

## APPENDIX M7

### TAILINGS GEOTECHNICAL ASSESSMENT FOR BIH PROJECT

## ANGAS PROCESSING FACILITY

MISCELLANEOUS PURPOSES LICENSE APPLICATION

2019/0826



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Dear Matt

## **Geochemical Interactions between Zn/Pb Sulphide and Gold Oxide Tailings**

### **1.0 Introduction**

Terramin Exploration Pty Ltd (Terramin) proposes to develop the Bird in Hand (BiH) Gold Project (the Project). The Project is located approximately 2.7km from Woodside in the Adelaide Hills and 35 km north of Terramin's existing Angas Zinc Mine (Angas) at Strathalbyn. The Project is expected to have a mine life of at least five (5) years.

Terramin proposes to mine the BiH Resource (reef gold deposit) by conventional underground mining methods. Mined ore will be transported via road haulage, along existing sealed road infrastructure, to the existing processing facilities at Angas. Ore will be crushed, ground and then processed via flotation based on sodium ethyl xanthate collector and methyl isobutyl carbinol (MIBC) frother to produce a gold bearing concentrate. Both oxide and sulphide ore will be processed together producing a combined tail that will be deposited to the existing tailings storage facility (TSF) at Angas. No acid leaching or cyanidation will be used in the process.

As part of the broader environmental assessment for the Project and to help facilitate project approval and development, Terramin commissioned AECOM Australia Pty Ltd (AECOM) to complete a geochemical assessment on the BiH tailings.

### **1.1 Objectives**

The main objectives of the geochemical assessment were:

- Evaluate the geochemical interactions over time between the existing sulphide rich tailings contained within the TSF at Angas and the carbonate rich tailings produced by the Project.
- Assess the potential environmental effects resulting from those geochemical interactions and the interaction of the products on the TSF's lining.
- Assess how the net acid potential of the combined Angas tailings and the BiH tailings may change from existing conditions.

### **1.2 Geology**

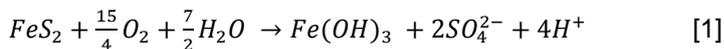
The Woodside goldfield is situated in the Adelaide Hills on the southern parts of the Mt. Lofty Ranges. The local site stratigraphy from oldest to youngest comprises the Tapley Hill Formation, the Brighton Limestone and Tarcowie Siltstone (Griessmann 2011). The Tapley Hill Formation comprises dark grey to blue, carbonaceous, pyritic, sandy metamorphosed dolomitic siltstones. The Brighton Limestone is a recrystallised, white marble unit with local beds of metasiltstone. The Tarcowie Siltstone is a grey to beige metasiltstone unit containing sandstone beds (equated to the Cox Sandstone Member).

The BiH gold mineralisation is hosted in quartz reefs within the Brighton Limestone. Quartz is the dominant gangue phase with minor carbonate (siderite and calcite). The mineralisation can be subdivided into a pyrite-dominated gold-only mineralisation and a mineralogically more complex gold-lead-zinc-copper-cadmium-silver mineralisation (Griessmann 2011). The gold-base metal mineralisation has a larger variety of minerals. Apart from quartz and pyrite, other minerals present are galena, sphalerite, chalcopyrite, bornite, chalcocite, covellite, greenockite, native gold/electrum

and a variety of carbonates (Griessmann 2011). Native gold occurs as fracture fill, inclusions and overgrowths on pyrite, and as isolated rounded grains in the quartz gangue. In the oxidised parts of the orebody, pyrite is replaced by goethite.

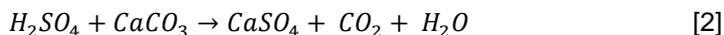
### 1.3 Geochemistry

The geology and mineralisation of the orebody play an important role in determining the geochemical characteristics of the BiH tailings material. The exposure of sulphide minerals, most commonly pyrite (FeS<sub>2</sub>), to atmospheric oxygen and water can result in the acid generation. The oxidation of pyrite is in itself a complex process; however, it can be represented by the following overall reaction (Equation 1):



As acidic (H<sup>+</sup>) water migrates through tailings it further reacts with minerals in the tailings, and may dissolve a range of metals and salts. As a result, acid drainage is characterised by low pH and elevated dissolved metals.

In some cases, the acid generated can be completely neutralised by the dissolution of carbonate minerals such as calcite, dolomite, ankerite and magnesite. This neutralisation reaction can be represented by the following reaction (Equation 2):



In general, tailings generated from oxide ore material are expected to be non-acid forming (NAF), whereas, those derived from sulphide ore are potentially acid-forming (PAF) depending on the inherent amount of carbonate assemblages present.

### 2.0 BiH Tailings

As part of the metallurgical test work for the Project, two (2) composite tailings samples were generated using drill core material derived from the 2016 resource drilling program. Table 1 shows the intervals selected to produce flotation tailings derived from both the oxidised and sulphide parts of the orebody.

The samples that went into each composite tailings sample were selected to be representative of the BiH ore. However, it is noted that future metallurgical test work would also contain 10% to 20% marble from the hanging wall and footwall to represent the dilution that will occur during the mining process (E.Whittaker, pers. comm., 20 April 2017). Furthermore, the galena (PbS) content in the sulphide tailings was considered to be too high to be representative of production tailings.

It is noted that testing of the aqueous component of the BiH tailings was not conducted as part of Terramin's initial metallurgical test work.

