Pilot System Construction Report

Dapo Coal AMD site of Huaxi, Guiyang

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31 December 2012

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1.0 Introduction

The ecological treatment system consists of three (3) components which constitute the treatment train. The first component removes iron by facilitating oxidation and nucleation of small iron particles. This occurs in two or more open ponds depending on the flow volume to be treated. The chemical characteristics of the AMD determine if aeration is needed. This can be achieved by passing the AMD flow over a cascade. In the first open pond the precipitates accumulate. Depending on the precipitate formation rate, the nucleation sites can be provided by installing sediment curtains into the pool. The relatively clear colorless acidic AMD is collected in the second open pond. This first step is the most important step, as effective removal of precipitated iron is needed to minimize coating of organic matter in the following component the ARUM (Acid Reduction Using Microbiology) ponds.

The second component is the construction of the ARUM ponds. For these ponds to function a microbial active sediment needs to be constructed and a living floating vegetation cover is placed over the surface of the pond. The sediment construction requires two types of organic matter easily degradable organic matter and highly recalcitrant material (slow or non degradable). The easily degradable organics will serve as food sources to the microbes and the recalcitrant material will provide the structure for the biofilms to housing the microbes. In these ponds low oxygen conditions prevail. The root mass suspended over the sediment of the living floating islands, provides organic acids or the easily degradable organic matter, to the sediment.

The detailed microbial activity of ARUM has only be assessed pragmatically, based on the scientific and microbiological knowledge, but not quantified. Geochemical simulations using PHREEQC (http://wwwbrr.cr.usgs.gov/projects/GWC_coupled/phreeqc) of the pore water which evolved in constructed sediments indicated that conditions for bio-mineralization are indeed given. The saturation indexes suggesting that relatively stable metals are formed in these constructed sediments. Furthermore in multiple empirical field and laboratory tests reliably increases in pH and decreases in Eh have been documented. Thus these ponds achieve significant reduction of metals in the AMD or ARD.

A third component of the treatment train might be a biological polishing pond. However this is not always needed and depends on the location of the discharge of the system and the location where compliance with the discharge regulations is expected. A biological polishing pond is an open pond in which through adsorption to algal cell walls elements are removed from the water. These would be elements, which would need to be oxidized in order to be adsorbed and which were not removed in the precipitation pond, were many metals are removed together with the precipitating iron. In most system constructed to date, such a pond was not needed. Depending on the geochemical characteristics of the AMD, all three components of the treatment train can be added in sequence. The determination of the sequence of the components, the sizing of the ponds is the main objective of the feasibility study, as this aspect is always site specific. Unfortunately for this project the elemental composition of the AMD and the two treatment components, iron oxidation / precipitation and ARUM, could not yet be determined, as the analytical instrumentation was out of order. **It is recommended that this aspect will be addressed, once the pilot system is constructed and taken into operation. From this data adjustments and alterations may well be needed.**

The Dapo site was selected based on economic and topographic criteria detailed in the site selection report (attached as Appendix 1). The pilot system is constructed based on the data obtained during the feasibility study. These data are key to designing effective functioning of the treatment. The oxidation rate of the AMD determines if an oxidation cascade is needed or not and it determines the size of the ponds for the iron precipitates to settle. In addition, tests have to be carried out to determine the suitability of the locally available organic matter to construct the ARUM sediments.

Finally with the running of the treatment system through two seasons (two dry and two rainy seasons) the design criteria are developed for the full treatment system of the site. With these data the scale up of the system is facilitated to achieve complete treatment of the effluents from the adit. **It is important to recognize, that pilot system implementation is a stepwise procedure, which, when carried out systematically, will provide the groundwork for other treatment system with similar AMD characteristics**.

