2000 Billings Land Reclamation Symposium

MATERIAL CHARACTERIZATION AND PRIORITIZATION OF REMEDIATION MEASURES AT THE ZORTMAN/LANDUSKY MINE SITES.

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ABSTRACT

Reclamation of the Zortman and Landusky gold mines in the Little Rocky Mountains of north-central Montana is currently being undertaken under the direction of the Montana Department of Environmental Quality and using the funds from the Reclamation Bond. As with many projects a balance must be found between the economics, technical, environmental and socio-economic issues at the sites. As part of the reclamation effort, a geochemical characterization program was developed which involved an intensive field geochemical assessment, supported by laboratory test work and 'historic' data. The objective of the characterization program was two-fold. Firstly, to identify the location, extent and probable contaminant loads from the sites; and secondly, to identify candidate materials for suitable cover and remediation purposes. Prioritization of remediation measures was then completed in an effort to assess and optimize the degree of remediation attainable with the limited financial resources available. This paper describes the material characterization program. It also describes the method and rationale developed to prioritize the remediation measures.

Additional Keywords: Zortman, Landusky, reclamation, geochemistry, remediation.

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INTRODUCTION

The Zortman and Landusky mines are located in Phillips County, Montana approximately 155 miles north of Billings (Figure 1). There has been mining in the area in one form or another since the first gold panner found a nugget in 1884. The first mill was built there in 1904 and mining continued underground off and on through to the 1970's ceasing intermittently during the two World Wars. Larger scale open pit mining and heap leach operations of the lower grade ore at Zortman and Landusky began in 1979 by Pegasus Gold Corporation and continued until 1995. Gold and silver were extracted by Carbon Absorption and Stripping and Merrill-Crowe precipitation. Both mines are currently closed and being reclaimed under the direction of the Montana DEQ using the Closure Bond Funds provided for by Pegasus under Montana Bonding requirements.

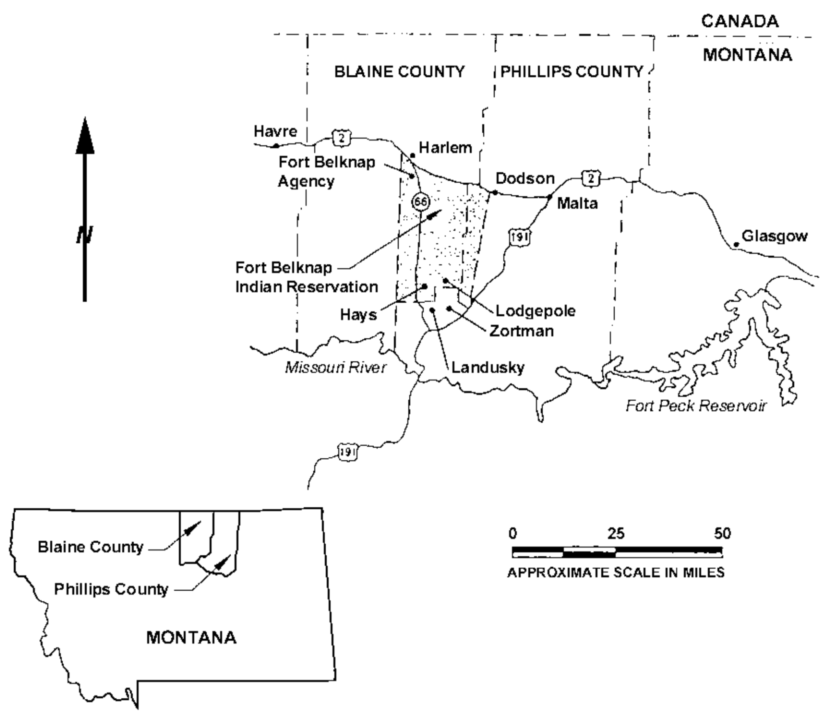

Figure 1. Location map of Zortman and Landusky Mine Sites
(after US DOI and MT DEQ, 1996)

Mine reclamation at the Zortman and Landusky mines, as with most mines, is faced with multidisciplinary issues and decisions in which compromises must be made and trade-offs evaluated. There are at least two critical issues for the Zortman/Landusky reclamation. There is (1) insufficient funding in the reclamation bond and (2) limited suitable construction material on site to complete the reclamation that was proposed in the Environmental Impact Statement (EIS) (US DOI and MT DEQ, 1996) and stipulated in the Record of Decision (ROD) (MT DEQ and US DOI, 1998) for the site. Therefore, an evaluation of the effectiveness of the specified measures and prioritization of reclamation areas and measures is being done. In order to complete this evaluation and prioritization a geochemical characterization program was undertaken.

