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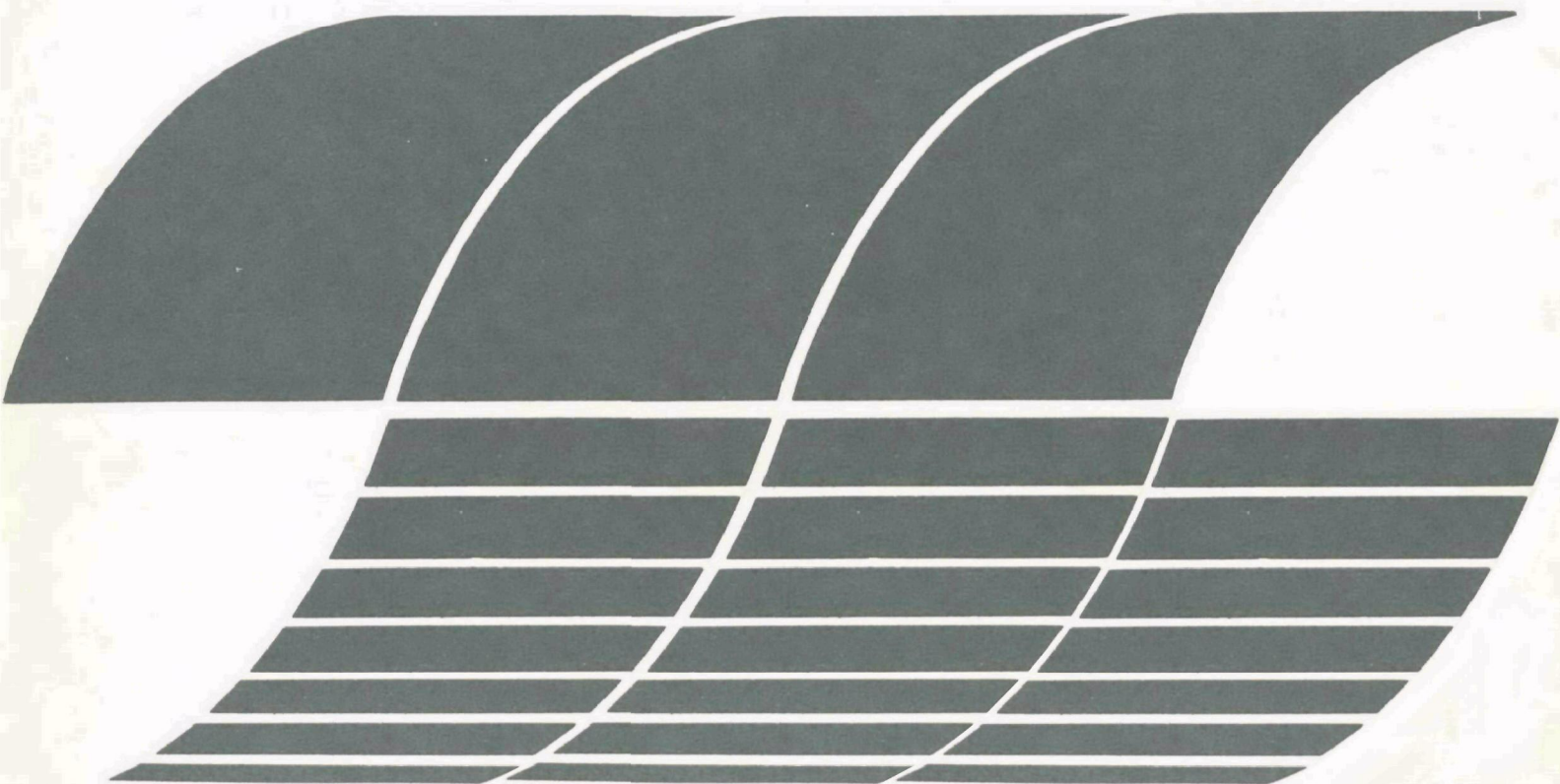
Rotating Disc Biological Treatment of Acid Mine Drainage

Interagency Energy/Environment R&D Program Report

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ROTATING DISC BIOLOGICAL TREATMENT
OF ACID MINE DRAINAGE

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FOREWORD

When energy and material resources are extracted, processed, converted, and used, the related pollutional impacts on our environment and even on our health often require that new and increasingly more efficient pollution control methods be used. The Industrial Environmental Research Laboratory - Cincinnati (IERL-Ci) assists in developing and demonstrating new and improved methodologies that will meet these needs both efficiently and economically.

This report describes studies that successfully utilized the rotating biological contactor (RBC) as a unit process in the treatment of acid mine drainage. The RBC, using indigenous bacteria, oxidized ferrous iron to the ferric state, thus making the mine drainage amenable to limestone neutralization and widening the mine operator's choice of treatment options. The information contained in this report will be of interest to mine operators, regulatory agencies, and academia. For further information, please contact the Resource Extraction and Handling Division.

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ABSTRACT

The rotating biological contactor (RBC) was investigated under field and laboratory conditions for application to Fe(II) oxidation in acid mine drainage. At three coal mining locations in Pennsylvania and West Virginia, treatment of six heterogeneous mine waters was investigated in experiments with pilot-scale (0.5-m diameter) and prototype (2.0-m) RBC units. In the field and laboratory, synthetic and supplemented natural mine drainage were used with bench-scale RBC units to study certain potentially influential factors on Fe(II) oxidation under controlled conditions.

Continuous biological oxidation of Fe(II) to less soluble Fe(III) was accomplished at natural mine water temperatures as low as 0.4°C at Hawk Run, Pa. and as high as 29°C at Crown, W. Va. Reduction of Fe(II) oxidation efficiency at 0.4°C amounted to 10 to 20 percent of that achieved at 10°C at the same site. Oxidation efficiency was above 80 percent at each location for both RBC field units at mine water temperatures of 10 to 29°C. Micro-biological oxidation with the 0.5-m RBC was unaffected at influent mine water pH values in the range of 2.18 to 5.50 (Crown, W. Va.). Lower influent Fe(II) in Hollywood, Pa. mine drainage (71.6 mg/ℓ) resulted in higher oxidation efficiency at equilibrium for the 0.5-m and 2.0-m RBC units as compared to treatment efficiency when mine water contained about twice the influent Fe(II) content (5.2- and 2.9-percent change, respectively).

Fe(II) oxidation efficiency was an average 10 percent lower with the 2.0-m than with the 0.5-m RBC under equivalent conditions with homologous mine drainages. The observed decrease in oxidation was due, in large part, to nonmicrobiological factors such as increased short-circuiting, lower residence time, and a smaller effective surface area which may be increased through proper design.

In experiments with synthetic mine drainage, Fe(II) oxidation in the bench-scale RBC was improved by supplementation with natural mine drainage. Examination of solids samples removed from disc surfaces of the 0.5-m RBC operating at Hollywood, Pa. revealed the presence of iron-oxidizing and heterotrophic bacteria in a gelatinous, iron-containing matrix. A gelatinous surface covering was not seen on disc surfaces in field experiments at Hawk Run, Pa., where Fe(II) oxidation efficiency was 10 to 20 percent less than at other locations. Heterotrophic bacteria recovered from mine water and disc solids may produce the gelatinous film.

Costs for Fe(II) oxidation with the RBC were estimated to be about twice the amortized capital costs and one-half the operating costs compared

to a conventional chemical oxidation process. Neutralization of RBC effluent and separation of precipitated iron solids must be applied in a complete treatment scheme to produce water of a suitable quality for stream-release.

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ABBREVIATIONS AND SYMBOLS

Al	=	aluminum
cm	=	centimeter
CO_2	=	carbon dioxide
DO	=	dissolved oxygen
Fe(II)	=	ferrous iron
Fe(III)	=	ferric iron
H^+	=	hydrogen ion
HCl	=	hydrochloric acid
H_2SO_4	=	sulfuric acid
kw	=	kilowatt
kwh	=	kilowatt-hour
ln	=	natural logarithm (base e)
log	=	common logarithm to base 10
Li	=	lithium
LiCl	=	lithium chloride
m	=	meter
m/min	=	meters per minute
m^3/d	=	cubic meters per day
$m^3/d \cdot m^2$	=	cubic meters per day per square meter
mg/cm^2	=	milligrams per square centimeter
mg/ℓ	=	milligrams per liter
$m\ell$	=	milliliter
MPN	=	most probable number
N	=	normality
NH_3-N	=	ammonia nitrogen
$(NO_2 + NO_3)$-N	=	nitrite plus nitrate nitrogen
Org-N	=	organic nitrogen
pH	=	negative log hydrogen ion activity
rpm	=	revolutions per minute
R	=	correlation coefficient
RBC	=	rotating biological contactor
RO	=	reverse osmosis
SEM	=	scanning electron microscope
Total Fe	=	ferrous iron plus ferric iron
Total P	=	total phosphorus
$\rlap{/}c/m^3$	=	cents per cubic meter
°C	=	degrees Celsius

ACKNOWLEDGMENTS

SECTION 1

INTRODUCTION

BACKGROUND

Acid mine drainage may occur as a consequence of mining activities. Iron and sulfur-bearing minerals present in coal seams and surrounding strata become exposed to air and water; all of which enter into the formation of mine drainage. Source abatement and the treatment of mine discharges are the two current means available for mine drainage pollution control.

Due to recent legislative requirements (67), acid and ferruginous discharges must be treated before stream-release to reduce the net acidity and metal content of drainage. A typical mine drainage treatment scheme includes a neutralization process to remove acidity followed by oxidation of reduced iron and subsequent removal of iron hydroxide solids from the water before effluent discharge. Oxidation of soluble ferrous iron [Fe(II)] is usually performed by chemical oxidation or addition of a commercial oxidant. Biological processes have been examined for treatment of Fe(II) in mine drainage although uncertainties exist regarding their overall applicability, cost, and process effectiveness.

The rotating biological contactor (RBC) process has been shown to provide appreciable reduction in the Fe(II) content of coal mine drainage (54). Biological oxidation of Fe(II) to Fe(III) precedes precipitation of the ferric species as insoluble ferric oxyhydroxides which are formed at the near neutral pH values required for discharge (see Section 4).

