5

# Missed opportunities? A case study from South Africa's mining sector

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SOUTH AFRICA REMAINS ONE of the world's largest producers of gold, despite the majority of its deposits being several kilometres below the surface. In the late 1960s, the depth of gold deposits motivated the Chamber of Mines Research Organisation (COMRO), the industry's cooperative research institute, to undertake research and development of alternative technologies to extract the gold-bearing host rock. With consistent support from the gold-mining industry, the institute oversaw the combination of several complementary technologies to produce an integrated all water-based (hydro) hydraulic mining extraction technology. This system had several advantages over conventional oil-based hydraulic technologies. Although South African hydro-hydraulic mining technologies are unlikely to become very widely used, the reasons for which are explained in this chapter, a range of niche applications of the South African technology have emerged in both resource and non-resource sectors.

This chapter begins with a description of the development of hydraulic technologies. Two distinct stages of hydraulic technologies are identified. Firstly, emulsion hydraulic (EH)[1] technologies were developed and commercially deployed between the mid-1960s and the late 1980s.

Secondly, 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 the displacement of EH technologies by HH technologies. The section highlights inter-relationships among hydraulic drilling and hydraulic power technologies as well as the role of COMRO, which was the principal organisation responsible for the development of HH technologies.

Markets for South African HH technologies and their international counterparts are examined in the next section. The niche nature of demand for South African HH technologies is contrasted with growing and diverse demand for other HH technologies. Despite the comparative robustness of South African HH technologies, they have not transformed their original large-scale systemic focus to accommodate the growing demand for smaller-scale applications of HH technologies. As a result, lateral migration of the South African technology appears to be rather limited. Linkages with the local resource sector remain significant, however, making the prospect for further lateral migration of the technology seem possible. As with the other case studies, the final section reflects on evidence across key dimensions that describe lateral migration.



## Development of hydraulic technologies

The development of hydraulic technologies originated within a far broader effort to decrease the labour intensity of gold mining on the Witwatersrand. Referred to as 'mechanisation', this transformation began to be expressed by the mining industry in the late 1950s (see Black & Edwards 1957; Hamilton 1963). In the 1920s, Witwatersrand mining had transformed stoping practices underground through the introduction of pneumatically powered rock drills.[3] In order to facilitate the replacement of predominantly expatriate white miners with this technology, the mines committed themselves to racial occupational mobility restrictions on black miners (see Johnstone 1976).

As production at existing gold mines went deeper and new fields in the Far West Rand of the Witwatersrand and the Orange Free State began developing deposits at ever-increasing depths, the racial occupational mobility restrictions created increasing burdens on the industry. With a legacy of internal racism and a broader political economy of racial discrimination impeding the removal of occupational mobility restrictions, mechanisation offered the Witwatersrand gold-mining industry a means to increase the efficiency of production. Greater output per worker underground, 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.[4]

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, the Chamber of Mines of South Africa (COMSA) became an increasingly important player in the research activities of the industry. A first step towards COMSA's 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 whether they warranted an industry-wide research initiative.

Although the RAC facilitated a certain degree of research coordination, COMSA commissioned a formal review of South African mining research in 1961. The review called for the appointment of a scientific advisor to COMSA. In 1962, COMSA appointed a science advisor, William Rapson, to the position of research advisor.[5] Rapson immediately began to integrate intra-industry research laboratories organisationally. This integration eventually led to COMSA's establishment of COMRO in 1964, with a linear focus on scientific research feeding into technological development.

Shortly after its formation in 1965, COMRO established a Mining Research Division (MRD) tasked with developing technologies to improve the efficiency of underground gold-mining operations. The MRD marked the beginning of coordinated research by the industry in the development of underground mining technologies. However, two changes to the structure of the gold market in the early-1970s led COMSA's Gold Producers' Committee (GPC) in 1974 to commit COMRO to a large systematic ten-year research initiative into the development of mechanisation technologies for operations underground.[6] Firstly, African countries in a post-colonial setting threatened the supply of relatively inexpensive black miners from across southern Africa (see Hermanus 1988; Spandau 1980). Between 1973 and 1976 the number of foreign workers on the Witwatersrand gold mines dropped from 336 000 to fewer than 200 000 (Crush et al. 1991: 101). Secondly, in 1971 the United States abandoned its underwriting of the fixed price of gold, leading to a marked appreciation. Between 1971 and 1973, the real annual compound price of gold in Rands rose at a rate of 42.4%. As operating under the racial occupational mobility restrictions fundamentally constrained production efficiencies, particularly at ever-increasing depths, and with few short-term solutions available, the industry turned to the mechanisation programme as a means of accessing the Witwatersrand deposits that continued deeper underground.



