



# Lessons for the future: the origins and legacy of COMRO's hydraulic technology programme

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## Synopsis

This paper traces the co-operative initiative undertaken by South Africa's gold mining companies through the Chamber of Mines Research Organization (COMRO) in development of hydraulic technologies. After a brief description of the structure of these technologies' development under COMRO's stewardship, the paper turns to an overview of the structure of innovation within which these hydraulic technologies were developed. A central focus of this paper is systematic review on whether similar technologies are likely to emerge in the present system of innovation and the role played by innovation policy.

## Introduction

This paper traces the co-operative initiative undertaken by South Africa's gold mining companies through the Chamber of Mines Research Organization (COMRO) in development of hydraulic technologies. After a brief description of the structure of these technologies' development under the COMRO's stewardship, the paper turns to an overview of the structure of innovation within which these hydraulic technologies were developed. A central focus of this paper is systematic review on whether similar technologies are likely to emerge in the present system of innovation and the role played by innovation policy.

There is an analysis with a description of the development of hydraulic technologies. Two distinct stages of hydraulic technologies' development are identified. First, emulsion hydraulic (EH)<sup>1</sup> technologies were developed and commercially deployed between the mid-1960s and the late-1980s. Second, water or hydro-hydraulic (HH)<sup>2</sup> 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. Supporting their development were 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.

Then 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 COMRO. COMRO's creation and eventual dissolution corresponds closely to the initiation and conclusion of systemic research into hydraulic technologies<sup>3</sup>. Therefore, this paper examines COMRO's origins, development, and demise. It thereby provides a previously undocumented history of the evolution of a major feature of the system of innovation in South Africa's mining sector.

The final section reflects on evidence from this case of hydraulic technology's development in South Africa and its subsequent significance. It considers whether similar technologies are likely to emerge in the present sectoral system of innovation.

Lastly, the role of current industrial and innovation policies in fostering domestic hydropower capabilities for future applications of the technology are reviewed.

## Development of hydraulic technologies<sup>4</sup>

### The development of hydraulic technologies

<sup>1</sup> Emulsion hydraulics involves mixtures with non-soluble oil finely dispersed in water.

<sup>2</sup> Hydro-hydraulics involves no oil and just utilizes water.

<sup>3</sup> Nonetheless, hydraulic technologies continue to be refined and developed by equipment manufacturers but they do not undertake systemic research.

<sup>4</sup> 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 author's.

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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<sup>5</sup>. In the 1920s, Witwatersrand mining had transformed stoping practices underground through the introduction of pneumatically powered rock drills<sup>6</sup>. 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<sup>7</sup>.

As existing goldmines went deeper and new fields in the Far West Rand (FWR) and Orange Free State (OFS) were developed in deposits that began at greater 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 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<sup>8</sup>.

Previously, many of the technologies that changed the Witwatersrand gold mining industry had been developed and diffused by the mining-finance groups. In the 1950s, some of the traditional technological leaders diversified out of Witwatersrand gold mining. Thus, the principal industry association, the Chamber of Mines of South Africa (COMSA)<sup>9</sup> became an increasingly important player in the industry's research activity<sup>10</sup>. 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<sup>11</sup>.

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 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 ten-year research initiative into the

development of mechanization technologies for operations underground<sup>12</sup>. First, African nations in a post-colonial setting threatened the supply of relatively inexpensive black miners from across Southern Africa<sup>13</sup>. Between 1973 and 1976, the number of foreign workers on the Witwatersrand gold mines dropped from 336000 to less than 200000 (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%<sup>14</sup>. 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 mechanization programme as a means to access the Witwatersrand deposits that continued deeper underground.

### *Development of emulsion hydraulic technologies*

Table I 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.