The emphasis of this project was to determine if naturally-occurring bacteria could be utilized to effectively and efficiently oxidize the ferrous ion to the ferric form. By visiting different acid mine drainage sources, a wider variety of real world situations could be evaluated.

STUDY OBJECTIVES

Both field and laboratory studies were conducted to examine the Fe(II) oxidizing capacity of the RBC in the treatment of acid mine drainage. Field studies were performed at several mine drainage locations under various conditions. A prototype RBC unit was evaluated under conditions simulating actual treatment of mine drainage. Unaltered, unsupplemented mine drainage was studied in field experiments.

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Bench-scale investigations were performed with synthetic and supplemented natural mine drainage in order to study certain factors under controlled conditions. Previous RBC studies were performed under field conditions using only a small pilot unit and a single source of mine water (54).

Specific objectives of the present study included:

1. Treatment of mine drainages of contrasting physical, chemical, and microbiological nature.

2. Comparative performance evaluation of different size RBC units for determination of potential scale-up problems in design and operation of the process.

3. Pattern of microorganism development on the rotating disc surfaces and their possible role in the treatment system.

4. Requirements for treatment of specific drainages and necessary modifications to accomplish desired effluent quality.

5. Estimated costs for use of the RBC process in mining pollution control and comparison with costs of other Fe(II) oxidation systems.

6. Required processes to be coupled with the RBC to provide a total package for treatment of mine drainage to a suitable quality for stream-release.

SECTION 2

SUMMARY AND CONCLUSIONS

Application of the rotating biological contactor (RBC) wastewater treatment system to Fe(II) oxidation in acid mine drainage was examined in the field and laboratory. Two sites in Pennsylvania and one in West Virginia provided six heterogeneous Fe(II)-containing acid waters for use in experiments with pilot scale and prototype RBC units. Specific characteristics examined in detail for their effect on biological treatment were pH, temperature, and Fe(II) concentration. Bench-scale investigations were performed with synthetic and supplemented natural mine drainage in order to study pH and the effect of constituents in mine waters other than Fe(II) and basal salts. Costs of RBC treatment were estimated and compared to costs of other Fe(II) oxidation systems. Neither the RBC nor other oxidation systems were considered to provide complete treatment of acid mine drainage. Neutralization of RBC effluent and separation of precipitated iron solids would be necessary in order to produce a water suitable for stream-release.

Within the limits of the experimental conditions set forth in this study, the following conclusions were drawn:

1. Under all conditions, continuous microbiological oxidation of Fe(II) to less soluble Fe(III) was accomplished.

2. Mine water temperatures as low as 0.4°C did not inhibit Fe(II) oxidation in field RBC units; however, oxidation efficiency was reduced 10 to 20 percent in comparison to performance at 10°C. The effect of temperature was less pronounced for the 2.0-m RBC than for the smaller (0.5-m) pilot unit.

3. The larger field RBC unit produced an average 10 percent lower Fe(II) oxidation efficiency than the 0.5-m unit under equivalent operating conditions. The observed decrease in oxidation for scale-up to the 2.0-m RBC was due, in part, to nonmicrobiological factors, which included the effect of an increased effective surface area for the 0.5-m RBC due to biological activity on the trough surfaces exposed to mine water, the longer residence time of mine water in the 0.5-m RBC trough (54.4 min) as compared to the larger unit (48.0 min), and an increased short-circuiting of flow through stages of the 2.0-m unit as determined by addition of a tracer (lithium) to RBC influents.

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4. No relationship was observed between Fe(II) oxidation efficiency and influent pH over the ranges examined in field experiments. Acid adjustments of influent mine waters of pH 4.05-5.74 to pH 3 did not result in improvement in maximum Fe(II) oxidation in bench-scale RBC units. The time to obtain an equilibrium oxidation efficiency increased by approximately five days for the RBC which received mine water adjusted to pH 3 as compared to the response on unadjusted mine water.

5. Lower influent Fe(II) in Hollywood mine drainage (71.6 mg/ℓ) resulted in a higher oxidation efficiency at equilibrium for the 2.0-m prototype RBC (95.7 percent) as compared to treatment efficiency when mine water contained about twice the influent Fe(II) content (90.5 percent). A similar but less pronounced observation was made for the smaller field unit (2.9 percent change). Oxidation efficiency exceeded 96 percent when the 0.5-m RBC treated the brine from the Crown reverse osmosis unit that contained between 356 and 453 mg/ℓ of ferrous iron. These higher influent Fe(II) concentrations did not correlate (5-percent level) with oxidation efficiency.

6. Amendment of synthetic mine water feed with natural mine drainage resulted in a net increase in rate of Fe(II) oxidation in the 10-cm bench-scale RBC.

7. Under similar operating conditions, Fe(II) oxidation efficiencies in treatment of Hawk Run mine waters with the RBC field units were 10 to 15 percent lower than treatment efficiencies observed with Hollywood mine drainage. A gelatinous outer layer on RBC discs seen during treatment of Hollywood mine drainage was not observed during experiments at Hawk Run. The oxidation efficiency for treatment of Hawk Run Mine Hole 1 discharge was increased to those levels observed at other locations by lowering of hydraulic loading to both RBC units from 0.16 to 0.08 m^3/d·m^2. The gelatinous layer did not form on RBC discs following the modification.

8. Disc solids, in treatment of mine waters at all field locations, contained iron (25 to 50 percent dry weight), a small proportion of aluminum (0.05 to 0.1 percent dry weight), and viable iron-oxidizing bacteria. Heterotrophic bacteria were recovered from disc surfaces of the 0.5-m RBC during treatment of Hollywood mine drainage.

9. Costs for Fe(II) oxidation with the RBC in treatment of 500 and 5,000 m^3/d of mine drainage were estimated to be 5.6 and 4.8 cents per cubic meter treated, respectively. For both design flows, amortized capital costs for the RBC method were estimated to be about twice those of the conventional oxidation process. Operating costs for the RBC, however, were almost one-half those estimated for chemical oxidation due to lower electrical, maintenance, and personnel requirements.

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10. Sizing the RBC for mine drainage treatment may be accomplished
     after determination of (1) mine water Fe(II), pH, and temperature,
     (2) desired effluent Fe(II)', and (3) expected mine water flow.
     The oxidation rate constant (k, min^{-1}) for a mine drainage
     closest in quality to one of the waters examined in this study
     would be inserted into equation 6.1 (see Section 6, page 49) to
     determine the required detention time (t, min). The required
     surface area would then be determined based on flow and RBC
     surface-to-volume ratio (available from manufacturer).

SECTION 3

RECOMMENDATIONS

The biological oxidation of Fe(II) in acid mine drainage treatment was accomplished using a commercial rotating biological contactor. Other devices are available for biological treatment which rely on the development of microbial films. Any of these devices may potentially perform equally as well as the RBC and could be more cost-effective for a particular application.

Regardless of the method used to complete biological oxidation of Fe(II), neutralization and solids separation of the effluent must follow. The choice of a neutralization system in conjunction with the treatment of the effluent discharged from the biological oxidation process may be expected to bear technically and economically on the total mine drainage treatment system.

Suggested general areas warranting further investigation are:

1. Evaluation of other fixed-film biological treatment devices which operate on the same principle as the RBC and may be more cost-effective for a particular situation. An example of such a unit is the biological tower (packed bed column).

2. Examination of a full-scale mine drainage treatment plant comprising rotating discs for biological oxidation of Fe(II) and alternative methods of acid neutralization.

Specific aspects of the research which did not provide detailed information and which deserve future study are:

1. Kinetic characterization of the RBC at extremely high influent Fe(II) concentrations (above 500 mg/ℓ).

2. Interrelationships between iron-oxidizing and heterotrophic microorganisms in the treatment process.

3. Additional detail on the physical and chemical make-up of solids formed on RBC discs.

4. Possible inhibition in Fe(II) oxidation by various types and concentrations of heavy metals and organic molecules.

SECTION 4

ACID MINE DRAINAGE POLLUTION

INTRODUCTION

The acid mine drainage problem is not new to the coal industry and is not restricted to the mining of coal. Acid discharges to streams have occurred long before the mining of coal. In fact, one method of locating coal seams during the early days of mining (1800's) involved the discovery of acidic, iron-bearing streams (2).

The production of acidity and dissolved contaminants in mine waters occurs through a complex chemical-biological process in which sulfide minerals, particularly pyrites (FeS_2), undergo an oxidation-reduction reaction as illustrated in Equation (4.1). Pyrite occurs naturally in association with many coal seams. A second group of reactions may occur spontaneously if the pH approaches neutrality [Equations (4.2) and (4.3)]. At distinctly acid pH, iron-oxidizing bacteria may mediate Equation (4.2). The Fe^{3+} generated may then chemically oxidize pyrite according to the stoichiometric reaction illustrated in Equation (4.4). Additional Fe^{2+} is formed which may re-enter the cycle via Equation (4.2).

$$FeS_2 \text{ (s)} + \frac{7}{2} O_2 + H_2O = Fe^{2+} + 2SO_3^{2-} + 2H^+ \tag{4.1}$$

$$Fe^{2+} + \frac{1}{4} O_2 + H^+ = Fe^{3+} + \frac{1}{2} H_2O \tag{4.2}$$

$$Fe^{3+} + 3 H_2O = Fe(OH)_3 \text{ (s)} + 3H^+ \tag{4.3}$$

$$FeS_2 \text{ (s)} + 14 Fe^{3+} + 8H_2O = 15 Fe^{2+} + 2SO_4^{2-} + 16H^+ \tag{4.4}$$
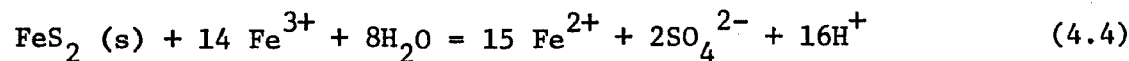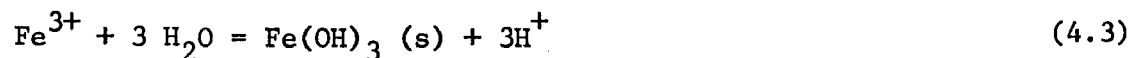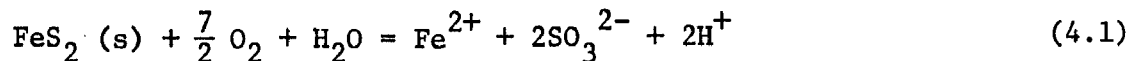
These mechanisms, acting independently or in combination, assist in formation of a highly mineralized, acid water. Mining enhances the production of mine drainage by exposing the sulfide materials to oxygen and water, thereby, permitting chemical reactions to proceed much more rapidly. Several publications may be consulted for a more complete discussion of the complex reactions which may occur in acid mine drainage, mechanisms believed to be important in mine drainage formation, nature and extent of the problems in mining regions across the nation and the world, and various control measures which may be employed to aid in prevention of mine drainage formation (2, 10, 14, 32, 33, 39, 40, 49, 58, 61).

