined by top management and then handed down to the departments responsible for the immediate evaluation of projects. This study will address the nature and scope of risk and uncertainty factors influencing the determination of the discount rate and use analytical techniques to determine appropriate discount rates for use in the economic evaluation process. The quantitative methodology for discount rate is tested using a case study of a Madagascar mining project.

Factors influencing the determination of discount rate

The magnitude of uncertainties in mine development projects are generally larger than

* *Masters Student at University of Pretoria.*

† *Former Senior Lecturer with University of Pretoria and now a Senior Mining Engineer/Project Manager with TWP Projects*

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in most other comparative industries. On the basis of exploration drilling information, a decision must be reached about development of a mine, its capacity in terms of rate and level of output, a processing plant, and a smelter/refinery complex. Uncertainty can arise in the estimates of reserves and their average metallic content, in the expected metal demand and prices for the mineral, and in any other aspects of the operation. Future revenues and costs associated with mineral development cannot be calculated accurately because the factors that determine these revenues and costs are impossible to know with certainty at the time of the investment. During initial exploration, for example, many outcomes are possible, ranging from no indication of commercial mineralization to geological evidence that eventually leads to a producing mine. During the development of a deposit, initial ore reserve estimates may have to be revised, thus altering estimates of future production and revenues. During production, mineral prices may be higher or lower than predicted at the time of investment, leading to higher or lower revenues than anticipated. These factors can be grouped into three categories of mineral-development risk according to the cause of the risk: technical risks, economic risks, and political risks[1].

Technical risks

The technical risks are divided into the following three sub-categories: reserve risk, completion risk, and production risk.

- *Reserve risk*—Reserve risk, determined both by nature (the distribution of minerals in the earth's crust) and the quality of ore-reserve estimates, reflects the possibility that actual reserves will differ from initial estimates. A complete understanding of the geology of the deposit is imperative to estimate accurately the distribution, grade, and tonnage contained in reserve estimates
- *Completion risk*—Completion risk reflects the possibility that a mineral development project will not make it into production as anticipated because of cost overruns, construction delays, or engineering or design flaws
- *Production risk*—Production risk reflects the possibility that production will not proceed as expected as a result of production fluctuations caused either because of problems with equipment or extraction processes, or because of poor management. Technical risks are at least partly under the control of the organizations active in mineral development.

Economic risks

The economic risks are divided into the following three sub categories: price risk, demand/supply risk, and foreign exchange risk

- *Price risk* (revenue risk)—Price risk is the possible variability of future mineral prices. Mineral prices are normally determined by the economic law of supply and demand. Mineral prices, together with production levels, determine revenues from mining. Thus, to the extent that actual future prices differ from the prices expected at the time of the cash flow analysis, actual revenues and profits will differ from those expected.
- *Demand/supply risk*—The dynamic economic environment has increased the difficulty in achieving reliable demand forecasts. The market demand/supply risk is the variability of future market demand/supply for minerals. General economic conditions directly impact on the fluctuation in demand. To the extent that actual and expected mineral demands differ, actual mine production and revenue are affected. A case in point is the recent economic downturn which started in 2008, resulting in a number of mining operations closing down or cutting back on production.
- *Foreign/exchange risk*—Foreign exchange rate risk is the natural consequence of international operation in a world where relative currency values move up and down. Rates of foreign exchange have a major influence on the costs and revenues in US dollars, of firms operating in countries with different currencies, as well as the costs of firms sourcing equipment in currencies other than the US dollar.

Political risks

The political risks are determined by the action of governments and reflect the possibility that unforeseen government actions will affect the profitability of an investment. Potential actions include nationalization and changes in regulations concerning, for example, the environment, taxation, or currency convertibility. These political risks are divided into the following four sub-categories: Currency convertibility, environment, tax, nationalization

- *Currency convertibility*—Currency convertibility affects guaranteed freedom of capital transfer.
- *Environment*—Environmental regulations affect the economic viability of mineral projects in three different ways[1]. First, they often increase the costs of mining and mineral processing by requiring, for example, scrubbers on smelter smokestacks that reduce the amount of sulfur dioxide emitted into the air, or plastic liners at the base of tailings ponds that minimize the release of toxic heavy metals into adjoining ground and surface water.
  Second, environmental regulation often increase the time spent on non-mining activities, such as conducting environmental baseline studies, filing environmental impact statements, and applying for mining permits and waiting for their approval. Corporate social responsibility and sustainable development would be included as requirements when applying for mining permits.
  Third, regulations often increase the risks associated with an investment in mining, because of the discretionary authority that some regulations vest in government agencies to halt development or mining even after significant expenditures have been made.
- *Tax*—Although mining companies know what the tax regimes are upfront, tax remains a risk as governments may, from time to time, want to review mining taxes. Recent examples are Australia and Zambia. There are other regimes that are currently considering reviewing mining taxation. Increased taxes affect operating costs and reduce the profits.

- *Nationalization*—In mineral-producing countries, nationalization is pursued to acquire control over mining companies operating in the country. Nationalization becomes a risk if no compensation is paid. Examples exist where governments have expropriated property without compensation.

Proposed quantitative methodology for discount rate

From the review of factors influencing the determination of discount rate carried out, it is concluded that the quantitative methodology for discount rate should be a process of identifying potential risk, analysing risks to determine those that have the greatest impact on mineral development, and determining the discount rate. It is therefore imperative to find a method whereby all mining risks, together with their probability and impact, and an understanding of the combined effect of all risks attached to the cash flow and the rate of return can be determined. Thus a way or a procedure of calculating risk scores is required. Heldman[2] proposed that the quantitative methodology for discount should consist of the following steps:

- Identifying risks
- Developing rating scales
- Determining risk values
- Calculating risk scores
- Determining discount rate.

These steps will be discussed briefly in the following section of the paper.

- *Identifying risks*—The first step in the determination of discount rate is identifying all the potential risks that might arise in the mineral development project. The identification of risk and attitudes towards it are very important in the life of a mine. The following risks should be considered:
  - *Technical risk*: reserve, completion, production
  - *Economical risk*: price, demand, foreign exchange
  - *Political risk*: currency conversion, environment, tax, nationalization.
- *Developing rating scales*—The risk scale assigns high, medium, or low values to both probability and impact. Most risks will impact cost, revenue, time, or scope to a minimum.
- *Determining risk values*—The way to create a risk scale is to assign numeric values to both probability and impact so that an overall risk score can be calculated. Risk is associated with events in the future and, therefore, very difficult to measure objectively. To overcome this difficulty it is suggested that one uses

Table I

Calculation of risk score in mineral development

Category	Risk	Probability	Impact	Risk score
Technical risk	Reserve	High-0.8	High-0.8	Probability × impact
		Medium-0.5	Medium-0.5	
		Low-0.1	Low-0.1	
	Completion	High-0.8	High-0.8	Probability × impact
		Medium-0.5	Medium-0.5	
		Low-0.1	Low-0.1	
	Production	High-0.8	High-0.8	Probability × impact
		Medium-0.5	Medium-0.5	
		Low-0.1	Low-0.1	
Economic risk	Price	High-0.8	High-0.8	Probability × impact
		Medium-0.5	Medium-0.5	
		Low-0.1	Low-0.1	
	Demand	High-0.8	High-0.8	Probability × impact
		Medium-0.5	Medium-0.5	
		Low-0.1	Low-0.1	
	Foreign exchange convertibility	High-0.8	High-0.8	Probability × impact
		Medium-0.5	Medium-0.5	
		Low-0.1	Low-0.1	
Political risk	Currency convertibility	High-0.8	High-0.8	Probability × impact
		Medium-0.5	Medium-0.5	
		Low-0.1	Low-0.1	
	Environment	High-0.8	High-0.8	Probability × impact
		Medium-0.5	Medium-0.5	
		Low-0.1	Low-0.1	
	Tax	High-0.8	High-0.8	Probability × impact
		Medium-0.5	Medium-0.5	
		Low-0.1	Low-0.1	
	Nationali-zation	High-0.8	High-0.8	Probability × impact
		Medium-0.5	Medium-0.5	
		Low-0.1	Low-0.1	

the quantitative risk analysis method. The quantitative risk analysis method assigns not only high, medium, low values but also assigns numeric values to both probability and impact, so that an overall risk score can be calculated. Cardinal scale values are numbers between 0 and 1.0. Probability is usually expressed as a cardinal value.

- *Calculating risk scores*—The risk, the probability, and the impact can be listed into a table as individual components, as shown in Table I.

The total risk score could be calculated by multiplying the probability by the impact. Using the reserve risk, for example, this risk has a low probability of occurring but a medium impact. Therefore, the risk score is calculated with 0.1×0.5 for a final value, also known as an expected value, of 0.05. Total risk scores are calculated by summing each risk score and converting risk premium.

- *Determining the discount rate*—The rate of discount can be regarded in two ways. In the first case, if a company raises funds from external sources, the discount rate is regarded as the cost of the capital. It is the percentage rate of return that the firm must generate to compensate the investors, who supply funds to the company rather than investing in another company or activity.

Secondly, if a company uses internal funds, the discount rate is regarded as the opportunity cost. This opportunity cost, therefore, is the best rate of return the company could earn by investing its money elsewhere. In an ideal world both scenarios should provide the same return on capital, as one would be using the same shareholders' funds. The greater the risk, the higher the discount rate should be, raising the discount rate reduces the NPV of a set of cash flows. Determining the risk-adjusted discount rate is the most difficult aspect of cash-flow analysis where it is important to determine discount rate by the systematic method.

The risk premium

A risk-adjusted discount rate may be developed by using a risk-free rate of return, plus a subjectively determined risk premium, which is expected to compensate the investors for the extra risk involved. In practice the selection of a risk-free rate of return is relatively simple. In the majority of cases, the yield on US Government bonds, under non-inflationary conditions, is adopted as the risk-free rate of return[3]. The real problem involves the selection of the risk premium, which must be sufficient to compensate for the additional risks associated with the investment at hand. When determining an appropriate risk premium, all risks affecting the discount rate should be considered. This, however, is an extensive exercise and will encompass a greater number of risks, which makes the determination very difficult to work through and use. Furthermore, there are significant difficulties in structuring an involved analysis with many factors, for the obvious reason that it is complex and multi-faceted. In order to facilitate the implementation of the determination, one has to focus on a definite number of key risks such as technical, economic, and political risks. To determine risk premium, an expected value (risk score) as calculated in the previous section has to be converted to an overall value and risk premium. The determination of risk premium is incumbent on the impact of the factor and the potential possibility of its affecting the success of the mineral development.

The risk-adjusted discount rate

Put simply but rather crudely, we can represent a risk-adjusted discount rate as follows:

Risk-adjusted discount rate = risk-free rate of return + risk premium

- *The risk-free rate of return*—for mineral development projects, it is advisable to use a 10-year bond that yields 1.2 per cent
- *The risk premium*—can range between 6~20 per cent.

The application of these numbers to the risk-adjusted discount rate formula yields the following risk-adjusted discount rate for mineral development projects.

Risk-adjusted discount rate = risk-free rate of return + risk premium = 1.2% + 6–20% = 7.2–21.2%

Thus, the risk-adjusted discount rate required by mining companies ranges between 7.2 and 21.2 per cent.

Case study

This case study is based on the development of the Ambatovy Project, a nickel mine in Madagascar. This project gives an example of the risks considered in selecting a discount rate. The variables considered included exploration, reserve calculation, construction phase, the operation, and the sales of the product. The discount rate for the Ambatovy project was selected by using the quantitative methodology explained in the previous sections to assess the economic viability of the project.

Introduction

Located in Madagascar, the Ambatovy project is a world-class, large tonnage nickel project that is positioned to be one of the world's biggest lateritic nickel mines in 2013. Sherritt, the project operator, has a 40 per cent ownership position, Sumitomo and Korea Resources each have a 27.5 per cent stake, and the project's engineering contractor, SNC-Lavalin, has a 5 per cent interest. Ambatovy is a long-life lateritic nickel project with annual design capacity of 60 000 tons of nickel and 5 600 tons of cobalt. The mine life is currently projected to be 27 years. The Ambatovy mine site is located 80 kilometres east of Antananarivo (the capital of Madagascar) near the city of Moramanga. It is within a few kilometres of the main road and rail system connecting Antananarivo and the main port city of Toamasina on the east coast. The project will consist of an open-pit mining operation and an ore preparation plant at the mine site. The slurried laterite ore will then be delivered via a pipeline to a process plant and refinery located directly south of the port of Toamasina.

Figure 1 and Figure 2 show the map of Madagascar and the project area respectively.

Figure 1—Map of Madgascar

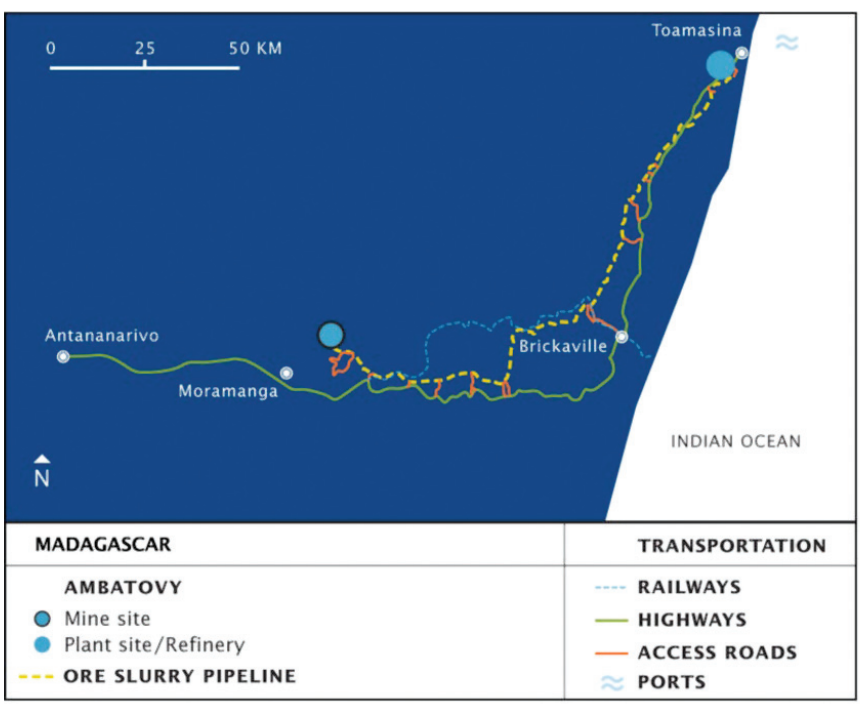

Figure 2—Ambatovy project location and access to port

Table II

Rating scales of the Ambatovy project

Category	Risk	Probability	Impact	Remarks
Technical risk	Reserve	Low	Low	Drilled: 1 282 holes, 54 888 m
	Completion	Medium	Medium	Period of construction: 36 months
	Production	Low	Medium	Utilizing globally proven technology
Economic risk	Price	Medium	High	Changes in the price range are large
	Demand	Low	Medium	Shortage of supply
	Foreign exchange	Low	Medium	Stable currency market forecast
Political Risk	Currency convertibility	Low	Medium	Low currency convertibility risk due to specialized law
	Environment	Low	High	EA approved by the government
	Tax	Low	Medium	Tax incentives due to specialized law
	Nationalization	Low	High	Low risk of nationalization

Development plan

Mineral reserves

- 125 million tones @ 1.04% Ni, 0.10% Co (0.8% nickel cutoff)
  - Additional 39.4 million tones @ 0.69% Ni, 0.064% Co
  - Potential to increase reserves with additional drilling.

Mining method

- 4 separate open pits
- Mine limonite and low magnesium saprolite 'LMS' after stripping overburden of 3 m from the surface
- Mine ore delivered by truck to ore preparation plant
- Ore then conveyed to scrubber where water is added to slurry the ore
- Slurry thickened and delivered to pipeline.

Transportation of ore

- Ore transformed in a slurry form at the Ore Preparation Plant is transported through the pipeline buried 1.5 m below the surface to the processing plant
- Pipeline is 220 km long and 600 mm in diameter
- Single pump station at mine site is installed to transport the slurry ore while using the gravity as a dragging force since the elevation difference is about 1,000 m.

Processing and refinery

- Project to utilize only proven metallurgical processes, all process unit operations can be found elsewhere operating on a commercial scale
- High Pressure Acid Leaching technique is used to produce nickel briquette and cobalt.
- This process is separated into two parts where pressure leach is applied to produce mixed sulphides and the stage where the mixed sulphides are smeltered and refined.

Capital expenditure (Capex): U$2,500 millions

Operating expenditure (Opex)

- Average Opex during 27 yrs of mine life
  - Ni - 1.99US$/lb (with credit, 0.97U$/lb)
- 10-year average after ramp-up period: operating expenditure
  - Ni - 1.75US$/lb (with credit, 0.77U$/lb).

Table III

Probability and impact scales of Ambatovy project

Scale	High	Medium	Low
Value	0.8	0.5	0.1

Determining the discount rate for the Ambatovy Project

Potential risks associated with the project are:

- Technical risk(reserve, completion, and production risk)
- Economic risk(price, demand, and foreign-exchange risk
- Political risk (currency convertibility, environment, tax, and nationalization). Effects of possible technical, economical and political risks on the project's schedule, budget, resources, deliverables, costs and quality are evaluated by the high-medium-low rating scales. The effects of potential risks on cost, revenue, time or scope are evaluated on the high-medium-low scale. Probability scales and risk impact scales of the Ambatovy Project are shown in Table II.

Determining risk values for the Ambatovy project

Numeric value needs to be applied in the probability and impact as explained in the previous section in order to calculate risk score of the project at the second stage. However, this process is very hard to carry out objectively with a view to calculating a value that represents a possible risk in the future.

Therefore, the quantitative risk analysis method was used to obtain the risk value of 0 and 1.0 for the probability and impact, as shown in Table III.

Table IV

Calculation of risk score of the Ambatovy project

Category	Risk	Probability	Impact	Risk score
Technical risk	Reserve	Low -0.1	Low-0.1	0.1×0.1 = 0.01
	Completion	Medium-0.5	Medium-0.5	0.5×0.5 = 0.25
	Production	Medium-0.5	Medium-0.5	0.5×0.5 = 0.25
Economic risk	Price	Medium-0.5	High-0.8	0.5×0.8 = 0.40
	Demand	Low-0.1	Medium-0.5	0.1×0.5 = 0.05
	Foreign exchange	Medium-0.5	Medium-0.5	0.5×0.5 = 0.25
Political risk	Currency convertibility	Low-0.1	Medium-0.5	0.1×0.5 = 0.05
	Environment	Low-0.1	Medium-0.5	0.1×0.5 = 0.05
	Tax	Low-0.1	Medium-0.5	0.1×0.5 = 0.05
	Nationalization	Low-0.1	High-0.8	0.1×0.8 = 0.08
Total				1.44
Sum of risk scores				1.44

Table V

Value and risk premium of the Amatovy project

Expected value	Value	Risk premium
4.46–6.40	High-high	20.0%
2.51–4.45	High	16.0%
1.51–2.50	Medium	12.0%
0.11–1.50	Low	9.0%
0–0.10	Low-low	6.0%

Calculating risk scores for the Ambatovy project

The risk, the probability, and the impact can be listed as individual components as shown in Table IV. Risk score can be calculated by multiplying the probability of the risk by the impact reviewed in the previous section.

Determining the discount rate for the Ambatovy project

The risk premium

To determine risk premium, an expected value (risk score) as calculated in the previous section has to be converted to an overall value and risk premium. An overall value and risk premium for the Ambatovy project was determined as shown in Table V.

The risk premium is calculated at 9.0 per cent since the risk score of the project calculated in the previous section is 1.44, which falls between 0.11 and 1.50.

The risk-adjusted discount rate

As seen in the previous section, the risk-adjusted discount rate can be assessed by applying the risk-adjusted discount rate formula shown below:

Risk-adjusted discount rate = risk-free rate of return + risk premium

- The risk-free rate of return – a 10-year bond that yields 1.2 per cent
- The risk premium – 9.0 per cent.

Thus, the risk-adjusted discount rate required for the Ambatovy project is 10.2 per cent.