**Table 1 Core interval samples used to generate sulphide and oxide tailings**

Tailings Type	Drill Hole	From (m)	To (m)	Number	Weight (kg)
Sulphide	BH056	140.85	141.00	266894A	0.555
		189.00	189.70	266913A	2.560
		191.00	191.50	266915A	1.855
		191.50	192.50	266916A	3.420
	BH057	206.06	207.22	266997A	4.415
		195.85	196.85	266984A	3.770
		203.70	203.94	266993A	0.670
		209.98	211.08	2001821A	4.765
	BH058	207.85	208.31	2002463A	1.680
		208.31	209.00	2002464A	1.620
		212.48	213.10	2002469A	2.745

Tailings Type	Drill Hole	From (m)	To (m)	Number	Weight (kg)
Oxide	BH054	192.90	193.30	266879A	1.475
		193.30	193.70	266880A	1.500
		193.70	194.08	266880A	0.650
		194.08	195.00	266882A	3.200
	BH056	192.50	193.00	266917A	1.795
		193.00	194.00	266919A	3.725
		194.00	195.00	266920A	3.435
	BH057	205.12	205.63	266995A	1.695
		205.63	206.06	266996A	1.800
	BH058	209.00	210.11	2002465A	2.470
		210.68	211.44	2002467A	1.740
	BH059	223.00	224.04	266764A	2.545
		227.24	228.00	266769A	1.840

### 2.1.1 Minerology

The mineralogy of the tailings samples was determined by X-ray diffraction (XRD). The XRD analyses indicate that the sulphide and oxide tailings consist predominantly of quartz with minor muscovite, calcite, goethite, pyrite (for sulphide tailings) and trace apatite and chlorite (Table 2). The absence of sulphide minerals such as galena (PbS), pyrite (FeS<sub>2</sub>) and sphalerite (ZnS) is characteristic of oxide tailings (Table 2).

**Table 2** Minerology of BiH sulphide and oxide tailings

Phase	Typical Composition	1019064 T05 Sulphide Ro Tail (wt%)	1019085 T08 Oxide Ro Tail (wt%)
Plagioclase	Na <sub>0.75</sub> Ca <sub>0.25</sub> Al <sub>1.25</sub> Si <sub>2.75</sub> O <sub>8</sub>	0.1	0 <sup>1</sup>
Apatite	Ca <sub>5</sub> (PO <sub>4</sub> ) <sub>3</sub> (F,Cl,OH)	0.7	1.0
Calcite	CaCO <sub>3</sub>	3.4	19.2
Chlorite	(Mg <sub>4.5</sub> Fe <sub>0.2</sub> <sup>II</sup> Fe <sub>0.2</sub> <sup>III</sup> Al)AlSi <sub>3</sub> O <sub>10</sub> (OH) <sub>8</sub>	1.6	0.4
Dolomite	CaMg(CO <sub>3</sub> ) <sub>2</sub>	0.9	0 <sup>1</sup>
Galena	PbS	0.3	0 <sup>1</sup>
Goethite	FeO(OH)	2.1	1.9
Muscovite	K <sub>0.8</sub> Na <sub>0.2</sub> (Fe <sub>0.1</sub> Al <sub>1.9</sub> )AlSi <sub>3</sub> O <sub>10</sub> (OH) <sub>2</sub>	5.0	2.1
Pyrite	FeS <sub>2</sub>	1.2	0 <sup>1</sup>
Pyrrhotite	Fe <sub>(1-x)</sub> S	0 <sup>1</sup>	0 <sup>1</sup>
Quartz	SiO <sub>2</sub>	84.6	75.2
Siderite	FeCO <sub>3</sub>	0 <sup>1</sup>	0 <sup>1</sup>
Sphalerite	(Zn,Fe)S	0.1	0 <sup>1</sup>

Note 1: If present, these phases occur in trace amounts.

**2.1.2 Acid Consuming Potential**

The potential for the tailings sample to generate acidity and/or alkalinity has been assessed based on the Net Acid Producing Potential (NAPP) and Net Acid Generation (NAG) testing. The NAPP is the difference between the samples' maximum potential acidity (MPA), based on total sulphur concentrations, and acid neutralising capacity (ANC). In contrast, the NAG test directly measures the net amount of acid generated by a sample because acid generating and acid neutralising reactions occur simultaneously in the assay.

Table 2 summarise the acid generating potential of the BiH tailings. Table 2 shows that the NAPP and NAG results are consistent, with both sulphide and oxide tailings having sufficient ANC that can neutralise all the acid that could be theoretically generated by the sample. The oxide and sulphide tailings are considered potentially acid consuming (ACM) and NAF, respectively, based on the geochemical classification system adopted by the Department of Industry, Innovation and Science (2016).

**Table 3 Acid generating potential of BiH tailings**

Parameter	Units	1019064 T05 Sulphide Ro Tail	1019085 T08 Oxide Ro Tail
Total sulphur (Leco)	%S	0.72	0.03
Maximum potential acidity (MPA)	kg H <sub>2</sub> SO <sub>4</sub> /t	22.0	0.92
Acid Neutralising Capacity (ANC)	kg H <sub>2</sub> SO <sub>4</sub> /t	47.1	262
Net Acid Producing Potential (NAPP)	kg H <sub>2</sub> SO <sub>4</sub> /t	-25.1	-261
NAG pH <sup>1</sup>	pH unit	8.4	11.0
NAG (pH 4.5) <sup>2</sup>	kg H <sub>2</sub> SO <sub>4</sub> /t	<0.1	<0.1
NAG (pH 7.0) <sup>3</sup>	kg H <sub>2</sub> SO <sub>4</sub> /t	<0.1	<0.1

Note 1: pH after NAG test reaction with hydrogen peroxide.

Note 2: Acidity due to free acid (i.e. H<sub>2</sub>SO<sub>4</sub>) and the release of iron and aluminium at pH < 4.5.

Note 3: Acidity due to metallic ions (such as copper and zinc) that precipitate out as hydroxides at pH values between 4.5 and 7.0.

