EXECUTIVE SUMMARY

PROJECT OVERVIEW

This project has involved an extensive application and review of the use of a range of geochemical assessment tools that are available for making predictions of future water quality impacts from mining sites. While the range of tools that are available (including those that were applied in this research project) are generally designed to be universally applicable to a wide range of mining facilities and scenarios, this project has specifically focused on their use and application in an underground coal mining scenario.

The tools that were evaluated in this research project were selected and agreed to by a workshop that included representatives from the mining industry, academia, consultants and other practitioners in the field. Persons that participated in this workshop are listed in the Acknowledgements section of this report. The tools that were selected represent the full range of tools available for assessments of this nature and specifically include those tools most commonly used. The tools that were selected are as follows:

STATIC TESTS
- Acid base accounting (ABA)
- Mineralogy (X-ray diffraction, X-ray fluorescence analysis, water extract, *aqua regia* extract, microscopy)

KINETIC TESTS
- Humidity cells

NUMERICAL MODELS
- Equilibrium modelling
- Kinetic modelling

It should be borne in mind that geochemical assessment tools, particularly numerical models, are being improved and developed all the time and that the tools used in this research project will also have already been improved. Some of the disadvantages mentioned in the report may therefore already have been addressed in revised and updated versions of the models. Persons undertaking geochemical assessment and impact prediction projects are expected to be specialists in their field and should ensure that they are fully acquainted with the latest available versions of the various tools under discussion in this report.

This project aimed to address the problem of lack of consensus on the correct tools for any particular situation being assessed. In addition to creating uncertainty, this situation also led to incorrect application of tools, with a focus on undertaking the cheapest type of assessment rather than the correct one. This research project has provided the information, through rigorous application of the various tools, and consultation with a wide range of specialists and roleplayers in the field, that will assist in providing clarity and guidance on the most appropriate tools for different applications.

The project was undertaken at two different underground collieries – one in the Witbank coalfield and one in the Vryheid coalfield. Extensive data collection exercises were undertaken over a period of time at both these test sites in order to provide the information, samples and material required to apply the various tools. This exercise is discussed in considerable detail in Chapters 2 and 3 of the report and important generically applicable lessons regarding an appropriate sampling and monitoring programme are captured and provided in Chapter 9 of the report.

The real body of the report is captured in Chapters 4-8 of the report, where the various categories of tools were applied to the different mine sites with the objective of establishing what future predictions could be made with each tool under consideration and what the limitations and uncertainties were

with each tool. As far as possible, different project specialists were given the task of assessing different tools in reasonable isolation from each other in order to determine what conclusions each could draw without cross-referencing the results from other more sophisticated tools. Each chapter that discusses a specific range of tools is also provided with a chapter summary.

In this context, the different tools were applied and reviewed as follows:
1. Use of ABA data without any reference to other geochemical or mineralogical data. The only other data available for this assessment were the information presented in Chapters 2 and 3.
2. Use of ABA data, together with all mineralogical data and information in Chapters 2 and 3.
3. Use of all ABA data, mineralogical data, humidity cell data and information in Chapters 2 and 3.
4. Use of all ABA data, mineralogical data, humidity cell data and Chapter 2 and 3 information and use of equilibrium geochemical model tools – Phreeqc and Geochemist's Workbench.
5. Use of all ABA data, mineralogical data, humidity cell data, equilibrium geochemical modelling results and Chapter 2 and 3 information and use of kinetic geochemical modelling tools – Phreeqc and Geochemist's Workbench.

Clearly, the five different scenarios reviewed above represent a progression from a screening level geochemical assessment all the way through to a full detailed kinetic modelling assessment.

SELECTION OF RESEARCH SITES

Site selection criteria were developed to allow for the identification of an old partially-flooded compartment and a working compartment at two underground coal mines. The former serves as the experimental test site while the latter is an optional test site for comparison and supplementary data collection for the actual test site. It was agreed that the old partially flooded compartment must meet the key criteria 1) isolated, well-defined compartment, 2) no contamination by other sources of water except for natural groundwater ingress, 3) no major water course overlying the compartment, 4) availability for access, 5) available historic mining information; 6) available information on material balance, 7) available information for water balance. The working compartment must meet the criteria of 1) accessibility, 2) bord/pillar mining, 3) wet, i.e. producing water.