The objective of the geochemical program was two-fold. Firstly, to identify the location, extent and probable current and future contaminant loads from the various facilities (leach pads, waste dumps and open pits) on the sites and to prioritize which areas most require a high degree of reclamation and which require less or minimal reclamation. Secondly, the program was aimed at identifying candidate materials on site for cover and remediation purposes. The characterization program was comprised of an assessment of historic information, a field reconnaissance survey and laboratory testing program. This paper presents the results of the characterization program and some discussion as to how this information will be used to prioritize remediation areas and measures.

CHARACTERIZATION PROGRAM

Historic Data

A fair amount of geochemical and geological information is available about the site, most of which was produced after 1990. In 1992, the mining company (Pegasus) filed an application for expansion of the operations. As a result, between that time and mid 1994, a number of studies were undertaken in preparation of an Environmental Impact Statement (EIS). These studies included extensive static and kinetic tests of drillcore aimed at predicting the acid generating potential of the rock mined and exposed as a result of expansion (Miller and Hertel, 1997). The mine expansion however never went forward. Therefore, the material characterized in those studies remains unmined. The vast amount of information produced in those studies is therefore of limited usefulness to the current reclamation program.

Prior to the application for expansion in the mid-1980's an extensive water monitoring program was implemented on both the Zortman and Landusky sites. As a result, a great deal of extremely valuable information has been collected on the geochemical behavior of mine elements and area, such as leach piles and mine pits. Water quality trends over time have proven very helpful in assessing the current contaminant loads from the sites and likely future water qualities. They allow trends to be established indicating the evolutionary behavior of large masses of mine disturbed materials. These results are discussed in greater detail later in the paper.

Another set of historic data that is often not fully exploited for geochemical characterization is the mined material itself. The pit walls, spent ore and waste rock materials that are currently exposed and have been for at least 5 to 10 years, since mining operations ceased, are essentially a large, 'historic' humidity cells. Simple tests such as paste pH, paste conductivity measurements and leach extraction tests on material exposed to weathering for this amount of time can provide more information than could be achieved in relatively short term laboratory tests. As a result, the field reconnaissance surveys at Zortman and Landusky were an extremely critical part of the characterization program.

Field Reconnaissance Program

The objectives of the field reconnaissance program were (1) to identify potential sources of NAG material (i.e. non-acid generating material that may be a potential source of construction and cover material) and (2) to identify and quantify potential sources of acid generating material and contaminant sources. The program consisted of paste pH and paste TDS analyses and visual identification of rock type, degree of alteration, degree of oxidation, surface precipitates and staining, presence of visible sulfides and any 'unusual' textures. Field logs (including photographs) were recorded and the sample locations were surveyed using a GPS system and plotted on a map.

The results of the field paste pH and paste TDS analyses are summarized in Table 1 organized by mine facility (or material type). As would be expected, samples with low pH values have higher TDS values (due to the presence of soluble minerals on the grain surfaces) and those samples with neutral pH results have low TDS values. The relationship between paste pH and paste TDS for the different material types on the Zortman and Landusky sites is shown in Figure 2. There is a clear trend whereby samples with pH values below approximately 5, show sharply increasing TDS concentrations. The samples that do not fall neatly within this trend are predominantly leach pad samples (designated by open circles on the figure) where the addition of lime and caustic soda in the leaching solutions account for moderate to high TDS values and still control the pH to circum-neutral values (i.e. the TDS results from alkalinity products not acidity/oxidation products).

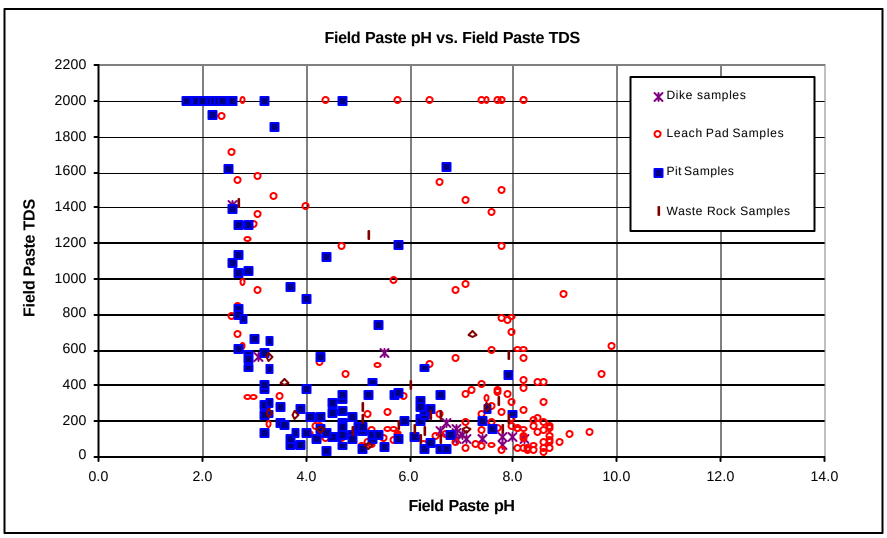

Figure 2. Paste pH versus paste TDS for Zortman and Landusky samples.

