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ARD ASSESSMENT HUSAB

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1. INTRODUCTION

Metago Water Geosciences Pty Ltd was requested by Metago Environmental Engineers Pty Ltd to evaluate the acid rock drainage potential and associated leachate quality of tailings, filter cake and waste rock material at the Husab mine, Namibia.

Acid rock drainage (ARD) refers to a water quality resulting from the exposure and weathering of sulphide-bearing mineralized zones. The waters are typically characterised by low pH values and elevated salt and metal concentrations leached from e.g. waste rock or tailings. The driving force of ARD generation is the direct (by oxygen) or indirect (by e.g. ferric iron) oxidation of sulphide minerals like pyrite or in some cases elemental sulphur. The oxidation of sulphide minerals occurs naturally when exposed to the atmosphere through geologic processes, but is often accelerated by anthropogenic activities such as mining or other excavation activities. The acid generating reactions are typically accompanied by acid neutralisation reactions due to the dissolution of carbonate and/or silicate minerals, which buffer the pH values over time along a series of pH plateaus (characteristic of the mineral assemblage and stage of oxidation). The dissolution of carbonate and silicate minerals adds to the composition of the final drainage, which shows different qualities for the different buffer plateaus over time.

The current geochemical assessment characterises the acid generation and metal leaching potential of different mine materials using static test procedures (see chapter 3) and should be seen as a first phase of a site specific geochemical characterisation programme.

2. TESTED MATERIAL

2.1. WASTE ROCK SAMPLES

Six composite waste rock samples, blending different lithologies and compositions (sulphur content, Table 1), were analysed by SGS, Australia for

- Acid-base Accounting (ABA) according to the EPA-600 modified Sobek method
- Sulphur speciation
- Grain-size distribution
- Total leachable metal content
- TCLP extraction tests
- SPLP extraction tests

In order to assess potential effects of the grain size as a proxy for the available surface area on the test results, each sample was split into two different grain sizes (ground to 80% passing 0.25 mm and stage crushed to 6 mm) prior to analysis.

Table 1: Inventory of composite waste rock samples Husab.

HoleID	mFrom	mTo	Rock Type	Zone 1	Zone 2	Sulphidic	Sample ID
RDD009	88	89	Sediment		*	*	WS001
RDD018	73	74	Biotite Schist	*			
RDD019	91	92	Biotite Schist	*		*	
RDD029	166	167	Gneiss	*			
RDD030	86	87	Sediment	*			
RDD053	180	181	Marble		*		
RDD053	221	222	Sediment		*		
RDD053	272	273	Sediment		*		
RDD062	45	46	Alaskite	*			WS002
RDD062	79	80	Calc-silicate	*		*	
RDD062	82	83	Calc-silicate	*			
RDD063	107	108	Alaskite	*		*	
RDD063	66	67	Calc-silicate	*		*	
RDD063	130	131	Sediment	*		*	
RDD064	137	138	Sediment	*			
RDD066	11	12	Cover	*			WS003
RDD066	161	162	Gneiss	*			
RDD066	72	73	Marble	*			
RDD068	39	40	Cover	*			
RDD080	232	233	Gneiss		*		
RDD085	119	120	Biotite Schist		*		WS004
RDD085	155	156	Calc-silicate		*	*	
RDD085	156	157	Sediment		*	*	
RDD086	271	272	Gneiss		*		
RDD100	97	98	Biotite Schist		*		WS005
RDD100	125	126	Biotite Schist		*	*	
RDD100	135	136	Biotite Schist		*	*	
RDD100	190	191	Alaskite		*		
RDD103	96	97	Biotite Schist	*		*	
RDD108	283	284	Marble		*		
RDD112	298	299	Calc-silicate		*		
RDD126	116	117	Sediment	*		*	WS006
RDD131	136	137	Calc-silicate	*			
RDD132	170	171	Marble	*			

2.2. PILOT PLANT RESIDUES SAMPLES

Two sets of pilot plant residues samples were retrieved from the pilot plant and analysed:

- One undifferentiated tailings sample 328-141 analysed in February 2010 by Genanalysis Laboratory Services Pty Ltd, Australia and
- A set of filter cake samples containing Zone 2 filter cake as well as filter cake samples representing year one to three of the operations analysed in September 2010 by SGS, Australia.

3. METHODOLOGY

3.1. ACID ROCK DRAINAGE

3.1.1. Acid-base accounting

Acid–base accounting (ABA) is an analytical procedure that was developed to screen the acid-producing and acid-neutralizing potential of overburden rocks prior to large scale excavations, but is nowadays also used to predict the mine drainage water quality. It is a static procedure and provides no information on the speed with which acid generation or neutralization will proceed, which is usually determined by kinetic weathering or leaching tests.

In ABA, the acid generating potential (AP, synonymous with maximum potential acidity MPA) from the oxidation of sulphur minerals in a rock sample and the acid neutralizing potential (NP) of a rock sample (neutralising bases, mostly carbonates and exchangeable alkali and alkali earth cations) are subtracted to obtain a Net Neutralization Potential (NNP): $NNP = NP - AP$

The results are customarily reported in tons calcium carbonate per thousand kg (or one ton) of overburden or parts per thousand, with negative NNP values indicating the potential to generate acid and therefore a predicted net acid drainage water quality from the rock. Positive values indicate acid-neutralising potential or a predicted net alkaline drainage water quality from a rock sample.

Alternatively the neutralising potential ratio ($NPR = NP/AP$) can be used to identify potentially acid producing rocks, with a ratio of at least 2 needed for complete acid neutralization (Cravotta et al., 1990). In case of preferential exposure or reactivity of sulphides the required ratio needed for complete acid neutralization might go up to 4 (Price et al., 1997) and is used as a precautionary screening value in the current assessment. NPR ratios between 1 and 3 are considered inconclusive, while NPR ratios below 1 indicate potential acid generation (if sufficient sulphur is available, > 0.3 %).

Australian laboratories often prefer to report the Net Acid Production Potential (NAPP), which is the difference between the Acid Production Potential (APP) and the Acid Neutralising Capacity (ANC, titration to pH 7), reported in tons sulphuric acid per thousand kg or 1 ton of waste rock.

The ABA tests assume generally that all sulphur in the sample will react to form sulphuric acid, while some of the sulphur may also be present in non acid producing sulphates. If a significant part of the total sulphur occurs as sulphate sulphur instead of sulphide sulphur, the overall risk of acid generation is reduced. Acid generation of samples with sulphide sulphur content below 0.3 % is furthermore considered to be short term (Price & Errington 1995, Soregaroli & Lawrence 1998). A plot of the Neutralization Potential Ratio (NPR) against the sulphide sulphur analysis is used for the ARD assessment of the results. The plot allows the simultaneous evaluation of the critical NPR values (> 4 for non-acid generating samples) and the critical sulphide sulphur content (> 0.3%) for potential long term acid generation.

3.1.2. Net Acid Generation

Net acid generation tests determine the acid generating potential (AP) of sulphur minerals by oxidation of waste rock with hydrogen peroxide.

Final NAG pH values below 3.5 after complete oxidation indicate a high risk, pH values between 3.5 and 5.5 a low risk and pH values above 5.5 no risk of acid generation. Titration of the leachate to a pH value of 4.5 or 7 gives the respective acid potential in kilograms of sulphuric acid produced per tonne of waste rock/tailings sample.

3.2. TCLP LEACH TESTING

The US Environmental Protection Agency (EPA) developed the Toxicity Characteristic Leaching Procedure (TCLP, EPA Method 1311) to determine the mobility of both organic and inorganic analytes in liquid, solid and multiphase wastes. The test was designed to simulate landfill conditions in order to differentiate between clearly hazardous waste and non-hazardous waste, not to predict the actual leachate concentration on a site-specific basis (Washington State Department of Ecology 2003). However, the test can be utilised for the analysis of mine wastes (US EPA 1992). For wastes containing greater than or equal to 0.5% solids, the liquid, if any, is separated from the solid phase and stored for later analysis. The solid phase is then extracted for 18 ± 2 hours with an extraction fluid of pH 4.9 (mixture of glacial acetic acid and sodium hydroxide) or 2.9 (glacial acetic acid) and a liquid-to-solid ratio of 20:1. The more acidic extraction fluid is used for very alkaline wastes/samples. Following extraction, the liquid extract is separated from the solid phase by filtration (combined with any potential initial liquid portion if compatible) and analyzed. If the initial fluid contained in the solids (waste) and the solid phase TCLP extract are not combined prior analysis, a simple mixing calculation can be done to arrive at an approximate final leachate quality for the combined waste stream (as per EPA Method 1311):

$$\text{Final Analyte Concentration} = \frac{V_1 C_1 + V_2 C_2}{V_1 + V_2}$$

V_1 = Volume of the first phase (L).

C_1 = Concentration of the analyte of concern in the first phase (mg/L).

V_2 = Volume of the second phase (L).

C_2 = Concentration of the analyte of concern in the second phase (mg/L).

Results of TCLP tests do not typically represent the leachate quality as observed under field conditions due to e.g. unrealistic liquid-to-solid ratio (20:1), potentially un-oxidised sulphides, usage of acetic acid instead of sulphuric or nitric acids (as would be expected in the field) or effects of kinetic reactions and preferred pathways. TCLP results should therefore not be directly used as source terms for impact prediction models, which are better determined using kinetic laboratory and field tests.

