


Employment-oriented Industry Studies

Innovation in Resource-based Technology Clusters: Investigating the Lateral Migration Thesis

An Analysis of Hydraulic Technologies in South Africa's Mining Sector

T.E. Pogue & M. Rampa

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An Analysis of Hydraulic Technologies in South Africa's Mining Sector

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Abstract

This paper examines a co-operative initiative undertaken by South Africa's gold mining companies through the Chamber of Mines Research Organisation (COMRO) in development of hydraulic technologies for mining in South Africa. After a brief description of the structure of these technologies development under COMRO's stewardship, the paper turns to an overview of the system of innovation. We highlight the important contribution of industry initiative and State policies in drawing domestic capabilities together with international expertise to develop this technology. These hydraulic technologies were at the international forefront in their development. However, to date the technology has only diffused in a limited way to other mining applications and less so in other non-mining applications. We examine reasons for the success and failure of hydraulic technologies, showing that while there remains huge potential for diverse application of the technology there is no certainty that that application will occur or have a significant impact on South African expertise.

Acronyms

AAC	Anglo American Corporation (AngloGold Ashanti Limited)
COMRO	Chamber of Mines Research Organization
COMSA	Chamber of Mines of South Africa
EH	Emulsion Hydraulic
GFSA	Gold Fields South Africa (Gold Fields Limited South Africa)
GPC	Gold Producers Committee
HH	Hydro-hydraulic
HSRC	Human Sciences Research Council
kPa	Kilopascal (1,000 Pa)
MPa	Megapascal (1,000,000 Pa)
Pa	Pascal
R&D	Research and Development
RA	Research Advisor
RAC	Research Advisory Committee
S&T	Science and Technology
TA	Technical Advisor
TAC	Technical Advisory Committee
TRAC	Technical and Research Advisory Committee
U.K.	United Kingdom
U.S.	United States

> "I presented the 2004 Technology Top 100 award for 'Outstanding Technological Innovation' to a company that has developed a sophisticated heavy-duty pneumatic rock drill. This is Sulzer Pumps and its hydro-mining division. They have developed a world first technological capability to drill with water rather than oil as the lubricant. Of special significance is that this achievement addresses a number of health and environmental issues in the mining industry. This innovation has the potential to revolutionise the entire drilling industry, from mining to construction."
>
> Mr. Mosibudi Mangena, Minister of Science and Technology, 22 November 2004

1 Introduction

This case is part of the Human Sciences Research Council (HSRC) Lateral Migration Project. Focus is on a set of hydraulic technologies developed between the 1960s and 1990s. Through a co-operative initiative of South Africa's gold mining companies these technologies created international markets for both equipment suppliers and mining consultants associated with their development.

Section two begins our analysis with a description of the development of hydraulic technologies. Two distinct stages of hydraulic technologies' are identified. First, emulsion hydraulic (EH)[1] technologies were developed and commercially deployed between the mid-1960s and the late 1980s. Second, water or hydro-hydraulic (HH)[2] technologies were developed and commercially deployed between the early 1980s and the early 1990s. While overlapping, the EH technologies were an important step in a learning process that eventually led to EH technologies displacement by HH technologies. Section two also highlights inter-relationships among hydraulic drilling and hydraulic power technologies. These applications symbiotically led to the eventual development of a suite of commercially viable hydraulic equipment and consultancy services.

In Section three, attention turns to the structure of innovation within which these hydraulic technologies were developed. The primary organization responsible for development of these technologies was the Chamber of Mines Research Organization (COMRO). COMRO's creation and eventual dissolution corresponds closely to the initiation and conclusion of research into hydraulic technologies.[3] Therefore, Section Three examines some reasons for the creation, transformation, and eventual dissolution of COMRO. The Section concludes with an evidence-based reflection on whether similar technologies are likely to emerge in the present system of innovation.

Section four examines the evolution of HH technologies and their demand since the dissolution of COMRO. In line with the focus of this project, the section is divided between the evolution and demand for HH technologies in its original market and HH technologies evolution and demand in alternative markets. In the original market HH technologies today form the core business of several South African based equipment manufacturers. Several mine consulting services firms also had linkages of varying strengths to HH technologies. Today, with several years of relatively stagnant demand for new systems based on HH technologies, these firms in the service sector find HH technologies have an ancillary role in their operations.

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[1] Emulsion hydraulics involves mixtures with non-soluble oil finely dispersed in water.
[2] Hydro-hydraulics involves no oil and just utilises water.
[3] Nonetheless, hydraulic technologies continue to be refined and developed by equipment manufacturers.

There are a host of other applications for HH technologies besides mining. Internationality, these technologies have also played an important role in the development of mining service organisations and equipment suppliers in a range of other activities. In many instances these indirect markets have already or promise to surpass in importance the direct application of the COMRO developed technologies. As such, this indirect migration illustrates another important dimension to the migration of technologies and the potential benefits of technology support initiatives.

The final section brings the analysis full circle by reflecting on evidence from this case on key dimensions that describe lateral migration. These dimensions consist of the absorptive capacity of firms, the role of foreign technology transfers, the role played by networked relationships, and the role played by industrial and innovation policy. This paper thus provides important evidence of lateral migration in South Africa's economy. In addition, it provides a previously undocumented history of the evolution of a major feature of the system of innovation in South Africa's mining sector.

2 Development of hydraulic technologies[4]

The development of hydraulic technologies originated within a much broader effort to decrease the labour intensity of gold mining on the Witwatersrand. Referred to as 'mechanization', this transformation began to be expressed by the mining industry in the late-1950s.[5] In the 1920s, Witwatersrand mining had transformed stoping practices underground through the introduction of pneumatically powered rock drills.[6] In order to facilitate replacement of predominantly expatriate white miners with this technology, the mines committed themselves to racial occupational mobility restriction over Black miners.[7]

As existing goldmines went deeper and new fields in the Far West Rand and Orange Free State were developed over deposits beginning at ever-increasing depths, the racial occupational mobility restrictions created ever-increasing burdens on the industry. With a legacy of internal racism and a broader political economy of racial discrimination impeding any likely removal of occupational mobility restrictions, mechanization offered the Witwatersrand gold mining industry a means to increase the efficiency of production. Greater output per worker under ground along with the static real wage being paid to Black miners at the time meant that the higher costs of production at depths could be covered.[8]

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[4] This section benefited from discussions with George Harper, Peter Hes, Noel Joughin, Geoff Minnitt, Mike O'Connor, Alex du Plessis, Julian Wills, and Denis Wymer. However, this section is not, necessarily, a reflection of their opinions and inaccuracies that exist are the authors'.

[5] See Black and Edwards (1957) and Hamilton (1963).

[6] Stoping practices are the underground operations removing the gold bearing host rock (reef). Underground mining uses tunnels, dug horizontally from the shafts, to access and transport the reef. The actual work area where the reef is extracted is called the stope. The basics of shaft digging, tunnelling, and stoping are similar processes; involving drilling small holes (blast holes) into the hard rock, planting and detonation of explosives in these blast holes and then clearing the blasted material..

[7] See Johnstone (1976).

[8] Wilson (1972) shows that the real wage paid to Black miners was static between the 1920s and early 1970s.

Previously, many of the technologies that changed the Witwatersrand gold mining industry had been developed by the mining-finance groups. In the 1950s, as some of the traditional technological leaders diversified out of Witwatersrand gold mining, COMSA became an increasingly important player in the industry's research activity.[9] Despite some misgivings and institutional rigidities favouring technical or engineering sciences, COMSA established COMRO in 1964 with a linear focus on scientific research feeding into technological development.[10]

Shortly after its formation in 1965 COMRO established a new Mining Research Division (MRD) tasked with developing technologies to improve the efficiency of underground gold mining operations. The MRD marked the beginning of co-ordinated research by the industry into development of underground mining technologies. However, two changes in the early-1970s to the structure of the gold market led COMSA's Gold Producers Committee (GPC) in 1974 to commit COMRO to a large systematic ten-year research initiative into the development of mechanization technologies for operations underground.[11] First, African nations in a post-colonial setting threatened the supply of relatively inexpensive Black miners from across Southern Africa.[12] Between 1973 and 1976, the number of foreign workers on the Witwatersrand gold mines dropped from 336,000 to less than 200,000 (Crush et al. 1991, p. 101). Second, in 1971 the United States abandoned its underwriting the fixed-price of gold leading to a marked appreciation. Between 1971 and 1973, the real annual compound price of gold in Rand rose at a rate of 42.4%.[13] As operating under the racial occupational mobility restrictions fundamentally constrained production efficiencies, particularly at ever increasing depths, and with little short-term solutions, the industry turned to the mechanisation programme as a means to access the Witwatersrand deposits that continued deeper underground.

2.1 Development of emulsion hydraulic technologies

Table 1 lists important dates in the development of hydraulic technologies. From the mid-1960s to the early 1970s, initial research into underground technologies by COMRO focused on alternative technologies for stoping. None of these technologies was of direct importance to the subsequent development of hydraulic technologies in mining operation. Nevertheless, because many of these technologies had significant power and energy requirements, they contributed to COMRO investigating hydropower as an energy source.