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TREATMENT OF ACID MINE DRAINAGE

Variations in mine drainage characteristics often exist in relation to geology of mining regions. Consequently, several treatment methods may be required. The method chosen for a particular discharge will depend on the quality and quantity of the mine drainage and the ultimate use of the water. Treatment in certain instances may be practiced for potable water production where no other suitable municipal or industrial supply exists (36, 71, 75).

In order to mandate improvement and maintenance of stream water quality, Water Pollution Control Act Amendments of 1972, P.L. 92-500, provides for regulation of the concentration of certain elements in mine discharges (55). Current discharge guidelines were published in the Federal Register on April 26, 1977 (67). A maximum daily effluent concentration of 7.0 mg/ℓ total iron was adopted with the restriction that a 30-continuous day average iron concentration may not exceed 3.5 mg/ℓ. The term "acid or ferruginous mine drainage", as defined in the Federal Register, means "any water drained, pumped or siphoned from a coal mine which before any treatment either has a pH of less than 6.0 or a total iron concentration of more than 10 mg/ℓ." In addition to regulations on total and dissolved iron content, neutralization of the acid is required to meet pH discharge requirements. This regulation may be met by addition of any of several neutralizing chemicals (47). Other limitations currently imposed include those for manganese and total suspended solids. The reader is referred to a report by the U.S. Bureau of Mines (66) for a more complete discussion of current regulations under P.L. 92-500 and their impact on the mining industry.

CHEMISTRY OF IRON IN MINE DRAINAGE

There are several forms of dissolved iron and these may be divided into two general categories based on oxidation state, namely, Fe(II) and Fe(III). Dissolved iron may exist in the free, dissociated state (Fe^{2+}, Fe^{3+}) or may be complexed with other elements (Table 1). Iron content in mine drainage is usually removed from solution by oxidation of soluble Fe (II) to the ferric state [Fe(III)] with corresponding neutralization of the water wherein Fe(III) becomes highly insoluble and will precipitate from solution as pure or impure Fe(III) oxyhydroxides (Figure 1). This precipitation of ferric hydroxide will occur above pH 4. Insoluble Fe(II) hydroxides, on the other hand, do not form to any significant degree unless the pH is elevated above 9 (Figure 2) which, together with the low density of the precipitates, contributes to the difficulty in removing the Fe(II) hydroxides from effluents by plain sedimentation (33).

Soluble Fe(II) - OH complexes are insignificant in ferruginous acid waters (Figure 2); however, Fe(III) - OH complexes are important in acid mine drainage and their presence accounts for the higher solubility of Fe(III) than would be expected when only Fe^{3+} is considered (Figure 1). Equilibrium relationships and calculations employed in constructing solubility diagrams (Figures 1 and 2) are given in Appendix A. Polynuclear complexes of iron are not considered in calculations and may be important in iron solubility. Most acid mine drainage waters contain appreciable concentration of sulfate (SO_4). Chemical equilibria calculations indicate that

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TABLE 1. EXAMPLES OF FORMS OF DISSOLVED IRON IN MINE DRAINAGE

Oxidation state	Free and complexed forms
Fe(II)	Fe^{2+}
	$FeOH^{+}$
	$Fe(OH)_2^{o}$ (aq)
	$Fe(OH)_3^{-}$
	$FeSO_4^{o}$ (aq)
Fe(III)	Fe^{3+}
	$Fe(OH)_2^{+}$
	$Fe(OH)_3^{o}$
	$Fe(OH)_4^{-}$
	$FeSO_4^{+}$

iron-sulfate complexes ($FeSO_4^{o}$ and $FeSO_4^{+}$) are also important in acid mine drainage. These forms contribute to further increases in soluble Fe(II) and Fe(III) above the level expected with free and hydroxy forms of iron (Figures 1 and 2). Therefore, large concentrations of soluble Fe(II) and Fe(III) may occur in acid mine drainage and their removal is facilitated by Fe(II) oxidation and subsequent hydrolysis to Fe(III) oxyhydroxides at the near neutral pH values required for stream-release.

OXIDATION PROCESSES FOR Fe(II)

Potential methods for oxidation of Fe(II) in mine drainage treatment may be broadly divided into chemical and biochemical classes with further subdivision of the chemical category to include processing using atmospheric oxygen, commercial oxidants, and electrochemical oxidation (Table 2).

Purely chemical Fe(II) oxidation with atmospheric oxygen as the sole oxidant is generally employed in contemporary mine drainage treatment plants. This method relies on the more rapid oxidation rates which occur in neutral and alkaline pH ranges (Figure 3). At lower pH values, the rate is

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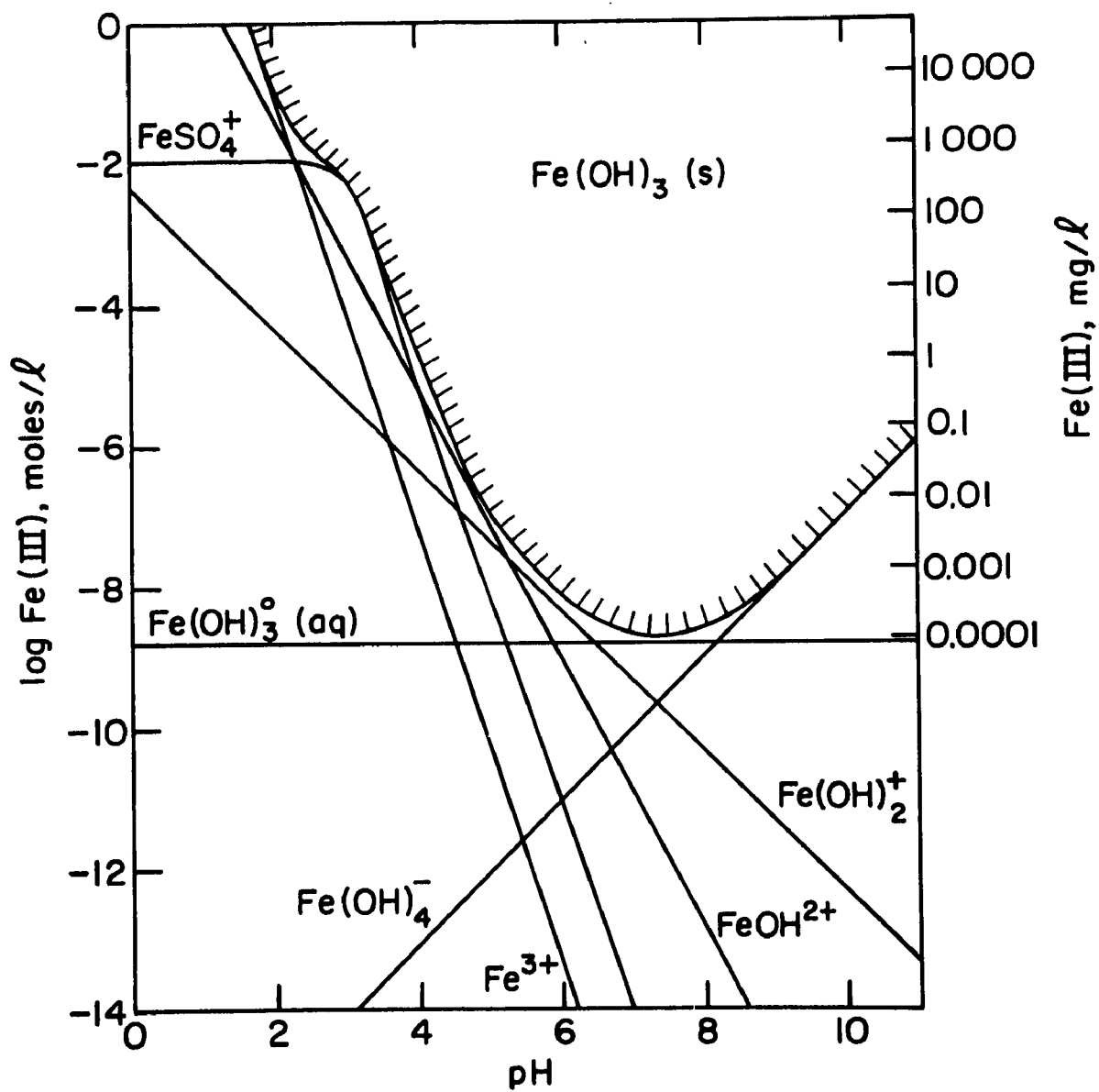
Figure 1. Solubility of pure $Fe(OH)_3$ in the presence of free Fe^{3+}, $Fe(III) - OH$, and $Fe(III) - SO_4$ complexes.
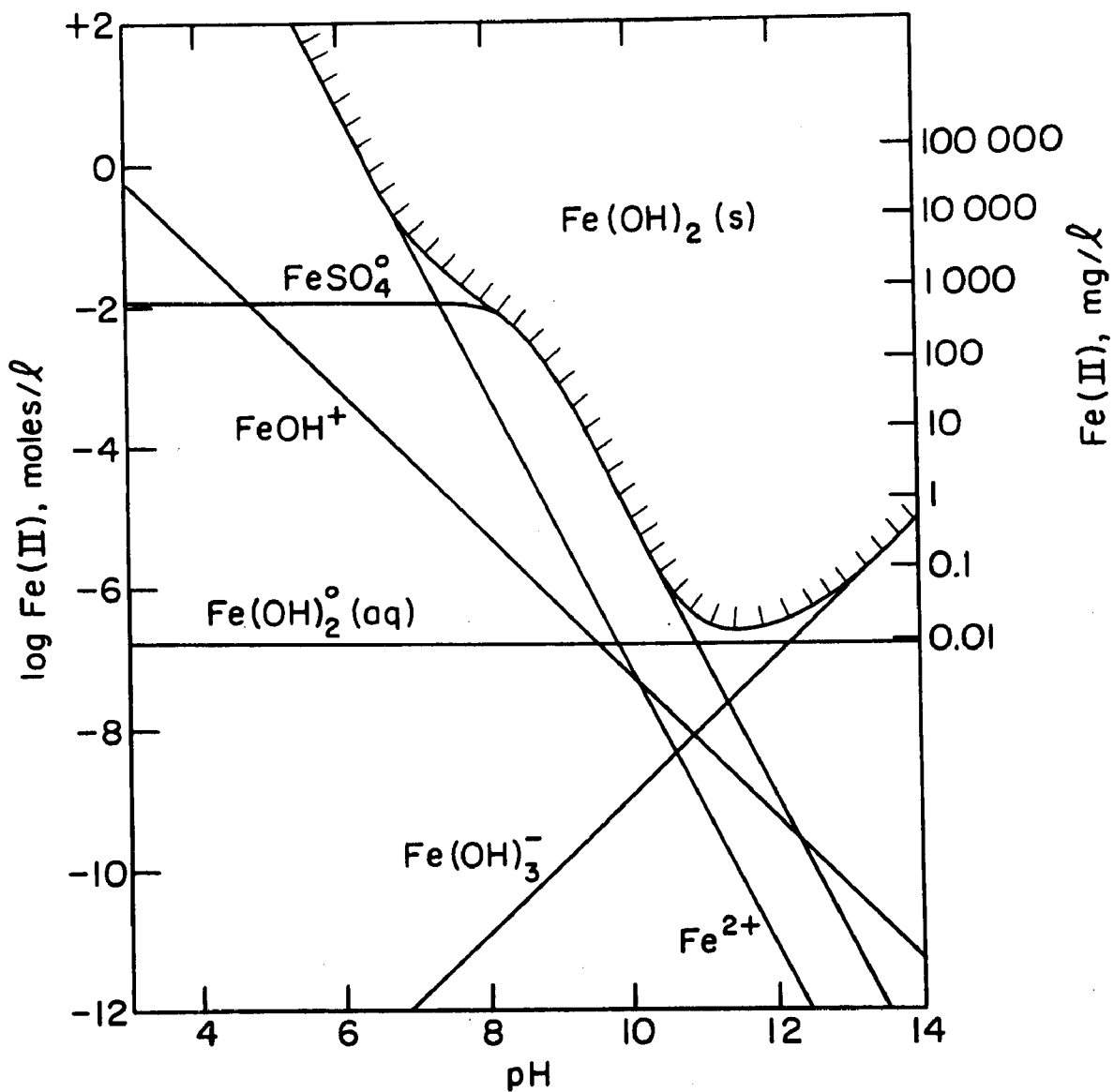
Figure 2. Solubility of pure $Fe(OH)_2$ in the presence of free
Fe^{2+}, Fe(II) – OH, and Fe(II) – SO_4 complexes.

