RI 9597

REPORT OF INVESTIGATIONS/1995

Reactivity Studies During Drying and Relocation of Lead-Zinc-Gold Tailings

Phase 1: Preliminary Evaluation and Laboratory Testing

UNITED STATES DEPARTMENT OF THE INTERIOR

UNITED STATES BUREAU OF MINES

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Phase 1: Preliminary Evaluation and Laboratory Testing

By L. J. Froisland and P. B. Lym

UNITED STATES DEPARTMENT OF THE INTERIOR
Bruce Babbitt, Secretary

BUREAU OF MINES
Rhea Lydia Graham, Director

This report had been technically reviewed, but it has not been copy edited because of the closure of the agency.

CONTENTS

CONTENTS-continued

ILLUSTRATIONS

TABLES

TABLES-continued

UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

cm	centimeter
m^3/h	cubic meter per hour
g	gram
g/cm^3	gram per cubic centimeter
g/d	gram per day
g/kg	gram per kilogram
h	hour
ha	hectare
kg	kilogram
km	kilometer
km/h	kilometer per hour
L	liter
m	meter
mg/kg	milligram per kilogram
mg/L	milligram per liter
pct	percent
wt pct	weight percent
°C	degree Celsius

REACTIVITY STUDIES DURING DRYING AND RELOCATION OF LEAD-ZINC-GOLD TAILINGS

PHASE 1: PRELIMINARY EVALUATION AND LABORATORY TESTING

By L. J Froisland[1] and P. B. Lym[2]

ABSTRACT

The U.S. Bureau of Reclamation requested U.S. Bureau of Mines (USBM) assistance in developing design data for moving lead-zinc-gold tailings from their current location without disrupting the existing chemically stable conditions. This report presents results of USBM work in determining (1) the minimum required time to air dry the tailings to approximately 20 pct moisture under various drying conditions both in the laboratory and in the field, (2) the degree of oxidation or reduction that occurs during drying, (3) the effect of lime or cement addition before drying, and (4) the likely equilibrium conditions of the dried tailings after deposition at the new location. The limited number of tests performed by the USBM in the available time frame established trends in oxidation levels but did not provide absolute statistical validity of data values. All data from drying and oxidation testing are included in appendices to this report.

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INTRODUCTION

The Jordanelle Dam, built by the U.S. Bureau of Reclamation (USBR) near Hailstone, UT, as part of the Central Utah Project, formed a large reservoir that would have inundated a small tailing impoundment about 1.5 km from the dam site. This tailing impoundment, known as the Olson-Neihart tailings, received lead-zinc-gold mill wastes from the Mayflower Mine until the early 1970's, when the mine was closed. The impoundment covered about 5.5 ha in surface area and was about 6 m deep at the maximum depth. Historically, the tailings have not contributed any contamination to surface waters in the area, indicating that they are chemically stable. USBR, who built the dam and also had responsibility for alleviating any danger to water quality in the new reservoir, requested U.S. Bureau of Mines (USBM) assistance in developing design data for selecting a method of moving the tailings from the Olson-Neihart tailings to a new location without disrupting that chemically stability and releasing metal contaminants into the environment. The USBR intended for the new impoundment to be a physically stable, engineered fill, which would require compaction of the tailings at or near the USBR-reported optimum moisture content of 21 pct[3].

The USBM research progressed through a series of preliminary characterization tests and in two major drying and equilibrium phases. In the first of these phases, data were gathered to determine (1) the minimum required time to air dry the tailings to the optimum moisture content under conditions likely to be encountered in the field, (2) the degree of oxidation or reduction occurring during such drying, (3) an estimate of airborne dust resulting from the drying operations, (4) the likely equilibrium conditions of the tailings after deposition at the new location, and (5) the possible result of reflooding the tailings until the moving operation began. The second phase of USBM testing included comparative laboratory and field drying tests and additional equilibrium testing with material from the Olson-Neihart tailings and with spill material from along the old slurry pipeline between the mill site and the tailings impoundment. The limited number of tests performed by the USBM in the available time frame did not provide absolute statistical validity of all data values, but the trends in oxidation levels were established.

Many tailing impoundments such as Olson-Neihart exist around the United States: impoundments that were isolated from human populations or influence at the time of their construction but which have since become less isolated because of community growth and/or industrial expansion. Relocation of these impoundments as they become potential hazards to human populations will require evaluation of chemical stability of toxic components before, during, and

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[3] U.S. Bureau of Reclamation. Intra-Agency Acquisition for Developing Drying and Reactivity Data for Use in Selecting a Stabilizing Method for the Olson-Neihart Tailings, Bonneville Unit, CUP. Intra-Agency Acquisition No. 9-AA-40-07690, April 1989.

after moving. Many impoundments have high moisture contents and may require drying before relocation. Techniques and data developed during USBM investigation of Olson-Neihart tailings provide a starting place for evaluating these other impoundments. This report describes the first phase of USBM work in (1) developing methods for evaluating drying data and changes occurring in the tailings during drying and (2) methods for evaluating likely equilibrium conditions in the tailings following drying and relocation.

OLSON-NEIHART TAILINGS HISTORY

Tailings in the Olson-Neihart impoundment came from lead-zinc-gold ore mined in the Mayflower Mine near Hailstone, UT. This mine followed three mineral veins labeled Mayflower vein, Pearl vein, and No. 3 vein. Mineralogies of these veins are described in the following excerpt.

> "In the Mayflower vein, quartz and pyrite are the principal gangue minerals with some chalcedony, calcite, and rhodochrosite usually present. Sphalerite and galena are the principal ore minerals, with chalcopyrite occurring in minor amounts. Hematite is not uncommon and gold and silver occur in much lesser amounts than in the Pearl and No. 3 veins.
>
> The Pearl vein is characterized by a band of friable, sugary quartz with lacing strands of sulfides. The sulfides are pyrite, galena, sphalerite, and chalcopyrite. Hematite is common and occasionally rhodochrosite is present. Gold is of primary economic importance. . . .
>
> The mineralogy of the No. 3 vein is similar to the Pearl vein. Quartz is the principal gangue mineral, hematite is nearly always present and rhodochrosite occurs occasionally. The sulfides are pyrite, sphalerite, galena, and chalcopyrite. Also, as in the Pearl vein, gold is of major economic importance, but the galena, sphalerite, and chalcopyrite are more uniformly distributed. In the lower levels and in the eastern part of the vein zone gypsum becomes a major gangue mineral. . . .
>
> Enargite, argentiferous tetrahedrite, and chalcocite have been important minerals in isolated ore shoots in the sedimentary rocks in the western-most part of the mine[4]".

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[4] Quinlan, J. J., and J. G. Simos. The Mayflower Mine. Ch. in Guidebook to the Geology of Utah, Number 22, Park City District, Utah, ed. by A. J. Erickson, Jr, W. R. Phillips, and W. J. Garmoe. Utah Geological Society, 1968, pp.40-55.

CHARACTERIZATION STUDY

The USBM characterization work on Olson-Neihart tailings was conducted on two tailings samples received from USBR: one from the surface of the tailings, labeled in this report as "oxidized" tailings, and one from below the surface, labeled "unoxidized" tailings. The oxidized tailings were light brown in color while the unoxidized tailings were dark gray. Physical, chemical, and mineralogical characteristics were determined in this initial study.

PHYSICAL CHARACTERISTICS

Moisture content, apparent bulk density, particle size distribution, and bacteria strains were determined or identified in both oxidized and unoxidized tailings.

Moisture Content

Moisture content values for all Olson-Neihart samples were calculated on a "dry" basis, meaning that values represent the water present as a percentage of the weight of dry solids. This method of moisture calculation yields higher moisture content values than does calculation based on the total weight of dry solids and water together. USBR personnel use this method in all calculations of moisture content in soils.

Samples of each tailing type were weighed and oven-dried at 80 °C until successive weights were within 5 pct. Moisture contents of the two types were then calculated and are shown in the following tabulation.

Tailing	Moisture content, pct
Oxidized	19.2
Unoxidized . .	25.3

Apparent Bulk Density

A sample of unoxidized tailings was cut into a block having dimensions of 3.5 by 3.5 by 2.3 cm and weighing 64.15 g. The apparent bulk density of the "as-received" unoxidized tailings was calculated to be 2.3 g/cm^3. No bulk density determination was made for the oxidized tailings because of the diverse nature of the material particles and the tendency for agglomerated particles to break apart.

Dry bulk density of the unoxidized tailings was calculated by applying the moisture content percentage to the weight of the cut block and recalculating the density value. This calculated dry bulk density was 1.7 g/cm^3.

Particle Size Distribution

Wet screening was considered to be the only reasonable method for determining the particle size distribution of these fine-sized tailings. Table 1 shows the wet-sieved particle size distribution for both the oxidized and the unoxidized tailings. The preponderance of small particle sizes is explained by the fact that only the slime fraction was sent to the tailing ponds. Larger, sand-sized

Table 1.—Particle size distribution of Olson-Neihart tailings, percent passing

Mesh size	Oxidized tailings[1]	Unoxidized tailings
65 . . .	96	99.5
100 . .	90	99
150 . .	83	97
200 . .	77	94
270 . .	72	90
325 . .	66	85
400 . .	61	82

[1] Increased particle size is probably due to agglomeration occurring during the oxidation process.

particles were returned to the Mayflower Mine as hydraulic backfill.

Bacteria Identification

Results from bacteria identification studies showed the presence of *Thiobacillus ferrooxidans* in both tailing samples with counts of 25 x 10^6/g in the oxidized zone and 18 x 10^6/g in the unoxidized zone. This strain has the capability of oxidizing sulfides and may contribute to the solubilization of sulfide minerals.

CHEMICAL ANALYSIS

Soil pH and bulk chemical analyses were determined for both oxidized and unoxidized tailings.

Soil pH

Soil pH was determined with the standard practice of making a saturated paste of the tailings in de-ionized water and letting the paste sit for at least 4 h before measuring the pH. Results of pH testing are shown in the following tabulation.

Tailing	Soil pH
Oxidized	3.01
Unoxidized . . .	5.29

Bulk Chemical Analysis

Samples of both oxidized and unoxidized tailings were dried at 105° C overnight and submitted for bulk chemical analyses. These analyses, presented in table 2, show that many metals considered as contaminants--Pb, Cu, Zn, and Al--are present. Also As is present at over 100 ppm, which is significantly higher than the average background level of 50 ppm in soil. Any increase in leaching characteristics brought about by the drying and relocation activity could cause water contamination from these elements.

It should be noted that these initial analyses were not performed according to strict EPA protocols as was done later in the test work. Inductively-coupled-

Table 2.—Chemical analyses of Olson-Neihart tailings used in preliminary characterization work

	Oxidized tailings	Unoxidized tailings
Analysis, ppm:		
As . . .	175	139
Se	3.1	2.5
Analysis, pct:		
Al	3.2	3.5
Cd . . .	<0.005	<0.005
Cu . . .	0.07	0.09
Fe . . .	11.6	13.4
Mn . . .	0.15	0.18
Pb . . .	0.2	0.2
S^{2-} . . .	6.6	8.0
Zn . . .	0.1	0.3
Analysis, g/kg:		
Ag . . .	0.022	0.022
Au . . .	0.0006	0.0006

plasma (ICP) techniques were used to analyze for Pb, Cu, Zn, Fe, Cd, and Mn. Atomic adsorption spectroscopy (AAS) was used to analyze for Al, As, and Se. Au and Ag were determined by fire assay with AAS finishing.

MINERALOGICAL ANALYSIS

Samples of both oxidized and unoxidized tailings were submitted for microscopic and x-ray analysis to determine the mineralogy. Completed analyses show that both tailings were very similar, as expected, since they came out of the same hole. Both tailings were examined under the binocular-reflecting light and petrographic microscopes where the basic mineralogy and relative abundance of the various mineral constituents were determined. Samples were mounted in epoxy and examined under the scanning-electron microscope. Composition of the minerals was determined by electron dispersive spectroscopy (EDS) and the percentage of sulfides was determined by image analysis techniques. Table 3 lists the major minerals found in each of the tailing samples along with approximate volume percentages.

Trace amounts of the following minerals were also found in both samples: sphalerite, chalcopyrite, galena, apatite, garnet, epidote, dolomite, zircon, and barite. Mineralogy of the tailings in this study agrees very well with mineralogy of Mayflower Mine deposits as reported by the Utah Geological Society[5].

A non-pulverized sample of the oxidized tailings was submitted for examination of a coating on the surface of some particles. Most of this yellowish-brown coating was limonite and other hydrated iron oxides and/or hydroxides. These minerals were minor constituents in the tailings and appeared to be more abundant than they actually were, probably because they were

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[5] Work cited in footnote 4.

Table 3.—Mineralogy of Olson-Neihart tailings, approximate volume percentages

Mineral	Oxidized tailings	Unoxidized tailings
Amphibole . . .	10-20	10-15
Fe-Mn oxide . .	ND	2-2
Gypsum	ND	10-15
K-feldspar	20-30	10-20
Mica-illite-clay .	20-30	15-20
Plagioclase . . .	5-10	10-15
Pyrite	3-4	3
Pyroxene	ND	5-10
Quartz	30-40	30-40

ND Not detected.

coating the surface of quartz and feldspar grains. A minor part of the coating consisted of iron, potassium, calcium, and sulfur (by EDS analysis) and was probably a mixture of gypsum and jarosite. The material was too fine-grained to determine whether the coating is a single phase or a mixture.

The vast majority of the identified minerals— quartz, K-feldspar, plagioclase, mica, illite, amphiboles, and pyroxene—are silicate minerals showing a moderate degree of weathering. Many of these minerals are chemically unstable at ambient conditions and slowly weather to clays. Common soil around the tailing pond is likely to consist of the same minerals. Because silicate minerals weather very slowly, it is improbable that these minerals would contribute any appreciable dissolved species to the reservoir water.

Pyrite and other sulfide minerals such as sphalerite, galena, and chalcopyrite may weather to oxide or sulfate forms quite rapidly, especially in periods of low water when the tailing surface could be exposed to air. Because none of the identified minerals contain arsenic as a normal constituent, the most probable source of arsenic in the tailings is arsenopyrite, present at levels too low to detect, but which reacts similar to the other sulfides. Some of these oxidation products are soluble in acids, such as sulfuric acid (H_2SO_4), which is another product of the sulfide weathering process. Such elements as iron, zinc, arsenic, and copper may be solubilized in minute quantities as a result of the sulfide weathering. Minerals such as gypsum and barite are not sufficiently soluble in water to contribute any detrimental chemical species to the reservoir water.

PHASE 1 DETERMINATION OF DRYING TIME

Two series of air drying tests were conducted under the phase 1 test program. The first series determined required drying times for both oxidized and unoxidized tailings to reach the optimum, 21-pct moisture level for physical stability at the new deposition site. The second series was conducted under selected test conditions to confirm results from the first series and to provide dried (19-23 pct moisture) tailings for long-term equilibrium testing. Drying-time data from both series are plotted in appendix A, showing moisture content plotted against time.

FIRST DRYING SERIES

A team of USBM and USBR personnel jointly collected samples from the Olson-Neihart tailings for the first drying test series. Variables selected for study in this laboratory series included type of tailings—oxidized or unoxidized; tailings depth in the drying pans; turning or not turning the tailings to expose fresh, wet surfaces to the air; and air flow across the tailings surface.

Sampling Procedure For First Drying Series

Samples of tailings for the first drying tests came from the north side of the Olson-Neihart impoundment. Weather conditions on the impoundment at the time of this sampling were very wet with a considerable amount of snow still on the ground, as shown in figure 1. Unoxidized tailings collected in this sample had moisture contents of 54 pct with pH values near 6.5; oxidized tailings had moisture contents of 80 pct with pH values ranging between 2.3 and 3. Based on previous sampling data, USBR expected the tailings moisture content to be about 40 pct during the actual drying and moving operation. Approximately 329 kg of oxidized tailings and 397 kg of unoxidized tailings were taken for these drying tests. Tailings were shoveled into plastic buckets, which were purged with nitrogen before sealing to minimize oxidation during transportation and storage. Safety procedures observed during this sampling were designed by USBR personnel and included wearing protective clothing such as Tyvex suits, gloves, and boots, and washing all equipment and vehicles thoroughly before leaving the site.

