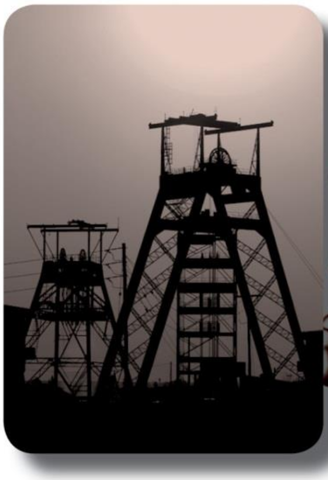
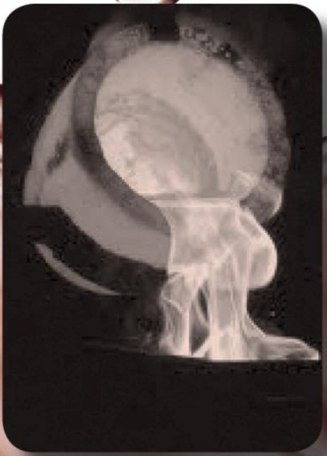


Water Resource Planning Systems Series

Water Quality Planning

Feasibility Study for a Long-term Solution to address the Acid Mine Drainage associated with the East, Central and West Rand underground mining basins



Treatment Technology Options

Study Report No. 5.4

P RSA 000/00/16512/4

May 2013

EDITION 1

water affairs
Department:
Water Affairs
REPUBLIC OF SOUTH AFRICA

DEPARTMENT OF WATER AFFAIRS

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Disclaimer:

The study was very dynamic in nature and the available information is continuously being updated and expanded. It is confirmed that each report has been prepared for the purpose of the study using the information relevant and available at the time of compilation of the report. All necessary skill, care and diligence were exercised by the authors, contributors and reviewers during the compilation and approval of the reports. The reader needs to determine the relevance, reliability or usefulness of the information and data reported in this study, if it is used in whole or in part, for their own purpose. Reports should not be interpreted in isolation, but in the context of the study and all its deliverables as a whole.

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SC: Study Component   Conf: Indication of Confidentiality

 # - These reports will not be made available until the appropriate implementation process stages have been reached as they may potentially compromise future procurement and legal processes.

PREFACE

1. Background to the Study

Gold mining in the East, Central and West Rand underground mining basins of the Witwatersrand goldfields (hereafter referred to as the Eastern, Central and Western Basins) started in the late 1880s. It is estimated that in the 1920s approximately 50% of the world's gold production came from the Witwatersrand mining belt, while in the 1980s South Africa was still the largest gold producer in the world. The large-scale mining in South Africa, in particular on the Witwatersrand, has decreased since the 1990s, and underground mining on the Witwatersrand essentially ceased in 2010. The mines of the Western, Central and Eastern Basins have produced a total of approximately 15 600 tons of refined gold since mining commenced. While the mines were operating, they pumped water to the surface to dewater their mine workings, but since mining stopped, the underground voids that were left after the mining have been steadily filling with water. The water in the mine voids interacts with the exposed sulphide bearing minerals in the rock formations to form Acid Mine Drainage (AMD), also known internationally as Acid Rock Drainage (ARD). AMD is characterised by a low pH and an excessive concentration of dissolved metals and sulphate salts.

In the case of the Western Basin, the AMD gradually reached the surface and started to drain out (decant) into surface streams in 2002. The water in the mine voids of the Central and Eastern Basins is rising steadily and will continue to do so until the water is pumped from the voids. It is predicted that the critical water levels will be reached in the Central Basin in late 2013 and in the Eastern Basin in mid-2014. If nothing is done, the water is predicted to reach the surface and decant at the lowest points in the Central Basin in the second half of 2015 and to reach the surface and decant in the Eastern Basin in late 2016. Decant would be uncontrolled and is likely to occur at several identified points, as well as at unexpected locations across each basin, due to varying water levels and connectivity between the near-surface aquifers and the voids.

If AMD, which has not been desalinated, is discharged into the Vaal River System, the high salt load will require large dilution releases to be made from the Vaal Dam to achieve the fitness-for-use objectives set for the Vaal Barrage and further downstream. This would result in unusable surpluses developing in the Lower Vaal River. Moreover, if dilution releases are still required after 2015, the acceptable levels of assurance of water supply from the Vaal Dam would be threatened. This will mean that there would be an increasing risk of water restrictions in the Vaal River water supply area, which will have negative economic and social implications. These negative impacts will be much greater if the catchment of the Vaal River System enters a period of lower-than-average rainfall with drought conditions. Since decant started in the Western Basin in 2002 the continuous flow of untreated AMD, and now the salt load from the continuous flow of the neutralised AMD from the Western Basin, impact on the Crocodile (West) River System.

The importance of finding a solution to the rising AMD and the need for inter-departmental cooperation led to the establishment of an Inter-Ministerial Committee (IMC) on AMD, comprising the Ministers of Mineral Resources, Water and Environmental Affairs, and Science and Technology, and the Minister in the Presidency: National Planning Commission. The first meeting of the IMC took place in September 2010.

The IMC established a Technical Committee, co-chaired by the Directors-General of Mineral Resources and Water Affairs, which instructed a Team of Experts to prepare a report advising the IMC on solutions to control and manage AMD in the Witwatersrand goldfields. In February 2011, Cabinet considered the IMC report and instructed that the recommendations be implemented as a matter of urgency. Funds were then allocated to the Department of Water Affairs (DWA) by National Treasury with the purpose of implementing some of the IMC recommendations, namely to:

- Investigate and implement measures to pump the underground mine water in order to prevent the violation of the Environmental Critical Levels (ECLs), i.e. specific underground levels in each mining basin above which mine water should not be allowed to rise so as to prevent adverse environmental, social and economic impacts;
- Investigate and implement measures to neutralise AMD (pH correction and removal of heavy metals from AMD); and
- Initiate a Feasibility Study to address the medium- to long-term solution.

The investigations and implementation actions proposed in the first two recommendations commenced in April 2011, when the Minister of Water and Environmental Affairs issued a Directive to the Trans-Caledon Tunnel Authority (TCTA) to undertake “Emergency Works Water Management on the Witwatersrand Gold fields with special emphasis on AMD”:

When the proposed pumping and neutralisation commences in the Central and Eastern Basins the situation will be similar to that which prevailed when underground mining and dewatering of the mine voids, and partial treatment of the water, were being carried out by the active mining companies. The saline AMD will flow into the Vaal River System and specifically into the Vaal Barrage. The high salt load will have the same impact on the Vaal River System as described earlier.

The third recommendation resulted in the Terms of Reference (ToR) for this Feasibility Study (DWA 2011a) being issued in July 2011. The ToR noted that the IMC had recommended that a Feasibility Study should be initiated as soon as possible, since the Short-Term Interventions (STI) might influence the roll-out of the desired medium- to long-term solution.

In January 2012, DWA commissioned the Feasibility Study for the Long-Term Solution (LTS). The Study period was 18 months, with completion at the end of July 2013. It was emphasised that this Study was very urgent, would be in the public eye, and that recommendations to support informed decision-making by DWA were required. The recommended solution must support the Water Resource Strategies for the Vaal and Crocodile West River Systems and take account of the costs, social and environmental implications and public reaction to the various possible solutions.

The urgency of reducing salt loading on the Vaal River System and the relatively short study period for such a complex study means that implementation decisions have to be based on the current understanding of the best available information and technical analyses that have been completed by the time the decisions must be made. Thus, a precautionary and conservative approach was adopted during the Study.

Opportunities have been identified where the solutions that are implemented can be refined, during operation, as more information becomes available.

2. Integration with the Short-Term Intervention

The final TCTA Due Diligence Report (TCTA, 2011) was submitted to DWA in August 2011, and tenders for construction in all the basins were invited in November 2011. Immediate works were implemented in the Western Basin in 2012, and construction in the Central Basin commenced in January 2013. It is anticipated that construction of the Eastern Basin will commence in the first quarter of 2014.

The Scope of Work (SoW) of this Feasibility Study, with respect to the STI, is to understand the proposed STI in sufficient detail to:

- Undertake a Feasibility Study of all options, irrespective of the STI, in the interests of finding the best LTS;
- Determine how to integrate the STI and LTS, and influence the STI as far as appropriate or practical;
- Identify any potential long-term risks associated with the proposed STI, and propose prevention or mitigation measures; and
- Assess the implications of the proposed STI for the suggested institutional model for the implementation, operation, maintenance and/or management of the preferred LTS.

3. Approach to the Study

The focus areas of the Feasibility Study comprise technical, legal, institutional, financial/economic and environmental assessments, as well as public communication and key stakeholder engagement. The Feasibility Study comprises three phases; the Initiation, Prefeasibility and Feasibility Phases. The main components and key deliverables of each phase are shown in **Figure 1**, and each phase is discussed in more detail below.

The technical assessments run in parallel with the legal assessment, and both feed into the options assessment. The component on stakeholder engagement and communication was started early in the Study so that a stakeholder engagement and public communication strategy could be developed as soon as possible and be implemented throughout the Study.

The planning showed the Feasibility Phase as following the Prefeasibility Phase, but the short study period meant that it was necessary for the Feasibility Phase components to commence during the Prefeasibility Phase and run in parallel.

In conducting the Study, it was important that each component developed key information and recommendations, which were then used in subsequent components. The logical and timeous flow of information and recommendations was essential in order to develop solutions and meet the Study programme.

Figure 2 gives an overview of the technical, institutional/financial and implementation components and the flow of information throughout the Study. It can be seen how the fixed information (e.g. ECLs, raw water quality, ingress, etc.) and the decisions to be made, or the options to be investigated (e.g. abstraction points, qualities and quantities required by potential users, locations of users, treatment technologies) feed into the options assessment and identification of the Reference Project. The Reference Project will define the option that uses proven technologies, has the least associated risk, and is used for financial modelling and budgeting. It will probably not be the same as the option that is implemented, but constitutes the benchmark against which implementation proposals will be judged.

The Concept Design is based on the Reference Project and includes the costing and land requirements. This in turn provides input for the evaluation of the institutional procurement and financing options and the Implementation Strategy and Action Plan.

The phases of the Study, the key components and their inter-relationships are described below and illustrated in **Figures 1 and 2**.

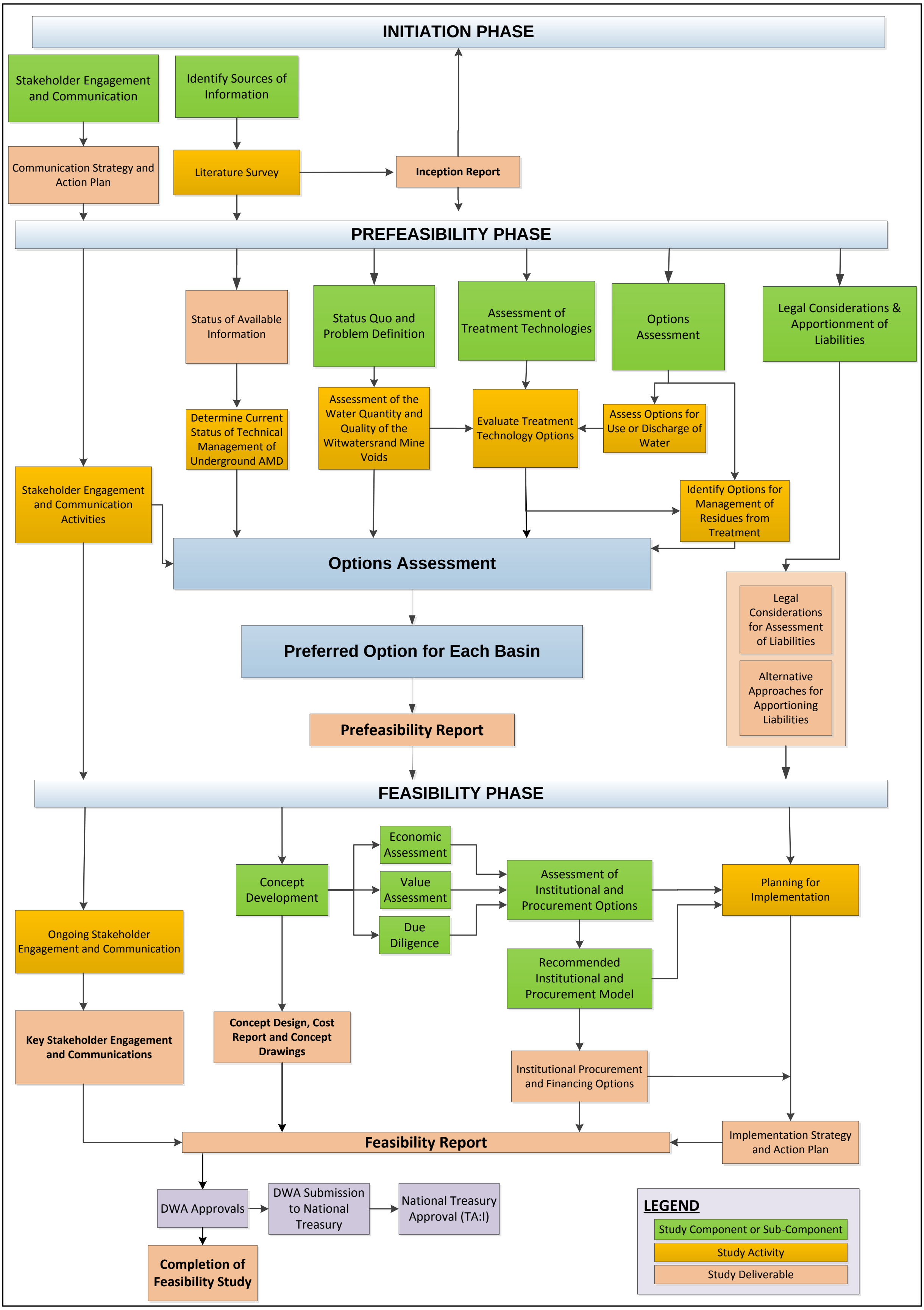

Figure 1: Study phases and components

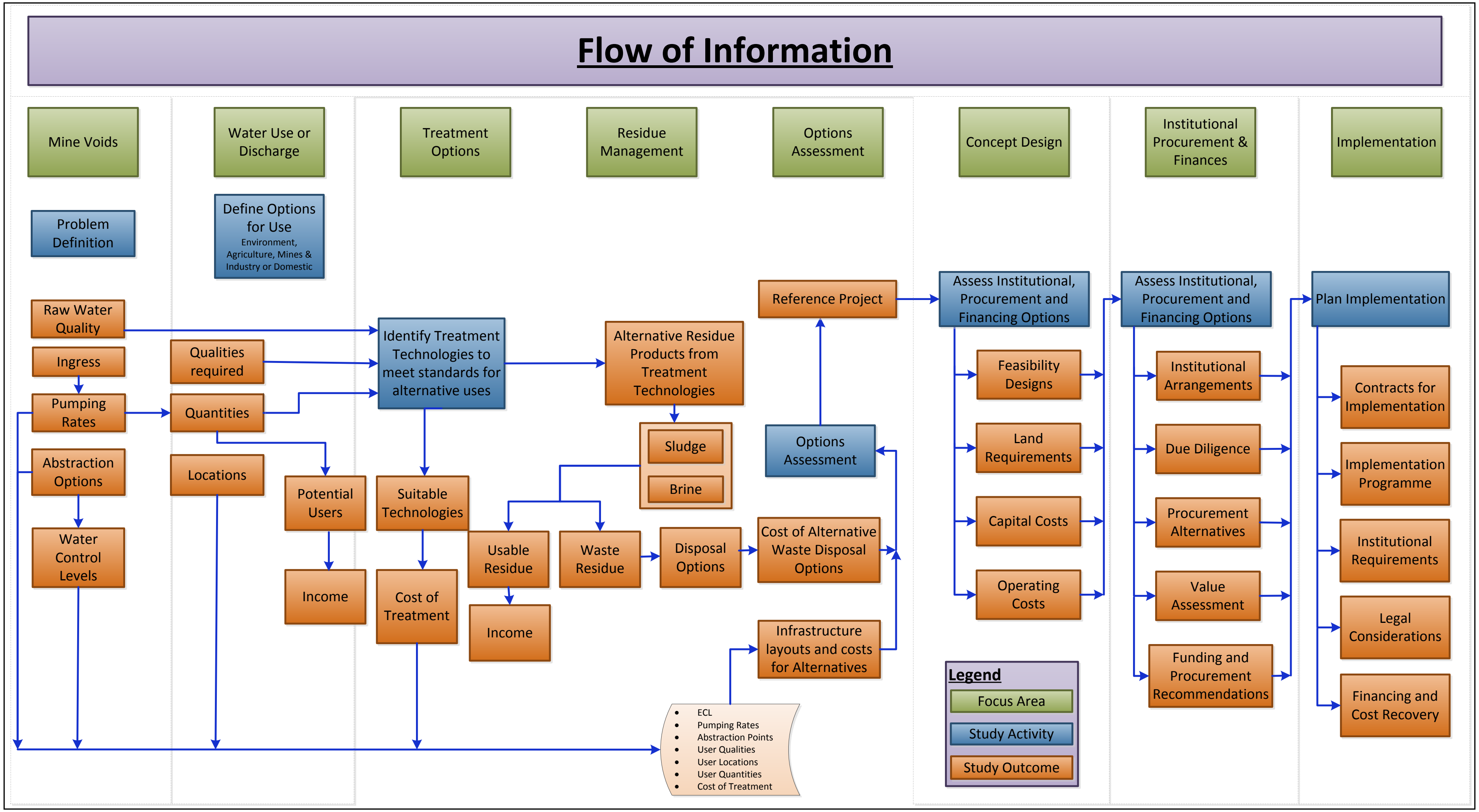

Figure 2: Flow of information throughout the Study

PHASE 1: Initiation

The objective of the Initiation Phase was to determine the approach and principles for the Study and understand the work already done by others. Numerous reports from previous studies, maps and research findings, relating to all components of the Study, were collated and reviewed. The SoW, proposed approach and the study programme were reviewed after initial consideration of the available information. The study objectives and priorities were reviewed and the results are presented in Study Report No. 1: ***"Inception Report"***.

The results of the complete literature survey, which continued after the Initiation Phase, are presented in Study Report No. 2: ***"Status of Available Information"***.

The Study Report No. 9.1: ***"Communication Strategy and Action Plan"*** was prepared so that key stakeholder engagement and communicators could commence as soon as possible and continue throughout the Study.

PHASE 2: Prefeasibility

The purpose of this phase was to understand and describe the current status and the environment for managing AMD and then to identify all apparently viable alternative solutions and, from those, identify the more feasible options, on the basis of technical feasibility, social and environmental acceptability and cost effectiveness. These were then considered in more detail, and the most feasible options were investigated in the Feasibility Phase.

The assessment of the legal liabilities and mechanisms for the apportionment of liabilities is a key stand-alone component that was commenced in the Prefeasibility Phase and finalised in the Feasibility Phase. This work is described in the confidential Study Report No. 3: ***"Legal Considerations for Apportionment of Liabilities"*** and confidential Study Report No. 4: ***"Alternative Approaches for Apportioning Liabilities"***.

The objectives of the Prefeasibility Phase were to:

- Understand the status quo;
- Define the problem;
- Understand the quantity and quality of water in the mine voids and how fast is it rising in each basin;
- Identify possible uses for the water;
- Identify treatment technologies that can treat the necessary volumes of AMD to the standard required by various users;
- Understand the residues (or waste products) produced by each process and how they can be managed;
- Define a wide range of options for possible solutions by combining alternatives for abstraction, water use, treatment and management of residues;
- Screen the alternatives to identify viable options; and

- Carry out prefeasibility costing of the most viable options and identify the most appropriate option to be used as the Reference Project.

To achieve these objectives, the Prefeasibility Phase needed to provide the team with:

i. A sound understanding of the STI, how it can be integrated into the LTS, and the impact of the STI on the selection and procurement of the LTS. This is described in Study Report No. 5.1: ***"Current Status of Technical Management of Underground AMD"***.
ii. A sound understanding of the hydrogeology, underground water resources, sources of surface water ingress, spatial distribution and connectivity of mined voids; and the current water quality and projections of future volumes, levels and water qualities. This was based on the substantial information from previous studies and is presented in Study Report No. 5.2: ***"Assessment of the Water Quantity and Quality of the Witwatersrand Mine Voids"***.
iii. An understanding of the DWA Water Resource Management Strategies for the Vaal River System and Crocodile West River System. These strategies provided the framework within which to develop a range of possibilities for the use or discharge of raw, neutralised or desalinated AMD to meet the objective of reducing the salt load in the Vaal River System and associated catchments to acceptable levels without having an unacceptable social or environmental impact. These possibilities are described in Study Report No. 5.3: ***"Options for Use or Discharge of Water"***.
iv. An assessment of suitable technologies for treating either raw AMD or the discharges from the STI to standards that will not negatively impact on the environment and will be acceptable to a range of users. This assessment is described in Study Report No. 5.4: ***"Treatment Technology Options"***.
v. Locality plans for the possible disposal of waste, or potential uses for residue products generated by treatment processes. These plans are described in Study Report No. 5.5: ***"Options for the Sustainable Management and Use of Residue Products from the Treatment of AMD"***.

The knowledge and data from the Prefeasibility Phase were used to combine the alternative locations for the abstraction, treatment and use or discharge of water and the disposal of waste, as well as the layouts of the infrastructure required (including pipelines and pump stations), into a large number of options. The alternatives were screened at a high level to give a short-list of practical technical options.

The capital and operating costs of the short-listed options were determined to give a present value of lifetime cost. Social and environmental screening for fatal flaws was carried out, and possible financial benefits from the sale of water or waste were considered. The anticipated public reaction to the options was also considered. The identification of the Reference Project was then completed on the basis of the costs, benefits and impacts. The costs and implications of possible alternatives were also defined. The results and an overview of all the components of this Prefeasibility Phase are described in Study Report No. 5: ***"Technical Prefeasibility Report"***.

PHASE 3: Feasibility

The main objective of this phase was to carry out intensive feasibility level investigations and optimisation of the most feasible layouts for each basin and to select a preferred option to be used as a Reference Project for each basin. The requirements for implementation were also considered and evaluated.

The Feasibility Phase comprises a number of components that build on the results of the Prefeasibility Phase; the results of the various components are reported separately and then integrated in a Feasibility Report for the solution to AMD.

The components in this Phase comprise:

i. Concept Development:

Once the Reference Project for each basin had been agreed, the layout for the treatment works, pipelines and waste storage and disposal sites was planned and costed. Environmental screening was undertaken for each of the identified sites that form part of the Reference Project. The results are presented in the confidential Study Report No. 6: ***"Concept Design"***, the confidential Study Report No. 6.1: ***"Concept Design: Drawings"*** and the confidential Study Report No. 6.2: ***"Concept Design: Costing"***.

ii. Institutional Procurement and Financing Options:

The following alternative procurement models for implementation were evaluated:

- a 'traditional' Government-funded and a traditionally procured Employer Design, Procure, Construct and Operate solution, which is the Public Sector Comparator model (PSC);
- a Design, Build, Operate and Maintain (DBOM) scenario funded by an Implementing Agent, using Private Sector or Government funding, which is also a Public Sector Comparator model (PSC); and
- a private sector-funded Public–Private Partnership (PPP).

The approach included a detailed risk-adjusted value assessment of the PSC and PPP models for the Reference Project in each of the three basins. The possible institutional arrangements were assessed in terms of the roles and responsibilities of the responsible organisations.

A due diligence assessment was carried out to establish the legal mandates of the institutions, as well as ownership of the land required for the Reference Project. These assessments are described in the confidential Study Report No. 7: ***"Institutional, Procurement and Financing Options"***.

iii. Implementation Strategy and Action Plan:

Throughout the Study, the requirements for implementation were considered in developing an Implementation Plan. Where necessary, the activities required for implementation that must commence in parallel with this Study were identified. This included the preparation of a Request for Information (RfI), which initiated a process through which service providers could register their interest with DWA. All the requirements for implementation are described in Study Report No. 8: ***"Implementation Strategy and Action Plan"***.

iv. Key Stakeholder Engagement and Public Communication:

Engagement with key stakeholders and public communication were very important components of the Study and were on-going from the commencement of the Study to the completion of the work. Study Stakeholder Committee meetings, Focus Group meetings, a RfI, one-on-one meetings, newsletters and a website were key elements. The process and results are presented in Study Report No. 9: "***Key Stakeholder Engagement and Communications***".

The final deliverable, Study Report No. 10: ***"Feasibility Report",*** summarises the results of the Study.

The Prefeasibility Phase and Concept Development in the Feasibility Phase are typical components of many planning studies. Solving the technical issues is not normally the biggest challenge, although this project does have several unique aspects. However, the Feasibility Phase components that lead to recommendations for appropriate institutional, financial and procurement models for implementation, particularly the assessment of the options for procurement, are not common components of DWA studies and were the most challenging, and certainly as important for a sustainable solution as all the technical components combined.

4. Way Forward

Completion of the Study will provide all the information required for implementation to proceed, although DWA plans to start the preparations required for implementation in parallel with Phase 3 of this Study.

Following from the Feasibility Study, implementation should be carried out as soon as possible. The key activities required for implementation include the following:

- DWA submitting the Feasibility Study Reports to National Treasury for their review and approval. The project has been registered with National Treasury, and Treasury Approval 1 (TA 1) may be required before procurement can commence;
- Conducting an Environmental Impact Assessment (EIA); and
- The preparation of procurement documents.

If procurement is for a Design, Build, Operate and Maintain (DBOM) contract, the procurement documents will comprise:

- A Request for Qualifications (RfQ) to allow DWA to short-list suitably qualified service providers.

  This will allow any service provider, especially those with proprietary technologies that may well be more cost effective than that used as the reference technology, to submit detailed information. Those that best meet the selection criteria, which will have to be agreed, will be short-listed; and
- A Request for Proposals (RfP) to be issued to the short-listed service providers, inviting them to submit tenders to implement a project that will deliver water to the specified standards.

If procurement is to follow the traditional process (with three sequential tenders for a service provider to prepare design and tender documentation, followed by tenders for construction, and then tenders for operation and maintenance), then the two-phase RfQ and RfP route may also be followed, with appropriate requirements specified at each stage.

The Reference Project could be implemented, but may not be the most effective solution. It will provide the yardstick methodology and costing which will be used to evaluate the tenders which are submitted.

DWA will also need to source the technical and contractual expertise required to enable them to manage the implementation of the desired long-term solution in each of the three basins.

NOTE: A List of Acronyms and Glossary of Terms appear on pages "xxiv" and "xxviii" respectively.

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In addition to the contributions received from the study committees mentioned above, inputs were also received from the following broad groups and sectors through focused discussions (a more comprehensive list is available on the DWA AMD website):

Academic institutions;
Funding organisations;
Global perspectives on AMD management;
Environmental and conservation groups;
Independent individuals in their private capacity;
Institutions, parastatals and research facilities;
Local, provincial and national government;
Mining sector;
Non-governmental organisations;
Organised agriculture;
Organised business, industry and labour;
Other specialist fields/consultants;
Tourism and recreation;
Utilities/water service providers; and
Various technology providers who offered information.

Organisations that provided considerable data and inputs for assessment and consideration, including the but not limited to, FSE, The Centre for Environmental Rights, Sasol, DST, WRC, Ekhuruleni Municipality, Rand Water, GDARD, DEA, CGS, DMR as well as various individuals in their private capacity, are thanked for their contributions.

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EXECUTIVE SUMMARY

There are various technologies available that can treat water to the required standards. Most of the processes, however, do not remove the monovalent ions, such as sodium (Na) and chloride (Cl) from the water, and hence some form of reverse osmosis is required in all instances where the monovalent ions in the feed Acid Mine Drainage (AMD) exceed the required standards for the treated water. This supplementary treatment could be added with relative ease to each of the processes that does not meet the SANS 241: 2012 specifications. In this instance, treating the full AMD stream would not be required; the requirement would be to remove only sufficient constituents to meet the applicable standards.

More important, therefore, are the residuals that are produced by each of the processes, as these substances need to be disposed of ad infinitum and would require extensive disposal sites. It is also important that the substances formed are adequately stable so as not to become a source of environmental pollution. The stability of the waste products, as well as the volumes produced, should therefore be a major criterion in the selection of the long-term solution.

A further factor to be taken into account is the level of development of a technology. The technologies are classified according to three levels of development (i.e. laboratory scale, pilot scale and proven technologies). Of all the technologies investigated, only the High Density Sludge (HDS) process and the conventional Reverse Osmosis (RO) processes can be classified as proven technologies. These processes have been implemented in plants at full scale, and with treatment capacities that are comparable with the capacities required for the treatment of AMD on the Witwatersrand. However, it would be simplistic to rule out all other technologies merely because there are no installations of comparable size. The role that other technologies could play must be considered.

In the evaluation of the technologies, it needs to be taken into account that the AMD problem on the Witwatersrand is currently one of the largest AMD problems in the world. Nowhere have plants been constructed to meet the level of demand on the Witwatersrand and South Africa is thus embarking on untested territory. It is therefore sensible also to evaluate technologies that have not been tested to the scale required to eliminate all risks.

There could be a significant reduction in the production of waste products if any of the following processes are employed:

- *Alternative RO (MiWaTek);*
- *Biosure; and*
- *Paques.*

A reduction in the production of waste products would reduce the problems associated with their disposal. This would have a major influence on the economics of the operation, especially if the indefinite horizon of the problem is taken into account.

It would thus make sense to be able to analyse the processes like those listed above and possibly others in detail by constructing pilot plants with the capacity to treat between 5 - 10 Mℓ/d in order to research and demonstrate the suitability of the processes.

The Biosure process has already been studied by the Water Research Commission in association with East Rand Water Care Company (ERWAT). Clarity needs to be obtained regarding the licensing of the process and the ownership of the intellectual property.

The ownership of the biological process from Paques is clear, and it would only be necessary to negotiate the rights to construct a plant that uses the processes. The owners of the intellectual property would inevitably have to be involved. The approach to the recommended research should ensure that South Africans are trained and educated in the process.

The capacity of the biological processes (Biosure and Paques) to treat the volume of AMD is restricted by the available organic material. The total volume of sludge produced in the south of Johannesburg and on the East Rand by the wastewater treatment works is inadequate to treat all the AMD. Additional sources of organic material would have to be identified and sourced.

The owners of the intellectual property related to the alternative RO keep it very confidential, and it is difficult to obtain adequate information to fully evaluate the process. The advantages of the process, however, appear to be very attractive, thus warranting further research.

AMD water is rising in the basins, and urgent action is required. There is simply no time left for experimentation in searching for optimal solutions for implementation in the near future. If any proven technologies are used, the solution that is implemented might later be shown to have contained some element of non-optimal expenditure. This fact has to be accepted, as time has simply run out.