TABLE 2. POTENTIAL METHODS FOR Fe(II) OXIDATION
IN ACID MINE DRAINAGE TREATMENT

Category	Process	References
Chemical (air) oxidation	Mechanical aerators Diffused aerators Cascade aerators Possibly activated carbons	(35, 47, 72, 73, 74) (27)
Commercial oxidants	Hydrogen Peroxide Ozone Chlorine Potassium Permanganate	(11, 17, 31, 60)
Electrochemical oxidation	Carbon electrodes	(28, 37)
Biological oxidation	Activated sludge Trickling filters Rotating biological contactors Possibly activated carbon	(29, 46, 48, 54, 65, 70) (27)

independent of pH and Fe(II) oxidation proceeds very slowly. For instance, Singer and Stumm (62) indicate half times on the order of 1,000 days for purely chemical Fe(II) oxidation at pH 3. Therefore, prior to the chemical Fe(II) oxidation step, mine drainage pH must be elevated to above pH 7 where Fe(II) oxidation can be accomplished by conventional diffused, mechanical, or cascade aeration. The neutralizing chemical must be able to elevate the pH to these levels and lime [CaO or $Ca(OH)_2$] is generally employed for this purpose. Limestone ($CaCO_3$), which has been reported to have certain advantages over lime (47), cannot elevate the pH to levels high enough to stimulate rapid chemical Fe(II) oxidation (72). Wilmoth (73) investigated a combination of lime and limestone for neutralization and found a potential for cost savings. Experiments on use of limestone alone, however, were not feasible with mine drainages containing high Fe(II) concentrations (35, 47, 72).

$$k'' = \frac{-d\ \log\ [Fe(II)]}{dt}$$

$P_{O_2} = 0.20$ atm.

Temp. 25°C
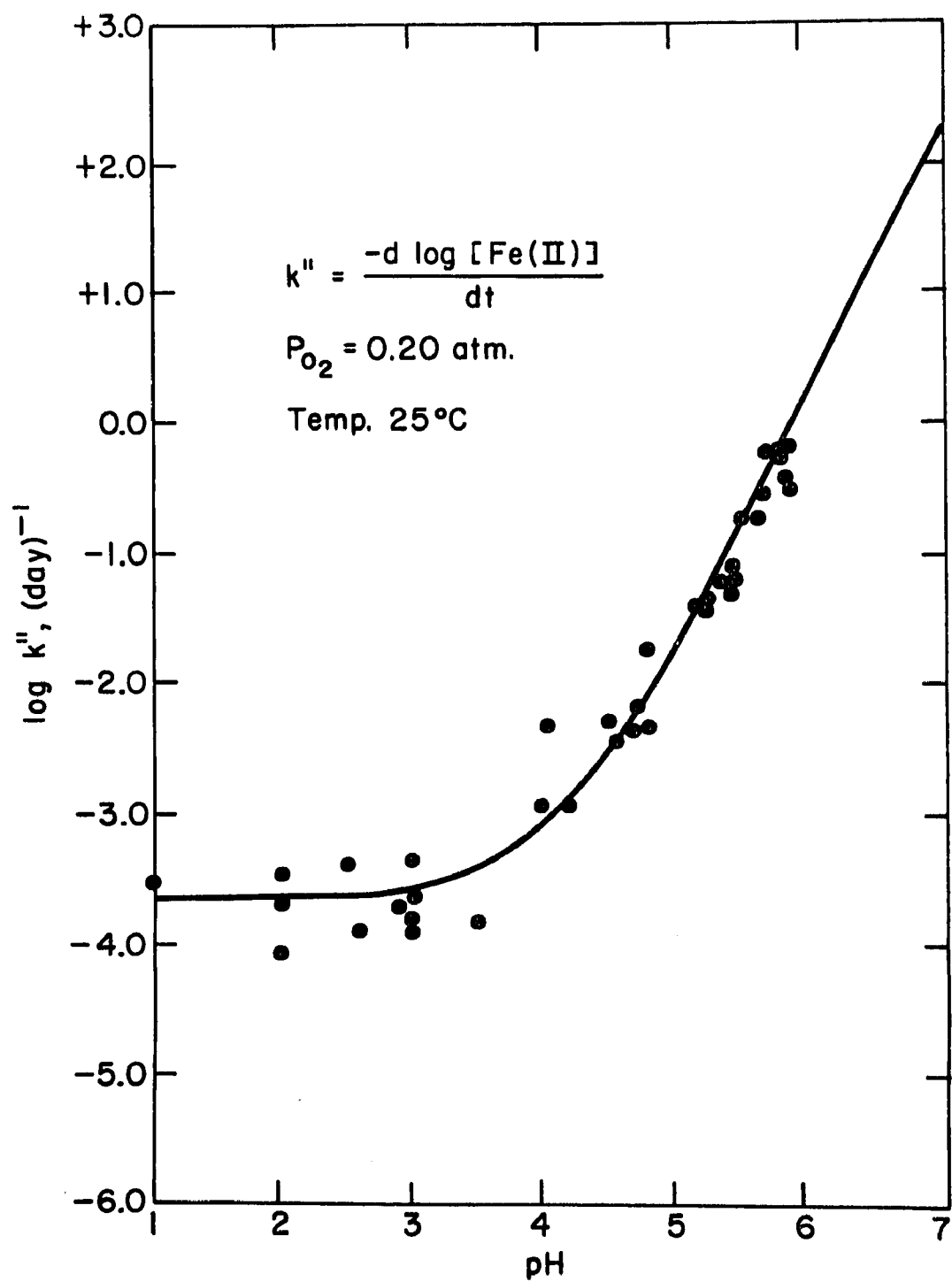
Figure 3. Chemical oxidation rate of Fe(II) as a function of pH (62).

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The alternative processes for Fe(II) oxidation listed in Table 2 may take place under acid conditions, thus allowing the use of limestone as the sole neutralizing agent. This reversal of plant unit processes (Figure 4) may be advantageous in process control and also provide chemical savings. In chemical Fe(II) oxidation, pH must be elevated to levels higher than minimum discharge requirements (pH 6) in order to provide rapid oxidation and combat post-oxidation acid release. This practice necessitates an increase in chemical costs.

Commercial oxidants and electrochemical systems have been investigated as alternative processes for Fe(II) oxidation. In general, either high electrical operating costs (electrochemical oxidation) or high chemical costs (commercial oxidants) have restricted use of these processes for most applications.

Jasinski and Gaines (37) developed an electrochemical process to oxidize Fe(II) in acid waters. The high acid and ionic strength of mine drainage allowed use of the ionic conductivity to promote oxidation of iron on carbon anodes. Type 316 stainless steel was used as the cathode and application of 0.8 volts oxidized 95 percent of the initial Fe(II) in a batch synthetic mine drainage solution. In addition to providing the desired oxidation, electrolytic hydrogen was produced as a by-product. The process was deemed feasible for practical application and cost estimates appeared attractive. However, all costs were estimated based on laboratory experiments with no supporting field data. Franco and Balouskus (28) further evaluated electrochemical processes at laboratory and pilot scale using natural mine drainage. An 18.9 liter/min pilot plant was operated with mine drainage feeds containing 40 and 250 mg/ℓ Fe(II) at pH 2 and 5. At the lower pH approximately 86 percent of influent Fe(II) was oxidized. At pH 5, however, the electrodes coated with Fe(III) precipitates which resulted in decreased Fe(II) oxidation efficiency to 55 to 78 percent. Although the process appeared technically feasible for low pH mine drainage, capital and operating costs for oxidation of 700 m^3/d of mine drainage containing 250 mg/ℓ Fe(II) were estimated to be higher than those for conventional air oxidation by factors of 5.0 and 1.7, respectively.