**3.0 Existing Angas Tailings**

The composition and acid and metalliferous drainage (AMD) potential of the existing tailings stored within the Angas TSF has been previously assessed (EGi 2005a; EGi 2005b; EGi 2006).

**3.1.1 Mineralogy**

The mineralogy of the existing tailings in the Angas TSF is summarised in Table 4. The results in Table 4 are based on XRD analysis of two (2) tailings samples, collected on 27 August 2013, as part of the broader AMD testing program in preparation of Angas being placed under Care and Maintenance.

Table 4 shows that the existing tailings is mainly composed of quartz, bassanite, pyrite, pyrrhotite, and mica and chlorite assemblages with minor to trace amounts of sphalerite and amphiboles. In comparison to the BiH tailings (Table 2), the existing tailings stored within the Angas TSF (Table 4) do not contain carbonates such as dolomite and/or calcite. The oxidation of sulphide minerals such as pyrite can result in the formation of secondary mineral phases (e.g. jarosite and gypsum). Bassanite (CaSO<sub>4</sub>•0.5H<sub>2</sub>O) was found to be present within the existing tailings possibly as a stable precursor phase to gypsum (CaSO<sub>4</sub>•2H<sub>2</sub>O).

**Table 4 Mineralogy of existing tailings stored within the Angas TSF 2013**

Phase	Composition	Tail 2 (wt%)	Tail 6 (wt%)
Mica group <sup>1</sup>	$X_2Y_{4-6}Z_8O_{20}(OH, F)_4$	27	15
Amphibole group	$XY_2Z_5(Si, Al, Ti)_8O_{22}(OH, F)_2$	-- <sup>4</sup>	5
Chlorite group	$(X_5Al)(AlSi_3)O_{10}(OH)_8$	9	12
Lepidocrocite	FeO(OH)	1	-- <sup>4</sup>
Bassanite	CaSO <sub>4</sub> •0.5H <sub>2</sub> O	8	8
Pyrite	FeS <sub>2</sub>	8	6
Pyrrhotite	Fe <sub>(1-x)</sub> S	12	13
Quartz	SiO <sub>2</sub>	34	47
Sphalerite	ZnS	1	1

Note 1: Mica Group in which X is K, Na, Ca; Y is Al, Mg, Fe; Z is mainly Si or Al but also may include Fe<sup>III</sup> or Ti.

Note 2: Chlorite group where X = Mg, Fe, Ni and Mn.

Note 3: Amphibole group where X is Na, K, vacant; Y is Na, Ca, Fe<sup>II</sup>, Li, Mn<sup>II</sup>, Mn<sup>III</sup>, Al, Mg; Z is Fe<sup>III</sup>, Mn<sup>III</sup>, Al, Ti<sup>IV</sup>, Fe<sup>II</sup>, Li.

Note 4: If present, these phases occur in trace amounts.

### 3.1.2 Acid Generating Potential

The acid generating potential of two Angas tailings samples, prepared as part of metallurgical test work conducted for the Angas Zinc Mine Project, are summarised in Table 5 (EGi 2005a; EGi 2005b). The tailings samples were found to contain high NAPP, with total sulphur concentrations ranging between 11.8% (EGi 2005b) and 20.8% (EGi 2005a). The NAG results confirm the high acid potential of the tailings.

Column leach testing of tailings (EGi 2005a) indicated that the acidification of tailings occur rapidly, with leachate of pH 3.5 being produced within the first two weeks of column leaching, and remained between pH 3.1 and pH 3.5 over a 44 week wet-dry leaching cycle. Over the same period, sulfate concentrations in leachate samples ranged between 1500 mg/L and 2000 mg/L for the first four weeks then increasing to 10,418 mg/L at week 12, indicating high sulphide mineral oxidation and sulfate release rates. This was followed by observed decreased in sulfate concentrations to about 1,900 mg/L at week 40.

The above studies predicted that the Angas tailings would be highly reactive and have the capacity to generate high sulfate and acid leachate if the solids are beached and exposed to atmospheric conditions (EGi 2005a; EGi 2005b).

Testing of production tailings (i.e. existing tailings from the Angas TSF) conducted as part of the 2016 Angas Zinc Mine Annual Compliance Report (Terramin 2017) confirm the PAF characteristics of the tailings material based on qualitative field peroxide oxidation (pH<sub>FOX</sub>) testing of surface tailings samples. This testing showed that tailings material sampled at depth (0.4 to 0.7 metres below the surface of the deposited tailings) was more neutral in pH than at the TSF surface. This is possibly due to a reduction in oxygen as a result of increased water saturation at depth compared to the surface layer, and hence slower oxidation rates.

**Table 5 Acid generating potential of existing Angas tailings**

Parameter	Units	Sample 1 (EGi 2005a)	Sample 2 (EGi 2005b)
Total sulphur (Leco)	%S	20.8	11.8
Maximum potential acidity (MPA)	kg H <sub>2</sub> SO <sub>4</sub> /t	636	361
Acid Neutralising Capacity (ANC)	kg H <sub>2</sub> SO <sub>4</sub> /t	5	13
Net Acid Producing Potential (NAPP)	kg H <sub>2</sub> SO <sub>4</sub> /t	631	348
NAG pH <sup>1</sup>	pH unit	2.4	2.0
NAG (pH 4.5) <sup>2</sup>	kg H <sub>2</sub> SO <sub>4</sub> /t	--	--
NAG (pH 7.0) <sup>3</sup>	kg H <sub>2</sub> SO <sub>4</sub> /t	462	342

Note 1: pH after NAG test reaction with hydrogen peroxide.