Just before initiating the ten-year mechanization research and development (R&D) programme in 1974, Miklos Salamon replaced William Rapson in the joint-post of COMSA Research Advisor (RA) and COMRO Director<sup>15</sup>. As COMRO's annual budget increased threefold, Salamon realigned COMRO's organizational structure to the mechanization research programme. With the ten-year programme, COMRO also defined its R&D ethos and staked-out its organizational routines. 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 realizing economies of scale and speed in development of the technologies through a broad base of participatory organization. Lastly, collaboration focused on equipment manufac-

<sup>5</sup> See Black and Edwards (1957) and Hamilton (1963).

<sup>6</sup> Stopping 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.

<sup>7</sup> See Johnstone (1976).

<sup>8</sup> Wilson (1972) shows that the real wage paid to black miners was static between the 1920s and early 1970s.

<sup>9</sup> For a history of COMSA and overview of its roles as the dominant industry association see Lang (1986).

<sup>10</sup> 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.

<sup>11</sup> See below for details on the creation of COMRO and its predecessors within COMSA.

<sup>12</sup> Besides stoping technologies, this research programme also investigated environmental and safety technologies, mining operations, and human resources.

<sup>13</sup> See Spandau (1980) and Hermanus (1988).

<sup>14</sup> See Table I for details of historic trends in the price of gold.

<sup>15</sup> See Appendix One for a list of COMSA RAs/COMRO Directors

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turers 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<sup>16</sup>, 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 per cent premium, effectively bearing the costs of design, construction and evaluation<sup>17</sup>.

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<sup>18</sup>.

The 1974 mechanization research programme consisted of two distinct groups of technologies: conventional and revolutionary. The conventional technologies focused on improving existing mining methods and under it, the hydraulic drill programme 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<sup>19</sup>. A drag-bit

miner operates in manner similar to a chain saw with rows of metal spikes mounted around a large cylinder. The spiked drum is driven into the host rock to break out gold-bearing ore. Promise of the drag-bit miner was important to hydraulic technologies as high-pressure water jets, around 30 megapascal (MPa)<sup>20</sup>, 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<sup>21</sup>. 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 functional maximum pressure for pneumatic equipment was reached at around 200 kilopascal (kPa)<sup>22</sup>, hydraulic technologies with their greater range of pressures promised to deliver more power to the stope face. In addition,

<sup>16</sup> For a critique of linear models of innovation see Kline and Rosenberg (1986).

<sup>17</sup> COMRO also had a 'low-risk' contract where equipment manufacturers bore design and construction costs while COMRO bore the cost of evaluation.

<sup>18</sup> For an explanation of why this can facilitate catch-up see Perez and Soete (1988).

<sup>19</sup> Other revolutionary technologies experimented with during this era were rock-cutters, swing-hammers, impact rippers and armoured face conveyors (Joughin, 1976).

<sup>20</sup> 1 MPa = 145 pounds per square inch (psi). An automobile tire is usually between 0.18 MPa and 0.25 MPa.

<sup>21</sup> See Whillier (1975), Clement (1975), and Marshall (1975).

<sup>22</sup> 1000 kPa = 1 MPa.

Table 1

### Dates in the development of hydraulic technologies (1965–1991)

1965	COMRO Mining Research Division established
1973	Hydropower as energy source investigated
1975	Chilled water service for mine cooling begins production trial (completed 1977)
1975	COMRO and Ingersoll-Rand begin developing 95-5 drill
1975	COMRO and 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 and 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 and 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, and 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 hydropower and 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 author



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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, 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 have an integrated chilled water service like its pneumatic counterparts.

While bearing those fundamentals in mind, it is important to realize 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 division of 95% water and 5% oil (95-5). Originally, COMRO worked with the United Kingdom 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. 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 enough quantities and with sufficient force, other equipment on the stope-like 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 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 high component 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 UK and the US all had some research initiatives into development of a hydraulic drill. In the 1970s, Australian and US coalmines were working on a 60% water, 40% oil (60-40) hydraulic drill. That was too high a component 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 US automobile manufac-

turers 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 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 more rapidly. Therefore, COMRO collaboratively developed special plastic seals and bearings (Walczak, 1984).

A second challenge arose because at a 95-5 division 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.

