GEOCHEMICAL TREATMENT AND PHYTOSTABILIZATION OF ACIDIC MILL TAILINGS IN THE SOUTHERN ROCKY MOUNTAINS [1]

by

Joe M. Cornelius, Ph.D., David L. Beeson, Walter G. Whitford, Ph.D., and Warren B. Zehner [2]

Abstract. Acid generating mill tailings resulting from hard rock mining pose significant environmental problems throughout the Western United States. One such example is the abandoned Mammoth Lode mine and mill facility in the Pinos Altos Mining District, Grant County, New Mexico. Mill tailings cover approximately one acre in area (3000 cubic yards) and are located inside primary drainage channels. In general the tailings are characterized by low pH, high exchangeable acidity, high future acid generation potential and elevated concentrations of several heavy metals. A plot study was performed to evaluate the potential for geochemical treatment and phytostabilization of the tailings. Six plot locations were selected and were collected for metals, acid/base accounting and soil fertility analyses. Based on the acid/base accounting data, geochemical amendments were added to neutralize the tailings and to bind toxic, soluble metals into insoluble forms. Upon pH stabilization, organic amendments were added and each plot was seeded with a mixture of cool and warm season native grasses. The test plots were monitored for one year. Soil and plant tissue samples were collected for laboratory analysis during the monitoring period. Data from the laboratory analysis indicated that the metals had been successfully immobilized, and that the acid generating potential and pH of the plots remained stabile.

Additional Key Words: reclamation, acid rock drainage.

Introduction

The Mammoth Lode site is an abandoned mine and mill facility located in the Pinos Altos Mining District, Grant County, New Mexico. The Pinos Altos District lies in the Pinos Altos Mountains, a small mountain range located approximately six miles north-northeast of Silver City, Grant County, New Mexico. Gold deposits were discovered in the Pinos Altos District around 1860 and were productive until the early part of the twentieth century. Both vein and placer deposits were exploited on a limited scale by the miners of Pinos Altos. Other metal production in the district included silver, lead, and zinc. The only large scale operation in the district was the Empire Zinc Cleveland Mine, on the west side of the range.

The Mammoth Lode mining claim was located in 1887. Initial development of the prospect consisted of two shallow pits and several trenches. A stamp mill was located down slope of the mine workings. The date of construction of the stamp mill is undetermined, but a diagram of the Mammoth Stamp Mill appeared in the 1902 edition of the Sanborn Fire Insurance Map for Pinos Altos, showing the location of a stamp battery, concentrating tables and an engine house. The claim was patented by Golden Giant Mining Company in March, 1928. Construction on the Mammoth property in the twentieth century included a ball mill and floatation cells located adjacent to the original mill. It is uncertain when production activities were abandoned at the site, but it appears to have been in the 1940s.

In 1995, the Mammoth Lode site consisted primarily of limited structural remains from the mining and milling activities, waste rock piles and mill tailings. The waste rock and fine-grained mill tailings occurred adjacent to the main shaft and mill area. The bulk of the tailings were within an ephemeral stream located down slope from the floatation cells. Tailings extended within the stream channel from the Mammoth Lode onto adjacent Bureau of Land Management (BLM) property and into Bear Creek (Figure 1).

The U.S. Environmental Protection Agency

[1]Paper presented at the 1997 National Meeting of the American Society for Surface Mining and Reclamation, Austin, Texas, May 10-15, 1997.

[2]Joe M. Cornelius, Ph.D. is Chief Ecologist and David L. Beeson is Senior Geologist, Ecology and Environment, Inc., Houston, TX 77056; Walter G. Whitford, Ph.D. is Senior Research Scientist, USEPA, Las Vegas, NV 89193; and Warren B. Zehner is Senior On-Scene Coordinator, USEPA, Houston, TX 77099.