Laboratory Drying System

Drying pans made from 19-L plastic pails were filled in the USBM laboratory with either oxidized or unoxidized tailings to depths ranging from 1.3 to 30.5 cm. These pans were placed in the laboratory in sections according to test conditions, as shown in figure 2. Tailings in some pans were turned daily to simulate disking in the field. Turning was accomplished by dumping the tailings into a tub, mixing them with a scoop and/or spatula, and replacing them in the drying pan. Tailings were turned, however, only after the moisture content decreased to between 30 and 40 pct; turning tailings with moisture contents above that level was impractical because of the very sticky nature of the tailings. Field disking at greater than 30 to 40 pct moisture may not be possible because of the sticky characteristics of fine-particle tailings.

Two oscillating fans provided an 8-km/h air flow across tailing surfaces in one section of drying pans to simulate windy conditions in the field. This air flow was measured with anemometers placed approximately 7 cm above the surface of the 30.5-cm-deep pans. Assuming a turbulent boundary layer above the tailings surface and using the Prandtl approximation for velocity in the boundary layer[6] resulted in a flux value of 127 m^3/h for air moving across the tailings between the surface and the anemometers. The small size of the drying pans made it unlikely that air outside of this boundary region would contribute anything to the drying.

Measurement of Moisture Content

Initial moisture contents of the tailings were determined by taking small samples from each bucket at the beginning of the tests, oven drying them at 105° C to constant weight, and calculating the moisture content. During the drying tests, USBM personnel monitored tailings moisture contents by weighing the pans daily. Weight losses were attributed solely to evaporation of water from the tailings. A computer program was developed to calculate moisture contents based on these daily weighings.

Several times during the tests, small grab samples were taken from one or more pans and dried in the oven as a check on the validity of calculated moisture contents. The two values were always within 10 pct of each other and most often within 5 pct. This method of determining moisture contents enabled USBM personnel to closely monitor the progression of the drying tests. Weights of moisture content check samples as well as weights of periodic samples taken from each pan for determination of pH and oxidation changes were accounted for in the computer program.

Data Reproducibility

Data reproducibility was measured by drying oxidized and unoxidized tailings in duplicate tests under the following conditions: 10.2-cm depth, 8-km/h air flow across the tailing surface, and periodic turning of the tailings. The resulting drying curves, shown in appendix A as figure A-1, indicate very good reproducibility of data.

Shallow Pan Tests

Shallow (1.3 to 5.0 cm) depth tests without air flow were conducted to determine thin-layer drying characteristics of both oxidized and unoxidized tailings. Results, plotted in appendix A in figure A-2, show that both oxidized and unoxidized tailings at 1.3- and 2.5-cm depths dried from field conditions to a constant moisture level of less than 5 pct in about 4 and 8 days (100 and 200 h), respectively. Unoxidized tailings at a 5.0-cm depth dried to a constant moisture level of less than 5 pct in about 12 days (300 h); oxidized tailings at a depth of 5.0 cm did not reach a constant moisture level in 22 days (530 h).

Required Drying Time

The first series of drying tests was conducted over a 3 week period of time, during which relative humidity, temperature, and air flow were monitored. Average values for these factors were 23 pct relative humidity, 24° C temperature, and 8-km/h air flow speed measured by anemometers placed among the drying pans.

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[6] Olson, R. M. Essentials of Engineering Fluid Mechanics. Int. Textbook, Scranton, PA, 1961, pp. 134-135.

Because tailings for these drying tests were much wetter than they were expected to be during actual drying and moving operations, the drying curves cover a greater range of moisture contents than will be needed to determine expected drying times for actual operations. Examination of the curves between the expected and desired moisture content levels yield an estimate of the required drying time.

Air flow across the tailing surface significantly increased the drying rate. Turning the tailings to expose fresh surfaces to the air also increased the drying rate, but the effect was not as pronounced as that of air flow. All depth and turning combinations in the air flow series (figures A-3 and A-4) reached the 21-pct moisture level after 22 days (530 h), and most were well below that point much earlier. Conversely, the only pans in the non-air flow series (figures A-5 and A-6) to drop below the 21-pct moisture level were the 10.2-cm pan containing oxidized, turned tailings; the 10.2-cm pans containing unoxidized, turned and unturned tailings; and the 20.3-cm pan containing unoxidized, unturned tailings. Table 4 presents the time required for tailings at each combination of depth, air flow, and turning to dry from initial field conditions to approximately 21 pct moisture. Values in this table are taken from the drying curves in appendix A.

Table 4.—Required time for oxidized and unoxidized tailings to dry from field conditions to 21 pct moisture in first drying series, hours

Depth, cm	Oxidized tailings[1]	Unoxidized tailings[2]
Airflow, with turning:		
10.2	116	64
20.3	203	141
30.5	328	200
Airflow, no turning:		
10.2	188	72
20.3	288	125
30.5	530	291
No airflow, with turning:		
10.2	515	184
20.3	>530	>530
30.5	>530	>530
No airflow, no turning:		
10.2	>530	294
20.3	>530	459
30.5	>530	>530

[1] Started at 80 pct moisture.
[2] Started at 54 pct moisture.

SECOND DRYING SERIES

Following evaluation of the first drying series, USBM and USBR personnel met and selected a drying procedure to be used in the second test series, which would confirm results from the first series and provide dried tailings for long-term equilibrium tests. The selected procedure was drying oxidized and unoxidized tailings in 30.5-cm-deep pans with an 8-km/h air flow and with turning of the tailings. The 30.5-cm pan depth was chosen as a "worst-case scenario" because it presented the longest drying time with the accompanying greatest possibility of oxidation during drying.

Sampling Procedure For Second Drying Series

Samples for the second drying series were collected by shoveling tailings into plastic buckets, which were then closed with vented lids, purged with nitrogen, and sealed to minimize oxidation during transportation. USBR developed stringent safety procedures that were followed during this sampling operation including wearing personal safety equipment, setting up contamination area limits, and using proper decontamination procedures for all personnel and/or equipment leaving the contamination area. Oxidized and unoxidized tailing samples totaled about 181 and 272 kg, respectively. Figure 3 shows sampling in progress for the second drying series, together with the decontamination area in the foreground.

Previous Olson-Neihart tailing samples came from the northern end of the impoundment; samples for the second drying series came from the southern end near the dike. Different sample locations and weather conditions can affect drying and equilibrium tests in three ways:

1. Tailings for the second drying test had a different texture than the earlier samples. Fine particulates were still evident, but portions of the tailings had a sandy texture. This difference in particle size affects both moisture content and moisture retention.
2. The second sampling location appeared to be higher in elevation with better drainage than was the first sample location; thus the moisture content of the sample for the second drying tests was lower than that of previous samples.
3. The drier weather conditions present during the second sampling operation decreased the moisture content of the sample.

These differences produced a bracketing effect on the drying rates. Tailings samples collected for the second drying test started with lower initial moisture levels and with somewhat larger particle sizes for comparison with drying rates determined in initial tests. This bracketing effect enlarged the data base for making final drying operation decisions.

Results showed significant differences in moisture contents between samples for the first and second drying series. Moisture contents of both oxidized and unoxidized tailings in the second samples were about 40 pct compared with approximately 80 pct for the oxidized tailings and 54 pct for the unoxidized tailings in the first samples. Oxidized tailings pH values were about 2.3, basically unchanged from the first sample; but the pH of the unoxidized tailings in the second sample was 5.0 compared with about 6.5 for the first sample. Different sample locations, weather conditions, and time of year were all factors in the variation in moisture contents and pH.

Drying Time

Individual tests in the second drying series were terminated when tailings reached the desired 19- to 23-pct moisture range. This occurred at 6 days with the unoxidized tailings and at 9 days with the oxidized tailings. The laboratory arrangement of the 30.5-cm-deep pans is shown in figure 4 with oxidized tailings in the first row of pans and unoxidized tailings in the second row. Relative humidity, temperature, and air flow across the tailings surface were again monitored throughout the test period; average values for these values were 31 pct relative humidity, 24° C temperature, and 8 km/h air flow speed. The dried tailings were sealed in containers and held for equilibrium tests.

Drying curves generated from the second series of drying tests are presented in figure A-7 for oxidized and unoxidized tailings. Initial moisture contents of these tailings varied only from 37 to 41 pct throughout the pans of unoxidized tailings and were nearly constant at 40 pct for the oxidized tailings. Starting points for the curves generated in this test series are plotted as the actual measured moisture contents in each drying pan. As in the first drying series, the data shows excellent reproducibility. The following observations are made concerning these curves:

1. Tailings were dried in 30.5-cm-deep pans with 8-km/h air flow across the surface and daily turning of the tailings to simulate field disking.
2. In the first series of drying tests, starting points for the drying curves were made uniform by taking the average of the initial moisture contents. If this were done in figure A-7, the curves would be virtually indistinguishable, indicating good data reproducibility from one test to another.
3. The apparent sharp change in drying rates exhibited in unoxidized tailings (fig. A-7) at about 3 days (70 h) occurred because the drying pans were removed from the air flow. At that point, the next opportunity to evaluate the tests was 2 days later, and the drying rate was fast enough that such a waiting period was likely to decrease the moisture content below the desired range. To avoid drying the tailings too far and having to add water back to the tailings to reach the target moisture level, USBM personnel discontinued air flow across those buckets. If the air flow had been maintained and the slope of the drying curve had not changed, the unoxidized tailings would have reached the desired 21 pct level in less than 4 days. The same circumstance occurred with the oxidized tailings after about 9 days (215 h), as shown by the change in the slope of the curves in figure A-7. These changes illustrate the differences in drying rates attained when air flow is present and when it is not.
4. One of the drying pans contained oxidized tailings with lime added. The drying curve for this pan,

which is included in figure A-7, is indistinguishable from the nonlimed curves, indicating that lime addition will not change the drying rate.

Some similarities and differences in results from the first and second drying series are noted below.

1. Drying rates differed greatly between the oxidized and unoxidized tailings in the second test series in contrast to the first series. This could be due to a number of sample differences noted previously. In the first series, both oxidized and unoxidized tailings in 30.5-cm-deep pans with air flow and turning of the tailings dried from 40 to 21 pct moisture in about 6 days (135 to 150 h), according to the drying curves in appendix A. In the second series, unoxidized tailings dried from an initial 40 to 21 pct moisture in an estimated 4 days (drying pans were removed from air flow after 3 days), while oxidized tailings took about 9 days (215 h).
2. The unoxidized tailings for the second series had the same appearance as did unoxidized tailings for the first series: very wet with fluid flow characteristics and excess water in the sample buckets. The oxidized tailings for the second series were much different in appearance than were the oxidized tailings for the first series. The initial oxidized samples had fluid flow characteristics and excess water in the buckets (just like the unoxidized tailings), but the second-series oxidized samples were dry in appearance. None of the buckets contained standing water, and the oxidized tailings were poured directly from the sample buckets into the drying pans just as one might pour sand from one bucket to another. The unoxidized tailings appeared much wetter than did the oxidized tailings throughout the drying tests.

Lime {$Ca(OH)_2$} was added to one drying pan of oxidized tailings. The intent was to add lime during the turning operation to raise the pH to approximately 7 in an effort to deactivate any bacterial leaching. *Thiobacillus ferrooxidans* thrive in the pH 2 range but are inactive above pH 4. The theoretical amount of lime (2.4 pct of the bone-dry tailings weight) was determined using the first tailing sample collected. One-fourth of the theoretical amount was to be added during each turning. However, the first addition took the pH from 2.2 to 6.7; and the second took the pH to 8.6. No further additions were made. Based on these lime additions, the amount needed to raise these oxidized tailings to approximately pH 7 was 0.6 pct of the bone dry tailings weight. Lime additions necessary to raise the oxidized tailings to pH 7 ranged from 0.6 pct to 2.4 pct for the two sets of samples.

EVALUATION OF OXIDATION DURING DRYING

Oxidation of tailings was monitored during each drying series by two methods: soil pH and leaching of water soluble oxidation products.

SOIL pH

Soil pH measurements did not indicate any oxidation of the tailings during either series of drying tests. Small samples of tailings were periodically taken from each pan and tested for soil pH, using a 1:1 tailings:distilled water slurry. A decreasing soil pH would indicate oxidation of the tailings with accompanying acid production. In the first series, oxidized tailings had a pH range of 2.3 to 3, and unoxidized tailings had a pH range of 6.5 to 8. Measured pH values during the second drying series ranged from 2.0 to 2.3 in the oxidized tailings and from 5.0 to 5.7 in the unoxidized tailings. Differences between ranges in the two tests were attributed to differences in original samples, as noted previously.

LEACHING OF WATER SOLUBLE OXIDATION PRODUCTS

A more rigorous evaluation of oxidation was performed by leaching small samples of the drying tailings in distilled water and analyzing the leachate solution for dissolved metals and sulfate ions. These leaches were performed by mixing deionized water and the moist tailings in a 1:1 ratio and agitating for 1 h at ambient temperature. Slurries from the leach vessel were washed into a centrifuge bottle for liquid/solid separation. Solutions were further clarified by filtration prior to analysis. Unlike the initial tailings analyses described earlier in this report, analyses of the leachate solutions were performed under strict EPA protocols with duplicate samples accounting for 10 pct of the sample load and reference samples accounting for 5 pct of the sample load. Table 5 presents the EPA protocol designations for the analytical methods followed in these determinations.

Table 5.—EPA analytical methods used to analyze oxidation leach solutions

Component	EPA method
As	206.2
Cd, high levels . .	200.7
Cd, low levels . .	213.2
Cu	200.7
Fe	200.7
Mn	200.7
Pb	239.2
SO_4	375.2
Zn	289.1

Detection limits for the different elements were established by agreement between the USBM and USBR.

Chemical data collected from the leach tests were evaluated by calculating a "reactivity" value for the tailings. Calculated reactivity, which is defined as the amount of any component leached per unit of dry solid, will remain constant over time if oxidation to water soluble compounds does not occur. Reporting units for reactivity are milligrams per kilogram of dry solid (mg/kg).

Chemical Assays

Leach parameters and chemical assays of leachate solutions from oxidation evaluations performed during the first and second drying series and during evaluation of the long-term equilibrium columns are tabulated in appendix C. Leach parameters included in this appendix include weights of the samples taken for leach tests; moisture contents of those samples; volumes of leachates, including residual solution in the cake after centrifugation; and leachate pH values. Leachate volumes and assays were required for calculation of reactivity values but the assays may also be used as very rough approximations of expected rainwater runoff composition. The leachate volumes reported in appendix C do not reflect the 1:1 leach ratio because of deionized water used to wash the slurry from the leach vessel into the centrifuge bottle. Leachate concentrations were expected to increase as drying progresses because the samples taken for leach testing contained more and more solids. Basing any judgments on these assays alone would not be correct because of the variations encountered in sampling and in the dilutions that occurred during the leach process. For this reason, the data were normalized by calculating the reactivity values. The leachate assays are included in this report for information. Leach parameters and leachate assays from the two duplicate sets of pans in the first drying series are shown in tables C-1 and C-2 in appendix C for oxidized and unoxidized tailings. These data are in good agreement, which confirms the high level of reproducibility between tests.

Reactivity

Reactivities, shown in appendix B, and patterns of change in the reactivities are of more practical use than simple chemical analyses in determining tailings-handling requirements. As previously stated, if oxidation does not occur in the drying tailings, these calculated reactivities should remain constant. A high value for reactivity is indicative only of the solubility of that element in water; it does not show changes occurring in the tailings. Oxidation of the tailings, which usually involves oxidation of sulfide minerals to sulfate minerals, is indicated by increases in reactivity.

Examination of the data for the duplicate 10.2-cm-deep pans in the first drying series (table B-1) shows that most of the element reactivities either remain constant or show a decrease. Only cadmium and lead in the unoxidized tailings show possible increases in reactivity, but the increases for these two elements occurred largely after the tailings moisture content had decreased well below the desired 21 pct level. This indicates that oxidation occurring during drying to the desired 21 pct moisture level was not significant and should not create any leaching problems with the relocated tailings.

Also included in appendix B are the calculated reactivities from oxidation evaluations made during the second drying series. Table B-2 presents values from the oxidized and unoxidized drying pans. Tables C-3 and C-4 present respective leach test parameters and leachate assays for these tests. The only increase in reactivity during drying occurred possibly with iron in the oxidized tailings, which increased from 200 mg/kg to 1000 mg/kg. Again, no problems with oxidation during drying were indicated.