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 mechanisms to wear at an unacceptable rate. After many iterations, a major breakthrough was realized when a quadruple plunger, ratchet and clutch, rotation mechanism was created<sup>23</sup>. 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 to the labour force organization to accommodate this new technology<sup>24</sup>.

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.

### *Development of water (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 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<sup>25</sup>. Remembering that the 1974 mechanization research programme was ending, three factors appear to be particularly significant in further development of HH technologies.

<sup>23</sup> As additional drill manufacturers subsequently became involved, other rotation mechanisms proved viable.

<sup>24</sup> See Glassborow and Veldsman (1982) and Veldsman and Pretorius (1983)

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First, as previously mentioned, the revolutionary mechanical rock breaking programme had found good performance in its drag-bits when used in conjunction with high pressure water, around 30MPa, on the rock surface. This performance resulted from the removal of waste rock under the teeth<sup>26</sup>. 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 an 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 the 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 utilizing 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<sup>27</sup>. A fundamental efficiency of HH power thereby emerged, since it could function as an integrated technology without necessitating duplicate cooling and compressed air systems. Therefore, in 1980 COMRO initiated research to combine 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. At its base 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 utilized to pump the water, tapping into this system required developing only 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, UK based Gullick also became involved in developing HH power pump technologies along with Hammelman, while Vickers Systems withdrew from the

research initiative<sup>28</sup>. 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 chilled water system<sup>29</sup>. 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 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 Fields South Africa's (GFSA) Far West Rand mines<sup>30</sup>. 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<sup>31</sup>. Gradually they dropped the level of emulsion in the drill until it 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 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 been subsequently established to manufacture its drills, demand surpassed Innovatek's capacity in the early 1990s, leading to a merger with 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<sup>32</sup>. However, after initial prototypes were developed production of Sulzer's drill was based in South Africa where further development of the drill also occurred.

<sup>25</sup> For instance, the US in the early 1980s were still working out problems in development of 60-40 EH systems.

<sup>26</sup> See Hood (1976) and Joughin (1978) for details.

<sup>27</sup> See Wagner and Joughin (1989) for details.

<sup>28</sup> Gullick had already been working on the COMRO mechanization initiative in impact rippers drawing on its UK experience in mechanization in coal mining with the UK coal board.

<sup>29</sup> See Brown and Joughin (1988) and Du Plessis and Soloman (1988) for details.

<sup>30</sup> See Westcott (1986), Holloway *et al.* (1987), and Du Plessis *et al.* (1989) for details.

<sup>31</sup> That drill was known as the HD-30.

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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 utilized for dynamic seals. For bearings, polymers were the only viable materials<sup>33</sup>.

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 water of the mines' was too harsh for the normal steel. Because existing alternative corrosion resistant material broke down under the mechanical forces to which the drill was subjected, COMRO initiated 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, in the end they adapted existing steel. In fact, while the problem was particularly severe for the drills, corrosion was also a concern in the other equipment as well as the piping and power systems themselves<sup>34</sup>.

Progress in the HH drill was made continuously through the late 1980s, even as COMRO's organizational future was in doubt and Ingersoll-Rand withdrew from the research initiative<sup>35</sup>. Thus, in the early 1990s when GFSM announced its commitment to an entirely HH system in its newly developed Northam Platinum mine, an important impetus 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<sup>36</sup>. 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).

### Conclusion

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<sup>37</sup>.

<sup>32</sup> This drill was known as the Turbo Drill.

<sup>33</sup> See Harper (1990).

<sup>34</sup> See Howarth (1990).

<sup>35</sup> See below for details.

<sup>36</sup> At a depth of two kilometres mines on the Witwatersrand were usually faced with an underground temperature of 32°C, at Northam at two kilometres the underground temperature was 65°C.

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.