Proceedings America Society of Mining and Reclamation, 1997 pp 571-578
DOI: 10.21000/JASMR97010571

https://doi.org/10.21000/JASMR98010571

was notified about the Mammoth Mill site by the New Mexico Environment Department (NMED), which was concerned about acid rock drainage (ARD) and potential metals migration from the site into Bear Creek. In 1995, the RPB began site characterization of the conditions present on the site. Based on the conditions identified at the site, a plot study was initiated to evaluate the potential for successful geochemical treatment and phytostabilization of the ARD material present on the site.

Materials and Methods

Site Characterization

Survey transects were established on the tailings materials at the Mammoth Lode site. *In situ* metals screening was conducted at fifty three transect nodes using a field portable X-ray fluorescence (XRF) spectrometer to obtain copper (Cu), lead (Pb) and zinc (Zn) concentration levels. Three XRF readings were obtained at each node. These readings were averaged to derive metals concentration values for each node. Ten percent of all XRF field-screening locations were sampled and analyzed for Target Analyte List (TAL) metals (EPA SW846/6010) for independent analytical laboratory confirmation of XRF results.

High accuracy (sub meter) Global Positioning System (GPS) surveys were conducted to obtain horizontal and vertical positional data for all XRF nodes. Because overhead obstructions limited GPS satellite reception in some locations, additional survey data were collected using a Total Station survey unit to enhance topographic resolution and define cultural features. Geostatistical modeling and kriging software were used to estimate grid node values for elevations and metals concentrations from the XRF, GPS and Total Station survey data. Elevation contour maps and metals concentration isopleth maps were created using commercially available contouring and mapping software (Figure 2).

Composite soil samples were collected from six of the transect node locations and analyzed for standard acid/base potential tests (EPA 600/2-78-054), including neutralization potential (NP), exchangeable acidity (EXA), and sulfur forms. Acid generation potential (AP) was calcuated from total sulfur. Soil samples were also analyzed for TAL metals (EPA SW846/6010), water extractable metals (Page 1982, ASA No. 9 10-2.3.2), DPTA extractable Cd, Chromium (Cr), Cu, Iron (Fe), Manganese (Mn), Nickel (Ni), Pb and Zn (Page 1982, ASA No. 9 3-5.2.3), saturated paste extraction cations (EPA 200.7), electrical conductivity (EPA 120.1), organic matter (USDA No. 60(24)), saturation percent (USDA No. 60 (2)), saturated paste soil pH (USDA No. 60(2)), texture by hydrometer (ASTM D422), water extractable nitrate (EPA 353.2) and potassium (EPA 200.7), $NaHCO_3$ extractable phosphorus (Page 1982, ASA No. 9 24-5.4.2),