DETERMINATION OF POTENTIAL DUST PROBLEMS

Air sampling during the first drying test was conducted downwind from the air-flow drying pans. Personal air samplers were placed in the air stream from the fans, and the air stream blowing across the pans was sampled for several hours on selected days during the drying test. Results of air sampling and visual observation of the tailings indicate no dusting until the moisture content is well below the desired 21-pct level. Some dusting was noted during the turning operations after the tailings were dried below 21 pct; loose dust left on the surface after turning was quickly blown away when the pan was again placed in the air flow. Air sampling results are shown in table 6. The USBM did not anticipate any dust generation during actual field drying and moving operations unless the surface was allowed to dry significantly below the 21-pct moisture level. Periodic turning of the tailings to expose damp surfaces to the atmosphere should be done to minimize any overdrying with resultant dust generation.

Table 6.—Results of air sampling during initial drying series

Days	Duration of sampling, h	Dust collection, g/d
2 . . .	4.0	$-6(10^{-6})$
6 . . .	7.3	$-5(10^{-3})$
7 . . .	7.3	$-1(10^{-2})$
8 . . .	[1]7.0	$-1(10^{-2})$
19 . . .	6.3	$6(10^{-3})$

[1] Visible particulates on filter.

LONG-TERM EQUILIBRIUM COLUMNS

The second drying series was conducted under selected test conditions to confirm results from the first series and to provide dried (21 ± 2 pct moisture) tailings for long-term equilibrium testing. These long-term equilibrium tests were designed to determine oxidation changes occurring under simulated conditions in the new tailings impoundment, complete with clay cap and isolation from the atmosphere. Plastic drill core liners, believed to be a form of butadiene polymer, were provided by USBR for use in the equilibrium tests. These 76-cm-long by 5.7-cm-diam tubes were sealed at one end with a permanent plastic cap, filled with dried tailings compacted to a target density, and sealed with 15 cm of clay to prevent contact with the atmosphere. The clay sample obtained for capping the equilibrium column tests came from a clay bed near the Olson-Neihart tailings. Evaluation periods for the filled equilibrium columns ranged from 1 week to 10 months. Figure 5 shows the laboratory arrangement of phase 1 long-term equilibrium columns.

Dried tailings were blended with bacteria inhibitors or nutrients or with lime as a pH modifier and compacted into some columns to test the effects of such additives. Unoxidized tailings at a moisture content between 25 and 30 pct were compacted into one column and a mixture of oxidized and unoxidized tailings was compacted into one column. The following sections describe the filling, compacting, and evaluation of the equilibrium columns.

COLUMN FILLING AND COMPACTING PROCEDURE

Near the completion of the second series of drying tests, USBR personnel visited the USBM laboratory to review the drying operation and to discuss compaction criteria for long-term equilibrium testing in the plastic columns. These compaction criteria were supplied by USBR and were reportedly taken from a report issued by a consulting engineering firm in November 1987.

The compaction criteria were in the form of Proctor maximum density and corresponding optimum moisture content. As the moisture content of a soil increases, the compactibility increases to a maximum point and then decreases again. This maximum point is called the Proctor maximum density and corresponding moisture content[7]. Engineered fills are constructed around this Proctor maximum density with most compaction targets being 90 or 95 pct of the maximum value.

USBM personnel assumed that unoxidized tailings were used in the Proctor test because of the sample depth noted in the test location description. The compaction curve in the engineer's report showed the optimum moisture content to be 21.5 pct and the corresponding maximum dry density to be 1.75 g/cm^3. USBR personnel initially designated target compaction criteria for the long-term equilibrium tests as 95 pct of the maximum Proctor dry density and a moisture content range of 19 to 23 pct moisture. Subsequently, USBR modified the density targets for both oxidized and unoxidized tailings to 90 pct of the maximum Proctor dry density of unoxidized tailings, feeling that this value should yield a "worst case" scenario.

Calculations by USBM personnel show the wet (21.5 pct moisture) density equivalent of the maximum dry value to be 2.12 g/cm^3 and the 90-pct compaction target to be 1.91 g/cm^3. This target density and the calculated column bed volume of 1.56 L were used to determine that 2992 g of moist tailings must be compacted into each column. A rounded value of 3,000 g per column was selected as the actual weight target. This yields a calculated density in the 5.7-cm-diam by 61-cm-high column bed

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[7] U.S. Bureau of Reclamation. Earth Manual: A Water Resources Technical Publication. 2nd Ed., 1974, pp.466-478.

of 1.92 g/cm^3 or 90.5 pct of the maximum Proctor dry density. USBR personnel reviewed and accepted these calculated values and targets.

When tailings reached the desired 19 to 23 pct moisture range in the drying operation, they were sealed in buckets to prevent further moisture loss and to even out the moisture content throughout the mass.

A test column was filled with 3,000 g of dried, unoxidized tailings; compacted to the target density; and capped with 15 cm of clay compacted to the same target density. This column was filled and compacted by weighing out and tamping 750-g portions of tailings with a wooden tamping rod into 15-cm segments of the column using 5- to 7.5-cm lifts. Large pellets of tailings (greater than 2.5-cm diam) were broken up by hand before loading into the column. This filling and compaction method resulted in very uneven tailings compaction. The top layer in each lift appeared to be well compacted, but the bottom layer contained large air pockets. This indicated that the compaction procedure needed modification.

Based on results of a small-scale blending test, USBM personnel anticipated that dried tailings would not pelletize in a mechanical blender; therefore, the tailings were screened through a 4-mesh sieve before blending. Pelletization did occur, however, necessitating a second screening before placing tailings in the columns. This second screening was easily accomplished because the pellets were small in size. Moisture content measured on the rescreened tailings showed 21.6-pct moisture, which was within the desired 19 to 23 pct range.

USBR personnel visited the USBM laboratory to examine the filled column and to discuss a modified compaction procedure. The following procedure was agreed on by USBR and USBM personnel and was used to fill the phase 1 columns.

1. The dried tailings were screened through a 4 mesh sieve before being placed in the columns. This required manual crushing of pellets and agglomerated tailings before screening.
2. Tailings were placed in the columns in 7.5-cm lifts and compacted to the target density using the wooden tamping rod.

Table 7 summarizes the long-term equilibrium tests set up with phase 1 dried tailings. Untreated, oxidized and unoxidized tailings were compacted in some columns both with and without clay caps; other columns contained tailings treated with bacteria inhibitors, bacteria nutrients, or with a pH modifier. Moisture content evaluation using several oven-dried samples showed the tailings being compacted in the columns to be between 20.5- and 20.9-pct moisture, which was within the limits proposed by USBR.

One column noted in table 7 was filled with unoxidized tailings at a reconstituted moisture content of 27 pct in accordance with discussions held between USBM and USBR personnel. The purpose of this test was to determine what would happen if water seeped into the 20-pct-moisture tailings after they were in place, but did not saturate them to the point where anaerobic conditions caused the *Thiobacillus ferrooxidans* bacteria to be inactive. There was, however, some

Table 7.—Long-term phase 1 equilibrium columns

Number of columns	Clay capped	Additives
Oxidized tailings:		
9	Yes	None.
2	No	None.
1	Yes	SLS[1].
1	Yes	NaAc[2].
1	Yes	Lime[3].
1	Yes	NaAc[2] + lime[3].
Unoxidized tailings:		
9	Yes	None.
2	No	None.
1	Yes	SLS[1].
1	Yes	NaAc[2].
1	Yes	Lime[3].
1	Yes	Water (27 pct moisture).
Mixed tailings:		
1	Yes	None.

[1] Sodium lauryl sulfate (SLS) added at 2.4 g/kg as a *Thiobacillus ferrooxidans* bacteria inhibitor.

[2] Sodium acetate (NaAc) added at 2.4 g/kg as a *Desulfovibrio* bacteria nutrient.

[3] Lime added as $Ca(OH)_2$ to bring tailings pH to 6.5.

misunderstanding between the USBM and USBR about the target density for this column with the result that the compacted density, which was 2.07 g/cm^3, may have been much too high. Compaction of the wetter tailings to this density was more easily achieved than should have been the case if the Proctor maximums were correct, which caused both USBM and USBR personnel to question the original Proctor values.

USBM and USBR personnel discussed the lack of Proctor values for oxidized tailings on several occasions; the consensus was that the USBM would attempt to reach the same compacted density with oxidized tailings as with unoxidized tailings. This density was not achievable. A segment of one column was filled with 750 g of oxidized tailings and compacted as much as possible using very shallow lifts. The resulting maximum achievable density was 1.75 g/cm^3 or 82.6 pct of the maximum Proctor value for unoxidized tailings. Filling a column with oxidized tailings compacted with the same techniques as were the unoxidized columns yielded a compacted density of 1.59 g/cm^3 or 75 pct of the maximum for unoxidized tailings.

Because of the lack of Proctor data on oxidized tailings and potential problems in applying the published unoxidized-tailing Proctor data to the current sample, USBR agreed to perform new Proctor evaluations on both tailing types. Dried samples (21 pct moisture) of both oxidized and unoxidized tailings (ca. 23 kg each) were supplied to USBR for additional Proctor tests on these tailings with the following results:

1. Optimum moisture content for unoxidized tailings was 18.2 pct

(dry basis). Corresponding dry density was 1.83 g/cm^3 and wet density was 2.16 g/cm^3. Ninety percent of the wet density value was 1.95 g/cm^3. Compaction levels in the phase 1 columns with unoxidized tailings ranged from 1.92 g/cm^3 to 1.94 g/cm^3, which was not too far from the new optimum value; but of course, moisture content in the columns was about 20.5 pct, which is about 2 pct higher than the new optimum.

2. Optimum moisture content for oxidized tailings was 27.2 pct (dry basis). Corresponding dry density was 1.50 g/cm^3 and wet density was 1.91 g/cm^3. Ninety percent of the wet density value was 1.72 g/cm^3. The current compaction was well below that point with the density being about 1.60 g/cm^3, but the moisture content was also well below the optimum moisture content. Packing the oxidized tailings as tight as possible at 21.6 pct moisture yielded a density of 1.75 g/cm^3 which was just above 90 pct of the maximum density at the higher moisture content.

COLUMN DISMANTLING AND EVALUATION

All phase 1 columns were dismantled according to the planned schedule, and the top layer of tailings in each column was water leached in the prescribed evaluation procedure to determine changes in the degree of oxidation. Leach parameters and leachate analyses are tabulated in tables C-5 through C-14 in appendix C. As stated earlier, the assay values were required for calculation of reactivities; but they do not form the basis for any judgments about oxidation changes. The pH measurements taken during oxidation evaluation leach testing did not show a decreasing pattern until the 10-month columns containing unoxidized tailings were dismantled (table C-5). The pH levels in these columns had decreased from the 5.0 — 5.5 range found in previous columns to between 3.3 and 3.5, which does indicate oxidation occurring in the unoxidized tailings. Tailings were evaluated as to effects of time in the columns, capping the tailings, additives to the tailings, higher moisture content than the optimum, and mixing the tailings.

Moisture contents of tailings evaluated after the specified periods of time revealed that the tubes used as columns in this study were not impermeable to the passage of water and thus probably not impermeable to the passage of air. Total weight losses in the columns signaled moisture passage through the plastic tube walls. After 10 months in the columns, compacted tailings moisture contents had decreased to about 12 pct.

Effect of Time on Tailings Oxidation in Columns

Effects of time on oxidation occurring in the columns were determined for both unoxidized tailings and oxidized tailings.

Unoxidized Tailings

Table B-3 presents calculated reactivity values for untreated, unoxidized tailings from the clay-capped equilibrium columns dismantled throughout the 10-month test period. During the filling and compacting operation, the sealed buckets of dried tailings were stored in the laboratory for periods of time ranging from 7 to 14 days. Because of this time lag, several samples of tailings were taken from the buckets and water leached to determine a baseline reactivity level for the beginning of the column tests. All of the elements except arsenic and lead exhibited much greater reactivity in these baseline determinations than in the ensuing column evaluations; and all baseline reactivities except arsenic, lead, and iron were higher than those found at the end of the drying tests. This finding is not readily explainable, but it does indicate that water percolating through the dried tailings before compaction and sealing may be contaminated with elements such as cadmium, manganese, zinc, and copper. Thus compacting and sealing the dried tailings at the new location should be done immediately after the drying is complete.

Reactivity values determined during the 10-month phase 1 equilibrium test period indicate that some chemical changes did occur. All metals, except arsenic and lead, showed increases in reactivity over the 10-month period, which indicates oxidation. In the case of iron and copper, however, the increases over 10 months only brought the reactivity levels back to those found in baseline tests performed on tailings fresh from the Olson-Neihart tailings. Sufficient oxidation occurred in unoxidized tailings to warrant prevention of water contact with the relocated tailings. If such contact does occur, the possibility exists for dissolution of elements such as cadmium, manganese, zinc, and sulfate into the water. No evidence was found that arsenic, iron, lead, or copper would leach into water percolating through dried, relocated, and compacted unoxidized tailings in amounts greater than those leaching from the tailings in the present impoundment.

Oxidized Tailings

Table B-4 presents calculated reactivity values for untreated, oxidized tailings from the clay-capped equilibrium columns dismantled throughout the 10-month test period. During the filling and compacting operation, several samples of tailings were taken from the buckets and leached to determine reactivity levels at the beginning of the column storage period for comparison purposes with reactivity levels determined throughout the test period. Again, samples of dried tailings leached throughout the filling and compacting operation show higher reactivity levels for most elements than those determined during the drying tests. Only lead did not follow this pattern. This increase in reactivity levels in tailings preserved in an uncompacted condition again confirms the need to compact and cap the dried tailings in the new impoundment as soon as possible after completion of the drying operation.

Unlike the results from columns filled with unoxidized tailings, the reactivity of most elements in the compacted, sealed oxidized tailings did not decrease from tests performed during filling and compaction to the first column evaluation at 1 week. Arsenic reactivity did decrease over this period with the reactivity returning to the approximate levels found in the drying tests (table B-2). Data contained in table B-4 show that increases in reactivity occurred only with manganese and sulfate during the 10 months of column evaluation. Reactivity of iron actually decreased over this period of time. This may be explained by precipitation of iron as jarosite, which is an insoluble iron sulfate mineral forming at pH levels near 2. No further oxidation over time with increased leaching of contaminants from oxidized tailings was found in the phase 1 long-term equilibrium tests.

Effect of Capping the Tailings

Table B-5 shows comparative 1- and 6-month calculated reactivity values for unoxidized tailings with and without clay caps on the columns. Uncapped columns showed a definite increase in reactivity over capped columns for all elements except arsenic and lead, indicating that the cap was necessary to prevent oxidation and increased solubility of contaminants.

Table B-5 shows comparative 1- and 6-month calculated reactivity values for oxidized tailings with and without clay caps on the columns. All elements except lead showed definite reactivity increases in uncapped columns over capped columns, indicating that (1) the "oxidized" tailings were not completely oxidized while in the original tailings impoundment and (2) the cap was effective in preventing further oxidation.

Effect of Additives

Table B-6 shows comparative 3-month calculated reactivity values for unoxidized tailings with and without additives intended to modify bacterial activity or pH in the compacted tailings. USBM saw no clear advantages to adding sodium lauryl sulfate (SLS) as a sulfide-oxidizing bacteria inhibitor, sodium acetate (NaAc) as a sulfate-reducing bacteria nutrient, or lime as a pH modifier. Because minimal oxidation was evident in the untreated tailings, bacterial treatment or pH modification was not necessary. Although lime addition to unoxidized tailings did decrease reactivity levels, the USBM did not recommend lime addition because of the already low reactivity levels and the expense and physical problems involved with mixing.

Bacterial modifiers added to oxidized tailings increased the reactivity levels of manganese, zinc, and sulfate and decreased the reactivity level of lead. These modifiers were not recommended for mixing with oxidized tailings. Lime added to the oxidized tailings to modify the pH did decrease reactivity levels of cadmium, iron, manganese, lead, zinc, and sulfate. Without treatment, these tailings showed no increase in reactivity levels either during drying or during time in the columns; therefore, addition of lime was not recommended.