### Aspects of mining's system of innovation<sup>38</sup>

Development of the hydraulic technologies described above depended fundamentally on COMRO. As a co-operative research organization 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 organizational culture. This section analyses the institutional architecture in which hydraulic technologies were developed. Therefore, it focuses on the formation of COMRO, how COMRO evolved, why COMRO dissolved as well as 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 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<sup>39</sup>. Besides the cyanide process patent, the Patent Committee took on a broader role reviewing South African applications for intellectual property rights, in the form of patent applications, in order to ensure patents were not granted to public technologies.

Early on COMSA also attempted to co-ordinate the research and development of technologies for the industry. In 1893 it established a Metallurgical Sub-Committee to support the commercial development of cyanide-based extraction technologies<sup>40</sup>. Then in 1908 COMSA established a Mine Trials Committee to foster development of pneumatic rock drill for stoping. Perhaps the most important steps that COMSA took in the coordination of technologies before COMRO were establishment of the Technical Advisory Committee (TAC) in 1922 and the independent position of Technical Advisor (TA) in 1923.

<sup>37</sup> 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.

<sup>38</sup> 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 author's.

<sup>39</sup> Cyanide based extraction was critical to mine economically 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.



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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 forwarded to it by the Gold Producers Committee (GPC). However, with the establishment of an independent position of TA<sup>41</sup>, 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 on the application of new technologies in the industry.

Prior to COMRO, COMSA 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 to develop treatments to make wooden stope supports more resistant to decay, which was also based at COMSA's headquarters. 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 the nearby suburb of Melville. These 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 took over a collaborative research initiative into underground rock bursts between a consortium of mining-finance groups and 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<sup>42</sup>. 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 they did not possess the necessary organizational capacity. Development of that capacity led to the establishment of a Research Advisory Committee (RAC), an independent Research Advisor (RA) and eventually COMRO.

In 1957, the Technical Advisor to COMSA, Michael Falcon, began a search for someone to direct the disparate COMSA research laboratories. That search led Falcon to the UK where he contacted Sir Basil Schonland, a leading South African expatriate scientist and science advisor<sup>43</sup>. Falcon's 1957 search for a director did not produce a suitable candidate, but it initiated 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 coordinating the development of new technologies for the industry (Austin, 2001)<sup>44</sup>.

<sup>40</sup> Strictly speaking, the Metallurgical Sub-Committee was acting to facilitate development of a viable metallurgical process to extract gold from the pyritic deposits.

<sup>41</sup> See Appendix Two for a list of COMSA's TAs.

<sup>42</sup> See Cartwright (1968) for details.

Table II

### 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 COMSA's 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	US Dollar convertibility to gold ended
1974	Malawi suspends COMSA labour recruitment
1974	COMSA launches large-scale 10-year mechanization research initiative with COMRO
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 finalized, effected in 1993

Source: Compiled by author

## Lessons for the future: the origins and legacy of Comro's hydraulic technology

A first step towards COMSA taking up the gauntlet of industry research came in 1960 when the RAC was formed. The RAC was tasked with the organization, 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 the RAC sent the proposal to the TAC. The TAC then forwarded the RAC's proposals to the GPC for budget authorization.

Throughout the projects' life the RAC was responsible for monitoring and evaluation on which it reported to the TAC. Before establishment of the RAC, there was only a piecemeal reporting structure by the COMSA laboratories to the TAC.

Although the RAC facilitated a certain degree of research coordination within COMSA, the various laboratories continued to operate independently. Realizing 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 COMSA. Acting on Schonland's review, COMSA established the post of RA<sup>45</sup> and the position was filled by William Rapson in 1962.

Rapson immediately began to promote an organizational 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 being both the RA and COMRO's director (Lang, 1990, p. 114). COMRO gradually established its role in industrial research under Rapson. Particularly important in this regard was the previously mentioned 1965 establishment of the MRD, 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 mechanization.

While the relevance of the 1974 research programme has already been discussed, it is important to reiterate some features. The need for the mechanization programme originated from the increasing depth of gold mining and the

racial occupational mobility restrictions of operations. As COMRO began this new research programme, Salamon restructured the organization to focus on mechanization.