The color of the Zortman and Landusky mined material (again with the exception of the spent ore on the leach pads) is a relatively good indication of pH, or acid generating conditions. Visual inspection therefore can provide the first assessment of a material's acid generating potential. The unoxidized porphyry materials containing fresh sulfide minerals (in particular pyrite and, on Landusky, marcasite) are typically grey in color. These materials are acid generating with pH values commonly below 3 and very high TDS concentrations. The partially oxidized porphyry material was often an olive-green to yellow color. This color is a reflection of the presence of secondary minerals produced when sulfide minerals oxidize, such as iron oxy-hydroxides and iron sulfates. These minerals are soluble and when dissolved produce acid, therefore they are sometimes referred to as ‘stored acid products’. The partially oxidized material is predominantly acid generating with pH values generally less than 4.5. The oxide porphyry material contains no visible residual sulfides and typically has paste pH values in the 4.5 to 6.0 range. This material is orangey-red in color and relatively easily differentiated from the other material types on this basis.

Table 1. Summary of mean, minimum, maximum and standard deviation values for paste pH and paste TDS results by mine facility.

ZORTMAN		**MEAN**	**MIN**	**MAX**	**STD DEV**
Leach Pad Samples	pH		1.8	9.0	2.3
	TDS	597	60	>2000	641
Pit Wall and Pit Floor Samples	pH		1.7	6.7	1.4
	TDS	758	30	>2000	786
Waste Rock Samples	pH		2.7	7.1	1.4
	TDS	316	60	1430	379
Dike samples	pH		2.6	7.4	1.6
	TDS	438	100	>2000	600
Roadcut Samples	pH		3.7	6.9	1.3
	TDS	235	70	460	192
Tailings	pH		5.8	7.6	0.7
	TDS	800	70	>2000	937
Topsoil	pH		5.0	6.8	0.7
	TDS	141	50	228	64
LANDUSKY		**MEAN**	**MIN**	**MAX**	**STD DEV**
Leach Pad Samples	pH	7.1	2.5	9.9	1.8
	TDS	602	20	>2000	678
Pit Wall and Pit Floor Samples	pH	4.2	1.9	8.0	1.9
	TDS	845	40	>2000	748
Waste Rock Samples	pH	6.2	3.3	7.9	1.6
	TDS	364	140	1250	300
Stockpile Samples	pH	7.6	6.9	8.0	0.6
	TDS	130	100	170	36
Dike Samples	pH	7.2	3.7	8.2	1.7
	TDS	117	70	190	40
Topsoil	pH	7.0	3.5	8.0	1.7
	TDS	560	90	>2000	723

Although color alone is not recommended to differentiate between material types, it is a useful classification tool for the Zortman and Landusky sites. Caution should be exercised when judging leach pad material as many surface minerals precipitating from leach pad solutions have coated the surface of much of the material and the color is a less dependent characteristic of the geochemistry. Field ‘clues’ including paste pH, paste TDS rock type and color description at these sites, where the material has been exposed to weathering conditions for an extended period of time, are relatively inexpensive and very valuable pieces of information. This type of survey is often not given enough credit in similar characterization programs. The outcome of the field reconnaissance survey were large maps of each site designating potentially acid generating, moderately acid generating and non-acid generating material on the sites. These maps are continually refined as new information about the sites is obtained (e.g. results of the laboratory testing program) and will be used in the prioritization of reclamation areas.

During the reconnaissance program, samples were collected for confirmatory laboratory testing. Sampling for lab testing concentrated on obtaining representative samples with respect to rock type and geochemical type (i.e. degree of oxidation, sulfide content etc.), as well as obtaining representative samples of each mine facility (i.e. each leach pad, pit, waste dump etc.). There was a slight bias in numbers of samples collected for lab testing towards both the potential NAG materials and the ARD/metal leaching materials. The lab testing program is described in detail in the Section below.

Laboratory Testing Program

All samples collected for the laboratory testing program were submitted for paste pH and paste conductivity measurements on the as-received 'fines', modified acid base accounting (ABA) tests, inorganic carbon and leach extraction analyses. Subsets of these samples were also analyzed via forward acid titration, multi-element ICP, net acid generation (NAG) tests and sieve analyses. Some of the more critical results from these tests are discussed in the following sub-sections.