2.0 AMD supply of the system: physical and chemical

The background to conducting a feasibility study is site specific information. The site history when mining started and terminated is useful to know and how much wastes were accumulated during this time. This information facilitates an assessment of the degree to which the wastes have weathered to date and the magnitude of the contamination which has likely accumulated downstream of the site. Water quality monitoring data from receiving rivers or lakes are relevant, particularly over the longer term, as chemical changes in the discharged AMD both seasonal and over the long term can be determined. Ground and surface water hydrology data specific to the area along with records of the atmospheric precipitation are needed, as they influence the water quality and the water volume discharging from the mine. Water infiltrating during the rainy season will either increase or decrease the metal concentration arriving at the adit unless the underground workings are protected by a stratigraphic formation with low hydraulic conductivity. Given the wild-cat coal mining activity in the Huaxi region in which Dapo is located, no records are available to determine the amount of coal waste or any other data. No mine plans are available. This lack of information is undesirable and increases the potential that the system is either over or undersized to accommodate the flow from the adit. **It is therefore recommended that monitoring of the adit water volume and its chemical composition are carried out two times per months. The water collected should be preserved (acidified to pH 1 or lower) immediately in the field and the determination of pH, Eh, and electrical conductivity is carried out in the running water of the adit. It is important not to filter the water.**

2.1 Estimating the Water Volume from the adit

A limited number of flow values (N=6) from the adit have been collected by Prof. Tangfu Xiao since 2010 intermittently. Based on these data the flow from the adit is estimated to range between 20 - 50 m^3 per day representing dry and rainy season respectively (Table 1). The number of flows measured during the dry season and rainy season are for both three (N=3). The values obtained are inconsistent but it is the best we have.

Table 1 Flow and concentrations of iron, manganese and sulphate

Date	Season	Flow（m^3/day）	pH	Fe (mg/L)	Mn (mg/L)	SO_4^{2-} (mg/L)
2010.10.15	Rain	*NM*	2.32	424.8	80.9	5009.4
2011.5.27	Dry	4.4	*NM*	*NM*	*NM*	*NM*
2011.7.24	Rain	21	3.12	428.76	205.85	*NM*
2012.3.16	Dry	*NM*	2.13	553.97	214.08	*NM*
2012.4.6	Dry	*NM*	*NM*	1060	124	*NM*
2012.7.20	Rain	50.8	2.29	1559.7	42.2	*NM*
2012.10.10	Rain	19.4	2.98	1347.9	168.7	5886.6
2012.11.17	Dry	17.1	*NM*	*NM*	*NM*	*NM*
2012.11.29	Dry	17.2	*NM*	*NM*	*NM*	*NM*

N.M. not measured

The average concentrations of Fe, Mn, SO_4^{2-} are, in the dry season, 807 mg/L for Fe, 169 mg/L for Mn, no value was determined for SO_4^{2-}, and in the rainy season, 940 mg/L for Fe, 124 mg/L for Mn, and 5447 mg/L for SO_4^{2-}. The averages are misleading and no trend is evident for either the dry or rainy season. The average Fe for the dry season is derived from two concentrations one value double that of the second value (554 mg/L, 1060 mg/L). In the rainy season, we have 4 values ranging from 429 to 1560 mg/L nearly 3 times higher. These large variances of the concentrations are clearly reflecting the unreliability of the average concentration.

One would expect that the rain either dilutes or adds more elements to the effluent, depending on the weathering (oxidation) conditions in the un-mined coal or gangue seams above underground workings. We can only hope that our estimates of flow to be handled by the pilot system are reasonably assessed to cover a storm event in the rainy season. The monitoring program which is recommended will facilitate, if needed, the constructions of a weir, which will regulate the volume of water entering the pilot system. Thus part of the volume if higher then estimated can be diverted into the old outflow channel. Once the pilot system performance is evaluated, the system can be expanded to treat the full flow from the adit. At present a safety factor of 2 times the average dry season flow is used. An overflow of the system during heavy storms would be quite destructive to the treatment until it has recovered or until the system is repaired. In Table 2 the calculations are presented which are used in the sizing of the ponds to reach the desired residence times.