The only solution that can be implemented with a reasonable degree of risk is the HDS process followed by conventional reverse osmosis. This process train should be analysed in detail, as it is able to address all associated risks, and costs can be assigned to the elimination of the risks. This would then be the base case against which all other processes would be compared and measured. However, since this base case produces large volumes of HDS, which is expensive to dispose of, it might later be shown that it is not the best long-term solution if some of the other technologies prove themselves.

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LIST OF ACRONYMS

ABC	Alkali-Barium-Calcium
Alk	Alkalinity
AMD	Acid mine drainage
ARD	Acid rock drainage
BKS	BKS Group (Pty) Ltd
BRI	Black Reef Incline
CAPEX	Capital expenditure
CB	Central Basin
CGS	Council for Geoscience
COD	Chemical Oxygen Demand
COO	Chief Operations Officer
CSIR	Council for Scientific and Industrial Research
CSIRO	Commonwealth Scientific Industrial Research Organisation
CSTR	Continuous stirred-tank reactor
DMR	Department of Mineral Resources
DO	Dissolved oxygen
DS	Dry solids
DST	Department of Science and Technology
DWA	Department of Water Affairs
EB	Eastern Basin
EC	Electrical conductivity
ECL	Environmental critical level
ERWAT	East Rand Water Care Company
FBR	Fluid bed reactor
GARD	Global Acid Rock Drainage
GDARD	Gauteng Department of Agriculture and Rural Development
HDS	High Density Sludge
IMC	Inter-Ministerial Committee
INAP	International Network for Acid Prevention
LTS	Long-term solution
Mintek	Council for Mineral Technology
N/A	Not applicable
NDA	Non-disclosure agreement
NECSA	South African Nuclear Energy Corporation
NEDLAC	National Economic Development and Labour Council
NEMWA (59:2008)	National Environmental Management: Waste Act, 2008 (Act No. 59 of 2008)
NGO	Non-governmental organisation
NS	Not specified
NWSSS	New World Sanitation & Solar Solutions
OPEX	Operating expenditure
P2W	Pollution to Water
PPP	Public–private Partnership
RO	Reverse osmosis
RWQO	Resource water quality objective
RSA	Republic of South Africa
SAC	Study Administration Committee
SALGA	South African Local Government Association

SANS	South African National Standards
SMBS	Sodium Meta Bisulphate
SMC	Study Management Committee
SRB	Sulphate reducing bacteria
SRK	SRK Consulting (Pty) Ltd
SSC	Study Stakeholder Committee
STI	Short-term intervention
SWV	South West Vertical
TA 1	Treasury Approval 1
TCTA	Trans-Caledon Tunnel Authority
TDS	Total dissolved solids
TIA	Technology Innovation Agency
TRL	Technology Readiness Level
TRU	Thermal Recovery Unit
TUT	Tshwane University of Technology
UK	United Kingdom
WB	Western Basin
WRC	Water Research Commission
WUC	Western Utilities Corporation
WWTW	Wastewater treatment works

LIST OF CHEMICAL CONSTITUENTS

Ag	Silver
Al	Aluminium
$Al(OH)_3$	Aluminium hydroxide
Al_2O_3	Aluminium oxide
As	Arsenic
B	Boron
Ba	Barium
$BaCO_3$	Barium carbonate
BaS	Barium sulphide
$BaSO_4$	Barite
Be	Beryllium
Bi	Bismuth
Br	Bromine
$C_{3.5}H_7O_2N_{0.196}$	Organic material
$C_5H_7O_2N$	Organic material
Ca	Calcium
$Ca(OH)_2$	Calcium hydroxide (slaked lime)
Ca^{2+}	Calcium ion
$Ca_3(PO_4)_2$	Calcium phosphate
$CaCO_3$	Calcium carbonate (limestone)
CaF_2	Calcium fluoride
CaO	Calcium oxide (unslaked lime)
$CaSO_4$	Gypsum
Cd	Cadmium
Cl	Chloride
CN	Cyanide

Co	Cobalt
CO_2	Carbon dioxide
Cr	Chromium
Cu	Copper
DO	Dissolved Oxygen
Fe	Iron
$Fe(OH)_2$	Iron(II) hydroxide
$Fe(OH)_3$	Iron(III) hydroxide (ferric hydroxide)
Fe^{2+}	Iron(II) ion (ferrous iron)
Fe^{3+}	Iron(III) ion (ferric iron)
FeS	Iron sulphide
Ga	Gallium
H^+	Hydrogen ion (hydron)
H_2O	Water
H_2O_2	Hydrogen peroxide
H_2S	Hydrogen sulphide
H_2SO_4	Sulphuric acid
HCN	Hydrogen cyanide
HCO_3^-	Hydrogen carbonate (bicarbonate) ion
HS^-	Hydrogen sulphide ion
K	Potassium
Li	Lithium
Mg	Magnesium
$Mg(OH)_2$	Magnesium hydroxide
Mg^{2+}	Magnesium(II) ion
Mn	Manganese
$Mn(OH)_2$	Manganese hydroxide
Mn^{2+}	Manganese(II)
Mo	Molybdenum
Na	Sodium
Na_2CO_3	Sodium carbonate
NaOH	Sodium hydroxide
NH_4	Ammonium ion
Ni	Nickel
NO_2	Nitrogen dioxide
No_3	Nitrate
O_2	Oxygen
Pb	Lead
PO_4	Phosphate
Rb	Rubidium
S	Sulphur
Se	Selenium
SiO_2	Silica
SO_2	Sulphur dioxide
SO_4	Sulphate
SO_4^{2-}	Sulphate ion
Sr	Strontium
Te	Tellurium
Tl	Thallium

U	Uranium
V	Vanadium
Zn	Zinc

UNITS OF MEASUREMENT

~	approximately
µg	microgram
µS	microsiemen
C	Celsius
cm	centimetre
d	day
ha	hectare
hr	hour
kℓ	kilolitre
kW	kilowatt
kWh	kilowatt hour
ℓ	litre
m	metre
m^3	cubic metre
mg	milligram
Mℓ	megalitre
mS	millisiemen
R	Rand
t	ton

GLOSSARY OF TERMS

Adit	An adit is an entrance to an underground mine which is horizontal or nearly horizontal, by which the mine can be entered, drained of water, and ventilated.
AMD	Acid mine drainage is formed when sulphide minerals in the geological strata, are exposed through mining activities and interact with oxygen and water to form a dilute solution of sulphuric acid and iron that leaches other metals from the material in which it forms. Acid mine drainage in the Witwatersrand typically has a pH value around 3 and is enriched in sulphate, iron and a number of metals, often including uranium.
Amphoteric	A molecule or ion that can react as an acid as well as a base.
Aquifer	Zone below the surface capable of holding groundwater.
Central Basin	Central Rand underground mining basin.
Decant (surface)	Spontaneous surface discharge of water from underground mine workings.
Decant (subsurface)	Subsurface flow of water from one mine compartment or geological structure to another, typically occurring when underground mine voids fill and cascade consecutively from one underground compartment to another adjacent connected compartment.
Discharge (groundwater)	Seepage of groundwater at the surface.
Eastern Basin	East Rand underground mining basin.
Environmental Critical Level	The level above which the water in the mine voids at the critical locations (that is where the environmental features to be protected are at the lowest elevations) should not be allowed to rise, to protect specific environmental features, including groundwater resources.
Ettringite	A hydrous calcium aluminium sulphate mineral.
Feasibility Study	An analysis and evaluation of a proposed project to determine if it is technically sound, socially acceptable, and economically and environmentally sustainable.
Freeboard	The vertical distance below the Socio Economic or Environmental Critical Level at the abstraction point, below which the water level should generally be maintained, to allow for hydraulic gradient across the basin, seasonal peak ingress, pump down time, and the like, i.e. to provide sufficient buffer capacity.
Groundwater	Water occupying openings below surface
Key stakeholder	Defined as directly affected parties, those who have a high level of negative or positive influence (in government and civil society domains, and on the direction and success of AMD long-term initiatives) and those whose input is critical to the study (for e.g., representatives of various National, Provincial, and Local Government, NGOs, organised business, mining, industry, labour, agriculture, affected mines, affected water utilities, community leaders, academics, etc.).
Layout	The arrangement or configuration (site layout, pipe route, etc.) of a specific option.

Long-Term Solution	A solution that is sustainable in the long term with regards to the technical, ecological, legal, economic, financial and institutional aspects.
Option	One of a number of combinations of abstraction works, treatment processes, and solutions for the disposal of waste and utilisation of treated water.
Preferred option	The solution, or combination of solutions, for the three basins respectively and collectively, that will be selected for further investigation in the feasibility phase, and if found feasible, that would eventually be recommended for implementation.
Reef	Term used on the Witwatersrand mines for conglomerate containing gold deposits.
Reference Project	The option which uses proven technologies, has minimum risk and which is used for financial modelling and budgeting. It will probably not be the option which is implemented but is the benchmark against which implementation proposals will be judged.
Reserve	The quantity and quality of water required to satisfy basic human needs and to protect aquatic ecosystems in order to secure ecologically sustainable development and use of the relevant water resource.
Resource Water Quality Objectives	Is a numeric or descriptive instream (or in-aquifer) water quality objective, typically set at a finer resolution (spatial or temporal) than Resource Quality Objectives to provide greater detail upon which to base the management of water quality. (Resource Directed Management of Water Quality, 2007).
Request for Information	A Request for Service Providers to provide information (RFI) on their product or service, e.g. technologies. It is not part of a procurement process.
Request for Qualifications	A Request for Qualifications (RFQ) from Service Providers to allow a shortlist to be prepared. It is normally the first step in the procurement process.
Request for Proposals	A request for technical and financial proposals (RFP) in compliance with a defined Scope of Work (SoW) and adjudication criteria from (Pre-Qualified) bidders to allow one of the bidders to be appointed to provide an agreed service. Equivalent to Expression of Interest (EOI) but used in infrastructure projects
Scenarios	An alternative projection of the macro environment which affects AMD, such as climate change, electricity load shedding, and changes in quality or quantity of water ingress to the mine void.
Service Provider	The generic term for the Special Purposes Vehicle (SPU) or contracting consortium that will design, build, operate and maintain and possibly finance the works.
Short-Term Interventions (Short-Term Solution as stated in Terms of Reference)	Emergency measures that are being implemented by the TCTA in the short-term in all three the basins while the long-term Feasibility Study is undertaken to protect the ECL, to neutralise the AMD and to remove metals from the AMD.
Target Operating Level	The level in the mine void at each abstraction point, at which the water level should generally be maintained by pumping or gravity flow to allow for hydraulic gradient across the underground mining basin, seasonal peak ingress, pump down time, and the like, i.e. to provide sufficient buffer capacity or freeboard required below the ECL or SECL across the basin.
Western Basin	West Rand underground mining basin.

1. INTRODUCTION

1.1 Introduction to this Report

1.1.1 Aims and Objectives of this Report

The principal aim of the feasibility study was to research and evaluate the options for treating Acid Mine Drainage (AMD) in the long term. Numerous organisations and individuals claim to have the technology to effectively treat AMD. These claims have to be scientifically investigated in order to understand:

- The validation of the claims;
- The risks associated with the technology;
- The feasibility of the technology;
- The standard to which the AMD could be treated; and
- The composition and the quantities of sludge and waste produced by the various proposed technologies. The management of the residue products from the treatment of AMD are discussed in DWA AMD FS 2013, Study Report No. 5.5: **"Options for the Sustainable Management and Use of Residue Products from the Treatment of AMD"**.

Due to the urgency for action related to the treatment of AMD, the Short-Term Intervention (STI) has been implemented ahead of the Long-Term Solution (LTS). The LTS can, if appropriate, be integrated with the STI, which necessitates an investigation of the STI.

The objectives of this component of the study are therefore as follows:

- Identify alternative technologies that could treat AMD to the various possible acceptable standards;
- Investigate and report on the chemical/physical principles of the technologies;
- Determine the quality of the treated AMD produced by the technologies;
- Determine the volumes and characteristics of waste produced by the technologies;
- Determine the composition of the waste produced, with a view of producing waste that could possibly be re-used; and
- Select a process that could be used as a reference process against which proposals could be measured. The reference process must meet all specifications, and include mitigation steps for any identified risks.

1.2 Structure of Report

The report is structured to cover the following aspects:

- Principles of the long-term solution;
- Classification of AMD treatment technologies;
- Study process;

- Quantity and quality of AMD to be treated
- Description of AMD treatment technologies;
- Evaluation of treatment technologies:
    - Pre-treatment technologies
    - Treatment technologies for neutralised AMD;
- Recommendations.

2. PRINCIPLES OF THE LONG-TERM SOLUTION

Although the STI is already being implemented, a holistic approach as the LTS should be adopted. Whereas the STI is being implemented to reduce the impact of a possible disaster in the short-term, the LTS will be required to provide a solution to the problem that can be sustained for a long period of time. The LTS should therefore seek to provide or identify:

- Technology that can treat the AMD to standards that would allow:
    - re-cycling as much as possible of the treated water to potential users; and
    - treat water to water quality standards outlined by SANS-241 (2011)
- Technology that produces residuals that:
    - do not create an environmental risk where they are disposed; and
    - preferably are in such a form that they have re-use value.
- Technology that is reliable; and
- Technology that is sustainable.

Due to the limited water supply available from the Vaal River System, the treated AMD should be viewed as an additional resource that can be used to meet the growing water demand. The technology should therefore meet this requirement.

The pollutants in the AMD inevitably cause the production of residual products. The magnitude of the residual products streams, as shown later in this report, poses a problem in disposing of them, and the technology should hence be able to address this aspect of the problem by producing products with re-use value. Alternatively, the residual products would have to be environmentally safe, so as not to become a source of environmental pollution.

The technology has to be reliable in order to ensure that the objectives are constantly met. Solving the problem will require an enormous financial investment; it is thus of the utmost importance that the technology should meet the demands. In this regard, it is important that the reliability of the technology be proven to an acceptable scale that is comparable with the requirements of the solution.

The technology provided has to be sustainable to ensure that it is applicable in the long-term. Adequate resources of admixtures, chemicals, spares, etc. need to be proven to ensure the sustainability of the technology. The sustainability also includes the adaptability of the technology to varying conditions that may occur over time (e.g. variations in water quantity and quality). It is not generally known how the quality of the AMD will vary over time, as the flow conditions in the mining voids are not known.

For the technology to be sustainable, it has to be affordable. The required capital expenditure (CAPEX) and operating expenditure (OPEX) must be such that the country can afford the technology. The technology will not be sustainable if the OPEX cannot be met, and pollution of the water resources will continue.

The technology that optimally balances the demands from the water re-use, environmental, reliability and sustainability perspectives must be identified.

2.1 Possible End-users of Neutralised Water

Neutralised water is the water produced by processes such as the High Density Sludge (HDS) process that is being implemented as the STI. This water still has very high salinity – in terms of total dissolved solids (TDS) or electrical conductivity (EC) – and the concentration of sulphate, in particular, is very high (1 800 – 2 500 mg/ℓ).

Experiments have been conducted in using the mine water generated by the coal mines on the Highveld for agriculture. Extensive work has been done by Prof. J Annandale[1] of the University of Pretoria and others, as reported in Study Report No. 5.3: Options for Use or Discharge of Water. It is important to ensure that the conditions under which this use of the water can be tolerated are very well understood, so as to ensure that the water will not damage the soils being irrigated, or leach the constituents from the neutralised saline mine water to the groundwater, or to the streams or surface water resources as run-off.

The consideration of direct use of the neutralised water is presented in Study Report No. 5.3 and is not considered further in this report.

If no viable direct use of the neutralised water can be found, it has to be treated to allow for safe release to the environment or for other consumptive use.

2.2 Typical End-users of Desalinated AMD

The neutralisation and desalination treatment processes will potentially produce three main streams of products:

- Water of a specified quality;
- Residual products; and
- Products with potential economic value, depending on their quality.

End-uses of the desalinated water are theoretically easy to find, and could include:

- Potable use by humans and associated domestic water users;
- Industrial use for process activities, including mining as an industry;
- Recreational use;

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[1] Annandale JG, Beletse YG, De Jager PC, Jovanovic NZ, Steyn JM, Benadé N, Lorentz SA, Hodgson FDI, Usher B, Vermeulen D, Aken ME; *Predicting the Environmental Impact and Sustainability of Irrigation with Coal Mine Water*, WRC Report No. 1149/1/07; Water Research Commission, Pretoria; 2007.

- Agricultural use for crops and the watering of domestic animals; and
- Environmental release fit for the aquatic environment and downstream users.

The possible uses of the treated water are listed here for the purpose of determining the specifications that the treated water will have to meet. At this stage, neither the social impacts on possible end-users, nor public perceptions that may influence the practical adoption of any of the possible end-uses, have been addressed.

If the water is treated to enable potable use, the quality of the water would be required at least to meet the standards of SANS-241 (2011). Rand Water's internal standards are even more stringent than SANS-241. Rand Water generally produces water of better quality because its water source (Vaal Dam) has a low sulphate content; it is therefore possible to ensure that customers' needs are met within a greater safety margin. This higher standard could be applicable to any desalinated water supplied to Rand Water.

The industries that can accept the treated water will determine the standards that will be applicable. Generally, industries would not be expected to accept water that would require further treatment to meet the water quality standards of their existing installation, and disposal of any residuals generated through that process.

2.3 Requirements of the Treatment Process

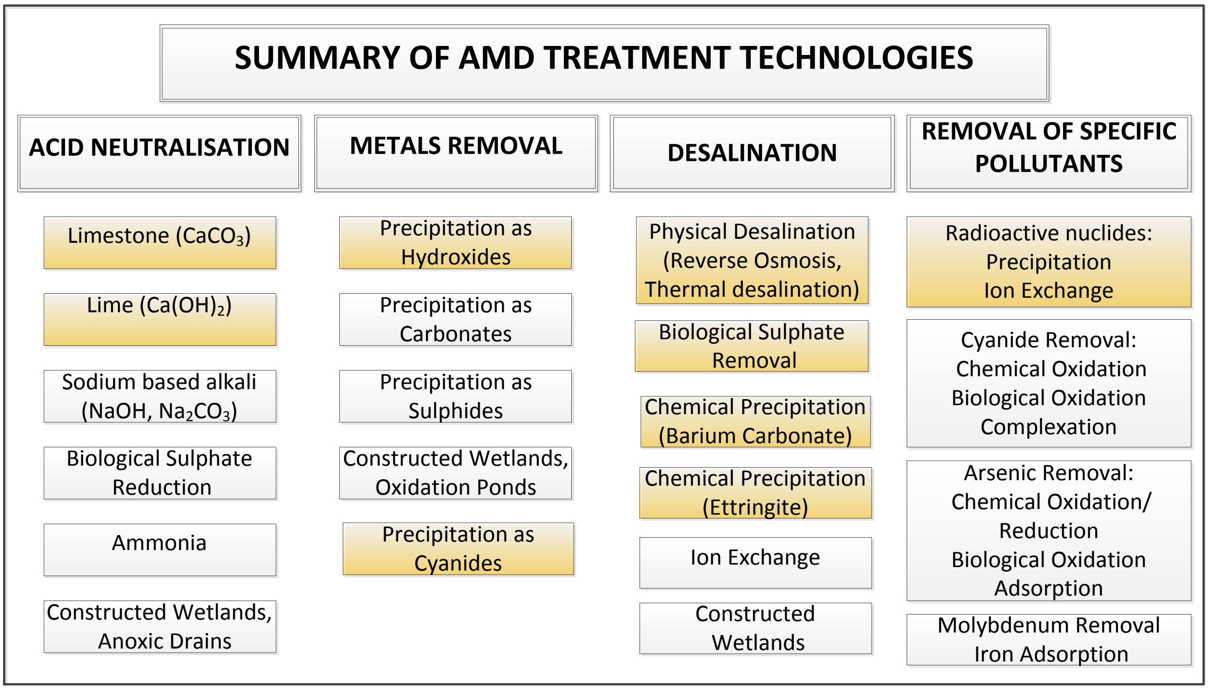
The process requirements for the treatment of the AMD are as follows:

- Adjusting the pH to circumneutral.
- Removal of heavy metals;
- Reduction of salinity to acceptable limits;
- Removal of specific substances such as radionuclides; and
- Processing of residual products for re-use or disposal;

The removal of metals generally requires increasing the pH of the AMD water to above a pH of 7. Each type of metal will precipitate out of solution at a different pH; for some metals the pH may need to be increased to a pH higher than 11. This process is not as simple as may be envisaged, as the addition of alkalinity, in whatever form, will generate waste products that have to be handled and disposed of. There are also secondary effects, such as the scaling of pipes and equipment, which become predominant in considering the selection and operation of processes for the treatment of AMD.

It can generally be stated that the treatment of AMD is centred mainly on the mitigation of the secondary effects of the treatment processes, and the safe disposal of the residual products, rather than processes for producing clean water. The handling and disposal of the waste products generated while treating the water have a marked influence on the selection of the treatment process, as the various processes produce different waste or recyclable products. Processes and process combinations with the highest likelihood of producing recyclable products, and of minimising the waste products so that safe disposal can be sustained, will be preferable.

The categories of processes and technologies for the treatment of AMD are summarised in **Figure 2.1** below. The highlighted technologies are considered to be the main technologies for consideration at this stage.



Note: Shaded blocks designate the processes pertinent to the feasibility study.

Figure 2.1: Summary of AMD treatment technologies

The main technologies are discussed in detail later in this report. The actual process to be applied will be a combination of the processes shown in **Figure 2.1**. Typically, the acid would have to be neutralised before the metals are removed, which requires operation at a higher pH. These processes generally precede processes for the reduction of salinity.

Figure 2.1 is a simplification of the processes, as the neutralisation of the acids will already remove some of the metals in the AMD, and thus also reduce the salinity. However, these processes cannot reach the low salinity concentrations that are required, and hence they act only as pre-treatment processes.

The treatment of the AMD to the required water quality standards will require a series of consecutive processes. Typically, most of the processes neutralise the AMD and remove the heavy metals to a greater or lesser extent before reducing the salinity of the components to below the required concentration limits. The following processes typically need to be provided:

- Acid neutralisation;
- Iron oxidation;

- Ferric hydroxide ($Fe(OH)_3$) precipitation to levels < 1.0 mg/ℓ;
- Gypsum precipitation; and
- Process to reduce the salinity (RO, Alkali-Barium-Calcium (ABC), biological sulphate reduction, SAVMIN, etc.).

The detailed process train for each technology will be provided in the discussion of the various technologies.

3. CLASSIFICATION OF AMD TREATMENT TECHNOLOGIES

Although there have been numerous occurrences of AMD worldwide during the past few decades, many of the available technology for treating AMD are still very much in the developmental stage. Some form of a classification system of the technologies according to their developmental stage is therefore required, in order to enable ranking of the risks associated with each of the proposed technologies.

Table 3.1 was obtained from the Department of Science and Technology (DST), where it is used to classify the developmental states of technology. The technology is evaluated according to a scale describing the level of development, called the 'technology readiness level' (TRL), ranging from 1 to 9, with 1 being the lowest level of development and 9 the highest.

Table 3.1: Technology readiness levels

Level	Definition	Description of readiness	Description of supporting information
TRL 1	Basic principles observed and reported	1. Lowest level of technology readiness. 2. Scientific research begins to be translated into applied research and development (R&D). 3. Examples might include paper studies of a technology's basic properties.	1. Published research that identifies the principles that underlie this technology. 2. References to who, where and when.
TRL 2	Technology concept and/or application formulated	1. Invention begins. 2. Once basic principles are observed, practical applications can be invented. 3. Applications are speculative, and there may be no proof or detailed analysis to support the assumptions. 4. Examples are limited to analytic studies.	1. Publications or other references that outline the application being considered and that provide analysis to support the concept.
TRL 3	Analytical and experimental critical function and/or characteristic proof of concept	1. Active R&D is initiated. 2. This includes analytical studies and laboratory studies to physically validate the analytical predictions of separate elements of the technology. 3. Examples include components that may not yet be integrated or representative of final component specifications.	1. Results of laboratory tests performed to measure parameters of interest and comparison to analytical predictions for critical subsystems. 2. References to who, where and when these tests and comparisons were performed.
TRL 4	Component and/or development model validation in a laboratory environment	1. Basic technological components are integrated to establish that they will work together. 2. This is relatively "low fidelity" compared with the eventual system.	1. System concepts that have been considered and results from testing laboratory scale development models. 2. References to who did this work and when. 3. Provide an estimate of how the development model and test results

Level	Definition	Description of readiness	Description of supporting information
		3. Examples include integration of "ad hoc" hardware in the laboratory.	differ from the expected system goals.
TRL 5	Component and/or development model validation in a relevant environment.	1. Fidelity of development model increases significantly. 2. The basic technological components are integrated with reasonably realistic supporting elements so that they can be tested in a simulated environment. 3. Examples include "high fidelity" laboratory integration of components.	1. Results from testing a laboratory development model are integrated with other supporting elements in a simulated operational environment. 2. How does the "relevant environment" differ from the expected operation environment? – How do the test results compare with expectations? – What problems, if any, were encountered? – How was the laboratory system refined to more nearly match the expected system goals?
TRL 6	System/subsystem model of prototype demonstration in a relevant environment.	1. Representative model or prototype system, which is well beyond that of TRL 5, is tested in a relevant environment. 2. Represents a major step up in a technology's demonstrated readiness. 3. Examples include testing a prototype in a high fidelity laboratory environment or in a simulated operational environment.	1. Results from laboratory testing of a prototype system that is near the desired configuration in terms of performance, weight and volume. 2. How did the test environment differ from the operational environment? – Who performed the tests? – How did the test compare with expectations? – What problems, if any, were encountered? – What are/were the plans, options, or actions to resolve problems before moving to the next level?
TRL 7	System prototype demonstration in an operational environment.	1. Prototype near or at planned operational system. 2. Represents a major step up from TRL 6 by requiring demonstration of an actual system prototype in an operational environment. 3. Examples include testing the prototype in a test bed.	1. Results from testing a prototype system in an operational environment. 2. Who performed the tests? – How did the test compare with expectations? – What problems, if any, were encountered? – What are/were the plans, options, or actions to resolve problems before moving to the next level?
TRL 8	Actual system completed and qualified through test and demonstration.	1. Technology has been proven to work in its final form and under expected conditions. 2. In almost all cases, this TRL represents the end of true system development. 3. Examples include developmental test and evaluation of the system in its intended "parent" system to determine if it meets design specifications.	1. Results of testing the system in its final configuration under the expected range of environmental conditions in which it will be expected to operate. 2. Assessment of whether it will meet its operational requirements. – What problems, if any, were encountered? – What are/were the plans, options, or actions to resolve problems before finalising the design.
TRL 9	Actual system proven through successful pilot operations.	1. Actual application of the technology in its final from (may be a pilot phase).	1. Examples include using the system under operational conditions. 2. Operational test and evaluation reports.

As can be seen, the system is fairly complicated, although it distinguishes in considerable detail the state of development. The system used in the study was simplified, recognising three main levels of development, as described below:

- Laboratory-scale technologies (typically TRL 1 to 3);
- Pilot-scale technologies (typically TRL 4 to 8); and
- Proven technologies (typically TRL 9).

The categories listed describe the state of development of a technology, which impacts directly on the risks associated with its implementation.

3.1 Laboratory-scale Technologies

The category of 'laboratory-scale technology' includes all technologies that have only been tested at a theoretical laboratory scale. The chemical, physical or biological principles associated with the technology have been demonstrated to be sound, and the reaction kinetics are generally understood, but not demonstrated. This is typically described as TRL 1 to 3.

The information required for a full-scale project is still limited, and no information is available on the secondary effects of the processes.

Technology at this level of development is associated with the highest risk if it is to be directly scaled up to a full-scale project. Aspects such as those listed below have not been fully simulated, or fully evaluated and quantified.

- Materials handling;
- Reactor configuration;
- Scaling or corrosion;
- Material failures;
- Process optimisation; and
- Financial implication.

3.2 Pilot-scale Technologies

Pilot-scale technologies are technologies that have been simulated in pilot plants to prove the chemical, physical or biological principles on a larger scale. These demonstrations include the identification of some of the secondary effects created through the process. The secondary effects can only be fully quantified in a demonstration-size or full-scale plant, with the result that the size of the pilot plant used for the demonstration will determine the level of knowledge of the process. This level compares with TRL 4 to 8.

The pilot plant should address aspects such as:

- Reactor configuration;
- Process optimisation;
- Effect and possibility of prolonged and continuous operation;
- Financial implications; and
- Secondary effects such as:
    - scaling or corrosion; and
    - material failures.

Aspects such as the materials handling required for the process can typically only be demonstrated in a fairly large installation. As the plants required for the treatment of the AMD can be classified as large installations, technologies need to have been proven in pilot plants of adequate size to demonstrate the requirements with respect to the handling of materials (e.g. chemicals supplied to the works, and waste products produced in the process).

The risks associated with technology that has been implemented on a pilot-plant scale may be somewhat less than the risks associated with laboratory-scale technology. However, there are still considerable risks that could cause failure of the technology, or could cause considerable costs to the project, since these aspects could not have been reasonably foreseen, or their magnitude and effect were underestimated.

3.3 Proven Technologies

‘Proven technology’ is technology that has been in operation at a scale comparable to the scale required for the application under consideration. The chemical, physical or biological principles, as well as the design principles, are proven, and the secondary effects (as listed above) are all well-understood. Measures for the mitigation of the negative effects have been proven. This level is equivalent to TRL 9.

This technology can be priced within a narrower band, and the associated risks are therefore relatively low.

4. STUDY PROCESS

The AMD problem has received enormous attention in recent times, and it has been debated in numerous forums. The Department of Water Affairs has received several statements by service providers that they can treat AMD water to the required standards. In order to try and assess all relevant technologies, all service providers who had previously shown interest or were already known were invited to present their respective solutions to the study team.

This approach allowed parties that have technology available, or that believe they can supply a solution, to present their products to the study team. Standardised background information was compiled and distributed to all interested stakeholders, and an advertisement was compiled for placement in the press by DWA. The advertisement was placed in December 2012, and the companies as listed in **Table 4.1** registered their interest.