Effect of Higher Moisture Content and Mixed Tailings

Table B-7 presents calculated reactivity values from the column containing unoxidized tailings at a moisture content of 27 pct and from the column containing a mixture of oxidized and unoxidized tailings. Both of these columns were evaluated 6 months after compaction. Values from duplicate columns of unoxidized tailings at 21 pct moisture are shown in table B-7 for comparison. A higher moisture content may result from rainfall during the drying operation or from water infiltration into the impoundment. The data show lower reactivity levels for most metals with a higher moisture content, indicating no oxidation caused by the added moisture. However, the physical stability of the wetter tailings must also be considered because compaction to optimum density may be more difficult. Mixed-tailings reactivity values were between those of oxidized and unoxidized tailings, as should be expected.

Loss of Moisture During Time in Columns

The observed loss of moisture from the equilibrium columns may have affected the reactivity levels of the longer-term columns. Such an effect was noticed in the first drying series where reactivities of some elements increased after moisture contents had decreased below the 21-pct level. In the columns, moisture contents of the compacted tailings decreased from about 21 pct at the start of the equilibrium tests to about 12 pct after 10 months. The pH in the top portion of duplicate 10-month columns with unoxidized tailings decreased from about 6 to 3.4, and the color changed from dark gray to a dark gray-green. An increase in visible gypsum in these columns was also noted. The reactivity values presented in this report for the 10-month columns represent a "worst case" scenario and were the basis for the USBM recommendation that USBR not let the Olson-Neihart tailings dry significantly below the 21 pct level.

REFLOODING THE TAILINGS

Tests were conducted early in phase 1 work to determine the effect of reflooding the tailings prior to moving them. Flooding the tailings in place was considered as a possible means of preventing further oxidation. Bulk chemical analyses of tailing samples collected for the flooded column tests are shown in table 8.

Samples of oxidized and unoxidized tailings were placed in columns similar to the equilibrium columns and flooded with water from McHenry Creek, which flows around the Olson-Neihart tailings. The bottom halves of four 76-cm long columns were filled with unoxidized tailings and the top halves were filled with oxidized tailings to simulate conditions found in the field. Four other columns were filled completely with oxidized tailings. A standing head of water was maintained in each column. Columns of both layered and all-oxidized tailings evaluated 2 weeks, 6 weeks, and 14 months after filling showed no pH changes in the flooded tailings.

After the first several days in the layered columns, a noticeable separation occurred between the oxidized and the unoxidized tailings. Even though a standing head of water was maintained on the columns, these separations did not appear to fill with water, indicating that the percolation of water through the tailings may be very slow. Gases,

Table 8.—Bulk chemical analyses of oxidized and unoxidized ON tailings for flooded-column tests

Component	Oxidized tailings	Unoxidized tailings
Analysis, ppm:		
Ag . . .	28	23
As . . .	140	150
Cd . . .	0.13	0.3
Cu . . .	400	625
Analysis, pct:		
Fe . . .	12.2	14.1
Mn . . .	0.43	0.54
Pb . . .	0.41	0.22
Zn . . .	0.14	0.25

which may have been air, CO_2, or H_2S, collecting in the separations may be the cause for the chemical changes noticed near the interface.

Tables C-15, C-16 (appendix C) and B-8 (appendix B) show respective leach test parameters, leachate assays, and calculated reactivities of tailings in the two types of columns, including leach tests of tailings as received from the Olson-Neihart tailings. Calculated reactivities for oxidized tailings in all of the columns show no significant changes; unoxidized tailings in the layered columns show rather wide swings in calculated reactivities. Samples taken from the unoxidized tailings near the interfaces in the 14-month columns especially showed signs of increased oxidation with reactivities being two- or three-fold those of unoxidized tailings fresh from the impoundment. This indicates that unoxidized tailings in contact or close proximity to the oxidized tailings will become more amenable to metal dissolution in water over a period of time, especially if air has access to the interface area, which in turn, indicates that mixing of the tailings during relocation may not be desirable. This was not totally unexpected because the oxidized layer of tailings on the Olson-Neihart tailings was probably formed through this same type of mechanism occurring at the interface.

Very interesting changes occurred in two additional columns filled with oxidized tailings neutralized to pH 4 and 7 with lime. These tailings were initially brown in color, just like normal oxidized tailings; but over time, the tailings changed color to black and then developed silver patches throughout the columns. Figure 6 shows the progression of these color changes with the pH 7 column on the far right and the pH 4 column next to it. Samples of these blackened tailings were withdrawn from the pH 4 and pH 7 columns and examined for mineral composition and bacterial strains and activity. Results of a mineralogical evaluation after approximately 1 year of standing submerged show that tailings in the pH 7 column had a sulfide content of approximately 5 wt pct. Oxidized tailings in the pH 4 column and in another column that had not been pH-adjusted contained between 1 and 2 wt pct sulfide. Biological examination revealed the presence of *Desulfovibrio* bacteria in the pH 7 column; these bacteria are known to reduce sulfate to sulfide.

These columns were completely dismantled after 14 months. The pH value in the tailings initially adjusted to 4 has increased to 5.6 and the pH in the tailings initially adjusted to pH 7 has decreased to 6.4 indicating that some chemical changes did occur during the time in the column. Calculated reactivities for the tailings originally at pH 4 show that iron and manganese were not affected by a pH adjustment to 4; however, zinc reactivity decreased by two orders of magnitude. With a pH adjustment to 7, all three metal reactivities decreased significantly with iron and manganese values decreasing by 90 pct and the zinc value again decreasing by two orders of magnitude. Reflooding the tailings in place before the moving operation may cause some interesting chemical changes, but it does not appear to offer any great promise for increasing the metal stability unless the pH is radically adjusted.

SUMMARY AND CONCLUSIONS

The extremely fine-sized particle distribution found in samples of Olson-Neihart tailings confirms the mining reports, which indicated that only the slimes from the milling process were piped to the tailing impoundment. Soil pH values indicated an acid soil, which again was in agreement with the sulfide weathering process. Microbiological characterization revealed no unusual strains of bacteria; *Thiobacillus ferrooxidans* found in the tailings are common bacteria in tailing environments.

The predominant minerals found in the tailings were silicates and should not contribute appreciable dissolved contaminants to water because they dissolve very slowly at the reported field conditions. The sulfide minerals will oxidize and may result in trace amounts of dissolved metals and other elements in the water. Microbial action may enhance this oxidation process.

In phase 1, data were gathered to estimate (1) the minimum required time to dry the tailings to the optimum moisture content under various drying conditions, (2) any oxidation or reduction of the tailings that may occur during drying, (3) airborne dust that may result from the drying operations, (4) the likely equilibrium conditions of the tailings after deposition at the new location, and (5) the possible result of reflooding the tailings until the moving operation begins. Conclusions drawn from USBM testing on each of the pertinent points are presented below.

1. Results from the second series of USBM laboratory air-drying tests with 8 km/h air flow across the tailing surface and daily turning of the tailings show that less than 4 days were required to dry a 30.5-cm bed of unoxidized tailings from 40 pct moisture to 21 pct moisture but that oxidized tailings will require 9 days to achieve the same result. USBM laboratory tests were conducted indoors without the benefit of direct sunshine on the

tailings. Actual weather conditions (e.g. rain, high winds, clouds) at the drying site will affect drying of the tailings and may shorten or lengthen the required time.

2. The only change in reactivity found during the drying of either oxidized or unoxidized tailings was an increase in the reactivity of iron. No changes in reactivity were found for the other components of interest: arsenic, cadmium, manganese, lead, zinc, copper, or sulfate. Based on these results, the USBM concluded that no oxidation resulting in increased leaching of elements into ground or surface water contacting the tailings would occur during the drying of Olson-Neihart tailings to 21 pct moisture. Thus the chemical stability of the tailings as far as contamination of the environment would be equivalent to that in the original impoundment.
3. Drying to levels below 21 pct moisture increased the reactivity as evidenced in the first drying series. The USBM recommended that the tailings not be allowed to dry much below the 21-pct moisture content level before compaction into the new impoundment. No detrimental effect on reactivity levels was found by drying tailings to a higher moisture content (27 pct), such as might occur during a rain event.
4. No evidence of dust generation was found in either drying series until the tailings moisture contents had dropped far below the desired 21-pct level. If delays occur in the actual drying operation and tailings on the surface of the pads dry to 10 or 12 pct moisture, dust generation during tailings handling could be a problem. This indicates that careful monitoring and control of the surface moisture is required to prevent overdrying and dust generation.
5. Laboratory equilibrium columns were established with dried, compacted tailings and were dismantled and evaluated for oxidation changes over periods of time ranging from 1 week to 10 months. Moisture losses from the columns through the plastic (again believed to be some form of butadiene polymer) walls introduced an uncontrolled variable into these tests. The reactivity of oxidized tailings did not change over the 10-month equilibrium period except for iron reactivity, which actually decreased--possibly due to the formation of jarosite.
6. Unoxidized tailings did show increases in reactivity over the 10-month phase 1 equilibrium period for elements such as cadmium, iron, manganese, zinc, and sulfate. However, the increases for cadmium, iron, and sulfate did not raise reactivity levels above those found in tailings fresh from the Olson-Neihart tailings. Sufficient evidence of oxidation occurring during the test period was found to recommend that water contact with the relocated tailings be minimized. If such contact does occur, increased leaching of manganese, zinc, or sulfate could take place. No evidence was found that arsenic, iron, lead, or copper would leach into water percolating

through dried, relocated, and compacted tailings in amounts greater than those leaching from the tailings in the present impoundment.

7. Adding sodium lauryl sulfate as a sulfide-oxidizing bacteria inhibitor or sodium acetate as a sulfate-reducing bacteria nutrient had no significant effect on reactivity levels during the course of this test program. The USBM did not recommend biological additives of this nature.
8. Addition of lime did decrease the reactivity of oxidized tailings. However, lime addition was not recommended because (1) the reactivity levels did not increase without lime addition and (2) mixing of lime into the tailings during drying poses material-handling problems.
9. Reflooding the tailings in place before the drying and moving operations begin was shown to not affect oxidation levels within the tailings unless the pH of the tailings was adjusted. Laboratory tests with reflooded tailings showed no decrease in reactivity unless the pH was adjusted to 4 or higher. There was no apparent advantage in reflooding tailings prior to moving.
10. Mixing of oxidized and unoxidized tailings should be minimized to prevent increased oxidation of the unoxidized tailings.

Figure 1

Collecting samples of Olson-Neihart tailings for first drying series in phase 1 program.

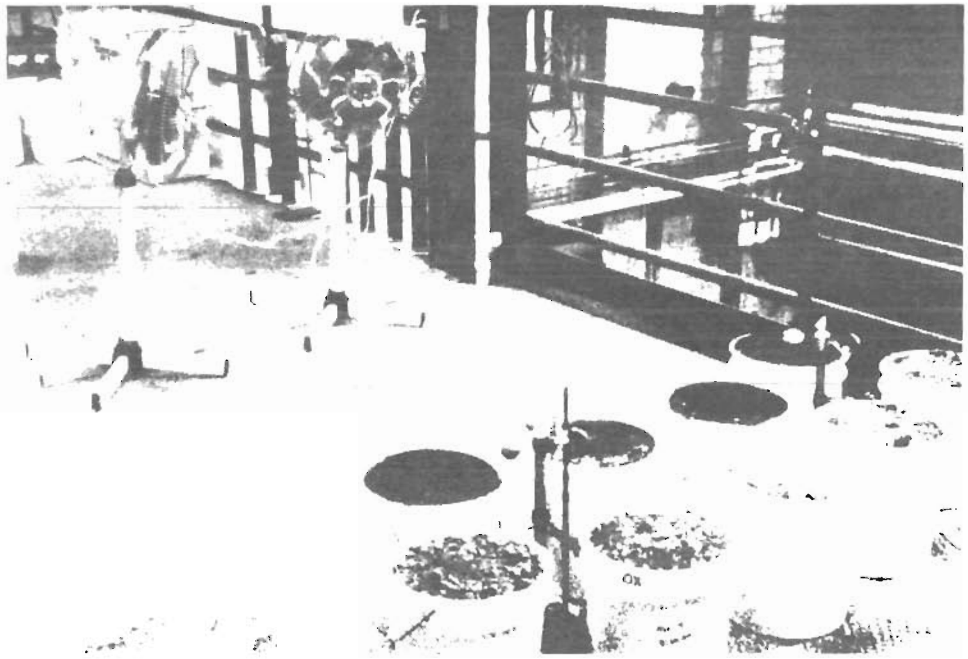
Figure 2

Laboratory plan placement for first drying series in phase 1 program. Pans with air flow across the surface are in the background.

Figure 3

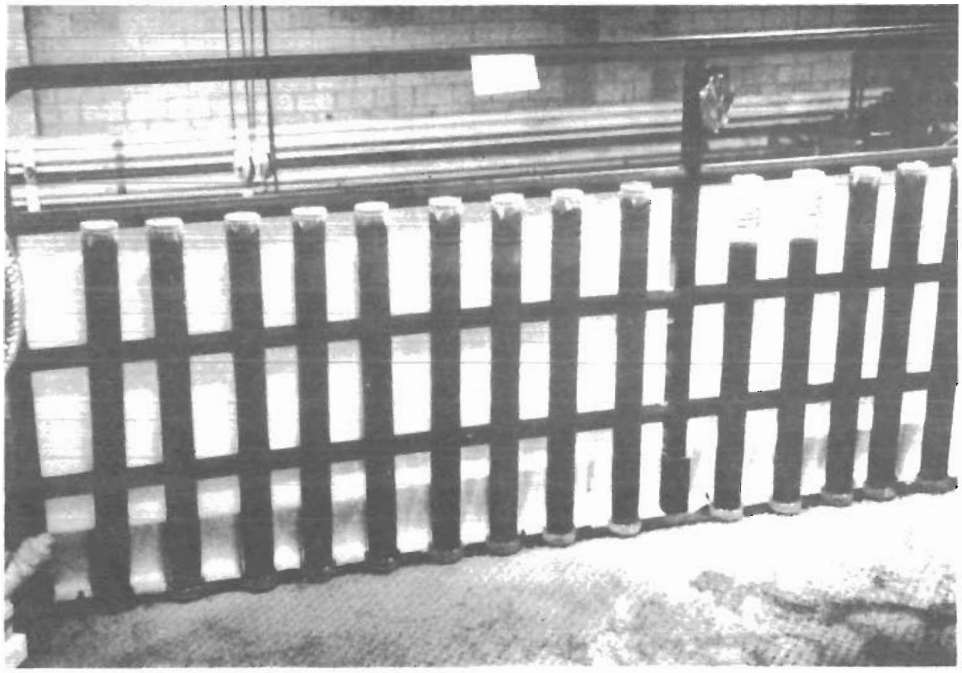
Collecting samples of Olson-Neihart tailings for second drying series in phase 1 program.