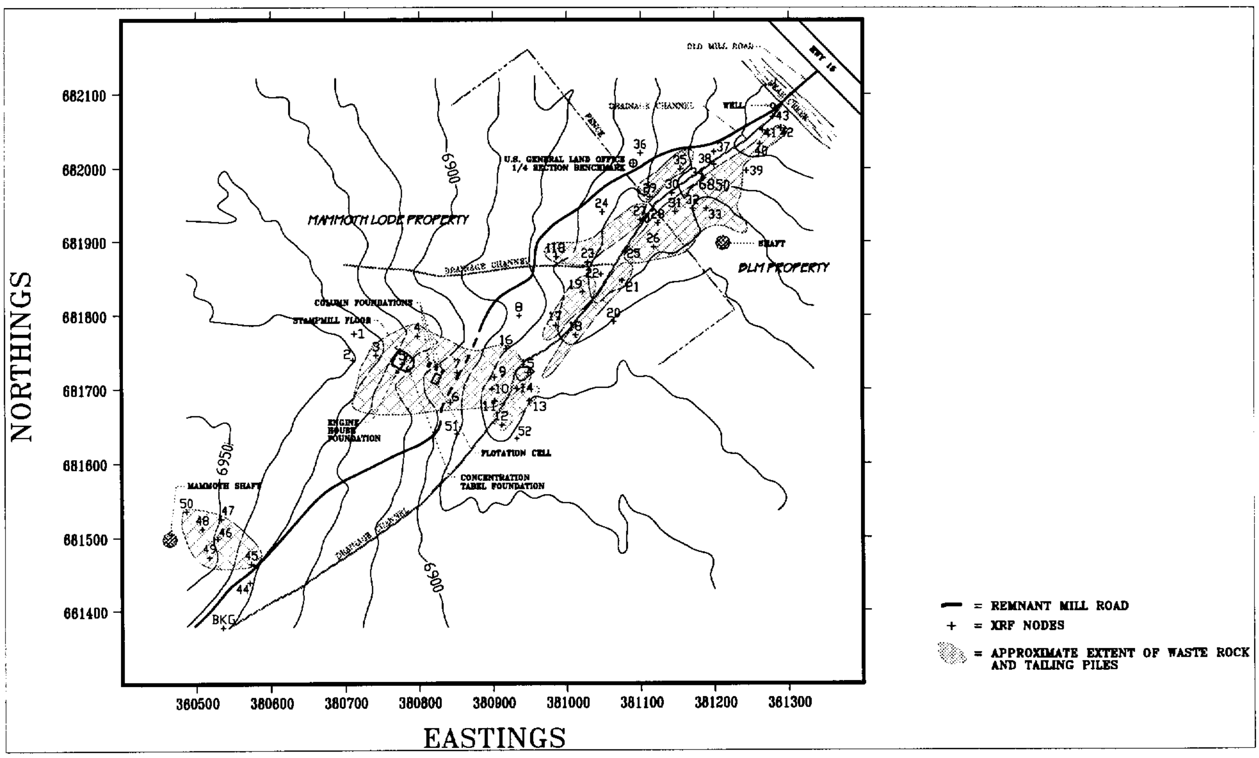

Figure 1. Mammoth Mill site feature map. Map coordinates are NAD27 New Mexico West State Plane.

No. 60 (2)), saturated paste soil pH (USDA No. 60(2)), texture by hydrometer (ASTM D422), water extractable nitrate (EPA 353.2) and potassium (EPA 200.7), $NaHCO_3$ extractable phosphorus (Page 1982, ASA No. 9 24-5.4.2), and water soluble boron. Results from the acid/base potential, standard soils test and nutrient analyses were used to develop a pilot study to evaluate the potential for geochemical treatment and revegetation of the mill tailings.

Revegetation Plot Study

Mill tailings associated with the Mammoth Mill site covered approximately one acre in area and possessed an estimated volume of 3000 cubic yards. The tailings were essentially void of vegetation and were characterized by elevated concentrations of heavy metals and a low average pH (3.7 units). Further, mine rock and tailings with Net Neutralization Potential (NNP = NP - EXA - AP) values less than -20 tons of calcium carbonate ($CaCO_3$)/kiloton and NP:AP less than 1:1 are considered potentially acid generating (Steffen, Robertson and Kirsten, Inc., 1992). The Mammoth Mill tailings had an average NNP of -22.27 and an average AP:NP ratio of 9:1, indicating a high potential for future acid generation (Table 1).

Utilizing the above data, a revegetation plot study was initiated in June, 1995 at the Mammoth Lode site to determine the potential for utilizing geochemical stabilization and revegetation to remediate the acidic, metals-contaminated mill tailings. The plot study addressed the following elements: 1) geochemical stabilization of the tailings; 2) addition of organic amendments and chemical fertilizers; and 3) revegetation and erosion control. In addition to the site specific data, the methodologies used in the plot study utilized information from the following sources: 1) the Streambank Tailings and Revegetation Studies-STARS (Reclamation Research Unit, et. al 1989; Schafer and Associates, et. al 1989; and Schafer and Associates and Reclamation Research Unit, 1993), a tailings revegetation study conducted on mill tailings in Silver Bow Creek, Butte, Montana by scientists from Schafer and Associates and the Reclamation Research Unit, Montana State University, Bozeman, Montana for the Montana