Conclusions

The Ambatovy study clearly demonstrates how one can arrive at a discount rate after taking all risks into account. The inherent disadvantage of this approach is that the selection of the risk premium is subjective and hence the reliability of the method is often suspect. The risk-adjusted discount rate is not the final criterion for a decision to invest in a mineral development project under consideration, although it is generally one of the motivating factors considered by the firm's management. The attitude of investors to risk-taking is entirely subjective and very difficult to express in quantitative terms. Investors who are not particularly averse to risk tend to choose the low level of discount rate, whereas the more cautious and risk-averse investors will usually tend to select the medium level of discount rate. The decidedly risk-averse investors will usually opt for a high level of discount rate.

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Titanium: the innovators' metal—Historical case studies tracing titanium process and product innovation

by S.J. Oosthuizen*

Synopsis

This paper examines innovation in relation to the availability of a new material: the metal titanium. The paper aims to highlight the need for the inclusion of entrepreneurial innovation as a necessary focus area in the development of a titanium metal value chain. Both the Department of Science and Technology (DST) and the Department of Mineral Resources (DMR) have identified the creation of titanium metals production capabilities as a key growth area for South Africa. Using historical literature as a source of data, the activities of selected innovators who used titanium metal as a central component in their success, were investigated. The origin of the process innovation behind the titanium metals industry, and two titanium product innovations: namely, medical implants and sporting goods, were detailed as case studies. It was found that individual innovators were responsible for the creation, and rapid growth, of the titanium industry and titanium product applications. There is a need to link the current research and development into titanium metals production with individuals and organizations capable of commercializing innovative processes and products.

Keywords
titanium, kroll, hunter, sport, medical, defense, innovation, entrepreneur.

Introduction

South Africa has abundant marketable natural resources, and is notably a major exporter of titanium-bearing minerals and a minor producer of processed titanium dioxide—used as pigment. When it comes to high-end titanium products, South Africa has no titanium metals industry and only limited capacity in titanium fabrication[1,2].

Titanium is a modern metal, commercially available only since the 1950s. Titanium has the strength of the best steels at only half the weight, is widely resistant against corrosion, and is biocompatible. Titanium is elastic and tough, hardly expands with increasing temperatures, and can withstand cold without becoming brittle. Importantly, for processing: it can be rolled, forged, and welded. Today titanium is associated with several technological advances in for example, medicine, and the aerospace and chemicals industries[2,3].

The establishment of a local titanium metal industry is a science and technology priority area for South Africa, with sustained efforts by government to support titanium-related research and development. The Department of Mineral Resources launched the Draft Beneficiation Strategy[4] for the minerals industry in South Africa in Midrand on 31 March 2009, which views the development of the titanium value chain (i.e. production of titanium pigment, metal, and downstream fabrication) as a potential key growth area for South Africa. Key points of the strategy aim at the development of a proprietary low-cost titanium metal production process, and the continued development and commercialization of technologies to compete cost-effectively in international titanium markets[4].

Considering that the national strategy for titanium is to markedly change existing technology, and to bring about an industrial revolution in low-cost titanium metal and products at both the national and international scale, it is deemed important to adequately understand the factors involved in the success of such innovations.

An aim of this paper is to introduce and highlight the function of individual innovators, who may be required to fully exploit new opportunities associated with the sudden availability of a new material, and to ultimately trigger significant positive socio-economic developments. The aforementioned aim is to be achieved through the identification

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and study of the entrepreneurs and innovators who, having made use of titanium, established associated markets and rapidly grew new ventures.

The reader should note that there is mention of research and development conducted in South Africa towards the establishment of an innovative low-cost titanium production process, i.e. the industry-sponsored South African Titanium/Peruke process, and DST supported development of CSIR titanium processes. The current strategic focus is therefore on process innovation: however, the delivery of low-cost titanium via an innovative process is also expected to unlock the potential for numerous product innovations, initially projected to be used in architectural and automotive applications. No further distinction is made between the unique requirements for process innovation, as per the first case study, and product innovations as discussed in the final two case studies.

The present article aims to address the following research questions:

- ➤ Does history indicate a relationship between the availability of a new material and technological advancement?
- ➤ Is there evidence to suggest that individual innovators were of primary importance in the establishment of markets for titanium?
- ➤ Can it be reasoned that South African strategy for titanium beneficiation should include efforts to develop and support innovation and entrepreneurship in this field?

Findings are presented in the form of distinct historical case studies, individually broadly outlining the emergence of the titanium metals industry and specific markets. This research is conducted to build a framework for the understanding of process and product innovation in the establishment of a titanium value chain. Such a framework may serve to assist decision-makers, researchers, and innovators in the identification and exploitation of opportunities for South African produced titanium and titanium products.

This paper has four parts. Firstly, it presents the method used in data gathering and building of case studies. Then a background section sets out to (a) establish the relationship between the availability of a new material and technological progress, (b) provide a brief overview of the metal titanium, and (c) infer the need for innovation and entrepreneurship in the creation of a new industry and markets for titanium. Thirdly, case studies are presented to establish the relationship between the innovator, innovation, and resulting industry/market for titanium. Finally conclusions are made and directions for future research suggested.

Method

For data on the relationship between titanium, innovation, and entrepreneurship, a literature search was conducted peer-=reviewed journal articles using combinations of the keywords Entrep*, Innova*, and Titanium. A study was also made of publications covering the history of the titanium industry, industry-standard market reports, as well as academic publications covering innovation. Case studies were compiled from publicly available secondary data.

From the initial literature search, the origin of the titanium industry and two well-documented and generally accessible titanium markets, namely medical implants and sporting goods, were selected for further analysis. In each of the two selected markets, details of the most prominent innovators and their respective applications of titanium were compiled as case studies. Literature searches were conducted in a reverse time-wise manner, starting with the most modern publications and tracing the history of titanium-based innovation to inception.

Background

Danish archaeologist and museum curator Christian Thomsen in 1816 defined the Stone, Bronze, and Iron Ages in an attempt to organize his museum's artefacts. In so doing he classified the stages of human development by the level of complexity of the materials employed. The fact that this method of classification has stood the test of time hints at an intimate connection between a society's level of advancement and the mastery of materials at its disposal. Thomsen's 'Three Age' system can be said to describe prehistoric variations of periods of technological revolution[5].

Austrian-born Professor of Economics at Harvard University, Joseph Schumpeter (1883-1950) identified cycles of technological advancement within modern history (Table I). These economic cycles were named after the Russian economist Kondratieff, who first proposed such cyclical activity. As with Thomsen's 'Three Age' system, each Kondratieff cycle can generally be associated with materials playing distinctive roles in shaping the respective technological revolution[6]. Similarly, the discovery and utilization of titanium can be seen to contribute to the characteristics of the modern technological age.

Table I

Schumpeter's Kondratieff cycles[6]

Cycle	Description	Material(s)
First Kondratieff (1780s–1840s)	Industrial Revolution: factory production for textiles	Cotton
Second Kondratieff (1840s–1890s)	Age of steam power and railways	Iron/coal
Third Kondratieff (1890s–1940s)	Age of electricity, chemicals and steel	Steel
Fourth Kondratieff (1940s–1990s)	Age of mass production of automobiles, petrochemicals and synthetic materials, Aerospace	Oil, Synthetics, Light Metals
Fifth Kondratieff (late 1990s)	Age of information, communication, and computer networks.	Semiconductors/silicon chips, composites and 'space age' materials

Titanium

As the fourth most abundant metal in the earth's crust, titanium ore is plentiful and widely dispersed over the planet. South Africa is currently the second largest producer of titanium-bearing minerals in the world, contributing 22% of the global output of roughly 6 million tons per annum[1].

Titanium has distinct physical and chemical properties which allow several industrial sectors to benefit from its application. Titanium's high strength to weight ratio is attractive to the aerospace and transport industries, its excellent corrosion resistance makes it an obvious choice in the chemicals, petrochemicals, and maritime industries, and biocompatibility allows for numerous medical applications[2,3,7].

Currently 95% of the titanium bearing minerals mined annually is used in the manufacturing of paints (TiO_2 pigment), paper, and plastics[1], and only 5% is converted to titanium metal[2]. The relatively small size of the titanium metals industry is due primarily to the difficulty and cost of commercial extraction and processing of the metal[2]. Illustrating this struggle to isolate the metal is the fact that, even though titanium was discovered in its mineral form in 1791 by English clergyman William Gregor, it was not until 1910 that the first small amounts of pure titanium metal were produced. Only as late as 1948 was a process finally commercialized, allowing limited-scale batch-wise production of the metal[8].

Titanium is not being utilized in the full range of potential applications, mostly due its high cost relative to aluminium and steel. Much of titanium's cost is due to the expensive and inefficient processes used in its production. Interestingly, a number of research projects in the pursuit of low-cost titanium production are supported/funded by the US military, with the goal to produce e.g. light, corrosion-resistant ships and armoured vehicles. Should production of low-cost titanium become possible, there is much potential for it to compete with e.g. the stainless steel mass market in most applications[2,3,7]. This potential is also acknowledged in South African efforts to develop cost reduction technologies for titanium processing[4].

Table II

Titanium Time Line[7]

Date	Event
1790	Rev Gregor discovers titanium in mineral form
1887	First preparation of impure titanium (Ti) metal
1910	Small amounts of Ti metal produced for General Electric.
1940s	Kroll develops process to commercially produce Ti metal
1950s	Ti used mostly in military aircraft/defence applications
1970s	Increase in orders for commercial aircraft and Ti market expansion
1980s	Ti increasingly used in medical implants
1990s	Ti increasingly used in sports and consumer goods applications
Present	Ti increasingly used in architecture, automotive, chemicals, etc.

The entrepreneur as Innovator

A key process in economic change, growth, and development is the process of innovation. Innovation can be defined as the exploiting of inventions to enable their trade in a marketplace[6]. Schumpeter[9] is credited with being the first to posit that cycles of economic growth and development did not simply occur, but required the entrepreneur as the prime mover, whose function is to innovate, or to carry out new combinations. Venkaraman[9] proceeds to quote Schumpeter at length, who stated that: '…the function of entrepreneurs is to reform or revolutionize the pattern of production by exploiting an invention or, more generally, an untried technological possibility for producing a new commodity or producing an old one in a new way, by opening up a new source of supply of materials or a new outlet for products, by reorganizing an industry and so on… This kind of activity is primarily responsible for the recurrent 'prosperities' that revolutionize the economic organism and the recurrent 'recessions' that are due to the disequilibrating impact of new products or methods'.

Schumpeter was not alone in identifying the entrepreneur as a central driving force in innovation; Herbig, Golden, and Dunphy[10] stated that 'Entrepreneurs and innovation go together like the proverbial horse and carriage. Entrepreneurs seek opportunities and innovations often provide the instrument for them to succeed.' The entrepreneur 'leveraging business and scientific knowledge… is therefore the linchpin of innovation, and if a society or locale wishes to generate innovation (either low or high technology), it is in a society's best interests to create an environment conducive to the entry and maintenance of entrepreneurs and the associated small new ventures that they produce.'[10]

There have been several instances where government/ public enterprise acted as the drivers of innovation, usually in cases of capital-intensive developments. Notably, initial efforts towards the commercialization of titanium were made by the US government[9]. Similarly, the South African Department of Science and Technology, via the Advanced Metals Initiative (AMI), intervenes to progress development of advanced metals capabilities in South Africa. While acknowledging its vital role and importance, government-led innovation falls outside of the scope of the present article, which aims to focus on the contributions of individual innovators.

Case studies

The initial attempt at titanium innovation

In 1910 the General Electric Company (GE) was searching for a material to replace the short-lived graphite filaments used in the incandescent light bulbs of the day. The importance of filament materials in GE's overall success cannot be adequately measured, but according to Friedel and Israel[11] there were up to 22 other inventors active in the field of electric lighting at the time when GE's founder and classical entrepreneur, Thomas Edison, achieved a significant competitive advantage.

Edison made the discovery that a bamboo filament that had been carbonized could last up to 1200 hours, and could therefore be commercialized. As the original filament was patented in the 1880s, by 1910 GE realized that to maintain competitive advantage, they needed to lead, or keep up with, research into metallic filaments[8,11].

Of primary importance to metallic filament construction was the metal's melting point, and since titanium had yet to be extracted in commercially viable metallic form, its properties were unknown. GE was hoping that titanium metal would withstand the operating conditions required in a long-life filament. Titanium was found to melt at 1668°C by metallurgist Matthew Albert Hunter, who extracted the first samples. The process used by Hunter, using sodium metal to reduce titanium tetrachloride to titanium metal[7,8], still bears his name.

Rather than joining the Third Kondratieff as a critical part of Thomas Edison's light bulb, titanium was abandoned for the metal tungsten, which has a much higher melting point (3422°C). It took almost a further three decades before titanium found its primary innovator. GE can, however, be mentioned as a prominent part of the Third Kondratieff, that of electricity, chemicals, and steel, and has grown to be the 10th largest company in the world (in terms of market capitalization) with a published net income in 2007 of 22.2 Billion US dollars[12].

Case Study 1—William Kroll, titanium process innovator

In her book *Black Sand: The History of Titanium*, Kathleen Housley[8] provides numerous facts from history of the development of titanium metal. The book dedicates a number of chapters to discuss the work of William Kroll (1889–1973), a Luxembourg metallurgist who is today known as the father of the metallurgical processes for the production of zirconium and titanium. Kroll was already a seasoned metallurgist when he set up his private laboratory in 1923 in the city of Luxembourg at the age of 34. His first production of titanium via the Hunter process was in September 1930. In 1932 he travelled to America where he attempted to interest the likes of GE and Bell Telephone in the metal, without success. Steel was widely used, since it was in sufficient supply and produced commercially at costs that did not warrant interest in the new metal, titanium.

Kroll returned to his laboratory and started work on developing a new production method to replace the Hunter process, which was deemed explosive and not entirely suitable for commercialization. In 1938 Kroll manufactured titanium via a process using magnesium to reduce titanium tetrachloride[13]; the patented process still bears his name. In the same year Kroll made another visit to the USA in an attempt to interest companies in the metal, but again failed in attracting support from industry to commercialize his process[8].

In 1940, in order to escape the invasion of Luxembourg by the advancing German army, Kroll fled to America. Aged 50 and armed with only patents to his name and his personal belongings, Kroll started over in the USA. Due to World War II, the US congress tasked the US Bureau of Mines to secure and stockpile strategic and critical materials. Among these materials were titanium and zirconium, both of which could be produced via Kroll's patented process. Kroll was approached and offered employment by the Bureau of Mines, which he took up in January 1945. Within two years the Bureau had produced two tons of titanium via the Kroll process[8]. The Kroll process is widely known to be costly and inefficient; however, to date no other process has been able to supplant it, and nearly all international production of titanium metal still occurs via the Kroll process[2,3].

Since becoming commercially available, the largest industrial application for titanium alloy remains the aerospace sector[2,3]. To survive in these harsh environments, the materials from which aerospace components are made must have high strength and be capable of surviving high temperatures in an oxidizing environment with severe acoustic loads. However, the materials should have low density and, for most applications, must be reusable[14]. Titanium is therefore ideally suited for aerospace applications. It can be argued that, were it not for Dr Kroll's push to develop and commercialize a viable process for titanium production, the aerospace age might have lacked a component critical to its rapid development.

Case Study 2—Per-Ingvar Brånemark,titanium product innovator

Titanium is well documented as being biologically inert, primarily due to its resistance to corrosion; however, factors such as being non-allergenic and non-toxic also enable the 'fit and forget' attitude to titanium implants[15,16]. Being non-magnetic, titanium also interferes less with a form of medical scanning called magnetic resonance imaging (MRI), where even the low ferromagnetic properties of surgical steel could lead to distorted images[17].

The most important aspect of titanium's application in medicine was, however, discovered by chance. Working at Lund University in the 1950s, Dr. Per-Ingvar Brånemark used an ocular piece inserted into a rabbit's ear to visually study bone healing. It was found that after completion of the study that the costly instrument, constructed out of titanium, could not be extracted. Titanium was found to integrate and be structurally accepted by bone, leading Dr Brånemark to call the discovery 'osseointegration'. This property is virtually unique to titanium[18].

The use of titanium at the time of the discovery was coincidental, in Dr. Brånemark's own words: 'By coincidence, an orthopaedic surgeon, Hans Emneus, in Lund, was studying different metals used for hip joint prostheses. At that time I happened to meet him and he indicated a new metal, titanium, from Russia used in nuclear industry, that might be optimal. I managed to get a sample from Russia via Avesta Jernverk, Director Gauffin, and from there on it has been pure titanium. Initially we tried tantalum, which was too soft.'[19]

Dr Brånemark sought to take his discovery to the market and approached relevant technology companies to assist in the commercializing of titanium implants. In 1978 Swedish chemicals and defence company Bofors agreed to partner with Dr Brånemark to develop his implants. Bofors Nobelpharma (later Nobel Biocare) was founded in 1981. In 2008 Nobel Biocare achieved turnover of 619 million EUR and gross profit of 374 million EUR[20].

Considering that NobelBiocare was officially started in 1981, but the innovation that the company is built on had been under development since the early 1960s[16], it took around 20 years for Dr Brånemark to commercialize his discovery. Dr Brånemark's mentioned that a primary reason for this was that osseointegration was looked upon with mistrust, which prevented penetration of the idea[16]. Without Dr Brånemark's persistence the market for medical titanium implants might still have been dominated by less efficient materials.

Dr Brånemark's innovation led to the establishment of vibrant new markets, Sweden is today known as having one of the leading clusters of biomaterials companies in the world, where Rickne[21] reported establishment of 25 new companies in the field in the period 1978–1993.

Titanium is also utilized by some of the leading US biomaterials companies, such as world-leading spinal implants company AcroMed of Ohio, which was founded in 1983 by spine surgeon A. Steffee and businessman E. Wagner. Acromed's time from invention to innovation took around two years; however, it can be argued that osseointegration was already well researched at that stage[16]. Competing with the Swedish cluster, in the period 1978–1998 the US state of Massachusetts saw the founding of 30 biomaterials companies, followed by Ohio with 18 companies in the same period[16].

Case Study 3—Ely Callaway, titanium product innovator

Titanium is 40% less dense (mass per unit volume) than steel, yet it possesses a higher strength-to-modulus ratio than steel. The combination of titanium's weight advantage and its improved impact resistance and spring-back following loading has brought forth innovations such as titanium bedsprings, tennis racquets, and fishing rods[22]. One of the largest and fastest growing consumer markets for the metal, however, came from its use in golf clubs.

Ely Callaway, retired president of multinational textiles firm Burlington, founded Callaway Vineyard and Winery in southern California, which he sold in 1981 for $14 million. Aged 60, Callaway went on to establish The Callaway Golf Company in 1983[23]. In 1994, Callaway Golf went to market with a golf club incorporating titanium in its construction. With the 'Great Big Bertha' titanium driver, Ely Callaway promised 'a driver that is not only easier to hit for distance without swinging harder, but significantly more forgiving of off-center shots'[23].

Optimal golf club head design requires the use of a metal/alloy having the best combination of high modulus of elasticity and high strength-to-density ratio; Dahl, Novotny, and Martin[24] asserted that such attributes allows for a larger 'sweet spot' (centre of percussion) without adding unacceptable weight. The combination of an enlarged center of percussion and increased energy transfer enables the golfer to drive the ball a greater distance and straighter, without swinging harder.

The use of lighter weight titanium is also said to have opened up the market for female golfers, who were reported to have problems with the heavier stainless steel clubs[23]. Froes[25] noted that by 1999, in the driver and woods segment of the market 40% of the clubs produced were made of titanium, 59% of stainless steel, and 1% other materials; and amongst producers in this segment, Callaway had achieved market leadership (42%) followed by Taylor Made (35%).

Table III

US Titanium-metal woods sales[25]

Year	Clubs sold (millions)
1994	~500 clubs
1995	0.19
1996	1.16
1997	1.72

The reason for titanium drivers not completely dominating the market was price; titanium drivers were sold for prices upward of $500 in the USA and in the range of $600-$1800 in Japan, which was comparable to an entire set of standard golf clubs[25].

The popularity and cost of the drivers were such that in 1998 an organized gang of robbers started to target golf stores, specifically stealing Callaway Great Big Berthas and Biggest Big Bertha drivers. In two months the gang had broken into 25 golf stores and stolen an estimated 1 500 Callaway drivers and other woods[26].

In 2000, the US Golf Association (USGA) which oversees golfing competition in the United States, banned one of the Callaway club designs, the ERC club, based on their evaluation that its titanium head provided unfair advantage[27].