Figure 4



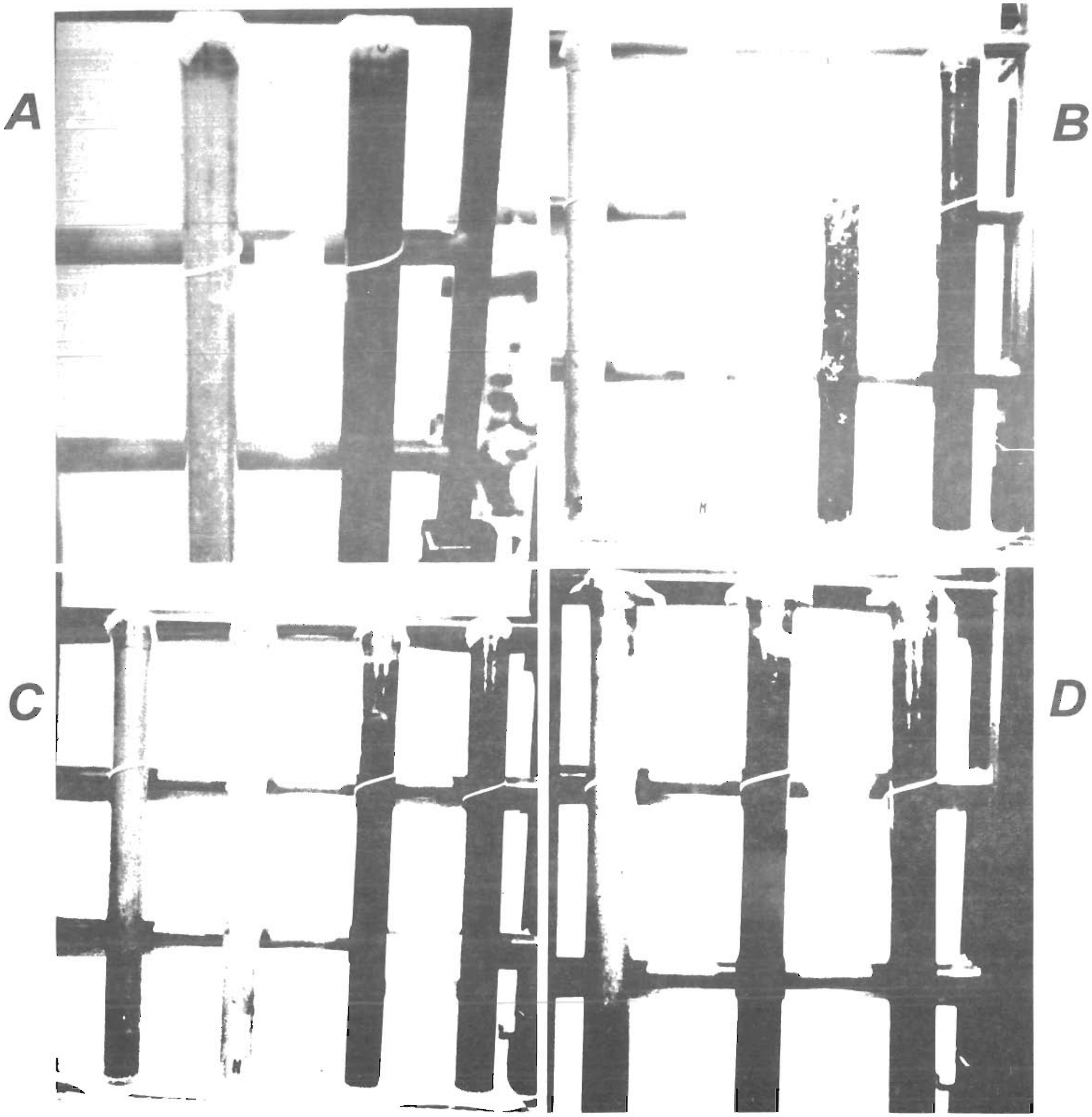
Laboratory pan placement for second drying series in phase 1 program. Pans with unoxidized tailings are nearest the fans.

Figure 5



Arrangement of phase 1 long-term equilibrium columns. Two columns without clay caps are located towards the right end of the array.

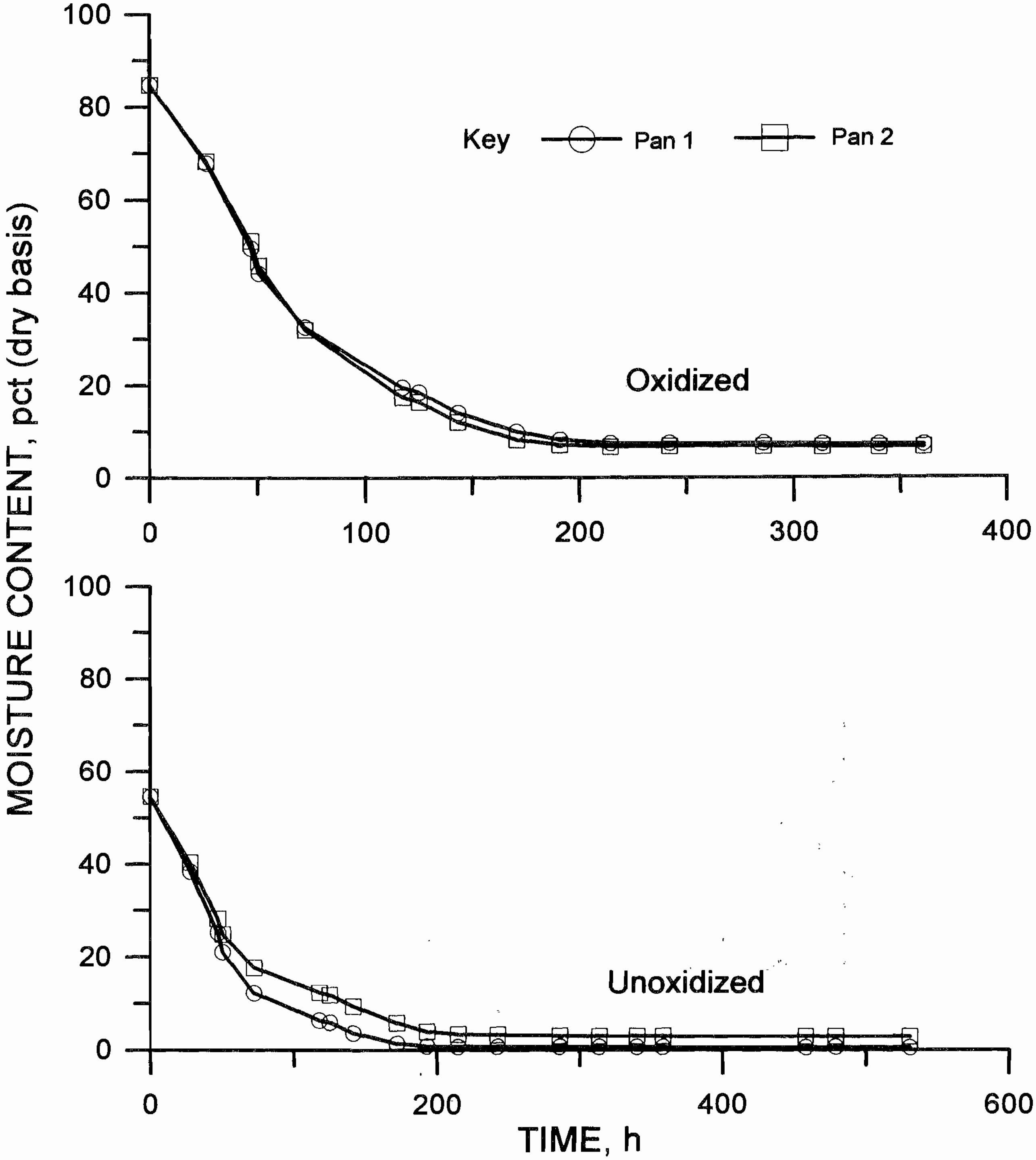
Figure 6



Flooded columns of oxidized Olson-Neihart tailings showing color change of pH-adjusted tailings over time. Tailings in far right column were adjusted to pH 7; tailings in the next column were adjusted to pH 4; tailings in the two columns to the left were not pH-adjusted. (A) 3 months after filling; (B) 5 months after filling; (C) 6 months after filling; and (D) 11 months after filling.

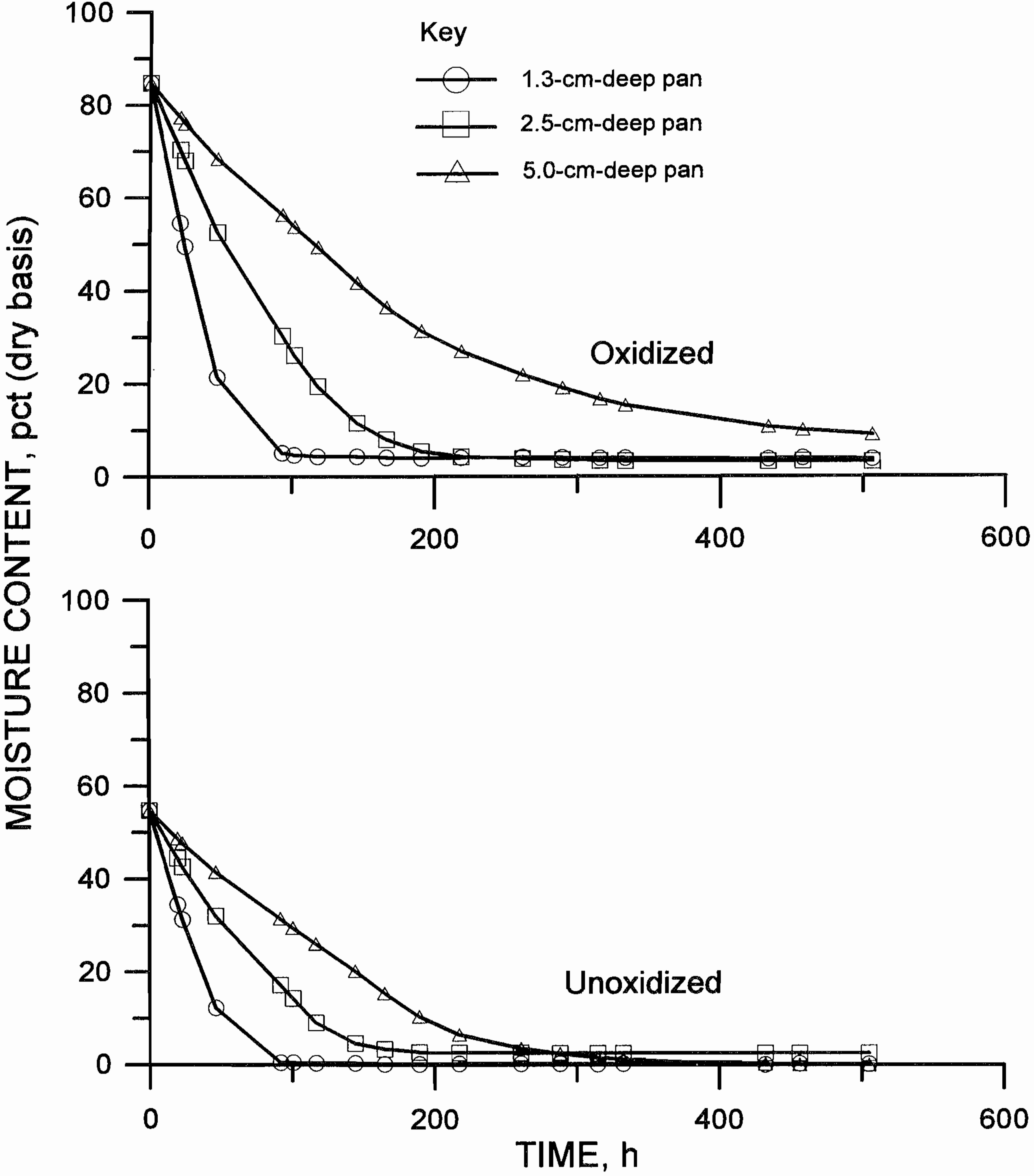
APPENDIX A.—DRYING CURVES FOR DRYING TEST SERIES

Figure A-1



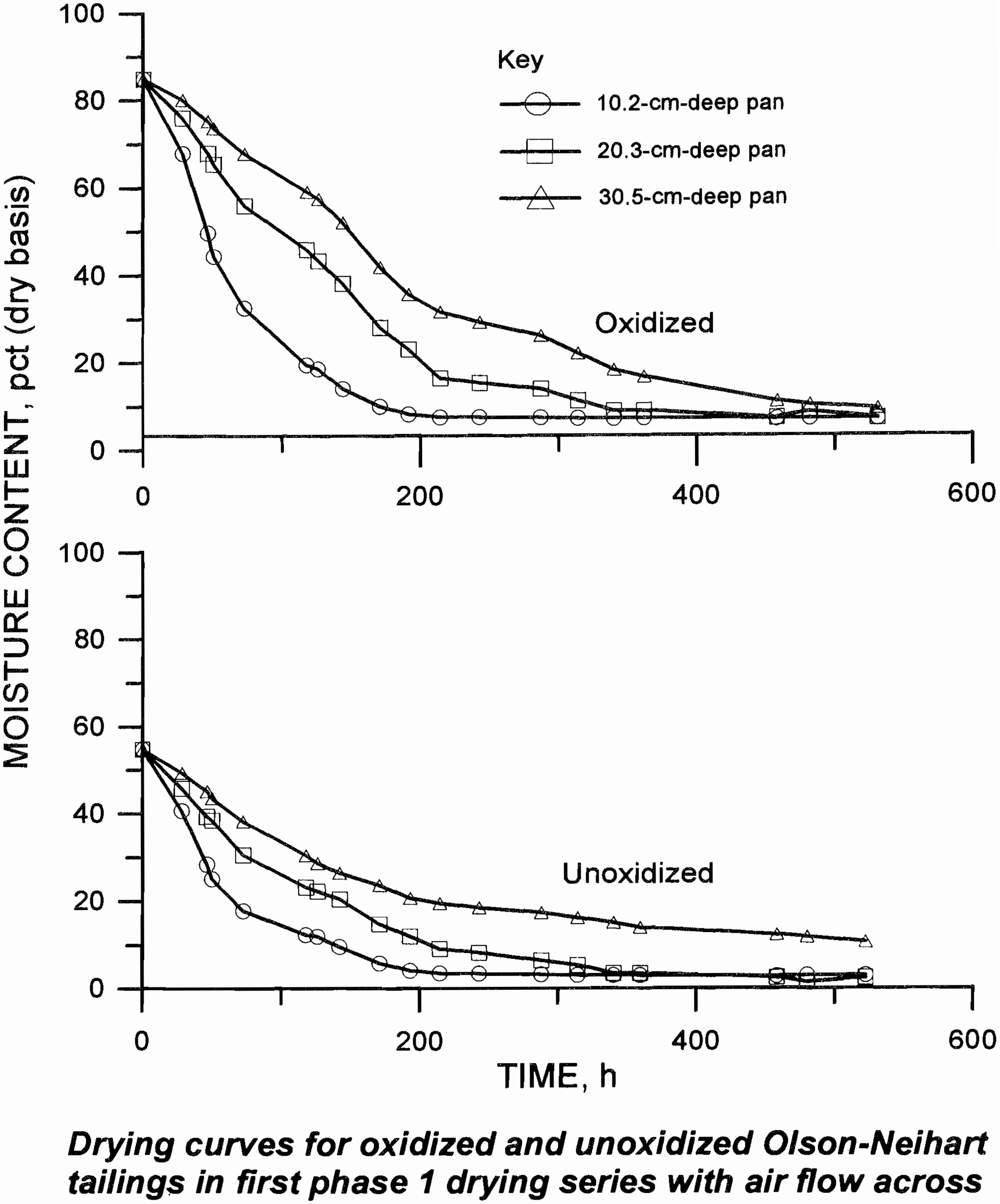
Good reproducibility of drying data from first phase 1 drying series with oxidized and unoxidized Olson-Neihart tailings. Duplicate pans were 10.2 cm deep with air flow across the surface and with daily turning of tailings.