Table 4.1: Request for Information Registration: Summary Table

	Company
1	Abengoa Water
2	Aqua Dynamics Process Technology Ltd
3	Aveng Water
4	Blue Waste to Energy
5	Cape Peninsula University of Technology
6	Coffees of the World (Acid Solutions)
7	Cwenga Technologies (Pty) Ltd
8	Dow Southern Africa (Pty) Ltd
9	East Rand Water Care Company (ERWAT)
10	Eclipse Management (Pty) Ltd
11	Enviro-Sec Ltd
12	Fraser Alexander (FAWT) & MiWaTek
13	Gemini Environmental Group Ltd
14	Imbewu Ventures cc
15	Individuals (Thakane Ntholi)
16	IWT – Industry AG
17	Marubeni Corporation
18	Mitsubishi Heavy Industries Ltd
19	Mixtec cc
20	Mott MacDonald
21	Murray & Roberts Ltd

	Company
22	Nano Water Technologies Africa (Pty) Ltd (Blue Gold)
23	Minus Engineering Ltd
24	Ngonyezi
25	NuWater (Pty) Ltd
26	Optima Agrik (Pty) Ltd
27	P2W Ltd
28	PD Naidoo & Associates
29	Process & Business Consultants
30	Project Assignments (SA) (Pty) Ltd (Projass) (Paques)
31	PROXA
32	PWC
33	RNE Pumps
34	Schlumberger Water Services
35	Sembcorp Utilities SA (Pty) Ltd
36	SOLACE
37	SYNCHRONA
38	Tenova Bateman Technologies
39	TUT (Tshwane University of Technology) and Key Structure Holdings
40	TWP Projects
41	Umlingo Solutions
42	Veolia Water Solutions & Technologies (Pty) Ltd
43	Western Utilities Corporation (WUC)

Due to the late advertising in the press of the advertisement, the study team had to invite technology stakeholders that had contacted DWA with respect to the AMD challenge at the time, as well as companies that were known to be operating in the field of AMD to present information on their technologies. The following technology stakeholders were invited at the beginning of the study:

Company	**Process**
• Aveng	Reverse osmosis
• ERWAT	Biological sulphate reduction
• Eclipse	Evaporation of AMD
• NWSSS (Blue Gold)	Electro coagulation and precipitation

Western Utilities Corporation (WUC)	Alkaline barium calcium process
MiWaTek	Reverse osmosis
Tshwane University of Technology	Alkaline barium calcium process
Veolia	SAVMIN
P2W	Electrocoagulation process
1 Source Group	Electrocoagulation process
Aquatek Water Solutions	Unknown process
Watsol	Electro-deionisation

The process proposed by Eclipse was considered but deemed inappropriate. The proposed process constitutes the operation of a stationary, ground-mounted jet engine and spraying of the AMD into the hot exhaust fumes of the engine to evaporate and disperse the water. The constituents are then released to the environment, causing fall-out in the surrounding area. This is not acceptable, and the process was discarded as not solving the problem that this study was required to address.

Insufficient information was provided by two service providers to allow objective evaluation of their proposed technology, namely:

- NWSS (Blue Gold); and
- Aquatek Water Solutions.

The technologies proposed by the remaining technology service providers are discussed below. As some of the technology is provided by more than one company, as is typically the case with reverse osmosis desalination, the discussions in this report are structured around the lines of the technology, and not the companies that were consulted.

All owners and providers of technology required the study team to commit to non-disclosure agreements (NDA) to protect the intellectual property of the companies. Even with the signing of NDAs, the companies were very reluctant to reveal technical details of their technologies. Only the bare minimum details were provided to briefly describe the physical and chemical principles on which the technology operates and enable a high-level analysis. In some cases, no details were divulged, with the result that these technologies could not be evaluated. Moreover, the companies generally did not present detailed and accurate economic values, as this was perceived to compromise their competitive edge.

The result of this reluctance to provide information was that the study team had to form their own opinions and conclusions based on their knowledge and experience. Where the technology was known, the study team calculated the quantities of chemicals used and the waste products formed. It was not always possible to verify the claims made by the technology providers, and in such cases the quantities are not reported.

Since the advent of the study, given the media attention that the AMD problem has received, various institutions have been very actively involved in researching solutions to the problem. Most of the technology that is currently being presented is still at various stages of research, and therefore poses significant risk of failure due to lack of experience. Very few technologies have been tested on a scale comparable with the problem experienced on the Witwatersrand.

The scale of the problem requires that proven technology be implemented, at least in the immediate future, to prevent catastrophic damage to the environment. Failure of the technology would not only constitute a serious financial loss, but would also probably cause irrevocable damage to the environment.

5. QUANTITY AND QUALITY OF AMD

The quantity and quality of the AMD to be treated by the technology were determined in Study Report No. 5.2: "Assessment of the Water Quantity and Quality of the Witwatersrand Mine Voids". The information is repeated in this report for ease of reference, and to enable comments on the impacts of the quantity and quality of the AMD on the technology.

The information presented in previous studies proved to have been based on statistical analysis of the available data at the 95th percentile, which means that the water quality at only 5% of the data points was worse than the data on the basis of which the AMD problem was defined. This way of defining the problem amounts to overstating it, as the reality would instead be around the 50th and 60th percentile.

The data available to the study team were therefore statistically analysed to determine various statistical constellations (i.e. at the 5th, 10th, 50th, 60th, 75th, 90th, and 95th percentiles of all the constituents). This gives an indication of the spread of the data, allows some interpretation of the variability of the AMD, and indicates what the reality of the situation might be. The analysis of the data, as described, is given in this report for easy reference.

The sets given in the tables represent merely the statistical analysis of the individual constituents, rather than the complete water samples. It is thus evident that the results will not be balanced. The data should therefore be used with care and where a balanced water quality is required for design purposes, the adjustment should be made taking the specific treatment technology into account to ensure that assumptions made are reasonable.

5.1 Expected AMD Quantities per Basin

5.1.1 Expected AMD Quantities as Estimated in the LTS

The volumes of AMD to be treated in the three Witwatersrand basins was estimated as part of this study, as shown in **Table 5.1**.

Table 5.1: AMD flow rates as estimated for the LTS[2]

Basin	Proposed pump capacity and pumping rate (this study) (Mℓ/d)		
	Capacity	**Range**	**Average rate**
Western	27	23 – 27	23
Central	50	46 – 50	46
Eastern	100	80 – 100	80

The calculations of this study are based on the following peak design flows:

- Western 40 Mℓ/24 hr;
- Central 60 Mℓ/24 hr; and
- Eastern 100 Mℓ/24 hr.

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[2] Study Report No. 5.2: Table 10.2

There average flows assumed for the estimation of operations and maintenance costs were:

- Western 23 Mℓ/24 hr;
- Central 46 Mℓ/24 hr; and
- Eastern 80 MℓI/24 hr.

These flows are based on the best available information at the time of the study. Certain actions, such as reducing infiltration into the voids and hence the generation of AMD, would reduce these values. Seasonal variations, and variations in the rainfall pattern, could impact on the volume of AMD that has to be abstracted from the voids. The technology to be selected will have to be sufficiently robust to tolerate variations, as mentioned above. This will be an important criterion in the selection of technology.

5.2 Expected Quality of AMD per Basin

The expected quality of the AMD in the various basins was estimated in this study by subjecting the available data to statistical analysis. As a reasonable approximation of the probable water qualities during abstraction, **Table 5.2** presents the water chemistry at the 95th percentile for underground samples only (or from direct decant sites in the case of the Western Basin). The values reported in the tables are for the dissolved elements and constituents in the AMD.

It can be seen that the values differ considerably for AMD from the three sources. Of major importance is the fact that the current estimates of the concentrations of iron, manganese and sulphate in all basins are significantly lower than the values presented in previous studies and reports, and previous studies have reported the presence of uranium in all basins. This necessitates careful consideration of the available data.

Table 5.2: Comparison of AMD water quality per basin at the 95th percentile[3]

Parameter	Unit	Basin 95th Percentile)		
		Western	Central	Eastern
pH[#]	@ 25˚C	3.5	2.4	5.9
TDS*	mg/ℓ	5 434	4 592	3 358
Electrical Conductivity	mS/m @ 25˚C	442	465	363
Ca	mg/ℓ	703	563	421
Mg	mg/ℓ	-	258	166
Na	mg/ℓ	227	171	264
SO_4	mg/ℓ	3 623	3 062	2 289
Cl	mg/ℓ	-	146	254
Acidity/Alkalinity	mg/ℓ	1 520	-	560
Fe	mg/ℓ	954	108	227
Al	mg/ℓ	-	193	2.4
Mn	mg/ℓ	89	50	5.9
*Estimated # 5th Percentile				

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[3] Study Report No. 5.2: Table 10.5

5.2.1 Western Basin

In the Western Basin, the most suitable sampling sites for predicting the expected water quality to be abstracted are the principal decant sites only (17 and 18 Winzes and Black Reef Incline (BRI)), the results for which are given in **Table 5.3**.

Table 5.3: Compositional ranges for water from 17 and 18 Winzes and BRI, Western Basin, (5th–95th percentiles)[4]

Parameter	Unit	Percentile						
		5th	10th	50th	60th	75th	90th	95th
pH	@ 25ºC	2.7	2.8	3.2	3.3	5	5.9	6.5
EC	mS/m@ 25ºC	291	311	363	374	390	412	426
TDS*	mg/ℓ	3 381	3 523	4 313	4 487	4 748	5 092	5 388
Acidity	mg/ℓ	21	194	719	825	965	1 086	1 255
Ca	mg/ℓ	419	458	544	561	597	723	823
Na	mg/ℓ	65	78	101	106	125	175	243
Fe	mg/ℓ	1	21	185	277	463	699	799
Mn	mg/ℓ	11	27	56	62	70	90	114
SO_4	mg/ℓ	2 140	2 230	2 730	2 840	3 005	3 223	3 410
*Estimated n = 651 for all parameters Data accumulated between January 2011 and March 2012								

For the Western Basin, there is no data for some of the constituents that have been reported for the Central and Eastern Basins (see **Tables 5.4** and **5.3**). It is not possible to consider the direct implications of constituents for which no data is available.

As the Western Basin has been decanting AMD for about a decade, and AMD has been pumped from the void continuously for a considerable time since the decanting started, the variations in the data are known, and consequently the risks associated with variations in the data are somewhat less than in the Central and Eastern Basins.

5.2.2 Central Basin

In the Central Basin, it is considered likely that the extensive shaft sampling data reflect dilution from surface ingress and possibly some degree of reaction with shaft cement linings.

Table 5.4 presents percentile values for the underground mine water samples only. Should pumping take place from deeper areas, as proposed for the STI at South West Vertical (SWV) Shaft, then these values are likely to be broadly representative of the water qualities to be expected. The impact on water quality of abstracting AMD from the void cannot be quantified until the pumping of the AMD begins. This is therefore an important variable and a risk that needs to be taken into account in evaluating the technology.

It is important to note that the concentration of uranium in the AMD exceeds the SANS-241 (2011) limit by several factors, even at the 50th percentile. Special treatment processes will be required to reduce this to the SANS-241 requirements. Refer to Appendix A for

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[4] Study Report No. 5.2: Table 6.11

background on the Ion Exchange process which are capable of removing the uranium in AMD.

The concentrations of heavy metals, especially cobalt, nickel and zinc are considered high and this needs to be taken into account in designing the treatment systems.

The concentration of the monovalent ions (Na and Cl) meets the water quality objectives of the receiving stream in the Central Basin, hence it can be expected that no brine disposal would be required for this basin if a process such as reverse osmosis were implemented.

Table 5.4: Water quality range for underground mine water in the Central Basin (5th–95th percentile)[5]

Parameter	Unit	Percentile						
		95th	90th	75th	60th	50th	10th	5th
T	°C	27	26	25.3	23.2	23	22	22
pH[#]		2.4	2.5	4.2	3.7	3.0	4.3	4.4
EC	mS/m	465	450	412	405	397	371	371
TDS^	mg/ℓ	5 118	4 952	4 429	4 319	4 363	4 085	4 078
Tot Alk	mg/ℓ CaCO3	34	29	8.9	2.5	2.5	2.5	2.5
Na	mg/ℓ	171	170	169	134	122	110	108
Mg	mg/ℓ	258	249	201	177	172	159	118
Al	mg/ℓ	193	184	133	129	122	21	10
K	mg/ℓ	13	12	7	5	5	3	3
Ca	mg/ℓ	563	459	403	351	279	243	241
Fe	mg/ℓ	108	94	48	41	40	2	1
Mn	mg/ℓ	50	50	49	47	47	24	13
F	mg/ℓ	4	4	2	2	1	0	0
Cl	mg/ℓ	146	144	141	138	137	87	84
NO3	mg/ℓ	34	33	29	26	23	12	10
PO4	mg/ℓ	15	11	0	0	0	0	0
SO4	mg/ℓ	3 062	3 041	2 953	2 879	2 831	2 597	2 429
Li	µg/ℓ	495	450	428		372	290	274
Be	µg/ℓ	25	24	23	21	20	4	2
B	µg/ℓ	712	361	318	300	280	245	214
V	µg/ℓ	12	9	4	1	1	1	1
Cr	µg/ℓ	148	130	129	100	87	5	5
Co	µg/ℓ	5 760	5 637	5 205	4 923	4 684	1 200	601
Ni	µg/ℓ	12 850	12 633	11 669	11 122	10 589	2 600	1 268
Cu	µg/ℓ	376	375	371	332	328	40	28
Zn	µg/ℓ	12	11	9 625	9 195	9	2	1
Ga	µg/ℓ	88	79	19	33	3	3	3
As	µg/ℓ	115	55	39	33	31	1	1
Se	µg/ℓ	47	46	45	42	40	10	6
Rb	µg/ℓ	42	38	25	19	19	15	15

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[5] Study Report No. 5.2: Table 7.13

Parameter	Unit	Percentile						
		95th	90th	75th	60th	50th	10th	5th
Sr	µg/ℓ	697	693	661	638	634	493	443
Mo	µg/ℓ	3	3	3	3	3	3	3
Ag	µg/ℓ	15	15	15	1	1	1	1
Cd	µg/ℓ	15	12	12	11	11	1	1
Te	µg/ℓ	1	1	1	1	1	1	1
Ba	µg/ℓ	2 213	2 053	442	18	11	5	5
Tl	µg/ℓ	1	1	1	1	1	1	1
Pb	µg/ℓ	276	132	80	35	28	7	5
Bi	µg/ℓ	2	1	1	1	1	1	1
U	µg/ℓ	695	682	657	645	606	123	56

Number of samples = 12 ^Estimated Data rounded

pH values in reverse percentile order, e.g. 95th percentile is 5th percentile

5.2.3 Eastern Basin

Table 5.5 presents the summarised compositional ranges of underground samples only and can therefore be considered as a reasonable approximation for the water qualities anticipated during pumping from the mine void.

Table 5.5: Water quality range (percentiles) for underground mine water in the Eastern Basin (5th–95th percentiles)[6]

Parameter	Unit	n	Percentiles						
			5th	10th	50th	60th	75th	90th	95th
T	°C	138	19	20	27	27	28	28	29
pH		101	5.9	6.1	6.5	6.5	6.6	6.9	7.1
EC	mS/m	144	98	161	280	293	314	351	363
TDS	mg/ℓ	138	484	781	2 292	2 468	2 840	3 196	3 358
Alkalinity	mg/ℓ$CaCO_3$	61	12	32	168	187	232	327	560
Total Hardness	mg/ℓ	23	1 481	1 500	1 655	1 692	1 700	1 749	1 759
Salinity	mg/ℓ	38	0	0	1	1	1	2	2
Na	mg/ℓ	139	58	67	208	223	238	252	264
Mg	mg/ℓ	51	0	0	54	62	119	163	166
Al	mg/ℓ	79	0	0	0	0	0	1	2
K	mg/ℓ	38	3	3	4	5	5	6	7
Ca	mg/ℓ	61	0	0	77	129	379	407	421
Fe	mg/ℓ	139	0	0	74	88	126	209	227
Mn	mg/ℓ	139	0	0	3	3	4	5	6
Cl	mg/ℓ	139	66	75	157	170	184	205	254
NO_2	mg/ℓ	38	0	0	0	0	0	0	0
Br	mg/ℓ	38	0	0	0	0	0	0	0

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[6] Study Report No. 5.2: Table 8.14

Parameter	Unit	n	Percentiles						
			5th	10th	50th	60th	75th	90th	95th
NO_3	mg/ℓ	38	0	0	7	11	15	20	31
PO_4	mg/ℓ	38	0	0	7	8	11	15	22
SO_4	mg/ℓ	139	240	364	1 148	1 273	1 610	1 917	2 289
Li	µg/ℓ	38	4	6	17	23	39	95	147
B	µg/ℓ	38	64	71	98	106	125	624	1 170
Ni	µg/ℓ	61	0	0	302	350	515	1 318	2 553
Co	µg/ℓ	38	0	0	45	61	96	446	748
Cu	µg/ℓ	38	0	0	0	1	10	73	499
Zn	µg/ℓ	38	520	524	586	647	1 021	3 131	4 416
Ga	µg/ℓ	38	0	0	0	0	0	23	43
As	µg/ℓ	38	0	0	0	0	12	57	112
Se	µg/ℓ	38	0	0	8	13	29	56	94
Rb	µg/ℓ	38	5	7	11	14	20	29	33
Sr	µg/ℓ	38	103	157	321	383	616	1 100	1 433
Ag	µg/ℓ	38	0	0	0	0	0	0	1
Cd	µg/ℓ	38	0	2	3	3	3	9	18
Ba	µg/ℓ	38	93	95	105	106	108	320	1 146
Pb	µg/ℓ	38	14	15	16	17	18	41	83
U	µg/ℓ	38	1	2	10	21	92	357	470
COD	mg/ℓ	67	11	12	32	38	53	166	180
DO	mg/ℓ	100	1.3	1.8	2.4	2.5	2.6	3.1	3.4
Data rounded	TDS as received from the source								

The water quality in the Eastern Basin is summarised in **Table 5.5**, which presents the compositional ranges of underground sampling data only. This was therefore considered a reasonable approximation of the water qualities anticipated during pumping from the mine void.

The expected quality of the water in the Eastern Basin is considerably better than the water in the Western and Central Basins. As with the Central Basin, the impact on water quality of abstracting AMD from the void cannot be quantified until the pumping of the AMD begins. This is therefore an important variable and a risk that needs to be taken into account in evaluating the technology.

The respectively higher pH and the presence of alkalinity in the water are of particular interest. The relatively high concentration of Na is of particular concern, however, and some form of reduction through processes such as reverse osmosis will be required to meet the Resource water quality objectives (RWQOs) of the receiving streams. A relaxation of this standard would simplify the treatment requirements, and hence also reduce the costs considerably. However, it is also cautioned that the water quantities and qualities used as the basis for the design might vary from the actual quantities and qualities generated over time, and the practical design basis for further treatment still requires verifiable water quantities and qualities.

The presence of relatively high Chemical Oxygen Demand (COD) concentrations requires further investigation to determine whether the COD is related to an oxygen demand to oxidise Fe^{2+} to Fe^{3+} or due to ingress of domestic wastewater into the mine workings. Most of the mine water treatment technologies are not designed for handling water contaminated with domestic wastewater. If the COD is due to domestic wastewater contamination additional treatment steps will be required and even with these additional treatment steps there may be undesired residual negative impacts on some of the salinity removal treatment technologies.

5.2.4 Discussion

The quality of the AMD in respect of the monovalent ions, particularly sodium, in the Western and Central Basins is such that the SANS-241 standards could be met through most of the conventional desalination processes without the production of brine. Significant savings in the CAPEX and OPEX could be realised if brine does not have to be treated. In the Eastern Basin, the sodium concentration exceeds the SANS-241 standards, and hence the treatment processes will produce brine.

In principle, assuming that the design basis water qualities are correct and will be consistent, by mixing the water from the Eastern Basin with the water from the Central Basin, after HDS treatment, the combined sodium concentration could meet the required specification for extended periods of times. However, if a higher concentration (> 250 mg/ℓ of Na) could be accepted in the Blesbokspruit (if that were the receiving stream for the Eastern Basin), the transfer of water from the Eastern Basin to the Central Basin would not be required, as both the receiving streams flow into the Vaal Barrage, where the blending could take place. The impact on the Vaal River would thus be the same, and no transfer would be needed between the basins at the site of the treatment works. This could effect a real saving in costs.

It is not possible to predict the actual concentration of sodium for each eventuality, and a general operations procedure would therefore have to be compiled to balance the concentrations of all the constituents and optimise the efficiency of the processes.

5.3 Design Feed and Product Water Quality

The quality of the AMD water before neutralisation (which would be the feed water to the neutralisation process) is summarised in **Table 5.6** below, which presents the AMD water quality values predicted in this study at the 95th percentile. The final required water quality for the LTS is assumed to be SANS-241 (2011) for the purposes of this study.

Table 5.6: Mine water qualities compared with potable water quality at the 95th percentile

Water quality parameters	Units	Feed water specification			SANS-241 (2011)
		Western Basin (95th)	Central Basin (95th)	Eastern Basin (95th)	
TDS	mg/ℓ	5 388	5 118	3 358	< 1 200
EC	mS/m	426	465	363	< 170
Ca	mg/ℓ	83	563	421	NS
Mg	mg/ℓ	18[1]	258	166	NS
Na	mg/ℓ	243	171	264	< 200
SO_4	mg/ℓ	3 410	3 062	2 289	250 (WB& CB) 350 (EB)
Cl	mg/ℓ	65[2]	146	254	< 300
pH		2.7	2.4	5.9	5.0–9.7
Alkalinity (as $CaCO_3$)	mg/ℓ	N/A	N/A	12	NS
Acidity (as $CaCO_3$)	mg/ℓ	1 255	NS		NS
Fe	mg/ℓ	799	108	N/A227	< 0.3
Al	mg/ℓ	54 Note 3	193	2	< 0.3
Mn	mg/ℓ	114	50	6	< 0.1
U	mg/ℓ	NS	0.695	0.470	< 0.015

NS = Not specified
Note 1: Assumed value to balance water
Note 2: Assumed value (value from TCTA report used)
Note 3: Assumed value (escalated value from TCTA Due Diligence Report (2011))

The proposed short-term solution will neutralise the AMD and remove metals as required for the STI. It should be noted that the feed water quality from the Eastern Basin shows that limestone neutralisation would not be required, as the feed water is already at a minimum pH of 5.9. Therefore a HDS process is proposed where only lime is dosed. Consideration might even be given to only installing an iron removal step, such as greensand filtration, or a simple iron oxidation removal step for the Eastern Basin as a short-term measure.

The feed water specification values at the 50th and 75th percentile are shown in **Table 5.7** below.

Table 5.7: Feed water specification values at the 50th and 75th percentiles

Water quality parameters	Units	Feed water specification values at the 50th percentile			Feed water specification values at the 75th percentile			SANS-241 (2011)
		Western Basin (50th)	Central Basin (50th)	Eastern Basin (50th)	Western Basin (75th)	Central Basin (75th)	Eastern Basin (75th)	
TDS	mg/ℓ	4 313	4 247	2 292	4 748	4 429	2 840	< 1 200
EC	mS/m	363	397	280	390	412	312	< 170
Ca	mg/ℓ	544	279	77	597	403	379	NS

Water quality parameters	Units	Feed water specification values at the 50th percentile			Feed water specification values at the 75th percentile			SANS-241 (2011)
		Western Basin (50th)	Central Basin (50th)	Eastern Basin (50th)	Western Basin (75th)	Central Basin (75th)	Eastern Basin (75th)	
Mg	mg/ℓ	75	172	54	18[Note 1]	201	119	NS
Na	mg/ℓ	101	122	208	125	169	238	< 200
SO_4	mg/ℓ	2 730	2 831	1 148	3 005	2 953	1 610	250 (WB& CB) 350 (EB)
Cl	mg/ℓ	65[2]	137	157	65[2]	141	184	< 300
pH[4]		5.0	3.0	6.5	3.2	2.7	6.2	5.0–9.7
Alkalinity (as $CaCO_3$)[4]	mg/ℓ	N/A	N/A	168	N/A	N/A	83	NS
Acidity (as $CaCO_3$)[4]	mg/ℓ	1 039	NS	N/S	1 174	NS	N/S	NS
Fe	mg/ℓ	185	40	74	463	48	126	< 0.3
Al	mg/ℓ	28[3]	122	0.0	4[3]	133	0	< 0.3
Mn	mg/ℓ	56	47	3.0	70	49	4	< 0.1
U	mg/ℓ	NS	0.647	0.01	NS	0.657	0.092	< 0.015

NS = Not specified
1: Assumed value to balance water
2: Assumed value (value from TCTA report used)
3: Assumed value (escalated value from TCTA report used)
4: 5th percentile values used where applicable

The objectives of the STI were as follows:

- Neutralise the acid in the AMD and adjust the pH to produce circumneutral treated mine water with some residual buffer capacity in the form of alkalinity;
- Remove the metals of concern, particularly iron, aluminium and manganese, to acceptable short-term discharge standards;
- Remove radionuclides, specifically uranium, to acceptable short-term discharge standards; and
- Achieve a degree of desalination by increasing pH to a level that causes gypsum ($CaSO_4$) to become oversaturated and precipitate out of solution.

The objectives of the STI can be achieved in a High Density Sludge (HDS) plant, where limestone and lime are used for pH correction.

The quality of the water treated with the HDS process has been estimated by the service providers for the STI,[7] as shown in **Table 5.8**. This water will be the source to the processes investigated for the LTS unless specifically stated other.

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[7] Contract TCTA 08-041: Process Design Report, Table 3

Table 5.8: Expected quality of the AMD treated by the HDS process as estimated for the STI

Water quality variable	Units	Value
pH	–	6.0–9.0
Iron (Fe)	mg/ℓ	< 1
Manganese (Mn)	mg/ℓ	< 3
Aluminium (Al)	mg/ℓ	< 1
Uranium (U)	µg/ℓ	< 50
Sulphate (SO_4)	mg/ℓ	< 2 400

6. DESCRIPTION OF AMD TREATMENT TECHNOLOGIES

The technologies available for the treatment of AMD were grouped as follows:

- Passive treatment processes;
- Pre-treatment processes;
- Physical processes;
- Chemical processes; and
- Biological processes.

The technologies will be discussed in the following sections.

6.1 Passive Treatment

According to the Global Acid Rock Drainage Guide (GARD Guide),[8] "passive treatment refers to processes that do not require regular human intervention, operations, or maintenance. It should typically employ natural construction materials, (e.g., soils, clays, and broken rock), natural materials (e.g., plant residues such as straw, wood chips, manure, and compost) and promote the growth of natural vegetation. Passive treatment systems use gravity flow for water movement. In some arid climates, it might also include use of evaporation or infiltration (e.g., soil amelioration and neutralisation) of small volumes of ARD." The development of the GARD Guide is supported by the International Network for Acid Prevention (INAP), which is an industry group created to help meet the challenge of acid drainage.

Passive treatment systems generally have low energy requirements in the form direct energy input such as physical processes (mixing, aeration) or chemical processes (chemically induced precipitation, oxidation, etc.) Because of the reduced direct energy input, the processes generally require long retention times in the process structures, which necessitates that these structures are voluminous. One such scheme indicated that a retention time of 90 days would be required to treat AMD (for removal of heavy metals and neutralisation of the pH). The implications are that an area of approximately 162 ha of biological reactor would be required for the treatment of the 27 Mℓ/d generated from the Western Basin, if it is assumed that the water in the biological reactor would be 1.5 m deep. This area does not take into account the space required for the maintenance of the scheme, or for any inefficiencies in the use of space related to the topography of the terrain. Adequate suitable land is not available for such a scheme as the primary process for treating AMD. Wetlands could, however, be used to protect the downstream environment against the adverse effects of AMD by polishing the treated effluent released into the environment.

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[8] INAP (International Network for Acid Prevention); *Global Acid Rock Drainage Guide (GARD Guide)*; 2010. [Online] Available at: http://www.gardguide.com/.

Passive treatment schemes have generally been investigated in small applications treating a few hundred kilolitres per day, rather than the enormous scale required in the Witwatersrand. It is also not known how the systems would react to variations in the quality of AMD, and it would be difficult to modify the process should this be required.

It was stated that the schemes could neutralise the pH and remove heavy metals. However, no mention was made of the removal of sulphate, or the reduction of the dissolved solids, as required to meet the envisaged standards.

In view of the above, passive treatment of AMD is considered appropriate for small flows only. The scale required for the treatment of the AMD generated in the Witwatersrand exceeds the current ability of the technology, which will therefore not be considered in further detail.

6.2 Pre-Treatment Processes

6.2.1 High Density Sludge (HDS) Neutralisation Process

The main characteristics of AMD are low pH (<6), and high levels of metals, mainly iron, manganese, aluminium and/or copper, being present in solution. The first step in treating AMD is to neutralise the pH and oxidise the metals. This results in the precipitation of these metals as metal oxides and hydroxides, after which they can be removed from the water by clarification. This process is known as the High Density Sludge (HDS) process in AMD treatment (see **Figure 6.1**).

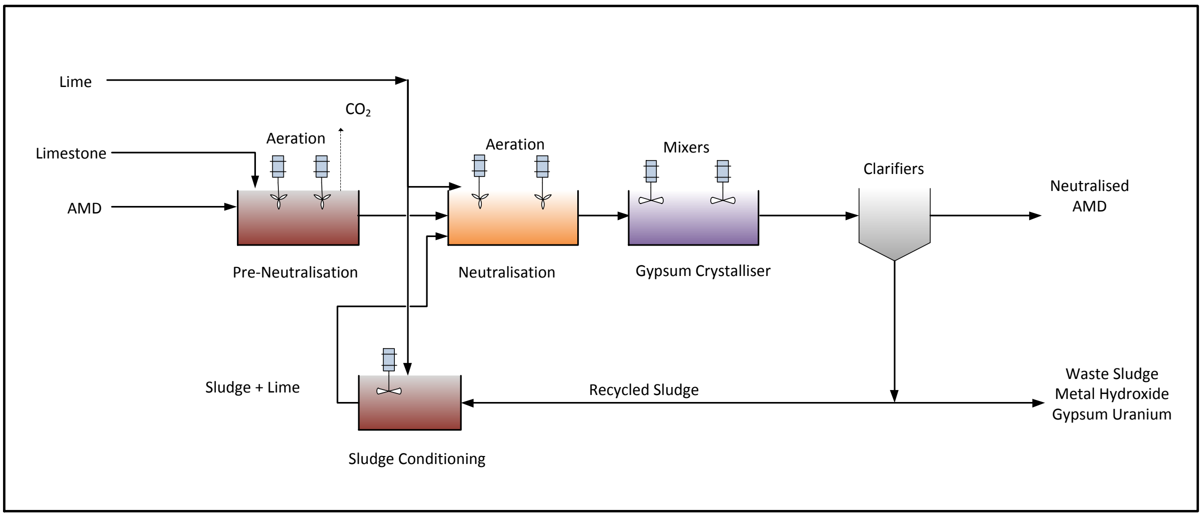

Figure 6.1: Simplified process diagram of the limestone pre-neutralisation and HDS Process

a) Description of the Process

Iron, which is present in mine water, is generally predominantly ferrous iron (Fe^{2+}); though ferric iron (Fe^{3+}) can also be largely present if oxygen interaction has occurred. Ferrous iron is highly soluble over a wide pH range; it should first be oxidised to form less soluble ferric iron (Fe^{3+}), which is precipitated as ferric hydroxide in order to remove it from solution. The rate of oxygenation of ferrous iron is first order with respect to the dissolved ferrous iron and/or oxygen concentration, but second order with respect to the hydroxyl ion (pH). This implies a reaction rate proportional to the dissolved oxygen concentration, or the initial ferrous iron concentration, but a hundred-fold increase in the rate with a unit pH increase, or a ten-fold increase with a 0.5 pH increase. The pH of the solution must be adjusted to at least 5.5 to 6.0 to observe noticeable transformation of Fe^{2+} to Fe^{3+}, while the optimum pH for this reaction is about 8.5. The aim is to initiate and maintain these conditions in an HDS plant.