Table 2 Estimation of resident time in the pilot system

	Audit flow (m3/day)	Safety factor	Total volume of ponds (m3)	Theoretical residents time (day)
Dry season	17.1	2	855	25
Rainy season	68.3	2	855	6

2.2 Lower part of the drainage basin – potential expansion area for full treatment

The seepage is presently leaving from the first platform (Plate 1).

Plate 1 The adit is located on the hill at the left side of the drainage

The AMD flows in a ditch constructed from coal wastes, leaving the classical stain from iron hydroxide particles adhering to the hill side and in the ditch. The AMD leaves the first platform being joined just before the end of the platform by small seep from the hillside (sample W3 Plate 2) before it runs over a 3 to 5 m steep terrace.

Plate 2 Sample code: W3

As the AMD runs alongside sticks and roots and down the face of the steep terrace, extensive concretions are formed from the iron precipitates, colored yellow brown is formed (Plate 3).

Plate 3 Sample code: W4

A water sample was collected (W4 plate 3) and the solid encrustment. On the second platform below the terrace with the encrustments a very small seep joins the seepage flow (Plate 4, sample W5)

Plate 4 Sample code: W5

Five (5) to 10 m away from the road, the AMD flow is very low (sample W6 plate 5) and finally disappears into the ground during the dry season. The ground is stained from the iron which reaches the road and its drainage channel during the rainy season. It has left iron stains on the ground in the dry season but no water discharges during the dry season. It can be expected to be quite different during the rainy season. **It is recommended that the seepages from the hillside and the agricultural field are assessed for flow and water quality in the monitoring program for the adit.** This will facilitate that all the AMD surface flow can be estimated and incorporated into the expansion of the pilot system and further groundwater contamination can be curtailed.

Plate 5 Sample code: W6

Plate 6 drainage channel

During the feasibility study a very crude assessment of the flows in the lower part of the drainage basin has been carried out by collection of AMD in bags over a given time period. The measurements were made about 3 times the bag was photographed and an equivalent volume determined in the laboratory.

In Table 3, these flow estimates are presented. The volume of AMD leaving the adit is estimated as 512 m^3 per month, but only 224 m^3 per month can be measured to arrive at the bottom of the drainage during the dry season, indicating that about 50% of the AMD flow per month which leaves the adit, disappears into the ground. Although these estimates are very preliminary, they are not surprising as the entire ground has a high hydraulic conductivity, i.e it is very permeable ground. **This is not only relevant to the construction of the ponds for the pilot treatment system as they might require a liner, but it is also relevant as further contamination of the groundwater in the region should be curtailed.**

Table 3 Estimation of flow in drainage basin and loss to groundwater

Site	Dry season l/h	m^3/day	m^3/month
W-1 audit	11	17	512
W3	4	0.096	3
W4 inflow	90	2	65
W4 outflow	208	5	150
W5	2	0.048	2
W6	5	0.120	4
TOTAL FLOW LOST TO GROUNDWATER			224

2.2.1 Erosion control of dams and upper drainage basin

The coal wastes are acidic (pH 3.1) but they have a low electrical conductivity (194 us/cm) given that they have been leaching for a long time and are mixed with eroded soil, which will adsorb many of the weathering products from the coal. The acidity of this slurry is with 71 mg equivalent of $CaCO_3$ /L very low. Slow release fertilizer (phosphate mine tailings) was placed at a dosage of 1 kg per 4 m^2 on the ground to promote a moss cover growth, which is intended to reduce erosion and reducing infiltration of atmospheric precipitation into the coal wastes. Several of such test plots were placed throughout the small Dapo drainage basin.

Moss growth covers are found widespread locally growing on coal waste. If the slightly neutralizing fertilizer is effective, it may represent an effective low cost erosion control measure needed for the upper part of the drainage basin. A run-off diversion channel is being constructed as required for construction sites by EPA regulation, to divert the run-off during the rainy season to the lower end of the platform alongside the first and second precipitation ponds and the access road to the first platform.