In an interview with Englade[23], Ely Callaway said: 'We went from the smallest golf company in the country in 1983 to the largest in 1995… It all was done on product. We make products that are the most rewarding in the world, products that are demonstrably superior to and pleasingly different from our competitors'. In 1997, Ely Callaway was inducted into Babson College's Academy of Distinguished Entrepreneurs[28]. Callaway Golf declared a $1.117 billion turnover and a gross profit of $486.8 million in 2008[29].

In what has been dubbed the Starbucks Effect[30], it has been observed that a trendy product can benefit the related market segment. The 1990s subsequently saw rapid growth in the overall use of titanium in the field of sport and recreation[31]. Beech *et al.* reported on the trend favouring titanium sporting equipment, observing that:

- The Mongoose Pro RX 10.7 bicycle's titanium frame weighed only three pounds, the high resilience imparted by the titanium frame was said to absorb shock better than other materials in use at the time
- Merlin VI SL titanium skis from K2 were both lightweight and claimed to produce less 'chatter' at speed than standard fibreglass and wooden skis, due to resiliency and durability of titanium
- Wilson's titanium line of golf balls reportedly increased ball sales by 50%. Wilson claimed that the titanium core offered a larger sweet spot, decreasing hooks and slices by three to four yards
- In October 1997 sporting company Head brought to market the titanium/graphite Ti.S2, which became the top-selling tennis racket worldwide.

Conclusions

This article investigated individual innovators and their use of a new material, specifically titanium, to establish new industries and markets.

History points to a relationship between availability of a new material and increased potential for technological and economic development. This relationship also proves to be accurate for the history of the development and commercialization of titanium metal and subsequent technological advances. Theory of innovation makes note of the entrepreneur, seen to be a driving force behind innovation. Entrepreneurs can be observed to e.g. innovatively use new materials, thereby causing technological change and economic growth.

The requirement for an innovator to unlock the potential of a new material has been shown in the histories of some of the leading figures in titanium production and applications: William Kroll, Per-Ingvar Brånemark, and Ely Callaway. From the case studies presented, it can be argued that without these individuals the required process and product innovations may not have occurred, and that the aerospace, medical implant, and sporting goods markets may not have undergone the revitalization and rapid growth set off by the introduction of titanium.

It is reasonable to expect that similar efforts will be required in the commercialization of the titanium technologies developed in South Africa's drive to beneficiate its titanium resources and create a titanium value chain.

The study is limited by the inclusion of only three successful and popularly published instances of innovation in titanium, and therefore cannot be considered conclusive. An investigation into the workings and potential integration of South African structures and systems for the development and support of entrepreneurship and innovation in advanced metals is perceived to be a valuable direction for further research.

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The relationship between the aspect ratio and multi-physical fields in aluminium reduction cells

by H. Zhang*, J. Li*, Y. Lai*, W. Liu*, Y. Xu*, Z. Wang*, and X. Zhang*

Journal Paper

Synopsis

The relationship between the aspect ratio and physical fields in aluminium reduction cells wase studied numerically. The aspect ratio was firstly defined and 7 kinds of 320 kA cells with different aspect ratios were put forward. By using numerical simulation, the relationship between the aspect ratio and the electric-magnetic flow fields, magnetohydrodynamic stabilities, and thermal stability was discussed. It is concluded that the electric-magnetic flow field distributions are greatly affected by the aspect ratio. From the perspective of magnetohydrodynamics stability, the larger the aspect ratio is, the more stable the cell will be. A larger aspect ratio is more beneficial for the thermal stability under the same current density.

Keywords

aluminium, electrolysis, aspect ratio, electric-magnetic flow fields, magnetohydrodynamics, thermal stability.

Introduction

Spatial dimension is one of the key parameters in aluminium reduction cells. It not only determines the distributions of multi-physical fields, such as electric-magnetic flow fields, magnetohydrodynamic (MHD) stability, and thermal stability, but also influences the cell structure and operation technology. Compared with the cell height, the cell length and width are more important, because they closely relate to the current density and also determine the economic and technical characteristics of the cell.

In the 1990s, the effects of aspect ratio (length width ratio) had been mentioned by researchers, but not studied as a key point. Sneyd[1] studied the stabilities of aluminium reduction cells by means of mode-coupling. His results indicated that an aspect ratio of about 7.7/3.0 maximizes frequency separation, but not all potential resonances actually lead to instability. Ziegler[2] studied the relationship between the instabilities of K-H (Kelvin-Helmholtz) and critical velocity, and found that the critical velocity was greatly influenced by the cell length and width. However, in this investigation, the cell length and width were set at 11.30 m and 3.08 m respectively, which mean that there were no discussions about the relationship between the aspect ratio and critical velocity. More recently in China, Yao[3] studied the instabilities of the GY320 cell and pointed out that the aspect ratio of the GY320 was 4.33, which is smaller than that of Pechiney AP-30 but larger than that of the 400 and 500 kA cell designed by Dupuis, and the cells would be more stable if the anode in GY320 was modified to 1.60 m × 0.80 m. In a word, the aspect ratio is an important parameter in an aluminium reduction cells but little research work has been done to date.

The spatial structure of the reduction cell is very complex. Altering the aspect ratio will lead to a change in the cell structure and eventually a change in physical fields. Using currently available techniques for modelling multi-physical fields in reduction cells, it is very difficult to construct cell models that can incorporate significant structural changes. This is why there are very few investigations of aspect ratio. Fortunately, in our research group, a fast modelling method has been established for constructing multi-physical fields simulation models, which could be used to study the effect of aspect ratio on physical fields in aluminium reduction cells.

The objective of this investigation was to study the relationship between the aspect ratio and physical fields numerically. In this paper, the definition of aspect ratio is given firstly, and then seven cells with different aspect ratios are designed. The relationship between the aspect ratio and electric-magnetic flow fields, MHD stabilities, and thermal stabilities is then discussed.

* *School of Metallurgical Science and Engineering, Central South University, Changsha, China.*

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Definition of aspect ratio and the research scheme

The aspect ratio (AR) of an aluminium reduction cell can be defined as:

$$AR = \frac{L}{W} \quad [1]$$

$$L = w_a \times n + g_a \times (n-1) \quad [2]$$

$$W = l_a \times 2 + g_c \quad [3]$$

where w_a is the width of the anode, g_a is the inter-anode channels width, n is half of the total anode number, l_a is the length of the anode, and g_c is the centre channel width.

Table I lists the structure parameters of several types of prebaked cell technologies being used in the aluminum industry. For 300 kA cells, the current densities are between 0.73~0.82 A·cm^{-2}, and the AR between 3.96~4.26; while for 320 kA cells, the parameters are 0.70~0.84 A·cm^{-2} and 3.56~5.44 respectively, 0.71 A·cm^{-2} and 5 for 350 kA cells; and 0.82 A·cm^{-2} and 4.02 respectively for 400 kA prototype cells. This indicates that there are dramatic differences in spatial structure for different cell types. Obviously, the AR of cells will affect the electric-magnetic flow fields, the MHD instabilities, and thermal equilibrium. The relationships between AR and multi-physical fields need to be discussed.

In this article, we construct models of 320 kA cells with different ARs. In order to ensure that AR is the only variable, the influences of AR on physical fields were analysed under the same current density and other technological parameters.

The detailed structure parameters of the seven designed cells are shown in Table II. The relationship studied in this article include the following:

- Distribution of electric-magnetic flow field in a 320 kA with AR changed from 3.2 to 5.4 cell at a current density of 0.71 A·cm^{-2}.
- MHD stabilities for all the cells in Table II.
- Qualitative analysis of thermal stabilities.

Since there are various kinds of busbar configuration for each cell and the difference between them can be significant, two problems will appear when considering the busbar in this paper. Firstly, it is difficult to decide which busbar configuration is the optimal; secondly, building the busbar model it is time-consuming. In comparison, the distributions of electric-magnetic flow fields caused by the internal conductors are more analogous and easier to model with good comparability. Therefore, in this article, the influences of busbar configurations are not included.

The multi-physical field modelling scheme is shown in Figure 1. The electric-magnetic models were developed with ANSYS by using the parametric design language, the computational domains were discretized by millions of eight-node hexahedral elements, and then the electric-magnetic fields were resolved using the finite element method. Multi-phase flow models were established with CFX by introducing

Table I

Structure parameters of several types of prebaked cell technologies[3–7]

	Marc-400	Alcoa-817	AP-30	VAW-300	SY-350	GY-320	GP-320	QY-300
Amperage, kA	400	320	320	300	350	320	320	300
Current density (ρ), (A·cm^{-2})	0.817	0.843	0.821	0.732	0.707	0.714	0.697	0.733
Number of anodes	36	32	40	32	24	40	48	40
Length of anodes, m	1.700	1.625	1.500	1.600	1.550	1.600	1.450	1.550
Width of anodes, m	0.800	0.730	0.650	0.800	1.330	0.700	0.660	0.660
Interanode channels width, mm	40	28	40	40	40	40	40	40
Centre channel width, mm	350	150	80	180	180	180	180	180
Length of cell (L), m	15.080	12.100	13.760	13.400	16.400	14.760	16.760	13.960
Width of cell (W), m	3.750	3.400	3.080	3.380	3.280	3.380	3.080	3.280
Aspect ratio	4.02	3.56	4.46	3.96	5	4.36	5.44	4.256

Table II

Structure parameters of designed prebaked cell technologies (I=320 kA)

	AAR1	AAR2	AAR3	AAR4	AAR5	AAR6	AAR7
Current density, A·cm^{-2}	0.714	0.714	0.714	0.714	0.714	0.714	0.714
Number of anodes	32	36	40	40	40	44	48
Length of anodes, m	1.868	1.776	1.620	1.600	1.580	1.570	1.430
Width of anodes, m	0.750	0.700	0.691	0.700	0.709	0.648	0.650
Interanode channels width, mm	40	40	40	40	40	40	40
Center channel width, mm	180	180	180	180	180	180	180
Number of cathodes	21	23	27	27	27	27	31
Length of cathodes, m	0.565	0.540	0.515	0.515	0.517	0.525	0.505
Width of cathodes, m	3.956	3.772	3.460	3.420	3.380	3.360	3.080
Intercathode channels width, mm	39	41	28	35	40	37	30
Anode side distance, mm	280	280	280	280	280	280	280
Anode end distance, mm	390	390	390	390	390	390	390
Length of cell, m	12.600	13.280	14.580	14.760	14.940	15.096	16.520
Width of cell, m	3.916	3.732	3.420	3.380	3.340	3.320	3.040
Aspect ratio (AR)	3.22	3.56	4.26	4.37	4.47	4.55	5.43

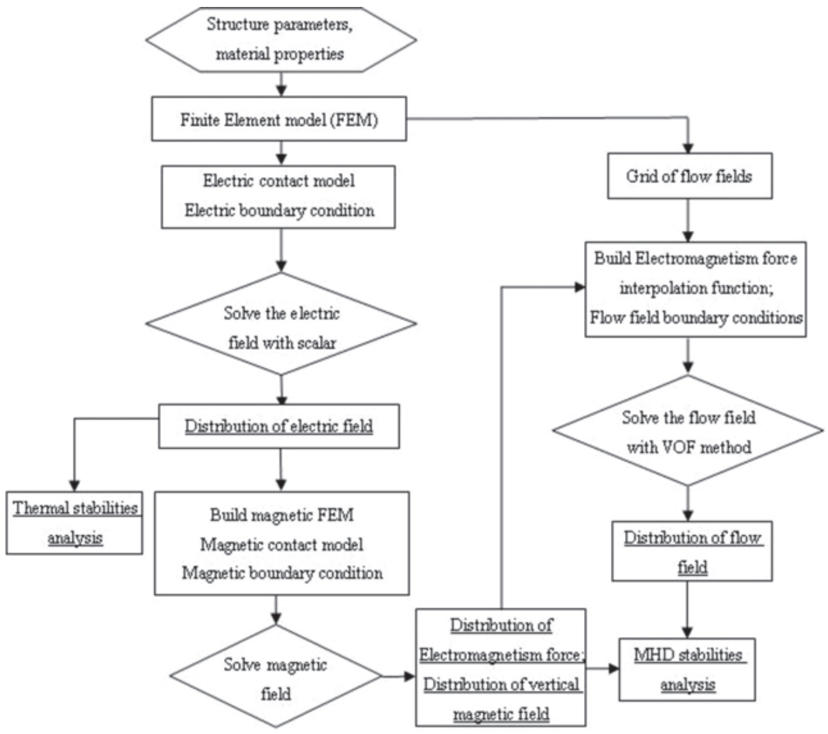

Figure 1—Flow chart of the research scheme

the electric-magnetic forces which were predicted by the electric-magnetic computation, and the flow fields were resolved using the finite volume method based on the SIMPLEC algorithm. The MHD stability equations are basically consistent with those developed by Urata[8,9], Bojarevics[10] and Droste[11], while in the solutions with a Fourier expansion method, the surface fitting functions based on the least-square method were built to introduce discrete electric-magnetic results calculated with ANSYS. The detailed methods in multi-physical fields modelling designed by our research group can be found in[12–14], and a 3D geometry modelling of the reduction cell corner used in the models is presented in Figure 2.

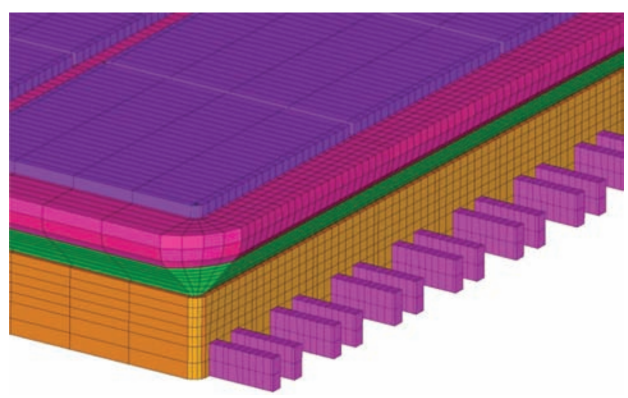

Figure 2—3D modeling of the reduction cell corner

Relationship between the AR and multi-physical field distributions

Electric field distributions

When I = 320 kA and ρ = 0.714 A·cm^{-2}, the voltage of the system, anode, and cathode under different ARs is shown in Figure 3, which indicates that the anode, cathode, and system voltage drops decrease with increasing AR.

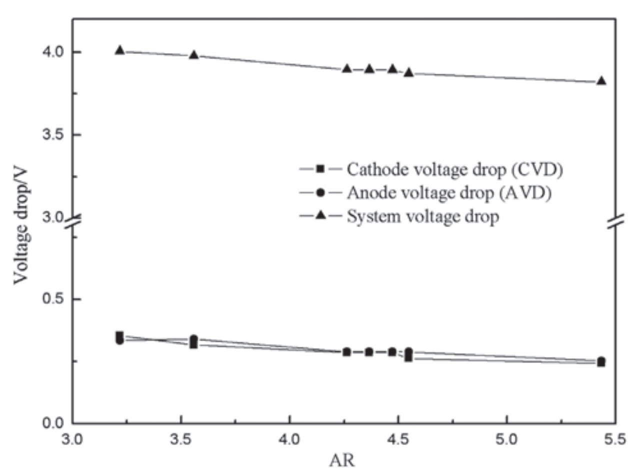

Figure 3—Voltage drop versus AR with I = 320 kA and ρ = 0.714 A·cm^{-2}

Magnetic field distributions

Figure 4 shows the magnetic field component of the cells with different ARs. It can be seen that the magnetic field component and total magnetic field decrease with increasing AR under constant current density.

Flow field distributions

Figure 5 shows the horizontal velocity vector distributions in the metal pads of AAR1, AAR2, AAR4, and AAR7 cells. It

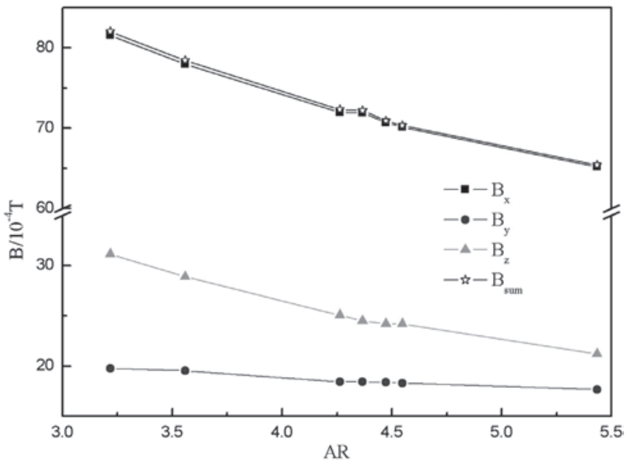

Figure 4—Maxmium magnetic field value versus AR with I = 320 kA and ρ = 0.714 A·cm^{-2}

can be seen that there are four vortices in the metal pad under symmetrical electric-magnetic forces, and the velocity in the middle is smaller than in the end and tape areas. The maximum velocities in AAR1, AAR2, AAR4, and AAR7 cells are 13.11 cm·s^{-1}, 11.31 cm·s^{-1}, 9.76 cm·s^{-1}, and 6.16 cm·s^{-1} respectively, and the average velocities are 3.04 cm·s^{-1}, 2.39 cm·s^{-1}, 1.94 cm·s^{-1}, and 1.12 cm·s^{-1} respectively, which means that the velocity is decreasing with increasing AR, as shown in Figure 6.

According to the electric-magnetic field results from our models, when the AR increased, the horizontal current density will decrease and the vertical current density will increase by almost the same amplitude; therefore the horizontal electric-magnetic force, which is the main driving force of the aluminium, electrolysis will also decrease since the horizontal magnetic field is much larger than the vertical. As a result, the peak and average velocities will decrease.

MHD instabilities

Using the surface-fitting method, the vertical magnetic field component was transformed from a discrete value and resolved with ANSYS to a continuous function that would be used in MHD instability analysis based on a Fourier expansion method.

Figure 7 show the oscillation spectrograms of the seven cells. It can be seen that the oscillation stabilities improve as the AR increases. One of the reasonable explanations is that the vertical magnetic field is smaller for cells with a larger AR, although the magnetic fields distribution is similar for all the cells studied in this paper.

In Figure 7(a), the red triangle symbol at y=0 represents the natural frequencies of the gravity wave, which indicates that the oscillations caused by gravity wave are quite stable.

Thermal stabilities

Beran[15] proposed the following equation to calculate the heat loss per unit current:

$$Q/I = V_{sys} - 1.649\eta - 0.48 \quad [4]$$

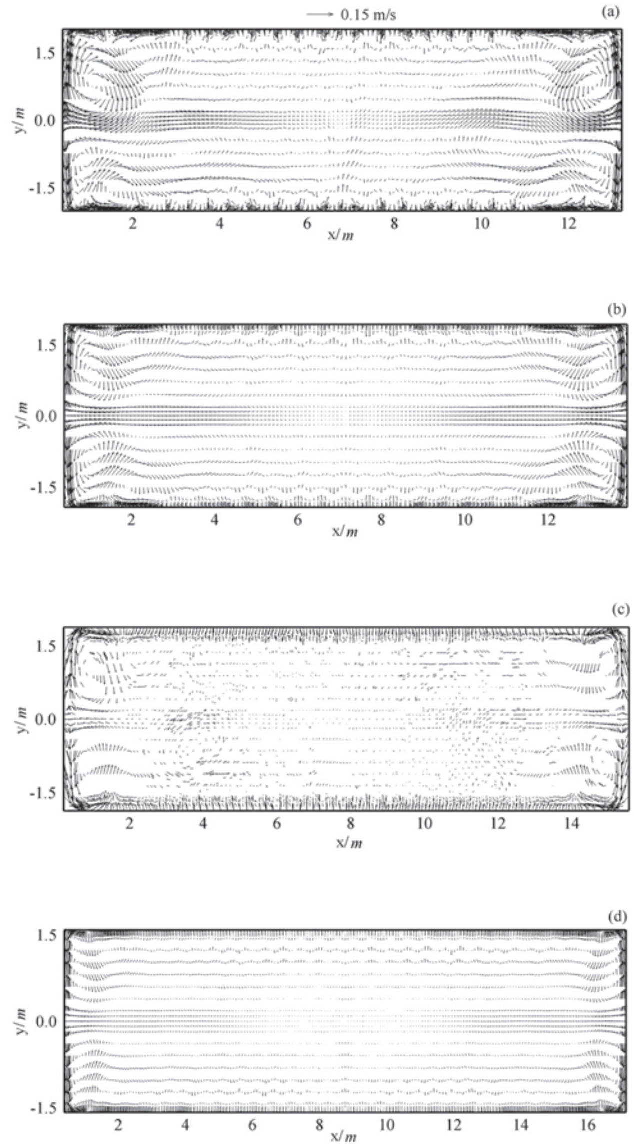

Figure 5—Velocity field in aluminum layer, (a) AAR1 (V_{max} = 13.11 cm·s^{-1}, V_{avg} = 3.04 cm·s^{-1}), (b) AAR2 (V_{max} = 11.31 cm·s^{-1}, V_{avg} = 2.39 cm·s^{-1}), (c) AAR4 (V_{max} = 9.76 cm·s$^{-1,}$ V_{avg} = 1.94 cm·s^{-1}), (d) AAR7 (V_{max} = 6.16 cm·s-1, V_{avg} = 1.12 cm·s^{-1})

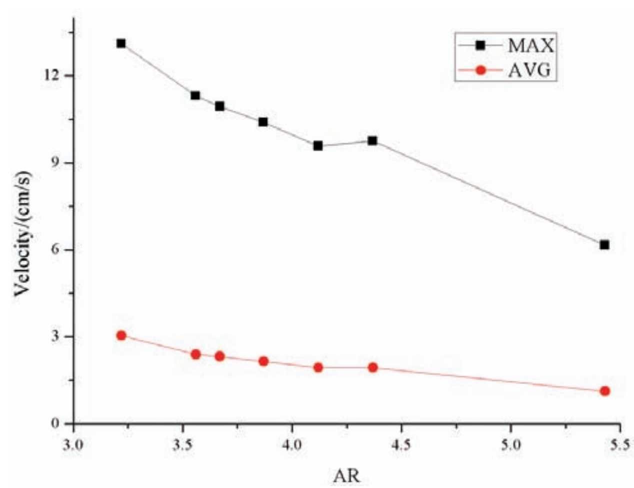

Figure 6—Velocity versus AR

where V_{sys} is the system voltage and η is the current efficiency. It indicates that as long as the current efficiency and system voltage stay the same, the heat loss is a constant for all cells even when the capacity of the cell varies.