[9] For instance in 1954, COMSA took over rock burst research that had previously been conducted under a collaborative research partnership between the mining-finance groups and the CSIR.
[10] See Section 3.1 for details on the creation of COMRO and its predecessors within COMSA.
[11] Besides stoping technologies, this research program also investigated environmental and safety technologies, mining operations, and human resources.
[12] See Spandau (1980) and Hermanus (1988).
[13] See table 17 in Chapter 4 for details of historic trends in the price of gold.

Table 1 - A selection of important dates in the development of hydraulic technologies (1965-1991)

1965	COMRO Mining Research Division established
1973	Hydro-power as energy source investigated
1975	Chilled water service for mine cooling begins production trial (completed 1977)
1975	COMRO & Ingersoll-Rand begin developing 95-5 drill
1975	COMRO & Vickers Systems begin developing 95-5 power system
1977	First prototype 95-5 drill tested at West Driefontein gold mine
1978	COMRO begins additional 95-5 power system development with Hammelmann
1979	Second prototype 95-5 drill tested at West Driefontein gold mine
1980	COMRO & Ingersoll-Rand develop quadruple plunger rotation mechanism for drill
1980	COMRO initiates research into combined hydraulic power and cooling systems
1982	Ingersoll-Rand production model 95-5 drill (tested West Driefontein June 1983 to March 1984)
1982	COMRO begins developing 98-2 & HH drills with Ingersoll-Rand, Seco, and Novatek
1983	First Prototype 98-2 power system developed (tested Kloof goldmine 1984)
1985	First Prototype HH power system developed (tested at Kloof goldmine 1985-1986)
1986	98-2 drills begin production tests in Far West Rand and Orange Free State gold mines
1987	COMRO leaves subsequent development of 98-2 drills to Ingersoll-Rand, Seco, & Novatek
1987	COMRO draws Crown Chrome Plating into hydraulic pump research as Vickers phased out
1988	COMRO working with equipment suppliers to develop open system of hydro-power & cooling
1989	Production models of 98-2 drills available
1980	Sulzer joins in COMRO hydraulic drill development initiative
1991	Production models of HH drills available

Source: Compiled by authors

Just before initiating the ten-year mechanization research and development (R&D) programme in 1974, William Rapson, COMSA's Research Advisor (RA) and COMRO's Director was replaced by Miklos Salamon. Thus, as COMRO's annual budget increased three fold, Salamon realigned COMRO's organisational structure to the mechanisation research programme. The mechanization research programme became COMRO's R&D ethos until the organisation's dissolution nearly twenty years later.

COMRO's strategy in developing stoping equipment was to maintain a critical stock of knowledge internally in order to ensure continuity in the technology's development. While maintaining that stock, COMRO sought to outsource its R&D to equipment suppliers, other research organizations, and South African Universities (Joughin, 1982). Nonetheless, a majority of basic research and early technical trials were done by COMRO itself. Collaboration with equipment manufacturers was emphasized and driven by several organizational priorities. Firstly, COMRO did not want to build itself into an equipment supplier, it also wanted to ensure market viability of its technologies and incorporate manufacturing know-how into the technologies' development as well as realize economies of scale and speed in development of the technologies through the broader base of all participatory organization. Lastly, collaboration focused on equipment manufacturers with local operations so that "…through the participation of manufacturers in the development it was hoped to encourage the timeous evolution in this country of a viable industry manufacturing mining equipment to supply the eventual requirements of the mines" (Salamon, 1976, p. 71).

Following a linear model of innovation,[14] when a technology's feasibility for development was established COMRO would involve equipment manufacturers. Working together closely in design, the manufacturers were responsible for construction and COMRO was responsible for evaluation. Rights for development of the technologies were vested with COMRO. As the hydraulic technologies were perceived to be high-risk, COMRO entered into a contract with equipment manufacturers where COMRO paid their costs plus a five percent premium, effectively bearing the costs of design, construction and evaluation.[15]

When more than one equipment manufacturer was involved in the development of a particular technology, COMRO would not exchange or transfer data about other equipment's performance between organizations. However, COMRO did advise each company whether a problem was unique to that company or if it had been experienced by one or more of the other companies. If a similar problem had been encountered by another partner, COMRO would advise whether a solution had been found. Thus, as we shall see later, this collaborative system structurally favoured late entrants because it made technological catch-up less burdensome than original development.[16]

The 1974 mechanization research programme consisted of two distinct groups of technologies: 1) conventional and 2) revolutionary. The conventional technologies focused on improving existing mining methods and under it, the hydraulic drill program fell. The revolutionary approach focused on changing the way of mining by moving from stoping by drilling and blasting to continuous mining with various methods of mechanical rock breaking. Early in the revolutionary technologies research, one of the most promising technologies was the drag-bit miner.[17] A drag-bit miner operates in manner similar to a chain saw, but it cuts with a large cylinder upon which rows of metal spike are mounted. The spiked drum is then driven into the host rock to break out the gold bearing ore. This promise of the drag-bit miner would be important as high-pressure water jets, around 30 mega Pascal (MPa),[18] were found to greatly increase its cutting efficiency (Hood, 1976). Emulsion sprays were simply not viable underground from both an environmental and economic perspective, so an early force for a pure water (hydro) system emerged.

In conventional technologies, alternatives for both pneumatic power and pneumatic equipment were sought because of the increasingly deep and fractured conditions underground.[19] Therefore, hydraulic technologies were investigated as alternatives to pneumatic technologies. Marshall (1975) gives a summary of early advantages and disadvantages of hydraulic technologies. In terms of energy efficiency, hydraulics had about a 30% rate of efficiency at the stope face compared to 10% for pneumatics. The physical law, force equals pressure times area, governs the power of a drill. Since, a

[14] For a critique of linear models of innovation see Kline and Rosenburg (1986).
[15] COMRO also had a 'low-risk' contract where equipment manufacturers bore design and construction costs while COMRO bore the cost of evaluation.
[16] For an explanation of why this would facilitate catch-up see Perez and Soete (1988).
[17] Other revolutionary technologies experimented with during this era were rock-cutters, swing-hammers, impact rippers and armoured face conveyors (Joughin, 1976).
[18] 1 MPa = 145 pounds per square inch (psi). An automobile tire is between 0.18 MPa and 0.25 MPa.
[19] See Whillier (1975), Clement (1975), and Marshall (1975).

functional maximum pressure for pneumatic equipment was reached at around 200 kilopascal (kPa),[20] hydraulic technologies with their greater range of pressures promised to deliver more power to the stope face. In addition, hydraulic drills have a stress wave of uniform amplitude. Therefore, a blow from a hydraulic drill with the same energy as a pneumatic drill has significantly less peak stress or for the same peak stress in a hydraulic drill there is a much higher energy content, both of which translate into greater economy of drill steel with hydraulic technology. Lastly, the hydraulic drills generate lower mechanical noise and much less exhaust noise than pneumatic drills making the work environment less hazardous to the drillers' hearing.

However, as hydraulic technologies were generally more complicated than the more established pneumatic technologies maintenance tended to require a higher level of skills. As a developing technology, hydraulics also tended to be less reliable than pneumatics. During this stage of development, hydraulic power for the drills was provided by electric hydraulic packs. Besides being cumbersome these packs generated a significant amount of heat, which was compounded by the fact that the early hydraulic drills did not having an integrated chilled water service like its pneumatic counter parts.

While bearing those fundamentals in mind, it is important to realise that development of the hydraulic drill and hydraulic power are separate stories with complementarities. As with the drill, the first generation of EH power equipment focused on a mixture of 95% water and 5% oil (95-5). Originally, COMRO worked with the United Kingdom (U.K.) based *Vickers Systems* in developing the 95-5 hydraulic power system, but in 1978 German-based *Hammelmann* also became involved. By the early 1980s, the initial electric-hydraulic packs on the stopes had been replaced by centralized stations, which made hydraulic technologies less cumbersome and did not introduce additional heat on the stopes. However, besides the drills development of EH power equipment held promise as an alternative to electric power. Because pneumatic power could not be efficiently provided in large quantities and generated little force, other equipment on the stope like the scraper winches utilized electric power. While electric power could be provided relatively efficiently in large quantities, it generated little force and introduced additional heat on the stopes. Therefore, EH power seemingly offered an important alternative to both pneumatic and electric power underground (Joughin, 1982).

In development of the first generation 95-5 EH drill, COMRO collaborated with United States (U.S.) based *Ingersoll-Rand*. Because of the rough operating environment, EH drills were not generally seen as viable. Inevitable leaks from an EH drill would expel environmentally and economically undesirable quantities of oil into the mine environment. Therefore, viable EH drills had to have a low ratio of water, which is why COMRO embarked with *Ingersoll-Rand* on the 95-5 drill.