When the ten-year mechanization 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 organizational know-how played an important role in their competitiveness and as such the role for a co-operative research organization 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 of other mine medical facilities was withdrawn. Within the Witwatersrand gold industry this transformation became apparent in the increasing decentralization of mining activities. In the 1980s standard systems employed across all mines in mining-finance group began to be replaced by greater customization to account for the variety of conditions.

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

Around the late 1980s the Government Mine Engineer (GME) saw the industry's withdrawal from COMRO with concern because of the associated reduction in safety research. In reaction, the GME made it clear that State mandated safety research would be a certainty in the near future. That move by the GME thereby put COMRO's dissolution as a systemic co-operative research organization 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, effectively formed COMRO's death warrant. Thus, in 1990 following further budgetary cuts and reductions in 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.

Deterioration of gold demand was often cited as a cause for the gold industry's withdrawal of support from COMRO and COMSA<sup>46</sup>. 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 rand rose at a sluggish 0.2%. Perhaps more important though was the sub-period between 1987 and 1991 when the average real annual compound price of gold in rand decreased by 5.2%.

In the 1980s, increasing discord emerged between the GPC, the TAC, and COMRO as the industry began to transform. 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).

<sup>43</sup> See Austin (2001) for a biography of Schonland.

<sup>44</sup> There has been a long historic divide between scientist and engineers, which although it perhaps not as evident today, has played a significant role in shaping their respective disciplines. See National Academy of Sciences (1985).

<sup>45</sup> 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.

<sup>46</sup> Concurrently, COMSA's mission as industry association radically transformed. This is reflected in COMSA staff decreasing from 6800 in the late 1980s to 70 in 2001.



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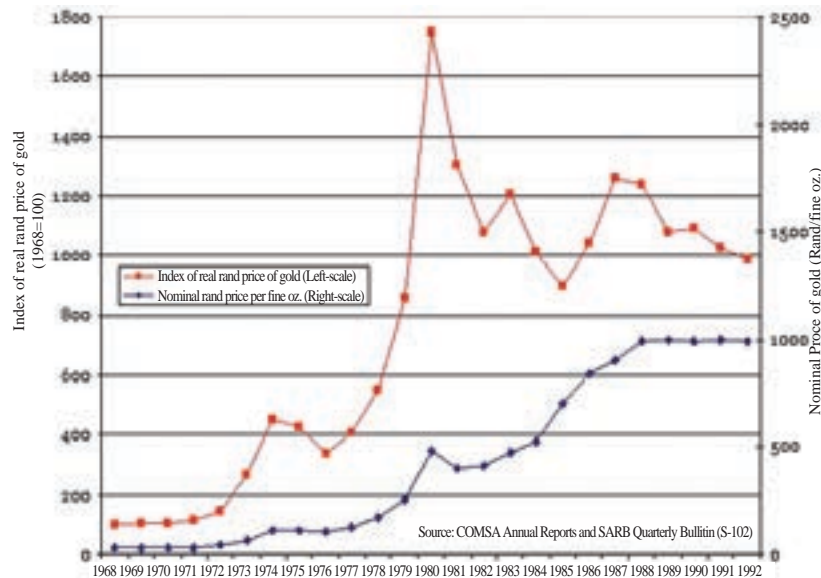


Figure 1—Demand for gold 1968–1992

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 shape the structure of State mandated mine safety research. Thus, when the Safety in Mine Research Advisory Council (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.

### Conclusion

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 organization from its predecessor. Notably CSIR-Miningtek no longer undertakes comprehensive management of a research project like COMRO did with hydraulic technology<sup>47</sup>. COMRO played a 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 shortcomings, in particular it had a very rigid organizational 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 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 internationalization of the South African economy since 1994 and the associated international diversification by South African mining-finance groups<sup>48</sup>, the mining sector experienced an international decrease in public research<sup>49</sup>. The dissolution of COMRO has left a gap in the systemic co-ordination of research and development in the 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 interconnected technologies.

