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APPENDIX A

PAPERS PRESENTED OR PUBLISHED FROM RESEARCH PRESENTED IN THIS THESIS


APPENDIX B

OVERVIEW OF RÖSSING

B1 HISTORY OF ROSSING

In 1910 Dr E Reuning first recognised the presence of radioactive materials in the Rössing area. He found a heliodore (golden beryl) in a pegmatite near Rössing Mountain which contained radioactive $\text{U}_3\text{O}_8$ (0.02-0.04%) (Berning, 1986). In 1921, Dr P A Wagner postulated that the uranium content of the heliodore indicated that the magmatide solution from which the pegmatite crystallised was also radioactive (Wagner, 1921). In 1928, Captain Peter Louw, a part-time prospector from Swakopmund, and his wife Margery measured radioactive levels on a sample of a heavy black mineral (pitchblende) found 20 kilometres from present day Rössing.

In 1932 (Prof TW Gevers) and in 1948 (CM Schwellnus and GSJ Kuschke) confirmed the presence of radioactive minerals but no economic importance was attached to their discoveries.

The Louw family formed a syndicate in 1953, obtained a prospecting grant and set out to relocate the original discovery. In 1954 they succeeded but were unable to arouse local interest. They approached the Anglo-American Corporation and signed a prospecting and option agreement. After extensive exploration and drilling they concluded that although the area contained several million tons of low-grade uranium, the grade was too low and the mineralisation too erratic to warrant economically viable mining.

In August 1966, the Rio Tinto Zinc Corporation Ltd (RTZ) acquired the rights to explore this area. Extensive evaluation in a 100 ton per day pilot
plant confirmed the possibility of establishing a low grade mine, but with a huge deposit and to which the techniques of bulk, low grade open pit mining could be applied. Rössing Uranium Ltd was formed in 1970 and in 1973 the uranium market picked up which enabled commissioning of the mine. The production capacity was set at 5000 annual short tons of oxide.

In mid-1974 the first ground in the open pit was broken and the process plant built producing the first yellow cake. The mine's development was rapid, but the granite Alaskite was highly abrasive resulting in excessive breakdown and maintenance problems.

Technical problems with the Rössing start-up necessitated a major modification programme that was implemented in 1978. Unfortunately at midnight on 24 May 1978 a section of the solvent extraction plant burnt down wiping out half the capacity of the biggest uranium solvent extraction plant in the world. However the plant was soon to be operational again.

At times the mine produced up to 5 000 short tons of yellow cake for a number of years. The strategic value of uranium diminished (along with an over-supply) when east/west confrontation politics disappeared during the mid and late 1980's and Rössing retrenched more than half of its work force during the 1989 - 1992 period. It is still producing yellow cake but at a much lower scale (2 000 short tons) and is currently operating with a manpower complement of approximately 1 300 employees. It still produces 7.7 per cent of the Western World's production.
MINING AND METALLURGICAL OPERATIONS

A. MINING: The uranium ore at Rosbag is recovered by chaffing, blasing, loading, and hauling. The water distribution of minerals is the ground, and one or one are often mixed together. Radioactive sources measure the radioactivity level of each track (19). This determines whether the material is sent to the primary crushers (20) or to a low-grade stockpile. Waste is transported to a separate dump.

B. CRUSHING: The material is sent to the primary crushers (21) in hardrock and then by conveyor to the coarse or stockpile (22). It passes through a series of classifiers and screeners (23) until the particles are smaller than 0.08 mm. After weighing (24) this fine ore is sent to another stockpile (25).

C. GRINDING: Wet grinding of the crushed ore by means of steel rods reduces it further to a slurry, with the consistency of mud. The four mills, which are 4.0 m in diameter, are in use, as required, by production levels and operate in parallel.

D. LEACHING: A combined leaching and oxidation process takes place in large mechanically agitated tanks (26). The uranium content of the pulped ore is oxidized by ferric sulphate and dissolved in a sulphuric acid solution. Sulphuric acid is produced through a pyrites roasting process on site (14).