Internationally, South Africa was not alone in its efforts to develop a hydraulic drill. In the 1970s, Australia, the U.K. and the U.S. all had some research initiatives into development of a hydraulic drill. In the 1970s, Australian and U.S. coalmines were working on a 60% water, 40% oil (60-40) hydraulic drill. That was too high a ratio of oil for South African mining conditions as well as the fire weary British coalmines. Thus, in the mid-1970s the British Board of Coal was also investigating development of a 95-5 EH drill. Similarly, in the mid-1970s U.S. automobile manufacturers were looking at using hydraulic cutters on a large scale and needing to economize on oil losses, they began to develop an 95-5 EH system. Accordingly, South Africa through

[20] 1,000 kPa = 1 MPa.

COMRO was participating in an international learning environment with a diversity of experiences to draw-on for technological development as well as expertise.

Three particularly significant challenges were met in developing a commercially viable 95-5 EH system for stoping on the Witwatersrand. First, because of the low viscosity it was necessary to introduce additional seals to prevent leakages. Those additional seals introduced additional friction, which caused all the seals to wear and deform much more rapidly. Therefore, COMRO collaboratively developed special plastic seals and bearings (Walczak, 1984).

A second challenge arose because at the 95-5 ratio the difficulties combining oil and water are no longer trivial (Wymer, 1976). The distances travelled by the low oil emulsions before reaching the drill would often cause a separation of the oil from the water i.e. a breakdown of the emulsion would occur. Eventually, a solution this problem of suspension came from U.S. oil corporations who developed micro-emulsions, which because of their much finer dispersion created a more stable mix of oil and water.[21]

Lastly, another major challenge in development of the hydraulic drill was in the mechanism to rotate the drill steel. The low-oil emulsions were causing traditional mechanism to wear at an unacceptable rate. After many iterations, a major break-through was realized when a quadruple plunger, ratchet and clutch, rotation mechanism was created.[22] By the early 1980s, *Ingersoll-Rand* and COMRO had developed two generations of prototype 95-5 EH drills as well as a production model. As they prepared for production trials COMRO also began systematic research into the necessary changes, innovations, to the labour force organisation to accommodate this new technology.[23]

With nearly a decade of diverse research behind them the 95-5 EH drills began their first production trials at West Driefontein gold mine in June 1983. Even before production trials began, significant optimism around the suite of hydraulic technologies had been building and applications beyond deep-level gold mining were envisioned. By the early 1980s, the next phase of research, development of a HH system, had also begun.

2.2 Development of water (hydro-) hydraulic technologies

By the late 1970s and early 1980s, senior managers at COMRO began to initiate researcher into HH (100% water) technologies. An intermediate step between 95-5 EH technologies and HH technologies were 98% water, 2% oil (98-2) EH technologies. At this time, under COMRO's direction, South Africa had become an international leader in these hydraulic technologies.[24] Remembering that the 1974 mechanization research programme was ending, three factors appear to be particularly significant in further development of HH technologies.

First, as previously mentioned, the revolutionary mechanical rock breaking program had found good performance in its drag-bits when used in conjunction with high

[21] In this, the interest of the U.S. automotive industry in a 95-5 EH cutter may have been important.

[22] As additional drill manufacturers subsequently became involved, other rotation mechanisms proved viable.

[23] See Glassborow and Veldsman (1982) and Veldsman and Pretorius (1983).

[24] For instance, the U.S. in the early 1980s were still working out problems in development of 60-40 EH systems.

pressure water, around 30MPa, on the rock surface. This performance resulted from the removal of waste rock under the teeth.[25] That research created a need for an all water high-pressure sprayer and development of that sprayer in the mid to late 1970s, gave COMRO important confidence in the feasibility of developing a HH power system.

Second, with the ever-increasing depths of mining on the Witwatersrand cooling had become critical. Previously, cooling had occurred at the surface and then the air was transported with pressure to required depth. However, the air warmed up in the process of transporting it and a significant amount of cool air escaped along the way to its final destination. Thus, gradually refrigeration units were moved underground. From 1972, COMRO undertook R&D into utilising chilled mine service water to directly cool the rock surface on the stope. With successful full scale trials between 1975 and 1977, it became clear that the direct application of chilled water on the rock surface was the best means to achieve a stable and tolerable underground temperature at increasing depths.[26] A fundamental efficiency of HH power thereby emerged, since it could function as both a cooling technology without the ad hoc difficulties of water-cooling with compressed air and simultaneous power source. Therefore, in 1980, COMRO initiated research into combined hydraulic power and cooling systems.

Lastly, with increasing depths of the gold mines' operations the latent energy in the column of mine service water was appreciated. A two kilometre column of water has a pressure of 20 MPa, which is the pressure needed to power the hydraulic drills. In hindsight, this resource was obvious. Water had to be pumped out of the mines anyway and since energy recovery turbines were already being utilised to pump water out of the mines, tapping into this system only required further development of sub-systems to keep the water in the pipes and move it to the rock face.

Therefore, in addition to the comparative drilling efficiencies of hydraulic drills over their pneumatic counterparts, HH power held systemic benefits for underground operations. Given this priority for hydraulic power, COMRO established an independent hydraulic power project and moved quickly toward development of HH power systems. By 1983, a prototype 98-2 EH power system had been developed and in 1984 it was tested at the number three shaft at Kloof gold mine (Joughin, 1986). Further development led to a prototype HH power system in 1985, which was also tested at Kloof along with ancillary HH equipment like scrapper winches and roof supports (Brown et al. 1986).

In the mid-1980s, South African based *Crown Chrome Platting* also became involved in HH power technologies while *Vickers Systems* withdrew from the research initiative. By the mid-1980s HH power had broadly proven its viability and awaited complementary development of ancillary equipment before it could be considered part of a truly commercially viable technology system. In 1988, COMRO began working with equipment manufacturers to develop an integrated open system with chilled water.[27] Because of the high pressures and associated dangers, technologies from the oil and nuclear industries were borrowed to guide development of HH piping systems. Safety systems from the nuclear industry were given particular attention because of their necessity for a rapid shut-down in case of failure.

In contrast to HH power systems, whose relative complexity reduced with the removal of oil, the complexity of HH drills increased. Nonetheless, as COMRO

[25] See Hood (1976) and Joughin (1978) for details.
[26] See Wagner and Joughin (1989) for details.
[27] See Brown and Joughin (1988) and Du Plessis and Soloman (1988) for details.

embarked on 98-2 EH drills on the way to HH drills, they were no longer in sole partnership with *Ingersoll-Rand* as the South African-based *Seco* and *Novatek* also joined the research initiative. Moving to the 98-2 drill was relatively straight forward, since the new emulsion mix, bearing and seal technologies transferred relatively easily from the 95-5 drill. Thus, in 1986 production trials of the 98-2 drill began on Anglo-American Corporations' (AAC) Orange Free State mines and on Gold Filed South Africa's (GFSA) Far West Rand mines.[28] After these trials in 1987, COMRO withdrew from further research in EH drills, concentrating on HH drills and leaving further development of EH drills to the equipment manufacturers. Nevertheless, by 1989 several production model 98-2 EH drills were available when Switzerland based *Sulzer* joined COMRO's initiative to develop a HH drill.

It is worth briefly describing the development of EH and HH technologies by the additional firms. *Seco*'s entry into the research initiative was highly significant since they dominated production of pneumatic drills sold in South Africa at that time. Seco took one of their oil hydraulic rock drills and converted it to a run on a 60-40 EH mixture.[29] Gradually they dropped the level of emulsion in the drill until it had was running as a HH drill. Despite good results in the laboratory the drill did not perform well in operation trials. Hence, as other companies released more reliable HH drills, Seco shifted further development of an HH drill to its U.K. facilities before eventually abandoning the project. *Novatek* was established expressly as a technology development company to participate in COMRO's hydraulic technologies programme. While a sister firm, *Innovatek* had been subsequently established to manufacture its drills, demand surpassed Innovatek's capacity in the early 1990s leading to a merger with U.K. based Gullick in 1992. Sulzer, in contrast to the other companies, developed its drills in Switzerland although in close collaboration with South Africans. Sulzer's first drill was based on the company's turbine pump technology.[30] However, after initial prototypes were developed production of Sulzer's drill was based in South Africa were further development of the drill also occurred.