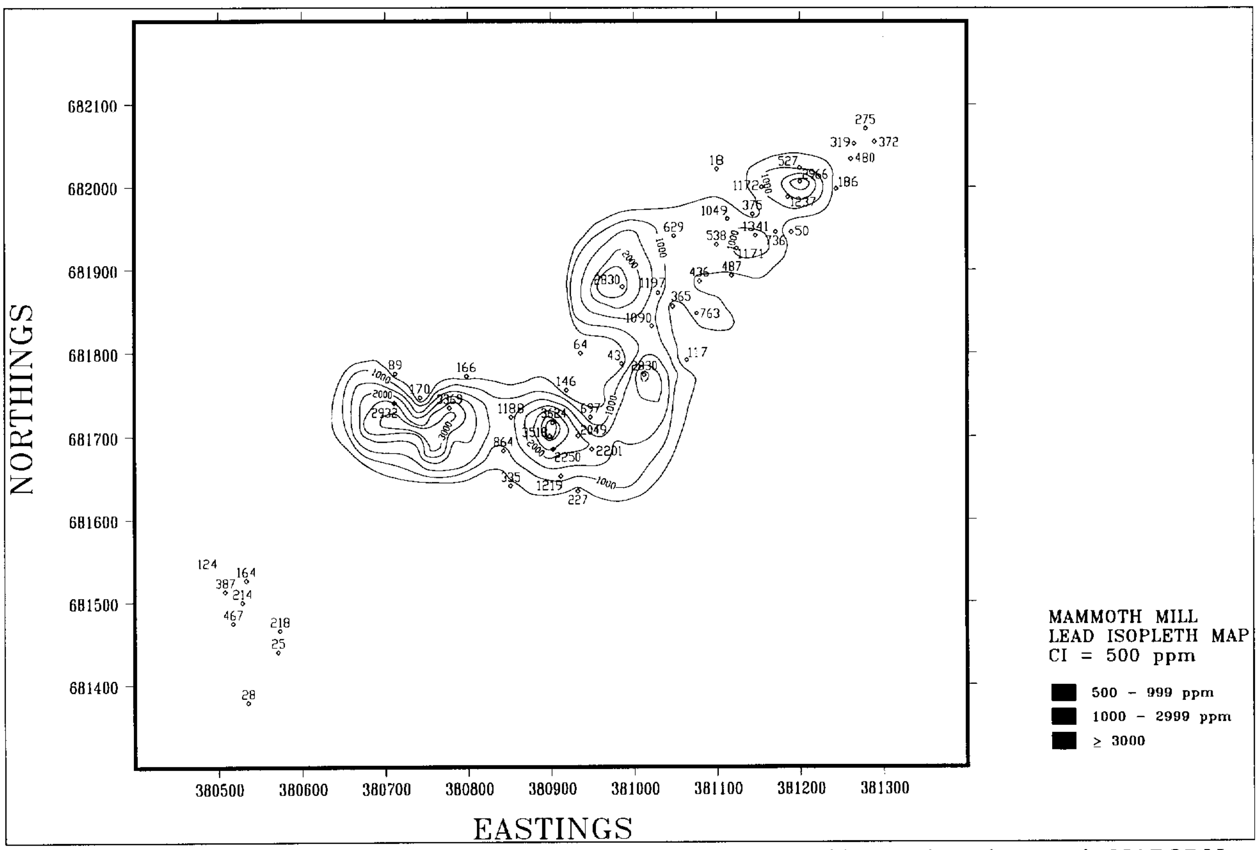

Figure 2. Lead concentration isopleth map from XRF survey of site. Northings and Eastings are in NAD27 New Mexico West State Plane Coordinates. Circles are XRF sample points and values are lead concentrations in ppm. Map coverage is the same as for Figure 1.