E. SOLVENT EXTRACTION: The product of leaching is a pulp containing suspended sand and slime. Cyclones separate these components and, after washing in flotation cells (27), the pulp is pumped through a pipe (28) to a tailings disposal area.

F. THICKENING: Counter-current decantation thickeners (29) wash the slimes from previous stages. A clear uranium-bearing solution (pregnant solution) overflows from No. 1 thickeners, while the washed slime is mixed with the sand and pumped to the tailings area (28).

G. CONTINUOUS LIGAND EXCHANGE: (30) The clear pregnant solution now comes into contact with beads of specially formulated resin. Uranium ions are adsorbed onto the resin and are subsequently extracted from the solution. Beads are removed periodically to elution columns where a strong and weak eluate removes the uranium from the beads. The eluate is then purified, and a more concentrated solution is obtained.

H. SOLVENT EXTRACTION: (31) The eluate from the ion exchange plant is mixed with an organic solvent which separates the uranium solution. In the second stage, the uranium solution is mixed with a neutral aqueous ammonium sulphate solution which takes up the uranium into the organic phase (OK liquor). The uranium-loaded organic solution is returned to the ion exchange plant.

I. PRECIPITATION: (32) The addition of excess ammonium to the OK liquor raises the solution pH, resulting in precipitation of ammonium diuranate, which is then thickened to a yellow-slush.

J. FILTRATION: (33) The ammonium diuranate is recovered on rotating drum filters as yellow powder (yellow cake).

K. DRYING AND ROASTING: (34) The cake drying dries off the ammonium leaving uranium oxide. The product is then packed into metal drums. Neither ammonium diuranate nor uranium oxide are explosive substances.

L. LOADING AND DISPATCH: (35) The drums of uranium oxide are loaded and exported to overseas customers for further processing. At full capacity, the plant can produce 5,000 short tons of uranium oxide each year.
Environmental Programme

- OCCUPATIONAL HYGIENE: IMPACT ON EMPLOYEES
  - RADIATION
  - NOISE
  - DUST
  - GASES etc.

- ENVIRONMENTAL SURVEILLANCE: IMPACT ON PUBLIC
  - BACKGROUND RADIATION
  - SULPHUR DIOXIDE
  - FUGITIVE DUST

- ENVIRONMENTAL TRAINING
  - RADIATION
  - NOISE
  - DUST
  - GASES etc.

- ENVIRONMENTAL GEOLOGY
  - SEEPAGE CONTROL
  - KHAN RIVER MANAGEMENT
  - GROUNDWATER QUALITY
  - DECOMMISSIONING
B2 ENVIRONMENTAL HEALTH AND SAFETY AT RÖSSING

RTZ is a multi-national mining organisation and required that Rössing Uranium embark on comprehensive preventative programs that conform to standards consistent with world best practices. The best available technology is applied to reduce the impact of the operations on humans and the environment. Conditions potentially hazardous to the health of the inhabitants and/or ecology of the area are carefully monitored.

Rössing is generally regarded as a safe mine. The NOSA (National Occupational Safety Association) programme was introduced in 1978 and the first goal was set to achieve the very highest star grading achievable. This grading took place in 1980 and 3 stars were awarded. To complement the NOSA system and to uphold strong motivation amongst employees internal, sectional, departmental and divisional safety competitions were arranged and each divisional manager is responsible for the auditing of sections and departments within his division.

In the following years Rössing's health and safety programme continued, improving successfully and winning major titles in the South African NOSA competitions. In 1981 Rössing was graded a 3-star company and in 1982 it achieved the highest award, namely 5 stars. In 1983, 3 million disabling injury-free man-hours were worked and in 1984 a first place in a National Mining Competition was attained, followed by the first place in 1985 in the National Safety Effort and Efficiency (SEE) open competition. In the same year Rössing bettered the South African record for fatality-free shifts when 3 032 039 shifts were exceeded.