Several additional challenges emerged as COMRO shepherded the initiative past 98-2 EH drills and on to HH drills. One fundamental challenge was around lubrication. Boundary lubrication prevents wear of two surfaces in contact. Even just atomic quantities of oil are sufficient to form a hydrodynamic film of fluid that would lubricate contact surfaces. However, in HH systems they found that boundary lubrication was not occurring. Thus, a range of solid lubricants like polymers, rubber and non-steel materials were investigated. Rubber was the eventually solution for static seals while polymers were utilised for dynamic seals. For bearings, polymers were the only viable materials.[31]

Another major challenge was the corrosion of steel because of its contact with the highly corrosive mine water. While 98-2 EH systems were sufficient to prevent corrosion, the pure water of the mines' was too harsh for the normal steel. Because existing alternative corrosion resistant material broke down under the mechanical forces that the drill were subjected, COMRO initiated development of novel corrosion resistant steels. These hybrid steels were developed in collaboration with U.S. and U.K. steel manufacturers. Despite good results from pilot melts, in the end they adapted existing steel. In fact, while the problem was particularly severe for the

[28] See Westcott (1986), Holloway et al. (1987), and Du Plessis et al. (1989) for details.
[29] That drill was known as the HD-30.
[30] This drill was known as the Turbo Drill.
[31] See Harper (1990).

drills corrosion was also a concern in the other equipment as well as the piping and power systems themselves.[32]

Progress in the HH drill was made continuously through the late-1980s, even as COMRO's organisational future was in doubt and *Ingersoll-Rand* withdrew from the research initiative.[33] Thus, in the early 1990s when GFSA announced its commitment to an entirely HH system in its newly developed Northam Platinum mine an important impetuous was created for the final drive in developing HH technologies. HH technologies were particularly appealing for Northam platinum mine because of its high underground temperature gradient.[34] While HH mining systems were still being developed, the technology was being deployed at Northam. Nevertheless, HH technology proved itself commercially viable through its deployment at Northam and by 1991 *Ingersoll-Rand*, *Novatek* and *Sulzer* each had production model HH drills (Solomon and Jones, 1994).

South African HH technologies for mining drew on international precedents in developing a unique technology. Under COMRO's stewardship important complementary international technologies were brought into the programme that eventually enabled viable HH technologies to be established. Representing the mining-finance group's demand COMRO interacted directly with a spectrum of research, development and equipment manufacturers in facilitating the emergence and commercial supply of an important alternative technology for stoping on South Africa's deep level gold mines.[35]

By the early 1990s, a commercially viable HH technology existed. In the early EH phases of its development fundamental drilling economies supported development of power systems, while efficiencies in the power systems assisted development of drills. While these mutual forces were important throughout, in the HH phases systemic efficiencies associated with the necessity to cool increasingly deep and hot mining environments as well as the static energy held in the column mine service water added significant optimism to the eventual diffusion and impact of HH technology.

However, the technical promise of HH technology has not been followed by the large uptake originally expected.[36] Currently, there are only four mines in the world that operate open HH systems and these were all involved in COMRO's development of the technology.[37] Among prominent reasons for the limited diffusion of HH technologies are differences between technical and operation efficiencies, the nature of the ore bodies that HH systems are designed, and inherent technological complexities.

Because there is no oil in HH equipment it must be manufactured to much greater degree of precision the oil hydraulic or EH equipment.[38] That greater precision adds a

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[32] See Howarth (1990).
[33] See Section Three for details.
[34] At a depth of two kilometers mines on the Witwatersrand were usually faced with an underground temperature of 32º C at Northam at two kilometres the underground temperature was 65º C.
[35] Notably international intellectual property rights did not play a significant issue in the development of HH technologies nor did foreign technology inflows enhance the incentives for innovation or diminish them.
[36] See Paraszczak et al. (1994), Wyllie (1990), and Joughin (1984) for examples.
[37] These are GFSA's Kloof and Beatrix Gold Mines, AAC's Tau Lekoa Gold Mine and Northam's Northam Platinum Mine.
[38] Acceptable precision in HH equipment is reportedly around +/- one micron (a millionth of a meter) compared to +/- twenty microns in oil hydraulic equipment.

fundamentally higher level of complexity and cost to the manufacture of HH equipment compared to other equipment. This inherent cost could be offset by production efficiencies and health and environmental savings,[39] but presently those benefits are not sufficient to induce the conversion of established mines to HH systems.

Another factor impeding the uptake of HH systems is that they are designed for relatively deep-level tabular ore bodies. The advantages of an HH system are greatest if it is part of the initial design of a mine. Presently, there is not much development of relatively deep-level mines because of the longer time necessary to realise a return on investment. As a result HH technologies must compete on a basis of ad hoc advantages over other established systems. In additions, the HH system was designed for mining Witwatersrand gold deposits which exist in the presence of a lot of mine service water. Few other ore bodies are reported to use nearly as much mine service water in their operations, which also reduces some of the inherent benefits of HH systems.

Lastly, underlying differences between technical and operating efficiencies have combined with the other factors to inhibit the diffusion of HH technologies. These differences between technical and operating efficiencies exist for several reasons. One issue is path dependence in the existing pneumatic-based system of stoping which creates agglomeration and routinization economies.[40] As long as pneumatic technologies predominate training and maintenance of personnel to utilise those technologies is common good. In contrast, similar economies can only be realised if a critical number of producers adopt HH technologies. To the extent that these economies exist, the concentration of mining activities acts to inhibit rather than facilitate technological progress. Some industry analysts have suggested that a limited absorptive capacity with the mining-finance groups themselves has also hindered the diffusion of HH technologies. When HH technologies were developed the engineering skills available were reported to be much higher than they are today. As a result, many mines do not have the requisite engineering capacity to divert from established operational practices or organisational routines.[41] Inter-agent authority over production also appears to be another important feature in the limited diffusion of HH technologies. In this respect, productive efficiencies from the introduction of HH systems on the stopes represent a potential reduction in the stoping workforce. Consequently, labour unions representing these workers have expressed resistance to the introduction of HH technologies.

[39] Among the more important environmental benefits of HH technologies are their removal of oil from the working and maintenance environment. In addition, HH drills have lower over-all noise than even muffled pneumatic drills which reduces worker hearing damage.
[40] See Arthur (1994) and David (1985) for further information on the concept of path-dependency.
[41] See Chapter Five in Nelson and Winter (1982) for an elaboration of the economics of organisational routines.

3 Aspects of mining's system of innovation[42]

Development of the hydraulic technologies described in section two depended fundamentally on COMRO. As a co-operative research organisation COMRO reflected interests of the South African mining industry, particularly the mining-finance groups and the Witwatersrand gold mines, but these interests were distinctly translated through COMRO's organisational culture. This section analyzes the institutional architecture in which hydraulic technologies were developed. Therefore, its central focus is on what gave rise to the formation of COMRO, how did COMRO evolve, why did COMRO dissolve, and what was the dynamic relationship between COMRO and hydraulic technologies. Since COMRO was part of COMSA, it is worthwhile to briefly review the role played by COMSA in the mining sector's system of innovation before COMRO.

From its earliest days COMSA engaged in the shaping of science and technology (S&T) policy. One of the most important and enduring means that COMSA did [does] this is through its Patents Committee. Established in 1892, the Patent Committee's original purpose was to contest the patent of the cyanide-based gold extraction process.[43] Besides settling the cyanide process patent, the Patent Committee took on a much broader role of surveying the granting of intellectual property rights in South Africa in order to ensure patents were not granted to public technologies.

Early on COMSA also attempted to co-ordinate the R&D of technologies for the industry. Thus, in 1893 it established a Metallurgical Sub-Committee to support the commercial development of cyanide based extraction technologies.[44] Then in 1908 COMSA established a Mine Trials Committee to facilitate development of pneumatic rock drill for stoping. Before COMRO, perhaps the most important step that COMSA took in the coordination of technologies for the industry was its establishment of the Technical Advisory Committee (TAC) in 1922 and the independent position of Technical Advisor (TA) in 1923.

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[42] This section benefited from discussions with George Ashworth, George Harper, Noel Joughin, Alex du Plessis, John Stewart, and Denis Wymer. However this section is not, necessarily, a reflection of their opinions and inaccuracies that might exist are the authors'.

[43] Cyanide-based extraction was critical to economically mine the vast majority of the Witwatersrand's gold deposits. Hence, in the face of a hostile Afrikaner government, the mining-finance groups undertook a role in ensuring intellectual property rights were not applied to public knowledge that would usually have been left to the patent office itself.

[44] Strictly speaking, the Metallurgical Sub-Committee was acting to facilitate development of a viable metallurgical process to extract gold from the pyritic deposits.

Table 2 - Select dates in the history of the mining sector's system of innovation (1896-1992)

1892	COMSA establishes Patent Committee
1893	COMSA establishes Metallurgical Sub-Committee
1908	COMSA establishes Mine Trials Committee
1914	COMSA establishes Dust Laboratory, based at COMSA head office
1922	COMSA establishes Technical Advisory Committee (TAC)
1923	Independent post of COMSA Technical Advisor (TA) established
1937	COMSA establishes Timber Research Laboratory, based at COMAS head office
1947	TAC raises need for separate labs for Dust and Timber laboratories - new facilities opened 1951
1953	COMSA conducts rock burst research previously done by Mining-Finance Groups and CSIR
1954	COMSA establishes Applied Physiology Laboratory at Crown Mines
1957	COMSA TA, M. Falcon, begins search for director of COMSA research
1960	COMSA establishes Research Advisory Committee (RAC)
1961	COMSA commissioned Schonland Report recommends establishing post of research advisor
1962	William Rapson becomes first COMSA Research Advisor (RA)
1964	Rapson unites research focuses of COMSA under single organization, COMRO
1971	U.S. Dollar convertibility to gold ended
1974	Malawi suspends COMSA labour recruitment
1974	COMSA commissions restructured COMRO on large-scale 10 year mechanisation research initiative
1988	COMRO review of delivery to industry leads to increased consulting emphasis
1989	COMRO budget cut significantly, COMRO tasked to co-ordinate mining research
1990	Further COMRO budget cuts lead to changing scope and structure, with safety research separated
1990	RAC and TAC merged to form Technical and Research Advisory Committee
1991	SIMRAC created, effected from 1993
1992	Merger of COMRO with CSIR finalised, effected in 1993

Source: Compiled by authors

The TAC was formed in the midst of a difficult transition of stoping practices on the Witwatersrand gold mines. The TAC consisted of one consultant and one mine manager from each of the seven principle mining-finance groups that operated on the Witwatersrand. Initially, the TAC was tasked with advising on issues forward to it by the Gold Producers Committee (GPC). However, with its establishment of an independent position of TA, the TAC was allowed to initiate investigations around technical issues that it identified as being important for the industry. While broadly concerned with new technologies that might be applicable to the industry and thereby R&D into those technologies, the TAC was first and foremost a committee of engineers focused upon the application of new technologies in the industry.