Increasing the AR can enlarge the surface area of cells. Figure 8 shows the heat loss intensity per unit area for different ARs. It suggests that the bigger the AR is, the lower the heat loss intensity is, and consequently the lower the sidewall temperature will be, which is beneficial for the formation of the ledge.

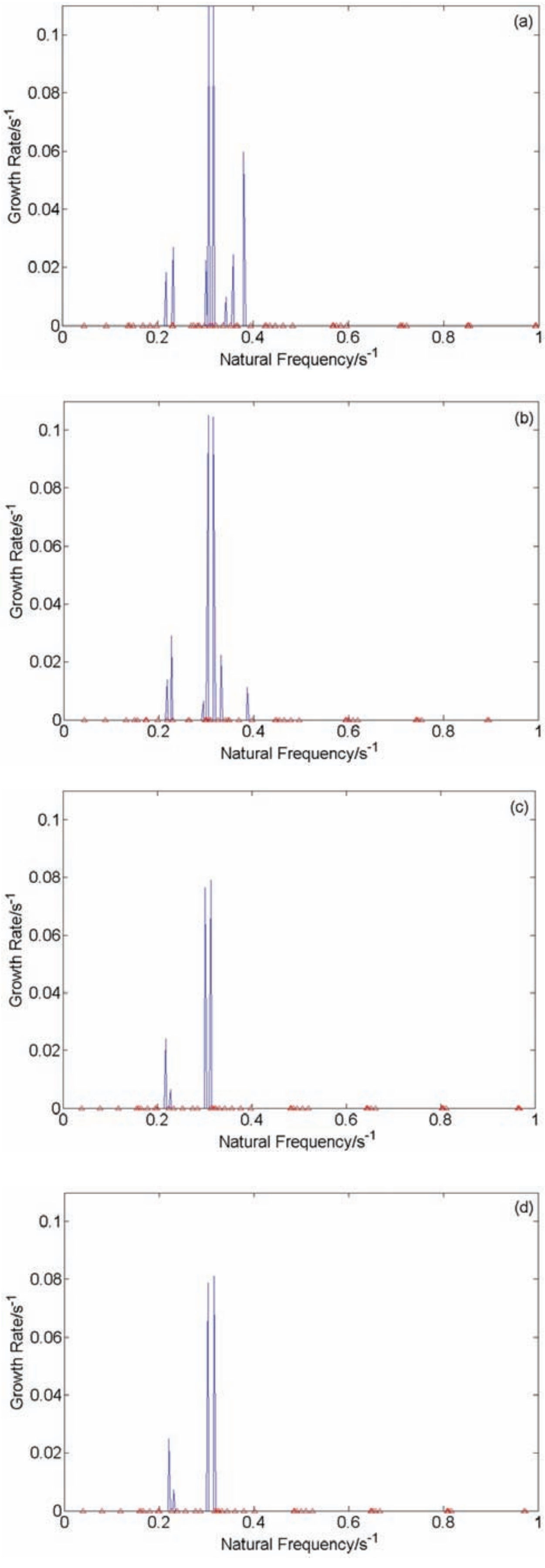

Figure 7—Oscillation spectrograms, (a) AAR1, (b) AAR2, (c) AAR3, (d) AAR4

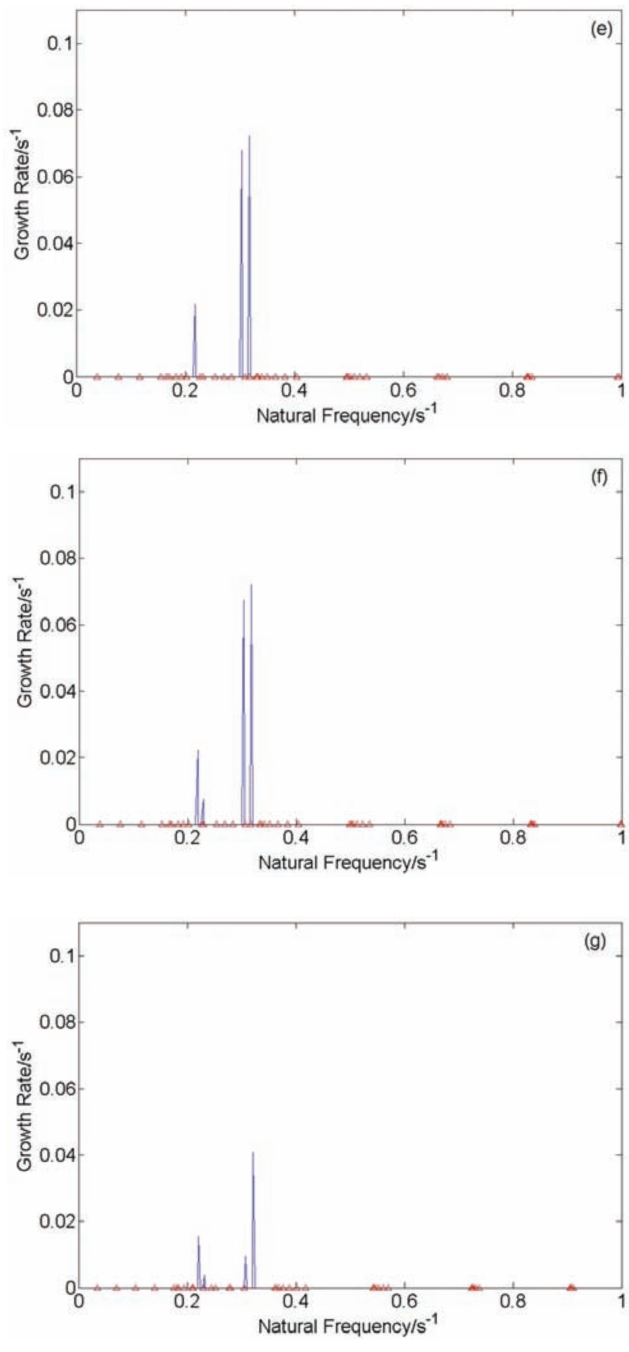

Figure 7 (continued)—Oscillation spectrograms, (e) AAR5, (f) AAR6, (g) AAR7

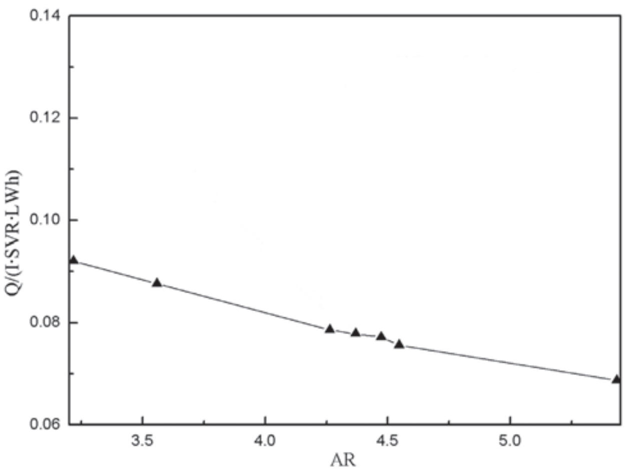

Figure 8—Heat loss intensity per unit area versus AR

Conclusions

This paper studies the relationship between the AR and the multi-physical fields in aluminium reduction cells. The definition of AR definition was first presented, and seven different 320 kA cells were then designed. The relationships between the AR and the electric-magnetic flow fields, MHD stabilities, and thermal stabilities were discussed. The following conclusions can be drawn:

- Under the same current intensity and density, the system, anode, and cathode voltages decrease with increasing AR
- The flow field appear to consist of four vortices in the metal pad, and the velocity in the middle is smaller than that in the end and in the four vortices corner. The velocity in the metal pad decreases with increasing of AR
- The analysis of MHD stabilities indicates that the cell become more stable as the AR increases, the reason for this being that the vertical magnetic field is smaller for cells with bigger ARs
- The discussion of thermal stabilities shows that, under the same current density, the thermal stabilities can be improved when the AR increases.

Acknowledgements

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A case study on stoping shift buffering at Impala Platinum: A critical chain project management perspective

by R.C.D. Phillis*, and H. Gumede*

Synopsis

Conventional stoping in hard rock mining is largely considered an operational environment. This paper suggests that stoping falls within the realm of a project management environment typified by uncertainty, variation, and large numbers of interdependencies. Stoping was then equated to a micro-project with many simultaneous activities that had to be executed accurately using finite resources within limited shift durations in order to reach specific goals.

Critical chain project management (CCPM) principles were applied to the stoping activities, and the results showed that the number of blasts per panel can be significantly increased by successfully moving the distribution of work as close as possible to the start of shift. Critical chain principles also assisted in facilitating re-focusing and teamwork among stoping crews as well as between day- and night-shift crews. The main recorded success was in managing inherent protective capacities/local contingencies/fat/buffers that are found in all projects.

The impact on mine health and safety (MHS) was significant as individual operators and crews became convinced that they could perform all stoping tasks (activities) without compromising accuracy or speed.

Keywords

buffers, critical chain, stoping shift.

Introduction

Despite all the advances in the field of project management, a good number of projects are invariably delivered with compromised basic deliverables of time, budget (cost), and content (which includes quality). In some quarters it has been institutionally accepted that projects will always be late. For a field with a number of publications comparable to most established fields, the following extensively quoted statistics of IT project failure rate[1] do not justify the cause—only quantitative quotes are referenced.†

- The Bull Survey: major findings were:
  - 75% of projects missed deadlines
  - 55% of projects exceeded budget
  - 37% of projects were unable to meet project requirements (content).
- The Chaos Report: This was commissioned in 1995 by the Standish Group in the USA and revealed the following:
  - 53% of the projects cost over 190% of their original budget
  - 31% of projects were cancelled before completion
  - 16% of projects met their project deliverables.

Leach[2] postulates that more than 30% of projects are cancelled before completion. After analysing 18 projects in the mining industry, Vallee[3] concludes that 78% of the projects had non-delivery issues.

These are just a few selected surveys that are available in the literature, and only the quantifiable bottom-line results are referred to. It is also worth mentioning that the academic debate on the statistical correctness of the above findings has been ignored because the paper is biased towards the bottom-line project management deliverables of time, budget, and content. In a typical mining scenario, bottom line results will manifest in the form of:

- Missed annual business plans
- Missed holing dates in development and stoping activities of the mining process
- Continuously shifting the shaft-commission dates
- As will be proved later, lost blasts.

A number of valid reasons are given to justify the missed deliverables, and a majority of these explanations have something to do with the uncertainties that seem to befall all projects. In the following subsections, this paper will describe the application of a relatively new project management

* *Ukhozi Project Management, Johannesburg, South Africa.*

methodology in South Africa. This new methodology places emphasis on the management of the uncertainties that always accompany projects.

Critical chain project management

The critical chain project management (CCPM) philosophy was introduced to the commercial world in the late 1990s by an Israeli philosopher Eliyahu M. Goldratt. Simply stated, it is a theory of constraint (TOC) way of managing projects.

The key aspects of CCPM are that it:

- Pays detailed attention to resource contention during the scheduling process
- Limits and discourages bad multi-tasking
- Takes into account the tendencies of people to procrastinate getting down to work or to divide work evenly throughout the estimated duration of work
- Uses the as-late-as-possible (ALAP) scheduling process
- Acknowledges the inherent existence of uncertainties in projects and attempts to quantifiably manage them through a process known as 'buffer management' (Leach, 2004[2]; Newbold, 1998[4]; Goldratt, 1998[5]).

Critical chain methodology

- *Scheduling phase*—The scheduling phase of CCPM is basically the same as that for critical path scheduling. In fact, without resource contention, the critical path is the same as the critical chain. The major difference is that in CCPM the project due date is set and protected/buffered against uncertainties. In simple terms, all task durations are halved prior to resource levelling. The remaining half of the task durations are ploughed back into the project plan as a protection of the project due date, which is known as the project buffer. This whole process of halving task durations is carried out so as to eliminate the adverse human behaviours that can interfere with task execution. The critical chain is then identified as the longest chain of dependent events taking into account the resource contention[2].
- *Execution and monitoring phase*—In CCPM, resources are forced to prioritize tasks that are on the critical chain. 'Bad multi-tasking'† is eliminated by releasing—as a rule of thumb—only three tasks per resource at any given time. The project monitoring phase during execution involves monitoring the amount of buffers consumed *vis-à-vis* the percentage of the critical chain completed[5]. The practical application of these principles is described in the following section.

CCPM application: case study on stoping shift buffering

Case study background

Although Impala Platinum's average monthly stoping productivity was 17m/month, its leadership was concerned that the overall stoping performance had plateaued and was starting to deteriorate. Impala Platinum, through its Best Practice Department, initiated an Accelerated Productivity Improvement programme (API) aimed at improving the overall productivity of the organization. It is a noteworthy observation that a metre improvement in productivity of the whole organization translated to a more than R1 billion increase in annual sales in the 2007 financial year (turnover of R17 billion at 17 metres per month). In addition, improving stoping productivity is a fundamental step towards achieving annual business plans.

The API programme started with an industrial engineering study at Impala No.12 shaft for the period between October 2006 and January 2007. The objective of the study was to identify the reasons for the fact that some stoping crews' performance were falling short of their monthly targets/blasts. It was anticipated that the causes of lost blasts could broadly be classified into three areas:

- *Input constraints*—system limitations caused by under-resourcing of human, physical, information, and/or financial inputs
- *Output constraints*—system limitations caused by the inability to move the broken rock from the stopes
- *Capacity constraints*—constraints in capacity that meant that it was not possible to complete all the stoping tasks in the available shift time.

The focus of the study was on the stoping capacity constraint, and only the day shift (drilling) will be discussed here. Inbound and outbound logistics and development (including construction and equipping) studies were also conducted, but these do not form part of this paper. The project team used both qualitative and quantitative research methodologies.

CCPM application methodology

The project team used the following methodology, which is based on research, correlation and implementation:

Stoping research study at Impala No. 12 shaft

Initially the project team did not know what the stoping capacity constraints were, other than management hypotheses. The project team set out to gather as much relevant data during time and motion studies.

Competent observers tracked selected stoping crews for both the day and night shifts and observed time from start of shift (SOS) to end of shift (EOS) and motion from shaft bank to bank.

The study was conducted on four panels, two of these being benchmark panels and the other two comparison panels.

Comparing and correlating the study results with best practice

The stoping resource schedule as shown in Figure 1 reveals the following:

- Time and motion studies average performance of the operator tasks were completed faster when compared to the time allowed in the best practice—stoping resource schedule.

†Bad multi-tasking may be considered as working on many concurrent tasks/paths that have an adverse effect on lead times, although effort and touch time remain unchanged.

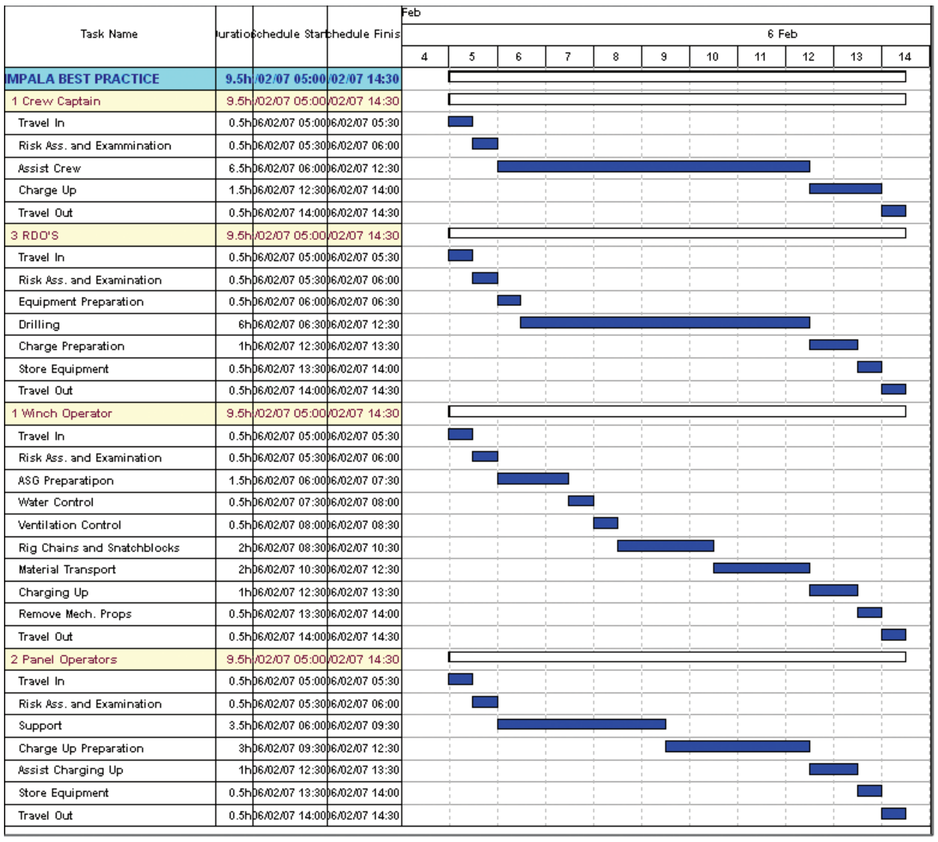


Figure 1—Best practice – stoping resource schedule

- Individual operators that constituted the stoping crews were efficient, as all operators were proficient in their best-practice-assigned responsibilities/jobs.
- It seemed that the main problem was the lack of the integration of all the stoping activities. This phenomenon was realized only when the project team observed the holistic motion of the stoping crews throughout the shift *vis-à-vis* the goal of each stoping-shift, i.e. 'A safe, quality blast per day, every day'.
- The resource-based nature of the stoping schedule encouraged each crew member to concentrate on his particular tasks and ignore the global goal. For instance, when one of the three rock drill operators (RDOs) completed their tasks, that particular RDO simply packed up and left the rest of the crew behind. The faster crew member did not stay on to assist other crew members complete the stoping schedule and achieve the goal. Also, all crew members became proficient, with a low reliance on the crew as a unit, i.e. individual operators did not find protection from the system.
- In the best practice schedule the focus on the resources and the integration of the resources was implicit. As such, crews divided all the work among operators, as evenly as possible. Miners would then drive continuous improvement of the efficiencies of each crew member in anticipation that, when added together, all the individual efficiencies would result in goal achievement.
- Idealizing tasks and/or resources meant that much emphasis was placed on finishing each task on time as the best way to achieve the goal.