A typical limestone pre-neutralisation and HDS Process plant consists of the following process steps:

- Addition of limestone, or lime, or a combination of limestone and lime, to increase the pH of the AMD to a level at which the oxidation and precipitation of metals, mainly targeting iron and manganese, will be enhanced.
- Addition of oxygen in the form of pure oxygen, or by aeration with air or other oxidising chemicals, to oxidise the dissolved iron from the ferrous to ferric state, and to oxidise the manganese.
- Reaction and aeration basin for the metal oxidation with a typical retention time of the order of ten minutes to further oxidise and mix the water.
- Clarification of the AMD, with HDS product water as the supernatant and high density metal rich sludge as the underflow of the clarifier.

i. Pre-neutralisation

The AMD feed is partially neutralised (Reaction 1) to a pH of 5.5 to 6.0 using a 10% limestone slurry. A large portion of the Al and Fe^{3+} is removed (Reaction 2). The reactions applicable to this process step are shown below:

Reaction 1 $2H^+ + CaCO_3 \rightarrow Ca^{2+} + CO_2 + H_2O$

Reaction 2 $2M^{3+} + 3CaCO_3 + 3H_2O \rightarrow 2M(OH)_3(s) + 3CO_2 + 3Ca^{2+}$ (M = Fe, Al)

When the pH of the AMD is close to the range of 5.0 to 6.0, as in the Eastern Basin, the pre-neutralisation step might not be necessary, and only lime could be used for pH adjustment.

Aeration is used in the first part of the reactor for mixing and iron oxidation, and to drive off carbon dioxide (CO_2).

Reaction 3 $4Fe^{2+} + O_2 + 10H_2O \rightarrow 4Fe(OH)_3 + 8H^+$

Reaction 4 $Fe^{3+} + 1.5Ca(OH)_2 \rightarrow Fe(OH)_3(s) + 1.5Ca^{2+}$

Fe^{2+} needs to be converted to Fe^{3+}, for the following main reasons:

- Fe^{2+} does not readily precipitate at a pH lower than ~ 7.5, and effective removal thereof to the level required only occurs at pH > 8.5. The removal of Fe^{3+}, if present, effectively already starts at pH > 3.5.
- Fe^{2+} causes armouring (precipitation on the surface) of the limestone particles, significantly reducing its reaction efficiency.
- $Fe(OH)_2$ sludge that is disposed of and over time comes into contact with oxygen can result in the oxidation of the Fe^{2+} to Fe^{3+}. Precipitation of the oxidised iron as $Fe(OH)_3$ consumes additional alkalinity. When there is insufficient alkalinity in the sludge the pH decreases and some of the previously solid iron again becomes dissolved iron that can leach from the sludge disposal facility. Disposing iron sludge as $Fe(OH)_3$ reduces the chances of iron leaching from the disposed sludge.

CO_2 needs to be removed in order to prevent the downstream reaction of lime and CO_2 (Reaction 5), which would significantly increase lime consumption. Another benefit of removing CO_2 is to increase the pH, thereby saving on the limestone or lime dosage. The CO_2 could possibly be captured and used for pH correction of the final water before discharge.

Reaction 5 $CO_2(g) + Ca(OH)_2 \rightarrow CaCO_3(s) + H_2O$

It is important to note that as soon as gypsum ($CaSO_4$) reaches saturation point with the addition of limestone, gypsum precipitation will be initiated (Reaction 6). It is also important to note that in all the reactions above, Ca is only a spectator ion and does not participate in the active reactions. Thus, the Ca concentration will rise as limestone is added and take the water closer to gypsum saturation levels. The gypsum precipitation reaction (Reaction 6) will only be partially completed, as the slower reaction kinetics requires a reaction time of at least three hours. The design of the STI allows a retention time of 30 minutes in the pre-neutralisation reactor, and most of the gypsum crystallisation will therefore only take place in the following reactor steps.

Reaction 6 $Ca^{2+} + SO_4^{2-} \rightarrow CaSO_4(s)$

No significant manganese precipitation or removal occurs in the pre-neutralisation step.

ii. Neutralisation

Calcium oxide (CaO) is slaked and dosed as 10% milk-of-lime slurry into the neutralisation reactor. In the neutralisation step, most of the remaining Fe and Al are precipitated. Aeration is once again used in the first part of the reactor for mixing and to oxidise residual Fe^{2+} to Fe^{3+} (Reaction 3), which is then removed as iron hydroxide (Reaction 4).

By dosing with lime, the pH is raised to 9.0, which causes manganese precipitation (Reaction 7) and further gypsum precipitation (Reaction 4).

Reaction 7 $Mn^{2+} + Ca(OH)_2 \rightarrow Mn(OH)_2(s) + Ca^{2+}$

The design of the STI allows a retention time of 60 minutes in the neutralisation reactor.

iii. Gypsum Crystallisation Reactor

The purpose of the gypsum crystallisation reactor is to provide the additional required retention time for gypsum crystallisation.

No dosing is performed in this stage, as the calcium required for sulphate removal by means of gypsum precipitation has already been added in the preceding steps.

Slow mixing is provided in this stage to enhance crystal growth.

The design of the STI allows a retention time of 120 minutes in the gypsum crystallisation step.

iv. Clarifier

The precipitated species formed in the reactor steps are in a suspended form and are removed in a clarifier. The precipitated species are mainly metals and gypsum.

The design upflow velocity in the clarifier is 1 m/hr, and the side wall depth is 4.5 m, which allows the suspended matter to settle out at the bottom of the clarifier. The settling of solids is further enhanced by the addition of a flocculant, which aids in the agglomeration of small particles.

The clarified water overflows at the top of the clarifier, where it is collected in the clarified water sump. This clarified water is the product water of the HDS process.

A sludge blanket forms at the bottom of the clarifier. The feed that flows from the top of the centre well is introduced into the clarification zone at the bottom of the centre well below the sludge blanket. The sludge blanket acts almost as a filter and aids in settling the solids.

The settled solids are scraped along the bottom of the clarifier cone to the extraction point in the centre and extracted from the clarifier as a sludge consisting of 7–14% (mass/volume) suspended solids. Part of the sludge is routed back to the process (as discussed later), and the other part is bled off as waste in order to control the amount of solids in the reactors.

v. Sludge Conditioning Tank

Heavy sludge particles are likely to accumulate in the sludge recycle lines causing pipes to block, and complete redundancy would have to be installed on the sludge recycle lines to allow for blockages to be cleared and/or for maintenance.

The recycled sludge is routed to the sludge conditioning tank, where 40% of the lime is dosed in order to condition the sludge and improve its settling characteristics.

The design allows for rapid mixing and a retention time of 30 minutes in the sludge conditioning tank.

vi. Sludge Recycling

From the sludge conditioning tank, the recycled sludge is routed to the neutralisation reactor again together with the raw water.

The recycled sludge, which contains a large fraction of gypsum, will seed, as crystal growth is enhanced if the nuclei already exist in the reactor.

b) Expected Quality of Neutralised AMD

The quality of the water expected from the HDS process is summarised in **Table 6.1** below.

Table 6.1: Expected product water qualities from the HDS process at the 95th percentile

Water quality parameters	Units	Water quality of HDS-treated mine water		
		Western Basin (95th)	Central Basin (95th)	Eastern Basin (95th)
TDS	mg/ℓ	3 017	3 997	3 621
EC	μS/cm	4 826	6 395	5 794
Ca	mg/ℓ	1 055	1 020	594
Mg	mg/ℓ	18	258	166
Na	mg/ℓ	227	171	264
SO_4^{2-}	mg/ℓ	1 649	2 399	2 339
Cl	mg/ℓ	65	146	254
pH		9.5	9.5	9.5
Alkalinity	mg/ℓ as $CaCO_3$	10	10	10
Acidity	mg/ℓ as $CaCO_3$	0	0	0
Fe	mg/ℓ	< 1	< 1	< 1
Al	mg/ℓ	< 1	< 1	< 1
Mn	mg/ℓ	< 10	< 10	< 10
U	mg/ℓ	N/A	< 0.05	< 0.05

Table 6.2: Expected product water qualities from the HDS process at the 50th and 75th percentiles

Water quality parameters	Units	Water quality of HDS-treated mine water					
		50th percentile			75th percentile		
		Western Basin (50th)	Central Basin (50th)	Eastern Basin (50th)	Western Basin (75th)	Central Basin (75th)	Eastern Basin (75th)
TDS	mg/ℓ	3 002	3 795	1 703	2 776	3 892	2 647
EC	μS/cm	4 803	6 072	2 725	4 441	6 228	4 235
Ca	mg/ℓ	859	615	74	879	725	442
Mg	mg/ℓ	75	172	54	18	201	119
Na	mg/ℓ	110	122	208	132	169	238
SO_4^{2-}	mg/ℓ	1 889	2 746	1 198	1 678	2 653	1 660
Cl^-	mg/ℓ	65	137	157	65	141	184
pH		9.5	9.5	9.5	9.5	9.5	9.5

Water quality parameters	Units	Water quality of HDS-treated mine water					
		50th percentile			75th percentile		
		Western Basin (50^{th})	Central Basin (50^{th})	Eastern Basin (50^{th})	Western Basin (75^{th})	Central Basin (75^{th})	Eastern Basin (75^{th})
Alkalinity	mg/ℓ as $CaCO_3$	10	10	10	10	10	10
Acidity	mg/ℓ as $CaCO_3$	0	0	0	0	0	0
Fe	mg/ℓ	< 1	< 1	< 1	< 1	< 1	< 1
Al	mg/ℓ	< 1	< 1	< 1	< 1	< 1	< 1
Mn	mg/ℓ	< 10	< 10	< 10	< 10	< 10	< 10
U	mg/ℓ	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05

c) Estimated Quality and Quantities of Waste Products

The waste product produced by the HDS process is sludge, as described in this section.

The estimated quality and quantity of sludge from the proposed HDS process for initial feed water qualities at the 95^{th} percentile are summarised below in **Table 6.3**. The following are noted:

- A dewatering facility will reduce the waste stream significantly if the required capacity for storage is not available for the sludge waste stream.
- Given the feed water quality in the Eastern Basin, the limestone pre-neutralisation component may not be required and the HDS lime dosing process may be sufficient. If the sulphate concentrations are low and Gypsum precipitation is not required then the reaction retention time can be reduced to 30 minutes. This would result in reduced capital and operating costs, as limestone storage and dosing equipment would not be required; fewer chemical reactors would be required; and chemical and sludge handling costs would be significantly reduced.
- It is recommended that a laboratory-scale test be performed in order to more accurately determine the removal efficiency of uranium by precipitation.

Table 6.3: Estimated sludge quantities and composition for feed water qualities at the 95^{th} percentile

Precipitate (dry basis)	Units	Sludge composition from Limestone Pre-neutralisation and HDS process for feed water quality at the 95^{th} percentile		
		Western Basin (95^{th})	Central Basin (95^{th})	Eastern Basin (95^{th})
$Fe(OH)_3$	%	29.9%	10.0%	37.3%
$Fe(OH)_2$	%	1.3%	0.4%	24.9%
$Al(OH)_3$	%	2.7%	28.4%	1.9%
$Mn(OH)_2$	%	2.4%	3.9%	1.6%
CaF_2	%	0.0%	0.0%	0.0%
$Ca_3(PO_4)_2$	%	0.0%	0.0%	0.0%

Precipitate (dry basis)	**Units**	**Sludge composition from Limestone Pre-neutralisation and HDS process for feed water quality at the 95^{th} percentile**		
		Western Basin (95^{th})	**Central Basin (95^{th})**	**Eastern Basin (95^{th})**
$Mg(OH)_2$	%	0.0%	0.0%	0.0%
$CaCO_3$	%	20.3%	11.8%	34.3%
$CaSO_4$	%	43.5%	45.4%	0.0%
Uranium precipitate	% as U	0.0027%	0.0313%	0.0715%
	kg/d	4.05	29.67	33.6
Total sludge (dry)	t/d	140.3	94.8	47.0
Total (if filter cake @ 65% solids)	t/d	215.9	145.8	72.3
Total (if filter cake @ 65% solids)	m^3/d	134.9	91.1	45.2
Total (if sludge @ 10% solids)	t/d	1 403.3	947.9	469.7
Total (if sludge @ 10% solids)	m^3/d	1 275.7	861.7	427.0

Note: The quality of the lime is unknown and therefore not included in the calculation.

The estimated quality and quantity of sludge for feed water qualities at the 50th and 75th percentiles are shown in **Table 6.4** below.

Table 6.4: Estimated sludge quantities and composition for feed water qualities at the 50th and 75th percentile

Precipitate (dry basis)	**Units**	**Sludge composition from HDS process for feed water quality at the 50^{th} percentile**			**Sludge composition from HDS process for feed water quality at the 75^{th} percentile**		
		Western Basin (50^{th})	**Central Basin (50^{th})**	**Eastern Basin (50^{th})**	**Western Basin (75^{th})**	**Central Basin (75^{th})**	**Eastern Basin (75^{th})**
$Fe(OH)_3$	%	37.5%	8.1%	11%	32.5%	7.2%	21.9%
$Fe(OH)_2$	%	1.6%	0.3%	8%	1.4%	0.3%	14.6%
$Al(OH)_3$	%	2.5%	39.1%	0%	2.8%	31.5%	0.0%
$Mn(OH)_2$	%	2.7%	8.0%	1%	2.5%	6.2%	1.1%
CaF_2	%	0.0%	0.0%	0%	0.0%	0.0%	0.0%
$Ca_3(PO_4)_2$	%	0.0%	0.0%	0%	0.0%	0.0%	0.0%
$Mg(OH)_2$	%	0.0%	0.0%	0%	0.0%	0.0%	0.0%
$CaCO_3$	%	7.2%	25.7%	80%	13.6%	19.0%	62.3%
$CaSO_4$	%	48.5%	18.8%	0%	47.2%	35.9%	0.0%
Total sludge (dry)	t/d	77.6	43.5	50.2	104.4	58.9	44.4
Total (if filter cake @ 65% solids)	t/d	119.3	67.0	77.2	160.6	90.6	68.2
Total (if filter cake @ 65% solids)	m^3/d	74.6	41.8	48.2	100.3	56.6	42.6
Total (if sludge @ 10% solids)	t/d	775.7	435.2	501.6	1 043.6	589.0	443.6
Total (if sludge @ 10% solids)	m^3/d	705.2	395.6	456.0	948.7	535.5	403.2

Given that the manganese concentrations in the Central and Eastern Basins are relatively low, this two-stage precipitation process might be an alternative worth considering for these two basins.

The second clarifier after the gypsum crystallisation reactor will produce sludge consisting mainly of gypsum and manganese hydroxide. Depending on the manganese hydroxide content, this sludge could have some re-use value in the form of crude building materials.

d) Chemical and Utility Requirements of the Limestone Neutralisation and HDS process step only

i. Chemical Consumption

The estimated chemical consumption for feed water quality at the 95th percentile is summarised in **Table 6.5** below.

Table 6.5: Estimated chemical consumption for feed water quality at the 95th percentile

Chemical	Unit	Chemical consumption for feed water quality at the 95th percentile		
		Western Basin	Central Basin	Eastern Basin
Calcium Carbonate	Tons/month	2 221.9	2 708.8	0
Calcium Hydroxide	Tons/month	762.5	421.1	1 233.7
Flocculent	Tons/month	0.4	0.7	0.2

The estimated chemical consumption for feed water quality at the 50th and 75th percentiles is summarised in **Table 6.6** below.

Table 6.6: Estimated chemical consumption for feed water quality at the 50th and 75th percentiles

Chemical	Unit	Chemical consumption for feed water quality at the 50th percentile			Chemical consumption for feed water quality at the 75th percentile		
		Western Basin	Central Basin	Eastern Basin	Western Basin	Central Basin	Eastern Basin
Calcium Carbonate	Tons/month	1 486.6	1 361.4	0	1 776.2	1 642.6	0
Calcium Hydroxide	Tons/month	219.0	386.2	980.6	425.3	394.6	997.7
Flocculent	Tons/month	0.4	0.7	0.2	0.4	0.7	0.2

e) Advantages

The advantages of the HDS process are considered to be the following:

- The process is well established and has been in operation for many years;
- The process is well understood;
- The process can be adapted to variable AMD quality and quantity;
- Measures to mitigate negative aspects are known and understood;
- The process is stable, and can be controlled relatively easily;
- The technology is relatively simple in that it does not involve handling any dangerous substances; and
- Standard unit process reactors are used that could be retrofitted for other purposes if required as part of the LTS.

f) Disadvantages

The following disadvantages have been identified:

- The HDS process requires multiple reaction stages, extended retention periods and therefore considerable hydraulic capacity, with associated high capital costs;
- The process produces large volumes of metal hydroxide and gypsum sludge that have no direct value and require safe disposal;
- The manufacturing of waste is contrary to the intentions of the waste hierarchy, ranging from prevention as the most preferred option, to disposal as the least preferred option, as prescribed in the National Waste Management Strategy of November 2011 that was developed in terms of the National Environmental Management: Waste Act, 2008 (Act No. 59 of 2008);
- The sludge does not readily dewater. Continuously constructed containment bunds will be required if the sludge is independently disposed of on surface, with associated capital, operational and closure costs;
- The lime demand is relatively high, with associated operational cost implications;
- The energy demand for aeration/oxidation and mixing is high, with associated operational cost implications;
- Due to the nature of the process, the equipment (pipelines and vessels) can become blocked with precipitate. Care needs to be taken in the design of the system, as well as in the operation and maintenance of the plant, to prevent damage as a result of precipitation; and
- The quality of the water does not meet the environmental or potable water quality specifications, and hence further treatment would be required.

6.2.2 Neutralising AMD with Wastewater from Gold Recovery Processing

The process of treating AMD with the wastewater generated during gold recovery processing was developed by Mintails, which operates a gold recovery process in the vicinity of Rand Uranium No. 8 Shaft in the Western Basin. This process is a very recent development, of which the study team was only made aware in September 2012. There have been discussions with the developers since then to analyse the process.

As the process is a very recent development, there is not much information available, other than what has been made available by the developers. There is therefore still substantial testing required to prove the efficiency and safety of the process. However, if the process can be proven to be effective, as claimed, it could be a real breakthrough in the treatment of AMD.

For the purposes of this report, this process will be referred to as the iron-cyanide (Fe-CN) process.

a) Description of the Process

The process through which gold is recovered from old mine tailings dams utilises cyanide at a pH of more than 11. Once the chemicals have been used, gold mines have to destroy or inactivate the cyanide, as this is a highly poisonous substance.

Mintails has developed a process whereby AMD can be used to neutralise the high pH of the gold recovery wastewater. The process utilises the Fe in the AMD to form a chemical complex with the cyanide contained in the wastewater. The Fe-CN complex appears to be fairly stable, although it may still be soluble in water. It will therefore have to be established whether the complex will definitely form a precipitate that can be disposed of with the slimes.

Reaction 8 $Fe^{2+} + 6CN^{-} \leftrightarrow [Fe(CN)_6]^{4-}$

This brief description of the principles of the process suggests that it could be of great advantage and result in major savings in the treatment of AMD. The process combines two wastewater streams in order to beneficially utilise the properties of each of the streams. The high pH of the gold processing stream is neutralised by the acidity of the AMD stream, thus saving the need for dosing with excessive quantities of lime, and avoiding the formation of problematic sludge. Secondly, the Fe in the AMD is used to bind with the cyanide. Through this process, two problematic substances are inactivated and converted to a new substance that can be disposed of with relative ease.

Mintails maintains that there are adequate sources of gold slimes to ensure that the process could be operated for approximately the next 30 years.

Typically, the following items need to be determined before this process could be implemented:

- Whether the chemical and physical principles of the process are sound;
- The conditions that could cause the process to fail;
- The adaptability of the process to varying conditions;
- Whether the process is safe to operate, given that hydrogen cyanide (HCN) is a very poisonous substance, either as a gas or dissolved in water;
- The operational parameters of the process need to be clearly established to prevent the release of HCN gas or dissolved HCN to the environment;
- Determine under what conditions the Fe-CN is complex safe and if the oxidation of the ferrous iron can cause the pH to drop when the complex is disposed of and then release HCN gas or dissolved HCN;
- Determine under what conditions the disposal with slimes is safe and sustainable; and
- Determine what happens to the uranium that is present in the slimes and if the concentration of uranium in the treated AMD will increase, which will necessitate uranium recovery processes.

Mintails is constructing a plant with the capacity to treat approximately 15 Mℓ/d of AMD in order to prove the process and to treat their waste streams.

b) Estimated Quality of Treated Water

The quality of AMD neutralised with wastewater from the gold recovery process would be similar to the quality of AMD neutralised through the HDS process. Once the Mintails plant is operational, extensive testing can be conducted to establish the quality of the treated water.

It is known that the sulphate concentration will not meet the requirements of desalinated water, and additional downstream treatment processes would be required.

c) Estimated Quality and Quantities of Waste Products

The quality and quantities of the waste products are not yet known. As the process is integrated with the disposal of the slimes from the gold recovery process, the disposal of the waste products would not pose a problem. The volume of the waste products would amount to only a fraction of the volume of the slimes processed by the mines, and problems are therefore not anticipated.

d) Advantages

The advantages of the Fe-CN process are considered to be the following:

- The process combines two waste streams to solve the problems of both streams;
- The volumes of waste products are significantly reduced;
- The disposal of sludge is simplified;

- Mines with experience of handling and treating cyanide are willing to operate the process; and
- If the process is proven to be safe and acceptable, it appears that it could be implemented for the next 30 years.

e) Disadvantages

The following disadvantages have been identified:

- The Fe-CN process has not been fully developed to the point where it is possible to prove beyond doubt that it is safe for implementation;
- The secondary effects, such as possible increases in heavy metals and uranium originating from the slimes, have not been researched;
- The quality of the water does not meet the environmental or potable water quality standards, and hence further treatment is required. The process is dependent on the gold mining industry; and
- The process cannot be operated in the absence of gold production. If wastewater from gold recovery processing were not available, the HDS process would have to be used to neutralise the AMD.
- The process is dependent on the gold mining industry. If no gold is produced, then the process cannot be operated, and the neutralisation of the AMD would have to be done by an alternative method

6.3 Physical Processes

All processes where the separation of the dissolved ions from the water is achieved by physical barriers, such as membranes, are included in the category of physical processes.

Typically, these desalination processes include all versions of reverse osmosis (RO), electrocoagulation, electrodialysis, etc.

6.3.1 Desalination Conventional Multistage Reverse Osmosis

Desalination through conventional RO is offered by a number of service providers. This technology was presented to the study team by the Aveng Group.

a) Description of the Process

Multistage RO concentration and gypsum precipitation is a well-known process, and several large-scale applications of this process exist for AMD treatment in South Africa.

It is important to note that this desalination process requires the removal of metals present in solution before the RO process to prevent the scaling of the RO membranes by precipitates (e.g.iron and manganese). **Reverse osmosis requires the application of an upstream**

treatment such as a HDS process to ensure that metals are removed to the standards required by the suppliers of RO membranes.

i. RO Concentration and Gypsum Precipitation

RO is used to remove ions from water by passing the water through very tight semi-permeable membranes. Through this process, the ions are retained in the reject water as brine, and the permeate is collected as the product.

Typical water recoveries of between 50% and 80% can be achieved on AMD fed to a single-stage RO unit, following metals removal or gypsum softening as pre-treatment. A single-stage RO process (without further brine treatment to increase the overall recovery) is not an option, because of the large volume of brine produced as well as the high cost and the environmental risk of storing the brine. For this reason, the application of RO in AMD treatment is applied mainly as a concentration step to allow the precipitation of multivalent ions and further concentration in a multi-stage RO process. This increases the overall recovery of the AMD treatment plant up to the point where the concentration of highly soluble monovalent species, such as sodium and chloride, limits the recovery and is discharged as a final brine stream. Depending on the number and the type of RO units applied, approximately 99% of the AMD can be recovered as desalinated permeate.

Where the monovalent species in the raw water are within the required limits, the treated brine can be blended back with the permeate produced to achieve a zero brine production plant. Based on the water qualities predicted by the short-term study team, this approach would be applicable to the Western and Central Basins. The Eastern Basin would require brine management, as sodium levels in the feed water are higher than the required limits.

A simplified flow diagram of the proposed RO concentration and gypsum precipitation process for the base case scenario is shown in **Figure 6.2** below.

The treated HDS product is fed into the first RO concentration step. Permeate water at low dissolved salt concentration is produced, while the constituents become concentrated and leave the process as a brine stream. The concentrated brine stream is further treated in a gypsum reactor, where the brine stream is dosed with lime in order to precipitate gypsum, which will effectively remove the sulphate from the AMD to the near saturation concentration. This step is followed by clarification to separate the gypsum sludge from the softened water before water is sent to the next RO step.

Any reverse osmosis process will require pre-treatment, which typically consists of pH adjustment of the clarifier overflow, followed by an ultrafiltration step, before concentration in the RO plant. To achieve the required limits and recovery of more than 99%, several such RO-concentration and gypsum-precipitation steps may be required, depending on the monovalent concentration.

The monovalent species concentrations in the raw AMD in the Western and Central Basins are below the required limits for extended periods of time. During such periods, the final RO concentration step would not be required, and the treated brine could be blended with the RO permeate (from previous RO stages) to produce the final product water without negatively affecting the quality.

As the sodium content of the water in the Eastern Basin is higher than the required limits set by SANS 241 (2011), the final RO concentration step is needed to reduce the total brine volume, and thereby increase the total water recovery to over 99%, before discharging the final brine to an evaporation pond.

For effective gypsum precipitation, a design retention time of three to four hours is required. The sizes of the reactors are determined on the basis of the maximum feed flow rates. The major plant parameters for each basin are summarised in **Table 6.7** below.

For the design of the Western and Central Basins, the number of RO concentration and gypsum precipitation stages is determined by the feed water composition, particularly the acidity and sulphate associated with monovalent cations such as sodium. Sulphate associated with monovalent cations will not precipitate in a gypsum reactor; this is the main reason that more gypsum precipitation stages are required for the Western Basin than for the Central Basin.

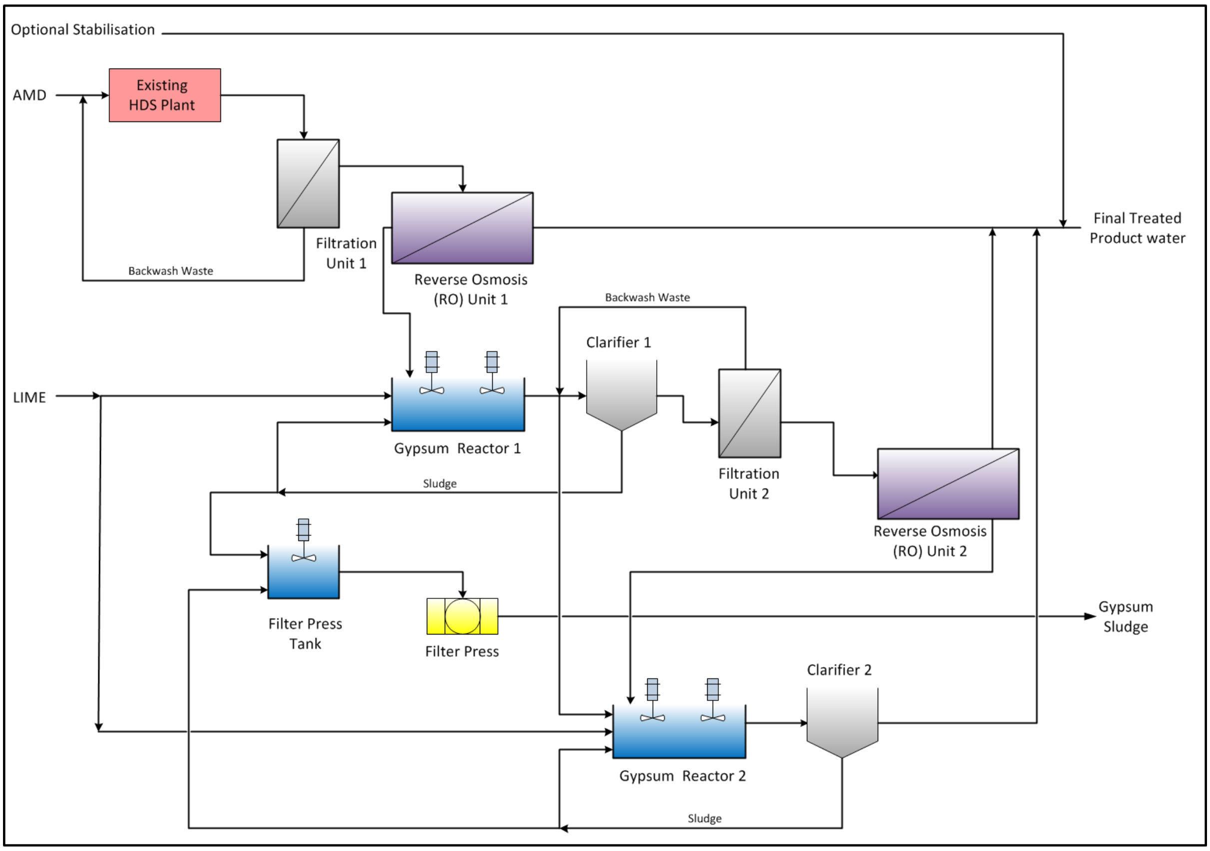

Figure 6.2: **Simplified diagram illustrating the concept of RO concentration and gypsum precipitation**

Table 6.7: Plant design parameters

		Units	Feed water quality at the 95th percentile		
			Western Basin	Central Basin	Eastern Basin
Maximum flow rate		Mℓ/d	40	60	100
No. of gypsum precipitation stages			5	2	2
Gypsum reactor capacities	Reactor 1	m^3	2 100	4 000	4 500
	Reactor 2	m^3	740	1 580	1 520
	Reactor 3	m^3	260		
	Reactor 4	m^3	100		
	Reactor 5	m^3	40		
Recovery (water)		%	99.5%	100%	100%

The required capacities of the gypsum reactors for feed water quality at the 95th percentile are shown in **Table 6.7**. Given the quality of the AMD, only two reactors would be required in the treatment plants for the Central and Eastern Basins, mostly due to higher recoveries through the first RO process step.