Two research sites were successfully selected although there were difficulties encountered in the site selection.

Brandspruit site

S7 compartment was selected as the test site at Brandspruit Colliery while S30 was selected as the working compartment. S7 meets all the site selection criteria, i.e. 1) isolated from other compartments and surrounded by dykes on three sides, 2) no water ever having been pumped into it from other compartments in the mine history, 3) no major watercourse overlying the compartment, 4) ready access to the site, 5) available historic mining information, 6) available information on material balances through field visits and floor sampling, 7) available information for water balances from the monitoring programme and prior studies, and 8) fairly old site, being closed in 1992. The major criteria that were not met, is the lack of a systematic historic mining record for material left on the ground and water quality data. However, the floor sampling and water monitoring programme carried out as part of the research project was able to largely compensate for these deficiencies.

S30 compartment was selected as a working compartment and enabled information to be obtained on the mining method and enabled the collection of fissure water samples for geochemical modelling.
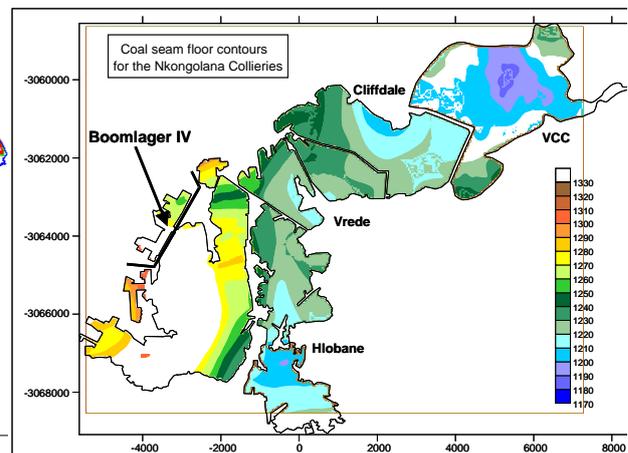
Hlobane site

Boomlager IV adit was selected as the test site at Hlobane Colliery although no working compartment was selected as all major mining operations had already ceased at Hlobane.

Boomlager IV meets most of the site selection criteria, specifically 1) isolated from other compartments and no water able to enter the adit area from other mining areas, 2) no major overlying

watercourse, 3) available historic information on mining methods, 4) available information for water balances from the detailed monitoring programme undertaken by the mine since 1997, and 5) fairly old compartment, being closed in 1995. The major criterion, not met is 1) no access to the adit due to its closure, although this is compensated for by the fact that the adit was well characterised in terms of flowpath, water balance, groundwater system.
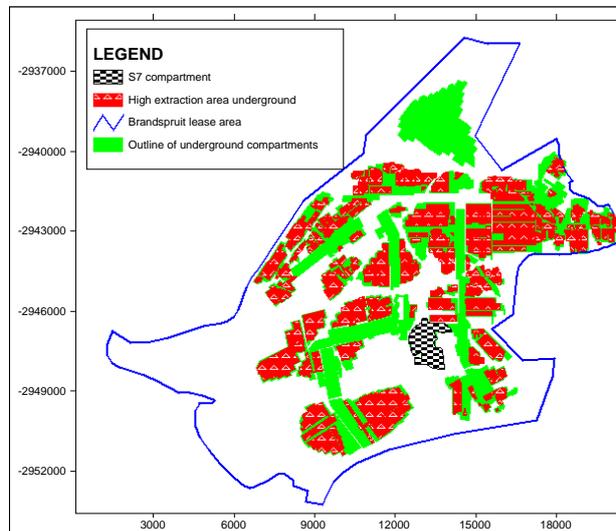
Brandspruit Colliery Test Site – Compartment S7 | **Location of Hlobane Colliery Test Site – Boomlager IV Adit**

DATA COLLECTION

Sampling of solid materials for geochemical assessment that was carried out in this study included:
- underground coalface sampling;
- surface borehole drilling and sampling; and
- floor material sampling in bord areas.

