

**FINAL REPORT - BERKELEY PIT  
INNOVATIVE TECHNOLOGIES  
PROJECT, PHASE III: MINE  
REMEDATION SERVICES  
DEMONSTRATION**

**MINE WASTE TECHNOLOGY PROGRAM  
ACTIVITY IV, PROJECT 7**

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**Prepared for:**

U.S. Environmental Protection Agency  
National Risk Management Research Laboratory  
Cincinnati, Ohio 45268

and

U.S. Department of Energy  
Federal Energy Technology Center  
Pittsburgh, Pennsylvania 15236  
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**REVIEWS AND APPROVALS:**

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February 1999

**FINAL REPORT—REMOVAL OF METALS  
FROM BERKELEY PIT WATER USING  
KAD TECHNOLOGY**

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## Foreword

Today, industries are developing and modifying technologies to more efficiently produce their products. The waste generated by these industries, if improperly dealt with, can threaten public health and degrade the environment. The U.S. Environmental Protection Agency (EPA) is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the EPA strives to formulate and implement actions leading to a balance between human activities and the ability of natural systems to support and nurture life. These laws direct the EPA to perform research to define, measure the impacts, and search for solutions to environmental problems.

The National Risk Management Research Laboratory (NRMRL) of the EPA is responsible for planning, implementing, and managing research, development, and demonstration programs to provide an authoritative, defensible engineering basis. This supports the policies, programs, and regulations of the EPA with respect to drinking water, wastewater, pesticides, toxic substances, solid and hazardous wastes, and Superfund-related activities. The Federal Energy Technology Center (FETC) of the U.S. Department of Energy (DOE) has responsibilities similar to the NRMRL in that FETC is one of several DOE centers responsible for planning, implementing, and managing research and development programs. In June 1991, an Interagency Agreement (IAG) was signed between EPA and DOE that made funds available to support the Western Environmental Technology Office's operating contractor, MSE Technology Applications, Inc. (MSE), and Montana Tech of The University of Montana for the development of the Mine Waste Technology Program (MWTP). This publication is one of the products of the research conducted by the MWTP through these two Federal organizations and provides a vital communication link between the researcher and the user community.

The objective of this demonstration was to remediate Berkeley Pit water to the extent that it could be safely used for agricultural applications, to demonstrate the suitability of the technology in allowing continuous on-line treatment that could be scaled up to match present inflows into the Berkeley Pit, and to evaluate the possible recovery of the economic minerals in the compacted precipitate.

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## Executive Summary

The goal of this project undertaken at Montana Tech of the University of Montana (Montana Tech) is to demonstrate the potential for a new material, termed Kaolin Amorphous Derivative (KAD), to effectively and economically reduce contamination in the Berkeley Pit acid mine drainage (AMD) to the designated water quality standard. The bench-scale protocol used to treat Berkeley Pit AMD has been designed to allow a preliminary evaluation of critical parameters used to plan an optimally engineered and scaled up treatment and recovery process. The overall approach in the use of the KAD technology aims to minimize materials handling at all stages of a treatment process (i.e., through recycling of KAD and maximum uptake of metals) to cost effectively separate solids from liquids and to recover valuable metals and/or products, the sale of which may reduce the overall cost of a treatment process.

KAD is part of a new suite of materials that can be produced from low-cost clay minerals through simple manufacturing methods (Mackinnon *et al*, 1997; 1996a, b) and offers a unique and innovative approach to the Berkeley Pit AMD problem. KAD materials show high cation exchange values, high surface area values and inherent basicity. The KAD technology was developed at The University of Queensland in Australia by Professor Ian Mackinnon and his staff at Advanced Ceramics Development. The first patent was lodged on June 17, 1993; two subsequent patents have been lodged to further protect this new suite of materials. In 1996, UniQuest Limited (the commercialization company of the University) entered into a Joint Venture Agreement with Cardia Mining NL, thereby forming Mine Remediation Services Pty Ltd. (MRS). MRS has exclusive license to the KAD technology for application in the mining industry, with the initial focus of development on AMD.

Development of the KAD technology in Australia is currently at pilot scale for materials production (~260 pounds per day) and at pilot demonstration scale for AMD treatment (~13,000 gallons per day). The pilot treatment plant is currently installed at the Mount Morgan pit lake in Queensland. Trials of this plant will result in extension of capacity and refinement of engineering processes for AMD remediation in a wide range of environments. In addition, these plant trials, which are at much higher scale, provide field-based benchmarks with which to evaluate the success of these trials on Berkeley Pit AMD.

The quality assurance project plan for the test program at Montana Tech was developed at the University of Queensland using simulated Berkeley Pit water based upon average water analyses provided in the Request for Proposal. This approved test protocol was followed, with the outcomes summarized as below.

The data presented in Tables E-1 and E-2 show that the proposed KAD treatment protocol for Berkeley Pit AMD will result in reduction of all metal ion concentrations to the target values within the required pH range. Aluminum metal is a possible exception to this outcome, although equivocal data on detection limits for the two analytical methods employed may imply that aluminum can also be reduced to below the target concentration using KAD technology. The treatment protocol also resulted in reduction of sulfate levels by approximately 50% although these levels are above the target concentration for sulfate.

**Table E-1. Summary of metals analyses (ppm) as determined by ICP analysis at Montana Tech Analytical Laboratory for treated Berkeley Pit AMD after KAD loading stage.**

<b>Sample ID</b>	<b>pH</b>	<b>Al</b>	<b>As</b>	<b>Cd</b>	<b>Cr</b>	<b>Cu</b>	<b>Fe</b>	<b>Mn</b>	<b>Ni</b>	<b>Zn</b>	<b>SO<sub>4</sub></b>
BP AMD	2.8	283	0.70	1.940	0.04	192	1020	229	1.08	611	9,750
3a (i)	6.3	<0.136	0.018	0.037	<0.011	0.050	<0.014	127.31	0.327	21.40	4,935
3b (i)	6.4	<0.136	0.071	<0.009	<0.011	0.015	0.019	28.13	<0.017	1.026	4,722
3c (i)	7.4	0.215	0.061	<0.009	<0.011	0.019	0.021	6.46	<0.017	0.079	4,707
3d (i)	7.9	0.348	<0.014	<0.009	<0.011	0.017	0.043	1.37	<0.017	0.018	4,761
3a (ii)	6.0	0.379	0.048	0.312	<0.011	0.255	0.024	187.44	0.834	187.43	4,794
3b (ii)	6.2	<0.136	0.048	0.029	<0.011	0.051	0.163	125.80	0.305	19.65	4,725
3c (ii)	6.4	<0.136	0.027	<0.009	<0.011	0.020	0.020	26.53	<0.017	1.007	4,746
3d (ii)	6.6	<0.136	<0.014	<0.009	<0.011	0.015	0.020	19.92	<0.017	0.970	4,695
3e (ii)	6.7	<0.136	0.042	<0.009	<0.011	<0.013	0.024	117.51	0.082	4.685	4,710
3f (ii)	6.1	0.288	<0.014	<0.009	<0.011	0.016	0.045	7.34	<0.017	0.037	4,734
3g (ii)	8.6	0.250	<0.014	<0.009	<0.011	<0.013	0.020	0.039	<0.017	0.018	4,770
Target	6.5-8.5	0.05*	0.05	0.003*	0.05	0.01*	0.30	0.05	0.10	0.10	500