Table 1. Statistical comparison of soil analytical results between revegetation plots before and after treatment of tailings.

Parameter	pH	EXA	NP	Total S	AP	A/B Pot	NP/AP	NNP	OM	EC	B	N	P	K
units	units	tons/kton	tons/kton	%	tons/kton	tons/kton	unitless	tons/kton	%	mmhos/cm	mg/kg	mg/kg	mg/kg	mg/kg
Plot ID	*Before Treatment - May 1995*													
W-1	3.3	11.1	1	0.46	14.4	-14	0.07	-24.5	1.16	1.9	0.05	0.5	2.5	19.0
W-2	3.0	12.1	1	1.22	38.1	-38	0.03	-49.2	0.29	2.9	0.05	1.0	1.5	17.0
E-3	4.3	7.3	1	0.68	21.3	-21	0.05	-27.6	0.43	3.0	0.05	0.9	4.1	14.0
E-1	4.3	6.3	1	0.03	0.9	-1	1.07	-6.2	0.36	0.1	0.05	0.5	3.6	33.0
E-2	3.4	8.8	1	0.41	12.8	-13	0.08	-20.6	0.31	2.5	0.05	0.5	2.0	15.0
E-4	3.9	7.4	5	0.10	3.1	2	1.60	-5.5	0.48	2.8	0.05	0.7	2.5	24.0
Average	**3.70**	**8.83**	**1.67**	**0.48**	**15.10**	**-14.17**	**0.48**	**-22.27**	**0.51**	**2.17**	**0.05**	**0.68**	**2.70**	**20.33**
Std Dev	0.55	2.31	1.63	0.43	13.55	14.50	0.68	16.12	0.33	1.10	0.00	0.22	0.98	7.15
Std Err	0.22	0.94	0.67	0.18	5.53	5.92	0.28	6.58	0.13	0.45	0.00	0.09	0.40	2.92
0.95 CI	0.57	2.42	1.71	0.45	14.22	15.21	0.72	16.92	0.35	1.15	0.00	0.23	1.03	7.50
Plot ID	*After Treatment - October 1995*													
W-1	5.7	6.1	34	0.26	8.1	26	4.18	19.8	2.12	5.0	0.05	190.0	440.0	99.0
W-2	6.0	5.9	10	1.12	35.0	-25	0.29	-30.9	1.74	3.8	1.01	130.0	78.0	99.0
E-3	5.9	4.5	18	0.05	1.6	16	11.52	11.9	1.48	4.9	0.55	170.0	430.0	90.0
E-1	6.6	2.8	55	0.04	1.3	54	44.00	51.0	2.34	3.8	0.17	140.0	420.0	82.0
E-2	6.8	3.5	18	0.74	23.1	-5	0.78	-8.6	1.29	4.4	0.57	150.0	74.0	53.0
E-4	6.9	2.2	38	0.08	2.5	36	15.20	33.3	1.39	6.8	0.67	290.0	280.0	74.0
Average	**6.32**	**4.17**	**28.83**	**0.38**	**11.93**	**17.00**	**12.66**	**12.74**	**1.73**	**4.78**	**0.50**	**178.33**	**287.00**	**82.83**
Std Dev	0.51	1.61	16.64	0.45	14.02	28.50	16.47	29.30	0.42	1.11	0.35	58.79	173.58	17.57
Std Err	0.21	0.66	6.79	0.18	5.72	11.63	6.72	11.96	0.17	0.45	0.14	24.00	70.86	7.17
0.95 CI	0.54	1.69	17.47	0.47	14.71	29.90	17.28	30.75	0.44	1.16	0.37	61.70	182.16	18.43
	Student's T Test Statistical Comparisons between Before and After Treatments													
T Value	19.51	5.72	5.55	0.41	0.41	2.80	2.01	3.06	9.37	5.82	4.06	15.10	5.62	17.59
OSL	**0.0000**	**0.0023**	**0.0026**	**0.6981**	**0.6981**	**0.0381**	**0.1004**	**0.0282**	**0.0002**	**0.0021**	**0.0097**	**0.0000**	**0.0025**	**0.0000**
Sig Level	***	**	**	ns	ns	*	ns	*	***	**	**	***	**	***