3.3. SPLP LEACH TESTING

The Synthetic Precipitation Leaching Procedure (SPLP, EPA Method 1312) is a laboratory extraction method designed to determine the leachability of both organic and inorganic analytes present in liquids (the filtered sample itself represents the extract), soils, and wastes under acid rain conditions. The solid phase is extracted over 18 hours with an extraction fluid (pH dependent on region), and liquid-to-solid ratio of 20:1. The pH of the extraction fluid is adjusted using a mixture of nitric and sulphuric acids, and these elements are therefore excluded from analysis/interpretation. Following extraction, the liquid extract is separated from the solid phase by filtration (combined with any potential initial liquid portion) and analysed. For the SPLP extraction of the samples a pH of 4.2 was chosen to represent acidic precipitation conditions. While the acids of the extraction fluid are more likely to represent actual field conditions, the same limitations with regard to liquid-to-solid ratio or kinetic reactions as for the TCLP test apply.

4. RESULTS

4.1. ACID-BASE ACCOUNTING

4.1.1. Waste rocks

The results of the ABA test on the composite waste rock samples by SGS, the sulphur speciation as well as the predicted risk for acid rock drainage based on NNP and NPR values are given in Table 2. Waste rock samples likely to generate a net acidic leachate quality are highlighted in orange.

Table 2: ABA results and sulphur speciation for composite waste rock samples Husab.

Sample ID	S _T [%]	S ²⁻ [%]	S ⁰ [%]	S ²⁻ + S ⁰ [%]	SO ₄ [%]	C _T [%]	Org_C [%]	CO ₂ _C [%]	Paste pH	NP [kg CaCO ₃ /t]	AP [kg CaCO ₃ /t]	NNP=NP-AP [kg CaCO ₃ /t]	NNP Risk	NPR=NP:AP	NPR Risk
WS001 (Stage-Crushed to -6 mm)									9.31	42		41	Low risk	27	Low risk
WS001 (Ground to %80 Passing 0.250 mm)	0.08	0.05	<0.01	0.05	0.03	0.85			9.69	71	1.56	71	Low risk	46	Low risk
WS002 (Stage-Crushed to -6 mm)									8.30	9.8		-35	High risk	0.22	High risk
WS002 (Ground to %80 Passing 0.250 mm)	1.56	1.42	0.14	1.56	<0.01	0.24			8.28	11	44.4	11	Low risk	0.24	High risk
WS003 (Stage-Crushed to -6 mm)									8.17	44		43	Low risk	145	Low risk
WS003 (Ground to %80 Passing 0.250 mm)	0.28	<0.01	0.03	0.03	0.25	1.21			8.61	90	<0.3	90	Low risk	301	Low risk
WS004 (Stage-Crushed to -6 mm)									9.35	4.9		4	Low risk	5.2	Low risk
WS004 (Ground to %80 Passing 0.250 mm)	0.03	0.03	<0.01	0.03	<0.01	0.13			9.79	15	0.94	15	Low risk	16	Low risk
WS005 (Stage-Crushed to -6 mm)									9.22	16		6	Low risk	1.5	High risk
WS005 (Ground to %80 Passing 0.250 mm)	0.51	0.40	0.06	0.46	0.05	0.21			9.32	20	10.4	20	Low risk	1.9	High risk
WS006 (Stage-Crushed to -6 mm)									9.28	40		40	Low risk	200	Low risk
WS006 (Ground to %80 Passing 0.250 mm)	0.13	0.03	0.07	0.10	0.03	0.93			9.59	84	<0.2	84	Low risk	420	Low risk
Waste Rock Composite (Stage-Crushed to -6 mm)															
Waste Rock Composite (Ground to %80 Passing 0.250 mm)	0.24	0.15	0.03	0.18	0.06	0.59									

The sulphur speciation results in Table 2 indicate for the majority of samples a predominance of sulphide sulphur (for total sulphur). Only sample WS003, which entails shallow cover sediments (Table 1), shows a predominance of sulphate sulphur as a result of oxidation.

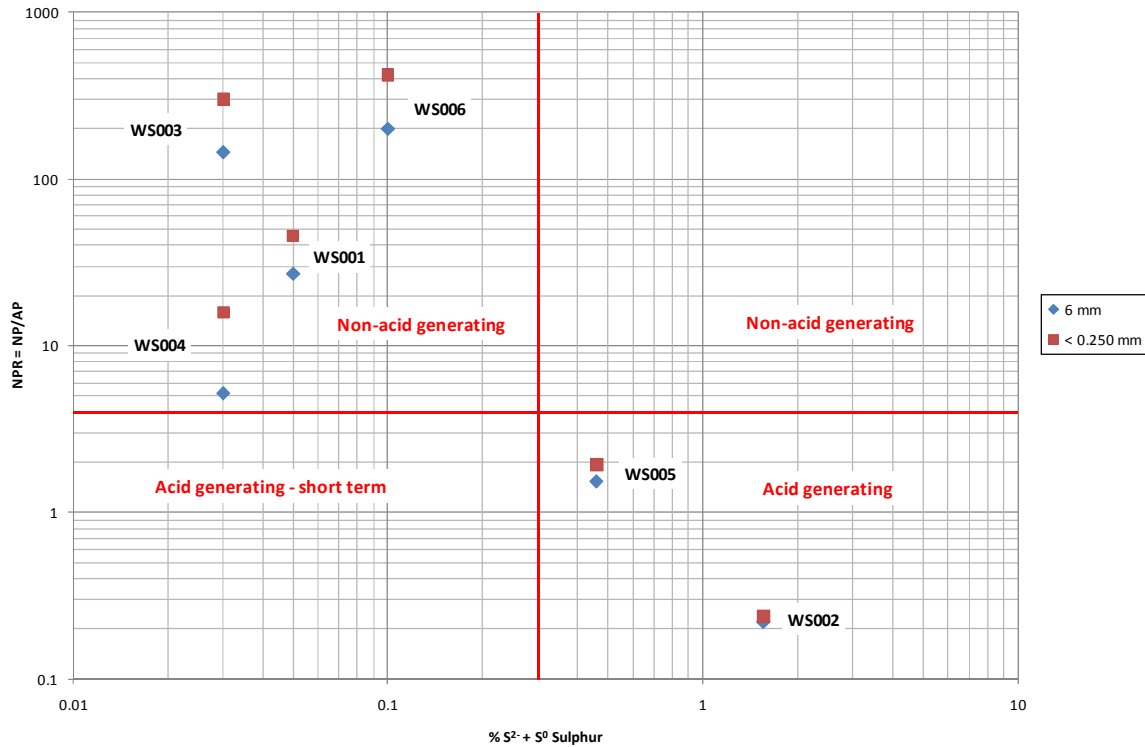


Figure 1: Neutralization potential ratio NPR (NP/AP) versus non-sulphate sulphur for waste rock samples Husab.

Based on the determined sulphur contents and neutralization potential ratios (Figure 1), all tested grain sizes of the waste rock samples WS002 and WS005 are classified as potentially acid forming (PAF).

The grain size of the samples is a proxy for the available and reactive surface area for neutralisation reactions only (analytical procedures for sulphur determination do not allow for a differentiation of grain sizes). As expected, a clear trend of increasing neutralisation potential with decreasing grain size respectively increasing surface area is observed in all samples. Nevertheless, even for the smallest tested grain size (0.25 mm), samples WS002 and WS005 are net acid generating. Considering that the expected grain size for the actual waste rock material at Husab is considerably larger (ranging predominantly from 200 to 500 mm, Figure 2), the actual neutralisation capacity (and rate) of the material in the waste rock dump is likely to be lower than the test results on smaller diameter samples suggest. However, the acid generation potential due to the oxidation of sulphide minerals should be affected in a similar manner by the available surface area of the waste material but is considered to remain unchanged as a precaution.

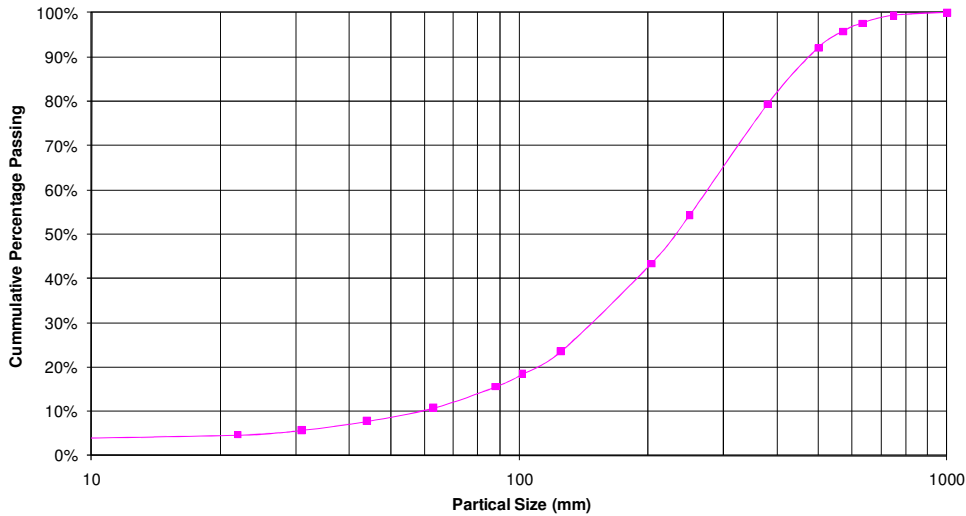


Figure 2: Estimated particle size distribution for Husab waste rock.