The shortcomings listed above indicated that the original best practice resource schedule as shown in Figure 1 had to be complemented with a best practice activity schedule (as seen in Figure 2) in the following manner:

- Shifting focus from the resources to the tasks/activities
- Making the schedule integration explicit (divergent and convergent points).

This solution was incomplete as it did not address stoping risks such as:

- Resource variation such as availabilities (e.g. absenteeism) and efficiencies in relation to stoping productivity
- Uncertainty caused by the erratic nature of the causes for failure to blast (lost blasts) and protection against things that could go wrong
- Resistance to change, shown in the crew's attitude to doing each and every task accurately, because each stoping task is an act of MHS.

CCPM methodology was then applied to the stoping activity schedule, with the main objectives including:

- Protection of the crew from uncertainties that result in lost blasts
- Facilitation of crew re-focusing on co-operation and teamwork
- Facilitation of the development of control charts (crew dashboard, a tool for crew synchronicity)
- Derivation of a single measure for behavioural change.

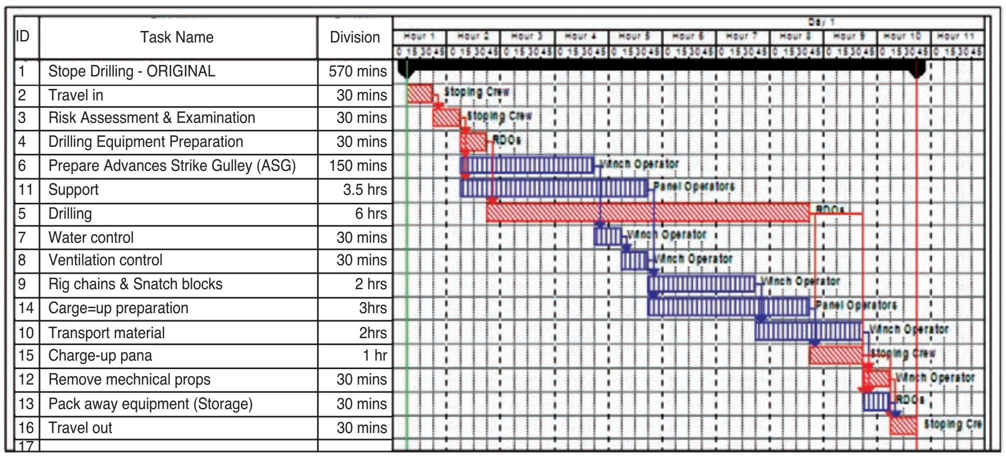


Figure 2—Best practice–stoping activity schedule

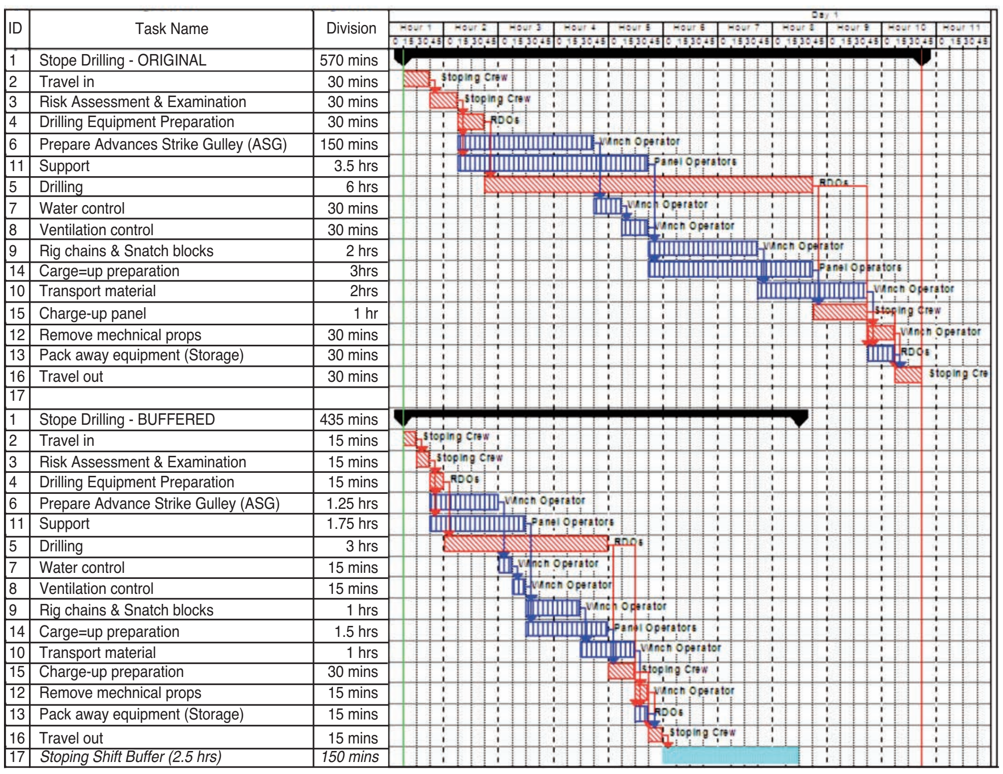


Figure 3—Impala Platinum—stoping production cycle on CCPM

Figure 3 illustrates the stoping activity schedule on CCPM, i.e. with resource allocation and buffering. The red bars indicate the actual critical chain while the blue bars are floating paths/tasks, each with their own buffers shown in light blue.

The buffers provided the opportunity to schedule floating tasks/paths as-late-as-possible (ALAP). The implications for MHS were that the entire crew could focus on the start-of-shift procedure. The crews were rationalized with due regard to waiting place procedure, risk assessment, and stope examination, which formed part of an MHS campaign at that time. Only when this (SOS procedure) was completed did the crew split up to take on specific tasks, as may be seen in Figure 3. Promoting teamwork and protecting the shift from lost blast, was more important than the convenience of individual operators. The CCPM stoping schedule was then implemented.

Implementation of the CCPM schedules at Impala No. 11 shaft included a buy-in process to ensure the active collaboration of the shaft leadership, line management and crews, which is obviously a critical success factor. The elements that had to be emphasized as part of the buy-in process are set out below:

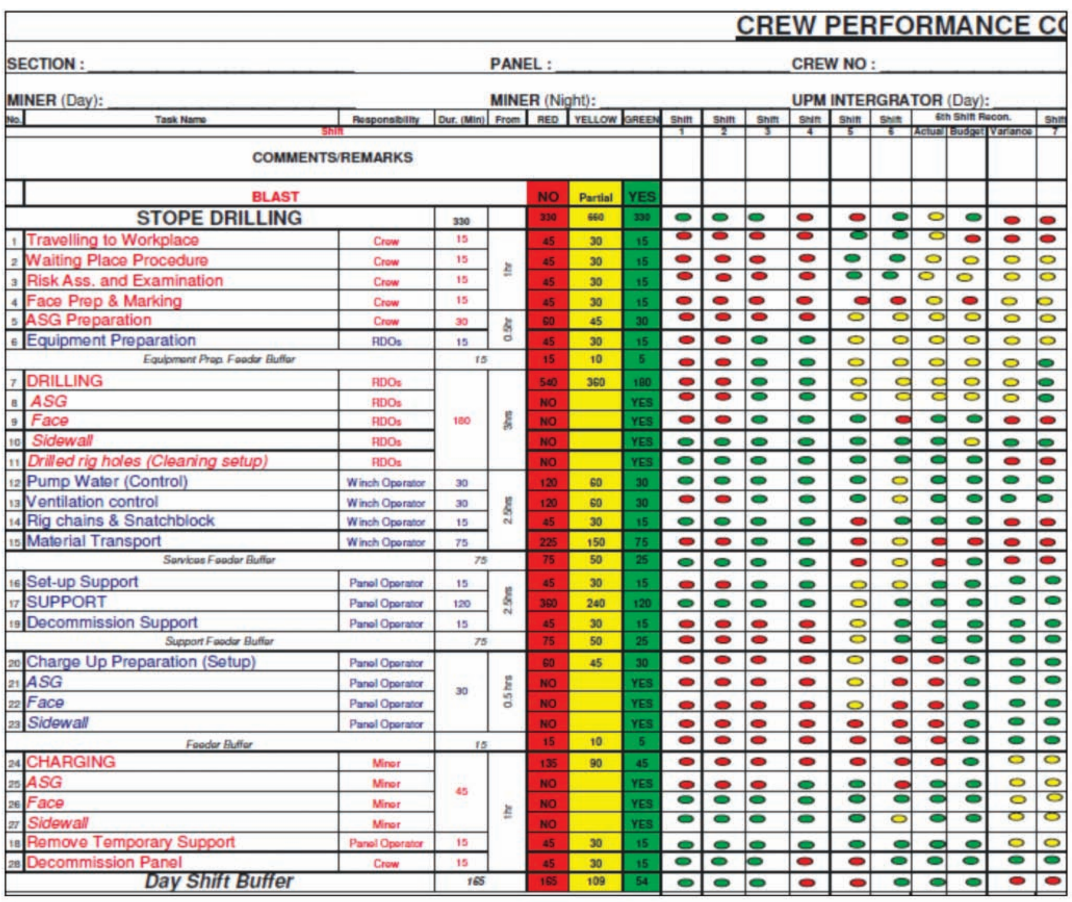
- ➤ It had to be ensured that the operators understood the logic of CCPM and were convinced that the overall blast protection took priority over task protection. This meant that management clearly understood and accepted that the halved estimates might never be achieved; and that if the halved-estimates were not achieved the management and/or the miner would not penalize operators.
- ➤ It was explained that the other halves of the time estimates would be pooled to the end of the shift (project) in a way that protects the shift, albeit at the expense of the halved estimates. It had to be over-emphasised that the project as a whole was protected.
- ➤ The crews were informed in simple terms of what was required. For instance, to eliminate the Student Syndrome and Parkinson's Law, the soccer analogy was presented to the crews and emphasis was placed on the fact that as a soccer team, the crew should score all their goals in the first half of the shift and then spend the second half defending.
- ➤ Stoping, being a daily repetitive micro-project carried out in uncertain ambient conditions (underground), called for a dashboard that had to be tracked and updated in real time. This assisted in influencing crew behaviour through the provision of timely warnings of schedule deviations. As a consequence crews could self-adjust or rationalize themselves in accordance with the required crew work rate.
- ➤ The miner (given a project manager role) was given a control chart to monitor the adherence to the schedule (as seen in Figure 4). Updating the control chart meant that the miner could maintain a holistic view of the shift.

Control charts also helped to empower the miner as he was now managing rather than operating. This new mode of operation was also independently monitored and tracked for a period of four months.

All of Impala No. 11 shaft crews were then adopted as the population universe (i.e. target population for the pilot implementation). The project team had potential access to all 95 crews, but only 20 crews were involved in this case, which represented 21% of the population universe. The selection of the sampled crews was non-random, because the shaft leadership identified the worst-performing crews (locally termed 'Intensive Care Unit (ICU)) Crews' for the pilot implementation.

Only 67% of the sampled data was used for deriving statistical graphs; the remaining 33% was not considered due to:

- ➤ Data being beyond the target sample (e.g. when the crews were sweeping, cleaning, and installing support during the production shift)
- ➤ Ukhozi internal quality checks
- ➤ Extra production shifts.



CREW PERFORMANCE C

SECTION : PANEL : CREW NO :

MINER (Day): MINER (Night): UPM INTERGRATOR (Day):

COMMENTS/REMARKS

No.	Task Name	Responsibility	Dur. (Min)	From	RED	YELLOW	GREEN
	BLAST				NO	Partial	YES
	STOPE DRILLING		330		330	660	330
1	Travelling to Workplace	Crew	15	1hr	45	30	15
2	Waiting Place Procedure	Crew	15		45	30	15
3	Risk Ass. and Examination	Crew	15		45	30	15
4	Face Prep & Marking	Crew	15		45	30	15
5	ASG Preparation	Crew	30	0.5hr	60	45	30
6	Equipment Preparation	RDOs	15		45	30	15
	Equipment Prep. Feeder Buffer		15		15	10	5
7	DRILLING	RDOs	180	3hrs	540	360	180
8	*ASG*	RDOs			NO		YES
9	*Face*	RDOs			NO		YES
10	*Sidewall*	RDOs			NO		YES
11	*Drilled rig holes (Cleaning setup)*	RDOs			NO		YES
12	Pump Water (Control)	Winch Operator	30	2.5hrs	120	60	30
13	Ventilation control	Winch Operator	30		120	60	30
14	Rig chains & Snatchblock	Winch Operator	15		45	30	15
15	Material Transport	Winch Operator	75		225	150	75
	Services Feeder Buffer		75		75	50	25
16	Set-up Support	Panel Operator	15	2.5hrs	45	30	15
17	SUPPORT	Panel Operator	120		360	240	120
19	Decommission Support	Panel Operator	15		45	30	15
	Support Feeder Buffer		75		75	50	25
20	Charge Up Preparation (Setup)	Panel Operator	30	0.5 hrs	60	45	30
21	*ASG*	Panel Operator			NO		YES
22	*Face*	Panel Operator			NO		YES
23	*Sidewall*	Panel Operator			NO		YES
	Feeder Buffer		15		15	10	5
24	CHARGING	Miner	45	1hr	135	90	45
25	*ASG*	Miner			NO		YES
26	*Face*	Miner			NO		YES
27	*Sidewall*	Miner			NO		YES
18	Remove Temporary Support	Panel Operator	15		45	30	15
28	Decommission Panel	Crew	15		45	30	15
	Day Shift Buffer		165		165	109	54

Figure 4—Stoping production cycle—control chart example

The plan was to improve the ICU crews and make them the best performing crews. The success of the ICU crew was expected to be imitated by other crews and spread to the whole shaft in this way. The implementation results and analysis are presented in the succeeding subsection.

Results analysis

During the implementation of API, Impala also introduced a new bonus system, namely the ‘Ama Ching-ching’ bonus, which suggests that some of the improvements in production could be attributed to this new system. However, it is worth mentioning that the project team was offering a unique product by promoting the concentration of work in the first half of the shift so as to eliminate the Student Syndrome and Parkinson’s Law. The project team had proposed/hypothesized that the number of blasts per panel could be increased significantly by shifting workflow distribution to the first half of the shift.

With that in mind, the project team measured this paradigm shift as it was the only parameter that could be attributed to CCPM. The paradigm shift was tracked through a comparison of monthly workflow distribution curves of the relevant crews. Monitoring the behavioural change before and during the implementation of the revised CCPM schedule involved gathering data underground in the form of time and motion studies and conducting statistical analyses. These analyses were carried out by:

- ➤ Subdividing the allocated times for the activities on the best practice schedule into hourly intervals (as indicated in Table I)
- ➤ Extrapolating results from time and motion studies to determine the number of times in which each activity was completed within the CCPM best practice schedule’s allocated time per shift, and calculating cumulative frequencies
- ➤ Plotting cumulative frequency and percentage probability distribution curves as illustrated in Figures 5 and 6
- ➤ Calculating areas under the probability distribution curves within a specific period to obtain the amount of work completed.

Only the results of one of the crews (BA44) are given in this paper.

The above statistical analysis methodology was adopted from Walpole *et al.* (1993)[6] and Gumede *et al* (2007)[7].

Figure 5 shows the percentage-frequency-density distribution of crew BA44’s completion of different tasks at section 114 on level 13. The probability distribution of completing different tasks is the area below each graph. In analysing Figure 5 there is a gradual increase in the area below the graphs midway during the shift for the period between February and May. This is illustrated by the consistent shifting of graphs towards the left from February to May, indicating a gain in percentage probability. As an illustration, in February, crew BA44 completed 47% of their day shift production cycle midway into the shift, as seen in the area under the black curve.

For the same period in May, the same crew completed 57% of their tasks—i.e. the area under the green curve—compared to 62% in April. This signifies a significant change in paradigm, as the crew concerned achieved a 10% increment in concentrating the work during the first half of the shift.

Table II summarizes the percentage distributions for all the crews that were monitored during the implementation, and there is a clear indication that crews gradually concentrated their efforts at the beginning of the shift (a paradigm shift).

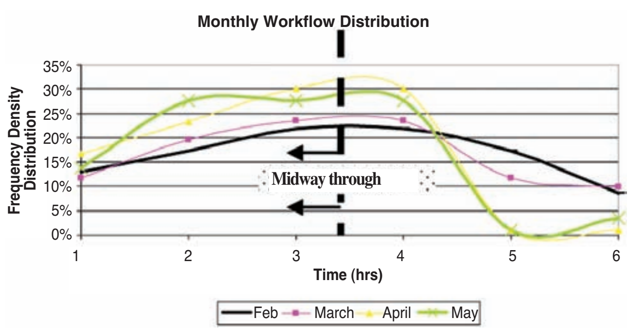


Figure 5—Monthly workflow distribution of completed critical tasks

Table II

Percentage distribution of completed work

Month	February	March	April	May	June
Average % probability	47%	49%	57%	56%	54%

Table I

Hourly interval activities on Impala Platinum’s original best practice schedule

	Time (h)	Tasks
0		Start of Shift (SOS)
1	0–1 hour	Travelling to workplace, waiting place procedure, risk assessment and examination, face preparation and marking
2	1–2 hour	ASG preparation and drilling
3	2–3 hour	Drilling
4	3–4 hour	Drilling
5	4–5 hour	Drilling and charging-up
6	5–6 hour	Decommissioning of shift
7		End of shift (EOS)

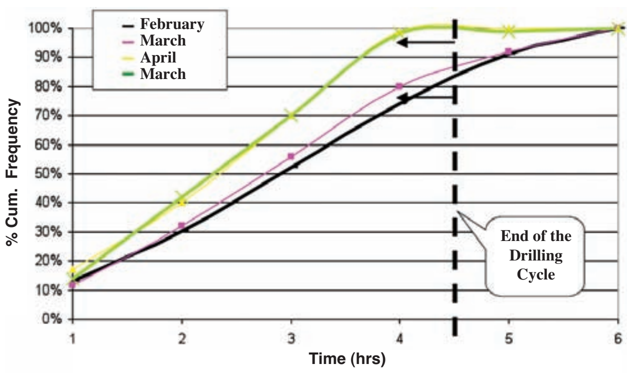


Figure 6—Workflow cumulative frequency distribution

An analysis of crew BA44 from the perspective of the probability of achieving a blast is given in Figure 6. In this case it was assumed that whenever crews completed their drilling tasks they would definitely achieve a blast. External causes for blast failures were ignored (e.g. material or equipment shortages and the unavailability of stopes). The comparison was pegged at the end of the drilling task on the best practice schedule.

Using the CCPM best practice schedule, the drilling task was scheduled to finish after four-and-a-half hours. Also, assuming that the crew always charges up after successfully completing the drilling task, the following conclusions can be drawn:

➤ In February crew BA44 had an 80% chance of achieving its target, while the same crew had almost a 100% chance of achieving its target for April and May 2007.

Table III summarizes the cumulative frequency distributions for all the crews that were monitored during the implementation.

Figure 7 demonstrates the overall performance of one of the sections that the project team worked on (section 114). In this particular section there was an approximately 45% improvement in production during the CCPM implementation.

Conclusions

The partial and holistic application of the CCPM methodology on the stoping production cycle has proven to be relatively simple to practise, and the bottom-line results are evident and quantifiable. Some of the advantages that the project team and client experienced were:

a. Keeping the entire stoping crew focused on the goal (crew synchronicity)
b. Facilitating crew co-operation and teamwork (rationalizing of resources)
c. Miner empowerment by inducing the miner to manage, in spite of the fact that the majority of miners believed that they were more effective operating instead of project managing
d. Application of simple CCPM principles that led to significant improvements on daily stoping performance and, ultimately, an improvement in returns on equity (ROE)
e. Emphasis being placed on accuracy instead of speed (which was inevitable) as the root cause of effective health, safety, quality, cost, production, and morale management at the stope face.