Paste pH and Paste Conductivity Results

Paste pH and paste conductivity tests on the as-received 'fines' were completed for two reasons. Firstly as a quality control/quality assurance check on the paste pH and paste TDS values obtained in the field using the hand held field instruments. The paste pH and paste conductivity measurements in the lab were taken on the as received 'fines' using a 1:1 solids to distilled water ratio to mimic as close to possible the methodology used in the field. Secondly, it is believed to be a more representative result than the paste pH and paste conductivity values on the same sample prepared for Acid Base Accounting (ABA) tests, i.e. the crushed samples. In effect, this crushing liberates the alkalinity from the matrix of a sample thereby effecting the paste pH. Figure 3 is provided to show the relationship between the field and lab paste pH measurements on the as-received fines (or un-crushed samples) as compared to the field and lab paste pH measurements on the crushed split sample for ABA testing. This graph clearly shows that crushing the samples liberates more alkalinity (and therefore results in higher pH values) than is available in the field. The results serve as a caution that one cannot rely on paste pH values obtained on a crushed sample as indicative of field conditions. Measurements of field paste pH should always be done on the uncrushed fines, this an important consideration when selecting a drilling method for sample recovery in waste rock and leach piles.

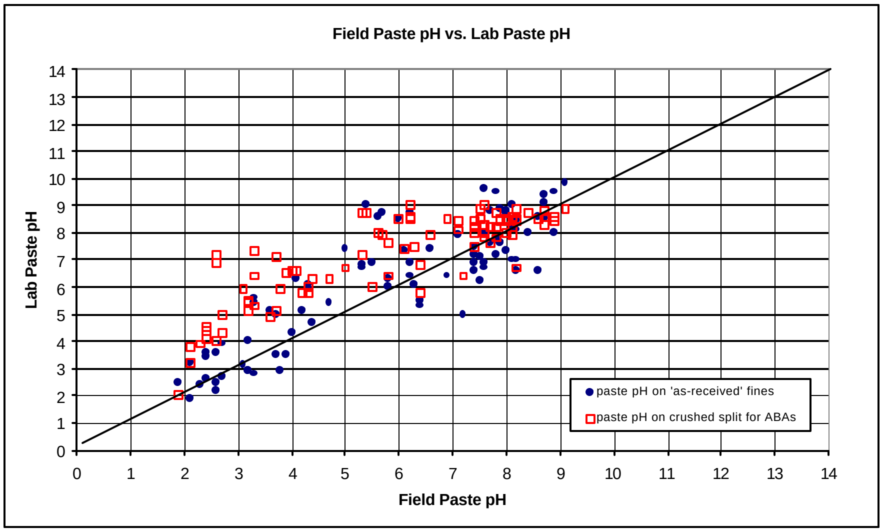

Figure 3. Field paste pH versus lab paste pH on un-crushed and crushed samples.

Modified Acid Base Accounting (ABA) and Inorganic Carbon Results

The modified ABA test is used to determine the balance between the acid producing (sulfides) and acid consuming components of a sample. The results of this test for the Zortman and Landusky samples are provided in summary form in Table 2 by material type.

A very definite trend can be seen in the samples (except for the leach pad material) with respect to the total percent sulfur and field paste pH (Figure 4). Almost all samples (excluding leach pad samples) with total sulfur contents greater than 0.2% have field paste pH values less than 5.0. This percentage of sulfur is far less than would be visible in the field. This suggests that there is very little neutralization or buffering capacity in the material except for that added to the leach pad material. It can be expected that once the alkalinity in the leach pad samples is exhausted that these samples will also plot within the dotted lines outlining the apparent natural trend of the other materials on site.

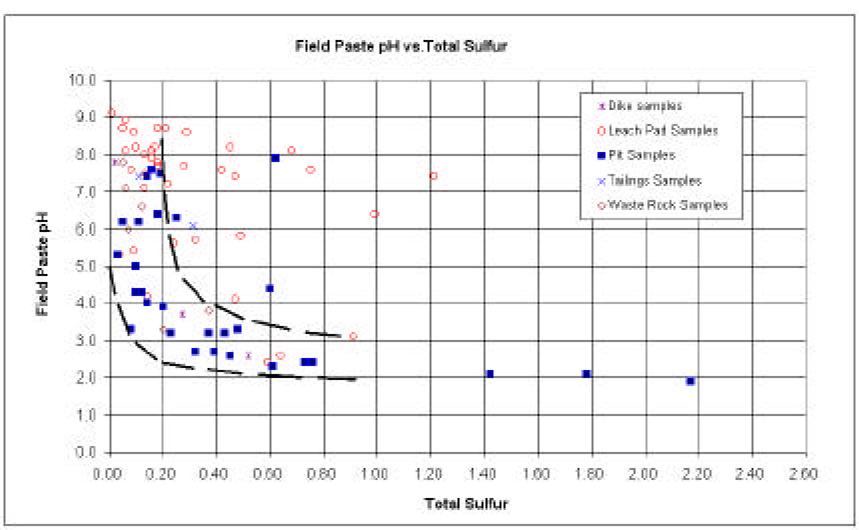

Figure 4. Field paste pH versus Percent Total Sulfur.