For feed water quality at the 50th and 75th percentiles, the same number of reactors would be required for all three basins, although the required reactor capacities might be smaller than for feed water quality at the 95th percentile. The reactor capacities must, however, be designed for feed water quality at the 95th percentile to ensure that the product quality is within specification 95% of the time.

For the Central Basin, the monovalent species in the feed water are within specifications, and recovery of 100% of the water is therefore possible, excluding the losses of water contained in the sludge or filter cake. For the Western and Eastern Basins, the sodium feed water values are slightly higher than the specified product water qualities (227 mg/ℓ for the Western Basin and 264 mg/ℓ for Eastern Basin at the 95th percentile level, compared with the standard of 200 mg/ℓ). In order to eliminate brine disposal and the associated treatment costs, it is proposed that a relaxed standard for sodium should be seriously considered for the Western and Eastern Basins.

The processes involved in the treatment of brine are described in the following sections.

ii. Final Brine Treatment

Final brine treatment or brine storage is required to manage the concentrated stream of mainly monovalent species that cannot be precipitated. The main technologies available for final brine treatment are:

- Evaporation pond;
- Mechanical evaporation and crystallisation; or
- Freeze desalination and crystallisation.

The production of final brine should be avoided as far as possible to minimise the costs, as well as the environmental and legacy risks, associated with brine management.

Evaporation pond

Evaporation ponds are widely used to store and manage brine or other effluent streams that are not viable for further treatment.

The main advantages of evaporation ponds are that the technology is simple and well established and has a low operating cost. The main disadvantages are the high capital costs and environmental risks, and the large areas of land required but not always available.

The applicability of evaporation ponds also depends largely on the local weather conditions, with ponds not considered suitable where the rainfall rate exceeds the evaporation rate of the concentrated brine.

Mechanical evaporation and crystallisation

Mechanical evaporation and crystallisation is also widely used for the treatment of brine. The main advantages of mechanical crystallisation are the small footprint and the fact that a dry salt product is produced, rather than liquid effluent. Moreover, the condensate can be recovered as product water to increase the overall recovery.

The main disadvantages are that the process is energy intensive, with high capital and operating cost, and the final salt has to be disposed of at an additional cost.

Freeze desalination and crystallisation

Freeze desalination is a novel process for the desalination of highly saline waters to produce fresh water and salts. Although there are no full-scale references in South Africa yet, this technology shows promise as an alternative to mechanical evaporation and crystallisation.

This technology is the opposite of evaporation, in that the water is purified by ice formation rather than steam formation. By using this technology, clean water as well as pure salt can be recovered from brine streams, considerably reducing highly saline effluent volumes.

The main advantages of freeze desalination over evaporative crystallisation are the reduced energy demands, reduced corrosion at low operating temperatures, and reduced risk of scaling.

The freeze desalination and crystallisation process can currently only be classified as a laboratory-scale process.

iii. Final brine treatment: Eastern Basin

Final brine treatment or brine storage is required for the Eastern Basin in order to manage the concentrated stream of mainly monovalent species that cannot be precipitated. The main technologies available for final brine treatment are:

- Evaporation pond, which is widely applied; has low operating costs; and was selected for base case evaluations; and
- Mechanical evaporation and crystallisation, which is widely applied; has higher operating costs; and storage of the final salt is required.

Evaporation ponds are widely used to store and manage brine or other effluent streams that are not viable for further treatment. The main advantages of evaporation ponds are that the technology is simple and well established, and operating costs are low. The main disadvantages, however, are the high capital costs, environmental risk, and the large areas of land required but not always available.

b) Estimated Product Water Quality

Table 6.8 below shows the estimated product water qualities for feed water quality at the 95th percentile, compared to the water quality standards for potable water, according to SANS-241 (2011).

Table 6.8: Estimated product water qualities for feed water quality at the 95th percentile, compared to the water quality standards for potable water

Water quality parameters	Units	SANS-241 (2011)	Product water composition for feed water quality at the 95th percentile		
			Western Basin	Central Basin	Eastern Basin
TDS	mg/ℓ	1 200	572	1 004	933
EC	mS/m	170	94	166	154
Ca	mg/ℓ		503	143	80
Mg	mg/ℓ		0	2	2
Na	mg/ℓ	200	142	170	261
SO_4	mg/ℓ	250 (WB&CB) 350 (EB)	246	184	339
Cl	mg/ℓ	300	41	145	251
pH		5.0–9.7	7.0	7.0	7.0
Alkalinity	mg/ℓ as $CaCO_3$		10	10	10
Acidity	mg/ℓ as $CaCO_3$		0	0	0
Fe	mg/ℓ	0.3	0.3	0.3	0.3
Al	mg/ℓ	0.3	0.3	0.3	0.3
Mn	mg/ℓ	0.1	0.1	0.1	0.1
U	mg/ℓ	0.015	0.01-0.1	0.01-0.1	0.01-0.1

Table 6.9 below shows the estimated product water qualities for feed water at the 50th and 75th percentiles, compared to the required water quality objectives for potable water, according to SANS-241 (2011).

Table 6.9: Estimated product water qualities for feed water quality at the 50th and 75th percentiles, compared to the water quality standards for potable water

Water quality parameters	Units	SANS-241 (2011)	Product water composition for feed water quality at the 50th percentile			Product water composition for feed water quality at the 75th percentile		
			Western Basin	Central Basin	Eastern Basin	Western Basin	Central Basin	Eastern Basin
TDS	mg/ℓ	1 200	673	458	731	779	567	820
EC	mS/m	170	111	76	121	128	94	135
Ca	mg/ℓ		274.9	13.6	24.8	320	42.1	80.1
Mg	mg/ℓ		2.6	1.2	1.2	5	1.5	1.8
Na	mg/ℓ	200	100	120.4	205.9	123	166.9	234.9
SO_4	mg/ℓ	250 (WB&CB) 350 (EB)	221.0	187.6	343.3	250	217.1	321.4
Cl	mg/ℓ	300	64.5	135.2	155.4	41	139.2	181.6
pH		5.0–9.7	7.0	7.0	7.0	7.0	7.0	7.0
Alkalinity	mg/ℓ as $CaCO_3$		10	10	10	10	10	10
Acidity	mg/ℓ as $CaCO_3$		0	0	0	0	0	0
Fe	mg/ℓ	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Al	mg/ℓ	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Mn	mg/ℓ	0.1	0.1	0.1	0.1	0.1	0.1	0.1
U	mg/ℓ	0.015	0.01-0.1	N/A	N/A	0.01-0.1	0.01-0.1	0.01-0.1

Although the water quality might meet the SANS-241 specification in respect of the sulphate concentration, this concentration would be higher than the sulphate concentration in the water that Rand Water has been supplying to potential users of purified AMD for many years. The differences would be noticeable and might require adjustments by consumers or careful blending by suppliers.

In Tables 6.8 and 6.9 above, it has been assumed that the brine from the RO process will be blended back with the treated water, which still produces product water quality that complies with SANS 241 standards. An alternative would be to dispose of the brine off site, which will deliver water wherein the TDS content is only between 2 – 4 % of the input TDS. The water delivered as a result of this (Table 6.10 below) will comply with Rand Water's limits.

Table 6.10: Expected TDS in RO product water if no brine is blended back

		Western Basin		Central Basin		Eastern Basin	
		50th %	95th %	50th %	95th %	50th %	95th %
Raw AMD TDS		4 313	5 388	4 363	5 118	2 292	3 358
Product TDS:	2%	86	119	87	102	46	67
	4%	173	237	175	205	92	134

Further treatment may be required to attain Sasol's water quality standards for cooling water purposes, but it will definitely be required if used for boiler feed water.

c) Estimated Quality and Quantities of the Waste Products Produced by the RO Process Step only

The desalination of the neutralised AMD will produce the following waste products:

- Sludge, in the form of dewatered gypsum; and
- Brine, in cases where the treated water specifications cannot be met as a result of the concentrations of the monovalent ions (sodium and chloride) exceeding the required standards.

The quantities of waste to be produced are calculated in the sections below. It should be taken into account that the RO process requires mandatory pre-treatment of the AMD. For the purposes of this report it was assumed that a limestone pre-neutralised and a HDS process were used for pretreatment. Estimations of the quantity of final waste products produced by the RO process must also include the volumes of waste products produced by the pre-treatment process (HDS).

Two types of sludge are produced in a reverse osmosis AMD treatment plant. The first is HDS sludge, as discussed in section 6.2.1. The second is gypsum sludge, which is produced in each of the gypsum precipitation steps. A portion of the gypsum could possibly be offset into the market at no cost to the client. This sludge is not hazardous and could possibly also be discharged on to nearby tailings dams. Alternatively, sludge storage facilities would have to be constructed in order to manage the sludge produced.

The estimated sludge production volumes and composition for feed water quality at the 95th percentile, produced by the RO process step only, are shown for each basin in **Table 6.11**.

Table 6.11: Estimated sludge production and composition for feed water quality at the 95th percentile produced by the RO process step only

Precipitate (dry basis)	**Units**	**Sludge composition for feed water quality at the 95th percentile**		
		Western Basin	**Central Basin**	**Eastern Basin**
$Fe(OH)_2$	%	0%	0%	0%
$Al(OH)_3$	%	0%	0%	0%
$Mn(OH)_2$	%	0%	0%	0%
CaF_2	%	0%	0%	0%
$Ca_3(PO_4)_2$	%	0%	0%	0%
$Mg(OH)_2$	%	2%	17%	13%
$CaCO_3$	%	1%	0%	0%
$CaSO_4$	%	97%	83%	87%

Precipitate (dry basis)	**Units**	**Sludge composition for feed water quality at the 95th percentile**		
		Western Basin	**Central Basin**	**Eastern Basin**
Total sludge (dry)	t/d	40.8	163.7	242.7
Total sludge (filter cake) 65% solids	t/d	62.8	251.9	373.3
	m^3/d	39.2	157.4	233.3
Total sludge (slurry) 10% solids	t/d	408.1	1 637.2	2 426.5
	m^3/d	371.0	1 488.4	2 205.9

The estimated sludge production volumes and composition for feed water quality at the 50th and 75th percentiles, produced by the RO process step only, are shown for each basin in **Table 6.12** below.

Table 6.12: Estimated sludge production and composition for feed water quality at the 50th and 75th percentiles produced by the RO process step only

Precipitate (dry basis)	**Units**	**Sludge composition for feed water quality at the 50th percentile**			**Sludge composition for feed water quality at the 75th percentile**		
		Western Basin	**Central Basin**	**Eastern Basin**	**Western Basin**	**Central Basin**	**Eastern Basin**
$Fe(OH)_2$	%	0%	0%	0%	0%	0%	0%
$Al(OH)_3$	%	0%	0%	0%	0%	0%	0%
$Mn(OH)_2$	%	0%	0%	0%	0%	0%	0%
CaF_2	%	0%	0%	0%	0%	0%	0%
$Ca_3(PO_4)_2$	%	0%	0%	0%	0%	0%	0%
$Mg(OH)_2$	%	7%	11%	10%	2%	13%	14%
$CaCO_3$	%	0%	0%	2%	0%	0%	0%
$CaSO_4$	%	92%	89%	88%	98%	87%	86%
Total sludge (dry)	t/d	55.0	173.9	102.2	44.7	170.0	164.1
Total sludge (filter cake) 65% solids	t/d	84.6	267.5	157.2	68.8	261.6	252.5
	m^3/d	52.9	167.2	98.3	43.0	163.5	157.8
Total sludge (slurry) 10% solids	t/d	550.2	1 739.0	1 022.0	446.9	1 700.4	1 641.0
	m^3/d	500.2	1 580.9	929.1	406.3	1 545.8	1 491.8

The final handling and disposal of sludge is a high risk to the project and should be further investigated in the pre-feasibility phase. The following options could be considered:

- Disposal of HDS sludge to existing tailings facilities;
- Construction of a lined waste disposal facility to discharge and store HDS sludge; or
- Placement of gypsum sludge into the market as a by-product.

d) Chemical and Utility Requirements of the RO process step only

i. Chemical Consumption

The estimated chemical consumption for feed water quality at the 95th percentile is summarised in **Table 6.13** below.

Table 6.13: Estimated chemical consumption for feed water quality at the 95th percentile

Chemical	Unit	Chemical consumption for feed water quality at the 95th percentile		
		Western Basin	Central Basin	Eastern Basin
Sulphuric acid	Tons/month	12.2	24.5	34.5
Coagulant	Tons/month	1.9	4.3	5.3
Disinfectant	Tons/month	11.3	21.5	37.0
Caustic soda	Tons/month	7.3	6.0	5.7
SMBS	Tons/month	12.4	26.1	36.9
Anti-scalant	Tons/month	10.9	27.1	22.7
Lime	Tons/month	418.9	1 098.5	1 473.8

The estimated chemical consumption for feed water quality at the 50th and 75th percentiles is summarised in **Table 6.14** below.

Table 6.14: Estimated chemical consumption for feed water quality at the 50th and 75th percentiles

Chemical	Unit	Chemical consumption for feed water quality at the 50th percentile			Chemical consumption for feed water quality at the 75th percentile		
		Western Basin	Central Basin	Eastern Basin	Western Basin	Central Basin	Eastern Basin
Sulphuric acid	Tons/month	10.9	21.8	31.4	10.7	22.3	32.7
Coagulant	Tons/month	1.7	3.4	4.1	1.6	3.6	4.6
Disinfectant	Tons/month	11.0	21.6	37.1	11.0	21.5	37.1
Caustic soda	Tons/month	5.0	6.0	5.7	5.0	6.0	5.7
SMBS	Tons/month	11.1	23.1	33.5	11.0	23.6	34.9
Anti-scalant	Tons/month	9.2	19.6	14.3	9.0	20.2	15.8
Lime	Tons/month	286.9	841.0	1 436.7	313.7	888.0	1 454.3

ii. Electricity Consumption

Table 6.15 shows the estimated required electrical installation and consumption for the selected base case process.

Table 6.15: Estimated electricity consumption

Electricity requirement	Units	Electricity requirement - TCTA Water Quality 95th percentile			Electricity requirement - New Feed Water Quality		
		Western Basin	Central Basin	Eastern Basin	Western Basin	Central Basin	Eastern Basin
kW Installed	kW	4 200	5 400	9 400	4 430	2 760	5 700
kW Absorbed	kW	3 400	4 275	7 500	3 540	2 205	4 560
kW/m^3 treated AMD	kW/m^3	3	1.8	2.2	2.75	1.4	1.3
R/m^3 treated AMD	R/m^3	2.25	1.35	1.65	2.05	1.1	1.0

iii. Conceptual Cost Indication

Capital cost indication

The capital cost estimates for the base case scenarios for the Western, Central and Eastern Basins are summarised in **Table 6.16** below. The capital costs are based on feed water quality at the 95th percentile, similar to the approach for process and equipment design.

Table 6.16: Capital cost estimate for feed water quality at the 95th percentile

Electricity requirement	Units	Capital cost estimate for feed water quality at the 95th percentile		
		Western Basin	Central Basin	Eastern Basin
Capacity	Mℓ/d	40	60	100
Hardware	R million	R129.4	R141.9	R252.8
Civil works	R million	R72.3	R91.0	R120.5
Mechanical works	R million	R49.2	R63.8	R103.6
Electrical control and instrumentation works	R million	R25.3	R56.7	R91.0
Engineering, project management, preliminary and general costs	R million	R11.3	R28.4	R37.9
Total CAPEX	R million	R287.5	R381.8	R605.8
R/Mℓ installed	R million	R7.2	R6.4	R6.1

Note: Excludes waste disposal and upstream limestone and HDS process.

Operating cost indication

Table 6.17 summarises the estimated operating costs for the Western, Central and Eastern basins for the 95th percentile values of the different feed water specifications.

Table 6.17: Operating cost summary for feed water quality at the 95th percentile

Description	Unit	Operating cost for feed water quality at the 95th percentile		
		Western Basin	Central Basin	Eastern Basin
Chemicals and consumables	R million/year	R31.412	R56.655	R63.309
Membrane replacement	R million/year	R5.034	R6 935	R13.214
Electricity	R million/year	R17.210	R18.469	R30.660
Operational personnel	R million/year	R9.360	R9.547	R12.480
Maintenance provision	R million/year	R5.750	R7.636	R12.116
Total annual operating cost	R million/year	R68.766	R99.242	R131.780
Operating cost	R/kℓ treated	R8.19	R5.91	R4.51

Note: Excludes waste disposal and upstream limestone and HDS process.

The operating costs for feed water quality at the 50th and 75th percentiles are shown in **Table 6.17**.

Table 6.18: Operating cost summary for feed water quality the 50th and 75th percentiles

Description	Unit	Operating cost for feed water quality at the 50th percentile			Operating cost for feed water quality at the 75th percentile		
		Western Basin	Central Basin	Eastern Basin	Western Basin	Central Basin	Eastern Basin
Chemicals and consumables	R million/year	R19.763	R54.104	R57.089	R23.682	R55.459	R58.921
Membrane replacement	R million/year	R5.034	R6.935	R13.214	R5.034	R6.935	R13.214
Electricity	R million/year	R17.210	R18.469	R30.660	R17.210	R18.469	R30.660
Operational personnel	R million/year	R9.360	R9.505	R12.480	R9.360	R9.550	R12.480
Maintenance provision	R million/year	R5.750	R7.636	R12.116	R5.750	R7.636	R12.116
Total annual operating cost	R million/year	R57.116	R96.691	R125.559	R61.036	R98.046	R127.391
Operating cost	R/kℓ treated	R6.80	R5.76	R4.30	R 7.27	R 5.84	R 4.36

e) Advantages

The advantages of the multi-stage RO process are considered to be the following:

- The quality of the treated water can meet all specifications that are laid down;
- The process has been used in large installations in South Africa and abroad;
- It is the only process that has been installed at the scale required for the treatment of AMD in the Witwatersrand;

- The process dynamics are well understood, and the associated risks are therefore understood;
- The process is relatively simple to operate, compared to some of the alternative processes; and
- The capacity of the RO treatment plant can be increased modularly.

f) Disadvantages

The disadvantages of the multi-stage RO process are as follows:

- Due to the required HDS pre-treatment, the process produces large quantities of sludge in terms of both mass and volume; large tailings storage facilities or dedicated sludge disposal ponds will therefore be required;
- The process uses large quantities of lime; and
- The process is energy intensive.

6.3.2 Desalination by Alternative Reverse Osmosis

An alternative to the classical RO process was presented by MiWaTek. The technology stakeholder is maintaining the process parameters as intellectual property, and only limited details were therefore made available.

It is the policy of the supplier that they would provide and operate the works (build, own, operate) for a period of ten years. Payment for the services would be at a rate per volume of treated water. MiWaTek would assume the risk of providing the capital required for the works (with a portion of the investment provided by Fraser Alexander).

a) Description of the Process

The alternative RO process, as envisaged and tested at limited scale by MiWaTek, is similar to the classical RO process. Two variations have been proposed by MiWaTek: in the first case the RO desalination process receives AMD direct from underground without pre-treatment, and in the second case pre-treatment is provided for metals reduction by dosing with hydrogen peroxide or other oxidants at a low pH. In this way, metal hydroxides are produced with very little gypsum to contaminate the metal sludge, and the resultant sludge can consequently be used in the production of iron and steel. A simplified diagram illustrating the second process is shown in **Figure 6.3** below. It is therefore important to note that no pre-treatment processes, such as the neutralisation of acid or the removal of iron and manganese, are required.

The process configuration is relatively flexible, as the metals do not necessarily have to be removed before processing in the primary RO unit. The membranes that are selected for the process are reportedly able to operate under the envisaged conditions of low pH, and elevated metal concentrations and salinity. This aspect has been proven in South America, where the membranes are used in the recovery of copper and other metals.

Following processing in the primary RO unit, gypsum is precipitated, and uranium and silica (SiO_2) are removed in separate processes. The gypsum formed is of a relatively pure nature, and MiWaTek claims that there is currently a market for the product, although the details have not yet been made available. Such a market could apply to gypsum produced through other technologies if they are proven to be viable and sustainable.

It is also stated that there appears to be a market for the metal oxides that are produced in the process, which would again be of great advantage in that the wastes to be disposed would be reduced. However, again the details have not been made available. Such a market could apply to metal oxides produced through other technologies, if they are proven to be viable and sustainable.

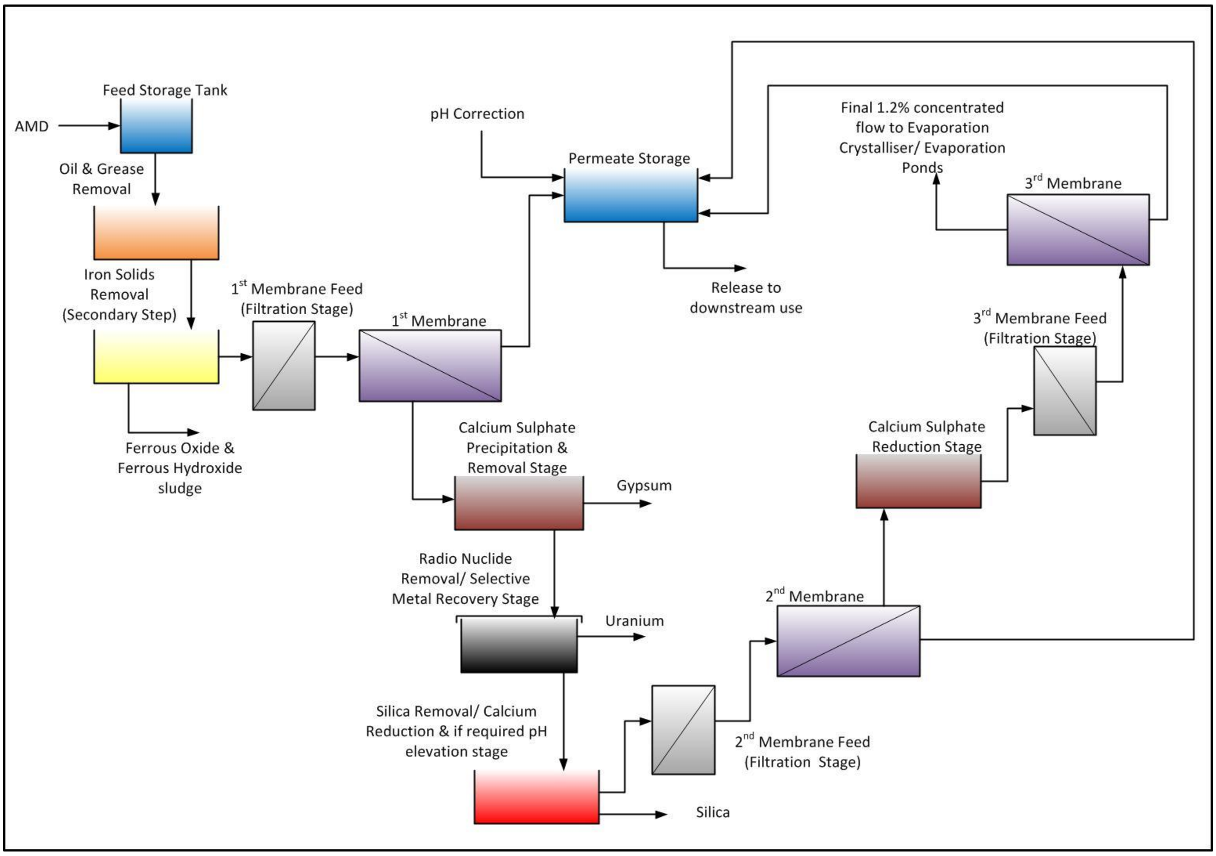

Figure 6.3*:* Simplified diagram of concentration and gypsum precipitation in the alternative RO process

The uranium that is produced would be disposed of in the manner prescribed by the relevant authorities. This would probably apply only in the Western Basin, as the presence of uranium has not been demonstrated in the AMD from the Central and Eastern Basins.

It is claimed that the process can be operated so as to produce brine only in cases where the concentration of monovalent ions exceeds the RWQOs. The volume of brine produced in such cases is expected to be limited, and could be disposed of in engineered evaporation ponds, or alternatively high-technology solutions could be implemented, if required.

The plants are currently conceptually designed in modules that can treat a flow of 100 ℓ/second, equating to 8.6 Mℓ/d, although no full-scale plant has been constructed to date, and design information and detailed costing information have not been made available.

b) Target Quality of Treated Water

The quality of the treated water is claimed to meet all specifications due to the nature of the process, which allows flexibility in the engineering; however, no performance data for the pilot plant have been made available.

c) Estimated Quality and Quantities of the Waste Products Produced through the Process

The quantities of sludge are not known at this stage, as the process is still in the development stage. Information is awaited from the supplier of the technology.

d) Estimated Cost

MiWaTek estimates the cost of treating the AMD, on the basis of a plant treating 8.6 Mℓ/d, at between R9.50 and R11.00 per kilolitre, with an initial capital contribution of R36 million for the former unit cost, or R18 million for the latter unit cost. These costs are for treating the AMD only, without allowance for the disposal of brine or sludge. Revenue from the sale of residual products produced in the process have also not been taken into account.

e) Advantages

The following advantages are claimed for this process:

- The quality of the treated water can meet all specifications laid down, although this has not been proven.
- The waste produced through the process is relatively easy to handle because:
  - The gypsum is of a relatively high quality; and
  - The metals produced are mainly in oxide and hydroxide form, and dewatering of the sludge is thus more easily achieved.
- A possible market for the residual products exists, which would reduce the disposal requirements, although this has not been demonstrated. It is, however, envisaged that the metal hydroxides could be beneficially re-used through reduction in a smelter to form metals. This complies with the National Waste Management Strategy to avoid the generation of waste products. At worst, the various by-product streams might need to be temporarily stored, which would constitute the prevention step in the waste management hierarchy.
- The volume of waste is significantly reduced, compared with the conventional RO process after HDS pre-treatment, because smaller quantities of chemicals such as limestone and lime are used, and the metal hydroxides are not mixed with the gypsum formed in the process of neutralising the acid in the AMD and raising the pH to enable

oxidation of the metals with oxygen. This is regarded as the reduction step with respect to manufacturing waste in terms of the waste management hierarchy.

- The process appears to be flexible. If the oxidation of the metals does not function as expected, then the process could revert to conventional RO with HDS pre-treatment.
- The system does not require an excessive footprint, as it does not require extensive HDS pre-treatment and sludge handling.
- The system lends itself to decentralised installations, which could offer opportunities for optimising the quality of AMD withdrawn directly from the various voids.
- A comparable process has apparently been used in Chile in the recovery of copper from mine process water, but not in South Africa. It must be emphasised, however, that no real data on the alternative RO application has been made available.

f) Disadvantages

The disadvantages of the process are considered to be the following:

- Although RO has been used in large-scale applications, this particular alternative RO process has only been demonstrated at pilot-plant scale;
- The fact that the technology stakeholders keep the intellectual property secret, and therefore do not want to alienate the plant, is a risk to the process. It would be difficult to implement mitigation measures in the event of failure;
- The removal of iron with peroxide is a well-known process, but not the removal of aluminium and manganese. There is still doubt whether the process will be able to remove all metals. The fact that the membrane systems are not designed to deal with high metal concentrations poses a great risk, in that the membranes might scale instantly with a resultant significant decrease in the plant’s capacity; and
- Due to the secrecy of the intellectual property, the full risks associated with the process cannot be assessed and evaluated.

6.3.3 Desalination by Electrocoagulation (P2W)

The electrocoagulation process was presented by P2W (Pollution to Water), an Israeli company. P2W has formed an association with the South African company, Tecroveer. The technology stakeholder did not divulge any specific details of the technology. The following description is based on what was gathered in discussions during a visit to the pilot plant at No. 8 Shaft in the Western Basin.

Detailed information about the process was requested, but not obtained.

P2W has apparently used a comparable process for treating water contaminated with metals and cyanide elsewhere, but not in South Africa.

a) Description of the Process

The treated effluent from the HDS plants is pumped to the electrocoagulation units, followed by dosing with various coagulants and flocculants. The process dissolves the electrodes, which consequently have to be replaced at regular intervals. The metal ions originating from the electrodes will form complexes with the sulphate, which coagulate and can be settled out in a clarifier.

The concentration of sulphate can be reduced to the order of 300 to 600 mg/ℓ of SO_4, which does not comply with the specifications for potable water as required in the final effluent of the works.

The power consumption of the works is approximately 1 kWh/kℓ of treated water.

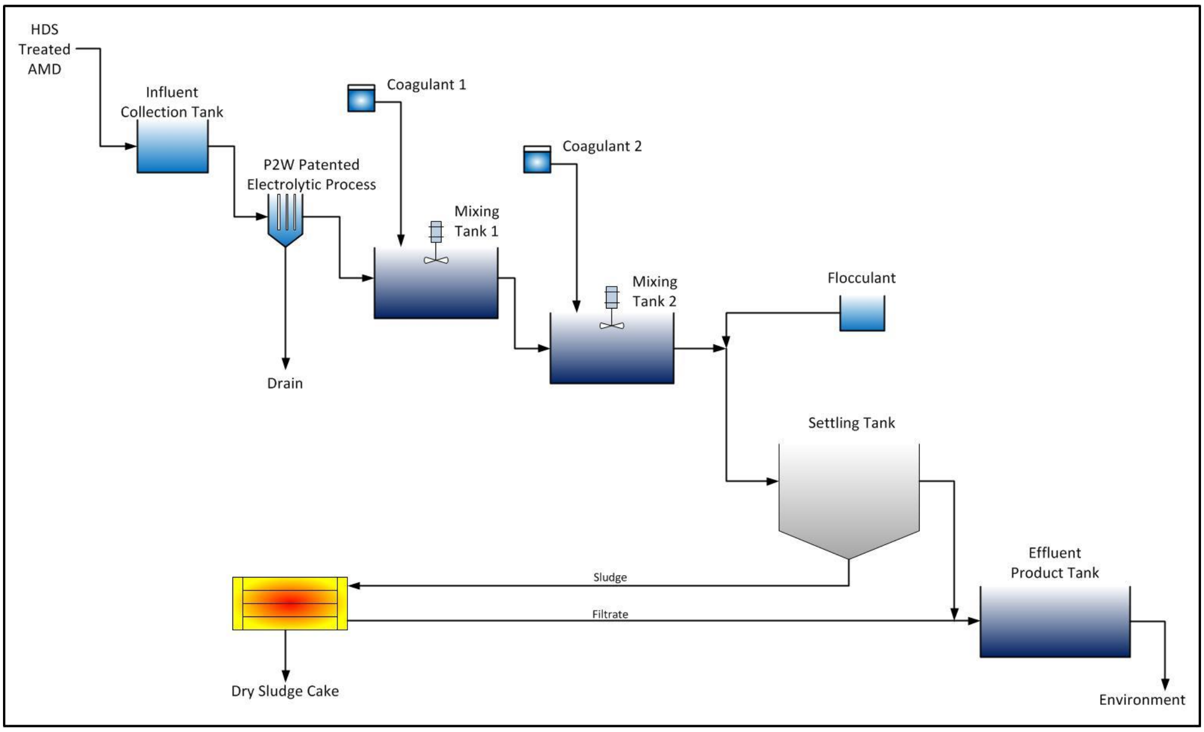

Figure 6.4: Simplified diagram of the electrocoagulation process and gypsum precipitation

b) Target Quality of Treated Water

No data on the treated effluent quality have been received thus far, and it is thus difficult to comment on the process.