The mine achieved its first NOSCAR award (the highest safety award) in 1986 and joined the ranks of only 36 holders in Southern Africa amongst more than 4 000 participating companies, of which just over 200 are 5-star achievers. The NOSCAR was retained and re-awarded to the mine in 1987 to 1994.
In December 1988, Rössing was acknowledged by the British Safety Council as being one of the 30 safest operations in the world, and presented with the coveted Sword of Honour in recognition of this achievement. The Sword of Honour was retained in 1989 for the second consecutive year, establishing the mine as only one of three companies in the world to maintain this achievement.

Graph 12

Total Injuries
Graph 13

On- and Off-the job Injuries 1998

Graph 14

Off-the-job Injury Profile 1998
B3 GEOLOGY

The Rössing uranium deposit lies within the central zone of the late Pre-Cambrian Damaran Orogenic Belt that occupies much of northern Namibia.

The genesis of the uraniferous deposits commenced in Pre-Cambrian times (one thousand million years ago) during the Damaran sedimentary cycle (Vernon, 1981). The initial deposition took place in a shallow turbulent sea, and consisted of cross-bedded, coarse sediments of the lower Etosis Formation. This was followed by the deposition of silt stones, greywackes and marls that, upon later metamorphism, were converted to the rocks of the upper Etosis Formation. Subsequently, stable conditions prevailed and the fine grained and homogenous sediments of the Khan Formation accumulated. At a later stage (Hakos period) quieter and deeper water conditions developed and more heterogeneous sediments of the Rössing Formation were deposited (marble and corderite gneiss).

Approximately 500 million years ago the great Damaran orogenic movements took place. The mass of sediments began sinking to depths of about 5km and resultant temperatures and pressures caused complex folding and metamorphism of the sediments (Vernon, 1981). At about this time, and again in a later phase, the deeper lying older rocks melted to form a granitic magma that began migrating upwards. This formed the pegmatitic granite known as alaskite that contains the primary uranium. The alaskite intruded into the Hakos and upper Nosob meta sediments, such that the alaskite is now present in a range of intrusive bodies, which vary widely in texture, size and emplacement habit (Vernon, 1981; Berning, 1986; Mouillac et al, 1986). Since then, sedimentary rocks and basalts from the Stormberg Series of the Karoo System were deposited and have largely eroded away, leaving thin terrestrial superficial deposits.
Also at this time, numerous dolomite dykes intruded through tensural fissures in the Pre-Cambrian rocks to the surface (Smith, 1965). These northeast and east-north-east trending dykes are still prominent features of the landscape. During the last 65 million years only superficial deposits have changed the geological landscape and large portions of the central Namib desert are covered by tertiary to recent superficial sands and duricrust deposits, such as gypscrote and calcrete (Jacob et al, 1986).

The Rössing orebody is unique in that it is the largest known deposit of uranium occurring in granite. The main deposit is located in the southwesterly flank of a large domal structure. The Rössing ore body is approximately 3km long and 1km wide. The uranium-bearing alaskites at Rössing are medium to coarse-grained and vary from grey to shades of pink and white. All of the primary uranium mineralisation and the majority of the secondary uranium mineralisation occur within the alaskite. The alaskite is not uniformly uraniferous and much of it lies unmineralised or of sub-economic grade (Vernon, 1982). Uraninite is the dominant radioactive mineral present and it occurs as grains ranging in size from a few microns to 0,3mm. It is included in quartz, feldspar, and biotite, but also occurs interstitially to these minerals or along cracks within them (Vernon, 1981; Berning, 1986). The arid climate is an important factor in beneficiating primary ores with secondary minerals released by weathering, and in reducing leaching by rainfall (Mouillac et al, 1986). The primary uranium minerals, uraninite and betaphyte give rise to secondary minerals that are usually bright yellow. Of the secondary uranium minerals, beta-uranophane is the most abundant and the mineral is not always confined to alaskite but may also be dispersed into the enveloping country rocks along cracks and fracture lines (Vernon, 1981). The average ore grade at Rössing Uranium is about 0,035% (Dames & Moore, 1984). Uraninite comprises about 53% of the uranium present in the
orebody, betaphyte less than 5% and the secondary minerals account for about 40%.