Table III

Overall cumulative frequency distribution

Month	Feb	Mar	Apr	May	Jun
% Cumulative Frequencies	82%	88%	96%	95%	94%

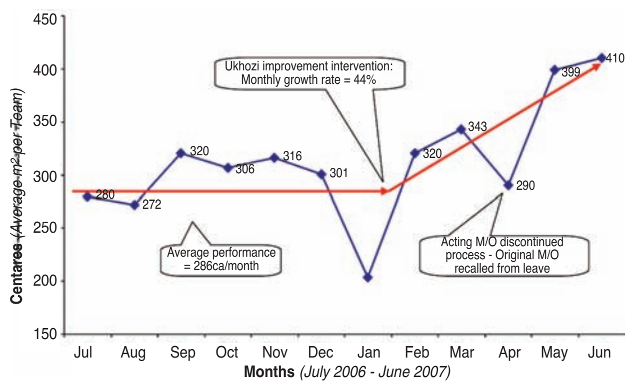


Figure 7—Impala Platinum No. 11 Shaft—section 114 performance chart

Acknowledgements

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Value creation in the resource business

by J.M. Garcia* and J.P. Camus*

Synopsis

This paper highlights several management practices from the oil and gas industry to support the proposition that financial performance in the finite, non-renewable resource business relates more to upstream rather than downstream activities. Based on the analysis of nine oil and gas companies, this study supports a previous study involving fourteen mining companies that showed reserves growth is one of the main levers of value creation in mining. Interestingly, this study also finds that the oil and gas industry has been historically more profitable than mining. The reason, it is argued, is that oil and gas companies count on management practices that focus primarily on the upstream segments of the business, compared to the traditional downstream focus of mining. This paper delves into these ideas to conclude that what mining may need to improve its competitive advantage is a new organizational framework. Another conclusion is that the upstream management focus is vital not only for strategy formulation in the resource business, but also for policy formulation in economies based on the export of finite, non-renewable resources.

Keywords

Value creation, mining, value chain, mineral resource management, resource business, non-renewable resources, oil and gas, mine planning, mining value chain.

Introduction

To understand how value is created in mining, Camus *et al.*[1] set out a research study that modelled the business using the value chain framework proposed by Harvard University professor Michael Porter[2]. Their model considers the primary activities that deal with the value chain, which are overarched by some support activities providing transversal services and other common resources to the business, as depicted in Figure 1.

Upstream are the resource-related activities that embody the holistic function of mineral resource management. The aim of this function is to discover mineral resources and transform them into economically mineable mineral reserves in the most efficient and effective way. Its output is a business plan that defines the fraction of the mineral resources that is worth mining (mineral reserves), along with the mine plan designed to extract these reserves.

Downstream activities are accountable for the execution of the business plan. These industrial-type activities begin with the project management task, with responsibility for the engineering and construction component of the plan. Following is the operations management unit, accountable for the production component of the plan. At the end is the marketing function responsible for market development and revenue realization.

In the mining industry, there is a deep-rooted belief that value creation rests primarily on the downstream, industrial-type activities that focus on production and costs, which in turn determine earnings. Instead, the research by Camus *et al*. proposes that value in mining is mainly the result of effective management of the upstream, resource-related activities that focus on mineral reserves growth. Recently, Standard & Poor's—one of the world's largest providers of investment ratings and financial research data—has also raised this point in a white paper[3]:

'Analysing a mining company is a bit different from analysing most companies. Mining companies are valued not according to earnings so much as assets, and so factors such as material reserves and production must be taken into account'.

Because of the lack of public domain information, the proposition that value in mining is more upstream than downstream is supported indirectly. The idea is to compare over time variations in the company share price plus dividends with variations in company mineral reserves plus production. In business parlance, the former variable is commonly known as Total Shareholder Return

* *Mining Engineering Division, The University of Queensland, Australia.*

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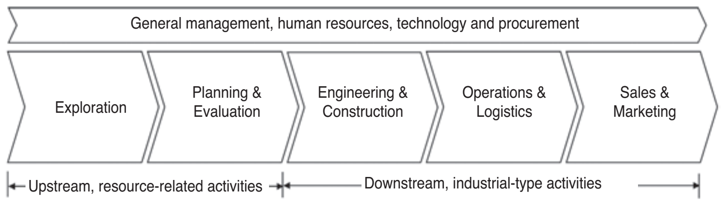

Figure 1—Mining value chain

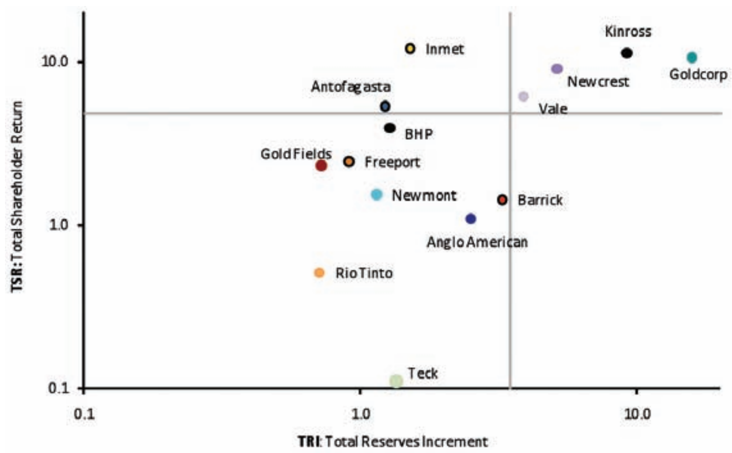

Figure 2—TSR vs. TRI for selected mining companies, 2000–2008[1]

(TSR), whereas the latter is effectively the mining company's upstream output, defined here as Total Reserves Increment (TRI).

Figure 2 shows both indices, TSR and TRI, for each of the fourteen mining companies in the previous study[1] over the period 2000–2008. The axes of the graph are in logarithmic scale to allow a better view of the whole results, which include the sample average for both indices. The results seem to confirm the hypothesis that leading companies that surpass the group's average TSR in the period also exceed the group's average TRI. There are two doubtful cases, but as Camus *et al.* suggest these are transitional companies in the process of converting promising mineral resources into mineral reserves, which the market anticipates. The sample adequately represents the worldwide mining industry, as eight out of the fourteen companies surveyed belong to the then world's top ten market capitalization list released by PricewaterhouseCoopers[4], a global consulting firm.

The previous model evinces that the disciplined growth of mineral resources and their effective conversion into mineral reserves underpins the creation of value in the mining business. This research also suggests that the structures, processes, and systems used by mining companies to manage their mineral resources (the upper part of the value chain) play a pivotal role in their effectiveness. This issue is not always addressed appropriately in the mining industry, as review of more than 80 case studies on mining companies, growth strategies confirms[5]. Instead, growth achievement seems to be more associated with production increase and cash costs reduction, these case studies suggest. Consequently, there seems to be wide room for innovation and developments in these areas.

To extend the scope of the previous research to the resource business at large, this study incorporates the oil and gas industry into the analysis. To this purpose, the next section presents a comparative analysis of both sectors—their different realities, problems, and evolutions—to thus set the stage for the following section that addresses the upstream/downstream concept widely used in the oil and gas industry. The subsequent section replicates the previous mining survey in the oil and gas industry. The penultimate section discusses the organizational implications of these results, which then gives way to some concluding remarks.

A different reality

Despite mining being called an industry of the 'old economy', it plays an important role in today's world economy. Similarly to the oil and gas industry, mining is a large and global business. This means that nearly all nations are impacted by the way that this market develops. An interesting feature of mining is that despite the latest resource supercycle that spanned from 2003–2008, it lagged behind the oil and gas industry in terms of long-term shareholder value creation. It seems that mining was much better at 'digging holes in the ground than unearthing returns for their shareholders'[6].

A comparison of price equity indices between mining and oil and gas over the last 15 years confirms the previous assertion, as illustrated in Figure 3. The gap between both sectors is notably marked prior to thesupercycle. This phenomenon was noticed by Crowson[7], who at the time

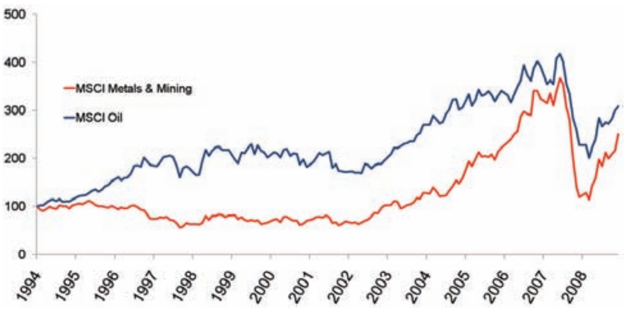

Figure 3—Morgan Stanley Capital International (MSCI) metals and mining and oil equity indices

claimed 'that the mining industry's profitability has been poor for most of the past two decades.' As Figure 3 also shows, this trend reverted somewhat during the last five years. Rather than mining management dexterity, it seems that the main explanation is the skyrocketing commodity prices that impacted mining profitability more favourably compared to oil and gas. Nonetheless, it is worth noting that both oil and metal price indices followed a similar path over the period 1994–2001, when the oil industry clearly outperformed the mining industry.

Interestingly, the mining industry and the oil and gas industry have many commonalities, perhaps the most important being that both are based on exhaustible resources. These are becoming increasingly difficult to find, particularly in developed economies. In the drive to secure energy supplies, international oil companies (IOCs) and national oil companies (NOCs) are facing intense competition for upstream access in emerging markets. As a result, the focus in seeking new deposits has shifted from stable economies to developing countries. Although the latter are less predictable geopolitically, some of these countries present considerable hydrocarbon potential[8].

The mining industry situation is not that different in this respect, although the role that national mining companies play in shaping the industry is less relevant than in the oil and gas sector. The low levels of explorations in the past three decades, and the preoccupation with cost control and efficiencies at existing operations during much of the same period, have resulted in a limited supply of good quality projects in companies' pipelines. This became evident with the unanticipated rapid development of the largest emerging economies, which caused a sudden increase in both metal prices and the development costs of mining projects. For example, BHP Billiton has estimated that these costs have double in real terms during the past thirty years[9]. Moreover, most of the world-class mining projects are now located in challenging areas of the globe, facing problems of infrastructure as well as political and legal uncertainties.

Despite the commonalities in both sectors, the oil and gas industry seems to have been more innovative in the way of organizing its business. The reason for this can be found in the profound transformation that the oil and gas sector experimented about 30 years ago. The shocks of 1974 and 1979/80 transformed the business environment of the oil and gas industry from one of stability to one of turbulence. As a result, the international oil majors were forced to reformulate their strategies and redesign their organizations to reconcile flexibility and responsiveness with the integration required to exploit the resource advantages of giant corporations[10].

Perhaps the most notable change was the implementation of a new operating model. This was based on the dissection of the business into two distinctive areas—upstream activities, which encompass the finding and development of new resources, and downstream activities, which involve the industrial transformation of raw resources into end products. Hence, the application of the value chain model was implemented successfully across the whole sector with a particular focus on the upstream segment of the business.

After a period of divestment and restructuring occurring from 1982 to 1992, possibly as a result of the new operating model, an important consolidation process occurred in the oil and gas sector during the 1990s. Among the most notable mergers that took place during the four years from 1998 to 2002 are Exxon with Mobil, British Petroleum (BP) with Amoco, Total with Petrofina, Chevron with Texaco, and Conoco with Phillips Petroleum.

Coincidentally, during the same period, almost all these oil giants also shed their mining subsidiaries, businesses they had entered in previous decades to diversify their portfolios. Some of these transactions are Shell's sale of Billiton, BP's disposal of Kennecott, and Exxon's sale of its 50 per cent interest in the massive El Cerrejon coal mine in Colombia and its copper mining operations in Chile (Disputada).

For similar reasons, some years later the mining industry followed an analogous consolidation. Thus, over the first decade of this century, a large number of mergers and acquisitions took place in the mining sector. In this case, the most notable companies involved were BHP, which acquired Billiton and then Western Mining; Rio Tinto which bought North Ltd and later Alcan; Anglo American, which acquired Disputada, Kumba, and more recently Minas Rio in Brazil; Xstrata, which acquired Mount Isa and then Noranda/Falconbridge; Vale, which bought Inco, and Freeport-McMoRan, which acquired Phelps Dodge. The consolidation has been more rapid in the gold sector, and now relatively new actors are leading the industry—Barrick, Goldcorp, Kinross, and Newcrest, for instance. It seems that mining was trying to take back control of its destiny, after being dropped from the eyes of institutional investors, and needed to merge in order to acquire critical mass in financial markets[9].

Unlike the oil and gas industry, the latest significant consolidation of the mining industry was not preceded by a more radical organizational refurbishment to focus the business on its core activity. Perhaps the only notable change in big mining corporations was the creation of product or customer groups, coordinated by a centralized bureaucracy commonly known as headquarters. However, how value is created within these groups and where it really comes from is still unclear under this model.

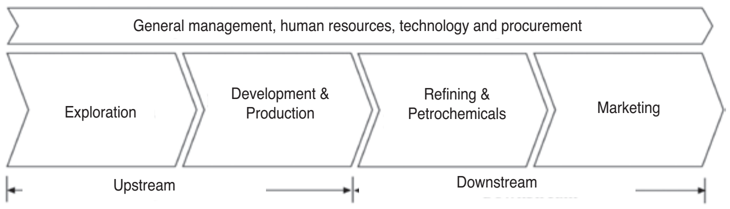

Figure 4—Oil and gas value chain

	1970-1973	1974-1978	1979-1982	1983-1985	1986-1988
Amoco+	71%	81%	80%	83%	84%
Arco+	46%	53%	84%	91%	74%
BP	42%	65%	83%	76%	73%
Chevron	42%	57%	69%	77%	71%
ENI	70%	80%	85%	89%	80%
Exxon	52%	73%	82%	85%	77%
Mobil	43%	63%	72%	66%	62%
Shell	30%	59%	66%	72%	56%
Texaco	61%	69%	73%	64%	68%

Figure 5—Upstream/downstream earnings ratio evolution[10]

The model adopted by the oil and gas industry, which gave way to a new era of growth and value creation for the fossils fuels industry, is the theme of the analysis of the next section.

Upstream/downstream in the oil and gas business

Oil and gas producers divide their business into two large segments; upstream activities accountable for exploration and production, and downstream activities responsible for the crude transformation, petrochemical business, and marketing. Figure 4 presents a value chain as would be applied generically to the overall oil and gas business.

The value chain concept has been ingrained in the oil business parlance for several years. This practice, shaped in the 1980s, was aimed at symmetrizing each activity's influence and weight when the oil sector faced one of the most difficult periods in history. As a consequence of the oil crisis, the transaction costs of intermediate markets fell, while the costs of internal transfer rose. Royal Dutch Shell was the first company to free its refineries from the requirement to purchase oil from within the group. Between 1982 and 1988, all the oil majors granted operational autonomy to their upstream and downstream divisions, placing internal transactions onto an arms-length basis. Upstream divisions were encouraged to sell oil to whichever customers offered the best prices, while downstream divisions were encouraged to buy oil from the lowest cost sources.

During the decade, all major oil players completed a steady evolution from the fully integrated scheme to a two-arm business scheme. In doing so, oil firms adopted new reporting systems for gathering and tracking relevant information to adequately assess business performance. A detailed analysis of the upstream/downstream earnings ratio shows that most of the oil majors nearly doubled the weight of their upstream operations in less than two decades, as depicted in Figure 5. Currently, international oil majors such as Exxon, BP, and Shell still show ratios in the top quartile and close to 100% for the almost exclusive upstream-focused companies, such as Saudi Aramco and Apache Corp.

Further costs analyses of the upstream-downstream specialization reveal broader insights in its implication for strategic considerations and interaction with the non-integrated sector of the industry. There is no ambiguity in the effect of upstream cost asymmetries: the integrated firm with the lower upstream cost will produce more both upstream and downstream than the one with the higher upstream cost, but its downstream production will be less important relative to its upstream production[11].

It is interesting to wonder why almost all oil and gas companies adopted a similar model and performed such an abrupt administrative change so quickly. The adoption of this innovation was perhaps a conventional response of companies in a mature industry facing severe adverse conditions or uncertainties. The 'herd behaviour' might be better explained using the institutional theory[12], which postulates that companies facing the same set of environmental conditions usually follow an evolutionary path from diversity to homogeneity.

Even though the value chain and upstream/downstream concepts are ingrained in the resources lexicon, the mining business still remains fully integrated from exploration to sales. As a result, financial information such as capital investment and earnings is not calculated for the different segments of the value chain, let alone value. In their annual reports, mining firms report separate information only for product groups or business units.

In summary, this analysis suggests that the most critical activities in the oil and gas industry and the resource business at large are in the upper part of the value chain. It appears that companies that excel in managing the upstream segment are likely to generate a higher value. To gain further insights into this proposition, a study of value creation in the oil and gas industry was carried out. The outcomes of this study are discussed in the following section.

Value creation in the oil and gas industry

The model used in this assessment is essentially the same as previously described in the introductory section for the fourteen mining companies. The only distinction is the period of analysis—ten years, instead of eight considered in the abovementioned mining study—from 31 Dec 1999 to 31 Dec 2009. The central hypothesis is that oil and gas companies that excel in TSR over an entire economic cycle are those that also excel in increasing their reserves and production, referred to here as TRI. To prove this, a group of nine international oil and gas companies trading on the New York Stock Exchange (NYSE) were examined using similar parameters to calculate their respective TSR and TRI. These companies, listed in Table I, were chosen because their production and reserves data was easily accessible and they cover an ample spectrum, representing the oil and gas industry adequately.

Information on oil and gas reserves and production was obtained from the companies' annual reports. Crude oil reserves are usually reported in millions of barrels, whereas gas volumes are in billions of cubic feet. As almost all companies produce crude oil as well as gas, production and reserves are reported in millions of barrels of oil equivalent. Since the conversion ratio varies slightly across companies, this study uses 5 800 cubic feet as one oil equivalent barrel.

The comparison of TSR and TRI for the oil industry, the results of which are depicted in Figure 6, shows a similar correspondence to that of Figure 2. Although the correlation is not perfect, the overall results seem to corroborate the hypothesis that companies excelling in incrementing their reserve base in the period are those that also obtained higher returns to their shareholders.

Some companies' indices in Figure 6 appear to deviate slightly from the general trend. This may be explained by various reasons. First, the different way oil and gas companies report resources and reserves, which compared to mining companies is less homogenous across jurisdictions. Second, the state of the balance sheet that is not considered in the calculation of the indices and therefore not part of the analysis. This may mask, for instance, reserves acquired at the peak of the cycle using too much debt, which in case of a sudden downturn damages the share price of debt-laden companies more.

The reporting of reserves of oil and gas companies that trade on the NYSEis under the regulations of the US Securities and Exchange Commission (SEC). Disclosure rules,

Table I

Oil and gas companies included in the study

Company	Headquartered in	Ticker symbol
Apache Corp.	USA	APA
British Petroleum plc.	UK	BP
Chevro Corp.	USA	CVX
ConocoPhillips Co.	USA	COP
Devon Energy Corp.	USA	DVN
Exxon Mobile Corp.	USA	XOM
Repsol YPF SA	Spain	REP
Royal Dutch Shell plc.	Netherlands	RDS.B
Total SA	France	TOT

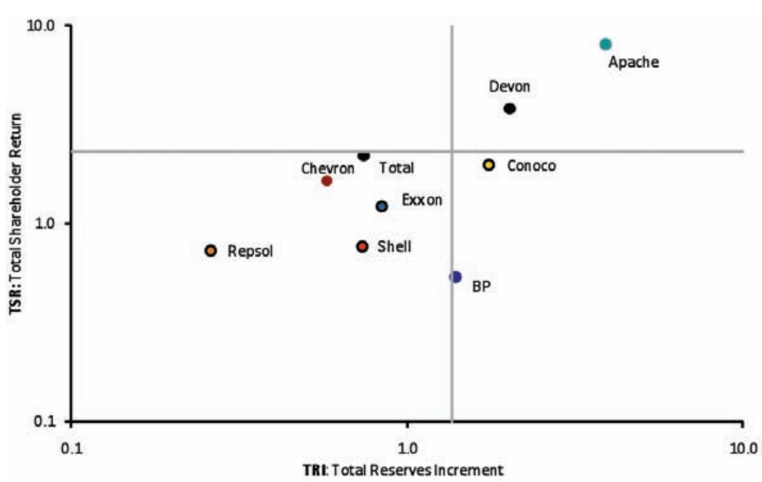

Figure 6—TSR vs. TRI for selected oil and gas companies, 1999–2009

in this case, were set in 1978 and allow only the reporting of proved reserves. But this is just one category of the overall pool of oil and gas resources controlled by companies. The impediment to reporting less reliable reserves, which is supposedly aimed at protecting shareholder integrity, may discourage the market from operating more openly and transparently.