Note 2: Acidity due to free acid (i.e. H<sub>2</sub>SO<sub>4</sub>) and the release of iron and aluminium at pH < 4.5.

Note 3: Acidity due to metallic ions (such as copper and zinc) that precipitate out as hydroxides at pH values between 4.5 and 7.0.

### 3.1.3 Tailings Water

The available water quality of the TSF Decant Pond and TSF Seepage Drain are summarised in Table 6. The results in Table 6 are derived from:

- Monitoring data collected on 16 January 2017 as detailed in Angas Zine Mine Annual Compliance Report 2016 (Terramin 2017).
- Water quality data ('Data Summary.xlsx') provided by Terramin (K. Fechner, pers. comm., 09 May 2017).

Table 6 indicate that the pH of the filtered TSF seepage is neutral compared to the water contained within the Decant Pond, which is highly acidic and contain relatively higher metal/metalloid concentrations.

**Table 6 Summary of TSF Decant Pond and Seepage Drain water quality**

Analyte	Units	TSF Decant Pond	TSF Seepage Drain <sup>1</sup>
pH	pH unit	2.70	7.29
EC	µS/cm	25400	41700
SO <sub>4</sub> <sup>2-</sup>	mg/L	5970	5030
Cl <sup>-</sup>	mg/L	7700	14650
Ca	mg/L	853	1006
Mg	mg/L	320	372
K	mg/L	107	298
Na	mg/L	4950	9365
As	mg/L	0.027	0.002
Cd	mg/L	0.214	0.0032
Pb	mg/L	2.83	0.001
Zn	mg/L	108	0.197
Mn	mg/L	7.54	1.84
Fe <sup>a</sup>	mg/L	138	1.80
Ionic Balance	%	8.68	2.6

Note 1: Based on the average of Seepage Drain 1 and Seepage Drain 2 results (Terramin 2017).

#### 4.0 Acid Forming Characteristics of Future BiH/Angas Tailings

Static geochemical testing indicates that the BiH tailings have moderate to high ANC, with the oxide tailings containing considerable excess neutralising capacity. Because the existing Angas tailings are the dominant source of acid potential, and BiH oxide and sulphide tailings are a source of neutralisation potential, the net acid potential of combined Angas/BiH tailings is a direct function of the mixing ratio of the two tailings.

It is therefore expected that future deposition of BiH tailings into the Angas TSF may have beneficial outcomes in mitigating the current acid forming process of the existing tailings contained within the TSF by providing some acid consuming capacity. To assess how the acid forming characteristics might change in the future, mass-balance calculations were conducted based on:

- Reported geochemical data provided in section 2.1.2 and section 3.1.2.
- Two (2) million tonnes of tailings currently contained in the Angas TSF (Terramin 2017)
- Stoichiometric Equation 2
- Current mining production schedule (*BiH tailings quantites and calcite content.xlsx*) provided by Terramin (M. Daniel, pers. comm., 11 August 2017).

The available NAPP data indicate that the BiH tailings (combined oxide and sulphide tailings) can consume 286.1 kg H<sub>2</sub>SO<sub>4</sub> per tonne of tailings. The deposition of 456,000 tonnes of BiH tailings into the existing Angas TSF has the potential to consume ~30,550 tonnes of H<sub>2</sub>SO<sub>4</sub>, which is theoretically equivalent to adding ~31,180 tonnes of CaCO<sub>3</sub> for acid neutralisation. Mass-balance calculations suggest that the addition of BiH tailings would reduce the NAPP value of the existing tailings in the TSF from 348 kg H<sub>2</sub>SO<sub>4</sub>/t to 333 kg H<sub>2</sub>SO<sub>4</sub>/t, representing ~4% reduction in the net acid generating potential.

Therefore, the BiH tailings are expected to have a mitigating effect on the acid forming characteristic of the existing tailings in the Angas TSF.

#### 5.0 Geochemical Modelling

To assess the potential risk of geochemical interactions over time between the existing tailings contained within the TSF at Angas and those produced by the Project, a kinetic-geochemical model was used to simulate the Angas TSF water - BiH tailings mineral system.

##### 5.1 Conceptual Model

Fine tailings at Angas were deposited as a slurry within the TSF and allowed to sediment (i.e. consolidate). Since diffusion of oxygen in air is approximately four (4) times greater than in water (Department of Industry, Innovation and Science 2016; Nicholson *et al.* 1998), oxygen ingress into tailings is relatively slow under water-saturated conditions. A reduction in oxygen ingress as a result of increased water saturation leads to slower mineral oxidation processes (Section 1.3).

The availability of oxygen and water is the main factor governing the overall reaction rate. This implies that oxidation, and hence acid production will predominantly occur in the unsaturated zone of tailings deposits. This is consistent with more neutral pH values observed in Angas tailings at depth compared to those measured in near surface.

Similar field observations of depletion of sulphides above the water table (phreatic surface) in tailings deposits are commonly reported (Holmström *et al.* 2001). In the modelling, the unsaturated zone was considered to be the major reactive zone in the tailings deposit and the main source of dissolved constituents in the groundwater. This zone was conceptualised as a single, completely-mixed flow-through reactor. The partial pressure of oxygen ( $pO_2$ ) and carbon dioxide ( $pCO_2$ ) was held constant (i.e. the system was buffered by atmospheric CO<sub>2</sub> and O<sub>2</sub>). Fe(II) and Fe(III) were specifically considered as separate components (i.e. decoupled) since ferrous iron added to solution by the dissolving pyrite must react with dissolved oxygen to produce ferric iron species, a process that proceeds slowly.