B4 MINE LOCATION AND ENVIRONMENT

The Rössing Uranium Limited (Rössing) mine and mill complex is located in the Namib Desert some 60 kilometres east-north-east of the town of Swakopmund, Namibia, at approximately 20° 27' south and 15° 02' east. The mine area is situated on the northern bank of the Khan River (a tributary of the Swakop River) 1.4 km from the river. The mine site has a mean altitude of 575m above mean sea level (a.m.s.l.).

Electrical power to the mine and the residential areas is relayed via a 220kW line. Water is pumped from sand wells in the Kuiseb River delta near Walvis Bay and from the Omaruru River delta to the north. Wells in the Khan River bed provide brackish water for dust suppression in the pit. Rössing uses between 17 000 to 27 000 cubic metres of fresh water (mostly for the process plant) and 12 000 cubic metres daily from the Khan. This water is supplemented by brackish water from the bottom of the open pit.

B5 THE CLIMATE

The Namib Desert area is dry and sometimes dusty with large variations in temperature and humidity. Precipitation is infrequent and averages less than 30mm per annum, but extremely heavy rainfalls of short duration may occur. The main elevation above sea level is 573 metres. The temperature ranges between 4.5°C and 40°C and humidity between 5% and 80%. Fog occurs on about 60 days during the night and on about 30 days during the day per annum. The precipitation from this fog is not measured.
B5.1 Winds

Surface winds tend to be from a southwesterly direction most of the year with strong easterly berg wind conditions developing in winter. Meteorological conditions combined with the effects caused by terrain features cause complex particulate and gas dispersion patterns (Earth Science Services, 1987). During the winter months (April to September) a cool down-valley wind sets in after midnight and prevails until 10:00 to 12:00. Between 11:00 and 14:00 general winds are strong and unmodified by local conditions. By 14:00 the local thermal and pressure gradients have reversed and a southwesterly up-valley wind prevails. From 15:00 to 18:00, the wind speed increases under the influence of the sea breeze. By 19:00 the sea influences precipitate, with another transition period between 22:00 and 24:00, after which the cycle is repeated. During the summer months (October to March) those parts of the cycle which are dependent on the cool air drainage are absent and the parts dependent on the heating process are more pronounced. Down-valley north easterlies are weak whilst the terminal north-westerlies prevail during the day from 08:00 to 14:00. These are interrupted by the inland penetration of afternoon sea breezes until approximately 20:00 when they are replaced by north/north westerly winds. These are relatively weak during the night but strengthen during the day and veer to become north westerly.

B5.2 Temperature

Air temperatures at Rössing vary greatly on a day-to-day basis, although seasonal variations are less marked. The mean diurnal temperatures range from 28,8°C in late autumn (May) to 15,4°C in spring (October), an annual range of 8,4°C. This is very similar to the 9° range reported for Swakopmund (Goudie, 1972). Minimum temperatures are recorded in the
early morning and range from 2°C in August to 12°C in March (Earth Science Services, 1987). In contrast, the range of maximum diurnal temperatures show very little month-to-month variation, ranging from 31.8°C in July to 39°C in January, due to the occurrence of hot beng winds during the winter months. On very hot days, air temperatures measured in the Khan River gorge near Rössing may reach 44°C and some 5°C higher than those measured at the mine (OJ Ashton, unpublished data). Monthly temperature ranges vary from 28°C in summer to 32.9°C in winter (Earth Science Services, 1987).

Whenever air temperatures are high, soil and rock temperatures reach even higher levels, particularly when they are dark. Temperatures of 60 - 70°C were recorded at the soil surface of the gravel plains of the central Namib and are similar to temperatures at Rössing.