Table 2. Summary of modified ABA and inorganic carbon results by material type

LOCATION DESCRIPTION		PASTE pH	S(T) %	S(SO4) %	AP	NP	NET NP	NP/AP	TIC %
ZORTMAN									
Leach Pads	MIN	4.1	0.1	0.0	0.0	-1.4	-25.5	0.2	0.0
	MAX	8.7	1.0	0.4	25.6	12.1	10.8	9.7	0.1
	MEAN		0.3	0.1	6.2	3.6	-2.6	1.7	0.0
	STD DEV		0.3	0.1	6.5	2.9	7.8	2.2	0.0
Pit Wall and Pit Floor Samples	MIN	2.0	0.0	0.0	-1.3	-27.7	-59.6	0.2	0.0
	MAX	9.2	2.2	1.1	49.4	19.6	17.1	7.9	0.2
	MEAN		0.5	0.2	10.4	1.8	-8.6	2.0	0.1
	STD DEV		0.7	0.3	14.3	11.2	21.3	2.2	0.1
Roadcut & Waste Rock Samples	MIN	4.9	0.2	0.2	-1.6	-0.2	0.9	0.2	0.0
	MAX	6.3	0.3	0.3	2.8	3.7	1.3	1.3	0.0
	MEAN		0.3	0.2	0.6	1.7	1.1	0.7	0.0
	STD DEV		0.1	0.0	3.1	2.8	0.3	0.8	-
LANDUSKY									
Leach Pads	MIN	5.9	0.0	0.0	-0.9	-0.8	-26.4	0.1	0.0
	MAX	8.9	1.2	0.3	27.2	15.6	12.8	5.6	0.2
	MEAN		0.4	0.1	8.3	4.1	-4.2	1.6	0.0
	STD DEV		0.4	0.1	9.6	3.6	11.1	1.9	0.0
Pit Wall and Pit Floor Samples	MIN	3.2	0.1	0.0	0.0	-5.4	-36.3	0.2	0.0
	MAX	9.0	1.6	0.5	50.0	389.4	387.8	249.2	5.0
	MEAN		0.6	0.2	12.9	47.5	34.6	23.2	1.0
	STD DEV		0.5	0.1	14.4	99.7	95.4	71.2	1.5
Waste Rock Material	MIN	5.9	0.1	0.0	0.3	0.2	-8.9	0.4	0.0
	MAX	8.7	0.4	0.2	9.1	215.8	215.4	690.4	2.5
	MEAN		0.2	0.1	3.1	94.5	91.5	212.8	1.4
	STD DEV		0.1	0.1	3.5	97.4	99.7	323.7	1.1

Figure 5 is a plot of neutralization potential (NP) versus acid potential (AP) in kg $CaCO_3$/tonnes equivalent. This type of graph is typically used to report results of ABA testing. In general, the samples that plot above the 1:1 line (~60%) would be considered potentially acid generating, those that plot below the 3:1 line (~28%) would be considered non-acid generating and those that fall between the two lines (~12%) would be dassified as 'uncertain' with respect to acid generating potential. It takes very little sulfur content in a sample for that sample to plot below the NP/AP ratio of 1:1, this again suggests that there is very little neutralization potential in the samples to 'balance' the acid generating potential imparted by less than a quarter of a percent sulfur.

Forward Acid Titration Results

The forward acid titration test is done to determine, qualitatively, the acid neutralizing capacity of a sample by adding measured amounts of acid to the sample to lower the pH. The amount of acid required to reach each pH interval is dependent on the amount of neutralizing material available. As the pH decreases, different minerals react to neutralize (or buffer) the added acid. Within the pH range of 5.5 to 7.0 carbonate minerals in the sample dissolve and neutralize the acidity. If there are significant carbonates present a 'step' or flattening out of the curve will occur within that pH range (i.e. 5.5 to 7.0). A few of the results are shown below in Figure 6. The leach pad sample is the only sample showing any degree of flattening in this range. This is likely a result of the added alkalinity in the leach pad solutions. Between the pH range of 3.0 to 3.7, limonite (FeOOH) will buffer acid. This may be occurring to some degree in these samples. At even lower pH values (i.e. below ~3), aluminosilicate minerals such as the feldspars in the samples will dissolve and buffer added acid. This is likely the reason that these results show a long flattening tail below pH of 2.0.