\* Indicated target values are not 2 x MDL

**Table E-2. Summary of metals concentrations (ppm) as determined by ACZ Laboratories using ICP analysis for final polished Berkeley Pit samples**

<b>Sample Name</b>	<b>KAD Addition</b>	<b>pH</b>	<b>Al</b>	<b>As</b>	<b>Cd</b>	<b>Cr</b>	<b>Cu</b>	<b>Fe</b>	<b>Mn</b>	<b>Ni</b>	<b>Zn</b>
<i>Berkeley Pit AMD</i>		2.8	283	0.70	1.940	0.04	192	1020	229	1.08	611
<i>Recycled KAD</i>											
5a(i-2.5A)	5 g KAD	7.2	0.08	<0.04	0.007	<0.01	0.03	<0.01	40.9	0.02	1.53
5b(i-2.5A)	10 g KAD	7.6	0.17	<0.04	<0.003	<0.01	0.03	<0.01	4.830	<0.01	0.21
5c(i-2.5A)	20 g KAD	7.9	0.30	<0.04	<0.003	<0.01	0.02	<0.01	0.407	<0.01	0.04
5d(i-2.5A)	30 g KAD	8.9	0.51	<0.04	<0.003	<0.01	0.04	<0.01	0.028	<0.01	0.01
5d(ii-2.5A)	10 g KAD	7.6	0.19	<0.04	<0.003	<0.01	0.04	<0.01	4.09	<0.01	0.21
5f(ii-2.5A)	5 g+3.9 gKAD	7.6	0.15	<0.04	<0.003	<0.01	0.02	<0.01	3.170	<0.01	0.20
5g(ii-2.5A)	10 g + 7.6 g KAD	7.9	0.29	<0.04	<0.003	<0.01	0.02	<0.01	0.386	<0.01	0.04
<i>Fresh KAD</i>											
5a(i-2.5B)	5 g KAD	8.5	0.38	<0.04	<0.003	<0.01	0.02	0.02	0.204	<0.01	<0.01
5b(i-2.5B)	10 g KAD	8.9	0.34	<0.04	<0.003	<0.01	0.02	0.02	0.02	<0.01	<0.01
5c(i-2.5B)	20 g KAD	9.2	0.59	<0.04	<0.003	<0.01	0.01	0.01	<0.005	<0.01	<0.01
5d(i-2.5B)	30 g KAD	9.6	1.80	<0.04	<0.003	<0.01	0.02	<0.01	<0.005	<0.01	<0.01
5d(ii-2.5B)	10 g KAD	8.9	0.37	<0.04	<0.003	<0.01	0.02	0.03	0.015	<0.01	<0.01
5e(ii-2.5B)	2.5 g + 1.9 g KAD		0.41	<0.04	0.004	<0.01	0.02	0.03	0.162	<0.01	<0.01
5f(ii-2.5B)	5 g + 3.9 g KAD	8.8	0.36	<0.04	<0.003	<0.01	0.02	0.05	0.008	<0.01	<0.01
5g(ii-2.5B)	10 g + 7.6 g KAD	9.4	1.11	<0.04	<0.003	<0.01	0.01	0.02	<0.005	<0.01	<0.01
	Target Values	6.5-8.5	0.05	0.05	0.003	0.05	0.01	0.30	0.05	0.10	0.10

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## 1. Introduction

In 1993, researchers at the University of Queensland in Australia discovered a chemical reaction that economically transformed kaolin into a new suite of materials that has an exceptional ability to remove metals from solution. This new suite of materials is named Kaolin Amorphous Derivative (KAD).

Proof-of-concept experiments at bench scale and also trials at pilot scale have demonstrated that KAD has the characteristics given below.

- The ability to reduce high concentrations of metal ions in solution (50-100 parts per million (ppm) and above) to below environmental standards [ $<10$  parts per billion (ppb)].
- Has high metal loadings, carrying up to 10% by weight for copper with higher values for lead and some other metals.
- Can be stripped of loaded metals, thus recovering metal products with high efficiency.
- Can be reused after the metal has been stripped.
- Is a basic material that increases solution pH during use.
- Can be manufactured through a simple batch process.

The primary market for the technology is the cleanup of acid mine drainage (AMD), an environmental toxic product of major concern for metalliferous and coal mining operations. Mining operations located in regions of excess precipitation or intrusive groundwater systems are most at risk for the production of AMD with high toxic metal concentrations. Tests on actual AMD solutions from a number of Australian mine sites have demonstrated that KAD can remove the toxic metal ions and increase the pH of the treated water

to neutral or basic conditions sufficient to satisfy required environmental standards.

The proof-of-concept research undertaken by the University of Queensland demonstrated the potential of KAD, leading to a joint venture company being established with Cardia Mining NL to develop and commercialize the material for mine site remediation. The vehicle for this joint venture is a company, Mine Remediation Services Pty Ltd (MRS), which is 60% owned by Cardia and 40% owned by UniQuest Limited. MRS has received Australian Federal Government funding to extend the understanding and application of the KAD materials as well as to construct a pilot treatment plant for demonstration at Australian mine sites. This plant is currently at the historic Mount Morgan mine in Queensland. The history of the Mount Morgan township and the mine parallels the history of Butte and the Berkeley Pit operation. Mount Morgan was a significant mining and smelting operation, beginning in the later half of the 1800s with copper the predominant metal produced. The pit lake contains more than 2 billion gallons of acid water at pH 2.7, containing significant concentrations of toxic metals of a variety and level similar to that in Berkeley Pit.

This pilot treatment plant essentially comprises two process steps, namely pretreatment and KAD treatment. Both limestone and lime are currently under trial at 13,000 gallons per day in the pretreatment section to elevate the pH of the AMD into the 4.5 - 5 region. A thickener/clarifier is used to settle the predominantly iron/aluminum hydroxide precipitate. The thickener overflow is pumped to the KAD circuit where different KAD dosages are tested to optimize the metal loading process. A thickener/clarifier is used to settle the metal-loaded KAD and to produce a treated water stream. The pilot treatment plant is in an early stage of trials; however, the initial results have confirmed that results achieved at bench scale can be related to larger scale engineering processes. The next stage of the pilot treatment plant trials at Mount

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Morgan will involve addition of a metal stripping process and recycling of the stripped KAD.

The bench-scale demonstration conducted at Montana Tech of the University of Montana (Montana Tech) follows the same fundamental sequence of process operations used in the pilot treatment plant, that is, pretreatment, KAD loading, and metal stripping as depicted in Figure 3-1. As

with the tests performed in Australia on simulated Berkeley Pit water, the KAD technology produced a marked reduction in the metal concentrations down to the target levels. In these bench-scale trials, there has been no specific attempt to reduce sulfate concentration below that which will result from lime precipitation. It is proposed that sulfate reduction would be affected by a separate process specially tailored for this purpose.

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## 2. Project Goals and Objectives

The primary goal of this project was to demonstrate the remediation of AMD from the Berkeley Pit to the target concentrations listed in Table 6-3 using bench-scale trials that exploit the unique properties of KAD. Secondary aims of the project included those given below.