Figure A-2



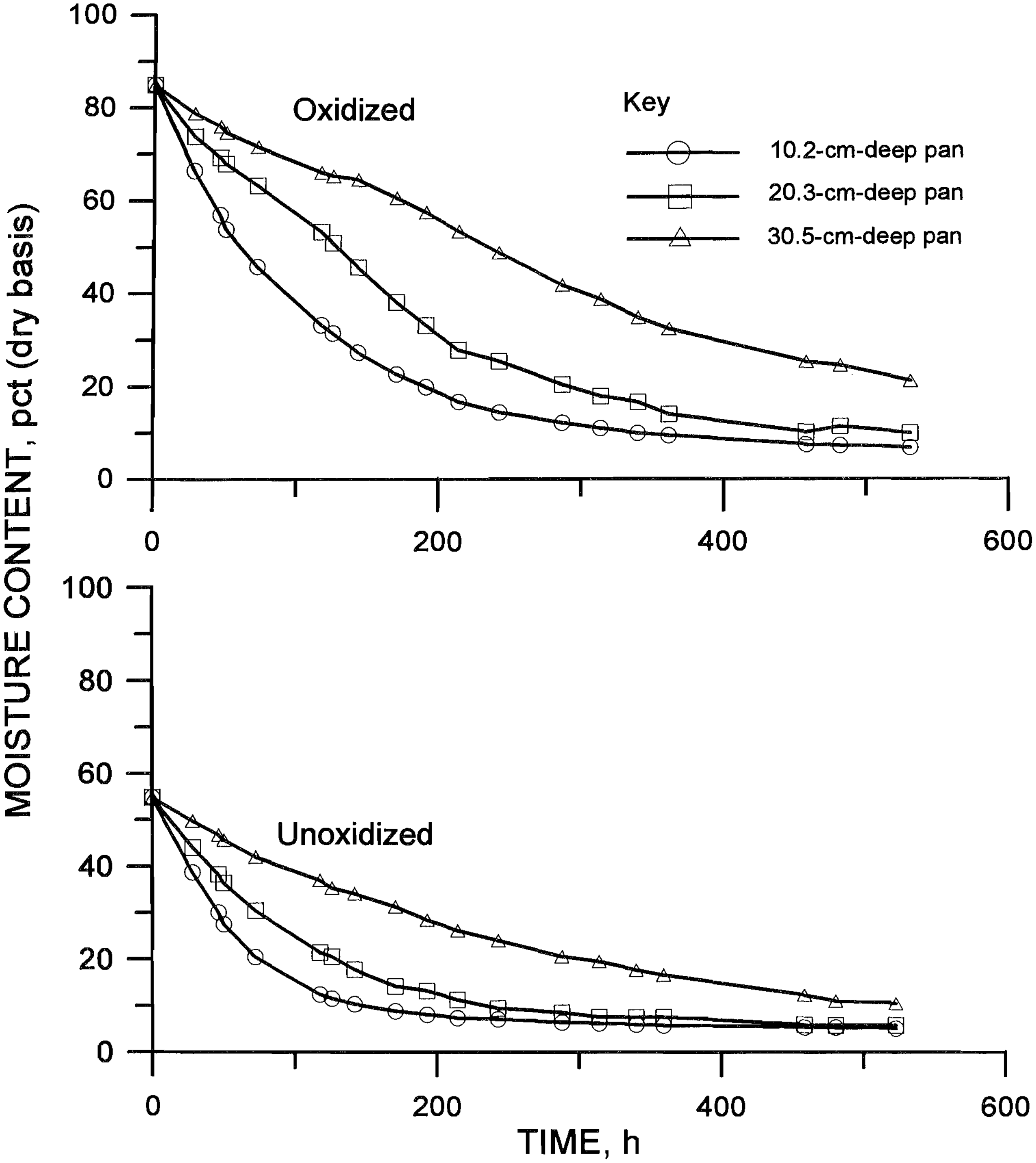
Drying curves from shallow pans in first phase 1 drying series with oxidized and unoxidized Olson-Neihart tailings. There was no air flow across these pans

Figure A-3



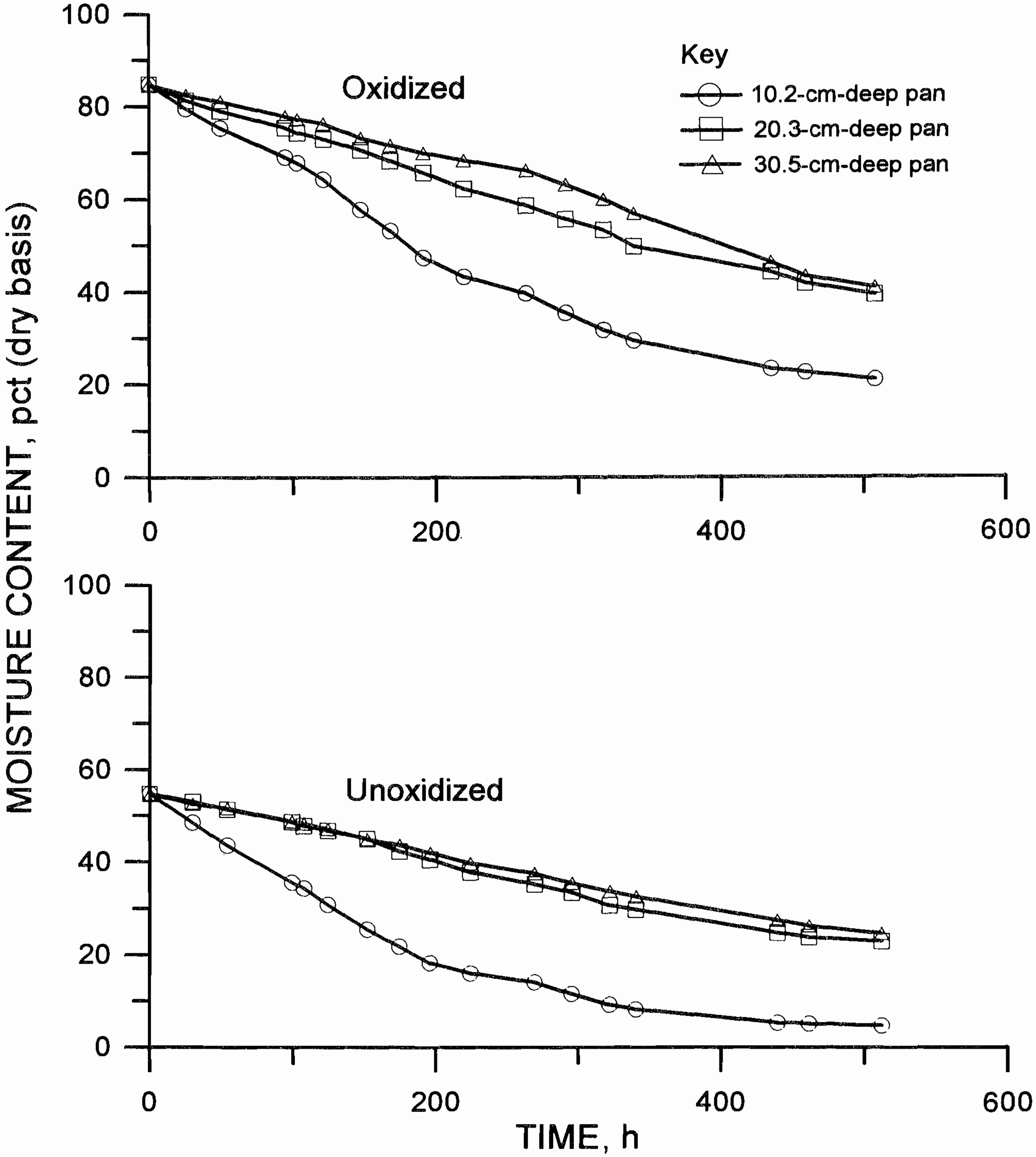
Drying curves for oxidized and unoxidized Olson-Neihart tailings in first phase 1 drying series with air flow across surface and with daily turning of tailings.

Figure A-4



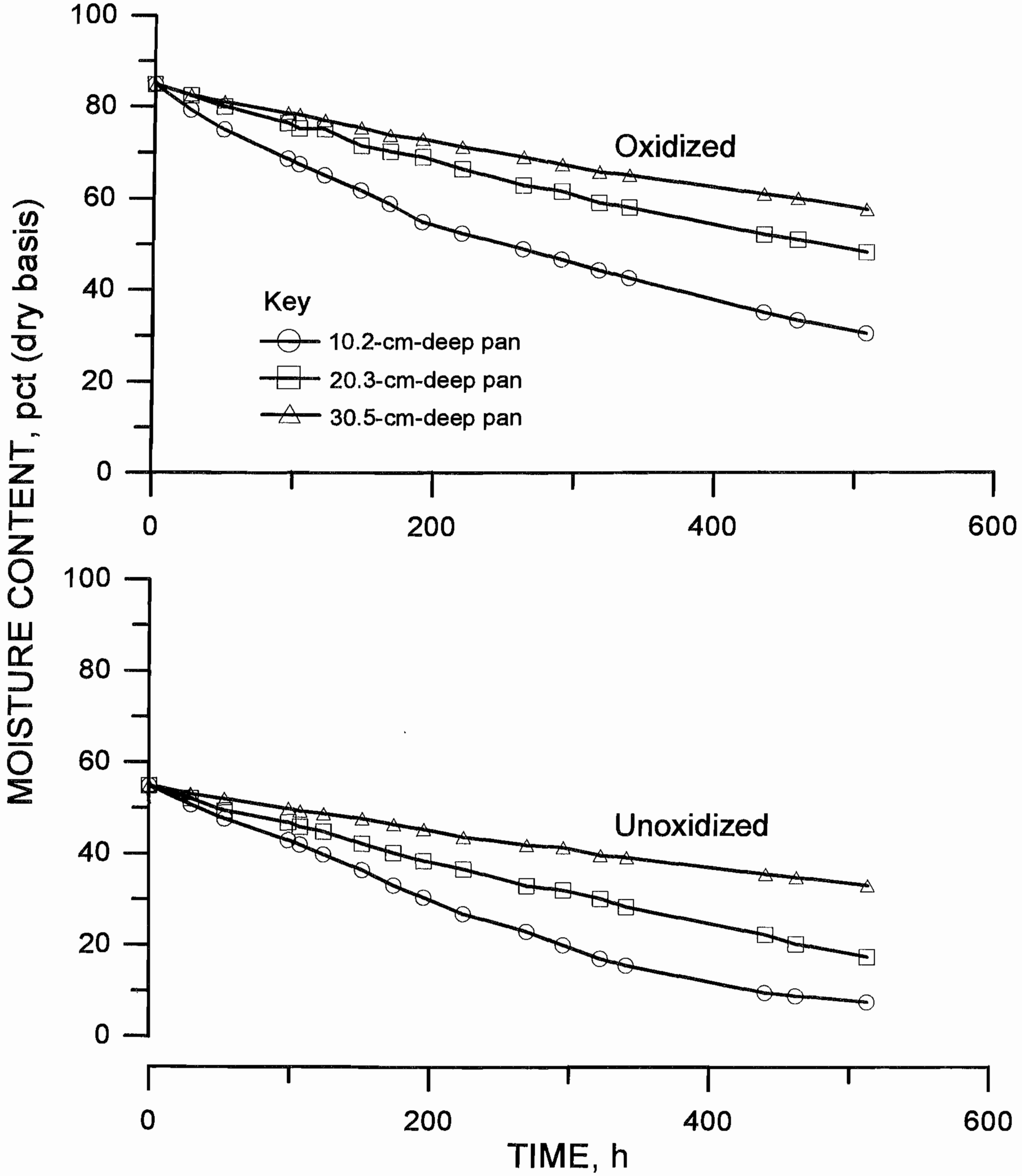
Drying curves for oxidized and unoxidized Olson-Neihart tailings in first phase 1 drying series with air flow across surface but without daily turning of tailings.

Figure A-5



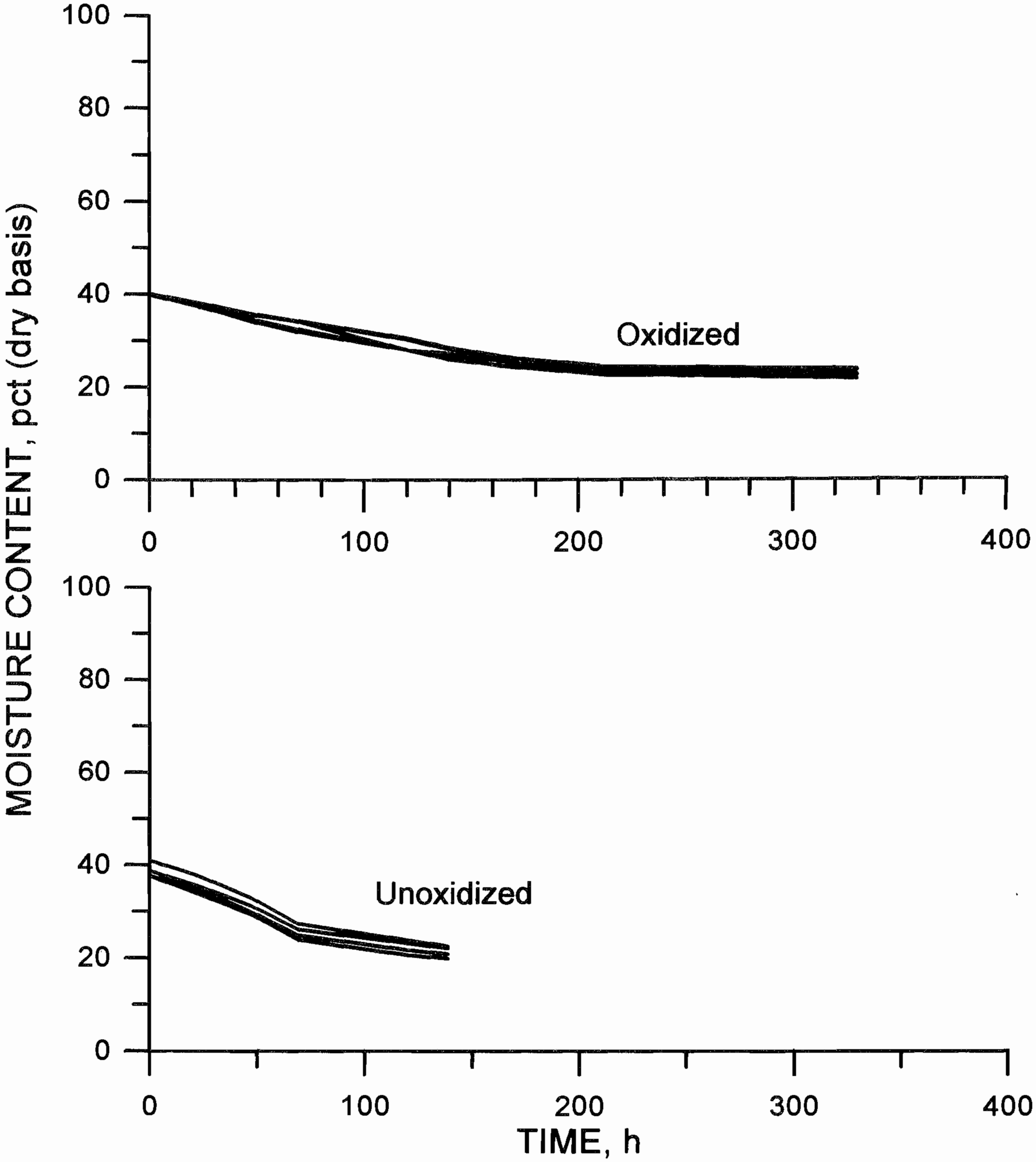
Drying curves for oxidized and unoxidized Olson-Neihart tailings in first phase 1 drying series without air flow across surface but with daily turning of tailings.

Figure A-6



Drying curves for oxidized and unoxidized Olson-Neihart tailings in first phase 1 drying series without air flow across surface and without daily turning of tailings.

Figure A-7



Drying curves for oxidized and unoxidized Olson-Neihart tailings in second phase 1 drying series. Tailings were dried in five 30.5-cm-deep pans with air flow across surface and with daily turning of tailings.

APPENDIX B.—CALCULATED REACTIVITY VALUES FOR OXIDATION EVALUATION TESTS

Table B-1.—Calculated reactivity in duplicate pans of oxidized and unoxidized tailings in first series of phase 1 drying tests, milligrams leached per kilogram of dry solid

Time in drying pan, h	As	Cd	Cu	Fe	Mn	Pb	Zn	SO_4
OXIDIZED TAILINGS								
Pan 1:								
26	<0.02	3	33	1,524	275	8	257	14,370
72	<0.02	3	26	1,117	250	4	227	9,940
125	<0.02	2	23	591	182	3	161	7,250
190	0.02	3	25	660	222	3	197	7,880
530	<0.02	3	36	601	269	2	235	8,980
Pan 2:								
26	<0.02	3	36	598	256	9	229	16,000
72	0.02	2	16	1,047	186	2	157	8,800
125	0.03	2	21	580	195	3	170	7,850
190	0.02	2	14	393	139	3	126	5,720
530	<0.02	2	27	382	195	2	163	7,090
UNOXIDIZED TAILINGS								
Pan 1:								
28	<0.01	<0.02	<1	24	24	0.1	3	5,015
72	<0.01	<0.02	<1	5	11	0.2	2	3,142
125	<0.01	0.03	<1	4	11	0.4	2	3,091
172	<0.01	0.01	<1	5	6	0.4	2	2,536
479	<0.01	0.04	<1	4	20	0.4	2	3,036
Pan 2:								
28	<0.01	<0.02	<1	27	34	0.2	5	5,370
72	<0.01	<0.02	<1	3	24	0.7	2	4,176
125	<0.01	0.06	<1	3	24	0.6	2	3,430
172	<0.01	0.06	<1	5	30	0.6	2	3,552
479	<0.01	0.10	<1	8	52	1.1	3	3,382

Table B-2.—Calculated reactivity of oxidized and unoxidized tailings in second series of phase 1 drying tests with untreated tailings, milligrams leached per kilogram of dry solids

Time in drying pan, h	As	Cd	Cu	Fe	Mn	Pb	Zn	SO_4
OXIDIZED TAILINGS								
0	<0.02	0.2	10	200	60	1.0	20	7,200
0[1]	<0.02	0.2	10	200	60	1.0	20	7,200
24	0.02	0.3	10	600	90	0.3	40	9,100
69	<0.02	0.2	10	400	50	0.2	20	7,800
120	0.02	0.3	10	700	60	0.4	30	8,600
163	0.02	0.3	10	900	70	0.2	30	9,000
215	0.05	0.3	10	1,000	70	0.1	40	10,100
UNOXIDIZED TAILINGS								
0	ND	6	10.6	740	200	6	200	6,900
0[1]	<0.02	6	10.6	930	200	6	200	6,900
23	<0.02	1	0.1	590	300	4	100	5,700
70	<0.02	1	0.5	540	300	4	100	6,500
119	<0.02	0.3	ND	160	500	4	200	5,100

ND Not determined.