Before COMRO, COMSA also had established several research laboratories. In 1914, it established the Dust Laboratory. Based at COMSA's head offices in downtown Johannesburg, the Dust Laboratory tested the quality of air underground. Then in 1937, COMSA established a Timber Research Laboratory, also based at COMSA's head quarters, to develop treatments to make wooden stope supports more resistant to decay. Housing these research laboratories at its administrative headquarters was not an ideal situation and in 1947 the TAC initiated development of separate facilities for these laboratories in a neighbouring suburb of Melville. The Melville facilities opened in 1951. A few years later in 1954, COMSA established an Applied Physiology

Laboratory at Crown Mines in order to conduct research in the physiology of working in the hot and humid underground environment of the mines. Around the same time, COMRO also replaced a consortium of mining-finance groups in collaborative research initiative into underground rock burst with the Council for Industrial and Scientific Research (CSIR).

Thus, in the late 1950s COMSA took an increasingly active role in R&D. To a certain extent this role was handed to COMSA as a result of the withdrawal of Rand Mines from South African mining operations.[45] Rand Mines had from the early days of Witwatersrand gold mining been a leading innovator with a policy of diffusing these practices to the other mining-finance houses. Rand Mines' withdrawal from this role of leadership in the industry's system of innovation therefore represented an important loss. While other mining-finance groups had quality internal R&D capacity, they were not apparently willing to replace Rand Mines as the industry's leader in innovations. COMSA was naturally positioned to act as a leading coordinator for the future productive innovations, but this was not true organisationally. Development of that organisational capacity would lead to the establishment of a Research Advisory Committee, an independent Research Advisor and eventually COMRO.

In 1957, the Technical Advisor to COMSA, Michael Falcon, began a search for someone to director the disparate COMSA research laboratories. That search led Falcon to the U.K. where he contacted Sir Basil Schonland, a leading South African expatriate scientist and science advisor.[46] Falcon's 1957 search for a director did not produce a suitable candidate, but it did initiate a dialogue with Schonland about the future of research within COMSA. An important issue thereby identified was the predominant engineering culture within COMSA. Schonland appears to have advocated COMSA's development of a science management capacity if COMSA was going to have an enhanced role in co-ordinating the development of new technologies for the industry.[47]

A first step towards COMSA taking up the gauntlet of industry research came in 1960 when the Research Advisory Committee (RAC) was formed. The RAC was tasked with the organisation, direction and control of all research conducted by COMSA (Findlay (1960). Operationally, the RAC reviewed all proposed research projects from COMSA members to determine if they warranted an industry-wide research initiative. Suitable projects were then referred to a steering committee to establish costs before RAC sent the proposal to the TAC. The TAC then forwarded the RAC's proposals to the GPC for budget authorisation. Throughout the projects' life the RAC was responsible for monitoring and evaluation upon which it reported to the TAC. Before establishment of the RAC, there was only a piece-meal reporting structure by the COMSA laboratories to the TAC.

Although the RAC facilitate a certain degree of research co-ordination within COMSA the various laboratories continued to operate independently. Realising that further changes were necessary, in 1961 COMSA invited Schonland to formally review all aspects of research currently being conducted by the industry and to make recommendation. Schonland's report highlighted the need within the industry to make research a career enhancing option for individuals with postgraduate qualifications (Austin, 2001, p. 589). His report called for the appointment of a scientific advisor to

[45] See Cartwright (1968) for details.
[46] See Austin (2001) for a biography of Schonland.
[47] There has been a long historic divide between scientist and engineers, which although it perhaps not as evident today it has played a significant role in shaping their respective disciplines. See National Academy of Sciences (1985).

COMSA. Acting on Schonland's review, COMSA established the post of Research Advisor[48] and the position was filled by William Rapson in 1962.

Rapson immediately began to promote an organisational integration of COMSA's various research laboratories as a first step to a more coordinated and larger role for COMSA in the industry's system of innovation. These efforts eventually led to the establishment of COMRO in 1964 with Rapson, as the Research Advisor, its Director (Lang, 1990, p. 114). COMRO gradually established its role in industrial research under Rapson. Particularly important in this regard was the previously mentioned1965 establishment of the Mining Research Division, which undertook research into underground equipment and began investigating alternative methods of mining.

1974 marked an important year in the development of COMRO's research activities. First, Salamon succeeded Rapson as RA. Second, Rand Mines' research laboratories in Melville, near COMRO's 1951 facilities, were taken over by COMRO. Lastly, the industry supported COMRO's initiation of a large ten year research programme into mechanisation.

While the relevance of the 1974 research programme has already been discussed at length, it is important to reiterate some features. The need for the mechanisation programme originated from the increasing depth of gold mining and the racial occupational mobility restrictions of operations. Salamon restructured COMRO in alignment with the mechanisation focus, importantly then given the scale of the programme, COMRO became research into mechanisation.

When the ten-year mechanisation programme was finished, the contextual environment that had originally supported it had significantly changed. The mining-finance groups began to position themselves within a broader environment of international operations. Increasingly, research and organisational know-how played an important role in their competitiveness and as such the role for a co-operative research organisation was circumscribed. In fact, the beginnings of the changing borders of gold mining cooperation was signalled in late-1970s when the mining-finance groups ended collaborative funding of mine hospitals in the OFS. A further signal then came in 1985 when collaborative funding other mine medical facilities was withdrawn. Within the Witwatersrand gold industry this transformation became apparent in the increasing decentralisation of mining activities. In the 1980s standard systems employed across all mines in mining-finance group began to be replaced by greater customisation to account for the variety of conditions.

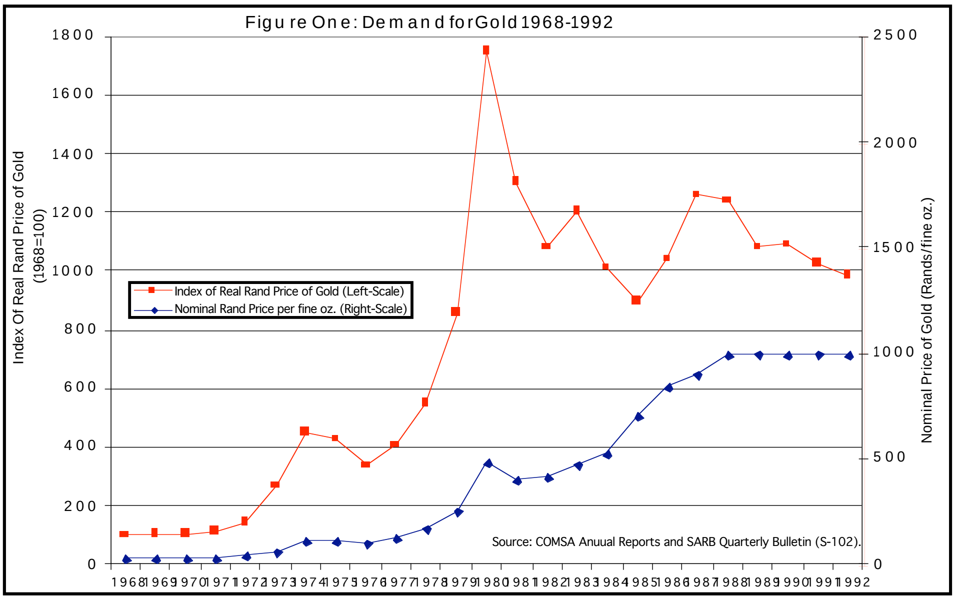
With the end of the ten-year mechanization programme COMRO continued a large research agenda after an organisational restructuring in 1985. The gold industry's enthusiasm for the co-operative research initiative was waning. In 1988, the GPC advised COMRO to increase it consulting activities following a review of its services to industry. Then in 1989, COMRO's budget was significantly reduced and its organisational objectives were redefined as being to co-ordinate industry research.