- Confirmation of pH values for effective pretreatment of Berkeley Pit AMD prior to treatment with KAD.
- Preliminary evaluation of the combinations of pretreatment chemical(s) and KAD dosage rates

for maximum extraction and recovery of metal ions in the Berkeley Pit AMD.

- Preliminary evaluation of the ability of the KAD material to recover metal in a single pass.

These secondary aims undertaken at bench scale, as batch mode experiments, provide some of the fundamental data necessary to assess the proposed continuous processing circuit(s) targeted for optimum full-scale engineering conditions.

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### 3. Process Technology

KAD materials can be designed to specific adsorptive capacities for a wide range of heavy and toxic metal concentrations in solution by the appropriate choice of manufacturing conditions. These new materials can be readily synthesized from any form of kaolin mineral (filler grade to paper grade) and most montmorillonites clays using simple chemical treatment methods and well-known mineral processing methods. In these trials on Berkeley Pit water, only one form of KAD material was used. The material offers a range of porosity sizes (from micropore to mesopore) and a known capacity, from trials of other AMD, for exchange of a broad range of metal ions. As with many AMD solutions, a limited amount of process and product redesign is required after bench-scale trials to achieve maximal results in an engineered process.

KAD can be supplied as a dry powder, as a filter cake, or in slurry form, depending on the application and materials handling requirements for specific site treatment processes. The treatment process can be tailored to each specific application or AMD solution compositions. In addition, the design of a treatment process using KAD may be dependent on the engineering objectives for a particular site. For example, some sites may only require cleanup of the AMD solution, whereas conditions at other sites may encourage recovery of certain metals from the treatment process as well as production of clean, treated water. A typical treatment flowsheet involves the following process stages:

- pretreatment and waste disposal;
- KAD loading;
- metal stripping and reuse of strip solution;
- metal recovery; and
- KAD recycling back to loading circuit.

This flowsheet block diagram is depicted schematically in Figure 3.1. A detailed flowsheet for a full-scale treatment facility, such as the one installed at Mount Morgan, is shown in Figure 3.2. The pretreatment circuit involves pH adjustment between 4.5 and 5 so that iron and aluminum

hydroxides precipitate with the bulk of other metal ions left in the AMD solution. Oxidation of  $\text{Fe}^{2+}$  ions to  $\text{Fe}^{3+}$  is undertaken by air sparging in agitated pretreatment vessels.

The metal loading process takes place when potassium and/or sodium cations on the KAD are removed by exchanging with other metal cations such as copper, zinc, cadmium, etc. In addition to the strong ion exchange capability, the high basicity of KAD assists in raising the pH of the AMD towards neutrality. Metal loadings onto KAD will vary according to the specific metal, the water chemistry, and the specific properties of the KAD; however, concentrations of 10% by weight for  $\text{Cu}^{2+}$  and higher have been produced in bench-scale trials in Australia. Complex, multielement solution compositions can be treated effectively to satisfy required regulatory standards.

When the metal ions are stripped from the KAD, recycling of the KAD back into the metal loading process forms an integral element of the overall process economics. The metal recovery process may be designed for a specific site and will depend on the type of stripping reagent used, the metals to be recovered, and the availability of a ready sales outlet for such metal/mineral products. In these bench-scale trials of Berkeley Pit AMD, only one stripping (ammonia) agent has been tested. Bench-scale trials on AMD from Australian mine sites suggest that other base stripping agents may also be used to similar or better effect. These other stripping agents may be more environmentally acceptable in sensitive regions and include ethylenediaminetetraacetic acid (EDTA), diethyl triamine and other amine-based compounds.

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A KAD polishing stage may be required in situations where stringent water quality standards must be achieved. In practice, this polishing step can be represented by a two-stage treatment of KAD to the AMD after pretreatment with lime or limestone. This type of polishing stage has been simulated in the bench-scale trials of Berkeley Pit AMD through staged dosages of KAD material, of both “fresh” KAD and “stripped” KAD. Clearly, additional polishing stages may provide lower levels of metal concentrations.

Bench-scale trials are limited in value compared with actual field-scale trials on AMD primarily because some processing options are not available to researchers at bench-scale. Alternatively, laboratory procedures, including convenience of implementation, often mean that essential steps required for engineering implementation may not be followed precisely. For example, the bench-scale trials on Berkeley Pit AMD do not mimic the larger scale pilot treatment plant currently in operation with regard to solid-liquid separation. The bench-scale trials use a centrifuge and extraction of eluent through a filtered syringe to separate metal-loaded KAD from treated water. In larger scale operations, a more efficient process using flocculation and thickening is used.