As a result of the high total sulphide sulphur contents (> 0.3 %) of waste rock samples WS002 and WS005, the acid generation is likely to be a persistent long-term risk. The predominant rock types in these composite waste rock samples are calcium-silicates, alaskites and sediments (WS002) respectively biotite-schist (WS005), though these rock types are also present in non-acid generating (composite) samples. The remaining samples show highly variable net neutralising potentials (4 – 90 kg CaCO₃/t) and are classified as non-acid forming (NAF), i.e. likely to generate a net alkaline leachate. Sample RRC376 (non specified rock type) shows an extremely high NNP around 930 kg/t and is considered as an outlier.

The acid-base accounting results for the composite waste rock samples are in agreement with an earlier assessment of single core samples by Metago (project reference M009-04, report number 01 Final, dated 10/2009), which identified a number of samples of different rock types as potentially acid forming (Table 3, PAF samples highlighted in orange).

Table 3: Summary of earlier ABA results for waste rock samples, Husab.

Sampled interval			Logged interval					Laboratory results and ARD assessment										
Hole ID	from	to	from	To	Lith1	Sulphide	Rock type	USEPA NP	USEPA AP	Total S	NAG_PH	NPR=NP/AP	NNP=NP-AP	Final assessment				
	[mbs]	[mbs]	[mbs]	[mbs]		Type	[%]	[kg/t CaCO ₃]	[kg/t CaCO ₃]	[%]	[-]	[-]	[kg/t CaCO ₃]					
Zone1																		
RDD019	91	92	89.39	93.17	Zbi	pyrite	8	biotite schist	29	3.75	0.12	7.3	no risk	7.73	no risk	25.25	no risk	Net alkaline
RDD003	94	95	93.46	102.2	Zbi			biotite schist	23.4	7.19	0.23	7	no risk	3.25	low risk	16.21	no risk	Net alkaline
RDD019	99	100	97.75	100.3	Zbi	pyrite	4	biotite schist	17.8	18.4	0.59	3.7	low risk	0.97	high risk	-0.6	high risk	Net acidic
RDD019	101	102	100.3	102.1	lak	pyrite	2	alaskite	35.3	10.3	0.33	5.8	no risk	3.43	low risk	25	no risk	Likely acidic
RDD003	119	120	118.4	120.8	lpg			pegmatite	22.1	2.5	0.08	7.4	no risk	8.84	no risk	19.6	no risk	Net alkaline
RDD004	155	156	154.6	162.2	lak	pyrite	10	alaskite	36	6.88	0.22	6.2	no risk	5.23	no risk	29.12	no risk	Net alkaline
RDD001	62	63	61.25	63	Mgn			gneiss	163	0.63	0.02	7.6	no risk	258.73	no risk	162.37	no risk	Net alkaline
RDD004	163	164	162.2	166.1	Mgn	pyrite	13	gneiss	10.5	67.8	2.17	2.1	high risk	0.15	high risk	-57.3	high risk	Net acidic
RRC325	15	16	15	16	Rsa			alluvium	25.9	28.4	0.91	10.3	no risk	0.91	high risk	-2.5	high risk	Net alkaline
Zone2																		
RRC384	100	101	100	101	Mcs(d)	pyrite	0	skarn	9.7	98.1	3.14	1.7	high risk	0.10	high risk	-88.4	high risk	Net acidic
RRC350	100	101	100	101	Zbi			biotite schist	32	0.31	0.01	7.7	no risk	103.23	no risk	31.69	no risk	Net alkaline
RDD054/RRC307	119	120	119	120	Zbi	pyrite	15	biotite schist	13.7	108	3.44	1.9	high risk	0.13	high risk	-94.3	high risk	Net acidic
RRC344	72	73	72	73	lak			alaskite	11.2	0.31	<0.01	7.1	no risk	36.13	no risk	10.89	no risk	Net alkaline
RRC293	100	101	100	101	lak			alaskite	93.3	0.31	<0.01	7.3	no risk	300.97	no risk	92.99	no risk	Net alkaline
RRC306	114	115	114	115	lak			alaskite	23.4	0.63	0.02	7.4	no risk	37.14	no risk	22.77	no risk	Net alkaline
RRC316	100	101	100	101	Mgr			gneiss	14.6	0.3	0.01	7.3	no risk	48.67	no risk	14.3	no risk	Net alkaline
RRC339	110	111	110	111	Mgn			gneiss	22	0.63	0.02	7.2	no risk	34.92	no risk	21.37	no risk	Net alkaline
RRC376	107	108							928	0.63	0.02	10.5	no risk	1473.02	no risk	927.37	no risk	Net alkaline

Based on the ABA tests on single and composite core waste rock samples, a portion of the Husab waste rocks are characterised as potentially acid forming (PAF). No correlation between ARD

potential and rock types, visually logged sulphide content or mining schedule of specific waste rock blocks could be established based on the available information, but such work is recommended for a site specific ARD management plan. Similarly, kinetic leach tests with waste rock samples of expected particle sizes as well as field plots for kinetic testing under actual site conditions are recommended for future characterisation work (www.gardguide.com).

4.1.2. Pilot plant residues

The results of the ABA test on the tailings sample 328-141 by Genanalysis Laboratory Services Pty Ltd, Australia are given in Table 4. A re-analysis of the sample for quality control purposes shows a good repeatability of results. Note that the acid generating and neutralising potential results are reported in kg H₂SO₄ per ton of material.

Table 4: Summary of ABA results for tailing sample, Husab.

Sample ID	ANC [kg/t H ₂ SO ₄]	paste pH [-]	Fizz rating [-]	final pH [-]	NAG [kg/t H ₂ SO ₄]	NAG_4.5 [kg/t H ₂ SO ₄]	NAPP [kg/t H ₂ SO ₄]	NAG_PH [-]	Final assessment [-]
328-141	6	4	0	1.4	14	9	17	2.8	Net Acidic
328-141 QC	6	4.1	0	1.4	13	8	18	3	Net acidic

Based on the NAG pH and NAPP values, the tested tailing material is classified as potentially acid forming (PAF) with a net acid production potential (NAPP) of 18 kg H₂SO₄ per ton of tailing. The determined NAPP is calculated based on the total sulphur content and does not differentiate between acid and non-acid generating sulphur species in the sample. However, the analytically determined (titration) net acid generation potential NAG of 14 (duplicate: 13) kg H₂SO₄ per ton is only slightly lower and confirms a high percentage of acid generating sulphide sulphur in the sample.

The results of the ABA test on the filter cake samples analysed in September 2010 by SGS, Australia are given in Table 5. Note that the acid generating and neutralising potential results are reported in kg H₂SO₄ per ton of material and that the acid potential was determined by actual titration (Sober 1978) instead of calculated from the sulphur content.

Table 5: Summary of ABA results for filter cake samples, Husab.

Sample ID	NAG [kg/t H ₂ SO ₄]	AP [kg/t H ₂ SO ₄]	NP [kg/t H ₂ SO ₄]	NNP=NP-AP [kg/t H ₂ SO ₄]		NPR=NP/AP [-]		Final assessment [-]
Zone 2 Filter Cake (# 150)	11.4	9.3	5.5	-3.8	high risk	0.59	high risk	Net Acidic
Year 1 Filter Cake (# 414)	8.1	4.7	3.3	-1.4	high risk	0.70	high risk	Net Acidic
Year 2 Filter Cake (# 120)	7.9	5.1	2.1	-3	high risk	0.41	high risk	Net Acidic
Year 3 Filter Cake (#412)	9.6	7.8	4.7	-3.1	high risk	0.60	high risk	Net acidic

Based on the acid-base accounting results, all filter cake samples are classified as potentially acid forming (PAF) with a net acid production potential (negative net neutralisation potential NNP) of between 1.4 and 3.8 kg H₂SO₄ per (NNP) ton or up to 4.8 to 5.9 kg H₂SO₄ per ton if completely oxidised by a strong oxidant (NAG test results used for NNP calculations). Following the precautionary principle, the latter values are recommended for the assessment of neutralisation requirements.

4.2. LEACH TESTING

4.2.1. Waste rocks

A summary of total leachable elements of the composite waste rock samples, determined by complete dissolution of the samples and analysis for selected elements, are given in Table 6. The complete digestion of the waste rock serves as a reference point of elemental concentrations in the rock prior to the assessment of their actual leachability under different environmental conditions as simulated in the TCLP and SPLP leach tests. The results are therefore given in ppm and not compared to any standard.

Table 6: Total leachable elements (in ppm) of composite waste rock samples, Husab.