## Development of emulsion hydraulic technologies

Table 5.1 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 which were of direct importance for the subsequent development of hydraulic technologies in mining operations. Nevertheless, because many of these technologies had significant power and energy requirements, they contributed to COMRO's investigating hydropower as an energy source.

**TABLE 5.1** *Some important dates in the development of hydraulic technologies (1965–1991)*

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| 1965 | COMRO Mining Research Division was established. |
| 1973 | Hydropower was investigated as an energy source. |
| 1975 | Production trials began with a chilled water service for mine cooling (completed 1977). |
| 1975 | COMRO and Ingersoll-Rand began developing the 95-5 drill. |
| 1975 | COMRO and Vickers Systems began developing the 95-5 power system. |
| 1977 | The first prototype 95-5 drill was tested at West Driefontein gold mine. |
| 1978 | COMRO began additional 95-5 power system development with Hammelmann. |
| 1979 | The second prototype 95-5 drill was tested at West Driefontein gold mine. |
| 1980 | COMRO and Ingersoll-Rand developed a quadruple plunger rotation mechanism for drills. |
| 1980 | COMRO initiated research into combined hydraulic power and cooling systems. |
| 1982 | The Ingersoll-Rand production model 95-5 drill was developed (tested at West Driefontein between June 1983 and March 1984). |
| 1982 | COMRO began developing 98-2 and HH drills with Ingersoll-Rand, Seco and Novatek. |
| 1983 | The first prototype 98-2 power system was developed (tested at Kloof gold mine in 1984). |
| 1985 | The first prototype HH power system was developed (tested at Kloof gold mine in 1985–1986). |
| 1986 | Production tests with 98-2 drills began in Far West Rand and Orange Free State gold mines. |
| 1987 | COMRO left the subsequent development of 98-2 drills to Ingersoll-Rand, Seco and Novatek. |
| 1987 | COMRO drew Crown Chrome Plating into hydraulic pump research as Vickers Systems was phased out. |
| 1988 | COMRO worked with equipment suppliers to develop open an system of hydropower and cooling. |
| 1989 | Production models of 98-2 drills became available. |
| 1980 | Sulzer joined the COMRO hydraulic drill development initiative. |
| 1991 | Production models of HH drills became available. |

Just before initiating the ten-year mechanisation R&D programme in 1974, William Rapson, research advisor of COMSA and director of COMRO, was replaced by Miklos Salmon. As COMRO's annual budget increased three-fold, Salmon realigned COMRO's organisational structure with the mechanisation research programme. The mechanisation research programme thus became the focus of COMRO's R&D ethos until the dissolution of the organisation almost 20 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 development of the technologies. While maintaining that stock, COMRO sought to outsource its R&D to equipment suppliers, other research organisations and South African universities (Joughin 1982). Nonetheless, most of the basic research and early technical trials were conducted by COMRO itself. Collaboration with equipment manufacturers was emphasised and driven by several organisational priorities. Firstly, COMRO did not want to build itself into an equipment supplier; it also wanted to ensure the market viability of its technologies and incorporate manufacturing know-how into the development of the technologies and realise economies of scale and speed in the development of the technologies through the broader base of all participating organisations. 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' (Salmon 1976: 71).

Following a linear model of innovation,[7] 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 in COMRO. As the hydraulic technologies were perceived to be high risk, COMRO entered into contracts with equipment manufacturers whereby COMRO paid their costs plus a 5% premium, effectively bearing the costs of design, construction and evaluation.[8]

When more than one equipment manufacturer was involved in the development of a particular technology, COMRO would not exchange or transfer data about the performance of other equipment between organisations. However, COMRO did advise each company whether a problem was unique to that company or 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.[9]

The 1974 mechanisation research programme consisted of two distinct groups of technologies: conventional and revolutionary. The conventional technologies focused on improving existing mining methods, and the hydraulic drill programme fell under it. The revolutionary approach focused on changing mining methods by moving from stoping by drilling and blasting to continuous mining with various methods of mechanical rock breaking. Early in the research into revolutionary technologies, one of the most promising technologies was the drag-bit miner.[10] A drag-bit miner operates in a similar manner to a chain saw, but it cuts with a large cylinder upon which rows of metal spikes are mounted. The spiked drum is then driven into the host rock to break out the gold-bearing ore. The promise of the drag-bit miner was important, as high-pressure water jets, around 30 megapascal (MPa),[11] 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 imperative 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 (see Clement 1975; Marshall 1975; Whillier 1975). 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 that force equals pressure times area governs the power of a drill. Since a functional maximum pressure for pneumatic equipment was reached at around 200 kilopascal (kPa),[12] hydraulic technologies with their greater range of pressures promised to deliver more power at 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 far 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 far 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 higher levels of skill. 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 have an integrated chilled water service, unlike their pneumatic counterparts.