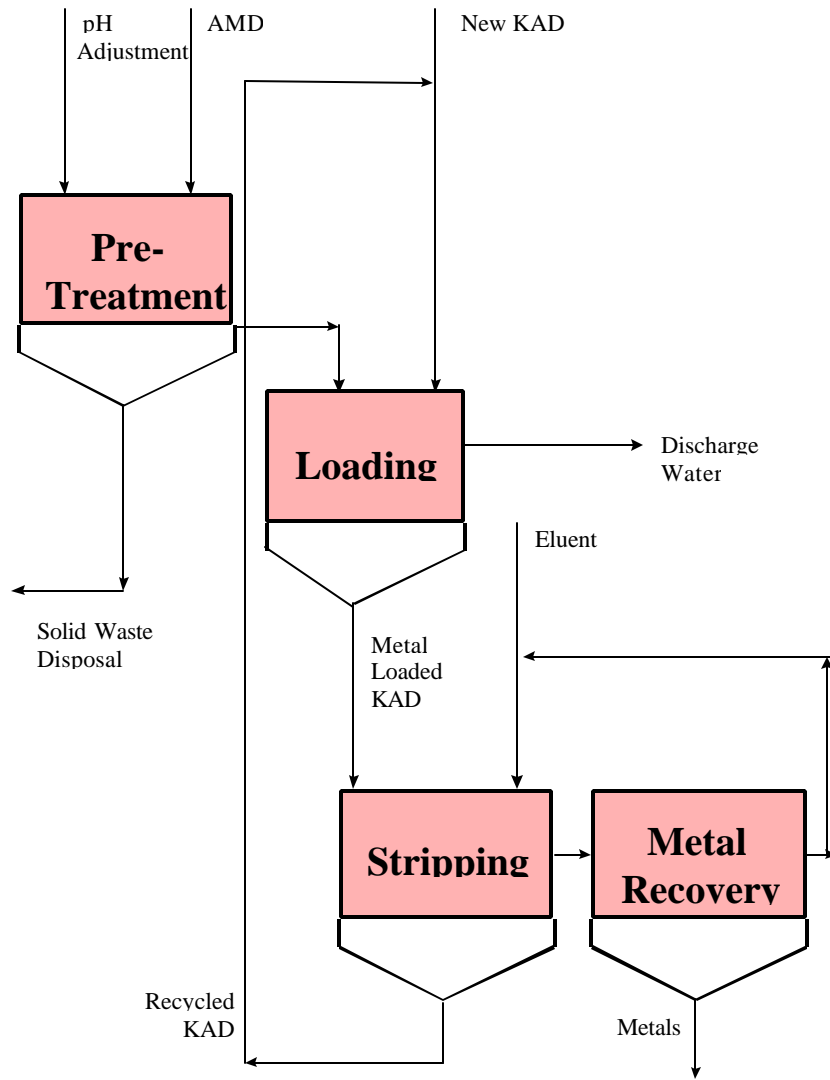
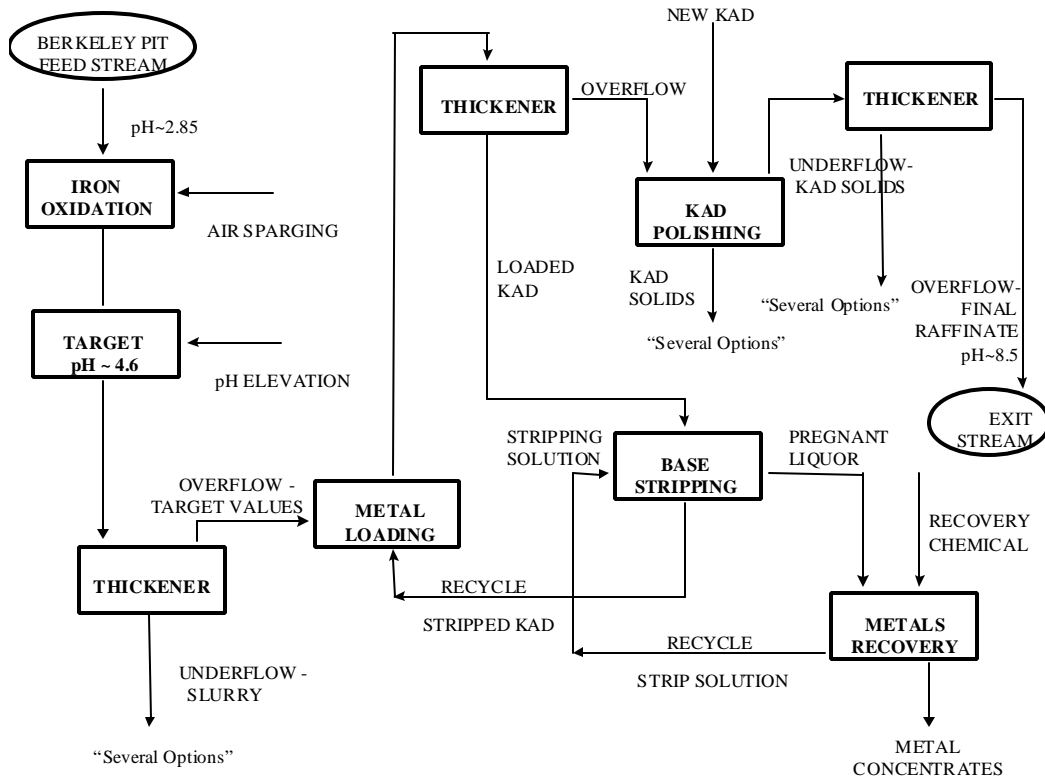


Figure 3-1. Standard AMD treatment process.



**Figure 3-2. Continuous circuit for AMD treatment and recovery of value metals using KAD.**

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## 4. Process Configuration for Bench-Scale Testing

The bench-scale trials on Berkeley Pit AMD involved the steps below.

1. Pretreatment of AMD feed by oxidation with hydrogen peroxide and addition of calcium hydroxide (hydrated lime) to achieve low iron, manganese, and aluminum contents at pH ~4.6.
2. Treatment with KAD material to load valuable metals.
3. Stripping of KAD material using low cost chemicals to selectively remove specific metal ions such as copper, zinc, nickel, and cadmium in forms suitable for sale. The metal-stripped KAD is then recycled back into the process to recover additional metals.

4. Final polishing with KAD to exchange remaining metals down to target concentrations.

The AMD used for the test program was collected from the 200-foot level in the Berkeley Pit two days prior to the beginning of testing. This sample was stored under nitrogen at 4 °C. Hydrogen peroxide was used as an oxidizing agent to ensure the ratio of  $\text{Fe}^{2+}$  and  $\text{Fe}^{3+}$  was similar to that expected when treating the surface water in a full-scale operation. As such, hydrogen peroxide would not be used in a full-scale operation, instead, air sparging would be used.

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## 5. Bench-Scale Testing Protocol

Typical KAD treatment of AMD is a five-stage process. The five steps are designated: (1) Pretreatment of KAD, (2) Pretreatment of AMD, (3) KAD Dosing, (4) Base Stripping of Loaded KAD and (5) Final Polishing.

### 5.1 Pretreatment of KAD

This step is not required for this particular bench-scale demonstration.

### 5.2 Pretreatment of AMD

From the supplied volume of Berkeley Pit AMD, three 50-milliliter (mL) samples were withdrawn, filtered through 0.2-micron syringe filters, and set aside for analysis (labeled 2III(i), 2III(ii), and 2III(iii)). A 5-kilogram (kg) aliquot of AMD was weighed into a labeled bucket. This bucket was placed under an overhead stirrer, and two electrodes were placed in the AMD to monitor pH and  $E_H$ . The stirrer was adjusted to a speed sufficient to maintain good circulation of the AMD, and 50 mL of 30% hydrogen peroxide was added. Over the next 90 minutes, the pH,  $E_H$ , and temperature readings were recorded. A total of 12 grams (g) of calcium hydroxide ( $\text{Ca}(\text{OH})_2$ ) was added in 2.5-g and 1.0-g lots until the pH reading was at 4.6. The resultant slurry was then filtered using a Buchner funnel and Whatman 542 filter paper. The filter paper and solids were collected and dried overnight at 105 °C. The next day, the filter paper and solids were weighed to allow the calculation of percent dissolved solids.

The filtrate was collected in 1-L Nalgene containers.

Three 30-mL samples were withdrawn, filtered through 0.2-micron syringe filters, and set aside for analysis. (Filters measuring 0.2 microns were used rather than 0.45-micron filters to maintain comparability with previous tests performed in Australia.)

### 5.3 Dosing of KAD

Two experiments were conducted to illustrate both single- and double-stage dosing.

#### 5.3.1 Single-Stage Dosing

Four 250-mL Nalgene screw-top bottles were collected and labeled 3a(i), 3b(i), 3c(i), and 3d(i). KAD was weighed into the individual bottles as follows:

- 3a(i) 5 g of KAD
- 3b(i) 10 g of KAD
- 3c(i) 20 g of KAD
- 3d(i) 30 g of KAD

Pretreated AMD (200 mL) from Stage 2 was added to each of the bottles. The resultant slurry was shaken for 2 hours on an orbital shaker, and the pH of each of the samples was noted at the end of this time. The samples were then centrifuged at 3,000 revolutions per minute (rpm) for 10 minutes before decanting the supernatant into labeled 250-mL Nalgene bottles. A 30-mL sample of supernatant was withdrawn from each of the bottles, filtered through a 0.2-micron syringe filter, and set aside for analysis (labeled 3a(i) to 3d(i)). The remainder of the supernatant was retained for Stage 5. The settled solids in the original Nalgene containers were retained for Stage 4.