[1] Duplicate assay

Table B-3.—Calculated reactivity of unoxidized tailings in phase 1 clay-capped equilibrium columns with untreated tailings, milligrams leached per kilogram of dry solids

Time in equilibrium column	As	Cd	Cu	Fe	Mn	Pb	Zn	SO_4
0 (leach 1)	<0.02	8	8.2	50	2,000	4	1,300	9,400
0 (leach 2)	<0.02	8	9.2	20	2,000	4	1,300	9,200
0 (leach 3)	<0.02	8	10.7	10	2,000	4	1,300	9,700
0 (leach 4)	<0.02	8	8.7	20	2,100	4	1,400	9,700
1 week	<0.02	3	0.1	<1	700	4	100	4,100
1 week[1]	<0.02	3	0.1	<1	700	4	100	4,200
2 weeks	<0.02	3	0.1	<1	800	4	200	4,400
2 weeks[1]	<0.02	3	0.1	<1	700	4	200	4,900
1 month	0.1	3	0.1	<1	900	4	200	5,100
1 month[2]	<0.02	4	0.3	4	900	4	300	5,500
1 month[1,2]	<0.02	4	0.3	4	900	4	300	5,300
2 months	<0.02	6	<2	1	2,100	4	700	1,200
2 months[1]	<0.02	6	<2	2	2,100	5	700	8,500
3 months	<0.02	4	0.2	2	1,400	3	500	6,000
6 months	<0.02	6	0.2	1	1,400	4	500	6,900
6 months[1]	<0.02	6	0.2	1	1,400	4	500	7,000
10 months	<0.02	14	60	121	3,100	4	2,200	23,200
10 months[1]	<0.02	14	60	119	3,100	4	2,100	27,200
10 months[2]	<0.02	14	64	167	3,000	4	2,300	3,900

[1] Duplicate assay.

[2] Duplicate column.

Table B-4.—Calculated reactivity of oxidized tailings in phase 1 clay-capped equilibrium columns with untreated tailings, milligrams leached per kilogram of dry solids

Time in equilibrium column	As	Cd	Cu	Fe	Mn	Pb	Zn	SO_4
0 (leach 1)	0.18	0.4	20	2,700	160	0.05	60	14,100
0 (leach 2)	0.24	0.4	20	3,400	170	0.04	60	17,200
0 (leach 3)	0.20	0.4	20	3,300	180	0.02	60	18,400
0 (leach 4)	0.24	0.4	20	3,300	200	0.03	90	20,200
0 (leach 4)[1]	0.24	0.4	20	3,300	190	0.03	90	19,800
1 week	0.08	0.4	20	2,600	180	0.02	60	15,200
2 weeks	0.04	0.4	20	2,800	180	0.01	60	14,800
1 month	0.05	0.4	20	2,000	190	0.01	60	17,300
1 month[1]	0.06	0.4	10	2,000	190	0.01	50	18,200
1 month[2]	0.11	0.4	20	1,900	190	0.01	50	16,800
1 month[1,2]	0.05	0.4	20	1,900	190	0.01	60	16,800
2 months	0.01	0.4	10	2,000	240	0.08	60	14,300
3 months	<0.01	0.4	10	1,500	240	0.37	50	10,900
6 months	<0.01	0.4	10	700	280	0.01	60	11,800
6 months[1]	0.02	0.4	10	700	280	0.01	60	12,000
10 months	<0.01	0.4	10	500	340	0.09	60	23,900
10 months[1]	<0.01	0.4	10	500	340	0.10	60	24,700
10 months[2]	<0.01	0.4	10	700	350	0.03	60	26,500

[1] Duplicate assay.

[2] Duplicate column.

Table B-5.—Calculated reactivity of oxidized and unoxidized tailings in phase 1 clay-capped and uncapped equilibrium columns with untreated tailings showing the effects of capping, milligrams leached per kilogram of dry solid

Time in equilibrium column	As	Cd	Cu	Fe	Mn	Pb	Zn	SO_4
OXIDIZED TAILINGS								
Capped columns:								
1 month	0.05	0.4	20	2,000	190	0.01	60	17,300
1 month[1]	0.06	0.4	10	2,000	190	0.01	50	18,200
1 month[2]	0.11	0.4	20	1,900	190	0.01	50	16,800
1 month[1,2]	0.05	0.4	20	1,900	190	0.01	60	16,800
6 months	<0.01	0.3	10	500	180	<0.01	40	7,600
6 months[1]	0.01	0.3	10	500	180	<0.01	40	7,700
Uncapped column:								
1 month	0.32	0.6	20	5,000	340	0.02	80	31,100
UNOXIDIZED TAILINGS								
Capped columns:								
1 month	0.1	3	0.1	<1	900	4	200	5,100
1 month[2]	<0.02	4	0.3	4	900	4	300	5,500
1 month[1,2]	<0.02	4	0.3	4	900	4	300	5,300
6 months	<0.02	6	0.2	1	1,400	4	500	6,900
6 months[1]	<0.02	6	0.2	1	1,400	4	500	7,000
Uncapped columns:								
1 month	<0.02	6	0.7	3	1,700	4	800	8,000
1 month[1]	<0.02	6	0.7	3	1,700	4	800	7,900
6 months	<0.02	13	16.6	21	3,000	4	1,800	14,800

[1] Duplicate assay.

[2] Duplicate column.

Table B-6.—Calculated reactivity of oxidized and unoxidized tailings in 3-month, clay-capped phase 1 equilibrium columns showing effects of adding bacteria and/or pH modifiers, milligrams leached per kilogram of dry solid

Treatment	As	Cd	Cu	Fe	Mn	Pb	Zn	SO_4
OXIDIZED TAILINGS								
Untreated	<0.01	0.3	<10	1,000	160	0.24	30	7,100
SLS[1]	<0.01	0.3	10	1,700	300	0.04	60	13,900
NaAc[2]	<0.01	0.4	10	1,200	310	0.01	50	16,000
Lime[3]	<0.01	0.3	<10	10	160	0.01	30	4,000
NaAc[2] + lime[3]	<0.01	<0.1	<10	<1	40	0.04	<10	3,600
UNOXIDIZED TAILINGS								
Untreated	<0.02	4	0.2	2	1,400	3	500	6,000
SLS[1]	<0.02	2	0.04	1	700	3	100	4,600
NaAc[2]	<0.02	2	0.05	0.4	700	3	100	4,300
Lime[3]	0.05	<1	0.04	<0.2	600	2	40	4,000

[1] Sodium lauryl sulfate added as sulfide-oxidizing bacteria inhibitor.
[2] Sodium acetate added as sulfate-reducing bacteria nutrient.
[3] Lime {$Ca(OH)_2$} added as pH modifier.

Table B-7.—Calculated reactivity of tailings in 6-month phase 1 clay-capped equilibrium columns with high-moisture (25-30 pct) unoxidized tailings and with a mixture of oxidized and unoxidized tailings, milligrams leached per kilogram of dry solid

	As	Cd	Cu	Fe	Mn	Pb	Zn	SO_4
Unoxidized tailings:								
21 pct moisture	<0.02	6	0.2	1	1,400	4	500	6,900
21 pct moisture[1]	<0.02	6	0.2	1	1,400	4	500	7,000
25-30 pct moisture	<0.02	2	0.1	4	900	4	100	4,800
Mixed oxidized/unoxidized tailings:								
21 pct moisture	<0.02	1	0.1	1,291	1,200	3	400	7,700

[1] Duplicate assay.

Table B-8.—Calculated reactivity of tailings in reflooded columns, milligrams leached per kilogram of dry solid

Time in flooded column	As	Cd	Cu	Fe	Mn	Pb	Zn	SO_4
TAILINGS BEFORE FILLING COLUMNS								
None:								
Oxidized	0.09	4.9	167	5,096	1,000	4.9	811	31,304
Oxidized[1]	0.10	4.9	169	5,023	988	4.6	784	31,547
Unoxidized	0.03	<0.03	6	859	344	<0.8	16	8,700
LAYERED COLUMNS								
2 weeks:								
Oxidized	0.05	5.1	165	5,282	1,014	3.4	718	41,600
Unoxidized	<0.02	<0.02	<0.5	61	154	0.4	2	7,700
6 weeks:								
Oxidized	0.04	5.3	161	5,578	1,231	1.5	790	46,200
Unoxidized	<0.02	<0.02	<0.5	7	59	0.1	1	6,100
14 months:								
Oxidized	0.03	2.4	21	2,465	806	5.2	400	32,153
Oxidized[2]	<0.02	2.8	5	5,604	1,350	6.2	518	49,418
Unoxidized	<0.02	0.02	<0.5	703	258	<0.1	2	8,149
Unoxidized[2]	<0.02	0.07	<0.5	1,579	411	0.1	4	660
14 months[3]:								
Oxidized	0.05	2.19	16	2,735	836	4.1	382	32,573
Oxidized[2]	0.07	1.04	1	5,594	1,160	7.1	357	50,680
Unoxidized	0.04	0.02	<0.5	2	1	<0.1	<1.5	5,208
Unoxidized[2]	<0.02	0.07	<0.5	2,582	545	0.2	25	28,551
COLUMNS WITH ALL-OXIDIZED TAILINGS								
2 weeks	0.09	5.1	171	5,018	1,031	0.7	784	50,400
6 weeks	0.06	5.2	148	4,860	1,128	3.0	746	46,700
14 months	<0.02	5.0	40	4,611	1,598	4.3	816	49,952
14 months[3]	<0.02	6.1	42	6,066	1,912	4.5	996	53,594
COLUMNS WITH OXIDIZED TAILINGS AT MODIFIED pH LEVELS								
14 months (initial pH = 4)	<0.02	0.07	0.2	6,300	1,174	0.8	3	46,982
14 months (initial pH = 7)	<0.02	0.03	0.1	578	224	0.1	<1.5	10,396

[1] Duplicate assay.

[2] Near interface.

[3] Duplicate column.

APPENDIX C.—LEACH TEST PARAMETERS AND LEACHATE ASSAYS FROM DRYING PANS AND EQUILIBRIUM COLUMNS

Table C-1.—Leach parameters from duplicate pans of oxidized and unoxidized tailings in first series of phase 1 drying tests

Time in drying pan, h	Sample wt, g	Sample moisture content, pct	Leachate vol, mL	Leachate pH
OXIDIZED TAILINGS				
Pan 1:				
26	66	67.9	178	2.8
72	94	32.6	135	3.0
125	102	18.6	141	2.6
190	100	8.3	127	2.7
530	100	4.6	135	2.8
Pan 2:				
26	58	68.4	184	2.9
72	88	32.0	140	2.8
125	102	16.5	138	2.7
190	100	7.1	137	2.9
530	100	3.9	135	2.7
UNOXIDIZED TAILINGS				
Pan 1:				
28	95	38.5	153	6.7
72	102	12.3	146	7.3
125	100	6.0	128	7.7
172	100	1.5	138	7.9
479	101	0.6	130	ND
Pan 2:				
28	84	40.5	160	6.6
72	104	17.8	153	7.1
125	98	11.9	125	7.6
172	100	5.9	116	7.5
479	100	2.9	121	ND

ND Not determined.

Table C-2.—Leachate assays from duplicate pans of oxidized and unoxidized tailings in first series of phase 1 drying tests

Time in drying pan, h	As, ppm	Cd, ppm	Cu, ppm	Fe, ppm	Mn, ppm	Pb, ppm	Zn, ppm	SO_4, g/L
OXIDIZED TAILINGS								
Pan 1:								
26	<0.01	0.08	8.2	384	69	2.1	65	3.6
72	0.01	2.0	15.2	674	151	2.3	137	6.0
125	0.01	1.5	16.4	430	132	2.2	117	5.3
190	0.02	2.2	21.2	564	190	2.4	168	6.7
530	<0.01	3.0	32.7	553	248	1.9	216	8.2
Pan 2:								
26	<0.01	0.6	7.5	332	53	1.8	48	3.3
72	0.01	1.1	9.9	637	113	1.5	96	5.4
125	0.02	1.6	15.9	434	146	2.4	127	5.9
190	0.02	1.8	12.4	345	122	2.4	111	5.0
530	0.01	1.9	24.6	353	180	1.9	151	6.6
UNOXIDIZED TAILINGS								
Pan 1:								
28	<0.01	<0.01	<0.05	13.1	13.1	0.08	1.7	2.7
72	<0.01	<0.01	<0.05	4.0	8.6	0.19	1.7	2.5
125	<0.01	0.03	<0.05	3.4	9.8	0.33	1.5	2.8
172	<0.01	0.01	<0.05	4.8	6.2	0.42	1.5	2.5
479	<0.01	0.04	<0.05	3.5	20.0	0.37	2.0	3.0
Pan 2:								
28	<0.01	<0.01	<0.05	12.0	15.0	0.09	2.2	2.4
72	<0.01	0.02	<0.05	2.2	17.9	0.48	1.5	3.1
125	<0.01	0.05	<0.05	2.7	19.5	0.51	1.6	2.8
172	<0.01	0.05	<0.05	4.9	27.2	0.53	1.8	3.2
479	<0.01	0.1	<0.05	7.5	49.3	1.0	3.3	3.2

Table C-3.—Leach parameters from oxidized and unoxidized tailings in second series of phase 1 drying tests

Time in drying pan, h	Sample wt, g	Sample moisture content, pct	Leachate vol, mL	Leachate pH
OXIDIZED TAILINGS				
0	201	42.0	276	2.3
24	100	37.3	109	2.0
69	100	34.2	140	2.2
120	100	27.9	136	2.1
163	100	25.6	117	2.0
215	100	22.7	122	2.1
UNOXIDIZED TAILINGS				
0	209	37.0	283	5.0
23	100	35.5	109	5.5
70	100	26.1	143	5.4
119	100	23.2	132	5.1

Table C-4.—Leachate assays from oxidized and unoxidized tailings in second series of phase 1 drying tests

Time in drying pan, h	As, ppm	Cd, ppm	Cu, ppm	Fe, ppm	Mn, ppm	Pb, ppm	Zn, ppm	SO_4, g/L
OXIDIZED TAILINGS								
0	<0.01	0.1	4.4	100	30	0.5	12	3.7
0[1]	<0.01	0.1	4.3	100	29	0.5	12	3.7
24	0.01	0.2	8.8	400	59	0.2	26	6.1
69	<0.01	0.1	4.1	200	27	0.1	13	4.1
120	0.01	0.2	5.9	400	37	0.02	18	5.0
163	0.02	0.2	7.6	600	48	0.1	23	6.2
215	0.04	0.2	8.0	700	47	0.1	24	6.8
UNOXIDIZED TAILINGS								
0	ND	3.1	5.7	400	121	3.2	84	3.7
0[1]	<0.01	3.2	5.7	500	121	3.2	83	3.7
23	<0.01	0.7	0.1	400	223	2.5	59	3.9
70	<0.01	0.6	0.3	300	184	2.1	55	3.6
119	<0.01	2.0	ND	100	300	2.7	94	3.1

[1] Duplicate assay.