All in [ppm]	Al	Ag	As	B	Ba	Be	Bi	Br	Ca	Cd	Ce	Cl	Co	Cr
WS001	-	<0.0001	1.19	45.8	554	1.9	0.31	-	-	0.08	43	-	-	-
WS002	-	0.06	0.05	10.1	366	10.4	0.59	-	-	0.11	97	-	-	-
WS003	-	0.02	0.02	7.7	407	3.3	0.12	-	-	0.11	34	-	-	-
WS004	-	0.09	<0.0001	40.9	610	5.0	0.21	-	-	0.10	68	-	-	-
WS005	-	<0.0001	0.399	10.7	480	5.4	0.28	-	-	0.36	87	-	-	-
WS006	-	<0.0001	1.17	10.7	450	1.4	0.17	-	-	0.07	21	-	-	-
Waste Rock Composite	-	<0.0001	1.06	7.9	445	3.2	0.17	-	-	0.09	45	-	-	-
All in [ppm]	Cu	F	Fe	Hg	K	Li	Mg	Mn	Mo	Na	Ni	P	Pb	S
WS001	-	-	-	0.07	-	25	-	-	1.8	-	-	373	18	800
WS002	-	-	-	0.05	-	44	-	-	4.6	-	-	376	29	15600
WS003	-	-	-	0.12	-	24	-	-	2.3	-	-	250	14	2800
WS004	-	-	-	0.09	-	63	-	-	3.3	-	-	569	12	300
WS005	-	-	-	0.06	-	47	-	-	124	-	-	562	28	5100
WS006	-	-	-	0.04	-	22	-	-	2.7	-	-	219	11	1300
Waste Rock Composite	-	-	-	0.07	-	31	-	-	19.8	-	-	334	14	2400
All in [ppm]	SO4	Sb	Sn	Se	Sr	Te	Th	Tl	Ti	U	V	W	Zn	
WS001	-	0.083	1.73	<0.001	160	<0.0001	11.2	0.72	841	12.22	72	2.4	-	
WS002	-	0.133	0.91	<0.001	108	0.09	38.3	0.95	1104	11.20	78	1.6	-	
WS003	-	0.060	2.53	<0.001	155	<0.0001	12.1	0.91	1113	6.34	62	4.0	-	
WS004	-	0.076	2.28	<0.001	146	<0.0001	20.1	1.37	3399	8.58	83	2.9	-	
WS005	-	0.073	4.38	<0.001	151	0.21	20.6	1.45	3332	10.43	108	3.3	-	
WS006	-	0.076	1.14	<0.001	77	<0.0001	6.2	0.92	1025	20.90	59	1.0	-	
Waste Rock Composite	-	0.076	1.93	<0.001	123	<0.0001	14.6	0.99	1643	7.81	73	2.3	-	

The analysed leachable element concentrations of the composite waste rock samples show a high degree of variability, especially with regard to molybdenum and total sulphur, which is likely to be reflected in the TCLP and SPLP results. Total sulphur concentrations in the waste rock samples range from 300 to 15600 ppm and molybdenum concentrations from 1.8 to 124. Interestingly titanium concentrations in the waste rock samples range from 841 to 3399 ppm.

Table 7 gives a summary of the TCLP leach test results for the Husab composite waste rock samples. The colour coding indicates that a parameter exceeds a respective guideline value Table 2. As expected, a general trend of increasing leachate concentrations with decreasing sample size (as a result of increasing surface areas) is observed for all samples. However, the ratio between element concentrations for one sample of different grain sizes rarely exceeds a factor of two.

Table 7: TCLP test results (in mg/L) for composite waste rock samples, Husab.

All in [mg/L]	Al	Ag	As	B	Ba	Be	Bi	Br	Ca	Cd	Ce	Cl	Co	Cr
WHO Drinking Water (2008)	0.2	N/A	0.01	0.5	0.7	N/A	N/A	N/A	300	0.003	N/A	250	N/A	0.05
Namibian Effluent Standard	N/A	N/A	0.5	1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0.5
Namibian Drinking Water - D	1	0.1	0.6	4	2	0.01	1	6	400	0.04	4	1200	1	0.4
IFC Mining Effluents (2007)	N/A	N/A	0.1	N/A	N/A	N/A	N/A	N/A	N/A	0.05	N/A	N/A	N/A	N/A
WS001 (Stage-Crushed to -6 mm)	<1	<0.002	<0.1	<0.1	0.3	<0.002	<0.002	-	900	<0.02	0.008	-	<0.05	<0.1
WS001 (Ground to % ₈₀ Passing 0.250 mm)	<1	<0.002	<0.1	<0.1	0.48	<0.002	<0.002	-	846	<0.02	0.010	-	<0.05	<0.1
WS002 (Stage-Crushed to -6 mm)	1	<0.002	<0.1	<0.1	0.15	0.006	<0.002	-	182	<0.02	0.031	-	<0.05	<0.1
WS002 (Ground to %80 Passing 0.250 mm)	2	<0.002	<0.1	<0.1	0.22	0.007	<0.002	-	225	<0.02	0.033	-	<0.05	<0.1
WS003 (Stage-Crushed to -6 mm)	<1	<0.002	<0.1	0.2	0.17	<0.002	<0.002	-	1160	<0.02	0.008	-	<0.05	<0.1
WS003 (Ground to %80 Passing 0.250 mm)	<1	<0.002	<0.1	0.3	0.23	0.002	<0.002	-	1830	<0.02	0.087	-	<0.05	<0.1
WS004 (Stage-Crushed to -6 mm)	1	<0.002	<0.1	<0.1	0.34	<0.002	<0.002	-	88.7	<0.02	0.016	-	<0.05	<0.1
WS004 (Ground to %80 Passing 0.250 mm)	2	<0.002	<0.1	<0.1	0.35	0.002	<0.002	-	157	<0.02	0.026	-	<0.05	<0.1
WS005 (Stage-Crushed to -6 mm)	1	<0.002	<0.1	X	0.19	<0.002	<0.002	-	214	<0.02	0.008	-	<0.05	<0.1
WS005 (Ground to %80 Passing 0.250 mm)	1	<0.002	<0.1	<0.1	0.21	0.004	<0.002	-	276	<0.02	0.012	-	<0.05	<0.1
WS006 (Stage-Crushed to -6 mm)	<1	<0.002	<0.1	<0.1	0.27	<0.002	<0.002	-	845	<0.02	0.014	-	<0.05	<0.1
WS006 (Ground to %80 Passing 0.250 mm)	<1	<0.002	<0.1	<0.1	0.38	<0.002	<0.002	-	908	<0.02	0.015	-	<0.05	<0.1
All in [mg/L]	Cu	F	Fe	Hg	K	Li	Mg	Mn	Mo	Na	Ni	P	Pb	S
WHO Drinking Water (2008)	2	1.5	N/A	0.006	N/A	N/A	N/A	0.4	0.07	200	0.07	N/A	0.01	N/A
Namibian Effluent Standard	1	1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	+90	N/A	1	1	N/A
Namibian Drinking Water Group D	2	3	2	0.02	800	10	200	2	0.2	800	1	N/A	0.2	N/A
IFC Mining Effluents (2007)	0.3	N/A	2	0.002	N/A	N/A	N/A	N/A	N/A	N/A	0.5	N/A	0.2	N/A
WS001 (Stage-Crushed to -6 mm)	<0.05	-	5	<0.02	13	<0.02	3.4	3.4	<0.002	1420	<0.1	<0.3	<0.2	2.2
WS001 (Ground to % ₈₀ Passing 0.250 mm)	0.06	-	2	<0.02	12	<0.02	3.9	3.1	<0.002	1410	<0.1	<0.3	<0.2	3.2
WS002 (Stage-Crushed to -6 mm)	0.05	-	1	<0.02	19	<0.02	6.7	2.3	<0.002	1480	<0.1	<0.3	<0.2	41.1
WS002 (Ground to %80 Passing 0.250 mm)	0.26	-	<1	<0.02	12	<0.02	8.6	2.6	<0.002	1420	<0.1	<0.3	<0.2	35.4
WS003 (Stage-Crushed to -6 mm)	<0.05	-	<1	<0.02	19	<0.02	13.8	3.9	<0.002	1420	<0.1	<0.3	<0.2	187
WS003 (Ground to %80 Passing 0.250 mm)	<0.05	-	1	<0.02	13	<0.02	32.7	10.8	<0.002	27.2	<0.1	<0.3	<0.2	172
WS004 (Stage-Crushed to -6 mm)	<0.05	-	5	<0.02	18	<0.02	3.6	1.2	<0.002	1370	<0.1	<0.3	<0.2	1.1
WS004 (Ground to %80 Passing 0.250 mm)	0.1	-	5	<0.02	17	0.03	6.2	1.8	<0.002	1410	<0.1	<0.3	<0.2	2.3
WS005 (Stage-Crushed to -6 mm)	<0.05	-	5	<0.02	16	<0.02	3.2	0.9	<0.002	1380	<0.1	<0.3	<0.2	2.9
WS005 (Ground to %80 Passing 0.250 mm)	<0.05	-	4	<0.02	14	0.02	4.6	1.1	<0.002	1420	<0.1	<0.3	<0.2	3.3
WS006 (Stage-Crushed to -6 mm)	<0.05	-	1	<0.02	14	<0.02	12.7	2.6	<0.002	1390	<0.1	<0.3	<0.2	2.2
WS006 (Ground to %80 Passing 0.250 mm)	<0.05	-	<1	<0.02	11	<0.02	13	2.5	<0.002	1410	<0.1	<0.3	<0.2	2.1
All in [mg/L]	Sb	Sn	Se	Sr	Te	Th	Tl	Ti	U	V	W	Zn		
WHO Drinking Water (2008)	0.02	N/A	0.01	N/A	N/A	N/A	N/A	N/A	0.015	N/A	N/A	N/A		
Namibian Effluent Standard	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	5		
Namibian Drinking Water Group D	0.2	0.4	0.1	N/A	0.01	N/A	0.02	1	8	1	1	10		
IFC Mining Effluents (2007)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0.5	0.5		
WS001 (Stage-Crushed to -6 mm)	<0.02	<0.01	<0.1	1.52	<0.01	<0.001	<0.01	<0.1	0.005	<0.02	<0.002	0.14		
WS001 (Ground to % ₈₀ Passing 0.250 mm)	<0.02	<0.01	<0.1	1.54	<0.01	<0.001	<0.01	<0.1	0.006	<0.02	<0.002	0.12		
WS002 (Stage-Crushed to -6 mm)	<0.02	<0.01	<0.1	0.56	<0.01	<0.001	<0.01	<0.1	0.012	<0.02	<0.002	0.21		
WS002 (Ground to %80 Passing 0.250 mm)	<0.02	<0.01	<0.1	0.41	<0.01	<0.001	<0.01	<0.1	0.017	<0.02	<0.002	0.18		
WS003 (Stage-Crushed to -6 mm)	<0.02	<0.01	<0.1	0.95	<0.01	<0.001	<0.01	<0.1	0.014	<0.02	<0.002	0.08		
WS003 (Ground to %80 Passing 0.250 mm)	<0.02	<0.01	<0.1	1.55	<0.01	<0.001	<0.01	<0.1	0.025	<0.02	<0.002	0.13		
WS004 (Stage-Crushed to -6 mm)	<0.02	<0.01	<0.1	0.11	<0.01	<0.001	<0.01	<0.1	0.009	<0.02	<0.002	0.14		
WS004 (Ground to %80 Passing 0.250 mm)	<0.02	<0.01	<0.1	0.19	<0.01	<0.001	<0.01	<0.1	0.016	<0.02	<0.002	0.16		
WS005 (Stage-Crushed to -6 mm)	<0.02	<0.01	<0.1	0.24	<0.01	<0.001	<0.01	<0.1	0.017	<0.02	<0.002	0.14		
WS005 (Ground to %80 Passing 0.250 mm)	<0.02	<0.01	<0.1	0.3	<0.01	<0.001	<0.01	<0.1	0.028	<0.02	<0.002	0.15		
WS006 (Stage-Crushed to -6 mm)	<0.02	<0.01	<0.1	0.73	<0.01	<0.001	<0.01	<0.1	0.012	<0.02	<0.002	0.13		
WS006 (Ground to %80 Passing 0.250 mm)	<0.02	<0.01	<0.1	0.78	<0.01	<0.001	<0.01	<0.1	0.012	<0.02	<0.002	0.1		