The modelling simulates the oxidation and dissolution of BiH tailings mineral phases due to contact with existing *in-situ* pore water in the TSF. The possible transport of soluble reaction products from the TSF to downstream groundwater receptors is dependent on the migration of contaminated pore

water derived from the leaching of *in-situ* tailings material and subsequent movement of that contaminated pore water through the unsaturated zone into the underlying saturated groundwater zone.

## 5.2 Model Input Parameters

The model input parameters are summarised in Table 7. In the absence of pore water data, the TSF Decant Pond water quality was used as a conservative estimate. The specific surface area was assumed to be 1000 cm<sup>2</sup>/g for each mineral phase, which is considered reasonable for sand-sized grains (Bethke 2008). The BiH metallurgical test work indicates that the average 80% passing size (P80) of the oxide and sulphide tailings were 215 µm and 209 µm, respectively.

As a first approximation, laboratory-derived reaction rate constants under acid conditions (where available) were used based on Palandri and Kharaka (2004), Acero *et al.* (2007) for galena, and Rimstidt *et al.* (1994) for sphalerite. Mineral reaction rates measured in the field are typically slower than laboratory-derived rates because actual geochemical processes commonly involve flow through porous media, where concentration gradients in the aqueous phase near mineral surfaces develop resulting in decreased absolute chemical affinity and slower reaction rates (Palandri and Kharaka 2004). Other contributing factors include grain size, preferred fluid flow paths, primary and secondary mineral coatings, and secondary minerals that may lead to decreased porosity and clogged pore spaces. Considering these factors and consistent with similar studies (e.g. Salmon and Malmström 2004), the laboratory-derived mineral weathering rates were decreased by two orders of magnitude in the kinetic-geochemical simulations.

**Table 7 Summary of geochemical model input parameters**

Parameter	Value	Source / Comments
TSF pore water	see Table 6.	Approximated based on TSF Decant Pond water quality. See section 3.1.3.
	Al	Based on kinetic leach column testing results EGi (2006).
	SiO <sub>2 (aq)</sub>	Calculated from Si data based on kinetic leach column testing results EGi (2006).
BiH tailings mineralogy	(see Table 2)	Based on XRD analysis of oxide and sulphide tailings generated from metallurgical test work See section 2.1.1
Mineral Surface Area (A <sub>s</sub> )	1000 cm <sup>2</sup> /g	Assumed. Bethke (2008)
Rate Constants (mol/cm <sup>2</sup> /sec)		
Plagioclase <sup>1</sup>	8.71 × 10 <sup>-15</sup>	Salmon and Malmström (2004)
Apatite <sup>2</sup>	1.86 × 10 <sup>-8</sup>	
Calcite	5.01 × 10 <sup>-5</sup>	
Chlorite <sup>3</sup>	7.76 × 10 <sup>-16</sup>	
Dolomite <sup>4</sup>	1.74 × 10 <sup>-8</sup>	
Goethite <sup>5</sup>	1.15 × 10 <sup>-12</sup>	
Muscovite	1.41 × 10 <sup>-16</sup>	
Pyrite	3.02 × 10 <sup>-12</sup>	
Quartz	1.02 × 10 <sup>-18</sup>	
Galena <sup>6</sup>	7.50 × 10 <sup>-15</sup>	

Parameter	Value	Source / Comments
Sphalerite <sup>7</sup>	$3.90 \times 10^{-14}$	Rimstidt <i>et al.</i> (1994)

Note 1: Based on K-feldspar; Note 2: Based on fluoroapatite; Note 3: Based on clinocllore;  
 Note 4: Based on hydrothermal (ordered) dolomite; Note 5: Based on rate constant under neutral conditions;  
 Note 6: Average of HCl and H<sub>2</sub>SO<sub>4</sub> treated galena powder; Note 7: Based on oxidation via Fe<sup>III</sup> at pH 2.0

### 5.3 Model Approach

The geochemical modelling was performed using The Geochemist's Workbench (GWB) Professional software version 9.0.9 (Bethke and The Board of Trustees 2008) to calculate the aqueous speciation and stability of minerals with respect to dissolved constituents following mixing.

The default thermodynamic database (thermos.dat) was used in all model simulations. This database is well established and is appropriate for this type of application.

The GWB code solves for the equilibrium state of a given geochemical system. The equilibrium represents the point at which the forward and reverse rates of all chemicals in a system are equal. Thermodynamically, the equilibrium represents the point of the lowest 'free energy' for a system. At this equilibrium point the activities ('effective' or 'active' concentrations) of both reactants and therefore products can be measured while the equilibrium state is expressed as K, the ratio of products to reactants.

K is called the distribution co-efficient or equilibrium constant, and the expression for the equilibrium constant is known as the mass action equation:

$$\log K_{rxn} = -\Delta G_{rxn}^0 / 2.303RT \quad [2]$$

Where:

R = universal gas constant (kJ/mole)

T = temperature (in Kelvin)

$\Delta G_{rxn}^0$  = free energy of a system from a chemical reaction under standard conditions (kJ)

Starting with the general component chemistry, the modelling program simultaneously solves a series of non-linear algebraic equations (matrices) consisting of the mass action equation, and corresponding equilibrium constant, for every possible aqueous species, mineral and gas in the thermodynamic database. As a result, possible outcomes may be limited by data in the database; however, metal speciation data are relatively well known and are included in the thermo.dat database. While solving the mass action equations, the code also solves an equation for overall system mass balance. The code uses iterative numerical methods (most frequently the Newton-Raphson method) to solve the matrices.

The mass action equation for a species, mineral or gas is only added to the solution matrices if it is present in the database and an amount for all the components in its mass action equation has been specified.