In 1942, Hann (31) considered the use of ozone as a means of oxidizing Fe(II) in near-potable quality water. Beller, Waide, and Steinberg (11) conducted a conceptual engineering design and economic study of the use of ozone in mine drainage treatment. The study involved analysis of available methods of ozone production and identified process configurations with limestone as the final neutralizing chemical which appeared to provide an attractive mine drainage treatment method. Conclusions of the report, however, were not verified by actual laboratory or pilot plant investigations. Simpson and Rozelle (60) reported preliminary results of laboratory and field studies on use of ozone for Fe(II) oxidation. Ozone was capable of providing appreciable Fe(II) oxidation (greater than 90 percent) although somewhat less oxidation occurred in natural mine drainage as compared to pure FeSO$_4$ solutions and this observation was attributed to oxidation of manganese (II). Recently, Cole et al. (17) investigated the use of hydrogen peroxide with some success to improve the efficiency of a cascade aerator at an existing mine drainage treatment plant. Such application of an auxiliary

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INFLUENT
ACID MINE DRAINAGE

Fe(II) OXIDATION

COMMERCIAL OXIDANTS

ELECTROCHEMICAL OXIDATION

BIOLOGICAL OXIDATION

NEUTRALIZATION

LIME ONLY

LIMESTONE AND LIME

NEUTRALIZATION

LIMESTONE ONLY
LIME ONLY

Fe(II) OXIDATION

CHEMICAL OXYGENATION

COMMERCIAL OXIDANTS

CLARIFICATION
SLUDGE HANDLING

CLARIFICATION
SLUDGE HANDLING

TREATED
EFFLUENT

TREATED
EFFLUENT

Figure 4. Location of alternative Fe(II) oxidation process
and neutralization options in two acid mine
drainage treatment schemes.

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oxidant may prove cost-effective by eliminating the need for treatment plant expansion in a manner an .lagous to polymer use to improve clarification processes.

BIOLOGICAL Fe(II) OXIDATION

In the preceeding discussion on chemical Fe(II) oxidation and its dependency upon pH, the term "purely chemical" was repeatedly stated. Its use was to clearly distinguish chemical activity from the interaction of microorganisms which influence the overall rate of transformation of Fe(II) to Fe(III). The oxidation of Fe(II) by iron-oxidizing bacteria may be illustrated by Equation (4.5).

$$Fe^{2+} = Fe^{3+} + e^- + 11.5 \text{ kcal} \tag{4.5}$$

The liberated electron can be used by the iron-oxidizing bacterium, Thiobacillus ferrooxidans, as the sole energy source. The energy is indirectly utilized for ultimate reduction of CO_2 into new cell material. Organisms which fix CO_2 as a primary carbon source and utilize inorganic chemicals or radiant energy are called autotrophs. This terminology allows differentiation from heterotrophic organisms which require preformed organic carbon for implementation of vital processes. Organisms which gain major energy from mineral sources as do the iron-oxidizing bacteria, are termed chemolithotrophs.

The iron-oxidizing bacteria related to T. ferrooxidans are ecologically compatible and indigenous to acid waters characterized by low pH and high oxidation-reduction potential (Eh). It is evident that these bacteria perform a substantial contribution to the production of acid mine drainage constituents by completing the cycle in the chemistry of mine drainage. Other microorganisms have been reported to exist in acid drainage and mine water polluted streams, e.g., gram-positive and gram-negative heterotrophic bacteria, algae, yeast, protozoa, and fungi (19, 23, 43).

BIOLOGICAL TREATMENT OF ACID MINE DRAINAGE

Initial attempts to utilize iron-oxidizing bacteria in mine drainage treatment were patterned after the conventional activated sludge sewage treatment process (29).

Glover (29) reported limited success with pilot scale biochemical Fe(II) oxidation. Nutrient supplemented acid mine drainage was fed in series to three, 140-ℓ aerated vessels. The continuous flow system required about 80 days to establish an equilibrium oxidation rate of 83 mg/ℓ Fe(II) per hour at a mine water temperature of 15 to 20°C. Attempts to improve the oxidation rate involved recycling combined bacterial-Fe(III) solids to maintain a high iron-oxidizing bacterial population in the aeration chambers. The overall activity was increased ten-fold by sludge recycle although few viable microorganisms were observed in the return solids. The oxidation rate was found to decrease ten-fold at freezing mine water temperatures. Glover considered these rates of Fe(II) oxidation to be sufficiently high to

warrant construction of a pilot plant to include neutralization using limestone. The plant was operated for 28 months and major problems were encountered with biological sludge deposition in reactors and piping. The main advantage cited for the process was the ten-fold reduction in sludge volume produced in comparison to the conventional lime process. Extremes in temperature, acidity and Mn(II) concentration were suggested as potential limitations in use of the process for acid mine drainage treatment.

Whitesell, Huddleston, and Allred (70) studied microbiologically mediated acid mine water treatment at laboratory and pilot scale and failed to achieve a rate of Fe(II) oxidation in 3,800 m^3 reactors similar to that observed in the laboratory. The reduction in surface-to-volume ratio through scale-up of the process was thought to be responsible for inability to achieve laboratory results in the field.

Lovell (47) compared a mechanically aerated activated sludge type system to a trickling filter for microbial Fe(II) oxidation. The fixed-film biological oxidation approach utilized in the trickling filter proved far superior in performance to the suspended growth system. Oxidation performance for the 10.7-m diameter trickling filter ranged from 60 to 94 percent Fe(II) oxidized during the six months in which continuous operation was reported. By comparison, the deep tank system was observed to be more sensitive to changes in Fe(II) concentration and flow rates although similar efficiencies were experienced by use of longer liquid retention times. During winter operation of the trickling filter, influent mine water froze at the surface of the reactor, preventing flow through the media. A plastic film placed over the reactor permitted continued operation in winter. Following one year of operation, hydraulic flow rates were reduced somewhat by Fe(III) deposits in the voids of the reactor media. The control and removal of these deposits were considered essential and Lovell suggested the need for further study. Additional experiments by Lovell (48) revealed that a polypropylene filter medium eliminated media disintegration problems and substantially reduced the problem of clogging.

Unz and Lieberman (65) studied the microbial populations and transformations of mine drainage percolated through columns of trickling filter media and postulated that, under suitable conditions, a fixed-film biological method was feasible for Fe(II) oxidation in acid mine drainage treatment. Baskets containing columns of either argillite stone or polypropylene filter media were inserted into cased cores in the prototype trickling filter previously examined by Lovell (47). Mine water was allowed to percolate through 30- and 60-cm columns of trickling filter media. The polypropylene filter medium was found to be superior to argillite stone under all conditions. At a hydraulic loading of 0.05 $m^3/d \cdot m^2$, oxidation efficiencies ranged from 87 to 96 percent for percolation through a 30-cm column of polypropylene media. Agrillite stone was observed to fracture and disintegrate following contact with mine water, apparently due to its inability to withstand the acidic nature of the drainage. Under the conditions encountered, it was concluded that Fe(II) oxidation in the columns was microbially mediated. Ferruginous solids formed on the filter media following continuous application of mine water contained gelatinous organic matter with embedded iron-oxidizing and heterotrophic bacteria. It was concluded that further

microbiological and engineering research was desirable to develop and optimize the method, and it was suggested that other biological treatment devices may be more effective in this regard.

Olem and Unz (54) conducted small pilot scale experiments with the RBC wastewater treatment device to provide optimized fixed-film biological Fe(II) oxidation in acid mine drainage treatment (see Section 5).

SECTION 5

ROTATING BIOLOGICAL CONTACTOR TREATMENT SYSTEM

PRINCIPLES

There are many types of fixed-film biological treatment methods that have been applied to the oxidation of biodegradable pollutants. These processes include trickling filtration, contact aeration, activated bio-filtration, biological towers, and other modifications of basic systems which rely on the attachment of microorganisms to an inert surface which in some way contacts the wastewater to be treated. Grieves (30) presented a detailed review of the history and application of fixed-film biological reactors for wastewater treatment. The RBC process will be discussed specifically in the following passage owing to its application in this study for oxidation of Fe(II) in mine drainage.

The RBC is a wastewater treatment system that provides for oxidation of biodegradable pollutants principally through aerobic microbiological action, although in treatment of organic wastes anaerobic transformations may well occur at the base of films. The device consists of a series of large diameter plastic discs which are mounted on a horizontal shaft and suspended in a trough through which the wastewater flows (Figures 5 and 6). The discs are approximately 40 percent immersed in the wastewater and slowly rotated. Following start-up, microorganisms naturally present in the incoming waste-water colonize the surfaces of the discs. Rotation provides intermittent contact with the wastewater for adsorption and assimilation of constituents and exposure to an atmospheric oxygen supply necessary for microbial respiration. The thin film of wastewater which adheres to the discs trickles down the surfaces and absorbs oxygen from the air. Rotation also provides continuous mixing of the wastewater and allows shearing of excess biomass from the discs which remain in suspension and pass through the system with the flow of wastewater. The biological film which develops on the inert plastic surfaces has been reported to be normally 1 to 4 mm in thickness for most domestic and industrial wastewater treatment applications (4).