While bearing those fundamentals in mind, it is important to realise that the 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 UK-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 electro-hydraulic packs on the stopes had been replaced by centralised stations, which made hydraulic technologies less cumbersome and did not introduce additional heat on the stopes. Besides the drills, the development of EH (emulsion hydraulic) 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, such as the scraper winches, utilised electric power. While electric power could be provided relatively efficiently in large quantities, it generated little force and introduced additional heat to the stopes. EH power therefore seemed to offer an important alternative to both pneumatic and electric power underground (Joughin 1982).

In developing the first generation 95-5 EH drill, COMRO collaborated with US-based Ingersoll-Rand. Because of the rough operating environment, EH drills were not generally regarded as viable. Inevitable leaks from an EH drill would expel environmentally and economically undesirable quantities of oil into the mine environment. Viable EH drills therefore had to have a low ratio of water, which is why COMRO embarked with Ingersoll-Rand on developing the 95-5 drill.

Internationally, South Africa was not alone in its efforts to develop a hydraulic drill. In the 1970s, Australia, the UK and the US all had some research initiatives on the development of a hydraulic drill. In the 1970s, Australian and US coal mines 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 for the fire-weary British coal mines. In the mid-1970s, the British Board of Coal was therefore also investigating the development of a 95-5 EH drill. Similarly, in the mid-1970s, US automobile manufacturers were considering using hydraulic cutters on a large scale and, needing to economise on oil losses, they began to develop a 95-5 EH system. South Africa, through COMRO, was accordingly 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. Firstly, because of the low viscosity, it was necessary to introduce additional seals to prevent leakages. The additional seals introduced additional friction, which caused all the seals to wear and deform far more rapidly. COMRO therefore collaboratively developed special plastic seals and bearings (Walczak 1984).

A second challenge arose because, at the 95 : 5 ratio, the difficulties of 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 (in other words, a breakdown of the emulsion would occur).

Eventually, a solution to this problem of suspension came from US oil corporations, which developed micro-emulsions that, because of their far finer dispersion, created a more stable mixture of oil and water.[13]

Lastly, a further major challenge in developing the hydraulic drill was in the mechanism for rotating the drill steel. The low-oil emulsions were causing the traditional mechanism to wear at an unacceptable rate. After many iterations, a major breakthrough was realised when a quadruple plunger, ratchet and clutch rotation mechanism was created.[14]

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 and innovations to the labour force of the organisation to accommodate the new technology (see Glassborow & Veldsman 1982; Veldsman & Pretorius 1983).

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 about 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, the development of an HH (hydro-hydraulic) system, had also begun.

## Development of hydro-hydraulic technologies

By the late 1970s and early 1980s, senior managers at COMRO began to initiate research into HH (100% water) technologies. An intermediate step between 95-5 EH technologies and HH technologies was 98% water and 2% oil (98-2) EH technologies. At this time, under COMRO's direction, South Africa had become an international leader in these hydraulic technologies.[15] Bearing in mind that the 1974 mechanisation research programme was ending, three factors appear to have been particularly significant in the further development of HH technologies.

Firstly, as already mentioned, the revolutionary mechanical rock-breaking programme had achieved good performance with its drag-bits when used in conjunction with high pressure water, of around 30 MPa on the rock surface. This performance resulted from the removal of waste rock under the teeth (for details, see Hood 1976; Joughin 1978). That research created a need for an all-water high-pressure sprayer, and the development of such a sprayer in the mid- to late 1970s gave COMRO important confidence in the feasibility of developing an HH power system.

Secondly, with the ever-increasing depths of mining on the Witwatersrand, cooling had become critical. Previously, cooling had occurred at the surface, and the air was then transported with pressure to the required depth. However, the air warmed up in the process of transporting it, and a significant amount of cool air escaped before it reached its final destination. Thus, refrigeration units were gradually moved underground. From 1972, COMRO undertook R&D into utilising chilled mine service water to cool the rock surface directly on the stope. Following successful full-scale trials between 1975 and 1977, it became clear that the direct application of chilled water to the rock surface was the best means of achieving a stable and tolerable underground temperature at increasing depths (for details, see Wagner & Joughin 1989). This revealed a fundamental efficiency of HH power, which could function as a cooling technology without the ad hoc difficulties of water-cooling with compressed air, and simultaneously as a power source. In 1980, COMRO therefore initiated research into combined hydraulic power and cooling systems.

Lastly, with increasing depths of operations in the gold mines, 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. With 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 subsystems to keep the water in the pipes and move it to the rock face.

In addition to the comparative drilling efficiencies of hydraulic drills over their pneumatic counterparts, HH power therefore held systemic benefits for underground operations. Given this priority for hydraulic power, COMRO established an independent hydraulic power project and moved quickly towards the 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 such as scraper winches and roof supports (Brown et al. 1986).