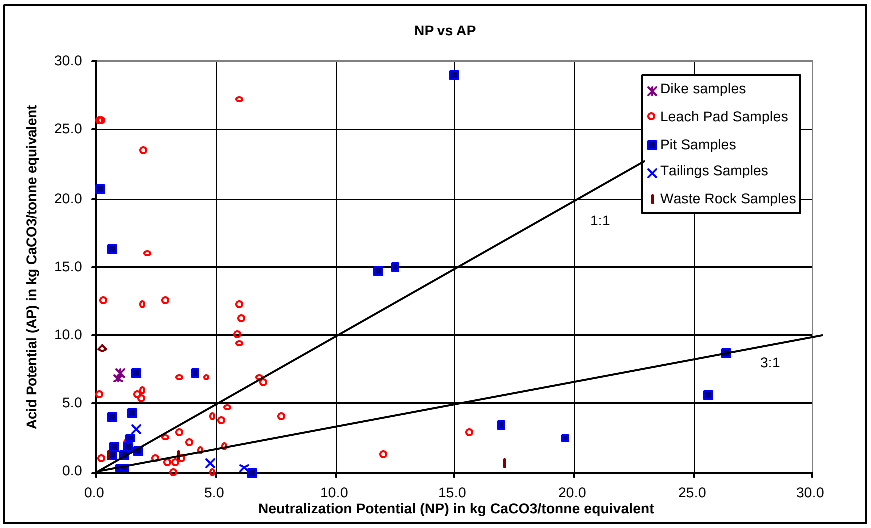

Figure 5. Neutralization Potential (NP) versus Acid Generating Potential (AP).

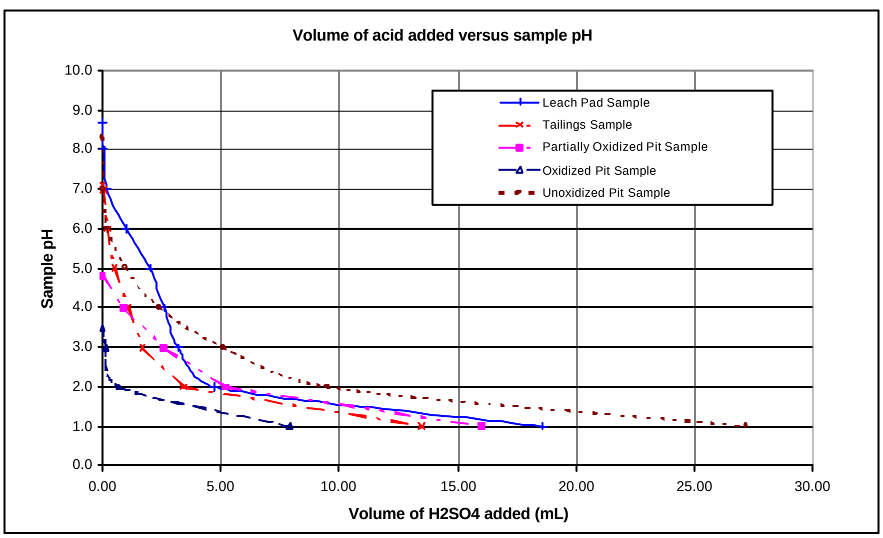

Figure 6. Forward Acid Titration Results.

Net Acid Generation (NAG) Results

The net acid generation test was used to determine the net acid remaining, if any, after complete oxidation of the materials with a strong oxidant (hydrogen peroxide) and allowing complete reaction of the acid formed with the neutralizing components of the material. The NAG test provides a direct assessment of the potential for a material to produce acid after a period of exposure and weathering and is used to refine the results of the ABA predictions. One of the great advantages of the NAG test is that it allows an assessment of the kinetics of the reactions in a sample in a relatively short period of time.

Some of the samples collected were analyzed using the NAG method with an industrial H_2O_2 reagent at a starting pH of 5.5. The experiments were run for approximately 3 days and the pH, Eh and temperatures were recorded at intervals throughout that period. The results of pH are plotted in Figure 7. The following classification criteria (Lapakko and Lauwrence, 1993) were used to assess the acid generating potential of those samples tested with the NAG method.

Final NAG_{pH} > 5.5	Non-acid generating
Final NAG_{pH} between 3.5 and 5.5	Uncertain to low risk acid generating potential
Final NAG_{pH} <3.5	High risk of acid generating potential

Therefore, based on these results, two of the samples tested (Tailings and Unoxidized Pit Samples) would be considered non acid generating (Final NAG_{pH}>5), one sample (Leach Pad Sample) would be classified as 'uncertain' (Final NAG_{pH} between 3 and 5) and two samples (Unoxidized and Partially Oxidized Pit Samples) would be considered acid generating (Final NAG_{pH} <3). After approximately 300 minutes (5 hours) the samples are at or very near their Final NAG_{pH}. The uncertain sample is "marginal" and results appear to indicate two clearly different and definable behaviors. The first three are non-acid generating (with little buffering capacity) and the latter two are clearly acid generating.