2.3 The chemical characteristic of AMD

Two types of AMD are investigated during the feasibility study, as they may display different characteristics, relevant to the performance of the oxidation and precipitation ponds. The AMD emerging from the adit and the AMD which is pooling in the ditch being in contact with adhered iron particles on the surfaces of the ditch. The passage of the AMD over the hillside has removed iron precipitates leaving its typical stain. This suggests that oxidation has already taken place underground, **but to what extent oxidation has proceeded is not known**. Iron particles promote aggregation of smaller forms of iron of less then < 0.45 µm they may adhere in the cascade so less settlement is needed in the ponds. If further oxidation is possible, then the seepage from the adit will be channeled over a series of cascades before entering the pond but if not it could be channeled directly into the oxidation and settling ponds.

2.3.1 Oxidation potential of AMD

The oxidation of iron and aluminum is accompanied by changes in pH and electrical conductivity. Hence these parameters are used to determine the degree to which the AMD would further oxidize. The very first measurements of these parameters are made in the field and immediately on return to the laboratory. After that the AMD is simply exposed in a beaker to the air. At irregular intervals pH and electrical conductivity are re-measured.

In Table 4 the results are summarized and it is concluded that changes in pH and of total iron after 319 h exposed to the air are insignificant considering the measurement errors.

Table 4 Results of long term water monitoring of adit and pool water

Site description	pH				Conductivity (µs/cm)				Total iron (mg/L)
Time recording	0	48 h	60 h	319 h	0	48 h	60 h	319 h	
Dapo mining adit (W-1)	NA	2.4	2.8	2.4	NA	5160	5050	4750	1077
Second platform of Dapo (W-2)	NA	2.0	2.5	2.2	NA	4900	4840	4900	1094

From these observations it is suggested that the AMD oxidizes very slowly, as none of the parameters change after 319 h. To gain further assurance that further oxidation is unlikely aeration tests were carried out. An aquarium pump and an air distributer stone were used to supply intensely air to both types of AMD samples. The aeration of the adit AMD (w1) for either 18 h or 42 h after 125 h to 167 h since collection in the field show no appreciable reduction of Fe^{2+} in the filtered (w1-2f) (Table 5) but a significant reduction from 823 to 571 mg/L in the unfiltered. This suggests that the particles are of relevance in the oxidation process. If the AMD is older and some of the particles are removed (w2-) aeration is more effective and most of the reduced iron is oxidized after 42 h of aeration. The acidities are expected to remain in the same range 4700 and 3500 mg equivalent of $CaCO_3$ /L and similarly the total iron concentration between 1000 and 1150 mg/L. In conclusion, aeration promotes oxidation further and hence cascades are recommended before the AMD is entering the oxidation and settling ponds (Table 6).

Table 5 Acidities, total and ferrous iron concentrations, filtered and unfiltered aerated

label	Date field NOV.	Date test NOV.	Aeration h	Time h	Acidity mg $CaCO_3$/l	Total Fe mg/l	Fe (II) Mg/l
w1-2f	17	22	0	125.5	4423	513	518
w1-2f	17	23	18	143.5	4570	1062	643
w1-2f	17	24	42	167.5	4480	1004	563
w1-2uf	17	22	0	125.5	3521	1155	823
w1-2uf	17	23	18	143.5	4475	1071	696
w1-2uf	17	24	42	167.5	4351	1036	571
w2-2f	20	22	0	50	4182	523	483
w2-2f	20	23	18	68	4341	963	201
w2-2f	20	24	42	92	3897	690	10
w2-2uf	20	22	0	50	4696	1037	531
w2-2uf	20	23	18	68	4607	983	203
w2-2uf	20	24	42	92	4734	828	11

The cascading of the water from the adit to the precipitation pond and the wave action in the pond should promote oxidation effectively as long as a resident time of 4 to 7 days is obtained based on the water characteristics of the dry season. **It is strongly recommended that oxidation tests are repeated with water of the rainy season, as the oxidation conditions may be altered which higher flows.**