Table C-5.—Leach parameters from unoxidized tailings in phase 1 clay-capped equilibrium columns with untreated tailings

Time in equilibrium column	Sample wt, g	Sample moisture content, pct	Leachate vol, mL	Leachate pH
0 (leach 1)	100	20.5	110	ND
0 (leach 2)	100	20.5	110	ND
0 (leach 3)	100	20.5	117	ND
0 (leach 4)	100	20.5	114	ND
1 week	150	19.2	180	5.7
2 weeks	150	19.3	188	5.6
1 month	150	18.9	183	5.5
1 month[1]	150	19.2	182	5.4
2 months	250	17.8	291	5.2
3 months	600	17.3	747	5.3
6 months	825	15.3	976	5.4
10 months	800	12.5	907	3.5
10 months[1]	400	13.8	466	3.3

ND Not determined.

[1] Duplicate column.

Table C-6.—Leachate assays from unoxidized tailings in phase 1 clay-capped equilibrium columns with untreated tailings

Time in equilibrium column	As, ppm	Cd, ppm	Cu, ppm	Fe, ppm	Mn, ppm	Pb, ppm	Zn, ppm	SO_4, g/L
0 (leach 1)	<0.01	5.8	6.2	37	1,490	3.0	980	7.1
0 (leach 2)	<0.01	6.0	7.0	14	1,490	3.0	981	7.0
0 (leach 3)	<0.01	5.8	7.6	4	1,450	3.0	952	6.9
0 (leach 4)	<0.01	5.7	6.3	16	1,510	3.0	989	7.0
1 week	<0.01	1.9	0.1	0.6	482	3.0	92	2.9
1 week[1]	<0.01	1.9	0.1	<0.55	485	3.0	92	3.0
2 weeks	<0.01	2.0	0.1	<0.55	518	3.0	131	2.9
2 weeks[1]	<0.01	2.0	0.1	<0.55	501	3.0	128	3.3
1 month	0.05	2.2	0.1	<0.55	603	3.0	153	3.5
1 month[2]	<0.01	2.5	0.2	2.5	622	2.8	207	3.8
1 month[1,2]	<0.01	2.5	0.2	2.5	609	2.9	206	3.7
2 months	<0.01	4.5	1	0.9	1,540	2.6	523	0.9
2 months[1]	<0.01	4.5	<1	1.1	1,520	3.3	516	6.2
3 months	<0.01	3.0	0.2	1.1	966	6.5	314	4.1
6 months	<0.01	4.6	0.2	0.6	1,050	3.0	335	5.1
6 months[1]	<0.01	4.6	0.2	0.5	1,040	2.9	333	5.2
10 months	0.01	10.8	47.4	95	2,450	3.3	1,690	18.2
10 months[1]	<0.01	10.8	47.5	93	2,410	3.3	1,660	21.3
10 months[2]	<0.01	10.7	48.3	126	2,240	3.1	1,700	2.9

[1] Duplicate assay.

[2] Duplicate column.

Table C-7.—Leach parameters from oxidized tailings in phase 1 clay-capped equilibrium columns with untreated tailings

Time in equilibrium column	Sample wt, g	Sample moisture content, pct	Leachate vol, mL	Leachate pH
0 (leach 1)	100	21.6	122	ND
0 (leach 2)	150	22.0	184	2.0
0 (leach 3)	150	21.6	183	1.9
0 (leach 4)	150	25.7	186	2.1
1 week	150	20.1	188	2.0
2 weeks	150	20.2	190	2.0
1 month	200	18.8	237	2.2
1 month[1]	200	17.7	235	2.1
2 months	250	17.7	272	2.1
3 months	501	15.8	611	2.3
6 months	800	13.8	945	2.3
10 months	800	12.5	912	2.3
10 months[1]	400	11.3	455	2.2

ND Not determined.

[1] Duplicate column.

Table C-8.—Leachate assays from oxidized tailings in phase 1 clay-capped equilibrium columns with untreated tailings

Time in equilibrium column	As, ppm	Cd, ppm	Cu, ppm	Fe, ppm	Mn, ppm	Pb, ppm	Zn, ppm	SO_4, g/L
0 (leach 1)	0.12	0.3	11.3	1,850	105	0.03	39	9.5
0 (leach 2)	0.16	0.3	11.9	2,240	117	0.03	40	11.5
0 (leach 3)	0.13	0.3	11.8	2,200	124	0.01	39	12.4
0 (leach 4)	0.15	0.3	10.7	2,110	127	0.02	56	13.0
0 (leach 4)[1]	0.15	0.3	10.3	2,100	125	0.02	56	12.7
1 week	0.05	0.2	11.1	1,700	118	0.02	38	10.1
2 weeks	0.31	0.2	10.8	1,820	120	0.01	38	9.7
1 month	0.04	0.3	10.7	1,410	134	0.01	40	12.3
1 month[1]	0.04	0.3	10.6	1,410	133	0.01	39	12.9
1 month[2]	0.08	0.3	11.1	1,390	137	0.01	37	12.1
1 month[1,2]	0.04	0.3	11.2	1,390	138	0.01	40	12.1
2 months	0.01	0.3	11.5	1,600	189	0.06	44	11.2
3 months	<0.01	0.3	5.3	1,090	171	0.3	37	7.7
6 months	<0.01	0.3	10.0	532	209	0.01	42	8.8
6 months[1]	0.01	0.3	9.6	524	207	0.01	41	8.9
10 months	<0.01	0.3	9.3	405	263	0.07	48	18.2
10 months[1]	<0.01	0.3	9.3	408	263	0.08	47	19.2
10 months[2]	<0.01	0.3	9.8	564	278	0.02	51	20.9

[1] Duplicate assay.

[2] Duplicate column.

Table C-9.—Leach parameters from oxidized and unoxidized tailings in phase 1 clay-capped and uncapped equilibrium columns with untreated tailings showing the effects of capping

Time in equilibrium column	Sample wt, g	Sample moisture content, pct	Leachate vol, mL	Leachate pH
OXIDIZED TAILINGS				
Capped columns:				
1 month	200	18.8	237	2.2
1 month[1]	200	17.7	235	2.1
6 months	800	13.8	945	2.3
Uncapped columns:				
1 month	250	22.2	305	1.9
6 months	800	14.6	924	2.1
UNOXIDIZED TAILINGS				
Capped columns:				
1 month	150	19.2	182	5.4
6 months	825	15.3	976	5.4
Uncapped columns:				
1 month	150	18.5	182	5.0
6 months	400	15.2	464	3.8

[1] Duplicate column.

Table C-10.—Leachate assays from oxidized and unoxidized tailings in phase 1 clay-capped and uncapped equilibrium columns with untreated tailingsshowing the effects of capping

Time in equilibrium column	As, ppm	Cd, ppm	Cu, ppm	Fe, ppm	Mn, ppm	Pb, ppm	Zn, ppm	SO_4, g/L
OXIDIZED TAILINGS								
Capped columns:								
1 month	0.04	0.3	10.7	1,410	134	0.01	40	12.3
1 month[1]	0.04	0.3	10.6	1,410	133	0.01	39	12.9
1 month[2]	0.08	0.3	11.1	1,390	137	0.01	37	12.1
1 month[1,2]	0.04	0.3	11.2	1,390	138	0.01	40	12.1
6 month\s	<0.01	0.3	10.0	532	209	0.01	42	8.8
6 months[1]	0.01	0.3	9.6	524	207	0.01	41	8.9
Uncapped columns:								
1 month	0.22	0.4	14.2	3,350	228	0.01	53	20.9
6 months	0.05	0.7	13.2	1,930	331	0.01	63	14.7
6 months[1]	0.06	0.6	13.3	1,990	341	0.01	66	15.5
UNOXIDIZED TAILINGS								
Capped columns:								
1 month	<0.01	2.5	0.2	2.5	616	2.8	207	3.8
1 month[1]	<0.01	2.5	0.2	2.5	622	2.8	207	3.8
6 months	<0.01	4.6	0.2	0.6	1,050	3.0	335	5.1
6 months[1]	<0.01	4.6	0.2	0.5	1,040	2.9	333	5.2
Uncapped columns:								
1 month	<0.01	4.2	0.5	2.4	1,180	3.1	545	5.6
1 month[1]	<0.01	4.3	0.5	2.4	1,180	3.1	546	5.5
6 months	<0.01	10.0	12.4	15.4	2,230	3.2	1,360	11.1

[1] Duplicate assay.

[2] Duplicate column.

Table C-11.—Leach parameters from oxidized and unoxidized tailings in 3-month, clay-capped phase 1 equilibrium columns showing effects of adding bacteria and/or pH modifiers

Treatment	Sample wt, g	Sample moisture content, pct	Leachate vol, mL	Leachate pH
OXIDIZED TAILINGS				
Untreated	501	15.8	611	2.3
SLS[1]	405	17.4	490	2.4
NaAc[2]	400	20.0	499	2.2
Lime[3]	300	16.3	361	3.1
NaAc[2] + lime[3]	401	19.3	474	5.1
UNOXIDIZED TAILINGS				
Untreated	600	17.3	747	5.3
SLS[1]	500	15.5	633	5.9
NaAc[2]	500	15.7	619	5.9
Lime[3]	500	16.3	631	6.3

[1] SLS added as sulfide-oxidizing bacteria inhibitor.

[2] NaAc added as sulfate-reducing bacteria nutrient.

[3] Lime [$Ca(OH)_2$] added as pH modifier.

Table C-12.—Leachate assays from oxidized and unoxidized tailings in 3-month, clay-capped phase 1 equilibrium columns showing effects of adding bacteria and/or pH modifiers

Treatment	As, ppm	Cd, ppm	Cu, ppm	Fe, ppm	Mn, ppm	Pb, ppm	Zn, ppm	SO_4, g/L
OXIDIZED TAILINGS								
Untreated	<0.01	0.3	5.3	1090	171	0.3	37	8
SLS[1]	<0.01	0.2	7.5	1220	213	0.03	39	10
NaAc[2]	<0.01	0.3	9.6	830	206	0.01	36	11
Lime[3]	<0.01	0.2	1.0	11	116	0.01	20	3
NaAc[2] + lime[3]	<0.01	0	0.03	<0.5	31	0.03	<0.7	3
UNOXIDIZED TAILINGS								
Untreated	<0.01	3	0.2	1.1	966	6.5	314	4
SLS[1]	<0.01	1.6	0.02	0.5	505	7.1	65	3
NaAc[2]	<0.01	1.3	0.01	0.3	491	6.5	60	3
Lime [3]	0.03	0	0.03	<0.22	429	9.9	26	3

[1] SLS added as sulfide-oxidizing bacteria inhibitor.
[2] NaAc added as sulfate-reducing bacteria nutrient.
[3] Lime [$Ca(OH)_2$] added as pH modifier.

Table C-13.—Leach parameters from tailings in 6-month phase 1 clay-capped equilibrium columns compacted with high-moisture (25-30 pct) unoxidized tailings and with a mixture of oxidized and unoxidized tailings

	Sample wt, g	Sample moisture content, pct	Leachate vol, mL	Leachate pH
Unoxidized tailings:				
21 pct moisture[1]	825	15.3	976	5.4
25-30 pct moisture	387	17.9	477	5.6
Mixed oxidized/unoxidized tailings:				
21 pct moisture	400	14.1	456	4.1

[1] For comparison with high-moisture column.

Table C-14.—Leachate assays from tailings in 6-month phase 1 clay-capped equilibrium columns with high-moisture (25-30 pct) unoxidized tailings and with a mixture of oxidized and unoxidized tailings

	As, ppm	Cd, ppm	Cu, ppm	Fe, ppm	Mn, ppm	Pb, ppm	Zn, ppm	SO_4, g/L
Unoxidized tailings:								
21 pct moisture[1] . . .	<0.01	4.6	0.2	0.6	1,050	3.0	335	5.1
21 pct moisture[1,2] . .	<0.01	4.6	0.2	0.5	1,040	2.9	333	5.2
25-30 pct moisture . .	<0.01	1.2	0.07	2.8	599	2.5	89	3.3
Mixed oxidized/unoxidized tailings:								
21 pct moisture	<0.01	1.0	0.05	994	903	2.4	309	5.9

[1] For comparison with high-moisture column.

[2] Duplicate assay.

Table C-15.—Leach parameters from oxidation evaluation of reflooded columns

Time in flooded column	Sample wt, g	Sample moisture content, pct	Leachate vol, mL	Leachate pH
TAILINGS BEFORE FILLING COLUMNS				
None:				
Oxidized	234	56.5	363	2.3
Unoxidized	234	54.0	425	6.6
LAYERED COLUMNS				
2 weeks:				
Oxidized	155	55.0	212	2.4
Unoxidized	180	51.8	237	7.0
6 weeks:				
Oxidized	219	73.2	310	2.5
Unoxidized	204	56.7	303	6.8
14 months:				
Oxidized	404	63.1	536	3.2
Oxidized[1]	400	63.1	546	3.2
Unoxidized	400	55.5	543	6.5
Unoxidized[1]	402	55.5	547	6.0
14 months[2]:				
Oxidized	402	59.8	547	3.2
Oxidized[1]	402	59.8	547	3.7
Unoxidized	405	51.9	552	7.8
Unoxidized[1]	407	51.9	546	5.9
COLUMNS WITH ALL-OXIDIZED TAILINGS				
2 weeks	150	55.0	224	2.3
6 weeks	202	65.7	327	2.5
14 months	500	53.7	667	2.9
14 months[2]	502	61.5	683	3.1
COLUMNS WITH OXIDIZED TAILINGS AT MODIFIED pH LEVELS				
14 months (initial pH = 4)	439	66.3	616	5.6
14 months (initial pH = 7)	470	66.1	656	6.4

[1] Near interface.

[2] Duplicate column.

Table C-16.—Leachate assays from oxidation evaluation of reflooded columns

Time in flooded column	As, ppm	Cd, ppm	Cu, ppm	Fe, ppm	Mn, ppm	Pb, ppm	Zn, ppm	SO_4, g/L
TAILINGS BEFORE FILLING COLUMNS								
None:								
Oxidized	0.038	2.02	69	2,100	412	2.0	334	12.9
Oxidized[1]	0.040	2.01	70	2,070	407	1.9	323	13.0
Unoxidized	0.011	<0.01	2	307	123	<0.3	5.7	3.1
LAYERED COLUMNS								
2 weeks:								
Oxidized	0.023	2.41	78	2,500	480	1.6	340	19.7
Unoxidized	<0.01	<0.01	<0.3	31	77	0.2	1.0	3.8
6 weeks:								
Oxidized	0.016	2.16	66	2,280	503	0.6	323	18.9
Unoxidized	<0.01	<0.01	<0.3	3	25	0.1	0.5	2.6
14 months:								
Oxidized	0.02	1.13	10	1,140	373	2.4	185	14.9
Oxidized[2]	<0.01	1.25	2	2,520	607	2.8	233	22.2
Unoxidized	<0.01	0.01	0.03	333	122	<0.01	0.8	3.9
Unoxidized[2]	<0.01	0.02	0.03	746	194	0.02	2.0	0.3
14 months[3]:								
Oxidized	0.02	1.01	7	1,260	385	1.8	176	15.0
Oxidized[2]	0.03	0.48	0.3	2,570	533	3.2	164	23.3
Unoxidized	0.02	0.01	0.02	1	0.6	0.02	<0.7	2.5
Unoxidized[2]	<0.01	0.04	0.08	1,260	266	0.1	12	13.9
COLUMNS WITH ALL-OXIDIZED TAILINGS								
2 weeks	0.03	2.20	74	2,170	446	0.3	339	21.8
6 weeks	0.02	1.92	55	1,810	420	1.1	278	17.4
14 months	<0.01	2.45	19	2,250	780	2.1	398	24.4
14 months[3]	<0.01	2.78	19	2,760	870	2.0	453	24.4
COLUMNS WITH OXIDIZED TAILINGS AT MODIFIED pH LEVELS								
14 months (initial pH = 4)	<0.01	0.03	0.07	2,700	503	0.3	1	20.1
14 months (initial pH = 7)	<0.01	0.02	0.06	249	97	0.05	<0.7	4.5

ND Not determined.

[1] Duplicate assay.

[2] Near interface.

[3] Duplicate column.

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