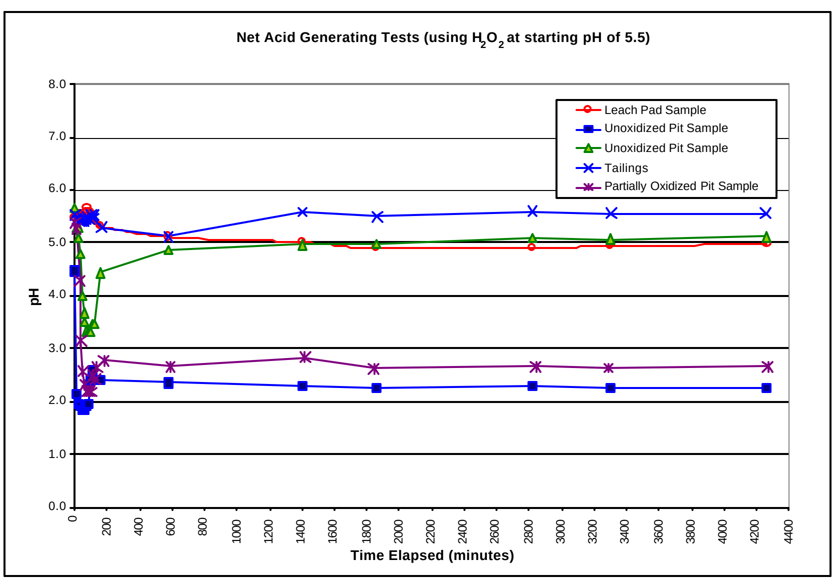

Figure 7. Net Acid Generation Tests – pH versus Time for Selected Samples.

Leach Extraction Tests

Leach extraction tests were completed in order to characterize and quantify the soluble contaminant content of a sample. The procedure used for these analyses was the EPA 1312 leach extraction test using a leachate reagent of de-ionized water acidified to a pH of 5.0 to 5.5 to represent rainwater. The procedure uses a solid to liquid ratio of 1:2. The leachate concentrations are representative of current ARD evolution state and the quantity of leach water compared with solid sample. Field conditions have much higher solid:liquid ratios and ARD conditions will mature with time. The resultant leachate concentrations therefore are not necessarily representative of what concentrations would be expected in the field. An assessment of the current field water qualities from material exposed on the surface was completed by accounting for the 'dilution' factor inherent in the leach extraction test and assuming a field moisture content of ~10% (as opposed to a moisture content of 200% used in the test). In other words, the leachate concentrations were multiplied by a factor of [10/(200+10)]. These calculated concentrations however do not yet represent field water qualities. During the leach extraction tests, the dilution of solute concentrations in the leachate can cause the dissolution of secondary mineral phases that were previously in a solid phase (i.e. oversaturated). It was therefore necessary to "re-instate" the solubility controls on the solute concentrations by modeling the calculated leachate concentrations using the geochemical equilibrium model MINTEQA2 (Allison et al., 1991). Water quality predictions were then made for the surface water runoff from the various material types. Table 3 provides the predicted water qualities from those areas considered highly acid generating, moderately acid generating and non-acid generating for both the Zortman and Landusky sites.

Table 3. Predicted water quality of material with various degrees of acid generating potential on both Zortman and Landusky.

Parameter	Predicted Water Quality of:					
(mg/L)	Highly acid generating material		Moderately acid generating material		Non acid generating material	
	ZORTMAN	LANDUSKY	ZORTMAN	LANDUSKY	ZORTMAN	LANDUSKY
pH	[< 3]	[< 3]	[3 - 5]	[3 - 5]	[> 5]	[> 5]
Al	161	925	59	87	0	0
As	1.34	6.01	0.00	0.00	0.00	0.00
Ca	40	85	154	146	10	218
Cd	0.00	0.10	0.15	0.10	0.00	0.00
CO3	0	0	8	0	26	17
Cr	4.90	0.47	0.37	0.15	0.00	0.00
Cu	1.62	1.18	0.71	0.00	0.10	0.30
Fe	0.24	2.37	0.00	0.05	0.00	0.00
K	0.0	0.0	305.0	0.0	0.0	78.7
Li	22.35	27.46	10.45	0.00	0.00	0.00
Mg	55	364	689	380	14	166
Mn	2	33	40	11	0	8
Ni	0.43	1.59	1.53	0.68	0.00	0.00
Pb	0.00	0.00	0.02	0.00	0.00	0.00
Si	0.12	0.03	0.53	0.70	0.85	0.30
SO4	3988	3245	394	494	11	148
Zn	0.77	15.48	0.72	4.66	0.06	0.23

WATER QUALITY MONITORING DATA

As mentioned above, a relatively extensive groundwater and surface water monitoring program was started at the site in the mid-1980's. Water quality trends over time have allowed us to predict apparent 'mature' water qualities. Sulfate concentrations and pH trends over time for two wells believed to be representative of the 'mature' water qualities as a result of acid generation and contaminant release on the both Zortman and Landusky are provided in Figures 8 and 9 respectively. It appears that the 'terminal' pH for ARD impacted waters on Zortman is approximately 0.5 of a pH unit lower than that on Landusky and the sulfate concentrations are also higher on Zortman (perhaps by a factor of 2).