#### 5.3.2 Double-Stage Dosing

Four 250-mL Nalgene screw-top bottles were collected and labeled 3a(ii), 3b(ii), 3c(ii), and 3d(ii). KAD was weighed into the individual bottles as follows:

- 3a(ii) 2.5 g of KAD
- 3b(ii) 5 g of KAD
- 3c(ii) 10 g of KAD
- 3d(ii) 10 g of KAD

Pretreated AMD (200 mL) from Stage 2 was added to each of the bottles. The resultant slurry was shaken for 2 hours on an orbital shaker, and the pH of each of the samples was noted at the end of this time. The samples were then centrifuged at 3,000 rpm for 10 minutes before decanting the supernatant into labeled 250-mL Nalgene bottles. A 30-mL sample of supernatant was withdrawn from each of the bottles, filtered through a 0.2-micron syringe

filter, and set aside for analysis (labeled 3a(ii) to 3d(ii)). The volume of the remaining supernatant from samples 3a(ii), 3b(ii), and 3c(ii) was noted and retained for the next stage of the double dose. The supernatant from sample 3d(ii) was retained for Stage 5. The settled solids in all of the original Nalgene containers were retained for Stage 4.

Three 250-mL Nalgene screw-top bottles were collected and labeled 3e(ii), 3f(ii), and 3g(ii). An amount of KAD was weighed into the individual bottles as follows:

- 3e(ii) 1.9 g of KAD
- 3f(ii) 3.9 g of KAD
- 3g(ii) 7.6 g of KAD

The supernatant from 3a(ii) was then added to 3e(ii), the supernatant from 3b(ii) was added to 3f(ii), and the supernatant from 3c(ii) was added to 3g(ii). The resultant slurry was shaken for 2 hours on an orbital shaker, and the pH of each of the samples was noted at the end of this time. The samples were then centrifuged at 3,000 rpm for 10 minutes before decanting the supernatant into labeled 250-mL Nalgene bottles. A 30-mL sample of supernatant was withdrawn from each of the bottles, filtered through a 0.2-micron syringe filter, and set aside for analysis (labeled 3e(ii) to 3g(ii)). The supernatant from each sample was retained for Stage 5. The settled solids in 3e(ii), 3f(ii) and 3g(ii) were added to the settled solids in 3a(ii), 3b(ii), and 3c(ii), respectively and retained for Stage 4. The settled solids in 3d(ii) were retained for Stage 4.

#### 5.4 Base Stripping of Loaded KAD

A 1-L ammonia strip solution was prepared by dissolving 152.8 g of AR grade ammonium sulfate and 90 g of AR grade sodium chloride in 840 mL of distilled water. Next, 160 mL of 28% w/w ammonia solution was added, and the resultant solution was mixed well. Strip solution was added to the settled solids collected at Stage 3 at the rate of 250 mL per 40 g of KAD:

Sample	Amount of KAD loaded (g)	Amount of strip solution added (mL)

4a(i)	5	31.25
4b(i)	10	62.5
4c(i)	20	125
4d(i)	30	187.5
4d(ii)	10	62.5
4a(ii) + 4e(ii)	4.4	27.5
4b(ii) + 4f(ii)	8.9	55.6
4c(ii) + 4g(ii)	17.6	110

The resultant slurry was shaken for 1 hour on an orbital shaker and then centrifuged at 3,000 rpm for 10 minutes. The pregnant liquor was decanted into labeled 250-mL Nalgene bottles. An equivalent amount of distilled water was then added to each of the settled solids. The resultant slurry was shaken for 30 minutes on an orbital shaker and then vacuum filtered using Whatman 542 filter paper. The filtrate of each was decanted into the labeled 250-mL Nalgene bottles and mixed thoroughly with the pregnant liquor. A 30-mL sample was then withdrawn from each bottle, filtered through a 0.2-micron syringe filter, and set aside for analysis (labeled 4a(i) to 4g(ii)). Next, 6 mL of 32% hydrochloric acid (HCl) was added to each of the samples for preservation purposes. The solids gained from the vacuum filtration were placed on a tray and dried overnight at 105 °C. The next day, the solids were each crushed lightly in a mortar and pestle and retained for Stage 5.

#### 5.5 Final Polishing

Final polishing of the AMD solution was conducted using both stripped and fresh KAD to illustrate the use of recycled KAD.

##### 5.5.1 Polishing using Stripped KAD

The following samples were prepared using the supernatant collected at Stage 3 and the dried, stripped KAD from Stage 4:

- 2.5 g of 4a(i) KAD was weighed into a 250-mL Nalgene bottle labeled 5a(i-2.5A); 50 mL of supernatant from aliquot 3a(i) was then measured into the bottle.
- 2.5 g of 4b(i) KAD was weighed into a 250-mL Nalgene bottle labeled 5b(i-2.5A); 50 mL of supernatant from aliquot 3b(i) was then measured into the bottle.

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- 2.5 g of 4c(i) KAD was weighed into a 250-mL Nalgene bottle labeled 5c(i-2.5A); 50 mL of supernatant from aliquot 3c(i) was then measured into the bottle.
  - 2.5 g of 4d(i) KAD was weighed into a 250-mL Nalgene bottle labeled 5d(i-2.5A); 50 mL of supernatant from aliquot 3d(i) was then measured into the bottle.
  - 2.5 g of 4d(ii) KAD was weighed into a 250-mL Nalgene bottle labeled 5d(ii-2.5A); 50 mL of supernatant from aliquot 3d(ii) was then measured into the bottle.
  - 2.5 g of 4f(ii) KAD was weighed into a 250-mL Nalgene bottle labeled 5f(ii-2.5A); 50 mL of supernatant from aliquot 3e(ii) was then measured into the bottle.
  - 2.5 g of 4g(ii) KAD was weighed into a 250-mL Nalgene bottle labeled 5g(ii-2.5A); 50 mL of supernatant from aliquot 3f(ii) was then measured into the bottle.

The resultant slurry was shaken for 8 hours on an orbital shaker, and the pH of each of the samples was noted. The samples were then centrifuged at 3,000 rpm for 10 minutes. The supernatant was then decanted into bottles labeled 5a(i-2.5A) to 5g(ii-2.5A), and a 30-mL sample was withdrawn, filtered through a 0.2-micron syringe filter, and set aside for analysis.

### ***5.5.2 Polishing using Fresh KAD***

The following samples were prepared using the supernatant collected at Stage 3 and previously unused KAD.

- 2.5 g of KAD was weighed into a 250-mL Nalgene bottle labeled 5a(i-2.5B); 50 mL of supernatant from aliquot 3a(i) was then measured into the bottle.
- 2.5 g of KAD was weighed into a 250-mL Nalgene bottle labeled 5b(i-2.5B); 50 mL of

supernatant from aliquot 3b(i) was then measured into the bottle.