The quality of the water would not meet the SANS-241 (2011) requirements, because the sulphate concentration cannot be reduced to the required levels.

The process is also not expected to improve the quality of the water in respect of the monovalent ions in the AMD.

c) Estimated Quality and Quantities of the waste products produced through the process

No information has yet been received regarding the sludge produced downstream of the HDS works.

d) Advantages

The advantages claimed for the process are considered to be the following:

- The footprint of the process appears to be relatively small;
- The chemicals that are used are not hazardous to handle; and
- The system can be designed in a modular fashion.

e) Disadvantages

The disadvantages of the process are considered to be the following:

- The process has only been demonstrated in a pilot plant in South Africa; no full-scale processes have thus far been constructed in South Africa;
- The process is dependent on the supply of metal electrodes, which are used consumptively. The composition of these electrodes constitutes part of the intellectual property of the company and was not disclosed;
- The process requires the pre-treatment of the AMD by means of the HDS process, which would result in the production of large quantities of waste sludge;
- As far as could be ascertained, the process is very sensitive to the pH at which the electrocoagulation takes place, and skilled and diligent operators would therefore be required; and
- The process is energy intensive.

6.3.4 Desalination by Electrocoagulation

The 1 Source Group presented information about electrocoagulation technology that they had obtained in the United Kingdom (UK). It is stated in the information that was made available that more than 60 installations using this technology exist in the UK, Europe and Canada.

Unfortunately the information supplied included only general information, and no details of specific applications were available in time for inclusion in this report. It is therefore not possible to evaluate the process in detail.

From the information supplied, it appears that the process would entail the AMD being treated directly as it is pumped from the mine void. No pH adjustments would be made. After a residence time of four minutes in the reactor, the iron would apparently be oxidised and would settle out, presumably as a metal hydroxide. It is not clear whether the process is aimed at removing sulphate, as nothing has been reported in this regard. If not, then this process would have to be followed by a process to reduce the sulphate concentrations to the specified limits. This additional process would generate large quantities of gypsum through the various chemical processes that form gypsum. Similar previous test work and applications show that this process is insufficient for treating non-neutralised AMD due to passivation and scaling of the electrodes by the iron hydroxide formed during the process.

Unfortunately, detailed information on the tests conducted in South Africa is unavailable, which makes it impossible to comment any further.

6.3.5 Desalination by Electroprecipitation and coagulation

BlueGold, in association with New World Sanitation & Solar Solutions (NWSSS), presented information based on electroprecipitation and electrocoagulation. According to the information supplied, this process has been applied in the recovery of precious metals, and it is believed that the technology could also be used successfully to treat AMD. The process is still viewed as pilot scale in respect of the treatment of AMD.

As far as the technology is understood, pre-treatment through the HDS process would be required prior to electroprecipitation and electrocoagulation. It is stated that the process could be modified to achieve the SANS-241 (2011) standard for potable water. It is not clear whether the process would remove any of the monovalent ions such as sodium and chloride.

The units are constructed in modular design, each treating 170 kℓ/hr, or approximately 4 Mℓ/d based on 24-hour operation.

BlueGold stated that the OPEX for treating the effluent from the HDS process amounts to R4.42/kℓ. These costs do not include HDS pre-treatment or disposal of the waste sludge.

The company envisages providing a pilot plant to prove the efficiency and suitability of this technology for treating AMD.

6.4 Chemical Processes

Chemical processes are those where the sulphate is removed predominantly through chemical processes. Thus far, only two such processes have been identified, namely:

- Alkali-Barium-Calcium (ABC) process; and
- Ettringite precipitation process.

These processes are discussed in detail in the following sections.

6.4.1 Alkali-Barium-Calcium Process

The ABC process is a chemical process in which sulphate is removed from AMD by means of chemical precipitation. Cations such as metals are allowed to react with soluble sulphate to form sulphate compounds, which are sparsely soluble in water and can therefore be removed from the water. As the solubility levels of these sulphate compounds are lower than the required specifications, it is claimed that the treated AMD meets the specifications.

The ABC process has been tested in limited pilot plants, but to the knowledge of the study team, the complete process train, which comprises a number of unit processes, has not undergone practical testing as a functional unit.

a) Description of the Process

The ABC process utilises the low solubility of barium sulphate, compared to gypsum (calcium sulphate), to reduce the sulphate concentration through precipitation to below 200 mg/ℓ. The level of 200 mg/ℓ of sulphate is arbitrarily selected to ensure that no barium carbonate remains in the treated water, as soluble barium salts are very poisonous substances. **Figure 6.5** shows a simplified diagram illustrating the ABC process:

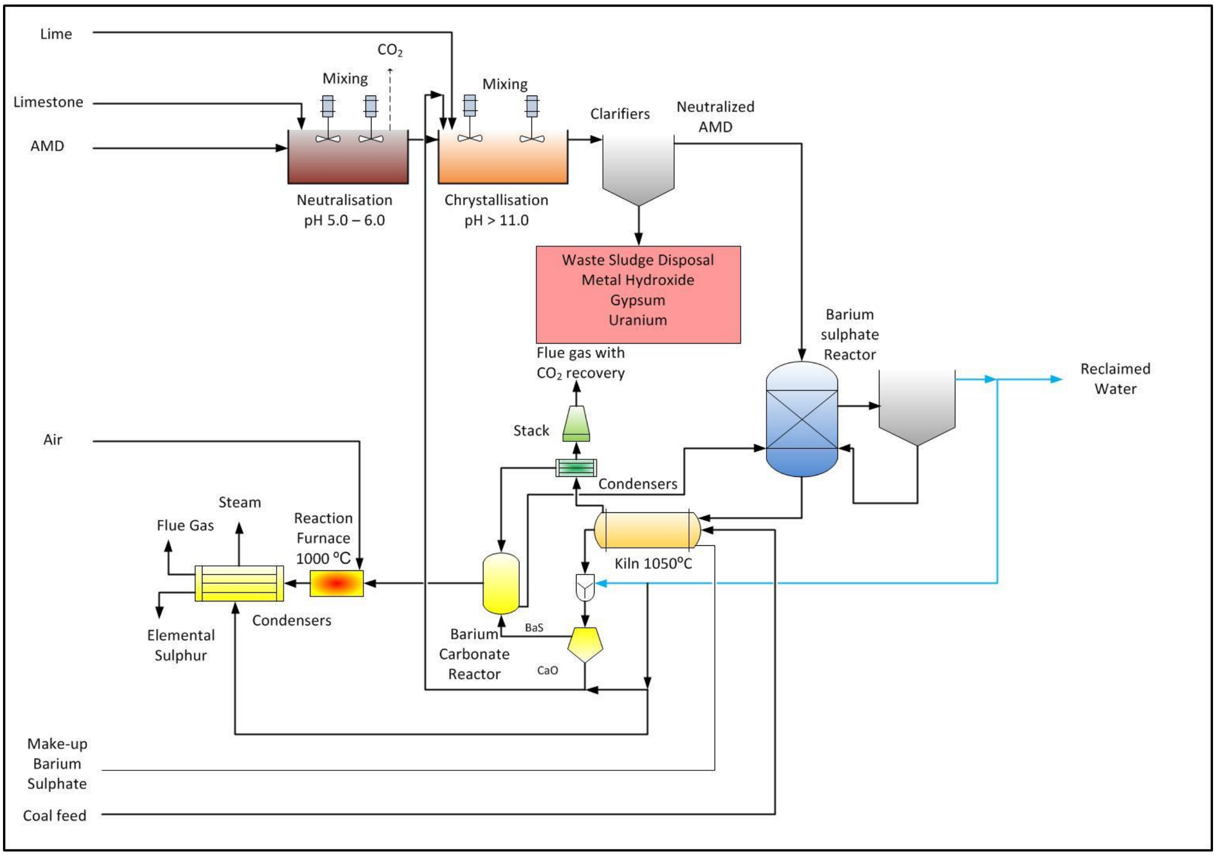

Figure 6.5: Simplified diagram of the ABC process

This integrated process consists of the following process units:

- AMD neutralisation as part of the HDS process;
- Sulphate precipitation as gypsum ($CaSO_4$) as part of the HDS process;
- Sulphate precipitation as barite ($BaSO_4$);
- Post-treatment of AMD (filtration and disinfection);
- Recovery of $BaCO_3$ and $Ca(OH)_2$ from the sludge; and
- Elemental sulphur production.

The following paragraphs discuss each of these process units in more detail.

i. AMD neutralisation

The pre-treatment step for the ABC process is the neutralisation of acid mine waters, as provided in the limestone pre-neutralisation and HDS-process. Neutralisation of the acidic water with limestone ($CaCO_3$) is proposed, thereby increasing the pH to 5.5 – 6.5. This neutralisation process is similar to the recommended pre-neutralisation step in the proposed STI.

ii. Sulphate Precipitation as Gypsum ($CaSO_4$)

The pre-neutralised water is routed to gypsum reactors where lime is added to increase the pH to 11.5. This high pH is required for magnesium removal in the form of magnesium hydroxide ($Mg(OH)_2$). This step also precipitates the sulphate associated with magnesium as gypsum. A reaction time of two to three hours is required for effective gypsum precipitation. The lime dosed in this step is the recovered and recycled product from the barium sulphate sludge processing steps.

From the reactors, the slurry is routed to a clarifier where the sludge is abstracted. The sludge consists mainly of gypsum and metal hydroxides, which are disposed of as a waste sludge.

This gypsum precipitation step differs from that in the proposed STI process, in that the pH is increased to 11.5, compared to 9.5 in the STI process. The residual sulphate requirement for the STI is 2 500 mg/ℓ. The increased pH will result in higher chemical usage, and will inevitably result in increased production of sludge. It is envisaged that the HDS equipment of the STI could be modified to accommodate the higher pH requirement. This high-lime treatment process step is routinely used in AMD treatment, and several references exist in South Africa.

iii. Sulphate Precipitation as Barite ($BaSO_4$)

The overflow from the gypsum clarifier is reduced from 11.5 to 9.0 through CO_2 dissolution before pumped to barium reactors. The CO_2 is collected from the thermal recovery unit (TRU) of the barium sludge processing plant.

In the barium reactors, barium carbonate ($BaCO_3$) is dosed to precipitate the remaining calcium and sulphate as calcium carbonate ($CaCO_3$) and barite ($BaSO_4$). A reaction time of one hour is recommended. The water is clarified and the sludge is processed to recover the $BaCO_3$, which is a costly raw material.

This section of the plant is novel, and no large-scale installation currently exists. The Western Utilities Corporation (WUC), together with the Council for Scientific and Industrial Research (CSIR), has conducted pilot-scale work on this process for treating AMD. This work has been followed up with more pilot work in two pilot plants at the Tshwane University of Technology. The eventual proposal was for a reactor of the continuous stirred-tank type

(CSTR), due to its ease of upscaling and proven consistency with respect to accurately predicting results on the pilot scale based on laboratory-scale simulations.

iv. Post-treatment of the treated AMD

If the treated AMD is intended for human consumption, the water has to be filtered and disinfected.

v. Recovery of $BaCO_3$ and $Ca(OH)_2$ from the Sludge

To make the ABC process economically feasible, the barium and calcium have to be recovered for re-use in the precipitation units. Several sludge processing steps are required, including thermal recovery at high temperatures.

A simplified diagram illustrating the operation of the thermal recovery unit is shown in **Figure 6.6**.

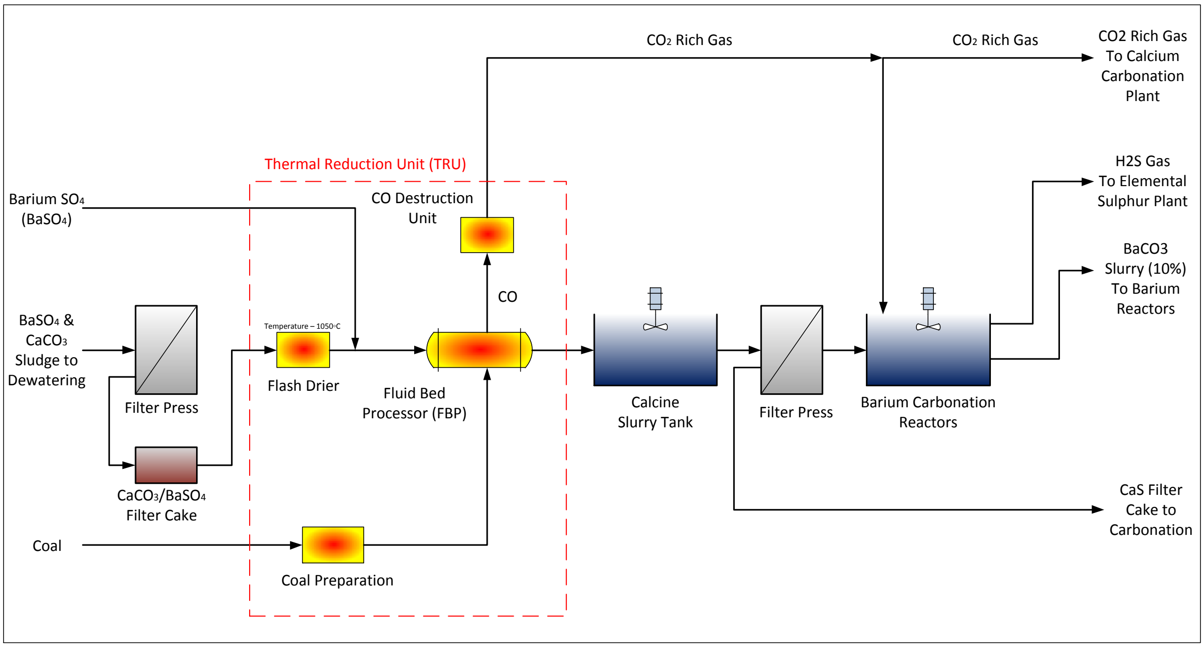

Figure 6.6: Simplified diagram of the thermal recovery unit (TRU)

The sludge from the barite clarifier is dewatered in a filter press and routed to the TRU in which the sludge is dried and converted in a fluid bed reactor (FBR) to barium sulphide (BaS) and calcium oxide (CaO).

Purchased barium sulphate is added before the FBR step to compensate for barium losses in the process.

After processing in the TRU, the BaS and CaO are slurried with water, as BaS is highly soluble and dissolves completely. The CaO is hydrated to form $Ca(OH)_2$, which stays in precipitated form and can be separated in a filter press.

The BaS-containing filtrate is reacted with CO_2 to form $BaCO_3$ and hydrogen sulphide (H_2S) gas. The H_2S gas is collected and sent to the elemental sulphur plant, and the $BaCO_3$ is routed to the barite precipitation reactors. This recovery of barium is essential, and the efficiency with which this is done determines the economic viability of the process.

vi. Elemental Sulphur Production

The processes described above produce H_2S, a very poisonous, corrosive and flammable gas; further treatment is required to stabilise the sulphide.

H_2S reacts with metals to form metal sulphide, which happen to be the precursor to the AMD problem. Metal sulphides, in the presence of oxygen and water, will again form sulphate to repeat the AMD cycle. Having the H_2S react with metals is thus not an acceptable process for the stabilisation of the sulphides in the long term, and other processes will have to be implemented.

Sulphide gases are instrumental in the production of concentrated sulphuric acid and elemental sulphur. Both products have a potential market value, but the processes to produce the products are complicated and constitute a high risk. The processes take place at extreme temperatures of over 1 000ºC. Furthermore, the gases are extremely corrosive and toxic, while some are explosive.

The process to produce elemental sulphur from the recovered H_2S gases formed during carbonation reactions is briefly described below to illustrate the complications.

The Claus process is proposed by the WUC as part of their solution to the AMD problem. The Clause process is reportedly the most widely used gas desulphurisation process worldwide. The Claus process can be divided into two steps, namely thermal and catalytic.

Thermal step

In the thermal step, H_2S-laden gas reacts in a sub-stoichiometric combustion at temperatures above 850°C, such that elemental sulphur precipitates in the downstream process gas cooler. The H_2S gas is burned in the following chemical reaction:

Reaction 9 $10H_2S + 5O_2 \rightarrow 2H_2S + SO_2 + 3.5S_2 + 8H_2O$

This equation shows that in the thermal step alone, two-thirds of the hydrogen sulphide is converted to sulphur. Usually, 60 – 70% of the total amount of elemental sulphur produced in the process is obtained in the thermal process step. The sulphur forms in the thermal phase as highly reactive S_2 di-radicals, which combine exclusively to the S_8 allotrope:

Reaction 10 $4S_2 \rightarrow S_8$

Catalytic step

The Claus reaction continues in the catalytic step with activated aluminium(III) or titanium(IV) oxide, and serves to boost the sulphur yield. More hydrogen sulphide (H_2S) reacts with the sulphur dioxide (SO_2) formed during combustion in the reaction furnace in the Claus reaction, resulting in the formation of gaseous elemental sulphur:

Reaction 11 $2H_2S + SO_2 \rightarrow 3S + 2H_2O$

The elemental sulphur combines to form a mixture of the S_6, S_7, S_8 or S_9 allotropic forms.

b) Target Quality of Treated Water

The target water quality is the SANS-241 (2011) standard for potable water. The sulphate concentration is kept at 200 mg/ℓ to ensure that no barium is present in the treated water. Soluble barium is potentially highly toxic to humans. This has been raised as a concern in discussions with Rand Water, which would require assurance that elevated residual barium would not enter the water supply. Although the water quality might meet the SANS-241 (2011) specification in respect of the sulphate concentration, this concentration would be higher than the sulphate concentration in the water that Rand Water has been supplying to potential users of purified AMD for many years. The differences would be noticeable and might require adjustments by consumers or careful blending by suppliers.

Note that the Barium Sulphate process cannot remove any of the monovalent ions from the feed water. For the Western and Eastern basins and the 95th percentile feed water quality, this process will not be able to reduce the sodium concentrations to within the limits required by SANS-241 (2011). Additional RO treatment of a small side stream followed by blending is one option to achieve the required SANS-241 (2011) standard when operating at the 95th percentile feed water quality.

c) Estimated Quality and Quantities of Waste Products Produced through the Process

The ABC process, or any derivative thereof, requires that metals are removed upstream of the process. However, magnesium would have to be removed from the AMD in addition to the Fe, with the result that the HDS process would have to be operated at a significantly higher pH (> 11.0, rather than between 8.5 and 9.0). The quantities of sludge produced through high-lime pre-treatment are expected to be higher than for the usual HDS process due to the higher pH at which the high-lime would be operated. The chemical consumption will also be higher for the high-lime treatment compared to the HDS process.

The process is configured to produce a minimum of waste products. Apart from the HDS and high-lime treatment sludge, all other ‘waste’ products could be viewed as by-products, including:

- Elemental sulphur or hydrogen sulphide;
- Lime to be re-used in the process;
- CO_2 to be re-used in the process; and
- Ash from the burning of coal.

The CaO that is produced is used in the process, contributing to a reduction in costs.

d) Estimated Costs

WUC reports that this process would cost R3.07/kℓ of water treated. These costs include only operation (labour, chemicals and power) and maintenance. No allowance has been made for the sale of lime and sulphur produced in the process.

The capital requirements for the proposal are estimated at R1.8 billion. A cost of R500 million has been reported as a contribution by the mining companies in the form of available infrastructure.

e) Advantages

The main advantages claimed for the ABC process are as follows:

- Compared to the traditional HDS-associated gypsum precipitation processes, the low solubility of barium sulphate will enable residual sulphate levels of < 200 mg/ℓ to be achieved, which would comply with the SANS-241 (2011) specifications;
- A portion of the sludge produced is processed as re-usable or saleable by-products, thereby reducing the total waste sludge volumes to be disposed of, although the viability and sustainability of such markets have not been demonstrated;
- The pre-treatment steps (neutralisation and gypsum precipitation) are widely applied and mature technologies. The risks associated with these processes are well understood; and
- The process produces elemental sulphur from H_2S gas, thus stabilising the sulphur to a potentially usable product. The proposed Claus process is the industry standard for the production of elemental sulphur.
- The process unit treatment cost decreases significantly as the treatment capacity increases. It becomes more economically attractive as the capacity of the facility increases due to economies of scale. In comparison: for RO the membrane related costs increase proportionally as the capacity increases

f) Disadvantages

The disadvantages and risks associated with the ABC process are perceived to be as follows:

- The process is not a complete desalination process; if the removal of monovalent ions is required, additional process steps, such as RO, would be necessary;
- The process has been demonstrated in limited pilot testing only; there is large risk associated with scaling up from a pilot plant to a full-scale plant;
- The feasibility of this process relies heavily on the recovery of $BaCO_3$ and $Ca(OH)_2$, and the production of elemental sulphur. The sensitivity of the production costs to varying recovery efficiencies should be investigated in detail to limit the risks;
- The viability and sustainability of markets for the residues, including sulphur, have not been demonstrated;

- The barium sulphate reaction and reactor design have not been proven in a large-scale application;
- Soluble barium is highly toxic, as is the H_2S gas that is produced in the process;
- H_2S gas is highly flammable and could lead to explosions should accidents occur;
- The ABC process relies on several different processes, including thermal processes at temperatures of 1 000ºC or above, which could give rise to operational difficulties. The number and level of expertise of the operational personnel required might increase the operating cost and negatively affect the economic viability;
- Due to the high temperatures at which the ABC process has to operate, as well as the corrosive nature of the gases produced, special materials are required to provide some durability to the equipment to be used;
- The environmental risks associated with the ABC process are considered to be very high, taking into account the explosiveness and toxicity of parts of the process, as well as the extremely high temperatures;
- The process has a high thermal energy demand; and
- Building redundancy into the process by having multiple parallel units reduces the benefit of economy of scale that the ABC process has over RO at large treatment capacities.

6.4.2 Ettringite Process (SAVMIN)

The Ettringite process is also called the SAVMIN process, and is known in South Africa under this name. It will therefore be referred to in this report as the SAVMIN process.

a) Description of the Process

The SAVMIN process consists of three process steps for the removal of sulphate:

- HDS for neutralisation and oxidation;
- Sulphate removal by precipitation as Ettringite; and
- Aluminium recovery.

The treated water has to be softened and re-carbonated due to the high pH at which the process is operated.

A simplified diagram illustrating the process is shown in **Figure 6.7** below.

i. HDS for Neutralisation and Oxidation

The HDS process will be operated at a high pH (> 12) to ensure that magnesium is also removed from the AMD. This will require additional lime and will produce more sludge. The type of sludge produced in this section of the treatment configuration will be very similar to the sludge produced in the usual HDS process.

As in the case of the HDS process, the gypsum will be allowed to crystallise. The reactions will typically be the same as reported in the section on the HDS process. The crystallisation step is important in this instance, because inadequate crystallisation will result in excess carry-over of sulphate to the Ettringite precipitation step. This would cause difficulties in controlling the process, as all dosages would have to be adjusted to meet the additional demand.

Neutralisation and oxidation

Reaction 12 $Me^{2+} + Ca(OH)_2 \rightarrow Me(OH)_2(s) + Ca^{2+}$

Reaction 13 $2H^+ + Ca(OH)_2 \rightarrow 2H_2O + Ca^{2+}$

Reaction 14 $4Fe^{2+} + O_2 + 10H_2O \rightarrow 4Fe(OH)_3 + 8H^+$

Reaction 15 $Fe^{3+} + 1.5Ca(OH)_2 \rightarrow Fe(OH)_3(s) + 1.5Ca^{2+}$

Magnesium removal

Reaction 16 $Mg^{2+} + Ca(OH)_2 \rightarrow Mg(OH)_2(s) + Ca^{2+}$

Gypsum crystallisation

Reaction 17 $Ca^{2+} + SO_4^{2-} + 2H_2O \rightarrow CaSO_4 \, . \, 2H_2O(s)$

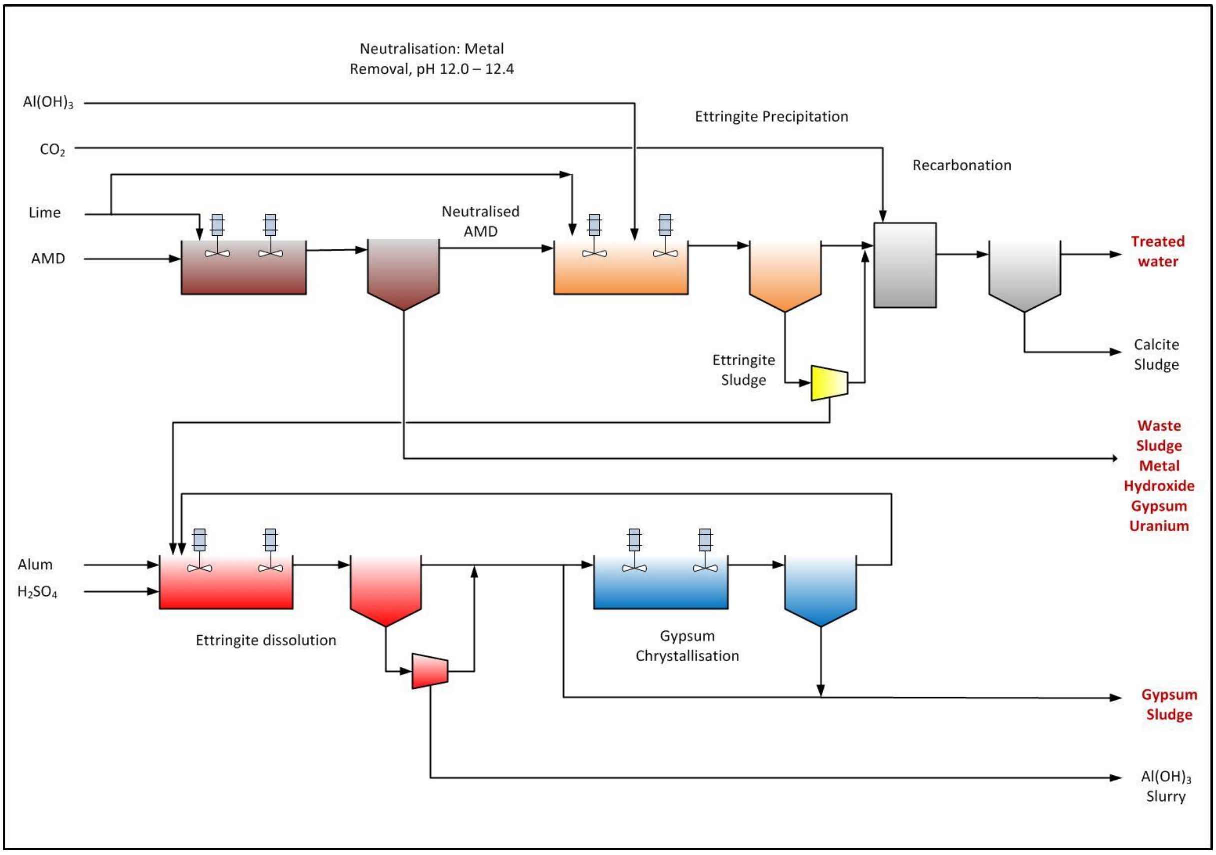

Figure 6.7: Simplified diagram of the SAVMIN process

This process step should remove most metals (except for some amphoteric metals such as aluminium, zinc, etc.), and partially remove the sulphate associated with magnesium and calcium.

ii. Sulphate Removal by Precipitation as Ettringite

The precipitation of Ettringite would require the addition of aluminium in the form of aluminium hydroxide, and calcium in the form of lime, as the reaction proceeds at an optimal rate at a relatively high pH (> 11.4). The precipitation reaction is as follows:

Reaction 18

$$6\ Ca^{2+} + 3SO_4^{2-} + 2Al(OH)_3 + 31H_2O \rightarrow 3CaO.3\ CaSO_4\ .\ Al_2O_3.\ 31H_2O(s) + 6H^+$$

As can be seen, the requirements for alkaline material would be high due to the acidity liberated in the reaction.

Ettringite is stable in the very tight pH range between 11.4 and 12.4. The process will fail if these conditions are not constantly maintained.

iii. Aluminium Recovery

The precipitated Ettringite is dissolved or decomposed by adjusting the pH with sulphuric acid to release aluminium hydroxide according to the following reaction:

Reaction 19

$$3CaO.3CaSO_4\ .\ Al_2O_3\ .\ 31H_2O(s) + 3H_2SO_4 \rightarrow 6Ca^{+2} + 6SO_4^{2-} + 2Al(OH)_3 + 31H_2O$$

The solid aluminium hydroxide is separated from the water and recycled to the Ettringite precipitation process, while the supersaturated calcium sulphate is allowed to crystallise as gypsum.

Efficient Ettringite precipitation takes place only if the mass ratios of the participating substances are controlled within a tight band.

This process is therefore relatively difficult to control.

b) Target Quality of Treated Water

It is claimed that the quality of the treated water would meet the SANS-241 (2011) specifications in respect of heavy metals, as well as calcium, magnesium and sulphate, although this has not been demonstrated at full-scale application. Special processes would be required in instances where the monovalent ions are outside the specifications.

c) Estimated Quality and Quantities of Waste Products Produced through the Process

Indicative figures for the sludge produced in the process are estimated to be as follows:

Metal hydroxide	600 kg/Mℓ/d
Gypsum sludge	450 kg/Mℓ/d
Calcite sludge	160 kg/Mℓ/d
Total mass of sludge	1 210 kg/Mℓ/d

d) Advantages

The main advantages claimed for the SAVMIN process are as follows:

- The process can produce water that complies with the SANS-241 (2011) specifications;
- The process does not involve high-risk processes, such as processes that produce toxic and explosive gases at high temperatures; and
- The process has a low energy demand.

e) Disadvantages

The main disadvantages of the SAVMIN process are considered to be the following:

- The process has not been demonstrated at full-scale application or for prolonged periods; The process requires tight process control within a relatively narrow pH band;
- The process is complicated to control;
- The process requires a high level of gypsum crystallisation. Failure to achieve this will cause the failure of the process; and
- The process requires high quantities of lime – more than the alternative processes – with associated cost implications.