HISTORY

According to Antonie (4), the RBC was conceptualized by Weigand in 1900 in Germany as a sewage treatment process for removal of biodegradable organic matter. A German patent was issued to Weigand for a device which consisted of a cylinder of wooden slats. A prototype was not developed until the 1930's and experiments at this time were discontinued when the
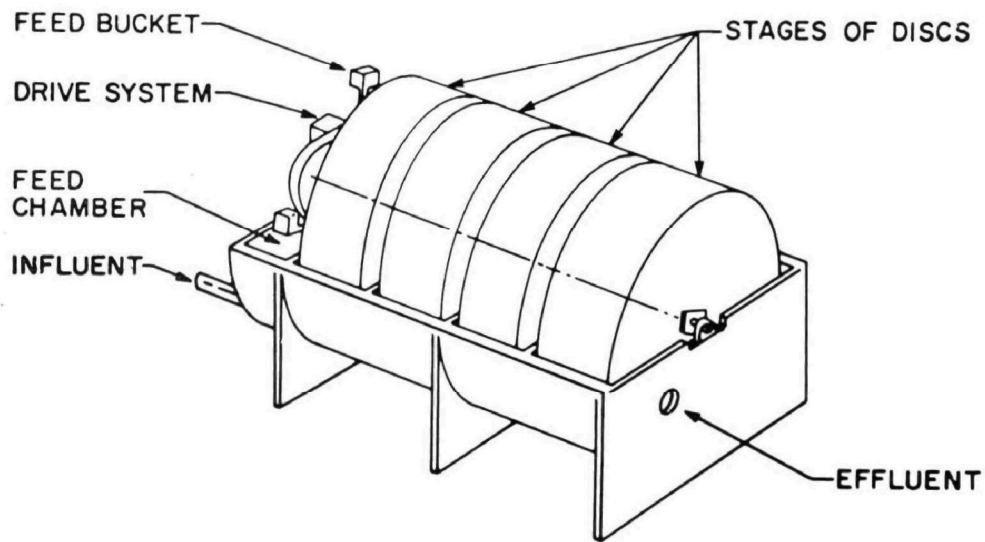
Figure 5. Schematic of rotating biological contactor package unit showing disc assembly suspended in contoured tank.
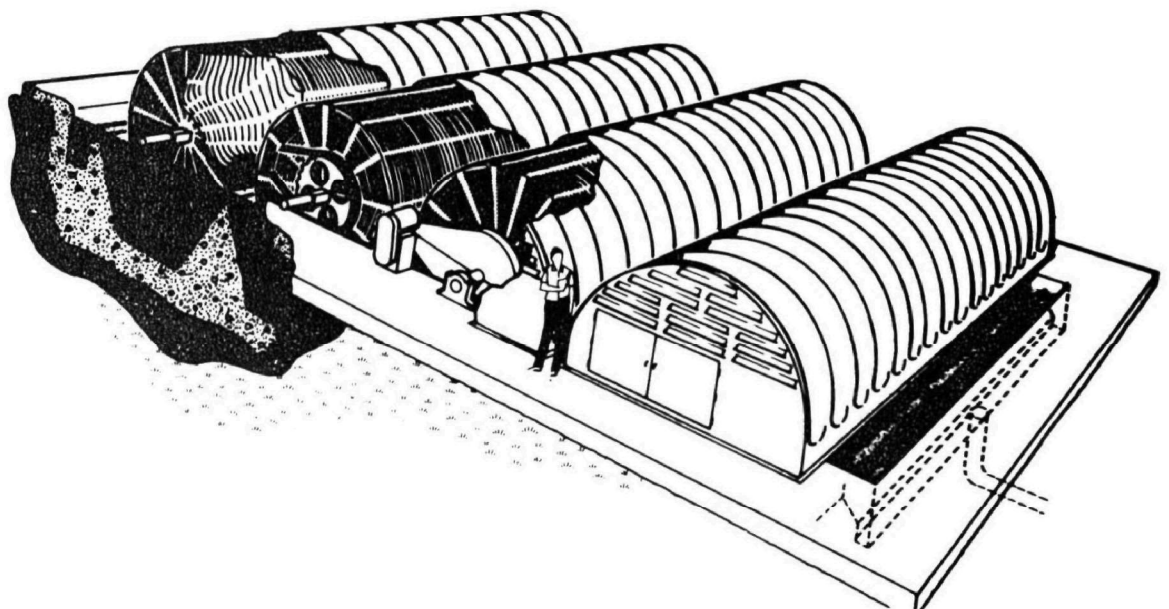
Figure 6. Large-scale rotating biological contactor installation showing disc assemblies suspended in below-ground concrete basins (courtesy of Autotrol Corporation).

unit experienced clogging problems. Doman (20) reported on the development of a rotating metal plate filter in the United States in 1929. In the same year, Allen (1) described the "biologic wheel" which consisted of rotating paddle wheels. Results were not encouraging on further process developments and no further work was reported in the popular technical journals of the time. In 1956, Morgan et al. (53) began pilot plant studies of the "Gresham biological filter", which consisted of rotating screen-wound reels or plywood discs. Results were encouraging in terms of organic matter removals, but construction materials available at that time were not adequate and no further developmental work was reported.

At approximately the same time work was being conducted in the U.S., Hartman and Pöpel at The Technical University of Stuttgart, West Germany, carried out experiments on the use of plastic discs for biological oxidation. Further development of the process using expanded-polystyrene discs resulted in commercial application in Europe. In 1957, the J. Conrad Stengelin Company of Tuttlingen, West Germany manufactured the first commercial 2-m and 3-m diameter polystyrene disc units for wastewater treatment. The process received relatively wide use but was mostly restricted to small installations (less than 1,000 population equivalent).

In the U.S., efforts toward commercial development of the RBC system for wastewater treatment began in the mid-1960's at Allis-Chalmers of Milwaukee, Wisconsin. In 1969, the first U.S. installations began operation at a small cheese factory and at a municipal sewage treatment plant at Pewaukee, Wisconsin.

Following purchase of the "bio-disc" operation from Allis-Chalmers, Autotrol Corporation, also of Milwaukee, Wisconsin, replaced the expanded-polystyrene disc system with corrugated sheets of high-density polyethylene. This modification increased surface area density from 53 m^2/m^3 to 120 m^2/m^3. Further increases in disc diameter and shaft length to 3.6 and 7.6 m, respectively, provided up to 9,290 m^2 of available surface area per unit. Autotrol branded their equipment "bio-surf" and recently other manufacturers have begun production of similar units under trade names such as "RBS" (rotating biological surface) and "bio-drum". The term rotating biological contactor or RBC has gained general acceptance as a generic term for rotating fixed-film biological reactors and will be used in subsequent sections.

PROCESS OPERATION

Wastewater, pretreated if necessary by either primary clarification, nutrient addition, or pH adjustment, is fed on a once-through basis to the RBC system for biological oxidation of waste matters. Recycling of RBC effluent was examined in early stages of development; however, results indicated that this option provided insufficient increase in treatment efficiency to justify the increased piping and pumping costs (4).

Within the RBC trough, wastewater passes through several stages of discs which are separated by baffles. Experience has indicated that staged operation improves residence time distribution and more closely approximates

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"plug flow" conditions (4). Staging is particularly important when it is desired to achieve both organic matter removal and ammonia nitrogen oxidation (nitrification). Fixed microbial cultures which degrade organic matter develop on initial stages of discs while nitrifying bacteria actively occur in the latter stages (4).

Rotational speed of the discs is an important consideration for a variety of reasons. An increase in rotational disc velocity improves the rate of aeration, increases the degree of contact between the microbial film and the wastewater, and more completely mixes the contents of each stage. Antonie and Koehler (7) suggested that peripheral disc velocity should be the design parameter of choice when it was discovered that different diameter RBC units provided similar results when operated at equal peripheral velocities even though the revolutions per minute (rpm) were different. Recently, however, Chesner and Molof (15) reported that the peripheral disc velocities used in pilot studies may produce unexpected results when applied in scale-up due to the high wastewater dissolved oxygen (DO) which may be generated in troughs of smaller diameter pilot units because of the higher rpm. Full size units normally rotate at 1 to 2 rpm. Higher rotational speeds may increase treatment capacity but the accompanying logarithmic increase in power costs have been shown to offset the improved performance capability in many instances (4).

Because solids are continually sheared from disc surfaces at equilibrium conditions, clarification of RBC effluent is generally required. Treatment of certain industrial wastes, however, results in low production of solids and these effluents do not require final clarification. In other instances, intermediate clarification may be required in order to remove excess solids having an oxygen demand which cannot be met by the agitation and aeration provided by the rotating discs.

The major parameter used for RBC design has been hydraulic loading, measured as cubic meters per day of wastewater flow per square meter of disc surface area ($m^3/d \cdot m^2$). This parameter does not aid in sizing the volume of the trough. Antonie (4) found that decreases in the ratio of disc surface area-to-trough volume improved performance by increasing liquid retention time. It was recommended that a surface-to-volume ratio of about 200 m^2/m^3 be employed in construction of RBC units. For units which have an equal surface-to-volume ratio, changes in hydraulic loading will directly affect liquid retention time. Increases in hydraulic loading will decrease retention time and vice-versa. These factors affect the probability of contact of microorganisms on disc surfaces with oxidizable matters in the wastewater flowing through the trough.

Because the RBC process relies on active microbial cultures, wastewater temperature has been shown to directly affect treatment performance (24). The degree to which efficiency is affected is a function of the nature of the resident microbial populations and the reaction of interest. Sharma and Ahlert (57), in a review of biological nitrification, revealed evidence of operational problems in wastewater nitrification systems at temperatures below 8.3°C.

Potentially toxic materials in the incoming wastewater may also
decrease treatment capacity by affecting the fixed biological population.
Several researchers have noted increased ability of fixed-film biological
systems to withstand the effects of potentially toxic or shock loads in
comparison with suspended growth processes.

In order to protect the biological growth on the rotating surfaces
from freezing temperatures and excess wastewater heat loss, enclosures usually
have been employed for the RBC. The enclosure may be a molded plastic cover
(Figure 6) or a separate building or frame structure. Insulation alone has
been shown to be adequate to maintain air temperatures within the enclosure
equal to that of the wastewater.

APPLICATIONS

At present, there are about 1,000 RBC installations treating organic
wastewaters in Europe, located primarily in West Germany, France, and
Switzerland, and almost as many plants in the U.S. (4). Size of plants vary
from those treating the sewage from single-family dwellings to municipal
and industrial facilities with wastewater flows up to 200,000 m^3/d (4). The
short-term large-scale application of the RBC in the U.S. has provided little
information on life of hardware and process stability. As more facilities
are constructed for different applications, operating experience will provide
additional information on the longevity characteristics of the RBC.