These three sampling exercises each have different objectives. The channel sampling method was employed to sample the underground coalface. Surface boreholes that cover the whole lithological sequences in terms of roof, floor, and coal materials are considered an absolute necessary sampling procedure in this study, and also as a reference for other studies. Floor material sampling was aimed at:
- estimating the volume and mass of the material;
- estimating composition of the materials in terms of lithology;
- determining material properties: and
- obtaining samples for detailed laboratory analyses such as ABA, humidity cell test and geochemical analyses.

The sampling results were used for interpretation of the prediction techniques, specifically for geochemical modelling.

Detailed water monitoring and sampling programmes were also undertaken in this study, specifically for S7 compartment, Brandspruit Colliery. The exercise included:
- grab and stratified sampling from underground stored water;
- sampling from the water pipe before and after pumping;
- sampling from water monitoring borehole

Selected analyses for monthly sampling and measurement and full analyses for bi-monthly samples were carried out following the water monitoring programme developed for S7 compartment, Brandspruit Colliery. The water sampling and monitoring programme for Hlobane Boomlager IV was

conducted earlier, prior to this project, and the data has been used for this study. In addition to the water sampling exercise listed above for Brandspruit Colliery, seepage water has also been collected from Boomlager IV Adit.

STATIC GEOCHEMICAL ASSESSMENT TECHNIQUES

Static tests are typically simple and inexpensive procedures to prove a preliminary assessment of the potential of a waste or other mine component to generate Acid Mine Drainage (AMD). They are primarily intended to examine the balance between the acid-producing and acid-consuming components of a sample. Static tests do not provide definitive answers to all questions regarding the future behaviour of wastes and should not be used as such. They do however provide a means to classify wastes according to their potential to produce AMD and indicate the extent and type of further testing and evaluations that should be carried out. The following procedures or methods for static tests are the most commonly used:

- Paste pH;
- Peroxide methods;
- Static Net Acid Generation (NAG) Procedure;
- BC Research Initial Test;
- Sulphur content;
- British Columbia (BC) Research Confirmation Test;
- COASTECH modified biological oxidation test;
- Sobek Neutralisation Potential Method;
- Carbonate NP determination;
- Modified ABA procedures for Neutralising Potential;
- Lapakko Neutralisation Potential Test Procedure;
- Calculated NP; and
- Net Carbonate Value (NCV) for ABA.

Based on interaction between the project team and the peer workshop mentioned in the Acknowledgements, the following static geochemical assessment techniques were selected for this research project:

- Paste/Initial pH and determination of solution products;
- Acid potential using hydrogen peroxide oxidation, analysis of oxidation products; and
- Neutralising potential using sulphuric acid adaptation of the Sobek method.

Conclusions from static tests for Brandspruit

Based on the ABA data and the conceptual hydrogeochemical model presented in Chapter 4, the following conclusions can be made:

- Under open system conditions, there are only two samples with more AP than NP;
- NNP values vary from –14.5 to 71 kg/t $CaCO_3$, averaging at around 27 kg/t;
- The ratio of NP:AP varies from 0.5 to >81, averaging at around 10:1 under open conditions. However, the distribution of these values indicates that less than half are definite non-acid generators with four times or greater NP to AP ratios;
- Analysis of the data to find an acceptable sample size indicates that for the distributions seen in this data a sample size of 30 as is present here appears to be adequate for an 80% confidence level in the results;
- Using the extraction ratios and mining types, a first order estimate of the total NP and AP material has been made. This indicates that the NP exceeds the AP. One of the areas, where it is felt there is insufficient data, is in the roof sediments. Where one sample has a NNP of –14.5 kg/t $CaCO_3$. Since a large proportion of S7 has been total extracted, a large proportion of the first few meters of roof sediments are expected to be in contact with water. Only two samples for this layer have been obtained and the confidence in these values is consequently not very high;
- Based on the expected excess of calcium-containing carbonates (unless repeated flushing is practiced) and calcium concentrations of around 200 mg/ℓ being maintained, sulphate values

should not exceed around 2800 mg/ℓ in the longer term. This value is based on the maximum solubility of gypsum (Ksp of $10^{-4.58}$) and conventional Solubility Index considerations;