6.5 Biological Processes

In biological processes, metal and sulphate removal are achieved through the application of biological processes, involving the reduction of the sulphate to sulphides by sulphate reducing bacteria (SRB). The sulphide then reacts with metals in the AMD to form metal sulphides, which can be separated from the water. Alternatively the sulphide can be stripped from the liquid phase and used to make elemental sulphur using a process such as the Claus process.

Biological sulphate reduction is an anaerobic process, where the sulphate is the electron acceptor that is reduced to sulphide. The sulphate reducing bacteria require energy for the process, which they can receive from the hydrogen, or from a carbon source such as methanol, or from any biodegradable organic material such as the primary sludge from wastewater treatment works (WWTW).

As the operators of WWTW are generally trained to operate biological processes, the biological processes for the reduction of sulphate should be investigated with a view to combining the processes of sewage treatment and AMD treatment. The synergy between the processes could be of great advantage to the economics of treating AMD where primary sewage sludge and AMD are both available in close proximity.

The metal sulphides are not sufficiently stable to be disposed of in the environment, as moisture and oxygen will start the reaction that created the AMD in the first place. Further treatment of these substances is therefore required. It is generally claimed that the metals can be recovered, while the sulphide can be used to produce elemental sulphur in chemical processes such as the Claus process, which are high-technology processes that require highly skilled operators and maintenance teams.

There are also biological processes that could be used to oxidise the sulphide to biologically formed elemental sulphur. Some of the processes are still under development and could at best be classified as laboratory-scale technology, while others might not have been used at the scale that would be required to treat AMD.

The biological processes produce treated effluent of similar quality to treated sewage effluent, especially if raw primary sludge from the WWTW is used as a carbon source. If chemical substances such as methanol or hydrogen are used, then the quality of the treated effluent would be better. Tertiary treatment would still be required to ensure compliance with the relevant standards.

Biological processes would not effect changes to the monovalent ions such as sodium and chloride, with the consequence that tertiary treatment would be required to meet the specifications where these substances exceed the required specifications in the raw water to be treated.

6.5.1 Biological Sulphate Reduction (Biosure) Process

The CSIR has conducted several studies over three decades on the biological sulphate reduction of AMD and industrial wastewater. The concepts have been adopted and further developed by other research institutions in South Africa and abroad. A presentation was made to the study group by ERWAT (East Rand Water Care Company, a section 21 non-profit company operating sewage treatment plants on the East Rand), the Water Research Commission (WRC), which has a licence agreement on an application of biological sulphate reduction with sewage sludge, referred to as the Biosure process, and a consulting group called Vitaone8. The process presented was based on the 10 Mℓ/d plant located at the Ancor sewage treatment plant that was used as a demonstration plant for treating AMD from the HDS plant at Grootvlei Mine on the East Rand.

a) Description of the Process

The Biosure process utilises sulphate reducing bacteria that reduce the sulphate to sulphide under anaerobic conditions. The bacteria require a source of readily biodegradable carbon to enable the process to proceed according to the following chemical reaction:

Organic material ($C_{3.5}H_7O_2N_{0.196}$) + $1.82SO_4^{2-} \rightarrow$ 0.093 organic material ($C_5H_7O_2N$) + $0.91H_2S$ + $0.91HS^-$ + $0.977HCO_3^-$ + $2.05CO_2$ + $0.103NH_4^+$ + $0.187H_2O$

From the chemical equation given above, it follows theoretically that 0.78 kg of SO_4 would be removed per kilogram of chemical oxygen demand (COD) consumed by the sulphate reducing bacteria. In real terms, it was found by running the pilot plant using sewage sludge, as well as organic material with a high content of readily biodegradable COD, that the ratio is 2 kilograms of COD per kilogram of SO_4 converted.

The sulphide produced can be reacted with the metals in the AMD to form metal sulphides, which will precipitate and can thus be removed from the water in a clarifier.

The Biosure process was investigated in a pilot plant with a capacity of 10 Mℓ/d, as stated above. The plant received the effluent from the Grootvlei HDS plant, and in a separate stream also the HDS sludge from the plant. The HDS effluent was treated in an anaerobic digester that was fed with raw primary sewage sludge, as well as other biodegradable waste material such as blood from abattoirs, ice-cream from an ice-cream factory, etc. to boost the carbon content of the sewage sludge when these wastes were available. The HDS sludge stream provided the metals that precipitate the sulphide formed in the anaerobic digester.

The effluent from the clarifier separating the metal sulphides from the AMD needs to be treated in an aerobic process to polish the effluent and to oxidise the remaining organic material and ammonia vto comply with treated sewage discharge quality limits. The quality of the treated effluent would therefore resemble the quality of treated sewage.

The sulphate reducing bacteria compete with methanogen bacteria in the anaerobic digester for the carbon source, and it is reported that factors such as retention time, SO_4:COD ratio, temperature and pH dictate the outcome of the competition. Hydrogen sulphide has also been reported as an inhibitor of the biological activity in the anaerobic reactor, especially if the pH is below neutral.

The sulphate reducing bacteria are reported to grow optimally at a pH close to neutral, which therefore does not allow the direct treatment of AMD. AMD generally has to be neutralised before it is fed into the sulphate reducing process. The HDS process or alike, albeit at a possibly reduced scale, is therefore a prerequisite for the biological sulphate reduction process. It has been found that the SRB population could adapt to the low pH conditions, which would eliminate the constant need to neutralise the AMD. As the sludge produced through the HDS process contains high concentrations of metals, it could be used to precipitate the sulphide produced as H_2S in the form of metal sulphides such as iron sulphide (FeS).

A simplified diagram illustrating the process is shown in **Figure 6.8** below.

The metal sulphide sludge needs further treatment to prevent pollution of the environment at the disposal site, because it will revert back to acid and sulphate on exposure to moisture and oxygen in the atmosphere, which is the cause of AMD in the first instance.

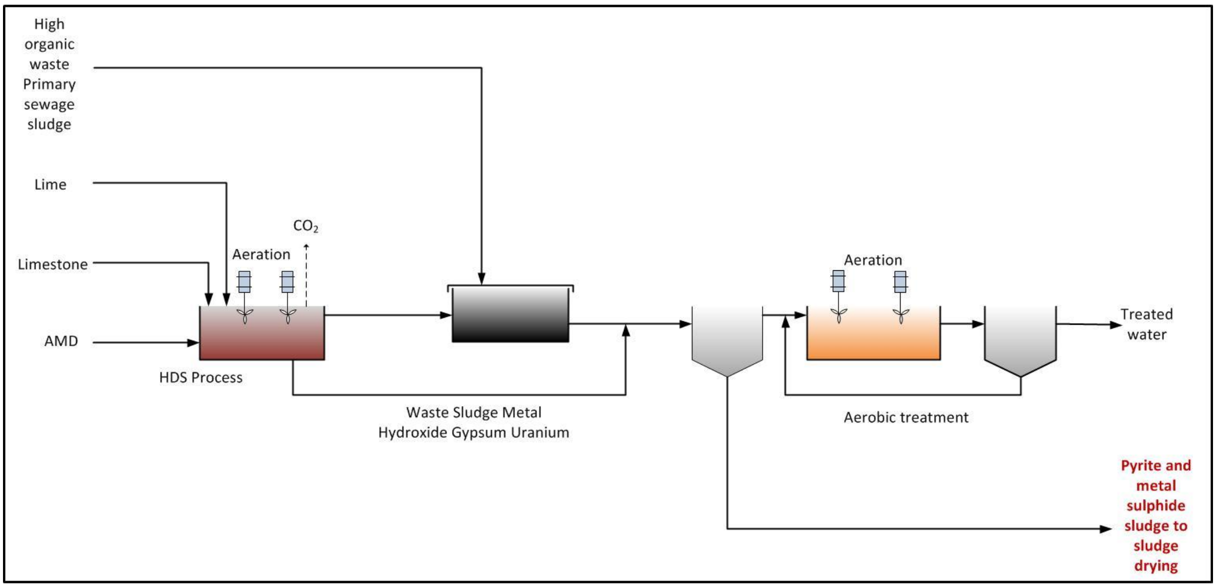

Figure 6.8: Simplified diagram of the Biosure process

b) Target Quality of Treated Water

The quality of the treated water should resemble that from an ordinary sewage treatment works. The sulphate concentration and the metals will meet the SANS-241 (2011) specifications. Monovalent ions will remain in the treated water at approximately the same concentration as in the feed water and additional salinity removal treatment (e.g. RO) on a side stream will be required if the feed water monovalent quality exceeds the specification limits.

c) Estimated Quality and Quantities of Waste Products Produced through the Process

The quantities of sludge still need to be verified.

d) Advantages

The main advantages of the Biosure process are considered to be the following:

- The process can produce water that complies with the general standards for wastewater;
- The process has been tested on a fairly large scale; and
- The process could be integrated with existing WWTW and this synergy could benefit both the WWTW operations and the treatment of AMD.

e) Disadvantages

The main disadvantages of the Biosure process are considered to be the following:

- The efficiency of the biological sulphate reduction is proportional to the mass of sulphate reducing bacteria established and maintained in optimal conditions within the anaerobic reactor. Sulphate reducing bacteria are slow growing and sensitive to operational conditions. Start-up and recovery from upsets will therefore take a relatively long time (i.e. in the order of weeks rather than days). It is therefore of utmost importance that the operational conditions are tightly controlled;

- Disposal of the metal sulphides is not acceptable, and sophisticated processing is thus required (e.g. the Claus process);
- Large volumes of primary sewage sludge and/or external readily biodegradable carbon sources are required to meet the sulphate reduction demand of the AMD. Adequate sources of suitable biodegradable carbon are currently not readily available at the proposed locations of the AMD abstraction and HDS plants;
- The availability of the carbon source determines the placement of the works. If the works were to be placed in close proximity to existing WWTW, a shaft would need to be developed on the western side of the Central Basin to gain access to the sewage sludge produced by the Bushkoppies, Goudkoppies and Olifantsvlei WWTW;
- Other industrial wastewater components in the primary sewage sludge (i.e. heavy metals, cyanide, solvents etc.) and domestic wastewater components might inhibit, or at least interfere with, the biological sulphate reduction kinetics. Recovery of the sulphate reducing bacteria from an inhibited state could take considerable time during which treated water produced will be out of specification;
- The liability for co-treating AMD with domestic sewage and/or industrial organic wastewaters, and associated assurance of discharge quality compliance and sludge disposal requirements for the WWTW, would require institutional decisions; and
- To sustain the biological sulphate reducing process based on the Biosure principle, adequate sources of readily available carbon would be needed to augment the carbon from sewage, or alternatively form the main carbon source. A variety of vegetative (plant) sources cultivated for this purpose have been identified.

6.5.2 Biological Sulphate Reduction (Paques Process)

The process proposed by Paques, a Netherlands-based wastewater treatment technology supplier, is similar to the Biosure process, except that the use of hydrogen, methanol, ethanol, or other organic material as electron donors is proposed, rather than primary sewage sludge or industrial wastewaters, although the use of wastewater sludge is not ruled out. The provision of a dedicated readily biodegradable carbon source allows more direct control of the biological sulphate reduction and ensures that there are no extraneous inhibitory components associated with the carbon source, such as pathogens, methanogens, etc. Paques is a leading company globally in the field of anaerobic treatment of wastewater.

a) Description of the Process

Paques has developed processes for the reduction of sulphate to sulphide, the precipitation of metal sulphides, and the production of bio-sulphur from wastewater. The SULFATEQ^{TM} process, which is used to reduce sulphate to sulphide, is generally provided downstream of the lime treatment of waste streams (HDS process). However, it is envisaged that the alkalinity formed during the reduction of the sulphate could be used to neutralise the acid in the AMD and precipitate the metals. The SULFATEQ^{TM} process produces hydrogen sulphide, which can either be used in the THIOTEQ^{TM} process to remove the metals such as iron and manganese in the AMD, or it can be oxidised to biologically produce elemental sulphur. The metal sulphides require further treatment to prevent the formation of acids during the disposal of the waste products.

As an alternative to the use of ethanol as a carbon source, a derivative of the process could be used where the micro-organisms use hydrogen as their energy source. The final decision on which source of energy to use depends on the availability of the various sources of energy.

A simplified diagram illustrating the processes is shown in **Figure 6.9** below.

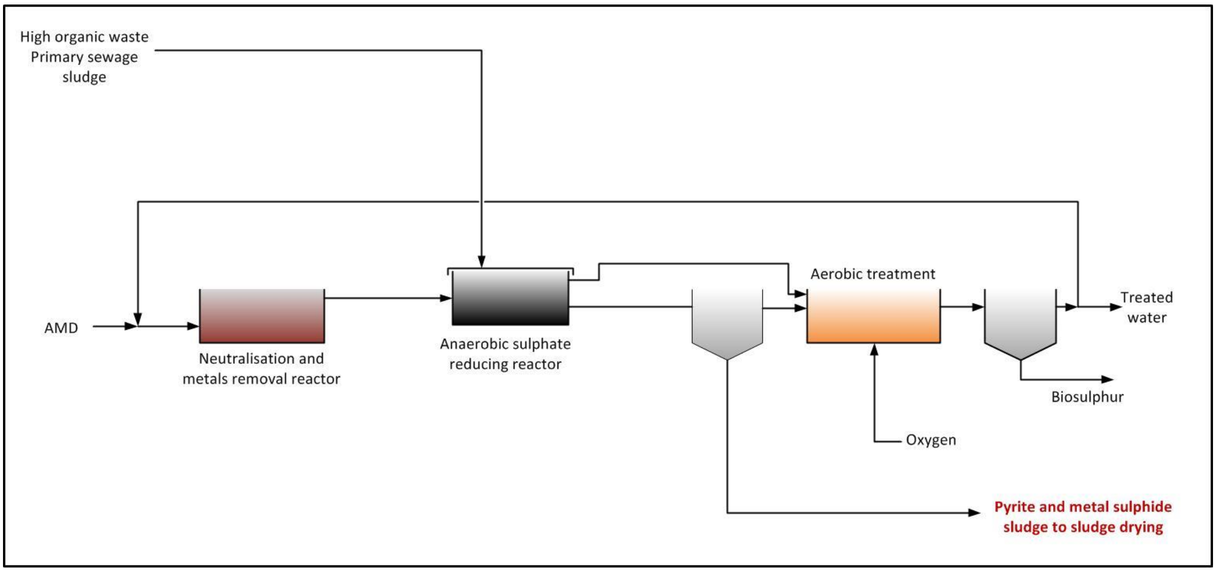

Figure 6.9: Simplified diagram of the Paques process

b) Target Quality of Treated Water

The quality of the treated water will depend on the feed of organic material, but it can be assumed that it will be similar to the quality of the water produced through the Biosure process.

The processes do not remove monovalent ions such as sodium and chloride, and they do not decrease the magnesium content of the water. Magnesium can be removed by water softening, resulting in the formation of additional sludge, while the monovalent ions can only be decrease through physical processes such as reverse osmosis.

c) Estimated Quality and Quantities of Waste Products Produced through the Process

The primary sludge stream from the SULFATEQ^{TM} process will be a mixture of bio-sulphur and calcium carbonate. Processing 25 Mℓ/d of AMD that has been pre-treated in an HDS step will nominally generate 36 per tons per day (36 t DS/d) of sludge, comprising about 75%

biosulphur and 25% calcium carbonate. If the slurry is dewatered in a filter press or centrifuges, it is anticipated that a cake dryness of 50% will be achieved.

Paques estimates that the sludge volume of their process is six to seven times lower than the equivalent metal hydroxide/gypsum combination resulting from simple physical/chemical processes.

d) Advantages

The main advantages claimed for the Paques process are the following:

- This process can produce water that complies with the general standards for wastewater;
- The process has been applied on a fairly large scale. In South Africa, an installation with the capacity to treat 3 Mℓ/d has been provided at the Anglo Coal Landau Colliery. Various electron donors have been tested at this installation;
- The process could be integrated with existing wastewater treatment works (WWTW); this synergy could be of benefit to WWTW operations and the treatment of AMD, although the technology provider does not prefer this approach. ‘Clean’ electron donors such as ethanol or hydrogen are preferred;
- The sludge produced through the process is of such a quality that it does not present an environmental risk provided that the metal sulphides can be re-used. Alternatively stable metal carbonates and hydroxides can be formed using an alternative process configuration;
- The process does not produce gypsum but bio-sulphur, which has a market value and could possibly be sustainable;
- The process considerably reduces the problem of sludge disposal; and
- The AMD water can be treated without a neutralisation step such as the HDS process using an alternative process configuration.

e) Disadvantages

The main disadvantages of the Paques process are considered to be the following:

- The efficiency of the biological sulphate reduction is proportional to the mass of sulphate reducing bacteria established and maintained in optimal conditions within the anaerobic reactor. The sulphate reducing bacteria are slow growing and relatively sensitive to operational conditions. Start-up and recovery from upsets will therefore take a relatively long time (i.e. in the order of two to three weeks rather than days). It is therefore of the utmost importance that the operational conditions are tightly controlled;
- Disposal of the metal sulphides is not acceptable, sophisticated processes, such as the Claus process may thus be required. It is important that the production of metal sulphides be reduced to the minimum to avoid this problem from occurring;

- It is envisaged that the use of hydrogen, with all its associated flammable gas handling risks, would be the most feasible energy source for application at the scale of this project; and
- The process would not be interfaced with municipal wastewater treatment works.

7. EVALUATION OF AMD TREATMENT TECHNOLOGIES

7.1 Evaluation Criteria

The following criteria were selected as a guideline for the evaluation of the technology presented by the prospective service providers:

- Quality of the raw water that can be treated with the technology;
- Quality of the treated AMD that can be achieved through the process;
- Chemicals used in the technology;
- Waste products produced;
- Requirements for the disposal of the waste products;
- State of development of the technology;
- Complexity of the process; and
- Risks associated with the technology:
    - Variations in the volume to be treated;
    - Variations in the quality of the AMD to be treated;
    - Health risks;
    - Environmental risks; and
    - Potential failure.

The costs of the various technologies will be evaluated using a comprehensive approach to ascertain the total costs, including the cost of disposing of the waste products, as well as the potential income from selling the water or some of the waste products.

In any final selection or tender process, additional criteria would be considered, including local representation and support, as well as local manufacture.

7.2 Evaluation of Technologies

7.2.1 Pre-treatment Technologies

a) Quality of the Raw Water that can be Treated with the Technology

The comparison of the pre-treatment technologies in respect of the quality of raw AMD that can be treated is summarised in **Table 7.1** below.

Table 7.1: Comparison of pre-treatment technologies in respect of the quality of raw AMD that can be treated

Technology	Supplier	Quality of raw water	Comments
HDS	Process technology is held by various suppliers	Process can be adjusted to variable situations with relative ease	Suitable process-control instrumentation needs to be provided to ensure that the plant is operated at optimal conditions
Fe-CN process	Mintails is the sole supplier	Acidity and Fe concentrations need to be carefully balanced with the cyanide concentration in the gold processing waste to be treated	Process-control instrumentation is of utmost importance to ensure that the process is operated correctly

b) Quality of the Neutralised AMD that can be Achieved through the Process

The comparison of the pre-treatment technologies in respect of the quality of neutralised AMD that can be produced is summarised in **Table 7.2** below.

Table 7.2: Comparison of pre-treatment technologies in respect of quality of neutralised AMD

Technology	Supplier	Quality of neutralised AMD	Comments
HDS	Process technology is held by various suppliers	Fe < 1.0 mg/ℓ pH > 8.1 Mn concentration depends on pH of operation SO_4 < 2 400 mg/ℓ No change in monovalent ions	See section 6.2.1 for details The concentrations of various components will vary in accordance with the variation in the raw feed that has to be treated Monitoring and process control are important
Fe-CN process	Mintails is the sole supplier	Fe < 1.0 mg/ℓ pH > 7.5 No change in monovalent ions Possible increase in uranium concentration No information on possible heavy metals Quality of neutralised AMD to be proven	This process is new, and no data are available at this stage

c) Chemicals Used in the Technology

The comparison of the pre-treatment technologies in respect of the chemicals used is summarised in **Table 7.3** below.

Table 7.3: Comparison of pre-treatment technologies in respect of chemicals used

Technology	Chemicals	Quantities used (t/d)	Comments
HDS	Limestone ($CaCO_3$)		
	Western Basin:	73	
	Central Basin:	89	
	Eastern Basin:	0	
	Slaked lime ($Ca(OH)_2$)		
	Western Basin:	25	
	Central Basin:	14	
	Eastern Basin:	41	
	Oxygen		
Fe-CN process	Chemicals used in gold recovery process: • Cyanide • Lime	Quantities unknown	Cyanide is poisonous, and experienced operators are required to operate the process

d) Wastes Products Produced

The comparison of the pre-treatment technologies in respect of the wastes produced is summarised in **Table 7.4** below.

Table 7.4: Comparison of pre-treatment technologies in respect of wastes produced

Technology	Waste product	Quantities produced (t DS/Mℓ)	Comments
HDS	Sludge, being a mixture of metal hydroxides and gypsum		The sludge is of a quality that cannot be used beneficially It will contain uranium, and therefore has to be classified as a hazardous waste
	Western Basin:	5.5	
	Central Basin:	6.1	
	Eastern Basin:	1.9	
Fe-CN process	Sludge in the form of an Fe-CN complex	The quantity of sludge is not known at this stage	The sludge is classified as a hazardous sludge It is co-disposed with the spent tailings from the gold recovery process

e) Requirements for the Disposal of the Waste Products

The comparison of the pre-treatment technologies in respect of the disposal of the wastes produced is summarised in **Table 7.5** below.

Table 7.5: Comparison of pre-treatment technologies in respect of the disposal of waste products

Technology	Waste product	Disposal method	Comments
HDS	Metal hydroxide/Gypsum sludge	Disposal in a purpose-designed sludge-disposal facility Needs to comply with standards of hazardous waste landfills	Sludge is classified as hazardous due to the possible heavy metal content and the known content of uranium
Fe-CN process	Sludge with Fe-CN complex	Co-disposal with spent tailings from gold recovery process	Disposal site needs to meet the specifications applicable to mining wastes

f) State of Development of the Technology

The comparison of the pre-treatment technologies in respect of the state of development of the technology is summarised in **Table 7.6** below.

Table 7.6: Comparison of pre-treatment technologies in respect of the state of development of the technology

Technology	Supplier	State of development	Comments
HDS	Process technology is held by various suppliers	The technology is proven (i.e. TRL = 9)	Well-known technology, with various suppliers being able to implement large-scale installations
Fe-CN process	Mintails is the sole supplier	The technology is new and considered to be in the pilot stage (i.e. TRL = 4)	Mintails, the owner of the technology, is in the process of installing a large-scale pilot plant at the Mogale Gold Mine at their own cost Results of the installation will be monitored closely

g) Complexity of the Process

The evaluation of technology in respect of its complexity is a subjective process, but in this instance the endeavour is to differentiate between processes, and to highlight the differences between the technologies. The comparison of the pre-treatment technologies in respect of the complexity of the process is summarised in **Table 7.7** below.

Table 7.7: Comparison of pre-treatment technologies in respect of the complexity of the process

Technology	Supplier	Complexity of technology	Comments
HDS	Process technology is held by various suppliers	Low to medium complexity	The technology is well known Complications are still being experienced with precipitation in structures and pipelines Requires good control of maintenance
Fe-CN process	Mintails is the sole supplier	Medium	Technology is not known, although mines have experience of handling and working with cyanide Very good and stringent process control is required The maintenance of control instruments is highly important Well-trained operators are required

h) Risks Associated with the Technology

The comparison of the pre-treatment technologies in respect of the associated risks is summarised in **Table 7.8** below.

Table 7.8: Comparison of pre-treatment technologies in respect of the associated risks

Technology	Risks in respect of variations		Health risks	Environmental risks	Risk to failure
	Volume to be treated	Quality of raw AMD			
HDS	Low risk in terms of the volume that can be treated; plant can be designed to whatever volume has to be treated.	Quantity of chemicals used is in direct relation to the chemical composition of the AMD. Plant can be designed to treat any chemical composition	Low risk: simple personal protective equipment required mainly to protect against lime dust.	Low risk to environment; no dangerous chemicals are used in the process.	Medium risk of equipment failure as a result of chemical blockages (precipitates).
Fe-CN process	Volume that can be treated is dependent on the production of the gold recovery plant.	Acidity of AMD and Fe concentration need to be balanced with the cyanide concentration in the gold recovery wastewater. Variable waste streams	High risk: cyanide is extremely poisonous. Operation needs to be closely controlled.	High risk: at failure, cyanide can be released to the environment as a gas or in solution. Mines have experience of operations using cyanide.	Medium risk: it is important that the balance between the waste streams is maintained.

Technology	Risks in respect of variations		Health risks	Environmental risks	Risk to failure
	Volume to be treated	Quality of raw AMD			
		increase the complexity of the process.			

7.2.2 Treatment Technologies for desalination of AMD

a) Quality of the Raw Water that can be Treated with the Technology

The comparison of the treatment technologies for neutralised AMD in respect of the quality of raw AMD that can be treated is summarised in **Table 7.9** below.

Table 7.9: Comparison of treatment technologies for desalination of AMD in respect of the quality of the raw water that can be treated

Technology	Supplier	Quality of raw water	Comments
Conventional Multistage RO	Numerous suppliers available	Technology requires pre-treatment, typically with HDS. Technology requires that Fe and Mn concentrations are low.	Fe and Mn become a problem at relatively low concentrations in that the life of the membranes is reduced, thus increasing the costs of the operation. If the pre-treatment is done within the specifications, the technology can accommodate any neutralised AMD.
Alternative RO	MiWaTek	No pre-treatment other than pH adjustment is required. The supplier states that only the pH needs to be controlled at around 4.0.	The process is not well known. A pilot plant is under construction at Shaft No 8 to prove the technology.
Electrocoagulation	P2W	Technology requires pre-treatment with HDS. The supplier states that the technology can be adapted to meet any demands.	The supplier has not divulged the principles of the technology as this is considered to be their intellectual property; it is therefore not possible to comment.
ABC process	Western Utilities Corporation	Technology requires pre-treatment with HDS. Lower concentrations of SO_4 may impede the viability and efficiency of the process.	HDS needs to be operated at a pH of 11.0 to remove Mg.
SAVMIN	Veolia/Mintek	Technology requires pre-treatment with HDS.	HDS needs to be operated at a pH of 11.0 to remove Mg.

Technology	Supplier	Quality of raw water	Comments
Biosure	ERWAT	Technology requires pre-treatment with HDS. Demand on carbon source in relation to the SO_4 concentration.	
Biological sulphate reduction	Paques	Technology requires pre-treatment with HDS. Demand on carbon source in relation to the SO_4 concentration.	

b) Quality of the Desalinated AMD that can be Achieved through the Process

The comparison of the treatment technologies for neutralised AMD in respect of the quality of desalinated AMD that can be produced is summarised in **Table 7.10** below.

Table 7.10: Comparison of treatment technologies for desalination of AMD in respect of the quality of desalinated AMD that can be produced

Technology	Supplier	Quality of desalinated AMD	Comments
Conventional RO	Numerous suppliers available	Any specification can be met. Can remove uranium from final product.	The production of brine is dependent on the specifications of the desalinated water. Uranium will be concentrated in the brine or removed in sludge.
Alternative RO	MiWaTek	Any specification can be met. Can remove uranium from final product.	The production of brine is dependent on the specifications of the desalinated water. Uranium will be concentrated in the brine or removed in sludge.
Electrocoagulation	P2W	Process does not remove monovalent ions or uranium. Specifications are unlikely not to be met without further treatment.	Further processes, such as RO, may be required if the monovalent ions exceed the specifications. The removal of uranium from the final product may require additional processes.
ABC process	Western Utilities Corporation	Process does not remove monovalent ions or uranium. Specifications are unlikely to be met without further treatment. Sulphate concentration is maintained at 200 mg/ℓ.	Further processes, such as RO, may be required if the monovalent ions exceed the specifications. A safety margin is required to prevent the release of soluble barium to the final product. The removal of uranium from the final product may require additional processes.

Technology	Supplier	Quality of desalinated AMD	Comments
SAVMIN	Veolia/Mintek	Process does not remove monovalent ions or uranium. Specifications are unlikely to be met without further treatment.	Further processes, such as RO, may be required if the monovalent ions exceed the specifications. The removal of uranium from the final product may require additional processes.
Biosure	ERWAT	Process does not remove monovalent ions or uranium. Specifications are unlikely to be met without further treatment.	Further processes, such as RO, may be required if the monovalent ions exceed the specifications. The removal of uranium from the final product may require additional processes.
Biological sulphate reduction	Paques	Process does not remove monovalent ions or uranium. Specifications are unlikely to be met without further treatment.	Further processes, such as RO, may be required if the monovalent ions exceed the specifications. The removal of uranium from the final product may require additional processes.

c) Chemicals Used by the Technology

The comparison of the treatment technologies for neutralised AMD in respect of the chemicals used is summarised in **Table 7.11** below.

Table 7.11: Comparison of treatment technologies for desalination of AMD in respect of the chemicals used

Technology	Chemicals	Quantities used (t/d)			Comments
		Western Basin	Central Basin	Eastern Basin	
Conventional RO	Sulphuric acid	12.2	24.5	34.5	See Tables 7.10 and 7.11
	Coagulant	1.9	4.3	5.3	These quantities were estimated by the study team.
	Disinfectant	11.3	21.5	37.0	
	Caustic soda	7.3	6.0	5.7	
	SMBS	12.4	26.1	36.9	
	Anti-scalant	10.9	27.1	22.7	
	Lime	418.9	1 098.5	1 473.8	
Alternative RO	Sulphuric acid Coagulant Disinfectant Caustic soda SMBS Anti-scalant Lime				It is expected that similar chemicals will be used for the cleaning of the membranes and the precipitation of the sulphate. Quantities are not available at this stage.

Technology	**Chemicals**	**Quantities used (t/d)**			**Comments**
		Western Basin	**Central Basin**	**Eastern Basin**	
Electrocoagulation	Chemical consumption unknown				Quantities are unknown.
ABC process	Lime Barium sulphate Carbon/coal Oxygen/air				Quantities are unknown for the different basins.
SAVMIN	Lime Aluminium sulphate Sulphuric acid Aluminium hydroxide Carbon dioxide				Quantities are unknown.
Biosure	Biodegradable substances such as high organic waste				2 kg biomass per kg of sulphate removed.
Biological sulphate reduction	Biodegradable substances such as high organic waste Hydrogen				Quantities are not known.

d) Waste Products Produced

The comparison of the treatment technologies for neutralised AMD in respect of the wastes produced is summarised in **Table 7.12** below.