Public interest in modifying the regulations for reporting oil and gas reserves information has intensified in recent years. Many business agents have noted that the previous rules did not serve the interests of investors well because the industry has changed in the more than 30 years since these rules were adopted. This has also been consistently denounced by engineering professional associations worldwide, as well as international accounting firms[13].

Perhaps this claim was part of the reasons behind SEC's recent change to the regulations on oil and gas reporting that came into force in January 2010. Among the changes is a 12-month average price that is now required (instead of the single-day price at year end) to calculate oil and gas reserves. New rules also direct companies to use first-of-the-month pricing to calculate the year's average, giving firms more time to prepare estimates. In addition, the number of different technologies that can be used to establish reserves has also been extended. This is useful to disclose non-traditional resources, such as bitumen, shale, and coal bed methane, as oil and gas reserves. Another important change is the optional disclosure of probable and possible reserves, which should give investors a richer insight into a company's long-term potential.

In relation to the financial aspect behind the oil and gas companies surveyed, it seems pertinent to comment on the two companies in Figure 6 that show a disparity in terms of both indices. These companies are British Petroleum (BP) and Conoco Phillips, both showing a relatively lower TSR compared to their relative higher TRI. Coincidentally, the two companies invested heavily in Russia during the 2000s. This effort allowed both companies to have access to enormous reserves that later proved to be difficult to develop because of problems with the Russian authorities and their business allies. These happen to be a few domestic oligarchic companies that allegedly use the help of Russian state authorities to act in their favour. To start cutting the losses inflicted by these unsuccessful businesses over the latest years, both companies are now selling out and downscaling involvement in Russia as state influence over the sector is growing.

The problems of BP seem to be aggravated by a series of safety and environmental issues that seriously affected the reputation of the company. The most notorious is an explosion at one of its US refineries in 2005, which killed 15 people and injured 170 more. Since then BP has suffered a series of other disasters. In 2006, several of its pipelines in Alaska sprang leaks, briefly forcing the closure of the USA's biggest oilfield and prompting oil prices to jump[14]. These incidents seem to be another cause of the BP poor share performance in the second half of the period under analysis. Towards the end of this period, BP reported a debt level of about $34.6 billion, with a total debt-to-equity ratio of 0.34, in line with its oil and gas peers. But to get to this point, BP had to shed its chemical assets, sell its US retail sites, and continue reducing its logistics footprint[15].

Conoco Phillips has also suffered from a hefty debt. At the end of the period, the company reported a total debt of US$28.7 billion, with a total debt-to-equity ratio of 0.45, one of the highest among its peers[16]. This debt has been used to build a large, diversified resource portfolio, which according to the company will offer years of ongoing development potential. To seize these opportunities, late in 2009 the company announced a plan to divest approximately $10 billion in non-core assets to reduce debt and improve the balance sheet.

Another interesting case is Apache Corp, a medium-sized independent oil company, which multiplied its TSR almost eight times in the period. As expected, its corresponding TRI was multiplied about five times. Interestingly, Apache focuses solely on the upstream segment of the business. The Apache formula has been 'growth as a priority', and the company has done this consistently and successfully since the 1990s, even in a strongly cyclical oil and gas business[17]. Apache has a reputation of being not only an efficient operator, but also an operator that can squeeze profitable production out of assets that other companies have not been able to successfully utilize.

Incidentally, Figure 6 shows that the best performers are indeed those companies that are solely focused on the upstream (Devon, Apache). Beyond supporting the initial proposition, it suggests that reserves growth seems to be a much tougher assignment for those larger and less flexible companies. Yet, there is no evidence that access to prospective resources is easier for smaller players; or that they may gain any competitive advantage because of their size.

The importance of oil reserves applies not only to independent publicly listed companies that trade in open markets, but also to state-owned corporations. This is reflected in the fact that the world's 13 largest oil companies in terms of reserves are totally or partially state-owned[18]. These companies have access to open financial markets, and most of them are also publicly listed and operate worldwide.

The most accessible and productive oilfields, including those in the Middle East and Russia, are now owned and operated solely by NOCs. In fact, between 2000 and early 2008, NOCs financially outperformed IOCs. NOCs have added more than twice as many reserves through new projects as IOCs have over the past five years[19]. This may indicate that the IOCs' value proposition has weakened and the future of their business model is increasingly challenged. And as the availability of 'bookable' reserves continues to diminish, the pace of growth of the major oil companies will likely suffer even more. As a result, less competent upstream companies will have a much more difficult time keeping their operations well funded[6].

In conclusion, outcomes from the oil and gas study support the model for value generation in mining discussed in the introductory section[1]. Moreover, both studies give solid grounds to the proposition that value creation in the exhaustible resource business is driven mainly by reserves growth. The model, however, provides no details as to why some companies perform this activity better than others or how this could be executed more efficiently. Some ideas to advance in this direction are analysed succinctly in the following sections.

An organization for the upstream

Once the fundamentals of strategy are understood and a strategy is set, the focus of the discussion switches to getting the right organzation to execute this strategy. In the resources business this encompasses the design of the administrative structures, processes, systems, and people[20]. This is in fact what apparently made the difference in the oil and gas industry in the late 1980s.

Regarding the structures employed by oil and gas companies, it must be acknowledged that the way in which people are grouped reflects plainly the importance that these companies give to the upstream segment of the business. The relevance of the exploration and production role is crucial, and at such it has a great deal of authority in the oil and gas firm. This position could be pragmatically redefined in the mining business as the mineral resource executive.

However, in the mining business this role rarely exists. Although in many instances it is common to find an exploration role, it hardly ever has the visibility and empowerment to execute the mineral resource management function as described here. In fact, this holistic function is usually overlooked in the traditional mining company. And when it does exist, it is usually fragmented and its parts allocated in the different downstream segments of the business; generally reporting to more operative executives whose activities are mainly driven by costs.

Processes are critical to business success as they are meant to ensure that decisionmaking occurs within the right context and decision variables are adequately appraised. Perhaps the most relevant process in the exhaustible resource business is the planning process—at the corporate level and business unit level as well. This is because of the finite, non-renewable nature of the mineral resource, which implies that alternative plans cannot be compared directly within a certain period. What is extracted in a certain period affects the extent and state of the remaining resource, so evaluations must extend over the life of the deposit and take into account variations in life as well as variations in schedules during the life.

Within this context it is much easier to assess the merit of an innovative tool called 'scenario planning', which found a breeding ground in the oil industry. This was created by Herman Kahn[§] and implemented in business successfully by Royal Dutch Shell more than three decades ago. Scenario planning is a process for learning about the future by understanding the nature and impact of the most uncertain and important driving forces affecting the world. Its goal is to craft a number of diverging stories by extrapolating uncertain and heavily influencing driving forces. Shell uses scenarios to explore possible developments in the future and to test its strategies against potential developments.

Systems are also central to strategy implementation as these ensure that plans are properly evaluated and execution is adequately tracked. Resource companies use numerous systems, but for the strategy viewpoint the most relevant are the capital budgeting and resource allocation systems, together with the compensation system. In both areas there have been interesting innovations in the past few decades, economic evaluation being a case in point. The traditional deterministic systems used by most resource companies—based on discounted cash flow techniques and central estimates for the main input variables—are being gradually replaced by stochastic systems such as simulation, decision trees, and real options. These techniques are more suitable for the evaluation of strategic scenarios as well as individual projects, which in the exhaustible resource business should be evaluated not incrementally with respect to a present situation (base case) but integrally using the chosen scenario.

To ensure organizational success, all of these components of the organizational design have to be closely aligned with people. Having the right talented people is crucial not only for strategy implementation but also for strategy formulation. A company, therefore, must ensure that its multi-skilled workforce fits the needs of the firm's strategy and, moreover, that the business strategy is clearly understood across the organization. Leadership is all about this, and this capability plays a pivotal role in the successful formulation and execution of the strategy.

Because of particular circumstances, the oil and gas industry counts on more appropriate practices to manage the upstream segment of the business that is core to its business strategy. Replicating this model in the mining business would require the consideration of the organizational design aspects previously discussed. The experience of the oil and gas industry, as well as additional research in the area, appears valuable for accomplishing this challenge. According to Bartlett, a promoter of a new managerial theory of the firm:

'[I]n the emerging organisational model, the elaborate planning, coordination and control systems are to be drastically redesign ... as management attention would shift towards the creation and management of process more directly to add value'[21].

On the whole, the quest for value in the resource business would require a fundamental reappraisal of the way companies plan and execute their businesses. This means focusing more attention on real value-adding activities[22]. The existing or potential resources represent nearly all the value ascribed to resource companies. The ability to manage them, therefore, is the main competitive advantage that a resource company has over its peers.

Conclusion

This study provides additional evidence to validate the proposition that the main levers of value creation in the

§Kahn's major contributions were the several strategies he developed during the Cold War to contemplate 'the unthinkable', namely, nuclear warfare, by using applications of game theory. Most notably, Kahn is often cited as the father of scenario planning.

resource business are in the upstream activities. This function is more prominent in the oil and gas industry, but not clearly defined in the mining industry. Lately, though, there has been more awareness about this issue in mining. An example of this is the creation of the mineral resource management function, which has been adopted by some mining companies in South Africa and Chile, although not with the same scope and emphasis discussed here.

At the corporate level, this function should foster the increase in resources through exploration and acquisitions and prepare the ground for their successful transformation into economic reserves to replace those consumed. At the business unit level, it aims to expand the resource base in the nearby area and plan the resource extraction more integrally so that value is maximized.

An effective separation of the business value chain is critical to achieve the benefit of this view of the business in the resource sector. The oil and gas industry made an effort in this direction more than 30 years ago and it seems it was worthwhile. Although the extent of the upstream segment in the oil and gas business is perhaps excessive—as it includes development and production—it could be useful for the mining industry to consider this experience in any change effort.

Beyond the common processes and systems for managing the value chain, what requires fixing in the resource business is the proper measurement of value—over the whole value chain and at each segment as well. The main missing part is the resource market value, which is usually overlooked at the time of measuring value creation and, more importantly, when planning the resource exploitation. In effect, as a resource is depleted its market value usually decreases, and this fact has critical implications in the determination of its optimal rate of extraction and rate of recovery.

The use of market-based transfer prices for inter-business sales seems to be a good option for an integrated company to measure value at each segment of the value chain. Thus, each segment is treated as an independent profit centre. For the upstream value measurement, the idea is to treat the resource as a capital asset and include its opportunity cost into the value equation. This notional cost refers to the option of selling the deposit and investing the proceeds elsewhere in a similar risk portfolio, which somehow has to be borne by the business. Successful value chain models need common and accepted methods to determine costs, margins, and investments[23]. In a value-driven company, everyone along the value chain should use the same numbers, speaks the same language, and aims, towards the same set of goals.

Focusing the resource business on the upstream segment is vital not only for strategy formulation in the resource company, but also for policy formulation in economies based on the export of finite, non-renewable resources. A country is potentially more prosperous and stable when it counts on a substantial and diverse resource base. This is especially valid in these days with the rapid development of the most populous emerging economies, hungry for resources. In fact, the latest global financial crisis affected the USA and Europe more severely than resource-endowed countries such as Australia, Canada, Chile, South Africa, and Brazil.

To improve nations' competitive advantage, governments may need to consider better policies for the resource business. Aspects such as foreign investment, property rights, taxation, and accessibility appear to be critical to generate stability and thus create a more favourable climate for resource exploration and development.

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An analytical solution to predict axial load along fully grouted bolts in an elasto-plastic rock mass

by H. Jalalifar*

Technical Note

Synopsis

Nowadays, fully encapsulated rockbolts have become a key element in the design of ground control systems. The main reason is that they offer high axial resistance to bed separation. In this research, the load transfer capacity of a fully grouted bolt is evaluated analytically in an elasto-plastic rock mass condition. The research considered the effect of bolt end-plate on load transfer capacity. Bolt and surrounding materials were assumed to be elastic and elastoplastic materials respectively. The load transfer mechanism of a fully grouted bolt is a function of parameters such as bolt length, shear stiffness of interfaces, *in situ* stress, presence of face-plate and distance along the bolt. These factors were analytically evaluated. Finally, the load along the bolt was predicted in different surrounding rock mass characteristics.

Keywords
fully grouted bolt, axial load, elastoplastic, analytical, numerical-load transfer.

Introduction

The interface shear stresses, rather than the grouting material itself, are of great importance in the overall resistance of a rockbolt system. There are limitations to pull tests in determining the resistance of interfaces, as stress distribution in the system is affected by the geometry of the bolt, borehole, and the embedment material properties. The characterization of the bolt surface has major effect on the load transfer capacity of a fully grouted bolt, because surface roughness dictates the degree of interlocking between bolt and resin.

In this research, to define the load developed along the bolt, an analytical model of a bolt embedded in elasto-plastic rock mass conditions was developed. The model was evaluated both with and without an end-plate. Finally, different surrounding rock characteristics were entered in the model and load transfer capacity along the bolt was predicted.

Load transfer capacity

During rock movement, the load is transferred from the bolt to the rock via the grout by the mechanical interlocking action between surface irregularities at the interfaces. When axial shearing occurs during rock movement, the load is transferred to the bolt as the grout interface shears[1]. The ability to transfer the load between bolt, grout, and rock depends on grout annulus, grout strength, bolt profile characteristics, the roughness and strength of the rock, and mechanical properties of the bolt.

Slippage may occur at the rock/grout or grout/bolt interfaces, both being called de-coupling. De-coupling takes place when the shear stress exceeds the strength of the interface. Failure in a laboratory test usually occurs along the bolt/grout interface. However, if rock, instead of a steel tube, is used as an outer casing element, then the failure may occur along the rock/grout interface, depending on the strength of the rock. If the rock is soft then failure occurs along the grout/rock interface because the mechanical interlock breaks down at low loads and frictional resistance comes into account. In hard rock the mechanical interlock would be dominant. Kilic[2] reported that when the surface friction of a borehole decreases, slippage occurs at the grout/rock interface, and when the length of the bolt and borehole exceed a critical length for a 21 mm diameter bolt in a 27 mm diameter hole, failure takes place at the bolt. This has been demonstrated by laboratory tests[3]. Figure 1 shows the schematic representation of load transfer generated at the interface together with the

* Department of Petroleum and Mining Engineering, Environmental and Energy Research Center, Shahid Bohanar University of Kerman-Iran.

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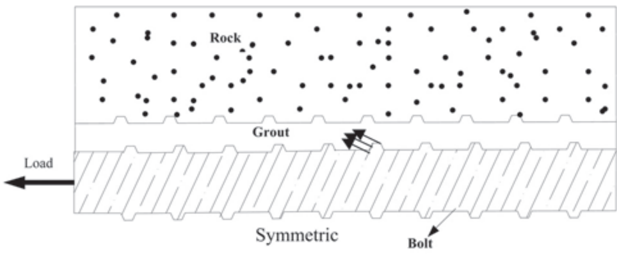

Figure 1—Sketch of bolt-grout-rock interface configurations

bolt profile configuration. This shows that mechanical interlocking occurs when irregularities move relative to each other (wedges are created).

During shearing, surface interlocking will transfer the shear forces from one element to another. When the shear forces exceed the maximum capacity of the medium, failure occurs and only frictional and interlocking resistance will control the load transfer characteristics of the bolt. Effective bonding between bolt, resin, and rock can be attributed to adhesion, friction, and mechanical interlocking, but their relative importance depends on the test conditions. Adhesion is normally almost negligible, and this was clearly demonstrated by sawing a column of resin block cast on a bolt along the axis. Each section of resin detached cleanly from the bolt with the force applied, which was also supported by the results of bolt/resin shearing tests carried out under constant normal stiffness[4]. Bonding strength is almost zero when normal stress is reduced. It should be noted that friction also depends on surface roughness. It is obvious that the confining pressure applied has a major influence on the level of friction and interlocking action at the bolt–resin interface. Kaiser *et al.*[5] reported that a mining-induced stress change is one of the most important parameters controlling bond strength.

Bond failure mechanism

When an axial load is applied to a bolt, it stretches longitudinally and contracts laterally because of Poisson's effect. When contraction occurs the bond breaks at the interface. Stretching and contracting is calculated in both pull and push tests during loading.

In pull and push laboratory tests, slip and yield occurred at the bolt/grout interface and the bolt did not fail internally[6]. For a bolt to undergo necking it must be gripped firmly at both ends, but pulling a bolt reduces its diameter longitudinally, resulting in contraction according to Poisson's effect, which would obviously affect its load transfer capacity. De-bonding and reduction occur after the load-displacement curve has risen linearly. Based on the numerical analysis of[6], there is a high level of load induced in the head, which reduces exponentially along the length. Increasing the load propagates the de-bonded area further along the bolt and expands it proportionally. From here the load decreases and the hinge point in the curve (load-displacement), called the maximum bearing capacity, is formed. After the peak point of the shear load, shear displacement depends on interlocking phenomena, which are a function of the profile specifications, resin grout properties, and resin thickness.

Analysis of an elastic bolt surrounded by plastic rock mass

The load transfer mechanism of a fully grouted bolt is a function of the surface condition, because surface roughness dictates the degree of interlocking between bolt and resin. The shear stress at interfaces, rather than of the grouting material, is of great importance in the overall resistance of a rock bolt system.

In modelling a single dimensional resin grouted anchor, Farmer[7] advanced a theoretical solution for a circular elastically anchored bar surrounded by an elastic grout confined in a rigid borehole. He derived a homogeneous linear differential equation describing the distribution of the force along the anchor. The decay function was exponential in form. Pull tests on concrete, limestone, and chalk yielded different results. Good correlation was obtained in concrete under low axial loads, but in weaker limestone and chalk the results were inconsistent. Farmer also found the shear stress in the resin annulus was a function of the resin grout.

Following Farmer[7], the equilibrium of a fully grouted rockbolt may be written:

$$A_b \delta\sigma_x = -F_x \Delta x \qquad [1]$$

$$\frac{\Delta\sigma_x}{\Delta x} = \frac{-F_x}{A_b} \qquad [2]$$

where;

A_b is the bolt cross-section area

F_x is the shear load due to the bond per unit length under elastic behaviour conditions.

$$\sigma_x = E_b \frac{du_x}{dx} \qquad [3]$$

Then substituting [3] into [2]:

$$\frac{d^2u_x}{dx^2} = \frac{-F_x}{A_b E_b} \qquad [4]$$

In other words, the shear force due to the bolt can be assumed as a linear function of the relative slip between the bolt and the rock[8].

Then,

$$F_x = K(u_r - u_x) \qquad [5]$$

where:

K = shear stiffness of the interface (N/mm^2)

u_r = rock displacement along the bolt (mm), which decreases with distance from the surface of the excavation and depends on various *in situ* parameters such as, initial stress, rock mass modulus, bolt length.

By combining [5] and [4] the following equation for a distribution of displacement along the bolt was obtained.

$$\frac{d^2u_x}{dx^2} - \frac{Ku_x}{A_b E_b} = \frac{-Ku_r}{A_b E_b} \qquad [6]$$

Moosavi[8] used Equation [6] for analysis of cable bolts, but he considered both bolt and rock mass in an elastic state. In this model the bolt and the rock mass are considered as elastic and elasto-plastic respectively.

In the above equation, u_r can be represented by an analytical function of the geometry of the tunnel and rock surface movement.

$$u_r = \frac{u_{r_o \cdot r_o}}{r_o + x} \qquad [7]$$

where

r_o = tunnel radius.

u_{ro} is the total deformation of the excavation wall, and is written as[9]

$$u_{ro} = \frac{r_o B}{f+1}[2(\frac{r_e}{r_o})^{f+1} + (f-1)] \qquad [8]$$

$$B = \frac{1+v}{E_r}(Po - \sigma r_e) \qquad [9]$$

$$\sigma r_e = \frac{2}{1+k}(Po+b) - b \qquad [10]$$

Parameters b, k, and f can be found from following Equations [9].

$$b = \frac{c}{\tan\varphi} \qquad [11]$$

$$k = \tan^2(45 + \frac{\varphi}{2}) \qquad [12]$$

$$f = \frac{\tan(45 + \varphi/2)}{\tan(45 + \varphi/2 - \Psi)} \qquad [13]$$

where

v = Poisson ratio of rock mass

Po = *in situ* stress

c = cohesion

φ = friction angle

r_e = the boundary between the zone of plastic and elastic deformation

By combining Equation [8] into Equation [7] and then Equation [7] into Equation [6] and solving, the following numerical method has been developed. It is noted that the numerical method was used as a powerful tool to solve the developed analytical model.