In the mid-1980s, Gullick (based in the United Kingdom) also became involved in developing HH power pump technologies along with Hammelmann, while Vickers Systems withdrew from the research initiative.[16] 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 (for details, see Brown & Joughin 1988; Du Plessis & Solomon 1988). Because of the high pressures and associated dangers, technologies from the oil and nuclear industries were borrowed to guide the 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, the relative complexity of which reduced with the removal of oil, the complexity of HH drills increased. Nonetheless, as COMRO 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 straightforward, since the new emulsion mixture, bearing and seal technologies transferred relatively easily from the 95-5 drill. Thus, in 1986, production trials with the 98-2 drill began on Anglo American Corporation's (AAC) Orange Free State mines and on Gold Fields South Africa's (GFSA) Far West Rand mines (for details, see Du Plessis et al. 1989; Holloway et al. 1988; Westcott 1986). After these trials in 1987, COMRO withdrew from further research on 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 Swiss-based Sulzer joined COMRO's initiative to develop an 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 it dominated the production of pneumatic drills sold in South Africa at the time. Seco took one of its oil-hydraulic rock drills and converted it to run on a 60-40 EH mixture. (That drill was known as the HD-30.) Gradually, they dropped the level of emulsion in the drill until it was running as an 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 UK 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 subsequently been established to manufacture its drills, demand exceeded Innovatek's capacity in the early 1990s, leading to a merger with

UK-based Gullick in 1992. Sulzer, in contrast with the other companies, developed its drills in Switzerland, although in close collaboration with South Africans. Sulzer's first drill (known as the Turbo Drill) was based on the company's turbine pump technology. However, after initial prototypes were developed, production of Sulzer's drill was based in South Africa, where 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 related to lubrication. Boundary lubrication prevents wear of two surfaces in contact; even atomic quantities of oil are sufficient to form a hydrodynamic film of fluid that would lubricate contact surfaces. However, in HH systems, it was found that boundary lubrication was not occurring. A range of solid lubricants such as polymers, rubber and non-steel materials was thus investigated. Rubber was the eventual solution for static seals, while polymers were utilised for dynamic seals. For bearings, polymers were the only viable materials (see Harper 1990).

Another major challenge was the corrosion of carbon steel through contact with the highly corrosive mine water.[17] While 98-2 EH systems were sufficient to prevent corrosion, in the HH system, the mine water was too harsh for carbon steel. Because existing alternative corrosion-resistant material broke down under the mechanical forces to which the drills were subjected, COMRO initiated the development of novel corrosion-resistant steels. These hybrid steels were developed in collaboration with US and UK steel manufacturers.

Despite good results from pilot melts, a more traditional and less expensive chromium-based solution was eventually adapted. In fact, while corrosion was particularly severe in the drills, it was also a concern in the other equipment, as well as the piping and power systems themselves (see Howarth 1990).

Continuous progress was made with the HH drill during the late 1980s. As a result, it was possible for GFSA to announce in the early 1990s that its newly developed Northam platinum mine would be developed with an entirely HH system. GFSA's commitment to the HH system was critical to the final commercialisation of HH technologies. HH technologies were particularly appealing for Northam platinum mine because of its high underground temperature gradient.[18] While HH mining systems were still being developed, the technology was already being deployed at Northam. HH technology proved itself commercially viable through its deployment at Northam and, by 1991, Ingersoll-Rand, Novatek and Sulzer had each developed production model HH drills (Solomon & Jones 1994).

South African HH mining technology drew on international precedents in developing a unique technology. Under COMRO's stewardship, important complementary international technologies were brought into the programme, which eventually enabled commercially viable HH technologies to be developed. Representing the demands of the mining finance groups, COMRO interacted directly with a spectrum of research and development parties 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.[19]

Despite its shepherding of the development of HH technologies, COMRO did not survive to see its conclusion. In the mid-1980s, the gold industry's enthusiasm for the cooperative research organisation declined. The highly hierarchical internal structure of COMRO led some to view it as being driven by internal dynamics rather than the needs of its cooperative patrons, the South African mining finance groups.

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 the coordination of industry research. By the early 1990s, a commercially viable HH technology had been developed, but COMRO's existence within COMSA had come to an end.[20]

In the early phases of EH development, fundamental drilling economies supported the development of power systems, while efficiencies in the power systems assisted in the development of drills. While these forces were mutually important throughout, in the HH phases, systemic efficiencies associated with the need to cool increasingly deep and hot mining environments, as well as the static energy held in the column mine service water, fuelled significant optimism with respect to the eventual diffusion and impact of HH technology.