To correct for the effect of interactions amongst ions in solution, activities of both reactants and products are used in the mass action equations. This is because the log K-value for a chemical reaction is dependent on the number of ions in solution. The GWB code uses the 'B-dot' equation (Helgeson, 1969; Helgeson and Kirkham, 1974), a variant of the Debye-Hückle activity model, for calculating activities for solutions up to 3 molal (~96,000 μS/cm if NaCl is the dominant solute) and ranging from 0 to 300 °C.

The REACT module was used to develop kinetic-reaction path models to predict changes in water chemistry due to dissolution or weathering of BiH tailings mineral phases in approximated pore water. For reaction path modelling, the software first performs a speciation calculation to bring the aqueous system to equilibrium. It then begins tracing the reaction path by adjusting a system component one incremental step at a time and recalculates the new equilibrium state. This continues until the reaction path steps (default is 100 increments) have been added. The sum of all steps is known as the reaction path.

The default rate law for mineral dissolution and precipitation was used to model mineral-water reactions:

$$r_k = A_s k_+ \left(1 - \frac{Q}{K}\right) \quad [3]$$

where:

- $r_k$  = reaction rate (mol/s, positive for dissolution)
- $A_s$  = mineral surface area (cm<sup>2</sup>/g)
- $k_+$  = rate constant (mol/cm<sup>2</sup>/s)
- $Q$  = ion activity product
- $K$  = equilibrium constant for the dissolution reaction

The mineral surface area ( $A_s$ ) is an expression of how much mineral surface is in contact with the fluid in the system.

The term  $Q/K$  is mineral saturation state variable, which adjust the magnitude of reaction rate according to how far it is from equilibrium, as well as the reaction direction. If the mineral is in equilibrium with the fluid,  $Q/K = 1$ , and the term  $(1 - Q/K) = 0$ , and the reaction cannot proceed. If  $Q/K > 1$ , the mineral is supersaturated,  $(1 - Q/K) < 0$ , and precipitation occurs (negative reaction rate). If  $Q/K < 1$ , the mineral is undersaturated,  $(1 - Q/K) > 0$ , and dissolution occurs (positive reaction rate). Mineral stability was evaluated for a limited number of geochemically credible phases that are likely or known to precipitate/dissolve relatively easily under the conditions present in the field.

Modelling was initially conducted based on a 5 year simulation time (reflecting the expected mine life), but was found to be computationally too intensive to complete within a reasonable runtime. Sensitivity testing of the simulation time indicated that the dissolution of carbonates mainly controlled aqueous concentrations, with reactions reaching equilibrium after relatively short simulation timeframes. Therefore, geochemical models were conducted using a simulation time of 7 days to demonstrate the occurrence of key geochemical processes under the modelled conditions.

To model the effects of BiH tailings mineral phases in contact with existing *in-situ* pore water in the TSF, we start the geochemical simulation by first equilibrating the pore water with atmospheric oxygen, and then 'pick up' the resulting fluid as the initial starting system fluid. We then add the mineral phases reported in the BiH tailings and letting them react with the fluid.

#### **5.4 Model Simulations**

The current mining production schedule ("*TailsCalc.xlsx*") provided by Terramin (K. Fechner, pers. comm., 27 April 2017) indicate that the amount of oxide tailings generated for the first 23 months of mining will exceed the production of sulphide tailings (oxide to sulphide tailings ratios ranging from ~1 to 3). Thereafter, more sulphide tailings are expected to be generated due to the depletion of oxide ore, with oxide to sulphide tailings ratio of 1 to 9.

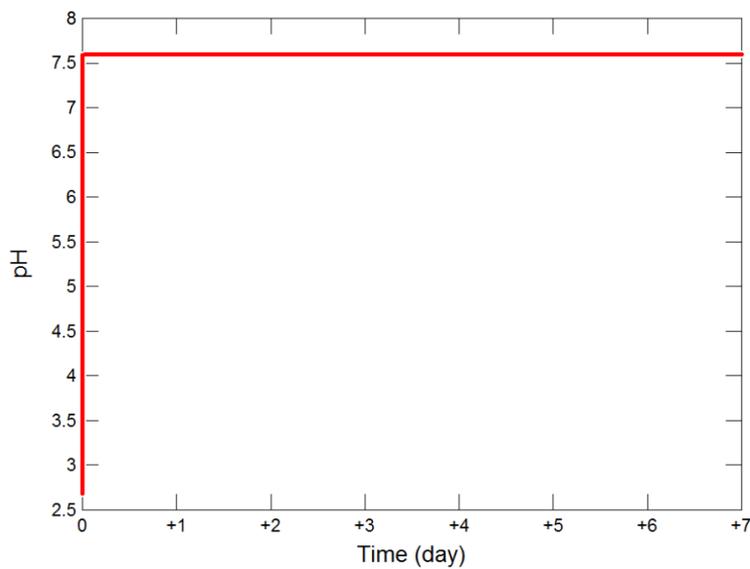
In view of this, two model simulations were conducted representative of:

- Angas TSF pore water - BiH oxide tailings mineral system
- Angas TSF pore water - BiH sulphide tailings mineral system