EXA=Exchangeable Acidity, NP=Neutralization Potential, AP=Potential Acidity, NNP=Net Neutralization Potential, OM=Organic Matter, EC=Electrical Conductivity

OSL = Observed significance level, Std Dev=Standard Deviation, Std Err=Standard Error of the Mean, Sig Level=Significance Level

T Critical (0.05, 5)=2.57, ns=not significant, *=p<0.05; **=p<0.01; ***=p<0.001

Department of Health and Environmental Sciences, Helena, Montana in association with U.S. EPA Region 8; 2) a greenhouse revegetation potential study conducted as part of the Removal Site Assessment for the Blackhawk Mill Tailings site near Hanover, Grant County, New Mexico (Cornelius, et al, 1996); and, 3) information in Munshower (1994).

Tailings geochemical treatment rates were derived from the site specific acid/base potential data according to criteria developed by the STARS project. The STARS project calculated a calcium carbonate amendment rate equivalent to the amount required to buffer all current acidity, plus potential future acid generation, plus an additional 25 percent [i.e., 1.25 * (NNP + EXA)]. The value derived from this calculation represents the amount of calcium carbonate to add per kiloton of tailings to be treated (one kiloton weighs approximately the same as six inches depth of soil over one acre, or about two million pounds).

Data from the STARS project indicated that a mixture of hydrated lime [$Ca(OH)_2$] and fine limestone ($CaCO_3$) gave the best neutralization results in field studies. In general, hydrated lime is added at a rate required to neutralize all of the current acidity in the tailings material plus 10-20 percent of the NNP [i.e., 1.25*(EXA+0.1*NNP)]. The treatment amendments are then tilled or plowed into the tailings to insure thorough mixing and maximization of buffering (neutralization) potential. Treated tailings are watered several (2 -3) times and re-tilled over a period of a few days, or left *in-situ* for a prolonged mellowing period, which allows pH to peak at its maximum value (11 - 11.5 units) and begin decreasing. After the pH begins dropping, limestone is added at a rate to neutralize all remaining future acidity (1.25*0.9*NNP). If the limestone is added too soon after the hydrated lime it can become coated with soluble metals, which will diminish its overall buffering capacity. It is also critical that the limestone be fine-grained, as large, cobble-sized material does not have sufficient surface area for proper buffering. After the addition of the limestone amendment, the tailings are again tilled and watered several times over a period of a few days, or left *in situ* for a prolonged mellowing period, to facilitate the buffering (neutralization) reactions.

Phosphogypsum or calcium phosphate may also be added if a phosphorus (P) deficiency is anticipated in the treated tailing materials. This can be of critical importance on sites with substantial concentrations of Zn in the tailings material to be treated. Zinc readily complexes with P and in areas with P poor soils all or most of the available P can be tied up with the Zn leaving a P deficiency for vegetative growth. All mining sites in southwestern New Mexico investigated by the Region 6 EPA RPB have required the addition of supplemental P to complex with Zn and to ensure the availability of sufficient P for revegetative plant growth. However, this is not the case in all parts of the western U.S. (e.g., Montana). Phosphorus amendments should be applied at a rate of about five tons/acre. This amendment is initially acidic and should be added before any of the alkaline amendments. Also, the amount of hydrated lime may have to be adjusted based on the acidity of the phosphorus compound used.