## Markets for hydro-hydraulic technologies

In comparison with previous practices, HH technologies clearly represent increased knowledge intensity in the production of resources. However, it appears that this increased knowledge intensity has in fact hindered the diffusion of HH technologies in the South African mining sector. These technologies form an alternative system for mining the relatively unique South African gold and platinum deposits. Supporting that system, a range of ancillary HH equipment was developed by upstream suppliers to the mining industry.

Contemporary analysis of demand for South African HH technologies suggests that South African expertise remains focused on relatively large-scale or systemic applications in the resource base.

In contrast, a large market for HH technologies has emerged internationally in non-resource-based sectors requiring small-scale applications. This section reviews the markets for HH technologies and the role played by non-South African organisations in supplying these markets, and it appears from this analysis that there are robust markets for HH technologies, but these are currently mostly not in resource-based sectors.

A critical challenge therefore exists to increase the scale by which South African HH technologies laterally migrate from their resource-based origins.

## Resource-based markets for hydro-hydraulic technologies

South African HH technologies were originally developed as an alternative underground mining system. In this market, the technical promise of HH technologies has not been followed by the large uptake originally expected.[21] 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.[22] There are two primary reasons for the limited diffusion of HH technologies: the greater knowledge intensity of the technology and the geological specificity of the technology's fundamental design.

Geological characteristics within and between mines require a significant degree of technological adaptation if a productive system is to operate efficiently. The HH system was designed for relatively deep-level tabular ore bodies where gravity provided the energy needs of the entire system. In this context, the advantages of an HH system are also greatest if the technology is part of the initial design of a mine. At present, there is not much development of relatively deep-level mines because of the longer time necessary to realise a return on investment. Even when a new deep-level mine is developed, HH technologies are at a disadvantage as production technologies because mining finance favours established technologies.

As a result, HH technologies must compete on the basis of ad hoc advantages over other established systems. The fact that the HH system was designed for mining in the presence of considerable mine service water is another geologically specific design feature that can hinder its adoption as a mining system. Few other ore bodies are reported to use as much mine service water in their operations as the Witwatersrand mines, which reduces some of the inherent benefits of HH systems. In addition, some minerals, such as platinum, are extracted more efficiently without the introduction of water into the mining process.

Significantly for the idea of leveraging knowledge intensity in the resource base, the knowledge intensity of the HH system appears to be a barrier to its diffusion. HH equipment uses no oil and must be manufactured to a far greater degree of precision than oil-hydraulic or EH equipment.[23] That greater precision adds a fundamentally higher level of complexity and cost to the manufacture of HH equipment. It also requires different maintenance practices, which include proactive servicing rather than reactive repairing of the equipment. This inherent cost could be offset by production efficiencies and health and environmental savings,[24] but presently the limited scale of adoption means that those benefits are not sufficient to induce the conversion of established mines to HH systems.

The existing less knowledge-intensive pneumatic-based system of stoping benefits from path-dependency associated with agglomeration and routinisation economies.[25] As long as pneumatic technologies predominate, training and maintenance of personnel to utilise those technologies is a common good. In contrast, similar economies can only be realised if a critical number of producers adopt HH technologies. To the extent that such 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 far 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.[26] Inter-agent authority over production 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.

## Upstream markets for hydro-hydraulic technologies

Despite the barriers to the adoption of South African HH technologies as a mining system, 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, which are used to facilitate the 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.[27] Demand for HH equipment such as HH shovels, winches, chainsaws and drill rigs has also developed. Niche applications of HH technologies typically utilise micro-HH packs to power the equipment.

One equipment supplier, Sulzer, has taken a proactive approach and sought to facilitate the introduction of HH technologies within the 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 an HH-lubricated pneumatic drill. In this way, Sulzer has developed a drill that operates on the pneumatic infrastructure that exists in most mines but that also introduces productive and, most importantly, environmental benefits associated with HH technologies.

Important dates in the development of the resource-based market for South African HH technologies are listed in Table 5.2. Given the limited



**TABLE 5.2** *Some important dates in the development of South African suppliers of hydro-hydraulic technologies (1975–2003)*

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| 1975 | Ingersoll-Rand undertook hydraulic drill development with COMRO. |
| 1975 | Vickers Systems undertook hydraulic power development with COMRO. |
| 1978 | Hammelmann undertook hydraulic power development with COMRO. |
| 1979 | Gullick undertook impact ripper development with COMRO. |
| 1982 | Seco and Novatek undertook hydraulic drill development with COMRO. |
| 1985 | Hydro Power Equipment (HPE) was established. |
| 1987 | TLC Software was established |
| 1989 | Sulzer undertook hydraulic drill development with COMRO. |
| 1990 | Turgis Consulting was established. |
| 1992 | Joules Technology was established. |
| 1996 | Sulzer began producing the New Generation Drill for HH technologies. |
| 2003 | Sulzer began developing an HH-air rock drill. |

number of firms supplying South African HH technologies, each of these firms and their involvement with HH technologies is briefly reviewed. Following that review, other resource-based applications of the technology are analysed. Notably foreshadowing non-resource-based markets in applications outside of mining, firms independent of the South African development of the technology appear to be the leading suppliers.