- 2.5 g of KAD was weighed into a 250-mL Nalgene bottle labeled 5c(i-2.5B); 50 mL of supernatant from aliquot 3c(i) was then measured into the bottle.
- 2.5 g of KAD was weighed into a 250-mL Nalgene bottle labeled 5d(i-2.5B); 50 mL of supernatant from aliquot 3d(i) was then measured into the bottle.
- 2.5 g of KAD was weighed into a 250-mL Nalgene bottle labeled 5d(ii-2.5B); 50 mL of supernatant from aliquot 3d(ii) was then measured into the bottle.
- 2.5 g of KAD was weighed into a 250-mL Nalgene bottle labeled 5e(ii-2.5B); 50 mL of supernatant from aliquot 3e(ii) was then measured into the bottle.
- 2.5 g of KAD was weighed into a 250-mL Nalgene bottle labeled 5f(ii-2.5B); 50 mL of supernatant from aliquot 3f(ii) was then measured into the bottle.
- 2.5 g of KAD was weighed into a 250-mL Nalgene bottle labeled 5g(ii-2.5B); 50 mL of supernatant from aliquot 3g(ii) was then measured into the bottle.

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The resultant slurry was shaken for 8 hours on an orbital shaker, and the pH of each of the samples was noted. The samples were then centrifuged at 3,000 rpm for 10 minutes. The supernatant was then decanted into bottles labeled 5a(i-2.5B) to 5g(ii-2.5B), and a 30-mL sample was withdrawn, filtered through a 0.2-micron syringe filter, and set aside for analysis.

Sampling and analysis of samples has been undertaken according to the project-specific quality assurance project plan (QAPP). All sampling, sample handling, shipping, and analytical work was performed by the Project Manager for the Berkeley Pit Innovative Technologies Project.

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## 6. Results

Water analysis of samples from certain stages of the bench-scale trials was not given critical measurement status in order to reduce costs and minimize delays. Instead, these noncritical samples were analyzed at the Montana Tech Analytical Laboratory as a benchmark for evaluation of critical measurements after KAD polishing. To ascertain the success of a pretreatment process using lime, hydrogen peroxide, or another oxidant, it is important to monitor not only pH and  $E_H$  of the solution but also the concentration of iron and aluminum. This approach is part of a standard treatment strategy used by researchers at The University of Queensland and Mine Remediation Services Pty Ltd. and has a sound basis for implementation.

*Pretreatment Step:* Table 6-1 shows inductively coupled plasma mass spectrometer (ICP-MS) data for analyses of Berkeley Pit water as well as the solution after pretreatment with different levels of hydrogen peroxide.

The data in Table 6-1 shows that treatment of the AMD with between 20 mL and 50 mL of hydrogen peroxide will reduce the level of aluminum and iron to concentrations that enable efficient use of KAD materials in a loading circuit and, at the same time, retains approximately 50% of copper in soluble form. Comparison of critical measurement values for these solutions (i.e., 283 ppm aluminum) with that obtained by ICP-MS (363 ppm aluminum)

indicates that care is required in the selection of analytical technique for specific elements. With ICP-MS analyses of aluminum in untreated AMD, the potential for interference of the aluminum peak may be due to the presence of soluble organics. A brief comment on appropriate choice of analytical technique, along with implications for the data presented in this report, is provided in the discussion section.

*KAD Loading Step:* Noncritical measurements of metal concentrations at this stage of the treatment protocol are summarized in Table 6-2. This data has been obtained by the ICP method using facilities at the Montana Tech Analytical Laboratory. In addition, noncritical measurements of sulfate concentrations obtained from the Montana Tech Analytical Laboratory are given in Table 6-2 for the samples as processed to the end of the KAD loading stage.

*KAD Polishing Stage:* Data obtained from ACZ Laboratories using ICP methods for the final polishing stage of this protocol is summarized in Table 6-3. Two sets of data are provided in Table 6-3 in order to demonstrate the effectiveness of KAD materials for reuse once the metal ions have been stripped from a loaded KAD. This data shows final treated water analyses for various loadings of both (i) fresh KAD and (ii) KAD that has been stripped of metal ions using an ammonium solution.

**Table 6-1. Preliminary Analyses After Peroxide Trials (values in ppm)**

	pH	Al	Fe	Cu
Berkeley Pit AMD	2.85	363*	1021	192
Filtrate I (20-mL peroxide)	4.60	41	1.07	88
Filtrate II (50-mL peroxide)	4.64	30	1.66	82
Filtrate III (1,230-mL peroxide)	5.00	12	1.84	33

\*note that analyses of this sample by ACZ Laboratories gave an aluminum concentration of 283 ppm.

**Table 6-2. Summary of Metals Analyses (ppm) as Determined by ICP Analysis at Montana Tech Analytical Laboratory for Treated Berkeley Pit AMD after KAD Loading Stage**

<b>Sample ID</b>	<b>PH</b>	<b>Al</b>	<b>As</b>	<b>Cd</b>	<b>Cr</b>	<b>Cu</b>	<b>Fe</b>	<b>Mn</b>	<b>Ni</b>	<b>Zn</b>	<b>SO<sub>4</sub></b>
BP AMD	2.8	283	0.70	1.940	0.04	192	1020	229	1.08	611	9,750
3a (i)	6.3	<0.136	0.018	0.037	<0.011	0.050	<0.014	127.31	0.327	21.40	4,935
3b (i)	6.4	<0.136	0.071	<0.009	<0.011	0.015	0.019	28.13	<0.017	1.026	4,722
3c (i)	7.4	0.215	0.061	<0.009	<0.011	0.019	0.021	6.46	<0.017	0.079	4,707
3d (i)	7.9	0.348	<0.014	<0.009	<0.011	0.017	0.043	1.37	<0.017	0.018	4,761
3a (ii)	6.0	0.379	0.048	0.312	<0.011	0.255	0.024	187.44	0.834	187.43	4,794
3b (ii)	6.2	<0.136	0.048	0.029	<0.011	0.051	0.163	125.80	0.305	19.65	4,725
3c (ii)	6.4	<0.136	0.027	<0.009	<0.011	0.020	0.020	26.53	<0.017	1.007	4,746
3d (ii)	6.6	<0.136	<0.014	<0.009	<0.011	0.015	0.020	19.92	<0.017	0.970	4,695
3e (ii)	6.7	<0.136	0.042	<0.009	<0.011	<0.013	0.024	117.51	0.082	4.685	4,710
3f (ii)	6.1	0.288	<0.014	<0.009	<0.011	0.016	0.045	7.34	<0.017	0.037	4,734
3g (ii)	8.6	0.250	<0.014	<0.009	<0.011	<0.013	0.020	0.039	<0.017	0.018	4,770
Target	6.5-8.5	0.05*	0.05	0.003*	0.05	0.01*	0.30	0.05	0.10	0.10	500

\* Indicated target values are not 2 x MDL

**Table 6-3. Summary of Metals Concentrations (ppm) as Determined by ACZ Laboratories using ICP Analysis for Final Polished Berkeley Pit Samples**