The Mammoth Lode revegetation study utilized three paired plots (six total) with a size of approximately 3 by 3 meters. Geochemical stabilization was accomplished by the addition of calcium hydroxide, calcium carbonate and dicalcium phosphate to the tailings as described above. Commercially available calcium hydroxide was added to each plot to neutralize all current acidity plus ten percent of potential acidity. One each of the three paired plots received enough additional calcium carbonate to neutralize the remainder of the potential acidity. The remaining plot of each pair received enough calcium carbonate to neutralize the tailings to a final NP:AP ratio of 3:1. Calcium carbonate was added as crushed limestone from a local quarry source. Commercially available dicalcium phosphate was added to the tailings to enhance binding of metals and to enhance available P. After the addition of each amendment, the test plots were thoroughly tilled, watered and allowed to mellow.

Once the pH of the treated tailings fell below 8.5 pH units, a mixture of bark and saw mill waste was added to the plots at a rate required to bring the overall organic matter content of the upper six inches of the tailings to approximately two percent. Soil fertility analysis results indicated that N:P:K fertilizer should be amended at rates of 100:50:50 pounds per acre. A commercial fertilizer was applied to the test plots at a rate of 50 lbs per acre, and boron was applied at a rate of 1.5 lbs per acre as borax. In July 1995 each plot was seeded with a mixture of cool and warm season grass species and a nitrogen-fixing filler species (Table 2). The test plots were covered with excelsior matting to provide surface erosion control and serve as a mulch for moisture retention.

The test plots were monitored and maintained through October 1995. Periodic maintenance included nutrient addition and irrigation of the plots. In October 1995, soil and plant tissue samples were collected for laboratory analysis. Test plots were also monitored without additional maintenance through September, 1996.

Vegetation cover was estimated within each plot from nine equally spaced Daubenmire quadrats (Bonham 1989) on August 30, October 18, and December 15, 1995 and March 14, 1996 to document results for the first growing season. Additional vegetation cover surveys were performed on June 7 and September 22, 1996 to document results of the second growing season.

Revegetation Plot Study Results

Results of the geochemical stabilization of the mill tailings are presented in Table 1. Average soil pH increased from 3.7 to 6.3 units, exchangeable acidity decreased from 8.8 to 4.2 tons/kiloton, neutralization potential increased from 1.7 to 28.8 tons/kiloton, and acid/base potential increased from -14.2 to +17.0 tons/kiloton. Native soils in the area of the Mammoth Mill site have soil pH values ranging from 5.5 to 7.5 units. No significant differences were observed in measured parameters from the test plots receiving the greater amount of calcium carbonate. The addition of logging waste increased the average soil organic matter 0.5 to 1.73 percent. Soil fertilizer amendments increased plant nutrients from very low levels to levels conducive to plant growth, including boron, nitrogen, phosphorus and potassium.

Results from this plot study indicate that revegetation was successful. Seed germination was observed within one week of sowing. Cover was relatively high on all sample dates (Tables 3 and 4), even though all plots showed signs of intense grazing damage from local populations of deer, elk, and javelina. Observed seed production was low on all plots during the 1995 growing season, and may have been due to the late planting date (July), intense grazing pressure, relative

Table 2. Species planting recommendations for the Mammoth Mill site.

Plant Species Name (Suggested Variety) *(Scientific Name)*	Individual Planting Rate lbs/acre PLS	Mixture (percent)	Planting Rate lbs/acre PLS	Plot Planting Rate lbs/plot PLS
Cool Season Grasses	---	**50**	**5.30**	**0.0304**
Arizona Fescue (Redondo) *(Festuca arizonica)*	5	20	1.00	0.0062
Hard Fescue (Duran) *(Festuca ovina var. duriuscula)*	5	10	0.50	0.0031
Tall Wheatgrass (Jose, Largo) *(Agropyron elongatum)*	20	7.5	1.50	0.0093
Intermediate Wheatgrass (Amvr, Tegmar) *(Agropyron intermedium)*	22	7.5	1.65	0.0078
Pubescent Wheatgrass (Luna) *(Agropyron trichophorum)*	13	5	0.65	0.0040
Warm Season Grasses	---	**50**	**5.15**	**0.0318**
Blue Grama (Hachita, Lovington) *(Bouteloua gracilis)*	3.5	10	0.35	0.0022
Side Oats Grama (Niner, Vaughn) *(Bouteloua curtipendula)*	18	20	3.60	0.0222
Little Bluestem (Pastura) *(Schizarchyrium scoparium)*	10	10	1.00	0.0062
Spike Muhly (El Dado) *(Muhlenbergia Wrightii)*	2	10	0.20	0.0012
Total Grasses	---	**100**	**10.45**	**0.0622**
Filler Species, N-fixer	---	---	---	---
Yellow Sweet Clover *(Melilotus officinalis)*	1	100	1.00	0.0618
TOTAL SEED	---	---	**11.45**	**0.1240**