The following companies have been involved as suppliers of HH technologies to the South African market:

- Hydro Power Equipment (HPE): Emerging in the mid-1980s around the COMRO HH research initiative, HPE is now a leading firm supplying hydropower 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 hydropower 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 the development of knowledge and expertise in HH technology. This includes running training courses in the utilisation and maintenance of its HH equipment as well as providing dedicated service engineers on-site for its larger customers.
- Ingersoll-Rand: Despite its leading role in developing 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 the drill were purchased by Joules Technology in 1999, which continued its manufacture until 2002, when demand for this relatively dated technology led Joules to discontinue manufacturing it.
- 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 already mentioned, Joules Technology produces a range of other HH 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 the development of an HH drill under COMRO's stewardship. In the early 1990s, it merged with UK-based Gullick, whose background in the UK coal industry had led to its involvement in COMRO's HH programme in the late 1970s. In the mid-1990s, a management buy-out led to Novatek's 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 or 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 classroom and on-the-job training in stoping with its HH drill.
- Seco: Despite its historic pre-eminence in supplying pneumatic rock drills to the South African mining industry in the early 1990s, Seco analysed the potential demand for HH drills and, perceiving it to be a niche technology, terminated its research efforts in the development of an HH drill, which had been transferred to its UK facilities.
- Sulzer: Entering into COMRO's HH programme in the late 1980s with its turbine technology, Sulzer's development of the lighter-weight New Generation Drill, based on a South African design, expanded its HH product demand in the mid-1990s. As already mentioned, 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 that HH technologies play an ancillary role in their businesses. One of the more prominent examples of this class of firm is the mining consultancy Turgis, which was founded in 1990 by several COMRO staff members that had been heavily involved in the HH programme. Despite its staff being knowledgeable about HH technologies, which is still one of its core competencies, Turgis has found that demand for other mining consultancy services greatly surpasses demand for its knowledge of HH technologies.

Another service firm that emerged from COMRO's HH programme was TLC Software, which was established by three COMRO employees that had designed the software, instrumentation and measurement system for the HH system. Today, TLC Software offers a range of specialist engineering software solutions. Similarly, Bluhm Burton Engineering (BBE), a mining consultancy specialising in cooling and ventilation, employed some staff that had worked on the COMRO HH programme. The 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, the only immediate competitive threat to South African HH equipment suppliers comes from a Swedish HH long-hole driller (Fraser 2006: 6). However, in other resource-based sectors, South African HH equipment plays a minor role relative to non-South African HH equipment. The oil and gas industry and the wood-processing and paper industry are two of the more significant other resource-based markets for HH technologies. In the oil and gas industry, HH technologies offer tremendous benefits because of their non-flammability. The technology's reduced risk of environmental pollution is important for it adoption in the paper industry. Wood processing has also become a target market for HH technologies, with water lubrication and the cooling of saw blades being used to reduce friction from the resin in wood.

## Non-resource-based markets for hydro-hydraulic technologies

The supply of South African HH equipment to non-resource-based markets indicates that the technology has migrated laterally. However, South African HH equipment in non-resource-based sectors services primarily local niche demand rather than large-scale international demand for HH equipment.

Despite the relative robustness of the South African HH system, particularly its ability to use water with some dirt content, the pervasive focus of the industry on the mining sector has prevented its accessing larger markets for the technology and their associated economies of scale.

Outside resource-based sectors, South African HH technology has found niche markets in hot-metal industries and high-pressure washing. HPE appears to be the primary South African equipment supplier for these markets. Specifically, HPE has developed HH equipment for the South African steel industry. Owing to the fire risk of oil hydraulics in the steel-manufacturing environment, HH technologies are a logical means of moving heavy equipment. HH descalars and tap hole 'mud gun' pluggers were therefore developed for arc furnaces. The HH descalar is used to clean the inside of a furnace, while the tap hole mud gun stops the flow of materials from an arc furnace 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. Internationally, hot-metal industries remain the biggest market for HH equipment, but it is a very small market for South African HH equipment manufacturers (Fraser 2006: 5).

Besides hot-metal industries, South African HH equipment is used in high-pressure cleaning of buildings and concrete rehabilitation. Ultra-high-pressure water is also used for profile cutting and demolition (Fraser 2006: 5). Non-South African HH equipment is also being used for industrial cleaning of cars, trucks, buses and trains. Other industrial cleaning applications of non-South African HH technology include street cleaners, container/silo cleaning and stockyard/stable cleaning.