Around the late 1980s the Government Mine Engineer saw the withdrawal from COMRO by industry with concern because of its associated reduction in safety research. State mandated safety research quickly thereby became a near certainty and thereby COMRO's transformation from a systemic co-operative research organisation was clearly on the cards. State mandated research implied a research levy on industry, which being over and above what industry was already paying for COMRO was an

[48] According to Austin (2001) the post of Research Advisor was chosen instead of Science Advisor to assuage any ill-feelings the engineers might have toward scientists.

effective death warrant for COMRO. Thus, in 1990 following further budgetary cuts and reductions to its mission, safety research programmes were separated from COMRO's other activities. The scale of these reductions is reflected in the fact that between the late-1980s to the mid-1990s COMRO staff decreased from over 650 to 200.

Figure 1 - Demand for gold



As the gold industry withdrew support from COMRO and COMSA,[49] the deterioration of gold demand was often cited. Figure 1 shows the real and nominal price of gold between 1968 and 1991. From 1984 to 1991 the average real annual compound price of gold in rose at a sluggish 0.2%. Perhaps, more importantly given the general restructuring that was occurring anyway, the average real annual compound price of gold between 1987 and 1991 decreased by 5.2%.

In the 1980s, as the industry began to transform increasing discord emerged between the GPC, the TAC, and COMRO. The TAC was historically a powerful committee, but gradually it grew distant from the GPC and by the late-1980s its power had been internally weakened in response. Thus, in 1990 the RAC and TAC were merged into a weaker Technical and Research Advisory Committee (TRAC).

With COMRO's demise eminent, Alan Munro from GFSA began steering COMRO's merger into the CSIR, upon which he sat as an Executive Board member. This led to a three to four year window in which elective cost sharing by the industry was closed out and COMRO focused on contract based research within the CSIR. Realizing the important role of mine safety research, COMRO actively sought to inform the structure of State mandated mine safety research. Thus, when SIMRAC was effected in 1993 with the Minerals Act, COMRO, or the CSIR's Mining Technology Division (CSIR-Miningtek) as it was then called, was well positioned as a preferred service provider to SIMRAC.

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[49] Concurrently, COMSA's mission as industry association radically transformed. This is reflected in COMSA staff decreasing from 6,800 in the late 1980s to 70 in 2001.

COMRO functioned as R&D management specialists with vested interest in the needs of the industry. It formulated broad, encompassing, technology strategies and limited nurturing its own capability to areas where expertise did not exist or was not available locally. While CSIR-Miningtek has continued to occupy COMRO's facilities it is a much different research organisation than its predecessor. Notably CSIR-Miningtek no longer undertakes comprehensive management of a research project like COMRO did with hydraulic technology. COMRO played facilitating role in research through its publication of research reports that were circulated to all members of COMSA. Complementary to this release was the diffusion of knowledge through professional societies like the Association of Mine Managers. COMRO had its short-comings, in particular it had a very rigid organisational structure coupled to a linear approach to innovation.

While many individuals and firms made major contributions to the development of HH technologies, without COMRO it is doubtful that an integrated HH system would ever have been developed. However, the highly hierarchical internal structure of COMRO led to some to view it as being driven by internal dynamics rather than the needs of its co-operative patrons, the South African mining-finance groups. COMRO emerged as a major player in the mining sector's system of innovation in a period when South African mining-finance groups were under pressure from international isolation. Thus, a certain degree of domestic insularity apparently co-existed with relatively extensive international research relationships.

Concurrent with the increased internationalisation of the South African economy since independence and the associated international diversification by South African mining-finance groups,[50] the mining sector experienced an international decrease in public research.[51] The dissolution of COMRO has left a gap in the systemic co-ordination of research and development in sector's system of innovation. Thus, South Africa at present has a fractured system of innovation in mining that is structurally unlikely to be capable of developing a similar system of inter-connected technologies.

4 Evolution of HH technologies[52]

This case is part of a project centrally concerned with the 'lateral migration' of technologies. The concept of 'lateral migration' has been discussed elsewhere and the authors' interpretation is briefly reviewed at the beginning of Section 4.2 below. Before turning to an analysis of the lateral migration of HH technologies it is important to describe the evolution of the original market for HH technologies. Therefore, Section 4.1 reviews the contemporary market structure for HH technologies in mining. Complementing our understanding of the evolution of HH technologies since the conclusion of the COMRO initiative, Section 4.2 examines applications of HH technologies in markets outside the mining sector. Section 4.2

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[50] Notably, the international diversification of South African mining-finance groups was also associated with a decrease in intra-industry ties that has decreased the scope for intra-industry cooperation.

[51] Among other international examples was the 1996 closure of the United States Bureau of Mines.

[52] This section benefited from discussions with Peter Fraser, Frank von Glehn, Bill Gore, George Harper, Peter Hes, Geoff Minnitt, Alex du Plessis, Mike O'Conner, and Julian Wills. However this section is not, necessarily, a reflection of their opinions and inaccuracies that might exist are the authors'.

there by describes actual and emerging markets for the lateral migration of HH technologies. In its entirety this Section gives one an indication of the comparative scale of markets for the 'lateral migration' of South African HH technologies from their origins in the mining sector.

4.1 Evolution of the original market for HH technologies

Geological characteristics within and particularly between mines require a significant degree of technological adaptation if a productive system is to operate efficiently. When different commodities are being mined an even greater degree of adaptation is necessary. Hence, when HH technologies are introduced they are not simply unpackaged and plugged in. Experiences with the introduction of HH technologies therefore are also intertwined with fundamental features of the ore deposits themselves. This incestuous nature is further reinforced in the case of HH technologies by the fact that only four mines, three South African gold mines and one South African platinum mine,[53] have adopted an open HH system. While some HH technologies are used in other mines across South Africa and internationally, these four mines remain the core source of demand for HH technologies in the mining sector. Thus, in discussing the evolution of the mining sector's demand for HH technologies this section focuses on that demand and the experience of the companies supplying HH technologies to that market.

In the conclusion of Section Two several reasons for the relatively limited adoption of HH technologies were discussed. These included inherent technological complexities, the specific nature of the ore bodies for which HH systems were designed and resistance because of technological path dependency. Notably, the four mines that have adopted open HH systems were all involved in the original COMRO project. The fact that HH technologies have not been adopted on a large scale is in part a circular reason why the principal demand for the technology remains centred around these four mines. The industry standard remains established pneumatic systems since there are added costs, risks and uncertainties associated with a non-standard technology like HH systems.

Despite these barriers several niches appear to have been established for the original HH technologies. At least on the gold mines one of the most significant of these appears to be HH sprayers used to facilitate removal of blasted material from the stopes. While the HH drills have not been used extensively in stoping they have had greater success in tunnelling or development.[54] Demand for HH equipment like HH shovels, winches and chainsaws and drill rigs has also developed. Niche applications of HH technologies typically utilise micro-HH packs to power the equipment.

[53] See Footnote 39 for a list of these four mines.

[54] Reportedly this greater uptake is associated with lower workforce resistance to HH technologies in these activities.

Table 3 - Select dates in market development of HH technologies

1975	Ingersoll-Rand undertakes hydraulic drill development with COMRO
1975	Vickers Systems undertakes hydraulic power development with COMRO
1978	Hammelmann undertakes hydraulic power development with COMRO
1979	Gullick undertakes impact ripper development with COMRO
1982	Seco and Novatek undertake hydraulic drill development with COMRO
1985	Hydro Power Equipment (HPE) established
1987	TLC Software established
1988	Crown Chrome Plating undertakes hydraulic power development with COMRO
1989	Ingersoll-Rand ends hydraulic drill development with COMRO
1989	Sulzer undertakes hydraulic drill development with COMRO
1990	Turgis Consulting established
1991	Northam Platinum mine commissioned on HH technologies
1992	Joules Technology established
1996	Sulzer begins producing New Generation Drill for HH technologies
2003	Sulzer begins development of HH-Air Rock Drill

Source: Compiled by authors

Prospects for the future diffusion of HH technologies retain a strong potential, despite the slow growth in demand so far. A primary reason for this optimism is that HH technologies remove polluting oil from operations. To date, the costs of HH technologies are still largely prohibitive in comparison to traditional oil hydraulic or EH technologies. Rising concerns with negative environmental externalities associated with oil-based technologies are therefore a fundamental source for optimism around the broader potential for HH technologies diffusion in the mining sector.

One equipment supplier, Sulzer, has taken a proactive role and sought to facilitate the introduction of HH technologies within the existing standard practices and organisational routines that exist in mining. This approach led them to develop a new generation of HH technology in their Aya Duma Duma drill, which is a HH lubricated pneumatic drill. Sulzer has thereby developed a drill that works on the pneumatic infrastructure existing in most mines, but that also introduces productive and most importantly environmental benefits associated with HH technologies.

Important dates in the development of the market for HH technologies are listed above in table 3. With a broad view of the productive system it is not surprising that besides equipment manufacturing there are a host of complementary services and firms providing services associated with the supply of HH technology. Given the limited number of firms associated with supplying HH technologies to the mining sector, these firms and their involvement with HH technologies is reviewed below. Services provided by equipment manufacturers are discussed in turn before turning to a review of specialist service firms associated to HH technologies.