Pilot studies have been performed with the RBC to examine treatment
potential for organic wastes such as those from meat and other food process-
ing plants (13), pulp and paper manufacture (12), beverage and distillery
industries (41), dairy farms (5), refineries (18), and textile industries (4).
The process has been applied to pretreatment of industrial wastewaters prior
to entry into municipal sewers as well as treatment of combined domestic and
industrial wastewaters (4). Its use may be combined with other biological
treatment devices such as activated sludge processes or trickling filters.
In the latter case, RBC treatment is added in order to satisfy requirements
for upgrading existing wastewater treatment facilities through increased
organic removals or enhanced nitrification.

Application of the RBC to the myriad of industrial wastewaters requires
varied design considerations unique to the industry. Consideration for
design of industrial and domestic wastewater treatment facilities may include
requirements for primary treatment, secondary clarification, metal or
phosphorus removal, chlorination, sludge handling and disposal, and appli-
cable advanced wastewater treatment. Several mathematical models have been
developed recently (15, 16, 25, 26, 30) to aid in prediction of RBC
performance under varied conditions.

INORGANIC REACTIONS

Nitrification is included in domestic wastewater treatment in order
to reduce ammonia nitrogen concentrations in effluent discharges. Ammonia
causes an oxygen demand in the receiving stream, stimulates eutrophication
and has been shown to be toxic to many species of aquatic life. Nitrifica-

tion may also be applied as a first step in a total nitrogen removal scheme (nitrification-denitrification) (3). The RBC has been used for domestic wastewater nitrification following other biological processes or as the sole biological treatment method whereby nitrifying organisms develop on latter stages of RBC disc surfaces (4).

Certain industrial wastes contain ammonia in excessive concentrations. Nitrification has been required for wastewaters from such industries as latex polymer production and electronics manufacture (4). Treatment of high ammonia sludge supernatant has also been successfully accomplished with the RBC (50).

The various biological reactions which have been discussed previously are considered to proceed optimally at neutral or alkaline pH conditions. Severe upsets in performance have been observed when pH values shift into the acid range, in part, due to the growth of undesirable microbial species, such as yeasts and fungi (4). Processes which require the oxidation of sulfide, thiosulfate, and Fe(II), on the other hand, have been applied successfully for treatment of low pH wastes from depilatory manufacture (4), base metal mining (4), and coal mine drainage (54), respectively. The micro-organisms which are operative in the oxidation of these inorganic ions require a low pH environment. The oxidized species are either suitable for effluent discharge (sulfate in the case of sulfide and thiosulfate oxidation) or more easily handled in a separation step due to its lower solubility [Fe(III) as described in Section 4].

Fe(II) OXIDATION - STUDIES AT HOLLYWOOD, PA.

Previous studies on biological Fe(II) oxidation were conducted with a 0.5-m diameter RBC pilot unit on a single source of mine water at the Experimental Mine Drainage Treatment Facility at Hollywood, Pa. (54). The mine drainage characteristics included a naturally stable pH of approximately 3, relatively constant temperature (9-12°C) and only slight (seasonal) variations in flow and certain physical and chemical characteristics. These experiments were mainly performed to examine the variables in RBC design which may permit appreciable transformation of Fe(II) to Fe(III). Variables examined included hydraulic loading and peripheral disc velocity.

A disc velocity of 19 m/min was observed to be more effective (above 90 percent Fe(II) oxidized) than 10 m/min. Higher disc velocities were not examined in view of the very high DO levels maintained in the reactor, high efficiency of Fe(II) oxidation observed, and a previously reported logarithmic increase in power consumption required for subsequent increases in disc velocity.

Five different hydraulic loading rates were applied to the RBC pilot unit (0.11, 0.16, 0.22, 0.31, and 0.44 $m^3/d \cdot m^2$) and each successive increase resulted in corresponding decreases in Fe(II) oxidation efficiency. Based on these observations, it was concluded that by application of proper design hydraulic loading, any degree of treatment down to 1 mg/ℓ effluent Fe(II) could be achieved for Hollywood mine drainage.

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Kinetics of Fe(II) oxidation reaction were found to follow a concentration dependent, first order relationship at all hydraulic loadings and disc rotation rates examined. Start-up characteristics and time to reach equilibrium oxidation and solids buildup conditions were examined along with an investigation of the chemical and physical characteristics of disc solids and viable iron-oxidizing bacterial populations in disc solids. No other mine drainages were investigated. It is important to note that the RBC and other fixed-film reactors previously observed to be capable of providing appreciable Fe(II) oxidation in field studies were examined only at the Hollywood facility. These limitations in previous studies inspired the present work reported in the remaining sections.

FIELD STUDIES: PENNSYLVANIA AND WEST VIRGINIA

LOCATION OF FIELD SITES

A continuous flow of mine water was maintained through RBC units in experiments conducted during (a) May 22 to July 13, 1977 at the U.S. Environmental Protection Agency Crown Field Site near Morgantown, W. Va., (b) September 8 to November 19, 1977 at the Commonwealth of Pennsylvania Experimental Mine Drainage Treatment Facility, Hollywood, Pa., and (c) January 6 to April 12, 1978 at the Commonwealth of Pennsylvania Hawk Run Mine Water Treatment Plant near Philipsburg, Pa.

Crown, West Virginia

At the Crown Facility two acid waters were available for study. The first water was raw acid mine drainage from an active coal mine pumped from an 85-m deep borehole located along Stewart's Run. A portion of this mine discharge was passed through an experimental reverse osmosis (RO) unit and provided the second water. The RO treatment system was capable of producing approximately 50-percent recovery of water of near potable quality. The remaining portion was continuously rejected from the unit as a concentrate. This "brine" contained approximately twice the original concentration of ionic constituents, including Fe(II), and had a low pH value due to the necessity of pretreatment with sulfuric acid (H_2SO_4) in order to prevent iron fouling of the RO membrane. These characteristics, along with temperature changes through the RO unit, provided a highly polluted, unique quality mine water for the RBC study.

Hollywood, Pennsylvania

The Proctor No. 2 coal mine at Hollywood, Pa. provided acid drainage which was pumped a distance of 180 m from the discharge point to the RBC building. This inactive mine produced a relatively constant flow of approximately 3,000 m^3/d.

Hawk Run, Pennsylvania

The Hawk Run facility is located near two mine holes which produce acid discharges. A third water resulted from the mixing of these two discharges. Mine water from the two mine holes and the combined flow were each examined separately. The drainage from Mine Hole 3 originated 3 km from the plant site and flowed in a shallow, wide stream (Hawk Run) which

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was readily subject to change in water temperature with ambient conditions. This mine hole provided nearly all the flow in Hawk Run. Mine Hole 1 is located at the research facility and the discharge blended with Hawk Run at the site. A schematic of the building which housed the RBC units and the mine drainage streams is presented in Figure 7 and includes the locations at which mine water was pumped to the building from each of the three sources.

MINE WATER CHARACTERISTICS

In order to more precisely interpret the findings of experiments on Fe(II) oxidation with the RBC, it was important to characterize the various mine waters using parameters which are related to the process. Mine waters were analyzed regularly (two to five times per week) during the respective periods of experimentation. Analytical methods are outlined in Appendix B. A summary of mine water characteristics for each of the locations is shown in Tables 3, 4, and 5 and includes statistical analyses for mean and standard deviation.

Crown, West Virginia

The Crown drainage had a higher pH (4.40 to 5.50) and temperature (15.5 to 18.8°C) than other acid mine drainage waters analyzed. The higher temperature may have been due to the effect of pressure on the groundwater and the insulation of the soil at the depth of the borehole (85 m). An extremely high iron-oxidizing bacterial population was observed for the Crown drainage. Wilmoth (73) conducted a more complete chemical analysis of the Crown mine drainage and noted a relatively high sodium ion content (280-670 mg/ℓ). The unusual characteristics of higher pH and sodium content than experienced at other mine drainage locations suggests that the active mine drains through or mixes with a high ionic strength aquifer which is possibly highly buffered and nonacid. A saline (NaCl type) aquifer is not likely because of the very low chloride content (17 mg/ℓ) of the drainage. The unusual characteristics of the mine drainage at Crown, W. Va. provided a high Fe(II)-containing water for experiments in RBC treatment.