toxicity of the tailings, or a combination of factors. Several treatment plots had small areas within them characterized by extremely low plant cover. These sparse areas may have been caused by problems with pH, phosphorous availability, or metals toxicity. Both seed production and grass cover increased during the second (1996) growing season.

Plant tissue analysis of clover and blue grama from the test plots showed elevated heavy metal concentrations relative to plants from comparative background areas (data not shown). However, average concentrations of all metals were below Maximum Tolerable Levels of Dietary Minerals (MTLDM) standards for cattle (Subcommittee on Mineral Toxicity in Animals, 1980), except for Cd and Mg. Cadmium standards were based on human food residue considerations, and likely are biased high.

Summary and Conclusions

The plot study at the Mammoth Lode was deemed a successful and viable application of geochemical treatment and phytostabilization of pyritic mine waste. The treated plots maintained a near neutral pH and an acceptable growing medium for the vegetative cover. The probabilities of long term stability of the treatment method also appear favorable. The percent cover and density of the vegetation increased from the first growing season to the second growing season, surviving both extensive grazing pressure and extended drought conditions without supplemental waterings or maintenance past the first growing season.

Table 3. Estimates of percent vegetative cover and grass seedling density in Mammoth Mill revegetation plots, October 18, 1995.

Plot	Clover	Side Oats Grama	Blue Grama	Other Species	Total Cover	Grass Density / m^2
W-1	45.6	30.0	5.0	1.1	81.7	46.7
E-1	47.2	19.9	0.6	1.6	69.2	37.8
W-2	32.2	11.4	1.0	1.8	46.4	37.8
E-2	31.7	15.8	0.2	0.0	47.7	42.2
E-3	33.1	21.4	0.0	0.0	54.6	44.4
E-4	28.0	8.1	0.1	0.0	36.2	30.0
Ave	36.3	17.8	1.1	0.7	56.0	39.8

Table 4. Estimates of percent vegetative cover, grass seedling density, and total number of species in Mammoth Mill revegetation plots, September 22, 1996.

Plot	Forbs	Cool Season Grass	Warm Season Grass	Total Cover	Grass Density / m^2	Total # Species
W-1	12.8	0.0	80.0	92.8	46	10
E-1	3.3	0.0	31.1	34.4	58	14
W-2	67.2	17.3	8.3	92.8	50	12
E-2	56.6	13.3	23.7	93.6	27	16
E-3	0.3	26.1	14.5	40.9	32	15
E-4	2.4	15.2	12.5	30.1	26	17
Ave	23.8	12.0	28.4	64.1	39.8	14.0

The success of the plot study led to the development of a full-scale treatment design. In October 1996, the Region 6 EPA RPB initiated a Superfund removal action using geochemical treatment and phytostabilization as the remediation option at the Mammoth Lode site.

Notice

The Mammoth Lode plot study was funded by the U.S. Environmental Protection Agency (EPA) under the Technical Assistance Team (TAT) Contract No. 68-WO-0037 and the Superfund Technical Assessment and Response Team (START) Contract No. 68-W6-0013. Information in this paper has been subject to the peer review and administrative review by the Region 6 EPA Emergency Response Branch and has been approved for publication. Mention of trade names or commercial products does not constitute an endorsement or recommendation for use.

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