Regardless of the grain size, all tested samples exceed acceptable drinking water limits for sodium (sample WS003 (Ground to %80 Passing 0.250 mm) is considered a typo). The leached sodium concentrations alone would furthermore increase the total dissolved solids load of the leachate beyond acceptable Namibian effluent standards (not more than 500 mg/L more than influent). Other identified constituents of concern are aluminium, iron and manganese, which exceed acceptable drinking water limits in numerous samples. Arsenic and lead, which were identified in earlier leach tests by Metago (project reference M009-04, report number 01 Final, dated 10/2009)

as elements of concern, do not exceed acceptable Namibian drinking water standards in the current TCLP leach tests of composite waste rock samples.

The highly elevated titanium concentrations observed in the completely dissolved samples (Table 6) are not leachable at all by TCLP (Table 7). Similarly, the highly elevated sulphur concentrations contained in the waste rock samples are only partially leachable. The highest sulphur concentrations in the TCLP extract (172 and 187 mg/L, Table 7) are observed for sample WS003 (mostly igneous rocks, Table 1), while the highest total sulphur concentrations (15600 ppm, Table 6) are observed for sample WS002 (mostly calcium-silicates, Table 1), a clear indication of different sulphur minerals of different solubility in the waste rock samples. A mineralogical analysis as well as a determination of the sulphur speciation is recommended for future leach tests.

The results of the SPLP leach tests for Husab composite waste rock samples are summarised in Table 10. None of the analysed elements in the leachate exceed acceptable Namibian drinking water limits (class D) or effluent standards. Due to insufficient limits of detection numerous elements (e.g. aluminium, arsenic or lead) in the leachate could not be compared to WHO drinking water guidelines. Similarly chloride, sulphate, or nitrate were not analysed in the current SPLP leach tests, but did not exceed acceptable limits in earlier leach tests by Metago (project reference M009-04, report number 01 Final, dated 10/2009).

Table 8: SPLP test results (in mg/L) for composite waste rock samples, Husab.

All in [mg/L]	Al	Ag	As	B	Ba	Be	Bi	Br	Ca	Cd	Ce	Cl	Co	Cr
WHO Drinking Water (2008)	0.2	N/A	0.01	0.5	0.7	N/A	N/A	N/A	300	0.003	N/A	250	N/A	0.05
Namibian Effluent Standard	N/A	N/A	0.5	1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0.5
Namibian Drinking Water - D	1	0.1	0.6	4	2	0.01	1	6	400	0.04	4	1200	1	0.4
IFC Mining Effluents (2007)	N/A	N/A	0.1	N/A	N/A	N/A	N/A	N/A	N/A	0.05	N/A	N/A	N/A	N/A
WS001 (Stage-Crushed to -6 mm)	<1	<0.002	<0.1	<0.1	<0.05	<0.002	<0.002	-	4.6	<0.02	<0.001	-	<0.05	<0.1
WS001 (Ground to %80 Passing 0.250 mm)	<1	<0.002	<0.1	<0.1	0.12	<0.002	<0.002	-	5.5	<0.02	<0.001	-	<0.05	<0.1
WS002 (Stage-Crushed to -6 mm)	<1	<0.002	<0.1	<0.1	0.07	<0.002	<0.002	-	25.8	<0.02	<0.001	-	<0.05	<0.1
WS002 (Ground to %80 Passing 0.250 mm)	<1	<0.002	<0.1	<0.1	0.07	<0.002	<0.002	-	37.7	<0.02	<0.001	-	<0.05	<0.1
WS003 (Stage-Crushed to -6 mm)	<1	<0.002	<0.1	0.2	0.09	<0.002	<0.002	-	173	<0.02	<0.001	-	<0.05	<0.1
WS003 (Ground to %80 Passing 0.250 mm)	<1	<0.002	<0.1	0.2	0.08	<0.002	<0.002	-	215	<0.02	<0.001	-	<0.05	<0.1
WS004 (Stage-Crushed to -6 mm)	<1	<0.002	<0.1	<0.1	0.09	<0.002	<0.002	-	3.4	<0.02	<0.001	-	<0.05	<0.1
WS004 (Ground to %80 Passing 0.250 mm)	<1	<0.002	<0.1	<0.1	0.06	<0.002	<0.002	-	3.6	<0.02	<0.001	-	<0.05	<0.1
WS005 (Stage-Crushed to -6 mm)	<1	<0.002	<0.1	<0.1	<0.05	<0.002	<0.002	-	<0.5	<0.02	<0.001	-	<0.05	<0.1
WS005 (Ground to %80 Passing 0.250 mm)	<1	<0.002	<0.1	<0.1	0.08	<0.002	<0.002	-	4.9	<0.02	<0.001	-	<0.05	<0.1
WS006 (Stage-Crushed to -6 mm)	<1	<0.002	<0.1	<0.1	0.05	<0.002	<0.002	-	5.8	<0.02	<0.001	-	<0.05	<0.1
WS006 (Ground to %80 Passing 0.250 mm)	<1	<0.002	<0.1	<0.1	0.06	<0.002	<0.002	-	5.6	<0.02	<0.001	-	<0.05	<0.1
All in [mg/L]	Cu	F	Fe	Hg	K	Li	Mg	Mn	Mo	Na	Ni	P	Pb	S
WHO Drinking Water (2008)	2	1.5	N/A	0.006	N/A	N/A	N/A	0.4	0.07	200	0.07	N/A	0.01	N/A
Namibian Effluent Standard	1	1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	+90	N/A	1	1	N/A
Namibian Drinking Water Group D	2	3	2	0.02	800	10	200	2	0.2	800	1	N/A	0.2	N/A
IFC Mining Effluents (2007)	0.3	N/A	2	0.002	N/A	N/A	N/A	N/A	N/A	N/A	0.5	N/A	0.2	N/A
WS001 (Stage-Crushed to -6 mm)	<0.05	-	<1	<0.02	<5	<0.02	<0.2	<0.1	<0.002	5.6	<0.1	<0.3	<0.2	3.1
WS001 (Ground to %80 Passing 0.250 mm)	<0.05	-	<1	<0.02	<5	<0.02	0.3	<0.1	<0.002	9.2	<0.1	<0.3	<0.2	4.3
WS002 (Stage-Crushed to -6 mm)	<0.05	-	<1	<0.02	<5	<0.02	1.5	<0.1	<0.002	8.7	<0.1	<0.3	<0.2	28.7
WS002 (Ground to %80 Passing 0.250 mm)	<0.05	-	<1	<0.02	<5	<0.02	2.3	<0.1	<0.002	11.4	<0.1	<0.3	<0.2	35.4
WS003 (Stage-Crushed to -6 mm)	<0.05	-	<1	<0.02	5	<0.02	3.3	<0.1	<0.002	19.5	<0.1	<0.3	<0.2	143
WS003 (Ground to %80 Passing 0.250 mm)	<0.05	-	<1	<0.02	7	<0.02	4.2	<0.1	<0.002	25	<0.1	<0.3	<0.2	175
WS004 (Stage-Crushed to -6 mm)	<0.05	-	<1	<0.02	<5	<0.02	0.4	<0.1	<0.002	5.9	<0.1	<0.3	<0.2	1.4
WS004 (Ground to %80 Passing 0.250 mm)	<0.05	-	<1	<0.02	<5	<0.02	0.3	<0.1	<0.002	7.8	<0.1	<0.3	<0.2	2.9
WS005 (Stage-Crushed to -6 mm)	<0.05	-	<1	<0.02	<5	<0.02	<0.2	<0.1	0.009	6.6	<0.1	<0.3	<0.2	0.3
WS005 (Ground to %80 Passing 0.250 mm)	<0.05	-	<1	<0.02	<5	<0.02	0.4	<0.1	0.004	8	<0.1	<0.3	<0.2	10.8
WS006 (Stage-Crushed to -6 mm)	<0.05	-	<1	<0.02	<5	<0.02	0.7	<0.1	<0.002	3.1	<0.1	<0.3	<0.2	4.9
WS006 (Ground to %80 Passing 0.250 mm)	<0.05	-	<1	<0.02	<5	<0.02	0.6	<0.1	<0.002	4.3	<0.1	<0.3	<0.2	6.1
All in [mg/L]	Sb	Sn	Se	Sr	Te	Th	Tl	Ti	U	V	W	Zn		
WHO Drinking Water (2008)	0.02	N/A	0.01	N/A	N/A	N/A	N/A	N/A	0.015	N/A	N/A	N/A		
Namibian Effluent Standard	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	5		
Namibian Drinking Water Group D	0.2	0.4	0.1	N/A	0.01	N/A	0.02	1	8	1	1	10		
IFC Mining Effluents (2007)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0.5	0.5		
WS001 (Stage-Crushed to -6 mm)	<0.002	<0.01	<0.1	0.02	<0.01	<0.001	<0.01	<0.1	<0.001	<0.02	<0.002	<0.05		
WS001 (Ground to %80 Passing 0.250 mm)	<0.002	<0.01	<0.1	0.02	<0.01	<0.001	<0.01	<0.1	<0.001	<0.02	<0.002	<0.05		
WS002 (Stage-Crushed to -6 mm)	<0.002	<0.01	<0.1	0.14	<0.01	<0.001	<0.01	<0.1	<0.001	<0.02	<0.002	<0.05		
WS002 (Ground to %80 Passing 0.250 mm)	<0.002	<0.01	<0.1	0.12	<0.01	<0.001	<0.01	<0.1	<0.001	<0.02	<0.002	<0.05		
WS003 (Stage-Crushed to -6 mm)	<0.002	<0.01	<0.1	0.43	<0.01	<0.001	<0.01	<0.1	<0.001	<0.02	<0.002	<0.05		
WS003 (Ground to %80 Passing 0.250 mm)	<0.002	<0.01	<0.1	0.65	<0.01	<0.001	<0.01	<0.1	<0.001	<0.02	<0.002	<0.05		
WS004 (Stage-Crushed to -6 mm)	<0.002	<0.01	<0.1	<0.01	<0.01	<0.001	<0.01	<0.1	<0.001	<0.02	<0.002	<0.05		
WS004 (Ground to %80 Passing 0.250 mm)	<0.002	<0.01	<0.1	<0.01	<0.01	<0.001	<0.01	<0.1	<0.001	<0.02	<0.002	<0.05		
WS005 (Stage-Crushed to -6 mm)	<0.002	<0.01	<0.1	<0.01	<0.01	<0.001	<0.01	<0.1	<0.001	<0.02	<0.002	<0.05		
WS005 (Ground to %80 Passing 0.250 mm)	<0.002	<0.01	<0.1	<0.01	<0.01	<0.001	<0.01	<0.1	<0.001	<0.02	<0.002	<0.05		
WS006 (Stage-Crushed to -6 mm)	<0.002	<0.01	<0.1	0.02	<0.01	<0.001	<0.01	<0.1	<0.001	<0.02	<0.002	<0.05		
WS006 (Ground to %80 Passing 0.250 mm)	<0.002	<0.01	<0.1	0.02	<0.01	<0.001	<0.01	<0.1	<0.001	<0.02	<0.002	<0.05		