- Since the total NP and AP can be obtained using these techniques, an assessment of which material is currently weathering can be used to determine whether long-term acidity might still arise (Banwart and Malmstrom, 2001). From the current ratios being observed in the water leaving the compartment it can be seen that currently the molar ratios are fairly equal. It is felt that this is skewed by the gypsum equilibrium in the water; therefore this might not be an accurate indication of the true reaction rates; and

- Superimposing the degree of flooding on the calculated ratios indicates that if the compartment is allowed to flood and kept at a flooded level rather than being emptied, the risks of acidification are considerably reduced.

Conclusions from static tests for Hlobane

With regard to the ABA data:

- Based on total sulphur (wt%) and the NP/AP ratio, the Hlobane samples, with the exception of the interburden shale, are potentially acid generating. The average total sulphur and NP/AP ratio, however, suggests that the Hlobane samples are as a whole, potentially acid generating (PAG);

- The NP and AP values of the samples are not very high although AP is slightly higher than NP as evidenced by the negative NNP values which are all <0 kg/t;

- The NP and AP values, NP/AP ratio, and the negative NNP values all indicate that the Hlobane samples have a potential to generate acid mine drainage. However the NNP values which are >-20 kg/t indicates the need to do further tests such as kinetic test/s and/or modelling to refine the interpretation of the ABA test.

With regard to the mineralogy and geochemistry data:

- Using the mineralogical and geochemical data, plagioclase is identified as the potential source of alkalinity in the materials;

- The sulphide concentrations in the samples are calculated based on the total sulphur content obtained from the ABA test and the XRF data. This demonstrates the need to have geochemical data to better quantify the trace minerals, mainly sulphides, which in most cases occur in concentrations lower than the detection limit of routine XRD techniques;

- The interpretation that these samples have low NP and AP is supported by mineralogy and chemical analyses of the samples which showed that the primary minerals which have the potential to generate acidity (sulphides) or alkalinity (carbonates) are either absent or present in insignificant amounts;

- The geochemical analysis and interpretation identified Cr, V and Zn as potential pollutants that may affect the quality of the water, provided the physico-chemical conditions prevailing in the Hlobane site allow leaching of these metals in significant amounts. Ni and Pb are intermediate in concentration whereas Co and Cu occur at less than 20 mg/kg, which makes them unlikely leachants to cause pollution. However this interpretation needs to be verified by the water quality assessment which is dealt with elsewhere in the report.

KINETIC GEOCHEMICAL ASSESSMENT TECHNIQUES

Kinetic tests were included as part of the analytical techniques to be evaluated for their predictive capability. Kinetic tests are intended to reproduce the natural field reaction processes, usually at an enhanced rate so that an indication of water quality evolution and the important factors affecting this process can be determined. For this project, it was agreed to use humidity cells as the kinetic test procedure and the humidity cells were operated at the PHD laboratories in Johannesburg, using the methodology prescribed by the ASTM (1996). The primary objectives of the humidity cell test are to:

- Generate leachate water chemical data;
- Measure stable reaction rates under specific geochemical conditions; and
- Calculate depletion times of acid generating, acid neutralising, and metal leaching minerals.

Conclusions from kinetic test results for Brandspruit

The humidity cell results from the eight cells run for this project provide several pertinent conclusions:

1. The kinetic tests provide an indication of the key reactions expected to affect water quality changes in underground compartments.
2. The results of the humidity cells are consistent with the static test results, in terms of defining the likelihood of acidification.
3. Twenty-week tests are not necessarily indicative of the full reaction sequence that could occur in the field.
4. The humidity cells confirm the static test finding that the roof lithologies are the most problematic layers in the S7 compartment. The only two cells that acidified over the period of testing, and the highest sulphate generators were from the composite roof samples tested.
5. Direct comparison between static testing and humidity cell testing was impeded by the use of composite samples rather than identical samples for both methodologies.
6. Sulphate generation rates form these cells show that a "stabilised" rate for roof lithologies would be in the order of 200 mg/kg/week and around 50 mg/kg/week for the coal.
7. The associated release rates for different parameters could be determined from the humidity cell tests.
8. In the coal cells, the Ca/Mg release rates indicate equal amounts of the two anions suggesting a dolomitic carbonate source. These two anions are also released in equal proportions to the sulphate.
9. In the roof cells, more Mg than Ca is released with equivalent sulphate production exceeding the amount of these cations released, consistent with findings of Morin and Hutt, 1998 and Usher *et al.*, 2001.
10. The humidity cell results indicate that sodium and alkalinity released from the coal is very low. The sodium-rich waters encountered in the southern parts of the Witbank/ Highveld coalfield appear to derive from connate water sources rather than weathering of primary mineralogical phases.
11. The humidity cell results confirm the important finding of the static test results, that in the proximity of S7, the overlying lithologies forming part of the goaf present the greatest threat to water quality deterioration. In terms of mining method selection, this could have significant implications.
12. In attempting to upscale the results of humidity cell tests to field applicability, the need for various assumptions was highlighted. Direct upscaling of results is not feasible in an underground coal compartment setting.
13. The importance of proper site characterisation and incorporation of a well-constrained conceptual model was illustrated by the upscaling results.
14. The results for compartment S7 indicate that the influence of influent recharge waters plays a very important role in the reactions taking place within the compartment. Proper characterisation of recharge water quality is vital for accurate hydrochemical predictions.

Despite the uncertainties associated with humidity cell results, the findings in this project suggest that these tests can play an important role in understanding the expected interactions at an underground compartment. As with any of the other techniques discussed in this report, proper definition of the purpose and limitations of the test will ensure that the results are used appropriately.

Conclusions from kinetic test results for Hlobane

With regard to pH and SO_4 generation:

- The leachates from the coal seams and the roof sandstone samples show low pH 3.5 to 5.5) throughout the test, whereas the pH values of the leachates from the interburden shale fluctuate around pH of 6.5 to 7.5. Close examination of the pH data, however, indicates that all the samples show an increase in pH from week 6 to week 13 and then a decrease in pH from week 14 onwards.
- SO_4 concentrations in the leachates decrease overall but stabilise from about week 17.

- The lower coal seam generated the highest cumulative sulphate (2000 mg/ℓ in 20 weeks) as compared to the lowest generated, which is about 1000 mg/ℓ for the interburden shale. The top coal seam and the roof sandstone generated slightly less sulphate than the lower coal seam.
- Although correlation is evident between pH and SO_4 concentration, SO_4 generation may not be solely from pyrite oxidation but also from sulphate salts such as Na-sulphate.
- By the end of the 20-week humidity cell test, about 80% of the total sulphur remained in the solid sample from the lower coal seam, about 93% in the interburden shale, and 92% in the upper coal and in the roof sandstone.

With regard to acid neutralisation:
- The calculated carbonate ($CaMg/SO_4$) and anorthoclase (Ca/SO_4) molar ratios are not clearly indicative of which mineral is the source of the neutralisation potentials in the Hlobane samples. The lack of a clear relationship between pH, SO_4 and the molar ratios preclude one from establishing the source of alkalinity with any certainty.
- NP generation in most cases is about 10 mg $CaCO_3$/kg/wk.
- 99.6% of the NP in the roof sandstone and 99.8% for the coal seams estimated by ABA test are still available at the end of the 20-week test. The NP of the interburden shale is 99.9% of the ABA NP.

With regard to mineral reaction rates:
- Plots of rates of production of SO_4, NP and pH show no clearly defined relationship. However, in the case of the roof sandstone, a slight increase in pH at week 11 is related to a slight increase in the NP consumption.
- The leaching rates are high for the first two weeks for all the metals, with the exception of Al;
- Although no apparent trend is established for Al and K by the end of the 20th week of the experiment, the depletion rates of Mg, Na and Ca seem to stabilise after week 7 with a slight progressive decrease towards the end of the test.
- SO_4 reaction rates range from 19 mg/kg/wk for the interburden shale to 56 mg/kg/wk for the lower coal seam with an average rate of 30.5 mg/kg/wk for the entire material.
- The leach rate for Ca ranges from 0.2 (interburden shale) to 1.61 (lower coal seam) with an average rate of 0.82 mg/kg/wk and for Mg from 0.18 mg/kg/wk (the interburden shale) to 1.33 (lower coal seam) with an average of 0.7 mg/kg/wk.
- Whether or not these reaction rates could be extrapolated into the future is difficult to ascertain with the current level of information regarding humidity cell tests in particular and kinetic tests in general. Literature suggests, however, that the reaction rates from humidity cell tests can persist within a factor of two for at least 5 years and stable rates from fresh rocks are similar to 5 year old rates (Norecol Dames and Moore, 1994).