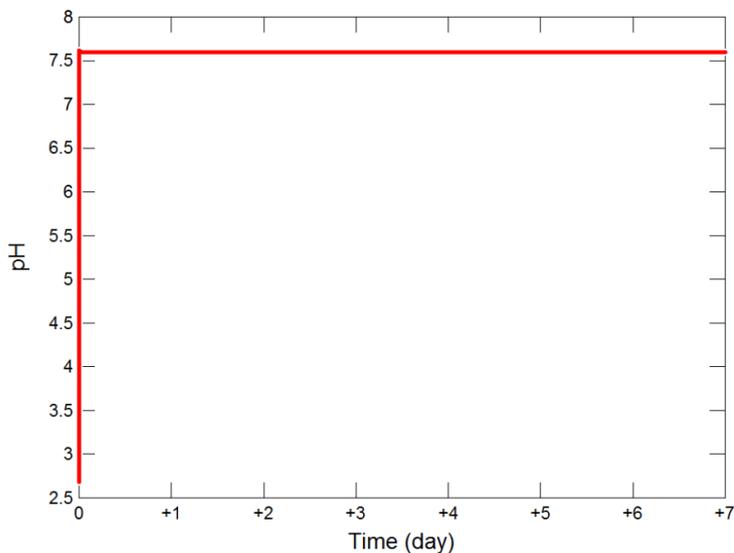
**6.0 Geochemical Model Predictions**

**6.1 Acid Buffering**

The most important control on the Angas TSF pore water chemistry is the nature of the non-sulphide minerals available to react with the acidic pore water in the unsaturated zone before subsequently migrating into the underlying saturated zone. The geochemical simulations indicate that the addition of BiH tailings may improve the TSF pore water quality by providing acid neutralising capacity. The addition of oxide (Figure 1) or sulphide (Figure 2) tailings resulted in an increase in pH, reflecting the acid-buffering capacity of the calcite and/or dolomite in the two BiH tailings streams.



**Figure 1** Variation in pH as BiH oxide tailings reacts with TSF pore water



**Figure 2** Variation in pH as BiH sulphide tailings reacts with TSF pore water

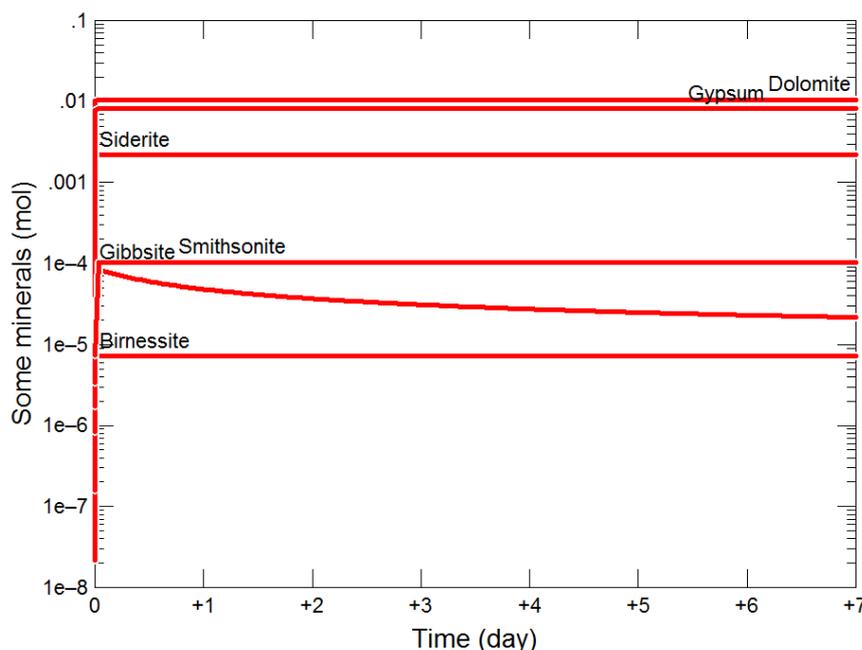
**6.2 Reaction Products**

Figure 3 and Figure 4 shows the predicted amount s of secondary minerals precipitated during the oxidation and dissolution of BiH tailings mineral phases in TSF pore water. Similar reaction products and predicted trends are observed for the oxide (Figure 3) and sulphide (Figure 4) tailings.

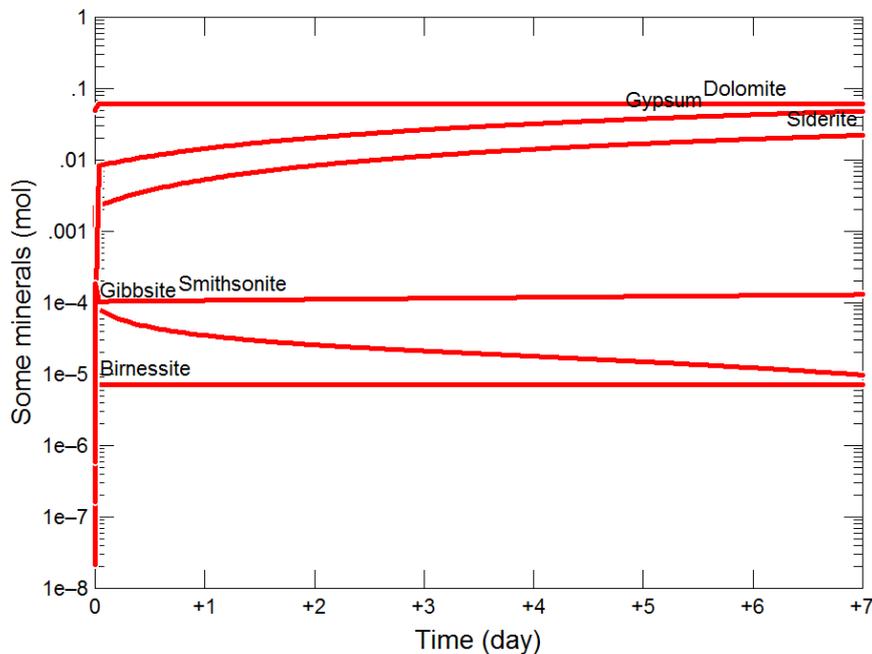
For the BiH oxide tailings, birnessite ( $MnO_2$ ) precipitates early in the reaction (Figure 3). Because of the mineral’s low solubility, virtually all of the pore water manganese added to the system is consumed by the precipitation reaction. Shortly thereafter, gibbsite forms (likely occurring as amorphous aluminium hydroxide) as a result of increasing pH values and alkalinity due to calcite dissolution. As the reaction proceeds, siderite ( $FeCO_3$ ) and dolomite ( $CaMg(CO_3)_2$ ) formation occurs progressively, with gypsum ( $CaSO_4 \cdot 2H_2O$ ) becoming saturated later in the reaction. Later in the reaction path, as pH and alkalinity continue to rise, smithsonite ( $ZnCO_3$ ) forms and some of the gibbsite begins to dissolve due to primarily the formation of  $Al(OH)_4^-$  species.