Sample Name	KAD Addition	pH	Al	As	Cd	Cr	Cu	Fe	Mn	Ni	Zn
<i>Berkeley Pit AMD</i>		2.8	283	0.70	1.940	0.04	192	1020	229	1.08	611
<i>Recycled KAD</i>											
5a(i-2.5A)	5 g KAD	7.2	0.08	<0.04	0.007	<0.01	0.03	<0.01	40.9	0.02	1.53
5b(i-2.5A)	10 g KAD	7.6	0.17	<0.04	<0.003	<0.01	0.03	<0.01	4.830	<0.01	0.21
5c(i-2.5A)	20 g KAD	7.9	0.30	<0.04	<0.003	<0.01	0.02	<0.01	0.407	<0.01	0.04
5d(i-2.5A)	30 g KAD	8.9	0.51	<0.04	<0.003	<0.01	0.04	<0.01	0.028	<0.01	0.01
5d(ii-2.5A)	10 g KAD	7.6	0.19	<0.04	<0.003	<0.01	0.04	<0.01	4.09	<0.01	0.21
5f(ii-2.5A)	5 g+3.9 g KAD	7.6	0.15	<0.04	<0.003	<0.01	0.02	<0.01	3.170	<0.01	0.20
5g(ii-2.5A)	10 g + 7.6 g KAD	7.9	0.29	<0.04	<0.003	<0.01	0.02	<0.01	0.386	<0.01	0.04
<i>Fresh KAD</i>											
5a(i-2.5B)	5 g KAD	8.5	0.38	<0.04	<0.003	<0.01	0.02	0.02	0.204	<0.01	<0.01
5b(i-2.5B)	10 g KAD	8.9	0.34	<0.04	<0.003	<0.01	0.02	0.02	0.02	<0.01	<0.01
5c(i-2.5B)	20 g KAD	9.2	0.59	<0.04	<0.003	<0.01	0.01	0.01	<0.005	<0.01	<0.01
5d(i-2.5B)	30 g KAD	9.6	1.80	<0.04	<0.003	<0.01	0.02	<0.01	<0.005	<0.01	<0.01
5d(ii-2.5B)	10 g KAD	8.9	0.37	<0.04	<0.003	<0.01	0.02	0.03	0.015	<0.01	<0.01
5e(ii-2.5B)	2.5 g + 1.9 g KAD		0.41	<0.04	0.004	<0.01	0.02	0.03	0.162	<0.01	<0.01
5f(ii-2.5B)	5 g + 3.9 g KAD	8.8	0.36	<0.04	<0.003	<0.01	0.02	0.05	0.008	<0.01	<0.01
5g(ii-2.5B)	10 g + 7.6 g KAD	9.4	1.11	<0.04	<0.003	<0.01	0.01	0.02	<0.005	<0.01	<0.01
	Target Values	6.5-8.5	0.05	0.05	0.003	0.05	0.01	0.30	0.05	0.10	0.10

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## 7. Discussion

In general, the results generated by this bench-scale treatment of Berkeley Pit AMD demonstrate that use of KAD can remove some metals in the AMD solution down or below the target levels. The data also shows that metal concentrations, except for aluminum, can be reduced to target values over a wide range of dosage and resultant pH conditions using either fresh KAD or KAD that has been recycled through a base stripping process, or alternatively, within the first KAD loading stage of the test protocol. With modification of the process circuit and possibly a variant of KAD material to that used in these trials, it is possible that all metal concentrations, including aluminum, will be reduced to below the target levels for treated Berkeley Pit AMD.

Proper use of engineered circuits as well as appropriate choice of analytical technique to measure metal concentrations at very low levels will ensure the KAD technology provides reproducible results for Berkeley Pit conditions. The robustness of the KAD material, as well as a strong ability to remove many metal ions at relatively low pH values (i.e., <8.5), suggests that process circuits can be designed with adequate control to maintain target concentrations in treated waters for significant periods of time.

*KAD Loading Stage:* Data for treated AMD after this stage (as shown in Table 6-2) clearly demonstrates the potential of the KAD technology for the removal of metals from AMD to target concentrations at pH values within the 6.5 to 8.5 band. At many dosage rates, the amount of KAD reduced many metal ions to below target concentrations [e.g., 3b (i), 3c (ii), 3e (ii)] even though analyses of certain metals such as aluminum may be unreliable.

*Loaded KAD Stripping Stage:* This segment of the treatment protocol is intended to simply obtain a "stripped" KAD or a recycled KAD that can be tested for continued removal of metal ions from the AMD. Data for eluate solutions obtained after stripping and

washing the metal-loaded KAD with ammonium solution are given in Table 7-1.

While these stripping trials are not a critical element of this specific protocol, there is indication that some metal concentrations can be achieved for simple loading/stripping cycles using KAD. As noted earlier, a number of other standard stripping solutions can be used in a more effective manner to achieve higher metal concentrations in an eluate. Nevertheless, the data in Table 7-1 also shows that copper, cadmium, and zinc will be preferentially concentrated by this stripping protocol. Other less desirable elements (for commercial exploitation through metal recovery or sulfidation to form a concentrate) are not preferentially concentrated through this mechanism.

*KAD Polishing Methods:* Given the above caveats on analytical techniques, the data presented in Table 6-3 compares favorably with the expected target values for treated Berkeley Pit AMD. For the elements arsenic, cadmium, chromium, iron, nickel, and zinc, the general trend of analyses in Table 6-3 suggests that KAD can be used to treat the Berkeley Pit AMD to target concentration levels in the required pH range by judicious use of a polishing step. Depending on the manner in which pH can be controlled with the use of "fresh" KAD in an engineered process circuit, the remaining metals, aluminum and manganese, can also be reduced to target levels or near target levels. Indeed, as demonstrated in Table 6-2, these elements are also reduced to below the target levels with an appropriate dosage of KAD.

The various dosage rates applied within the polishing stage of this protocol have been designed to provide insight into optimum strategies for complete removal of metal ions at specified pH values. This approach allows some evaluation of process circuit conditions, although to precisely mimic conditions in a process circuit, as demonstrated in the field in Australia, would require more complex bench-scale protocols.

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Nevertheless, it is apparent that polishing methodology in which double doses of smaller amounts of KAD (whether “fresh” or recycled) results in a lower pH value of the treated solution for similar metal concentrations than a single dose of equivalent KAD mass. This data implies that two- or three-stage treatment “columns” or “thickeners” will effectively (and selectively) reduce the metal concentrations to target levels and are likely to maintain the pH of treated solutions at 8.5 or less. This approach also shows potential for achieving similar metal concentrations in the treated solution for lower total additions of KAD to the polishing circuit.

The higher pH values for “fresh” KAD additions to the polishing process are due primarily to the state of the KAD material after manufacture. For example, the nature and extent of the washing process after manufacture influences the pH elevation experienced by a solution in contact with KAD. KAD basicity values, or a measure of the pH elevation on a solution, will vary according to the final washing process used in manufacturing. This basicity value may vary by a factor of two or three depending on the method of manufacture. In bench-scale trials, it is not a trivial matter to control the pH of test samples with the protocols used for these Berkeley Pit trials. However, in a full-scale engineered process, circuit equilibrium can be designed so that overflow pH < 8.5 and thus certain metal concentrations can be kept to target values by judicious use of polishing stages. In a large-scale engineered process, the type of KAD manufactured and the level of basicity required, matched with an appropriate pore structure that influences cation exchange capacity, will be important “optimization strategies” to be evaluated.