Apart from the two niche markets discussed, at least one South African HH equipment manufacturer envisages further lateral migration of the technology. If Sulzer's Aya Duma Duma drill can show its commercial viability in replacing pneumatic drills on the mines, Sulzer plans to develop related HH equipment for the construction and manufacturing industry. Despite the real and potential lateral migration of South African HH technology, however, most non resource-based markets for HH technologies are currently being supplied by organisations that developed HH technologies outside the resource base.[28]

The energy and food industries, and fire-fighting, humidification and water desalination applications, are some of the other markets for HH technologies outside the market of South African suppliers. HH technologies offer compact and powerful energy that is simultaneously safe, hygienic and environmentally friendly. These characteristics have led to the rapid growth of HH technologies in a variety of non-resource-based international markets.



## 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, HH technologies have not diffused significantly from their original applications. There is clearly potential for these technologies to move further out into the mining sector and other resource and non resource-based sectors. However, the slow diffusion of South African HH technologies, in contrast to the rapid growth of non-South African HH technologies, raises serious concerns over the likelihood of the technologies' significant lateral migration in the future. Bearing this in mind, we turn now to an analysis of the four principal dimensions of lateral migration: absorptive capacity; the role of foreign technology; linkages and interactions; and industrial policy.[29]

## Absorptive capacity

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

HH technologies are comparatively more skills intensive than the precursors they were designed to replace. This is partly because of the inherent complexities in HH technologies, but the skills intensity of the technologies is also relatively elevated because routines, standards and organisational practices in the established competing technologies have significantly reduced the requisite skills. Interviews with individuals active in the industry indicate that changes in the organisational structure of the industry have enhanced this barrier to the diffusion of HH technologies, the diminishing engineering skills on mines means that they have reduced capacity to experiment with alternative operational practices.

While international precedents were important in the initial stages of the initiative, the unique features of the working environment led to the development of the technology 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 unique technology.

Despite originating within the mining sector, an important characteristic of the research initiative was that it fostered the development of domestic manufacturing capacity. While specifically targeting the development of manufacturing capacity for the mining industry, that level of inter-industry development and common goods illustrates the high level of segmented social capital that existed within the South African economy before democracy in 1994. 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 the mining sector appear to have considerably greater potential scope than has thus far been realised. The principal lateral migration of South African HH technologies so far has been by one firm, HPE, in its development of HH equipment for the steel industry. Among the other technologies with potential for lateral migration, Sulzer's HH-lubrication technology for pneumatic equipment appears to be one of the most promising.

## The role of foreign technology

While deliberately fostering domestic absorptive capacities, COMRO was pragmatic in the HH programme in 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, efforts in coal mining by Australia, the United Kindom and the United States were considered. Among these international sources, the skills developed within the British National Coal Board 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 providing a foundation of knowledge that South Africa leveraged in accelerated catch-up to reach the international forefront of HH technology.

Apart from the role of related foreign HH technology, the complexity of the HH system benefited from COMRO's international search for the best technical solutions across sectors. In this regard, COMRO partnered with Ingersoll-Rand (based in the United States) 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 the development of micro-emulsions by US oil companies, emergency safety valve technology from the foreign nuclear and oil industry, and specialised steel alloy development steel producers in the United States and the United Kingdom.

## Linkages and interactions

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

The international isolation faced by the South African mining finance houses contributed to some extent to the depth of the linkages that characterised the development of HH technology. Moreover, during the decades when HH technologies were being developed, the international mining sector was characterised by collaboration in production, concurrently with fierce competition to secure mineral rights. Organisationally, the hierarchical structure of the South African gold industry under the system of mining finance groups facilitated inter- and intra-organisational transfers of technologies and the organisation of production between mines across the Witwatersrand deposits. COMRO is perhaps the best indication 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. Firstly, increased internationalisation of the South African economy in the 1990s led South African mining finance groups to integrate and diversify their operations globally, and in so doing undermine some of the common cause that had previously supported social capital and collaboration in the industry. Secondly, mergers and acquisitions in the international mining sector shifted the borders of competition and cooperation, so that cooperative research and development was no longer viable among the mining firms. This reduced the scope for further collaborative development and diffusion of HH technologies to the point most clearly illustrated by the dissolution of COMRO itself. Lastly, as from the 1980s as part of the general restructuring of hierarchical control by the South African mining finance groups, individual autonomy at the Witwatersrand gold mines was increased simultaneously with reduced capacity to significantly alter operations. This led to a situation in which mines increasingly customised mining operations to suit the geology of their deposits rather than just applying standard operational practices across all the mines of a given group. 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 previously.