HH technologies originated within a collaborative initiative supported by the South African gold mining industry that was trying to increase the mechanization of stope operations. These efforts for mechanization emerged from internal competitive imperatives as well as successful local and international precedents in coalmining mechanization. COMRO, the industry's co-operative research organization, played a major role in 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 because routines, standards, and organizational practices in the established competing technologies have

<sup>47</sup> Deep-Mine has not been at the same scope or nature as COMRO mechanization initiative.

<sup>48</sup> 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.

<sup>49</sup> Among other international examples was the 1996 closure of the United States Bureau of Mines.

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significantly reduced the requisite skills. Changes in the organizational 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 or organizational routines<sup>50</sup>.

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 integrated 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 to foster development of domestic manufacturing capacity. While targeting development of manufacturing capacity for the mining industry, the level of inter-industry development and common goods illustrates the high level of social capital that previously characterized the sector.

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.

In its deliberately fostering domestic absorptive capacities, COMRO was pragmatic in the HH programme, drawing on organizations with the best capabilities. International precedents were important in providing incentives to initiate research into HH technologies, in particular Australian, UK and US efforts in coal-mining were consulted. Among these international efforts the mobility of skilled individuals from the British Board of Coal played an important role in South Africa's ability to create innovative HH technologies. Overall the body of existent foreign research created a foundation of knowledge South Africa leveraged in accelerating its catch-up in HH technology and position the country 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 specialized steel alloy development with UK and US steel producers.

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 paper

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, without 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 systemic alternative technology like the HH technologies. As a result there is less opportunity for knowledge spillovers from South Africa's mining industry to the rest of the economy.

South African HH technologies were developed over more than two decades under the comprehensive direction of COMRO. While they have established a viable market niche, that demand is rather tenuous owing to the non-renewable nature of the resources upon which it is based. In the mining sector there is clearly a potential for these technologies to move into the mainstream as environmental externalities become an increasing concern during what many believe to be a long-term boom in the resource sector<sup>51</sup>. However, path dependence in the pneumatic-based system of stoping seems to be creating agglomeration and routinization economies that to date have functioned as an effective barrier to HH technology's larger-scale adoption<sup>52</sup>.

The paper has detailed the origins of South Africa's international leadership in HH technology for the mining sector. This technology possesses significant potential for both continued deployment in the mining sector as well as in other applications. The review thereby highlighted an important era in the mining sector's system of innovation as well as precedents for contemporary initiatives aimed at enhancing domestic competitiveness to draw on.

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<sup>50</sup> See chapter five in Nelson and Winter (1982) for an elaboration of the economics of organizational routines.

<sup>51</sup> For further discussion of lags between an invention proving its efficacy as an innovation and that innovation's impact on the productive system, see Jaffe (1986), and Soete and Turner (1984).

<sup>52</sup> See Arthur (1994) and David (1985) for further information on the concept of path-dependency.

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## Appendices

### Appendix One: COMSA RAs / COMRO Directors

William S. Rapson	1/1/1962 to 31/12/1973
Miklos D.G. Salamon	1/1/1974 to 31/12/1985
Horst Wagner	1/1/1986 to 12/31/1988
Noel Joughin	1/1/1989 to 12/31/1990
John Stewart	1/1/1991 to 12/31/ 1992

### Appendix Two: COMSA Technical Advisors

C.R. Davis	1/7/1922 to 31/10/1923
Frank G.A. Roberts	1/11/1923 to 31/12/1937
J.P. Harding	1/11/1938 to 14/7/1951
Michael Falcon	15/7/1951 to 25/3/1961
Vacant	26/3/1961 to 31/3/1961
Alec B. Daneel	1/4/1961 to 31/12/1970
Gordon H. Grange	1/1/1971 to 31/12/1985
D.B. Gaynor	1/1/1986 to 31/12/1988
Vacant	1/1/1989 to 12/31/1993
H.R. Hume	1/1/1994 to 21/31/1996