According to the preliminary design provided by Rockrong Engineering at present the total pond system will hold 855 m^3 if completely full. As indicated above with a flow of 17 m^3/day from the adit, the system will have a theoretical residence time of 25 day in the dry season and 6 days during the rainy season. This time is well within the time needed to promote oxidation effectively but on the settling of the particles little information could be obtained during these tests. The total iron concentrations in the aged samples deceases in the unfiltered samples between 120 to 204 mg/L but much less in the filtered samples (Table 5) as the larger precipitates have remained on the filter paper. This can be expected as larger particles assist in the removal of smaller iron forms as stated above. Inadvertently too much water was filtered through 0.45µm which was used to determine the mass of the particulate matter settling in the cells. Consequently less unfiltered water was available for testing.

In order to estimate the effect of removing iron particles, a known area of cheesecloth was exposed to a known volume of AMD with particles. The cloth was weighted before emerging and reweight after drying the same. Two surface areas were exposed one double the size of the other both inserted into roughly into the same amount of AMD while the water was aerated for 2 day. The cheesecloth gained about 3 g per m^2 collected over 2 days. This suggests that once nucleation of precipitates has started on the surface the removal is consistent with the area of exposed cloth. **This rough test is used to suggest, that baffles or sedimentation curtains for the first and second oxidation and settling pond are recommended. The amount of cloth suspended needs to be tested best in the field, as it is expected that the field conditions are better than those assessed roughly in the laboratory.** Removal of the precipitates is needed, as otherwise the organic matter used to construct the sediments are coated with iron precipitates essentially petrifying the organics and thus restrict microbial access to the organics and the coatings hinder exchange between the sediment and the water column.

Table 6 Adding surfaces for nucleation of iron particles

Label	Age at filtration (Day)	Water volume (ml)	Weight on filter 0.45µm (g)	Weight per liter (g/L)	Weight (g/m^2/day)
W-1	4	1200	0.12	0.1	
W-4	3	1400	0.12	0.086	
W-1*	4	1480	0.12	0.81	2.7
W-2*	1	1370	0.52	0.38	3.7

* aerated 2 days

2.3.2 The ARUM Ponds

Testing the sediment construction material available locally is needed as local organic materials have a different nutrient content along with differing degradation rates. These two characteristics of the organic material support the increases in pH of the AMD. The increase in pH in the AMD will lead to metal precipitation from the water to the sediment where they are ultimately stabilized by microbial bio-mineralization.

2.3.3 Components of the sediment

In order to utilize local material to construct the sediment, rice and corn stalks along with wild hay collected in the vicinity of the project was tested, if it would provide sufficient microbial nutrients for alkalinity generation. In 2 L jars about 100 g of the mixture of the organics was placed and 1.5 L of water was added to the organics form W-1 and W-2. A sample of tap water was added also added to organic matter to demonstrate the difference in the changes in the measured parameters of pH and electrical conductivity when AMD is added.

The tap water in the laboratory is ground water with a relatively high conductivity of 783 us/cm (Table 7).

Table 7 Adding organic matter to stimulate microbial activity to construct sediment

Jar code			1		2	4
Sample code	water position	Days	control water	Days	W-w	V-w
			Tap		**dapo adit**	**First platform**
con(µS/cm)	**original**	**0**	**783**		**5050**	**4840**
		2	1909	0	5040	5520
		8	2160	6	6280	6860
		12	2260	10	6300	6910
		23	2360	21	6360	7000
pH	**original**	**0**	**6.96**		**2.83**	**2.51**
		2	6.32	0	2.86	2.57
		6	6.48	4	3.56	3.37
		8	6.58	6	3.41	3.22
		12	6.35	10	3.42	3.23
		23	6.63	21	3.81	3.95
T Fe(g/l)			< 5		1076	1094

When it was added to the organic matter the release of dust and dirt doubled or tripled the conductivity. In contrast, the electrical conductivity did not increase much when AMD from the adit is added to the organics. With progressing decomposition taking place in the tap water and in the AMD the conductivity increases. Relevant to the ARUM process is only the fact that this value increases as this is indicative of decomposition. The important variable is pH were a slight decrease might be expected due to release of organic acids as noted with the tap water, but in the AMD the pH should increase due to the microbial iron reduction f oxidized iron until all of the oxidized iron is reduced.