The analysis suggests that strong linkages persist between individuals and organisations involved in the development of South African HH technologies. However, the loss of COMRO removed a critical institutional champion of the technology. In the face of these additional challenges, the adoption of HH technologies is now dependent on their promotion by HH equipment manufacturers. As a result, South Africa's HH technology continues to face severe hurdles in its diffusion into the domestic and international mining sectors. Without increased adoption of the technology in this target market, most firms with HH capabilities appear reticent to venture into non-resource-based markets, despite their seemingly greater demand.

## Industrial policy

While state taxation and fiscal policies generally favoured the mining industry, these indirect measures were the only public support for the development of HH technologies. As such, this case study illustrates the power and importance of intra-sectoral cooperation in fostering the productive capacity of a sector.

The role played by COMRO's systemic coordination has not yet been appreciated in policy debates related to enhancing the competitiveness of South African mining. Despite valid criticisms of COMRO itself, without a similar stakeholder in the sector's system of innovation, it is almost certain that no equipment supplier would ever undertake the development of a radically alternative technology such as the HH system. It is therefore less likely that a domestically developed broad platform technology will laterally migrate in the future. Notably, industrial policy has thus far not been a significant factor in the lateral migration of HH technologies. Clearly, this is an area that needs further policy consideration.

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



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## Notes

1 Emulsion hydraulics involves mixtures with non-soluble oil finely dispersed in water.

2 HH involves no oil and just utilises water.

3 Stoping practices are the underground operations that remove 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 detonating explosives in these blast holes, and then clearing the blasted material.

4 Wilson (1972) shows that the real wage paid to black miners was static between the 1920s and early 1970s.

5 According to Austin (2001) the post of Research Advisor was chosen instead of Science Advisor to assuage any ill-feelings the engineers might have had towards scientists.

6 Apart from stoping technologies, this research programme also investigated environmental and safety technologies, mining operations and human resources.

7 For a critique of linear models of innovation, see Kline and Rosenberg (1986).

8 COMRO also had a 'low-risk' contract whereby equipment manufacturers bore the design and construction costs, while COMRO bore the cost of evaluation.

9 For an explanation of why this would facilitate catch-up, see Perez and Soete (1988).

10 Other revolutionary technologies experimented with during this era were rock cutters, swing hammers, impact rippers and armoured face conveyors (Joughin 1976).

11 1 MPa = 145 pounds per square inch (psi). The pressure in an automobile tyre is between 0.18 MPa and 0.25 MPa.

12 1 000 kPa = 1 MPa.

13 In this, the interest of the US automotive industry in a 95-5 EH cutter may have been important.

14 As additional drill manufacturers subsequently became involved, other rotation mechanisms proved viable.

15 For instance, the United States in the early 1980s was still addressing problems in the development of 60-40 EH systems.

16 Gullick had already been working on the COMRO mechanisation initiative in impact rippers, drawing on its UK experience in mechanisation in coal mining with the UK National Coal Board.

17 Carbon steel is the most common type of steel alloy produced. It contains about 2% carbon by weight and the remainder is iron.

18 At depths of 2 km, mines on the Witwatersrand were usually faced with underground temperatures of 32 °C; at a depth of 2 km at Northam, the underground temperature was 65 °C.

19 Notably, international intellectual property rights did not play a significant role in the development of HH technologies, nor did foreign technology inflows either enhance or diminish the incentives for innovation.

20 In a four-year period between 1989 and 1993, COMRO's cooperative industry funding was withdrawn and its reduced operations were transformed into a contract-based research division of the Council for Scientific and Industrial Research (CSIR) called the Mining Technology Division.

21 See Joughin (1984); Paraszczak et al. (1994); and Wyllie (1990) for examples.

22 These are GFSA's Kloof and Beatrix gold mines, AAC's Tau Lekoa gold mine and Northam Platinum Ltd's Northam platinum mine.

23 Acceptable precision in HH equipment is reportedly approximately 1 micron (a millionth of a metre) compared with 20 microns in oil-hydraulic equipment.

24 Among the more important environmental benefits of HH technologies are their removal of oil from the working and maintenance environment. In addition, HH drills are less noisy even than muffled pneumatic drills, which reduces hearing damage among workers.

25 See Arthur (1994) and David (1985) for further information on the concept of path-dependency.

26 See Nelson and Winter (1982: Chapter 5) for an elaboration of the economics of organisational routines.

27 Reportedly, this greater uptake is associated with lower workforce resistance to HH technologies in these activities.

28 Currently, the most important supplier of HH technology internationally is Danfoss, which originated as a Danish refrigerator valve manufacturer. See www.danfoss.com for more information.

29 See Lorentzen (2005).



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