4.2.2. Pilot plant residues

A summary of the TCLP and SPLP leach test results of the solid phase as well as an analysis of the interstitial filter cake liquors (fluid phase) by SGS are given in Table 9 to Table 11. The colour coding indicates that a parameter exceeds a respective guideline value Table 2.

Table 9: TCLP results [all in mg/L] for filter cake samples Husab.

All in [mg/L]	Al	Ag	As	B	Ba	Be	Bi	Br	Ca	Cd	Ce	Cl	Co	Cr
WHO Drinking Water (2008)	0.2	N/A	0.01	0.5	0.7	N/A	N/A	N/A	300	0.003	N/A	250	N/A	0.05
Namibian Effluent Standard	N/A	N/A	0.5	1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0.5
Namibian Drinking Water - D	1	0.1	0.6	4	2	0.01	1	6	400	0.04	4	1200	1	0.4
IFC Mining Effluents (2007)	N/A	N/A	0.1	N/A	N/A	N/A	N/A	N/A	N/A	0.05	N/A	N/A	N/A	N/A
Zone 2 Filter Cake (# 150)	9.6	-	<0.001	-	-	-	-	-	277.1	0.003	-	-	0.035	0.148
Year 1 Filter Cake (# 414)	6.9	-	<0.001	-	-	-	-	-	334.5	0.001	-	-	0.036	0.163
Year 2 Filter Cake (# 120)	10.0	-	<0.001	-	-	-	-	-	157.4	0.001	-	-	0.030	0.102
Year 3 Filter Cake (#412)	17.2	-	<0.001	-	-	-	-	-	318.1	<0.001	-	-	0.042	0.125
All in [mg/L]	Cu	F	Fe	Hg	K	Li	Mg	Mn	Mo	Na	Ni	P	Pb	S
WHO Drinking Water (2008)	2	1.5	N/A	0.006	N/A	N/A	N/A	0.4	0.07	200	0.07	N/A	0.01	N/A
Namibian Effluent Standard	1	1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	+90	N/A	1	1	N/A
Namibian Drinking Water - D	2	3	2	0.02	800	10	200	2	0.2	800	1	N/A	0.2	N/A
IFC Mining Effluents (2007)	0.3	N/A	2	0.002	N/A	N/A	N/A	N/A	N/A	N/A	0.5	N/A	0.2	N/A
Zone 2 Filter Cake (# 150)	0.042	-	10.9	-	8.7	-	26.8	25.6	0.033	2523.2	0.120	<0.01	0.207	327.7
Year 1 Filter Cake (# 414)	0.073	-	0.6	-	5.8	-	18.7	24.2	0.012	2544.2	0.127	<0.01	0.100	343.0
Year 2 Filter Cake (# 120)	0.113	-	3.0	-	4.1	-	17.5	23.6	0.004	2532.6	0.076	<0.01	0.083	207.5
Year 3 Filter Cake (#412)	0.135	-	30.8	-	6.6	-	28.1	36.0	0.004	2537.9	0.110	<0.01	0.463	407.3
All in [mg/L]	Sb	Sn	Se	Sr	Te	Th	Tl	Ti	U	V	W	Zn		
WHO Drinking Water (2008)	0.02	N/A	0.01	N/A	N/A	N/A	N/A	N/A	0.015	N/A	N/A	N/A		
Namibian Effluent Standard	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	5		
Namibian Drinking Water - D	0.2	0.4	0.1	N/A	0.01	N/A	0.02	1	8	1	1	10		
IFC Mining Effluents (2007)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0.5	0.5		
Zone 2 Filter Cake (# 150)	-	-	-	0.374	-	0.029	-	0.008	0.251	0.260	-	0.702		
Year 1 Filter Cake (# 414)	-	-	-	0.379	-	0.069	-	0.011	0.405	0.244	-	0.749		
Year 2 Filter Cake (# 120)	-	-	-	0.199	-	0.071	-	0.007	0.316	0.265	-	0.705		
Year 3 Filter Cake (#412)	-	-	-	0.286	-	0.197	-	0.013	0.620	0.262	-	0.789		

The quality of the TCLP extract from the filter cake samples exceeds Namibian drinking water standards for numerous analysed elements (Al, Fe, Mn, Na, Pb) and/or WHO guideline values (Ca, Cr, Ni, U). Of potential health concern are the elevated aluminium, manganese and lead concentrations. While uranium concentrations exceed the provisional WHO guideline value clearly, they are still within the acceptable Namibian drinking water standard. The highly elevated sodium and sulphur concentrations will contribute to the potential salt load of the leachate.

The results of the TCLP leach test (Table 9) show only for chrome, lead, potassium, sulphur and especially sodium significant higher concentrations than the SPLP extract (Table 10). Most elemental concentrations are apparently not affected by the different acids in the TCLP and SPLP leach test.

Considering that the filter cake is potentially acid (sulphuric acid) generating and the SPLP test results therefore more representative of the potential leachate quality under field conditions, the elements of concern include aluminium, iron, lead, manganese (exceeding Namibian drinking water standard class D) and chrome (exceeding WHO drinking water guidelines).

Table 10: SPLP results [all in mg/L] for filter cake samples Husab.