In this case the bolt was divided into equal parts, and then the load distribution can be obtained by linking these small sections together. Thus to solve the reference equation (Equation [6]), dimensionless quantities are defined.

$$x' = \frac{x}{r_o}, \quad u'_x = \frac{u_x}{u_{ro}}, \quad u'_r = \frac{u_r}{u_{ro}}$$

This can be written as;

$$\frac{d^2u'_{x'}}{dx'^2} - \frac{Kr_o^2}{A_bE_b}u'_{x'} = \frac{Kr_o^2}{A_bE_b}u'_r \qquad [14]$$

$\frac{Kr_o^2}{A_bE_b}$ is a dimensionless quantity. By defining $\gamma = \frac{Kr_o^2}{A_bE_b}$, it can be written as,

$$\frac{d^2u'_{x'}}{dx'^2} - \gamma u'_{x'} - \gamma u'_r \qquad [15]$$

By dividing the bolting to n equal sections (Figure 2), and defining $\Delta x' = x'_{i+1} - x'_i = L/(nr_o)$, the expressions for the derivatives of $u'_{x'}$ at $x' = x'_i$ are given as

$$\frac{du'_{x'}}{dx'} = \frac{u'_{x'}(x'_{i+1}) - u'_{x'}(x'_{i-1})}{2\Delta x'} \qquad [16]$$

or

$$\frac{du'_{x'}}{dx'} = \frac{u'_{x'}(x'_{i+1}) - u'_{x'}(x'_i)}{\Delta x'} \qquad [17]$$

$$\frac{d^2u'_{x'}}{dx'} = \frac{u'_{x'}(x'_{i+1}) - 2u'_{x'}(x'_i) + u'_{x'}(x'_{i-1})}{(\Delta x')^2} \qquad [18]$$

Equation [15] for $i = 2, \bullet\bullet\bullet, n$ can be written as;

$$u'_{x'}(x'_{i-1}) - \left[2 + \gamma(\Delta x')^2\right]u'_{x'}(x'_i) + u'_{x'}(x'_{i+1}) = -\gamma(\Delta x')^2 u'_r(x'_i)$$

These n-1 equations with two boundary conditions will form a tri-diagonal system of n + 1 linear algebraic equations with n + 1 unknowns, $\{u'_{x'}(x'_i)\}$, thus we have

$$u'_r = \frac{1}{1+x'} \qquad [19]$$

A bolt under tension compresses the rock, which prevents bed separation and frictional forces developing between the layers, but this does not mean that more tension creates better stability[10]. When a bolt is pre-tension loaded it would influence the shear strength of the joint with forces acting both perpendicular and parallel to the sheared joint by inducing confining pressure. A general rule for determining maximum pre-tension is that it should not exceed 60% of the bolt yield strength or 60% of the anchorage capacity[13]. In this research the following two cases are examined;

- *Case 1*—Bolt installed without face plate $F_x = 0$ at $x = 0$ and $F_x = 0$ at $x = L$

where

$$F_x = A_bE_b(\frac{u_{ro}}{r_o})\frac{du'_{x'}}{dx'} \qquad [20]$$

Defining the normalized force $F'_x = F_x/(A_bE_b)$, the above boundary conditions will be equivalent to:

$$u'_{x'}(x'_2) - u'_{x'}(x'_1) = 0 \text{ and}$$
$$u'_{x'}(x'_{n+1}) - u'_{x'}(x'_n) = 0 \qquad [21]$$

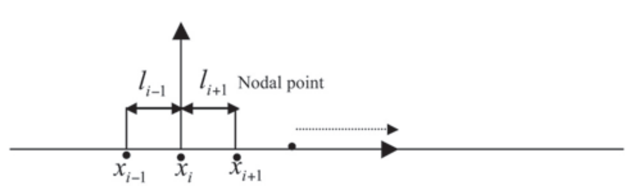

Figure 2—Notation for numerical formulation

➤ *Case 2*—Bolt installed with attached face plate $u_x = u_{r0}$ *at* $x = \mathbf{0}$ and $F_x = \mathbf{0}$ at $x = L$, or $u'_{x'}(x'_1) = 1$ and $u'_{x'}(x'_{n+1}) - u'_{x'}(x'_n) = 0$

The load developed along the bolt in both the above cases was analysed and following results were obtained.

Case 1: Bolt without face-plate

Figures 3 to 8 show the distribution of axial load developed along the bolt and normalized displacement, without a face-plate, installed in surrounding plastic materials. Three different bolt lengths, namely 2.1 m, 5 m, and 10 m were used for the analyses. The results are in agreement with the findings of Tang *et al.*[11], who applied a generalized finite element technique. The input data for the surrounding materials are used according to Strata Control Technology's report[12]. The initial stress and rock modulus of elasticity are considered to be 25 MPa and 15 000 MPa respectively. Figure 3 shows the axial load profile along the bolt in different lengths. With increased length, the axial load is increased and also the peak point of the load moves towards the end of the bolt. In addition, the load is concentrated near the excavation surface. Figure 4 shows the normalized displacement as a function of bolt length. It shows that with an increase in length, displacement of rock is reduced.

Figure 5 shows normalized displacement as a function of length for a 2.1 m bolt, in 15 MPa initial stress and with different interface shear stiffness values. It can be seen that, with an increase in interface stiffness, displacement is reduced. Using Equations [8] to [10], the value of u_{ro} in 15 MPa and 25 MPa initial stress is 6.3 mm and 10 mm respectively.

Figure 6 shows the load developed along the bolt increasing with an increase of initial stress at a constant stiffness. Figures 7 and 8 show load distribution along the bolts 2.1m and 10 m long respectively at 25 MPa initial stress for different values of rock modulus of elasticity. It shows that softer rocks generate higher load along the bolt. From the figures it is noted that the maximum load developed along the bolt is close to the bolt face-plate in the long bolt and almost centralized in normal length (2 m), which is in agreement with the field results and bolts installed in jointed rocks. When rockbolts are installed in the tunnel, the load generation initiates at the bolt/grout/rock structure. The full length of the bolt can experience loading. In reality, when adjacent rock blocks are sheared, due to joint roughness dilation occurs and this generates tensile forces in the bolt.

The results obtained from the analytical developed model were verified with the results obtained from the field investigation as shown in Figure 9[13]. The load developed on the bolt is with respect to the retreating longwall face positions. For example, the load developed long the bolt was monitored

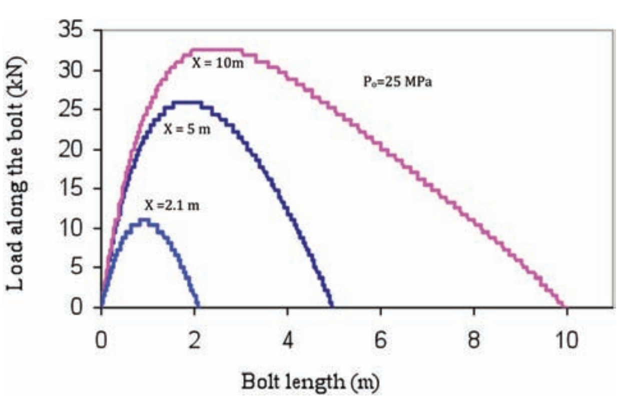

Figure 3—Axial load along the bolt versus bolt length, with 25 MPa initial stress and 15 GPa modulus of surrounding rock, no face plate

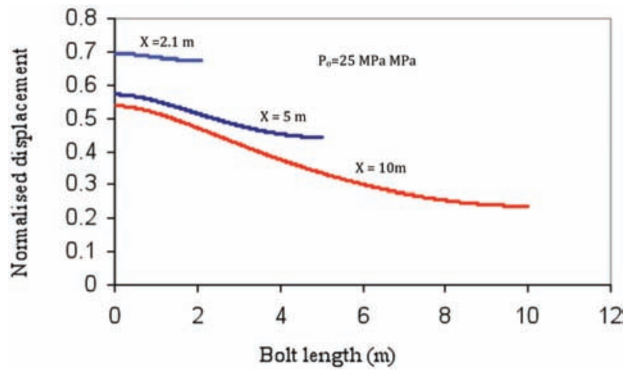

Figure 4—Normalized displacement versus bolt length for a bolt without a plate with 25 MPa initial stress and 15 GPa modulus of surrounding rock

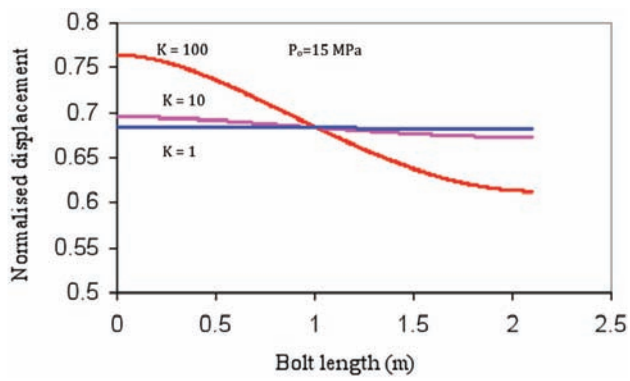

Figure 5—Normalized displacement versus bolt length for a bolt without a plate, with 15 MPa initial stress and 15 GPa modulus of surrounding rock at different *k* (shear stiffness, N/mm²) values

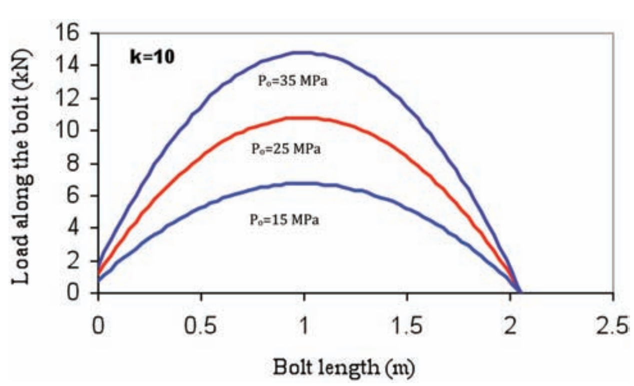

Figure 6—Load developed along the bolt versus bolt length in case of a bolt without a plate, with 15 GPa modulus of surrounding rock at different initial stresses

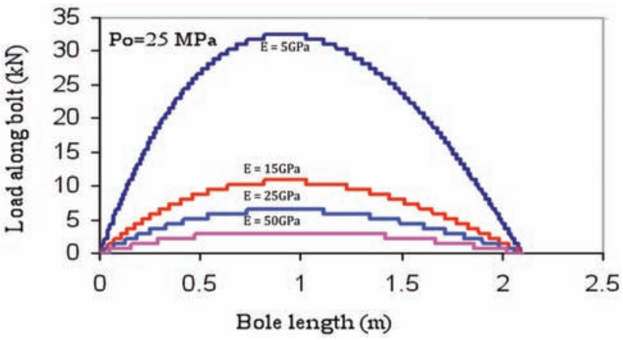

Figure 7—Load developed along the bolt versus bolt length in case of a bolt without a plate, with 25 MPa initial stress and different modulus of surrounding rock at *k*=10 (shear stiffness, N/mm²), *L* = 2 m

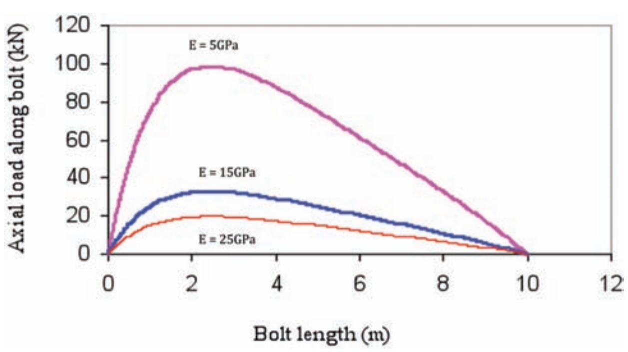

Figure 8—Load developed along the bolt versus bolt length in case of a bolt without plate, with 25 MPa initial stress and different modulus of surrounding rock at *k*=10 (shear stiffness, N/mm²), *L* = 10 m

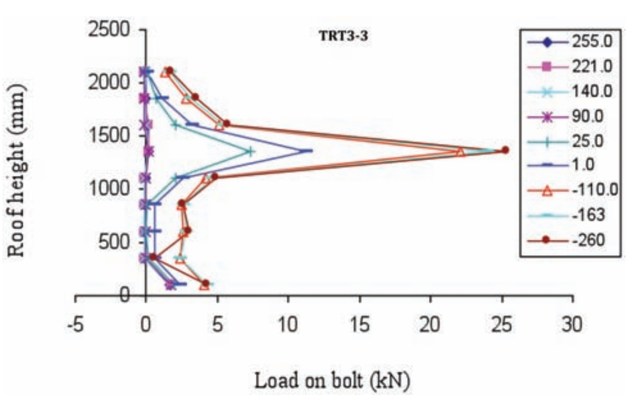

Figure 9—Load transferred on the bolt installed at the Metropolitan Colliery with the time lapsed (after Jalalifar[13])

from the initial longwall position 255 m ahead of the site to when the longwall face passed the site by 260m. As Figure 9 shows, the maximum load is approximately at the middle of the bolt, when the bolt is installed through the roof, which verifies the developed analytical approach.

Case 2: Bolt with face-plate

Using Equation [17] and boundary conditions in case 2 (using an end-plate), the axial load built up along the bolt and distribution of the bolt interface displacement for different bond strength, rock mass modulus of elasticity, and bolt length in various initial stresses were analysed. Figures 10 and 11 show respectively the axial load and distribution of the bolt displacement in two different bond stiffness conditions. It can be seen that the bond has significant influence on the development of load along the bolt length and the displacement. Figure 12 shows the distribution of axial load for different values of rock modulus and different

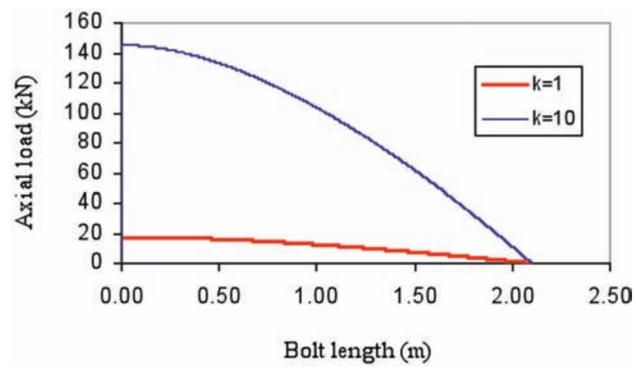

Figure 10—Load developed along the bolt versus bolt length in case of using end plate with 25 MPa initial stress and different k (shear stiffness, N/mm²), at E_r = 5 GPa

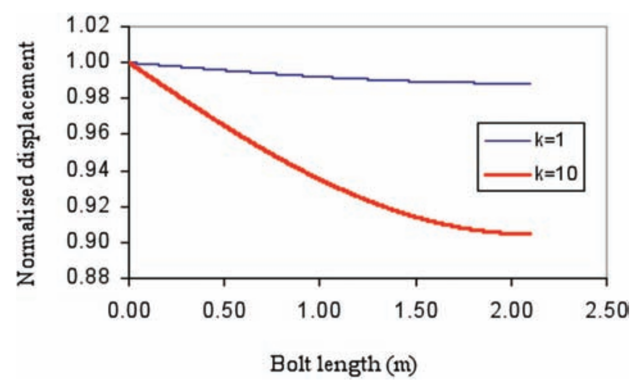

Figure 11—Normalized displacement versus bolt length in case of using end plate with 25 MPa initial stress and different *k* (shear stiffness, N/mm²), at E_r = 5 GPa

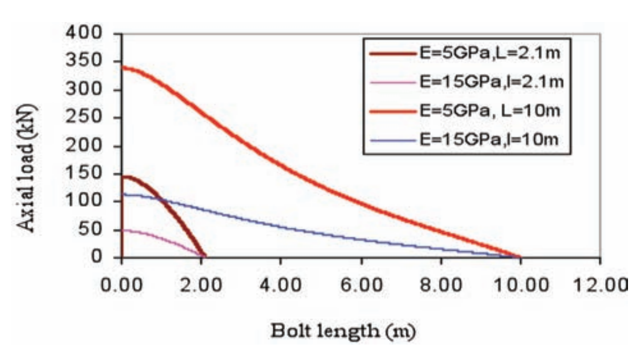

Figure 12—Axial load versus bolt length in case of using end plate with 25 MPa initial stress and different rock modulus and bolt length, k=10 (shear stiffness, N/mm²)

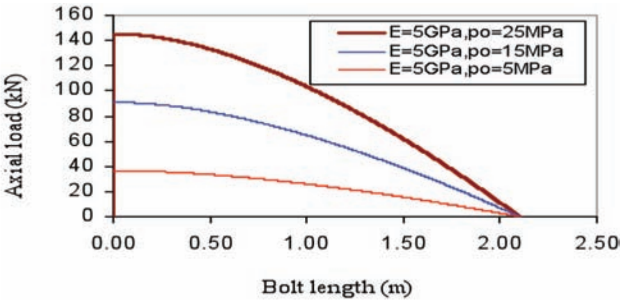

Figure 13—Axial load versus bolt length in case of using end-plate in different initial stress conditions with 5 GPa rock modulus, *k*=10 (shear stiffness, N/mm^2)

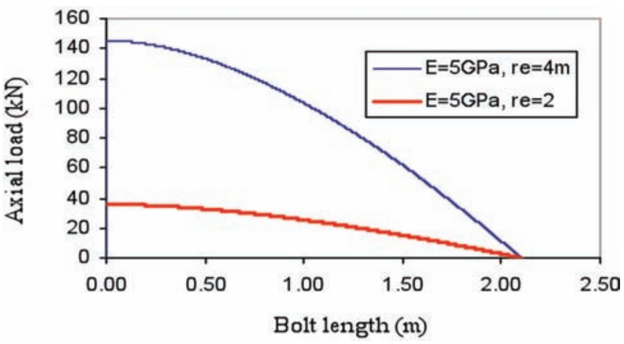

Figure 14—Axial load versus bolt length in case of using end-plate in different plastic zone radius with 5 GPa rock modulus, k=10 (shear stiffness, N/mm^2)

bolt lengths. It shows that a higher rock modulus of elasticity generates a lower axial load along the bolt. This trend decreases exponentially towards the bolt end for both bolt lengths. Figure 13 shows the axial load distribution along the bolt in different initial stress conditions. It reveals that the surrounding rocks with higher initial stress induce a higher axial load along the bolt. As Figure 14 shows, the axial load reduced with decreasing radius of the plastic zone around the tunnel.

Conclusion

From the axial load developed along the elastic bolt surrounded by elasto-plastic materials in a circular tunnel, it can be inferred that bond strength, rock mass modulus, and initial stress have a significant affect on the load distribution level. Also, when a bolt is not anchored at both ends, the peak maximum axial load appears in the middle of a bolt 2.1 m in length. However, increasing the bolt length shifts the peak position closer to the surface of the excavation.

From the above both cases analyses, it can be inferred that:

- Higher values of k generate higher axial loads.
- Axial load increases with greater level of the initial stress
- Higher values of rock modulus of elasticity induce higher values of axial loads
- The distribution of bolt displacement is narrower with increasing bond strength and bolt length
- A lower value of the plastic zone reduces the value of bolt load generation.
- Softer rocks generate higher loads along the bolt.

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Contact: Jacqui E'Silva
Tel: +27 11 834-1273/7,
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E-mail: jacqui@saimm.co.za
Website: http://www.saimm.co.za

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Contact: Raymond van der Berg
Tel: +27 11 834-1273/7,
Fax: +27 11 838-5923 / 833-8156
E-mail: raymond@saimm.co.za
Website: http://www.saimm.co.za

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Contact: Jacqui E'Silva
Tel: +27 11 834-1273/7,
Fax: +27 11 838-5923 / 833-8156
E-mail: jacqui@saimm.co.za
Website: http://www.saimm.co.za

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Tel: +27 11 834-1273/7,
Fax: +27 11 838-5923 / 833-8156
E-mail: raymond@saimm.co.za
Website: http://www.saimm.co.za

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Tel: +27 11 834-1273/7,
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Tel: +27 11 834-1273/7,
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Tel: +27 11 834-1273/7,
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Website: http://www.saimm.co.za

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