- *Crown Chrome Plating* – Having been involved with the development of pumps for HH technologies with COMRO, *Crown Chrome Plating* continues to manufacture micro-HH packs for HH technologies under its Cemo Pumps subsidiary. These packs are driven by a positive displacement pump that is also sold to the construction, food processing, manufacturing, and agriculture sectors in applications ranging from milk processing to plastering and injection mortar.
- *Hydro Power Equipment (HPE)* – Emerging in the mid-1980s around the COMRO HH research initiative, *HPE* is now a leading firm supplying hydro power systems and equipment. Among the equipment supplied by HPE are HH rock shovels, compressors for loading explosives, saws for roof support timbers, drill rigs, and in stope water jets. *HPE*'s hydro power systems include high pressure couplings,

reticulation systems, valving, roof support props, drill rigs, high-pressure control and safety systems, and turbines. In terms of complementary services, *HPE* actively fosters development of knowledge and expertise in HH technology. This includes running training courses in the utilization and maintenance of their HH equipment as well as providing a dedicated service engineers on-site for their larger customers.

- *Ingersoll-Rand* – Despite their leading role in development of the HH drill by the late 1980s and early 1990s *Ingersoll-Rand* was withdrawing resources from further development of HH drills. Nonetheless, Ingersoll-Rand produced a commercial HH drill. Rights to manufacture that drill were purchased by *Joules Technology* in 1999 who continued its manufacture until 2002 when demand for this relatively dated technology led *Joules* to discontinue manufacturing.
- *Joules Technology* – Established in 1992, *Joules Technology* became an important supplier of HH based cooling and ventilation equipment. In addition to the licensed manufacture of *Ingersoll-Rand*'s HH drill mentioned above, *Joules Technology* produces a range of HH other equipment including HH winches, chainsaws, and in stope water jets. In terms of complementary services, *Joules Technology* provides on-site workshops for its larger customers.
- *Novatek* – Emerged in the early 1980s as an organisation focused on development of an HH drill under COMRO's stewardship. In the early 1990s it merged with U.K.-based *Gullick* whose background in the U.K. coal industry had led to their involvement with COMRO's HH programme in the late 1970s. In the mid-1990s a management buy-out led to Novatek again being an independent, South African based, HH drill manufacturer. In partnership with its sister company *Nestek*, *Novatek* offers a small HH drill that runs on either a high-pressure system or a low-pressure system. In terms of complementary services, *Novatek* offers HH drill maintenance contracts in conjunction with several on-site workshops as well as hosting a training department that provides class-room and on-the-job training in stoping with their HH drill.
- *Seco* – Despite its historic pre-eminence in supplying pneumatic rock drills for the South African mining industry, in the early 1990s *Seco* analyzed the potential demand for HH drills and perceiving it to be a niche technology ended its research efforts in the development of an HH drill, which had been transferred to their U.K. facilities.
- *Sulzer* – Entering into COMRO's HH programme in the late 1980s with its turbine technology its development of the lighter-weight New Generation Drill based on a South African design expanded its HH product demand in the mid-1990s. As mentioned above, since the early 2000s *Sulzer* has taken an important initiative in HH technology in its development of the HH lubricated pneumatic drill.

A few firms in the service sector also had ties to COMRO's HH programme. In contrast to the HH equipment suppliers most of these firms now find HH technologies to play an ancillary role in their businesses. One of the more prominent examples of this class of firm is the mining consultancy *Turgis*. It was founded in 1990 by several COMRO staff members that were heavily involved in the HH programme. Despite its staff's knowledge of HH technologies still forming a core competency, *Turgis* has found demand for other mining consultancy services to greatly surpass demand for its knowledge of HH technologies.

Another service firm that emerged from COMRO's HH programme was *TLC Software*. It was established by three COMRO employees (Terry, Louis and Chris) who had designed the software, instrumentation and measurement system for the HH system. Today, *TLC Software* offers a range of specialist engineering software solutions. Similarly, *BBE* a mining consultancy specialising in cooling and ventilation had some staff that worked on the COMRO HH programme. This knowledge of HH technologies continues to play a minor role in BBE's business, but the vast majority of its operations are focused on other mine cooling and ventilation technologies.

In terms of HH technology for the mining sector, South Africa is an international leader. The niche role played by HH technologies in mining activities both in South Africa and internationally has insulated these capabilities from strong international competition. Potential application of this technology on a much greater scale in the mining sector persists, but to date demand has remained relatively static.

4.2 Lateral migration of HH technologies

With this project's focus on 'lateral migration' we are focusing on evidence of technology's application in a distinct sector and context from that which it was originally developed. Even though the legacy of HH technologies described in Section 4.1 included the emergence of HH technologies within the service sector, that migration was inter-related to HH technologies' application in the mining sector and therefore is not a case of lateral migration. These applications are briefly discussed below before turning to a review of international applications of HH technologies outside of the mining sector. The potential for the South African HH technology to grow through its deployment in these applications then concludes this section.

The clearest evidence of lateral migration for South African HH technologies is found in *HPE*'s development of equipment for the steel industry. Owing to the hazards of having oil in the working environment around steel manufacture HH technologies are logical means to move heavy equipment. *HPE* has therefore developed HH de-scalars and tap hole 'mud gun' plugger for arc furnaces. The HH de-scalar is used to clean the inside of a furnace while the tap hole mud gun is stops the flow of materials from an arc furnace's tap hole by pumping clay into its tap hole. The high pressure HH mud gun can rapidly inject a large quantity of stiff mud to safely and effectively seal the furnace. While this equipment accounts for a minority of *HPE*'s business it is a clear example of lateral migration.

Besides *HPE*'s equipment for the steel industry this analysis has not been able to find evidence of other significant lateral migration of the South African HH technologies developed under COMRO's stewardship.[55] Nonetheless, there are a host of areas where HH technologies have been applied internationally. Denmark-based *Danfoss* is one of the leading HH technology firms internationally outside of the mining sector. Its *Danfoss Nessie* subsidiary has developed HH technologies for a range of sectors since the late 1980s.[56]

On oilrigs, *Danfoss Nessie* has developed HH pumps for energy generation, these HH pumps are also being used to increase the energy efficiency of water desalination. In wood processing, *Danfoss Nessie* has developed water lubrication and cooling of saw blades to reduce friction from the wood's resin. That reduction in friction has

[55] It is possible that Crown Chrome Plating/Cemo's positive displacement pump is linked to the COMRO HH programme, but so far it has not been possible to meet with a representative.
[56] For more information on Danfoss Nessie and its various applications see: www.nessie.danfoss.com

increased productivity and lowered energy costs. Additionally, *Danfoss Nessie* has developed a range of HH heavy equipment to replace polluting oil hydraulics and EH equipment. That HH heavy equipment, such as a HH lifting garbage truck, has been adopted by municipalities in Europe who are increasingly concerned with the environmental effects of oil hydraulic leakages.

While South African HH technologies have not so far migrated into these alternate applications, their origins in the rough underground working environments of the mines has led to their developing more robust HH technologies than their international counterparts. In this regard *Sulzer*'s development of the HH lubricated pneumatic rock-drill appears to hold tremendous promise for lateral migration to other sectors. If the Aya Duma Duma drill can show its commercial viability in replacing pneumatic drills on the mines, it would have a strong base to further develop similar HH lubricated equipment for the construction and manufacturing industry. Thus, the potential for lateral migration of South African HH technologies remains highly significant even if unrealised.

5 Conclusion

South African HH technologies were developed over more than two decades under the comprehensive direction of COMRO. They have established a viable market niche in the mining sector. Despite what many believe to be a long-term boom in the resource sector the HH technologies have not diffused significantly from their original applications. There is clearly a potential for these technologies to move further out into the mining sector and a variety of other sectors as environmental externalities become an increasing concern. However, the slow diffusion of HH technologies thus far is clearly an area of concern.

While there has also been lateral migration of South African HH technologies these have been small in comparison to the demand from the mining sector. International experience has demonstrated a large variety of applications for HH technologies that also hold a tremendous potential for further lateral migration of South African HH technologies. Bearing this history and subsequent evolution of HH technologies in mind, the remainder of this paper turns to a discussion of the four principal dimensions of lateral migration from the present projects conceptual framework.[57]

5.1 Absorptive capacity

The HH technologies described in this case originated within a collaborative initiative supported by the South African gold mining industry that was trying to increase the mechanisation of stoping operations. These efforts for mechanisation emerged from internal competitive imperatives as well as successful local and international precedents in coal mining mechanisation. COMRO, the industry's co-operative research organisation, played a major role initiating the research and directing its development to the point of commercial viability.

HH technologies are comparatively more skill intensive than the precursors they were designed to replace. This is partly because of inherent complexities in HH technologies, but the skill intensity of the technologies are also relatively elevated

[57] See Lorentzen (2005)

because routines, standards, and organisational practises in the established competing technologies have significantly reduced the requisite skills. Interviews with individuals active in the industry have indicated that changes in the organisational structure of the industry have also enhanced this barrier to HH technologies' diffusion as fewer engineering skills on mines reduce their capacity to experiment with alternative operational practices.