The pH with organics and tap decreased from a value of 6.9 to 6.6 and in the AMD the increase in pH over the same time period 1 to 1.5 pH units. The increase appears to be at a steady pace of about 0.2 units every 2 days. Once all the iron is reduced alkalinity generation will cease equally when the nutrients released during decomposition are consumed. This point was not reached after 23 days. At that time, a concentrated nutrient can be added to the organics in the ARUM pond in the form of guineepig pellets which sink to the bottom of the pond. The dosage needed has to be tested in the laboratory**. It is recommended that these tests are carried out on the actual organics or the mixture there of which is actually being used in the pilot test system**.

The pilot treatment system is a flow through system and thus ARUM pools are continuously supplied with oxidized iron to be reduced by the microbes to consume hydrogen ions and thus generate alkalinity. Therefore in the stagnant tests in the jars, oxidized iron needs to be supplied regularly. Thus laboratory tests can only provide a general guidance but very useful microbial information could be collected, if possible. The production of easily degradable organics by the root mass could be quantified in relation to alkalinity generation.

Although this is not needed for the system to work, but it would be useful to further document the ARUM process. In order that the nutrients are not depleted and reducing conditions are supported living floating mats are placed as a cover over the pool. However it will take 1-2 years until the root system from the floating living mats will be large enough to supply sufficient nutrients for the microbial activity. This during the first year it may be necessary to add supplemental nutrients, such as the guinea-pig pellets.

2.3.4 The floating cover development

As the vegetation is placed over acidic water suitable plants have to be selected. From experience all Typha species are well suited, as they develop also an extensive root mass below the floating structure. Comparable plants can be used, but should be tested for their root development as some water plants are either not acid tolerant or do not develop extensive root system. Further the plants need to be perennial plants with rhizomes, that the root mass increases in size with time.

It is recommended that plant are selected in consultation with ecologists and with these plants test should be carried out by growing the plants in a bucket filled with acid mine drainage from the site or in a sludge pond such as available at the Maochong site. Some examples of construction of floating rafts are given in Headely et al (supplied by e-mail and part of Zingpengs doc) and pictures are given at the end of this discussion report.

3.0 Placement of pilot system with construction comments

The AMD emerges out of a small adit on the left side of sloped drainage. The water runs down a steep hill, leaving a bright brown strain (Plate 7). This location is referred to as W-1. The flow from the adit will be contained in a steep cascade loosing 2.5 m in elevation over a short distance to enhance iron oxidation. It will enter a small holding pond from which it will flow over a second short cascade, loosing less elevation, into the first iron oxidation pond. In plate 8 the approximate location of the second cascade is depicted with the view from the adit. After the first oxidation pond the water is directed into the 2nd precipitation settling pond and flows into two ARUM ponds.

The flow throughout the system is ensured through placement of the ponds such, that slight but exact decreases in the elevation are assured, so that the flow is given from one pond to the next, in both seasons. The connection between the ponds will be facilitated by weirs, which can regulate the variable water level with the installation of movable boards. The first precipitation ponds might be equipped with baffles, representing surfaces for iron hydroxide nucleation. The water flows from the second precipitation pond into two ARUM ponds in sequence.

These ponds will be equipped with organic sediment and covered with floating living vegetation to support reducing conditions and supply organic matter to maintain microbial activity in the sediment. The discharge of the ARUM cells will be connected to the lower part of the drainage basin (described below) flowing into the existing ditch down to the road and its drainage channel.

Plate 7

Plate 8

Plate 9

Plate 10

Plate 11

Plate 12

Plate 13

Plate 14