The BiH sulphide tailings (as tested) is characterised by relatively less calcite and the presence of dolomite and sulphide minerals (during production the sulphide is expected to contain 10% dilution from the marble footwall and hanging wall). The dissolution of dolomite occurs initially in the reaction path until pH is buffered to near neutral values (pH 7.14) due to the dissolution of calcite. The formation of birnessite then occurs shortly thereafter, followed by gibbsite which occurs in greater amounts than from the reaction with oxide tailings. Siderite, smithsonite and dolomite then progressively become saturated, and more of these minerals also form from the fluid than from the reaction with oxide tailings. As pH further increases the dissolution of gibbsite begins due to the formation of anionic species.

The above reaction products or secondary minerals formed are geochemically benign and are not predicted to have adverse impacts to the existing Angas tailings over time. The conditions formed are unlikely to cause degradation of the TSF liner and associated seepage drain systems from a geochemical context.



**Figure 3 Predicted minerals precipitated during the reaction between BiH oxide tailings and Angas TSF pore water**



**Figure 4** Predicted minerals precipitated during the reaction between BiH sulphide tailings and Angas TSF pore water

### 6.3 Tailings Pore Water Quality

The deposition of BiH tailings into the Angas TSF is expected to reduce the current acid forming characteristic of the Angas tailings by providing some acid consuming capacity. Geochemical simulations indicate that this acid consuming characteristic may also improve the TSF pore water quality. The predicted resultant TSF pore water quality was compared to the unreacted TSF pore water concentrations and TSF seepage drain water quality.

Table 8 shows that the addition of BiH tailings into the Angas TSF resulted in improved pore water quality in terms of pH, EC, TDS, sulfate, Fe and Mn concentrations under the simulated conditions. It is recognised that further improvement is likely to be attained in the field considering natural attenuation processes such as sorption onto particle surfaces (e.g. hydrous ferric oxide) were not incorporated into the kinetic-geochemical models.

**Table 8** Predicted TSF pore water composition compared to TSF seepage and unreacted tailings pore water

	pH	EC (µS/cm)	TDS (mg/L)	SO <sub>4</sub> <sup>2-</sup> (mg/L)	As (mg/L)	Fe (mg/L)	Mn (mg/L)	Pb (mg/L)	Zn (mg/L)
Predicted BiH sulphide tailings pore water	7.60	19776	20308	5195	0.027	16.1	<0.001	5.72	101
Predicted BiH oxide tailings pore water	7.60	19752	20281	5191	0.027	16.1	<0.001	2.83	101
TSF pore water <sup>1</sup>	2.70	25400	18400	5970	0.027	138	7.54	2.83	108

	pH	EC ( $\mu\text{S/cm}$ )	TDS (mg/L)	$\text{SO}_4^{2-}$ (mg/L)	As (mg/L)	Fe (mg/L)	Mn (mg/L)	Pb (mg/L)	Zn (mg/L)
TSF seepage <sup>2</sup>	7.29	41700	31800	5030	0.002	1.8	1.84	0.001	0.197

Note 1: Based on TSF Decant Pond water quality as a first approximation due to the absence of field pore water quality data.

Note 2: Based on the average of Seepage Drain 1 and Seepage Drain 2 results (Terramin 2017).

## 7.0 Conclusions

Static geochemical testing indicates that the BiH tailings have moderate to high ANC, with the oxide tailings containing considerable excess neutralising capacity. Mass-balance calculations suggest that the deposition of 456,000 tonnes of BiH tailings into the Angas TSF would result in the minimum addition of ~31,180 tonnes of equivalent  $\text{CaCO}_3$  for acid neutralisation.

The addition of BiH tailings streams would reduce the NAPP value of the existing tailings in the TSF from 348 kg  $\text{H}_2\text{SO}_4/\text{t}$  to 333 kg  $\text{H}_2\text{SO}_4/\text{t}$ , which represents ~4% reduction in the net acid generating potential. Therefore, the BiH tailings are expected to have a positive impact on the acid forming characteristic of the existing tailings in the Angas TSF.

Based on REACT kinetic-geochemical simulations under the assumptions and conditions of the modelled systems, the addition of the BiH tailings into the existing Angas TSF is expected to:

- Improve the TSF pore water in terms of pH, EC, TDS, sulfate, Fe and Mn concentrations, while recognising that further improvement may be attained in the field considering natural attenuation processes such as sorption onto particle surfaces (e.g. hydrous ferric oxide).
- Form reaction products or secondary minerals that are considered geochemically benign and are not predicted to have adverse impacts to the existing Angas tailings over time.

The geochemical assessment show that the deposition of BiH tailings into the Angas TSF will not adversely impact or increase the geochemical risk profile of the existing tailings, or result in conditions that would cause degradation of the TSF liner and associated seepage drain systems from a geochemical context. Rather, the addition of BiH tailings is expected to reduce the net acid generating potential of the existing tailings in the Angas TSF and help improve pore water quality (in terms of pH, EC, TDS, sulfate, Fe and Mn concentrations under the simulated conditions).

## 8.0 References

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Yours sincerely



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