While international precedents were important in the initial stages of the initiative, unique features of the working environment led to the technology developing quite independently of other initiatives. In particular, the open HH system connecting stoping equipment with the latent power and cooling capacity in the South African mines created a one of a kind technology. Despite originating within the mining sector an important characteristic of the research initiative was to foster development of domestic manufacturing capacity. While specifically targeting development of manufacturing capacity for the mining industry that level of inter-industry development and common goods illustrates the high level of social capital that existed within South Africa's economy before liberation. Under COMRO's direction South African universities were also drawn into the programme where possible to develop and sustain tertiary capacities that would support HH technology as well as the broader sectoral system of innovation.

As with diffusion in the mining sector itself, applications outside of the mining sector appear to have a lot more potential scope than has been realized so far. The principal lateral migration of South African HH technologies so far has been by one firm, HPE, in their development of HH equipment for the steel industry. Among the other technologies with substantial potential for lateral migration, Sulzer's HH lubrication technology for pneumatic equipment appears to be one of the greatest. Internationally, related HH technologies are being used in a variety of sectors. Given the comparatively robust nature of the South African HH technologies this domestic capacity appears well positioned for further lateral migration.

5.2 The role of foreign technology

While deliberately fostering domestic absorptive capacities, COMRO was pragmatic in the HH programme trying to draw on organisations with the best capabilities internationally. International precedents were important in providing incentives to initiate research into HH technologies, in particular Australian, UK and US efforts in coal mining were discussed. Among these international sources the skills developed within the British Board of Coal played an important role in South Africa's ability to create innovative new HH technologies. Overall this existing body of research created an important incentive for the development of South African HH technologies by giving a foundation of knowledge that South Africa leveraged in accelerated catch-up to become at the international forefront of HH technology.

Besides this role of related foreign HH technology, the complexity of the HH system benefited from COMRO's international searching for best technical solutions across sectors. In this regard, COMRO partnered with US based Ingersoll-Rand in the initial phase of EH development because of its extensive in-house research capacity. Further examples of the international transfer and mutual development of novel technologies in this case include development of micro-emulsions by US oil companies, emergency safety valve technology from the foreign nuclear and oil industry, and specialised steel alloy development with UK and US steel producers.

5.3 Linkages and interactions

Linkages between equipment suppliers, the mines, and COMRO were particularly significant in this case. The evolution of the mining sector's system of innovation was reviewed in Section Three with particular focus on the emergence of COMRO, the sector's co-operative research organisation. A highly networked structure can therefore clearly be associated with the development of HH technology in the mining sector.

International isolation faced by the South African mining-finance houses contributed to some extent to the depth of linkages that characterised development of HH technology. In addition, internationally during the decades when HH technologies were being developed the mining sector was characterised by collaboration in production concurrent with fierce competition for securing mineral rights. Organisationally, the hierarchical structure of the South African gold industry under the mining-finance group system facilitated inter- and intra-organisational transfers of technologies and the organisation of production between mines across the Witwatersrand deposits. In COMRO is perhaps the best indicator of the cooperation that existed in research and development.

However, just as HH technologies reached commercialisation several factors transformed the previously deep connections to a point where they no longer structurally facilitated the introduction and diffusion of the HH system. First, increased internationalisation of the South African economy in the 1990s led to South African mining-finance groups to integrate and diversify operations globally, thereby undermining some of the common cause that had previously supported social capital and collaboration in the industry. Secondly, internationally mergers and acquisitions in the mining sector shifted the borders of competition and co-operation so that cooperative research and development was no longer viable among the mining firms. Thus, the scope for further collaborative development and diffusion of HH technologies was reduced, a point most clearly illustrated by the dissolution of COMRO itself.

Lastly, beginning in the 1980s as part of the general restructuring hierarchical control by the South African mining-finance groups, individual autonomy at the Witwatersrand gold mines was increased simultaneously with a reduced capacity to significantly alter operations. This led to a situation where the mines increasingly customised mining operations to suit the geology of their deposits rather than just applying standard operational practices across all of the group's mines. This further raised the barriers of path dependency for HH technologies to overcome as pneumatic based stoping became entrenched at a far more localised level than it had been previously.

The interviews in the course of this project made it clear that within the community of HH technologies linkages remain to this day with close and relatively frequent interactions between individuals and organisation. However, the loss of COMRO removed a critical champion of the technology and in the face of these additional challenges it is now dependent on the HH equipment manufacturers to promote adoption of HH technologies. As a result South Africa's HH technology continues to face severe hurdles in its diffusion in the domestic and international mining sectors. With out greater adoption of the technology in their target market most of the firms with HH capabilities appear reticent to venture into other uncertainties through the lateral migration of their technology.

5.4 Industrial policy

While State taxation and fiscal policies generally favoured the mining industry, when HH technologies were being developed these indirect measures were the only public support that these technologies received. As such this case illustrates the power and importance of intra-sectoral co-operation in fostering the productive capacity of a sector. Currently, the role played by COMRO's systemic coordination has not been appreciated in policy debates around enhancing South Africa's mining competitiveness. Despite valid criticisms of COMRO itself, with out a similar stakeholder in the sector's system of innovation it is virtually certain that no equipment supplier would ever undertake the development of a radically alternative technology like the HH system. As a result there is less likelihood that a domestically developed broad platform technology will laterally migrate in the future. Notably, so far industrial policy has also not been a significant factor in the lateral migration HH technologies. Clearly this is an area that needs further policy consideration.

This case has shown how a complex systemic technology developed for the mining sector has laterally migrated. While its economic significance to date has not been momentous, it remains a technology with significant potential in both its original sector and in others. The case has also highlighted an important era in the mining sector's system of innovation which serves is an important precedent contemporary initiatives aimed at enhancing domestic competitiveness.

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Afterword

Introduction

I would first and foremost like to thank the Human Science Research Council for providing an auspicious platform for personal growth and development by allowing me to engage in such intense research experience. The opportunity to conduct academic research under the supervision and guidance of Dr. Tomas Pogue of the IERI (whom I so honour) has been both rewarding and interesting. I am grateful for this opportunity because it has enriched my academic and Research pursuit, as I have learned both within of the classroom and on the field. I can definitely say I have grown academically, mentally and professionally.

With no prior mining experience to begin with, it started out as an immense challenge.

First draft

As I commenced to gather useful insight into the topic it allowed me to reach far beyond the surface of sensitive issues that are often not accessible or even perceptible to the average man. My direct learning about the Hydraulic technology situation, the conditions faced, the perspectives of the various stakeholders involved and the theoretical perspectives used to frame this topic has renewed my interest in the field to the extent that I am seriously considering pursuing one or more of these aspects of the project further in terms of my professional development.

In the beginning phase of the project I started out with great optimism. With no solid knowledge of the field I soon realised that I had to suppress much of my enthusiasm to ensure the topic at hand is properly tackled.

Two distinct categories of lateral migration associated with hydraulic technology were identified and my role was to scrutinise these areas in detail. First, the establishments of mining consultancies, and secondly the applications of the technology in other industries and sectors. A series of interviews were conducted with the various mining consultancies. The experience, expertise and knowledge gained from conducting these interviews were truly humbling and remarkable in the same light. Various equipment manufacturers were also identified. This however left us with a very broad overwhelming scope and serious refining was necessary.

Conference

The International Workshop on Lateral migration held at the Manhattan Hotel in Pretoria, broadened my knowledge in this regard. This gave another dimension to the project as I learned that not only within the domestic setting but also internationally this project was carried out. This being my first conference and having minimal knowledge within the mining segment sort of had to be on the absorbing end rather than more intensively involved so as to grasp the fundamental basics and I feel this workshop played a vital in the success of this project's delivery or output. During this time it was also an intriguing moment of networking with various delegates, especially the likes of Dr Adi Peterson, to explore the issue of lateral migration. During the presentation of different approaches to the issue at hand, it was great to take notice of other cases relative to lateral migration from Lea Velho, Dr Walker, Juana, Elisa and yourself Jo (since I was very keen to meet out boss).

Final draft

During and after the workshop, I was also expected to prepare for other academic presentations since during this period exams at varsity normally would run but however my efforts in this were facing impediment. Through this time I learned numerous life aspects like commitment, authenticity, discipline, decision-making and time management, which I find, building a noble character to an individual. Furthermore, my enthusiasm grew even deeper in the project since I had built psychological belonging into the project, which allowed me to allocate additional hours doing a research endeavour of this stature to exude both understanding and professionalism. At this stage confidence had submerged into my attitude and from this stage I would easily say I knew what I was doing and where I was heading.

Conclusion

As far a you would have liked to provide criticism I can only go as far as admiration for a astonishing academic endeavour that aided insightful discovery of useful information and know-how and I am hopeful that these cases case reach publication. In a nutshell I would like to emphasise my gratitude in this regard for exposing me to such majestic task and hope that our relationship has not reached its maturity. In the latter I dearly thank you.