All in [mg/L]	Al	Ag	As	B	Ba	Be	Bi	Br	Ca	Cd	Ce	Cl	Co	Cr
WHO Drinking Water (2008)	0.2	N/A	0.01	0.5	0.7	N/A	N/A	N/A	300	0.003	N/A	250	N/A	0.05
Namibian Effluent Standard	N/A	N/A	0.5	1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0.5
Namibian Drinking Water - D	1	0.1	0.6	4	2	0.01	1	6	400	0.04	4	1200	1	0.4
IFC Mining Effluents (2007)	N/A	N/A	0.1	N/A	N/A	N/A	N/A	N/A	N/A	0.05	N/A	N/A	N/A	N/A
Zone 2 Filter Cake (# 150)	8.40	-	<0.001	-	-	-	-	-	252.80	0.001	-	-	0.037	0.056
Year 1 Filter Cake (# 414)	5.88	-	<0.001	-	-	-	-	-	301.90	<0.001	-	-	0.033	0.054
Year 2 Filter Cake (# 120)	10.18	-	<0.001	-	-	-	-	-	143.60	<0.001	-	-	0.029	0.084
Year 3 Filter Cake (#412)	14.78	-	<0.001	-	-	-	-	-	278.20	<0.001	-	-	0.036	0.062
All in [mg/L]	Cu	F	Fe	Hg	K	Li	Mg	Mn	Mo	Na	Ni	P	Pb	S
WHO Drinking Water (2008)	2	1.5	N/A	0.006	N/A	N/A	N/A	0.4	0.07	200	0.07	N/A	0.01	N/A
Namibian Effluent Standard	1	1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	+90	N/A	1	1	N/A
Namibian Drinking Water Group D	2	3	2	0.02	800	10	200	2	0.2	800	1	N/A	0.2	N/A
IFC Mining Effluents (2007)	0.3	N/A	2	0.002	N/A	N/A	N/A	N/A	N/A	N/A	0.5	N/A	0.2	N/A
Zone 2 Filter Cake (# 150)	0.039	-	12.12	-	2.33	-	27.71	26.75	<0.001	25.75	0.124	<0.01	0.028	308.00
Year 1 Filter Cake (# 414)	0.049	-	0.78	-	1.32	-	18.24	23.96	<0.001	19.14	0.109	<0.01	0.013	322.10
Year 2 Filter Cake (# 120)	0.094	-	2.48	-	0.99	-	15.78	21.14	<0.001	14.35	0.071	<0.01	0.008	191.10
Year 3 Filter Cake (#412)	0.112	-	26.13	-	2.60	-	24.01	30.46	<0.001	26.31	0.082	<0.01	0.028	352.60
All in [mg/L]	Sb	Sn	Se	Sr	Te	Th	Tl	Ti	U	V	W	Zn		
WHO Drinking Water (2008)	0.02	N/A	0.01	N/A	N/A	N/A	N/A	N/A	0.015	N/A	N/A	N/A		
Namibian Effluent Standard	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	5	
Namibian Drinking Water Group D	0.2	0.4	0.1	N/A	0.01	N/A	0.02	1	8	1	1	10		
IFC Mining Effluents (2007)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0.5	0.5		
Zone 2 Filter Cake (# 150)	-	-	-	0.331	-	0.005	-	0.003	0.235	0.263	-	0.629		
Year 1 Filter Cake (# 414)	-	-	-	0.324	-	0.004	-	0.001	0.296	0.307	-	0.699		
Year 2 Filter Cake (# 120)	-	-	-	0.171	-	0.004	-	0.009	0.255	0.254	-	0.723		
Year 3 Filter Cake (#412)	-	-	-	0.228	-	0.007	-	0.002	0.407	0.267	-	0.732		

The sampled waste stream from the pilot plant consisted of solid phase filter cake samples as well as the interstitial filter cake liquor, which was analysed separately (Table 11).

The liquor clearly exceeds for most analysed elements, including uranium, acceptable standard or guideline values. Of particular health concern are the highly elevated metal concentrations, though numerous metals are supersaturated and likely to precipitate if the liquor is neutralised (reported pH values between 1.97 and 2.34) or exposed to the atmosphere.

Table 11: Analysis [all in mg/L] of interstitial filter cake liquor, Husab.

All in [mg/L]	Al	Ag	As	B	Ba	Be	Bi	Br	Ca	Cd	Ce	Cl	Co	Cr
WHO Drinking Water (2008)	0.2	N/A	0.01	0.5	0.7	N/A	N/A	N/A	300	0.003	N/A	250	N/A	0.05
Namibian Effluent Standard	N/A	N/A	0.5	1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0.5
Namibian Drinking Water - D	1	0.1	0.6	4	2	0.01	1	6	400	0.04	4	1200	1	0.4
IFC Mining Effluents (2007)	N/A	N/A	0.1	N/A	N/A	N/A	N/A	N/A	N/A	0.05	N/A	N/A	N/A	N/A
Zone 2 Filter Cake (# 150)	1324	-	0.125	-	1.051	-	-	-	191.6	-	-	-	1.983	7.384
Year 1 Filter Cake (# 414)	1148	-	<0.1	-	1.029	-	-	-	188.6	-	-	-	2.033	6.475
Year 2 Filter Cake (# 120)	1336	-	<0.1	-	2.021	-	-	-	202.8	-	-	-	2.613	6.011
Year 3 Filter Cake (#412)	1628	-	0.189	-	1.596	-	-	-	186.3	-	-	-	2.7	7.483
All in [mg/L]	Cu	F	Fe	Hg	K	Li	Mg	Mn	Mo	Na	Ni	P	Pb	S
WHO Drinking Water (2008)	2	1.5	N/A	0.006	N/A	N/A	N/A	0.4	0.07	200	0.07	N/A	0.01	N/A
Namibian Effluent Standard	1	1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	+90	N/A	1	1	N/A
Namibian Drinking Water Group D	2	3	2	0.02	800	10	200	2	0.2	800	1	N/A	0.2	N/A
IFC Mining Effluents (2007)	0.3	N/A	2	0.002	N/A	N/A	N/A	N/A	N/A	N/A	0.5	N/A	0.2	N/A
Zone 2 Filter Cake (# 150)	11.53	-	1971	-	323.9	-	1338	1760	0.048	1031	5.043	26.31	0.474	7493
Year 1 Filter Cake (# 414)	13.07	-	1707	-	288.1	-	1136	1629	0.105	979	4.37	19.35	0.516	6793
Year 2 Filter Cake (# 120)	16.81	-	2420	-	392.3	-	1260	1849	0.818	1186	3.46	85.94	2.739	8142
Year 3 Filter Cake (#412)	21.44	-	3356	-	476.6	-	1505	2195	1.079	1437	3.742	79.44	3.672	10100
All in [mg/L]	Sb	Sn	Se	Sr	Te	Th	Tl	Ti	U	V	W	Zn		
WHO Drinking Water (2008)	0.02	N/A	0.01	N/A	N/A	N/A	N/A	N/A	0.015	N/A	N/A	N/A		
Namibian Effluent Standard	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	5	
Namibian Drinking Water Group D	0.2	0.4	0.1	N/A	0.01	N/A	0.02	1	8	1	1	10		
IFC Mining Effluents (2007)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0.5	0.5		
Zone 2 Filter Cake (# 150)	-	-	-	1.465	-	25.817	-	1.906	30.464	4.603	-	8.766		
Year 1 Filter Cake (# 414)	-	-	-	1.346	-	29.123	-	1.663	15.704	4.77	-	9.039		
Year 2 Filter Cake (# 120)	-	-	-	1.461	-	50.199	-	7.483	13.807	7.12	-	12.22		
Year 3 Filter Cake (#412)	-	-	-	1.455	-	77.464	-	9.054	29.616	9.522	-	15.54		

Since the liquor and TCLP or SPLP extracts from the solid filter cake samples were analysed separately, a simple mixing calculation can be done to arrive at an approximate final leachate quality for the combined waste stream (as per EPA Method 1311). Based on a fluid (liquor) content of 20% (high level water balance from Elbert de Kock, email dated 26 September 2010), the calculated approximate final SPLP leachate chemistry is given in Table 12. Only the SPLP leachate quality as the more likely scenario was calculated.

Despite the lower percentage of higher mineralised interstitial liquor in the balance, the calculated leachate quality still exceeds numerous Namibian drinking water or IFC effluent limits. As for the liquor alone, the highly elevated metal concentrations are of particular concern.

Table 12: Calculated leachate concentrations [all in mg/L] of SPLP extract (80%) and interstitial filter cake liquor (20%), Husab.