CONCLUSIONS

The research undertaken and reported here clearly demonstrates the value that can be derived from proper application of the range of available tools. The report also documents the limitations of the various tools in making long-term predictions. These limitations are mostly appropriately summarised in Chapter 8 where each tool is assessed in terms of its ability to answer the following key questions that typically require to be answered in a mine impact prediction exercise:

Q1:   Will non-acidic drainage be produced?
Q2:   Will the water become acidic?
Q3:   How acidic will the water become?
Q4:   When will the water become acidic?
Q5:   What is the long-term acidity status?
Q6:   Is the water quality expected to vary with time?
Q7:   Is it possible for the mine water quality to recover in future?
Q8:   How can the mine water be remediated?
Q9:   What is the predicted load of TDS, SO_4 or other contaminants?

Q10:   What is the predicted load of pollutants, e.g. heavy metals?
Q11:   Is calibration, modification throughout life of mine (LOM) and sensitivity analysis possible?
Q12:   What provisions can be made for wastewater management, treatment and utilisation?
Q13:   Is the confidence level of the prediction sufficient to allow for making sound decisions?

While a discussion of the performance of each of the tools in answering questions such as the 13 posed above is provided in the relevant chapters, the conclusions have been summarised in Table E-1, where it is clear that use of a full suite of tools is capable of providing extensive information on potential future water quality impacts from mine sites, with the following provisos:

1. Suitably qualified specialists must be employed to use these tools, especially the more sophisticated tools as detailed knowledge of mineralogy, water balances and chemistry is essential in using the tools and interpreting the data produced.
2. Suitable datasets are available and statistical review of data has been undertaken to define the level of confidence that can be placed in the data.
3. Appropriate sensitivity analyses are undertaken to define the effects of data uncertainty on predicted outcomes and impacts.
4. Implementation of appropriate monitoring programmes to collect data to be applied in validation and calibration of model predictions – especially where geochemical models have been applied.

Table E-1: Summary of capabilities of geochemical assessment tools

	AMD questions	ABA	HC	Equilibrium	Kinetic
Q1	Will non-acidic drainage be generated?	High (certain)	High (certain)	High (certain)	High (certain)
Q2	Will the water become acidic?	Intermediate, for the worst case	High	Yes, but low	Yes
Q3	How acidic will the water become?	Low	Yes, but in short term	No	Yes
Q4	When will the water become acidic?	No	Yes, but with caution	No	Yes
Q5	What is the long-term acid status?	No	Yes, but with caution- short term	No	Yes
Q6	Is the water quality expected to vary with time?	No	No	Yes, confirm with monitoring	Yes
Q7	Is it possible for the mine water quality to recover?	No	Yes, but with caution- short term	No	Yes
Q8	How can the mine water be remediated?	No	No	No	Yes
Q9	Quantitative prediction of TDS, SO_4 load?	No	Yes, with limitations	No	Yes
Q10	Quantitative prediction of pollutants, e.g. heavy metals?	No	Yes, with limitations	Yes, can be determined	Yes
Q11	Calibration, modification through L.O.M, and sensitivity analysis capability?	No	No	No	Yes
Q12	What provisions can be made for wastewater management, treatment and utilisation?;	No	No	Yes, using titration model, chemical treatment	Yes, using titration model, chemical treatment
Q13	Is the confidence level of the prediction sufficient enough to allow making sound decisions?	No	Yes, to the some degree	Yes, to some degree	Yes, with calibration of experimental or field data