Table 7.12: Comparison of treatment technologies for desalination of AMD in respect of wastes produced

Technology	**Waste product**	**Quantities produced**			**Comments**
		Western Basin	**Central Basin**	**Eastern Basin**	
Conventional RO	Gypsum sludge (t DS/d)	40.8	163.7	242.7	See Tables 7.8 and 7.9 for sludge composition.
	Brine (kℓ/d)	115	0	0	The production of brine is dependent on the quality of the raw AMD and the specifications for the treated water.

Technology	Waste product	Quantities produced			Comments
		Western Basin	Central Basin	Eastern Basin	
Alternative RO	Metal hydroxide sludge Gypsum sludge (t DS/d) Brine (kℓ/d)	No data available.			
Electrocoagulation	Gypsum sludge	No data available.			
ABC process	Elemental sulphur Lime	No data available per basin.			Lime can be used to reduce the requirements for lime in the HDS process.
SAVMIN	Gypsum	No data available per basin.			
Biosure	Metal sulphides or Biosulphur Biological sludge	No data available per basin.			Reduced sludge volumes compared to metal hydroxide and gypsum producing options.
Biological sulphate reduction	Biosulphur Biological sludge Metal sludge (Carbonates & hydroxides, or Sulphides)	No data available per basin.			Reduced sludge volumes compared to metal hydroxide and gypsum producing options.

e) Requirements for the Disposal of the Waste Products

The comparison of the treatment technologies for neutralised AMD in respect of the disposal of the wastes produced is summarised in **Table 7.13** below.

Table 7.13: Comparison of treatment technologies for desalination of AMD in respect of the disposal of wastes

Technology	Waste product	Disposal method	Comments
Conventional RO	Gypsum sludge (t DS/d) Brine (kℓ/d)	Gypsum sludge may be used beneficially in the cement and construction products industry. Brine goes to evaporation ponds.	There is currently an oversupply of gypsum in the country, and hence the market value of the product is very low. The brine consists of a mixture of; hence it would be costly to remove certain constituents selectively.
Alternative RO	Metal hydroxide sludge Gypsum sludge (t DS/d) Brine (kℓ/d)	The supplier states that there is interest in the metal hydroxides. Gypsum sludge may be used beneficially in the cement industry. Brine goes to evaporation ponds.	There is currently an oversupply of gypsum in the country, and hence the market value of the product is very low. The brine consists of a mixture of ions and molecules, hence if would be costly to remove certain constituents selectively.
Electrocoagulation	Gypsum sludge	Gypsum sludge may be used beneficially in the cement industry.	There is currently an oversupply of gypsum in the country, and hence the market value of the product is very low.
ABC process	Elemental sulphur Lime	Elemental sulphur can be sold at market value. The lime can be used in the HDS process upstream of the ABC process.	South Africa currently imports elemental sulphur and sulphuric acid and local production can reduce imports.
SAVMIN	Gypsum	Gypsum sludge may be used beneficially in the cement industry.	There is currently an oversupply of gypsum in the country, and hence the market value of the product is very low.
Biosure	Metal sulphides or Biosulphur Biological sludge	Metal sulphides need disposal on special waste disposal sites. Elemental sulphur can be sold at market value. Biological sludge can be disposed in the same way as the sludge from WWTW.	Metal sulphides are considered a pollutant, as the sulphides will be oxidised in the atmosphere to generate surface ‘AMD’. The process for biologically converting sulphide to elemental sulphur has not been finalised (TRL = 4); alternatively, the SULFATEQ^{TM} process should be implemented (Paques patent).
Biological sulphate reduction	Biosulphur Biological sludge	Elemental sulphur can be sold at market value. Biological sludge can be disposed of in the same way as the sludge from WWTW.	South Africa currently imports elemental sulphur and sulphuric acid and local production can reduce imports.

f) State of Development of the Technology

The comparison of the treatment technologies for neutralised AMD in respect of their state of development is summarised in **Table 7.14** below.

Table 7.14: Comparison of treatment technologies for desalination of AMD in respect of their state of development

Technology	**Supplier**	**State of Development**	**Comments**
Conventional RO	Numerous suppliers available	Technology is proven (TRL = 9).	The technology has a wide application. There are several large installations in South Africa.
Alternative RO	MiWaTek	Technology is in pilot plant stage (TRL = 6).	Pilot testing is currently under way.
Electro-coagulation	P2W	Technology has not been used in South Africa, but installations of comparable size are being provided in Ghana (TRL = 8).	Installations in other parts of the world need to be investigated (e.g. Ghana).
ABC Process	Western Utilities Corporation	Technology is considered to be in the pilot plant stage (TRL = 5).	Elements of the process have been tested in relatively small pilot plants.
SAVMIN	Veolia/Mintek	Technology is considered to be in the pilot plant stage (TRL = 5).	
Biosure	ERWAT	Technology is considered to be in the pilot plant stage (TRL = 8).	The production of biosulphur has not been tested adequately. Experiments are being conducted to find alternative sources for biomass.
Biological Sulphate Reduction	Paques	Technology has been applied abroad, but not at the capacity required in South Africa (TRL = 7).	This process has been installed elsewhere, but not at the scale required in this instance.

g) Complexity of the Process

The comparison of the treatment technologies for neutralised AMD in respect of the complexity of the process is summarised in **Table 7.15** below. There is no scale to measure the complexity of processes, and therefore the comparison was done by ranking the various technologies. Comments on the complexity can, however, be made.

Table 7.15: Comparison of treatment technologies for desalination of AMD in respect of the complexity of the process

Technology	Supplier	Complexity of Technology	Comments
Conventional RO	Numerous suppliers available	Medium complexity.	The technology entails the following of a number of processes, hence requiring good knowledge of all processes and tight control on the operation.
Alternative RO	MiWaTek	Medium complexity, yet higher than conventional RO.	The technology entails the following of a number of processes, hence requiring good knowledge of all processes and tight control on the operation. It is a new technology and not all operational parameters are known and fully understood.
Electro-coagulation	P2W	Medium, but perceived to be slower than conventional RO.	The technology appears to have less process steps than conventional RO. It is a new technology and not all operational parameters are known and fully understood.
ABC Process	Western Utilities Corporation	High.	The technology has a number of highly complex processes following each other. The technology is new. The processes produce explosive, toxic and corrosive substances at a high energy level (around 1 000°C). Of all the proposed technologies, this is the most complex technology. Failure of some of the processes could be catastrophic.
SAVMIN	Mintek	Medium, but higher than conventional RO.	The technology entails the following of a number of

Technology	Supplier	Complexity of Technology	Comments
			processes, hence requiring good knowledge of all processes and tight control on the operation – more than what is required at the RO - processes. It is a new technology and not all operational parameters are known and fully understood.
Biosure	Erwat	Medium in respect of the reduction of the sulphate, however the production of bio sulphur is considered to be more complex than the reduction process.	Technology is new, and not all parameters are known and fully understood, especially the production of bio sulphur. Production of carbon source is still a complex process.
Biological Sulphate Reduction	Paques	Medium complexity, depending on the energy source. If hydrogen is used, then the complexity is significantly increased due to the higher energy levels being applied in the technology.	The process has not been applied at the scale required; hence the complexity of the required installation could be underestimated.

h) Risks Associated with the Technology

The comparison of the treatment technologies for neutralised AMD in respect of the associated risk is summarised in **Table 7.16** below.

Table 7.16: Comparison of technologies in respect of the associated risk

Technology	Risks in respect of variations		Health risks	Environmental risks	Risk of failure
	Volume to treat	Quality of raw AMD			
Conventional RO	Independent of volume to be treated.	Independent of quality of raw AMD.	No significant health risks; normal personal protective equipment required.	No significant risks. No damage other than untreated AMD being released to the environment.	No catastrophic consequence of failure (except membrane replacement).
Alternative RO	Independent of volume to be treated.	Independent of quality of raw AMD.	No significant health risks; normal personal protective equipment required.	No significant risks. No damage other than untreated AMD being released to the environment.	No catastrophic consequence of failure (except membrane replacement).

Technology	**Risks in respect of variations**		**Health risks**	**Environmental risks**	**Risk of failure**
	Volume to treat	**Quality of raw AMD**			
Electrocoagulation	Independent of volume to be treated.	Risk not known.	No significant health risks; normal personal protective equipment required.	No significant risks. No damage other than untreated AMD being released to the environment.	No catastrophic consequence of failure (except membrane replacement).
ABC Process	Technology requires large quantities to gain benefit from economies of scale and become competitive.	It is perceived that higher concentrations of sulphate would benefit the process.	High risk due to the substances being used and produced (barium carbonate and hydrogen sulphide gas).	High risk due to the substances being used and produced (barium carbonate and hydrogen sulphide gas).	High risk due to the substances being used and produced (barium carbonate and hydrogen sulphide gas). Failure could have catastrophic consequences.
SAVMIN	Independent of volume to be treated.	Aluminium content may have an impact on the make-up aluminium required.	No significant health risks; normal personal protective equipment required.	No significant risks No damage other than untreated AMD being released to the environment.	No catastrophic consequence of failure.
Biosure	Independent of volume to be treated.	Independent of quality of raw AMD.	No significant health risks; normal personal protective equipment required.	No significant risks. No damage other than untreated AMD being released to the environment.	No catastrophic consequence of failure (except long ramp-up time after biomass loss).
Biological Sulphate Reduction	Independent of volume to be treated.	Independent of quality of raw AMD.	No significant health risks; normal personal protective equipment required.	No significant risks. No damage other than untreated AMD being released to the environment.	No catastrophic consequence of failure (except long ramp-up time after biomass loss).

7.3 Summary of Processes

There are various technologies that can treat the AMD-derived water to the required standards. Most of the processes, however, do not remove the monovalent ions from the water, and hence some form of RO is required in all instances where the monovalent ions in the feed AMD exceed the target standards for the treated water. This supplementary treatment could be added with relative ease to each of the processes that do not meet the specifications. It would not be necessary to treat the full stream of AMD in the process, as it would only be necessary to remove an adequate mass of constituents to meet the applicable standards.

More important, therefore, are the waste products that are produced through each of the processes, as these substances need to be disposed of as long as AMD from the mining basins is being abstracted and treated; extensive disposal sites would be required. It is also important that the substances formed are adequately stable so as not to pollute the environment. The stability of the waste products, as well as the volumes produced, should therefore be a major criterion in the selection of the long-term solution.

A further factor to be taken into account is the level of development of the technology. As stated earlier in the report, there are three levels of development according to which the technology has been classified (i.e. laboratory scale, pilot scale and proven technologies). Of all the technologies investigated, only the HDS process and the conventional multistage RO process can be classified as proven technologies. These processes have been implemented in plants at full scale with treatment capacities that are comparable with the capacities required for the treatment of the AMD on the Witwatersrand. It would be too simplistic to rule out all other technologies only on the grounds that there are no installations of comparable size, since some of the technologies may be applied successfully after further development.

In the evaluation of the technologies, it needs to be taken into account that the AMD problem on the Witwatersrand is currently one of the biggest AMD problem in the world. Nowhere have plants been constructed to meet the level of demand that is required on the Witwatersrand, and South Africa is thus embarking on untested territory. It is therefore sensible also to evaluate technologies that have not been tested to the scale required. It will therefore be advisable to test the alternative technologies that show potential at demonstration scale to assess all risks.

There could be a reduction in the production of waste products if the following processes are employed:

- Fe-CN process;
- Alternative RO (MiWaTek);
- Biosure;
- Paques; and
- Electrocoagulation.

The Paques process probably has the potential to produce the lowest volume of waste products.

A reduction in the production of waste products would reduce the problems associated with the disposal of the waste products, which would have a major influence on the economics of the operation, especially if the indefinite horizon of the problem is taken into account.

It would thus make sense to be able to analyse these processes in detail, by constructing pilot plants with the capacity to treat about 10 Mℓ/d in order to research and demonstrate the suitability of the various processes.

The Fe-CN process appears to have great potential; however, there are still significant issues that need to be cleared and proven. Due to the perceived advantages, it is recommended that this process be investigated in detail to either prove it safe, or to motivate its rejection.

The Biosure process has already been studied by the Water Research Commission in association with ERWAT. Clarity needs to be obtained regarding the licensing of the process and the ownership of the intellectual property.

The ownership of the Paques biological process is clear, and it would only be necessary to negotiate the rights to construct such a plant. The owners of the intellectual property would inevitably have to be involved. The approach to the recommended research should ensure that South Africans are trained and educated in the process.

The capacity of the biological processes (Biosure and Paques) to treat the volume of AMD is restricted by the available organic material. The total volume of sludge produced by the wastewater treatment works in the south of Johannesburg and on the East Rand is inadequate to adequately treat all the AMD. Additional sources of organic material would have to be researched and sourced.

The owners of the intellectual property of the alternative RO keep it very confidential, and it is difficult to obtain adequate information to evaluate fully the process. The advantages of the process appear to be very attractive, however, thus warranting further research.

AMD water is rising in the basins, and urgent action is required. There is simply no time left for experimentation in searching for the optimal solutions for implementation in the near future. If any proven technologies are used, the solution that is implemented might later be shown to have contained some element of ‘non-optimal’ expenditure. This fact has to be accepted, as time has simply run out.

The only solution that can be implemented with a low risk is the HDS process followed by conventional multistage RO. The product water by this process train is also the most versatile in terms of re-use options and is most likely to be accepted by the public or industry should it be considered for potable use or re-use. This process train should be analysed in detail, as it is able to address all associated risks, and costs can be assigned to the elimination of the risks. This will then be the base case against which all other processes would be compared and measured. However, since this base case produces large volumes of sludge as well as some brine (feed and target product water quality dependent), which are expensive to dispose of, it may later be shown that it is not the best long-term solution if some of the other technologies prove themselves. Note that options to beneficiate the sludge streams and the brine are being researched and could in future reduce the liability associated with the waste disposal for the conventional multistage RO process.

8. RECOMMENDATIONS

Following the above discussion, from a process perspective we recommend that:

a) The implementation of the long-term solution in the Western Basin should comprise installation of one or more pilot scale technologies to allow them to be tested and refined. The suitability of the following processes is of particular interest:

   (i) Fe-CN-process;
   (ii) Alternative RO (MiWaTek);
   (iii) Biosure process (ERWAT);
   (iv) Paques process;
   (v) Electrocoagulation (P2W).

   The research should include the construction of pilot plants with capacity to treat about 10 Mℓ/d, which should be successfully operational for at least two years to allow all secondary effects and all materials handling elements to be adequately proven.

b) A limestone and HDS pre-treatment plant would be constructed in the Central Basin in line with the STI, followed by a conventional multistage RO plant, with an operational horizon of not more than 15 years. This would allow competition at that stage with other technologies that have been proven by then.

c) In the Eastern Basin more water quality sampling should continue to give more confidence in the results presented in this study. If these results are confirmed, then a HDS plant, as discussed, should be implemented. This should be followed by a conventional multistage RO plant. These plants should have a planned operational life of not more than 15 years, for the same reasons as for the Central Basin.

REFERENCES

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Appendix A

Background Information on Ion Exchange

Ion Exchange

Several ion exchange processes were presented by Cwenga Technologies for desalination or the removal of uranium.

General Process Description

Ion exchange is used to remove specific ions from solution. The ions removed depend on the resin media used. Figure 1 is an illustration of the ion exchange and regeneration process.

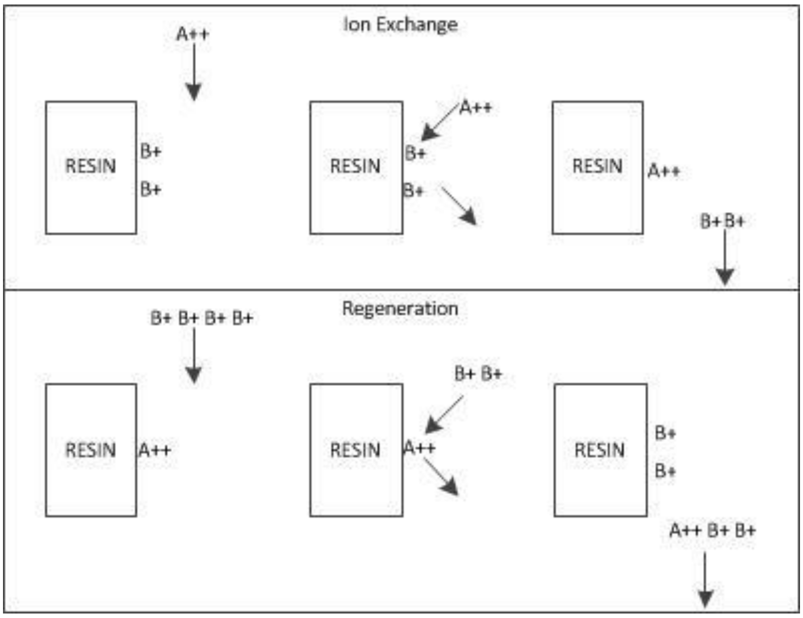

Figure 1: Illustration of Ion Exchange Process

Ion exchange operates as a batch process. The water to be treated is passed through a resin media where the ions to be removed attached to the resin and an ion with the same charge is released into the water. The ions that are generally released from the resin are monovalent ions. This is so the ions released do not increase the TDS and electrical conductivity of the treated water.

Once all the active sites on the resin are filled the resin is considered saturated and the unit must be taken offline and the resin regenerated. During regeneration strong chemical solutions are used to reverse the ion exchange process. The ions that were removed from solution are released from the active site and an ion from the regeneration solution attaches to the resin active site. The regeneration solution required depends on the type of resin used.

To maintain the efficiency of the ion exchange and extend the life with the media pre-treatment of the water is often required. Suspended solids, organics and oil and grease can poison the resin and decrease the efficiency.

Selective Uranium Removal

All three basins contain uranium at levels exceeding the limits set by SANS241:2011 (Uranium tests were only done for the Central and Eastern basins but it is believed that all three basins contain uranium). A selective resin is used to remove the uranium from the AMD as an anionic complex. As the resin has a high capacity and the uranium concentrations are fairly low, the resin requires infrequent regeneration.

Sulphuric acid is used to regenerate the resin. The hydrogen ions attach to the resin releasing the uranium forming uranium sulphate. The solution produced from the regeneration of the ion exchange can potentially be sold as a by-product to recover the uranium. Due to the low infrequent regeneration the amount of uranium recovered and the cost that can be recovered would be minimal and is only likely to recover the operating cost associated with the process.

Placing the process upstream of all other processing units ensures that any residual streams formed in downstream processes, such as HDS sludge, will maintain the uranium concentrations within acceptable limits. If the HDS sludge or other residual streams contain high levels of uranium, the residuals will influence whether the sludge be classified as a hazardous substance. The residuals will in all probability not be able to be used as a by-product and may make disposal of the sludge more difficult. However, if the HDS can be disposed of in a dedicated disposal site which can accept sludge with high uranium concentrations the ion exchange process may not be required. The inclusion or exclusion of ion exchange will depend upon an economic Cost-Benefit Analysis (CBA) to be done during procurement by tenderers.

Target Quality of Treated Water

The uranium concentrations that can be achieved through ion exchange for each of the basins are shown in Table 1. These results assume that the ion exchange unit is placed upstream of the HDS plant.

Table 1: Uranium concentration in treat water

Location	Uranium Concentration 50th Percentile (µg/L)	Uranium Concentration 75th Percentile (µg/L)
Eastern	<10	<10
Central	10	10
Western	N/A	N/A

Waste Products Produced

A residual is produced during the regeneration of the ion exchange resin. This solution produced from regeneration will contain the uranium removed from the AMD in the form of uranium sulphate. As the solution has a high uranium content it can potentially be sold as a by-product to recover the uranium. Due to the high uranium content the solution is classified as a hazardous substance. This increases the risks associated with handling, storage and transportation of the solution. Operators will have to be properly trained to handle the substance to reduce risks to personnel and the environment.

Chemical Requirements

Sulphuric acid is required to regenerate the ion exchange resin. Sulphuric acid is relatively cheap and can be sourced easily. The amount required is dependent on the mass of the resin and the frequency of regeneration.

Sulphuric acid is a highly corrosive substance and is classified as a hazardous substance. This increases the risks associated with handling, storage and transportation of the solution. Specialised infrastructure and equipment will be required to safely manage the chemicals and reduce risks of chemical release. Operators will have to be properly trained to handle the substance to reduce risks to personnel and the environment.

Costs

Table 2 shows the capital expenditure based on the individual basins water quality and a 30ML/day flowrate for all basins. The table also provides the net annual operating expenditure.

Table 2: CAPEX and OPEX associated with all three basins

	Western Basin		Central Basin		Eastern Basin	
	50th Percentile	75th Percentile	50th Percentile	75th Percentile	50th Percentile	75th Percentile
CAPEX	R66 960 000	R66 960 000	R66 950 000	R66 950 000	R66 950 000	R66 950 000
Annual OPEX	R4 590 000	R4 590 000	R1 999 600	R1 786 900	R4 048 700	R4 078 600

Advantages

The advantages of the ion exchange uranium removal process are considered to be the following:

- The uranium concentration in the treated water meets specifications laid down;
- HDS sludge and other downstream residuals do not contain uranium. Constraints on disposal or sale of residual will be less stringent;
- A possible market for the residual products exists, which would reduce the disposal requirements, although this has not been demonstrated.
- The process dynamics are well understood, and the associated risks are therefore understood.

Disadvantages

- High capital costs;
- High risk associated with the handling, storage and transportation of sulphuric acid;
- If market for regeneration solution does not exist will need to manage the disposal of hazardous waste product.

Desalination with Ion Exchange (Ca, Mg, Fe, Mn, SO$_4^-$)

Desalination of the AMD water can also be achieved using ion exchange. Two process options have been put forward by Cwenga including different resin media and regeneration solutions. Both options include two ion exchange units with different resin which are operated in series. The first unit contains a strong acid cation (SAC) resin and the second contains a weak base anion (WBA) resin.

Option 1: With Nitric Acid and Ammonia Regeneration

This process can be used to treat AMD before or after the HDS process. The SAC resin removes all cationic components in solution such as calcium, magnesium, manganese and iron. The WBA removes anionic compounds mainly sulphate.

$$SAC\ Ion\ Exchangec \quad \begin{cases} Ca^{2+} \\ Mg^{2+} \\ Fe^{2\,/3+} \end{cases} (Solution) + H^{+}(Resin) \rightarrow \begin{cases} Ca^{2+} \\ Mg^{2+} \\ Fe^{2\,/3+} \end{cases} (Resin) + H^{+}(Solution)$$

$$SAC\ Regeneration \begin{cases} Ca^{2+} \\ Mg^{2+} \\ Fe^{2\,/3+} \end{cases} (Resin) + H^{+} + NO_3{}^{-}(Solution) \rightarrow \begin{cases} Ca^{2+} \\ Mg^{2+} \\ Fe^{2\,/3+} \end{cases} + NO_3{}^{-}(Solution)\ H^{+}(Resin)$$

$$WBA\ Ion\ Exchange \quad SO_4\ (Solution) + OH^{-}(Resin) \rightarrow SO_4\ (Resin) + OH^{-}(Solution)$$

$$WBA\ Regeneration \quad SO_4\ (Resin) + NH_4{}^{+} + OH^{-}(Solution) \rightarrow SO_4\ NH_4{}^{+}(Solution) + OH^{-}(Resin)$$

Nirtic acid is used to regenerate the SAC resin. The hydrogen ions attach to the resin releasing the cations forming a mixture of metal nitrates. Ammonium hydroxide is used to regenerate the WBA resin. The hydroxide ions attach to the resin releasing the anions forming primarily ammonium sulphate. Both streams have the potential to be sold for the production of explosives and fertiliser.

Option 2: With Sulphuric Acid and Lime Regeneration

This process can be used to AMD after the HDS process when the AMD is saturate with calcium sulphate. The SAC resin is designed to primarily remove calcium. The WBA resin is designed to primarily remove sulphate.

$$SAC\ Ion\ Exchangec \quad Ca^{2+}\ (Solution) + H^{+}(Resin) \rightarrow Ca^{2+}(Resin) + H^{+}(Solution)$$

$$SAC\ Regeneration\ Ca^{2+}\ (Resin) + H^{+} + SO_4{}^{-}(Solution) \rightarrow Ca^{2+} + SO_4{}^{-}(Solution) + \ H^{+}(Resin)$$

$$WBA\ Ion\ Exchange \quad SO_4\ (Solution) + OH^{-}(Resin) \rightarrow SO_4\ (Resin) + OH^{-}(Solution)$$

$$WBA\ Regeneration \quad SO_4\ (Resin) + Ca^{2+} + OH^{-}(Solution) \rightarrow SO_4 + Ca^{2+}(Solution) + OH^{-}(Resin)$$

Sulphuric acid is used to regenerate the SAC resin. The hydrogen ions attach to the resin releasing the calcium forming calcium sulphate (gypsum). Lime is used to regenerate the WBA resin. The hydroxide ions attach to the resin releasing the sulphate forming calcium sulphate (gypsum). Both streams produce gypsum which has the potential to be sold as a building material. Any supernatant collected from the residual gypsum can be returned to the feed resulting in zero liquid discharge.

Target Quality of Treated Water

The table below is the water quality produced from a nitric acid and ammonia ion exchange unit upstream of the HDS.

Table 3: Water quality of treated water Option 1

Water quality parameters	Units	SANS-241 (2011)	Western Basin		Central Basin		Eastern Basin	
			50th %tile	75th %tile	50th %tile	75th %tile	50th %tile	75th %tile
Ca	mg/ℓ		137.11	5.83	2.79	4.03	0.77	3.79
Mg	mg/ℓ		5.83	N/A	1.72	2.01	0.54	1.19
SO_4	mg/ℓ	250 (WB&CB) 350 (EB)	154.10	162.84	141	148	57.3	80
Cl	mg/ℓ	300	5.83	N/A	68	70	7.8	9
Fe (II)	mg/ℓ	0.3	6.61	7.71	0.4	0.48	0.74	1.26
Al	mg/ℓ	0.3	5.83	NS	NS	NS	NS	NS
Mn	mg/ℓ	0.1	0.56	0.7	0.47	0.49	0.03	0.04
Zn	mg/ℓ		5.83	N/A	0.09	0.10	0.01	0.01
Co	mg/ℓ		5.83	N/A	0.05	0.05	0.00	0.00

Water quality parameters	Units	SANS-241 (2011)	Western Basin		Central Basin		Eastern Basin	
			50th %tile	75th %tile	50th %tile	75th %tile	50th %tile	75th %tile
Ni	mg/ℓ		5.83	N/A	0.11	0.12	0.00	0.01
U	mg/ℓ	0.015	5.83	N/A	0.01	0.01	0.01	0.09

The table below is the water quality produced from a sulphuric acid and lime ion exchange unit downstream of the HDS.

Table 4: Water quality of treated water Option 2

Water quality parameters	Units	SANS-241 (2011)	Central Basin 50th Percentile
Ca	mg/ℓ		2.79
Mg	mg/ℓ		1.72
SO_4	mg/ℓ	250 (WB&CB) 350 (EB)	141
Cl	mg/ℓ	300	68
Fe (II)	mg/ℓ	0.3	0.40
Al	mg/ℓ	0.3	NS
Mn	mg/ℓ	0.1	0.47
Zn	mg/ℓ		0.9
Co	mg/ℓ		0.05
Ni	mg/ℓ		0.11
U	mg/ℓ	0.015	0.01

Waste Products Produced

Option one produces two residual streams one consisting of metal nitrates and the other ammonium sulphate. This residual have a potential to be used with the fertilizer and explosives industry. If residuals cannot be sold disposal of the residuals will entail high risks. Nitrate is a hazardous substance and will have to be managed in an appropriate and approved waste disposal facility. Both residual streams will require separate disposal and handling as contact between the two residuals has the potential to form ammonium nitrate which is considered as dangerous goods. This process is only viable if sale of the by-products is possible due to the high cost associated with handling and disposing of the hazardous waste.

Option two produces gypsum; a portion of the gypsum could possibly be offset into the market at no cost to the client. The gypsum is not hazardous and could possibly also be discharged on to nearby tailings dams. Alternatively, sludge storage facilities would have to be constructed in order to manage the sludge produced.

The final handling and disposal of the residuals is a high risk to the project and should be further investigated in the pre-feasibility phase. The following options could be considered:

- Disposal of gypsum to existing tailings facilities;
- Construction of a lined waste disposal facility to discharge and store residuals; or
- Placement of residual into the market as a by-product

Chemical Requirements

Considerable amounts of Nitric acid and ammonia or sulphuric acid and lime are required to regenerate the ion exchange resins. Nitric acid and ammonia are relatively expensive when compared to sulphuric acid. It may also be difficult to source nitric acid and ammonia in the amounts required.

All of these chemicals are considered hazardous substance. This increases the risks associated with handling, storage and transportation of these products. Specialised infrastructure and equipment will be required to safely manage the chemicals and reduce risks of chemical release. Operators will have to be properly trained to handle the substance to reduce risks to personnel and the environment.

Costs

The capital and operating cost estimates for the Western, Central and Eastern Basins for Option and 1 and 2 are summarised in Table XX and Table XX below. The capital costs are based on feed water quality at the 50th and 75th percentile and a flowrate of 30ML/day.

Table 5: CAPEX and OPEX associated with Ion Exchange Desalination Option 1

	Western Basin		Central Basin		Eastern Basin	
	50th Percentile	75th Percentile	50th Percentile	75th Percentile	50th Percentile	75th Percentile
CAPEX	R179,500,000	R179,500,000	R179,500,000	R179,500,000	R179,500,000	R179,500,000
OPEX (Annual)	R316,500,000	R368,100,000	R227,900,000	R269,600,000	R58,900,000	R206,500,000

Table 6: CAPEX and OPEX associated with Ion Exchange Desalination Option 2 for Central Basin

	Central Basin
	50th Percentile
CAPEX	R233,300,000
OPEX (Annual)	R51,200,000

The comparison of the cost associated with the central basin 50th percentile show that the second option has a slightly higher capital cost and a considerable reduction in the annual operating costs. The difference is operating costs is primarily due to the price of the chemicals used during regeneration. Nitric acid and ammonia are considerably more expensive than sulphuric acid and lime. This coupled with the large volumes that are required for regeneration has a large impact on the operating costs.

Advantages

The advantages of desalination with ion exchange are considered to be the following:

- The sulphate and chloride in the treated water meets specifications laid down;

- A possible market for the residual products exists, which would reduce the disposal requirements, although this has not been demonstrated.

Disadvantages

The disadvantages of the desalination ion exchange process are as follows

- High capital expenditure
- High operating costs compared to other desalination options;
- Large chemical usage required for regeneration;
- High risk associated with the handling, storage and transportation of sulphuric acid;
- If market for regeneration solution does not exist will need to manage the disposal of hazardous waste product.