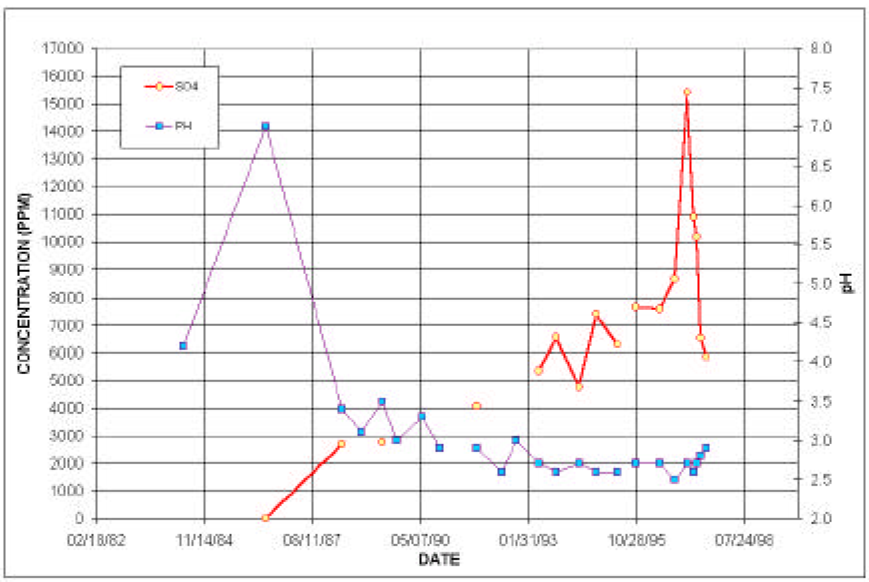

Figure 8. SO_4 conc. and pH over time at a groundwater monitoring well on Zortman.

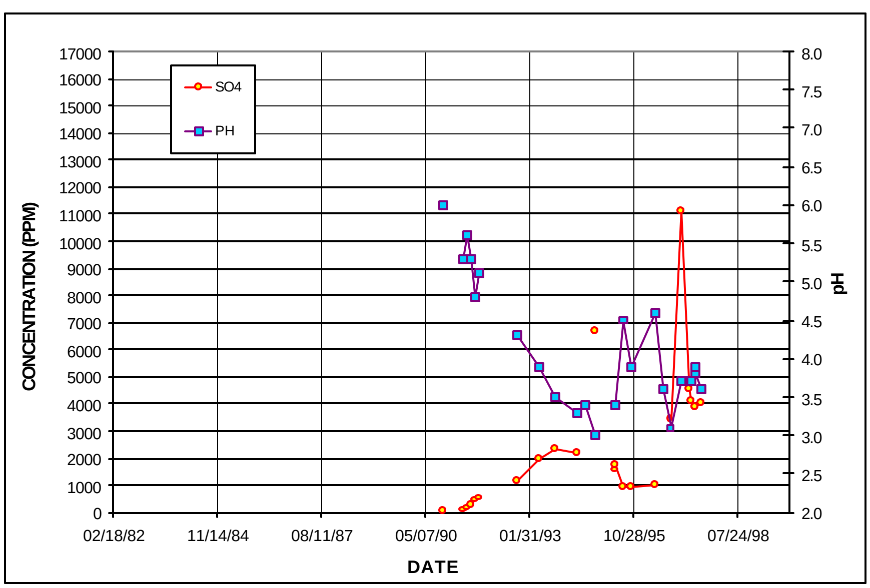

Figure 9. SO_4 conc. and pH over time at a groundwater monitoring well on Landusky.

PRIORITIZATION OF REMEDIATION AREAS AND MEASURES

The field reconnaissance results, laboratory test results, predicted surface water qualities and the data obtained from the surface and groundwater monitoring program at the sites, together with the site water balances are being used to develop current and likely future mass balance and contaminant load estimations for the sites. These estimations along with the engineering volume mass balance and material costing will be incorporated into a Multiple Accounts Analysis, or MAA, (Robertson and Shaw, 1998) decision-making tool for the prioritization and evaluation of the likely results of certain reclamation areas and measures. The MAA evaluation of the various reclamation alternatives is currently underway as a cooperative effort between ourselves, the Montana Department of Environmental Quality, the U.S. Bureau of Land Management, U.S. Environmental Protection Agency and the Fort Belknap Tribal Council. Past experience with this type of decision making has proven extremely successful for multi disciplinary projects involving multiple stakeholders such as with the Zortman and Landusky Reclamation Project.

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