**B5.3 Humidity**

Atmospheric humidity levels at Rössing are very variable on both an hour-to-hour and day-to-day basis (Earth Science Services, 1987). The lowest values (5 - 8%) are recorded at midday, whilst the highest values (up to 84%) are usually recorded during the early morning. Humidity levels rise rapidly immediately after one of the infrequent rainfalls and the afternoon sea breeze also contains appreciable humidity levels. However, these high humidity levels are usually of short duration and the diurnal average humidity level is usually below 15%.
B5.4 Radioactivity

The irregular distribution of the uraniferous material gives rise to a highly irregular radioactivity pattern for the area. It is complicated by the fact that two major radiochemical parameters affect the actual measurement of the radiation.

B5.4.1 Secular disequilibrium where the relative loss or gain of radioactive components in the $^{238}$U decay chain leads to incorrect measurements;

B5.4.2 Mineralogical characteristics, in particular variations in the uranium thorium ratio and the uranium potassium ratios that affect estimates of the uranium grade, present.

The degree of disequilibrium is generally not constant within a uranium deposit and is usually higher both where secondary minerals predominate and within the zone of fluctuation of, or above, the water-table. While Rössing falls into this category, it is buffered by the arid climate prevailing in the Namib Desert. An intermediate nucleate radon 222, the noble gas daughter product of radon 226, is particularly mobile in open environs such as fracture zones or weathered rock. Background environmental radon concentrations in areas away from the uraniferous Rössing deposit (example Swakopmund) vary between 25 to 50 becquerels per m² (Grundlingh et al, 1988).

The shales in the vicinity of the Rössing mine are generally very shallow (less than 25cm) and grey-ochre in colour, with a large proportion of coarse fragments and occasional calcium carbonate concretions.
THE OPERATION

The orebody is contained in granite rock known as alaskite. This ore is recovered by open pit mining and involves the removal of a series of 15 metre high benches in the pit that is 3km long and 1km wide, to a depth of 450m. Rössing is a high tonnage, low-grade mine with a stripping ratio of 2.5:1. The mining sequence is conventional drill, blast and load operation using Gardner Denver 120 drills, P & H 2100 and Marian shovels and a fleet of Wabco and Euclid 170 ST haul trucks. The material is sent to the primary crushers or to a low-grade stockpile whilst waste goes to a separate dump. Ore is delivered to the primary crushers and then by conveyor to the coarse ore stockpile.

It passes through a series of crushers and screens until the particles are 14mm in diameter. This is referred to as fine ore and, after weighing, is stored in another stockpile. The grinding process involves the wet grinding of the crushed orebody by means of steel rods and reduces it further to slurry with the consistency of mud. The four-rod mills (4.3 metres in diameter) operate in parallel.

The metallurgical process is conventional acid leach with ion exchange solution concentration and solvent extraction purification followed by precipitation of ammonium diuranate and roasting to uranium oxide. The metallurgical plant also has a pyrite burning sulphuric acid producing plant.

Leaching

A combined leach and oxidation process takes place in large mechanically agitated tanks. The uranium content of the pulped ore is oxidised by
manganese dioxide and dissolved by the action of sulphuric acid at elevated temperatures.

B6.2 Sand/Slime Separation

The product of leaching is a solution containing suspended sand and slime. Cyclones separate these components and the sand, after washing in rotoscoops to remove traces of solution, is pumped through pipes to a tailings disposal area.

B6.3 Thickening

Counter-current decantation thickeners wash the slimes from the previous stages. The clear uranium bearing solution (pregnant solution) overflows from the No.1 thickener while the washed slime is mixed with the sands and pumped to the tailings area.

B6.4 Continuous ion exchange (CIX)

The clear pregnant solution now comes into contact with beads of specially formulated resin. Ions containing uranium are absorbed onto the resin and are preferentially extracted from the solution. Beads are removed periodically to elution columns where a strong acid wash removes the uranium from the beads. The resulting eluate contains uranium solution.

B6.5 Solvent Extraction (SX)

The acidic eluate from the ion exchange plant is mixed with an organic solvent which takes up the uranium-bearing component. In a second stage the organic solution is mixed with a neutral aqueous ammonium