All in [mg/L]	Al	Ag	As	B	Ba	Be	Bi	Br	Ca	Cd	Ce	Cl	Co	Cr
WHO Drinking Water (2008)	0.2	N/A	0.01	0.5	0.7	N/A	N/A	N/A	300	0.003	N/A	250	N/A	0.05
Namibian Effluent Standard	N/A	N/A	0.5	1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0.5
Namibian Drinking Water - D	1	0.1	0.6	4	2	0.01	1	6	400	0.04	4	1200	1	0.4
IFC Mining Effluents (2007)	N/A	N/A	0.1	N/A	N/A	N/A	N/A	N/A	N/A	0.05	N/A	N/A	N/A	N/A
Zone 2 Filter Cake (# 150)	271.52	-	-	-	-	-	-	-	240.56	-	-	-	0.43	1.52
Year 1 Filter Cake (# 414)	234.30	-	-	-	-	-	-	-	279.24	-	-	-	0.43	1.34
Year 2 Filter Cake (# 120)	275.34	-	-	-	-	-	-	-	155.44	-	-	-	0.55	1.27
Year 3 Filter Cake (#412)	337.42	-	-	-	-	-	-	-	259.82	-	-	-	0.57	1.55
All in [mg/L]	Cu	F	Fe	Hg	K	Li	Mg	Mn	Mo	Na	Ni	P	Pb	S
WHO Drinking Water (2008)	2	1.5	N/A	0.006	N/A	N/A	N/A	0.4	0.07	200	0.07	N/A	0.01	N/A
Namibian Effluent Standard	1	1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	+90	N/A	1	1	N/A
Namibian Drinking Water Group D	2	3	2	0.02	800	10	200	2	0.2	800	1	N/A	0.2	N/A
IFC Mining Effluents (2007)	0.3	N/A	2	0.002	N/A	N/A	N/A	N/A	N/A	N/A	0.5	N/A	0.2	N/A
Zone 2 Filter Cake (# 150)	2.34	-	403.90	-	66.65	-	289.77	373.40	-	226.80	1.11	-	0.12	1745
Year 1 Filter Cake (# 414)	2.65	-	342.03	-	58.68	-	241.79	344.97	-	211.11	0.96	-	0.11	1616.3
Year 2 Filter Cake (# 120)	3.44	-	485.98	-	79.25	-	264.62	386.71	-	248.68	0.75	-	0.55	1781.3
Year 3 Filter Cake (#412)	4.38	-	692.10	-	97.40	-	320.21	463.37	-	308.45	0.81	-	0.76	2302.1
All in [mg/L]	Sb	Sn	Se	Sr	Te	Th	Tl	Ti	U	V	W	Zn		
WHO Drinking Water (2008)	0.02	N/A	0.01	N/A	N/A	N/A	N/A	N/A	0.015	N/A	N/A	N/A		
Namibian Effluent Standard	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	5		
Namibian Drinking Water Group D	0.2	0.4	0.1	N/A	0.01	N/A	0.02	1	8	1	1	10		
IFC Mining Effluents (2007)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0.5	0.5		
Zone 2 Filter Cake (# 150)	-	-	-	0.56	-	5.17	-	0.38	6.28	1.13	-	2.26		
Year 1 Filter Cake (# 414)	-	-	-	0.53	-	5.83	-	0.33	3.38	1.20	-	2.37		
Year 2 Filter Cake (# 120)	-	-	-	0.43	-	10.04	-	1.50	2.97	1.63	-	3.02		
Year 3 Filter Cake (#412)	-	-	-	0.47	-	15.50	-	1.81	6.25	2.12	-	3.69		

5. ARD MITIGATION

The currently preferred concept for the disposal of tailing material by the client entails its placement within the waste rock dump. This is a common approach in the mining industry to mitigate the formation of acid rock drainage from potentially acid forming material (tailings and/or waste rock) by co-disposal with alkaline, acid neutralising material (limestone or appropriately classified waste rock). The success of such mitigation measure is determined by the

- ratio of acid producing and acid neutralizing materials including their types, availability reactivity,
- degree of mixing and nature of the contact (e.g. “hot spots” of acid generation),
- chemical armouring of alkaline materials,
- pathways and type of water movement through the system.

The current assessment considers only the mixing ratio of acid producing and acid neutralizing materials under the assumptions of a perfect contact and mixing, no armouring of alkaline material and equilibrium between materials. The assumptions limit the confidence of the study results, which should be increased by kinetic laboratory and field testing prior to commencing of co-disposal.

Under these assumptions the required mixing ratio of potentially acid forming (PAF) and non-acid forming or acid neutralizing material (NAF) is determined by their net acid production (NAPP), respectively net neutralising potential (NNP) expressed in kg H₂SO₄ or CaCO₃ per ton of material. If the sulphide bearing PAF material is preferentially exposed or reactive, the net neutralisation potential should exceed the acid production by a factor of 4 to ensure a complete acid neutralization (Price et al., 1997). A separate column for the net acid production potential under these scenarios (NAPP_{preferential exposure}) was therefore incorporated in all calculation tables.

The leachate from three potentially acid forming mine residues identified in chapter 3.1, i.e. PAF waste rocks, tailings material and filter cake (Table 13), require neutralisation using the available NAF waste rock. Following the precautionary approach, the maximum determined acid production potential of the PAF tailings and filter cake samples are used in the calculations. The acid production potential of the PAF waste rock is calculated using a sulphide sulphur content of 1.5 to 3% as given by Neal Culpán, Extract Resources in a memo on Sulphide content of waste rocks at Husab Zones 1 & 2, dated 4th December 2009.

Table 13: Net acid production potential of mine residues, Husab.

PAF Material	AP	NP	NAPP	NAPP _{preferential exposure}
	[kg/t H ₂ SO ₄]	[kg/t H ₂ SO ₄]	[kg/t H ₂ SO ₄]	[kg/t H ₂ SO ₄]
Waste Rock @ 1.5% sulphide	47	10	-37	-149
Waste Rock @ 3% sulphide	94	10	-84	-336
Tailings	-	-	-18	-72
Filter cake	11	6	-6	-24

To account for the highly variable net neutralising potential observed for the composite (Table 2) and single core (Table 3) NAF waste rock samples, the mixing ratio calculations are split accordingly (Table 14 and Table 15). Note that the acid production and neutralisation potential are both expressed in kg/t H₂SO₄.

Due to the large difference between the minimal and maximal neutralising potential of the waste rocks, the mixing ratios required for complete neutralisation range over an order of magnitude.

Table 14: Mixing ratios based on neutralisation capacity of composite waste rock samples.

PAF Material	NAF Material	NNP [kg/t H ₂ SO ₄]		Mixing ratio NAF:PAF		Mixing ratio NAF:PAF _{preferred exposure}	
		min	max	max	min	max	min
Waste Rock @ 1.5% sulphide	Waste rock	4	90	9.3	0.4	37.2	1.7
Waste Rock @ 3% sulphide				21.0	0.9	84.1	3.7
Tailings				4.5	0.2	18.0	0.8
Filter cake				1.5	0.1	5.9	0.3

The highest mixing ratios are generally required for the PAF waste rocks (Table 14). If approximately 10% of the waste rock material contains 1.5 to 3% sulphide as estimated by Neal Culpan (memo on sulphide content of waste rocks at Husab Zones 1 & 2, dated 4th December 2009), a large portion of the available NAF waste rock would be required to neutralise the PAF waste rock itself.

A similar variability of mixing ratios is observed if the determined net neutralisation potential of the single core waste rock samples is used (Table 15), though the overall ratios are around a factor of 2 lower.

Table 15: Mixing ratios based on neutralisation capacity of single core waste rock samples.

PAF Material	NAF Material	NNP [kg/t H ₂ SO ₄]		Mixing ratio NAF:PAF		Mixing ratio NAF:PAF _{preferred exposure}	
		min	max	max	min	max	min
Waste Rock @ 1.5% sulphide	Waste rock	10	160	3.7	0.2	14.9	0.9
Waste Rock @ 3% sulphide				8.4	0.5	33.6	2.1
Tailings				1.8	0.1	7.2	0.5
Filter cake				0.6	0.04	2.4	0.1

All determined mixing ratios of PAF and NAF material range over an order of magnitude as a direct result of the heterogeneity (NNP) of the waste rock material. A more detailed characterisation of the waste rocks is therefore required before implementable mixing ratios can be determined.

6. SUMMARY

- Based on the ABA test results, a portion of the Husab waste rock sequence is characterised as potentially acid forming (PAF).
- The tailing and filter cake samples are generally characterised as PAF.
- No correlation between ARD potential and lithological units is yet available.
- The acid neutralising potential of non acid forming waste rock samples is highly variable and results in a wide range of mixing ratios for neutralisation of PAF mine residues.
- The SPLP extract of the Husab composite waste rock samples meets Namibian drinking water limits (class D) or effluent standards.
- The SPLP extract of the Husab filter cake samples and the associated liquor exceeds for numerous elements the Namibian drinking water limits (class D) or effluent standards. Numerous highly elevated metal concentrations are of environmental concern.

7. RECOMMENDATIONS

Based on the assessment of acid generation potential for the Husab mine residue samples, the following recommendations are given for further analysis and assessments:

- Detailed characterisation of entire waste rock sequence, especially sulphide content and NNP.
- Kinetic assessment of acid generating and non-acid generating samples to establish the duration and kinetics of acid generation, respectively neutralisation.
- Since the net acid generation as well as net neutralisation potential has been established for numerous samples, a site specific volume adjustment/assessment of the ABA data (linkage to rock types and actual waste volumes) is required.
- The site specific volume adjustment should consider different ARD mitigation and control measures.
- Additional leach tests on single core samples covering the entire waste rock sequence to broaden database and increase confidence in leachate prediction.
- Future leach tests should simulate more acidic conditions as expected for ARD.
- Future leach tests should cover all elements at appropriate limits of detection.

8. DISCLAIMER

A critical success factor for any geochemical characterisation program is the selection of representative samples considering material type (e.g. lithology), spatial (e.g. vertical and horizontal area to be mined) and compositional (e.g. all material types based on sulphur content) representation as well as sample storage and handling (e.g. fresh or weathered samples). The mine geologic model might be used in the selection of representative samples.

No information regarding the sample collection, sample preservation or representativeness of the samples was provided by the client. Metago Water Geosciences therefore does not accept liability for the representativity of the tested samples.

Several TCLP and SPLP leach test results excluded major elements like chloride from the analysis or showed insufficient limits of detection for trace elements like chromium to be compared against WHO guideline values. The assessment of the leach test results is therefore incomplete with regard to the total salt load.

9. REFERENCES

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