Lower pH values for similar dosages of recycled KAD in all polishing trials confirm the expectation about degree of washing for KAD during the manufacturing cycle. For example, for serial additions of 5 g and 3.9 g of KAD to 50 mL of liquid, the pH values are 7.6 and 8.8, respectively, for recycled KAD and “fresh” KAD. In each of these cases, with the exception of manganese levels, all other metal ions have been removed to similar concentration levels. In the case of recycled KAD, the ammonia stripping stage has also removed small amounts of caustic that have been entrained in the KAD material during manufacture. Thus, in a larger scale process circuit operating at equilibrium using an optimized KAD, it is reasonable to expect that all target metal concentrations will be met within the required pH range.

All data was produced by ACZ Laboratories, Inc., and quality control (QC) summaries of all data are available.

## 7.1 Data Quality

Samples were collected according to the frequency outlined in the project-specific QAPP. Data for critical and noncritical analyses was generated by the Montana Tech Analytical Laboratory with independent data validation by the Montana Tech Associate Project Manager.

Confirmatory analysis of critical samples was performed by ACZ Laboratories. As part of the analytical report, ACZ included QA/QC summaries, which are available by request from Montana Tech. The data was validated according to the EPA’s *Contract Laboratory Program National Functional Guidelines for Inorganic Data* Review by the Montana Tech Associate Project Manager. All data contained in this report has been appropriately flagged.

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**Table 7-1. Elute Metal Concentrations (ppm) Obtained from Loaded KAD\***

Sample Name	Primary KAD Addition	Al	As	Cd	Cr	Cu	Fe	Mn	Ni	Zn
4a(i)	5 g KAD	1.46	<0.04	2.136	0.024	192.0	0.048	17.64	0.924	889.2
4b(i)	10 g KAD	0.84	<0.2	1.440	<0.05	98.88	<0.05	30.00	0.888	480.0
4c(i)	20 g KAD	0.50	<0.04	0.492	0.024	35.52	0.06	10.55	0.348	198.0
4d(i)	30 g KAD	0.78	<0.2	0.059	<0.05	4.90	<0.01	0.018	0.120	40.7
4d(ii)	10 g KAD	0.77	<0.04	1.021	0.024	93.60	0.024	24.72	0.636	428.4
4f(ii)	5 g + 3.9 g KAD	0.73	<0.04	1.145	0.012	107.6	0.036	23.88	0.54	482.4
4g(ii)	10 g + 7.6 g KAD	0.58	<0.04	0.581	0.012	47.16	0.048	18.12	0.36	247.2

\*results as received are for 30-mL samples diluted with 6 mL HCl - this table gives the undiluted concentrations

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## 8. Process Economics

In general, it is difficult to precisely translate bench-scale experimental data to a scaled up engineering process for the treatment of AMD. However, there are consistencies in bench-scale data that can be used to estimate, with a limited amount of accuracy, some of the potential operating costs for the use of KAD technology in the treatment of Berkeley Pit AMD. For example, bench-scale treatments of both simulated and actual Berkeley Pit AMD both consistently demonstrated that the pretreatment, KAD loading, and KAD polishing stages all used similar dosage levels of materials and achieved, for the most part, similar levels of metal ion concentration in the treated water.

Experience with a 25 times scaleup (from 520 gallons per day to 13,000 gallons per day) indicates that bench-scale trials and smaller scale processing trials generally overestimate the amount of KAD material required to achieve a certain metal concentration in the treated water. Thus, estimates of operating costs for using KAD technology to cleanup Berkeley Pit AMD are necessarily inaccurate and possibly a “worst-case” costing.

These bench-scale trials also demonstrated that metal-loaded KAD can be stripped of metals into a concentrated solution, and then the stripped KAD can be reused to efficiently reload more metals from the AMD. Optimized trials of this approach to reduction of process economics could not be undertaken on the Berkeley Pit AMD due to limitations to time and funds. However, it is apparent that significant levels of copper and zinc

could be efficiently recovered from the Berkeley Pit AMD if KAD technology was used. Up to 50% of the available copper metal as well as almost all of the available zinc could be recovered from the Berkeley Pit AMD using a scaled up engineering process for the utilization and recycling of KAD materials.

For a 3-million-gallons-per-day treatment and recovery operation, as required to match the inflow of AMD into the Berkeley Pit, preliminary estimates of operating costs can be made for a process based upon the thickener/filtration method as exemplified with a 13,000-gallons-a-day treatment plant. Flocculant usage is based on consumption at this pilot-scale plant currently operating at Mount Morgan in Australia. Unit costs for reagents are also based on known costs in Australia converted to U.S. dollars at the exchange rate prevailing at the time this report is written.

Using consumption rates for lime and KAD during the test program and the expected flocculant usage as indicated above, the daily reagent costs are calculated at \$23,200 based on a treatment rate of 3 million gallons per day. This equates to 0.77 cents per gallon of AMD treated. Inclusion of a metal recovery stage in the KAD process circuit will reduce this estimate of average operating cost. The amount of reduction to the average operating cost will be dependent on the metal recovery process used (e.g., metal plating or sulfidisation) and the prevailing market price of the metal or metal concentrate.

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## 9. Independent Summary

These bench-scale trials of one type of KAD material for cleanup of Berkeley Pit AMD demonstrate that, with the exception of aluminum for which analytical results and methodology are equivocal, metal ions can be reduced to the target concentrations within the specified pH range for treated water. In trials of other AMD systems, it is apparent that aluminum can be reduced to at least the target concentrations

for Berkeley Pit AMD. Data obtained from complementary trials related to engineering scaleup of a treatment process also suggests that KAD can be reused in a process circuit for treatment of Berkeley Pit AMD and that certain valuable metals such as copper and zinc can be concentrated in a “pregnant liquor” with potential for the recovery of the metal or metal concentrate.

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## 10. Conclusions

The flexibility of the KAD manufacturing process, as well as the robustness of KAD materials, implies that a process circuit can be developed for the economic cleanup and recovery of metals from the Berkeley Pit AMD. In comparison to other competing technologies, such as precipitation through pH adjustment or coprecipitation using pH adjustment, the KAD technology offers the advantages given below.

- Significantly reduced consumption of lime, precipitating agents and/or oxidants.
- Significantly reduced levels of waste solids such as lime sludge etc. (because lime-based pH adjustment and oxidation occurs at  $\text{pH} < 4.6$ ).
- Achievement of lower metal ion concentrations for a given pH value for the range  $4.5 < \text{pH} < 9.0$ .
- Reduction of metal ion concentrations (with the possible exception of Al) to target values within the required pH range ( $6.5 < \text{pH} < 8.5$ ).
- Inherent increase in pH value for treated acidic water with use of KAD; equilibrium value for process circuit trends toward the required pH range.
- Capacity to reuse the KAD material (estimated reuse for up to 20 times) by base removal of loaded metals.
- Reuseable KAD material incorporated into a "polishing strategy" in which difficult elements can be reduced to target levels with minimal contamination of valuable metals.
- Low volume demand for KAD material due to reuse, hence minimized solid waste disposal as "spent KAD" may be environmentally acceptable.
- Flexibility in scaled up engineering design to allow reuse of KAD and recovery of metals in a continuous process circuit.
- Flexibility in scaled up process design to integrate with other materials or processes that may reduce other contaminants such as sulfates.
- Capacity to design modular and/or alternative process circuits to accommodate flow rate and or consumption issues at major environmental cleanup sites.

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## 11. References

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