The RO brine had a very low pH (2.18 to 2.66) and had about double the ionic strength of the original mine water. It was evident from the low Fe(III) content of the brine that Fe(II) oxidation could not occur during passage of Crown drainage through the RO unit. Hence, treatment of the brine required Fe(II) oxidation. At a 50-percent clean water recovery rate for the RO process, one-half the original mine drainage flow would be rejected as brine which must be then treated prior to stream-release. Clearly, if the RO process becomes a feasible system for potable water production from mine drainage, particularly, with improved clean water recovery rates, very high Fe(II) concentrations present in the brine would require an economical Fe(II) oxidation step in the treatment. It was of interest, therefore, to determine the capability of the RBC for biological Fe(II) oxidation and correspondingly to determine the microorganism survival through the high pressures which developed in the RO modules (approximately 400,000 kg/m^2). Apparently many, but not all, iron-oxidizing bacteria survived the pressures and were rejected along with the other constituents (Table 3). An analysis
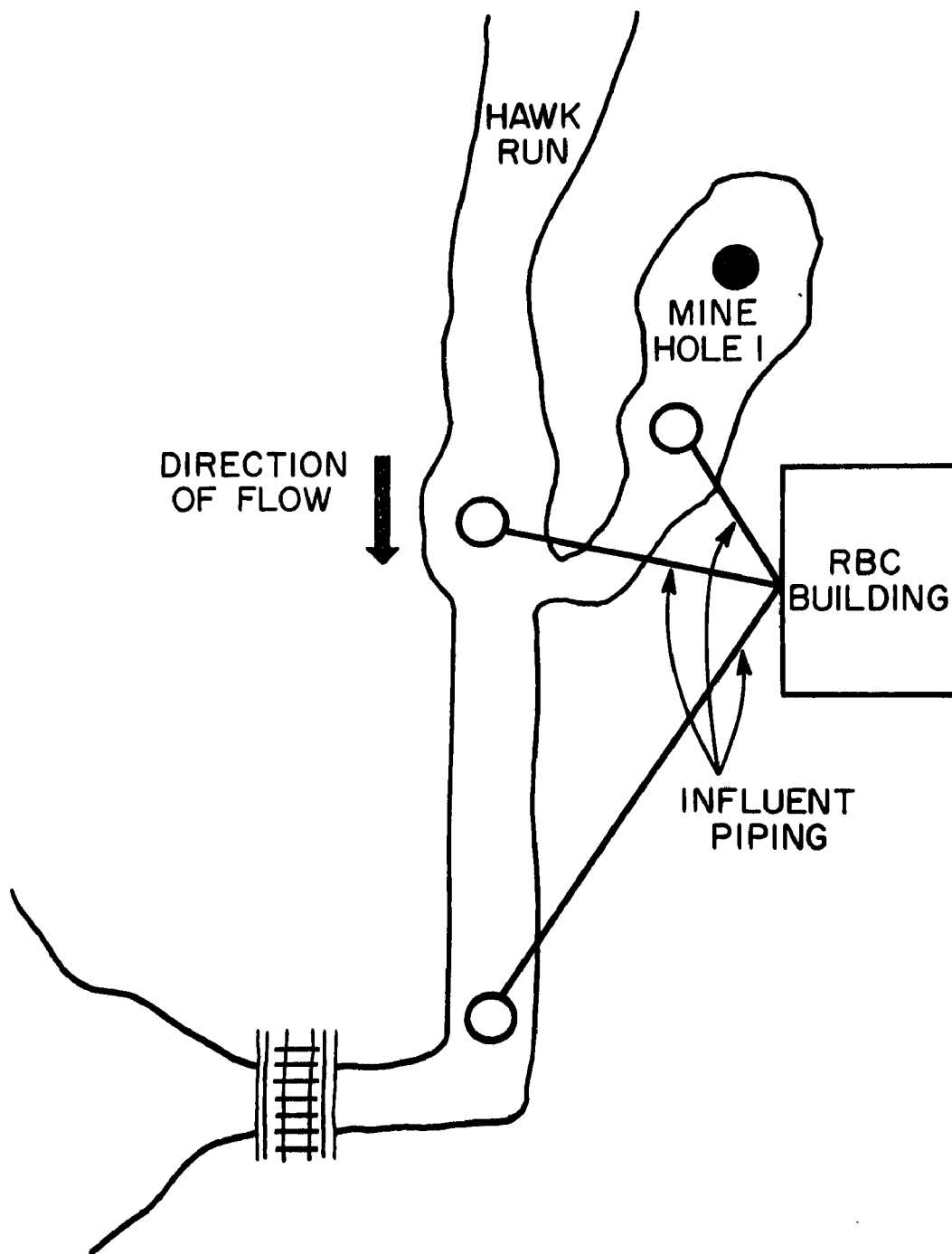
Figure 7. Schematic of mine drainage streams available at Hawk Pa. showing locations of mine water feed lines.

TABLE 3. CHARACTERISTICS OF ACID MINE DRAINAGES STUDIED
AT THE U.S. EPA CROWN FIELD SITE NEAR MORGANTOWN, W. VA.

Parameter	Crown drainage [a]		RO brine [b]	
	Mean	Std. dev.	Mean	Std. dev.
Temp., °C	16.7 (32)[c]	0.7	23.9 (10)	2.1
pH	4.83 (32)	--	2.34 (10)	--
Fe(II), mg/ℓ	195 (32)	28	356 (10)	47
Fe(III), mg/ℓ	7 (30)	16	10 (9)	16
Al, mg/ℓ	9.9 (31)	4.4	19.7 (9)	12.5
DO, mg/ℓ	2.4 (10)	1.1	2.2 (6)	0.8
Total N, mg/ℓ	2.44 (3)	1.12	3.18 (6)	1.11
Org-N	0.76 (3)	0.81	0.54 (6)	0.53
NH_3-N	1.83 (3)	0.38	2.62 (6)	0.66
$(NO_2 + NO_3)$-N	0.03 (3)	0.02	0.01 (6)	0.02
Total P, mg/ℓ	0.41 (3)	0.34	0.11 (6)	0.12
Iron-oxidizing bacteria, MPN/100 mℓ	45,000	17	5,200	2

[a] Samples were collected from May 23 to July 2, 1977.

[b] Samples were collected from July 2 to July 13, 1977.

[c] Number of analyses applied to statistical determinations.

TABLE 4. CHARACTERISTICS OF ACID MINE DRAINAGE STUDIED AT
THE EXPERIMENTAL MINE DRAINAGE TREATMENT FACILITY AT HOLLYWOOD, PA.

Parameter	Proctor No. 2 mine drainage[a]		Std. dev.
	Mean		
Temp., °C	10.4	(23)[b]	0.6
pH	2.74	(23)	--
Fe(II), mg/ℓ	146	(23)	69
Fe(III), mg/ℓ	121	(13)	31
Al, mg/ℓ	57.5	(13)	1.6
DO, mg/ℓ	2.2	(20)	0.8
Total N, mg/ℓ	1.21	(15)	0.28
Org-N	0.14	(15)	0.21
NH_3-N	1.03	(15)	0.18
$(NO_2 + NO_3)$-N	0.04	(15)	0.03
Total P, mg/ℓ	0.05	(15)	0.06
Iron-oxidizing bacteria, MPN/100 mℓ	3,400		2
Heterotrophic bacteria[c], cells/100 mℓ	610		2

[a]Samples were collected from September 8 to November 19, 1977.

[b]Number of analyses applied to statistical determinations.

[c]The term "heterotrophic bacteria" refers to organisms which were shown not to be able to oxidize Fe(II); however, these organisms could not be subcultured on organic media.

TABLE 5. CHARACTERISTICS OF ACID MINE DRAINAGES STUDIED AT THE HAWK RUN
MINE WATER TREATMENT PLANT NEAR PHILPSBURG, PA.

Parameter	Mine Hole 1[a]		Hawk Run[b]		Hawk Run + MH 1[c]	
	Mean	Std. dev.	Mean	Std. dev.	Mean	Std. dev.
Temp., °C	10.0 (16)[d]	0.1	4.6 (7)	3.6	8.2 (18)	1.0
pH	3.77 (16)	--	3.15 (7)	--	3.42 (18)	--
Fe(II), mg/ℓ	62.8 (16)	8.8	32.8 (7)	4.3	53.2 (18)	2.0
Fe(III), mg/ℓ	6.9 (10)	2.4	11.4 (6)	5.6	9.6 (18)	2.8
Al, mg/ℓ	6.2 (12)	1.4	10.1 (6)	2.3	8.6 (18)	0.4
DO, mg/ℓ	2.2 (14)	0.3	10.8 (6)	1.7	7.4 (14)	0.5
Total N, mg/ℓ	1.04 (6)	0.29	0.96 (6)	0.37	0.55 (9)	0.67
Org-N	0.37 (6)	0.36	0.37 (6)	0.34	0.01 (9)	0.01
NH_3-N	0.58 (6)	0.03	0.31 (6)	0.08	0.42 (9)	0.04
$(NO_2 + NO_3)$-N	0.09 (6)	0.05	0.27 (6)	0.05	0.13 (9)	0.03
Total P, mg/ℓ	0.06 (6)	0.05	0.06 (6)	0.05	0.10 (7)	0.17
Iron-oxidizing bacteria, MPN/100 mℓ	2,000	4	440	1	630	4

[a]Samples were collected from March 8 to April 12, 1978.

[b]Samples were collected from February 23 to March 8, 1978.

[c]Samples were collected from January 6 to February 23, 1978.

[d]Number of analyses applied to statistical determinations.

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of the product water indicated the presence, although low, of iron-oxidizing bacteria (300 MPN/100 mℓ).

Hollywood, Pennsylvania

Results of analyses of Proctor No. 2 mine drainage (Table 4) in the present study were very similar to those previously reported by Olem and Unz (54) in earlier work with Proctor No. 2 mine water. Unlike the drainage at the Crown Site, a large portion of the iron exists in the Hollywood drainage as Fe(III).

Dissolved oxygen (DO) was measured by probe in the feed well of the RBC units as described in Appendix B. Measurements taken from the point of mine water discharge prior to pumping to the treatment units showed DO values less than 0.5 mg/ℓ. This observation suggests that underground mine waters, such as the Crown and Hollywood drainages, contain little DO prior to surface discharge.

Hawk Run, Pennsylvania

The mine waters at the Hawk Run facility had a generally lower iron content than the drainages at other locations. Mine Hole 1 water contained iron mainly as Fe(II) and temperatures (9.6 to 10.3°C) were similar to those reported for most underground mine waters just following surface discharge (15). DO values less than 0.5 mg/ℓ were measured prior to pumping as was the case of the other underground mine waters analyzed. Other than the lower iron and aluminum content, Mine Hole 1 discharge appeared similar to the Proctor No. 2 drainage including nutrient and iron-oxidizing bacteria content.

Analysis of samples collected from Mine Hole 3 at the point of surface discharge revealed chemical and microbiological characteristics similar to those of Mine Hole 1. Apparently, dilution of drainage by surface runoff to the stream and the precipitation of insoluble ferric iron (evident from ferruginous deposits on stream bed) resulted in a lower iron content in the water when collected and analyzed at the downstream location depicted in Figure 7.

Total nitrogen content of the Hawk Run water was similar to the levels present in Mine Hole 1 discharge; however, a greater percentage of nitrogen was in the form of NO_2 or NO_3 in the Hawk Run water. Biological nitrification was not likely due to the low pH of the environment (57). Therefore, the small surface drainage most likely contributed NO_3 to Hawk Run. A few localized septic tank tile field systems may have contributed a nitrified effluent to the stream.

Exposure to ambient climatic conditions over the distance traveled by Hawk Run from its origin at Mine Hole 3 to the point of pumping and subsequent analysis (3 km) resulted in changes in the water temperature, which was initially consistently 10°C. During the period February 23 to March 8, 1978, continuous temperature monitoring revealed water feed temperatures to the RBC units ranged from 0.4 to 9.8°C. At the lower temperatures, DO levels

were 8.4 to 12.8 mg/ℓ due to natural aeration of the shallow, fast moving stream. Hawk Run provided a Fe(II)-containing water which differed from the other drainages examined in several of the characteristics listed in Table 5.

A mixture of Mine Hole 1 water and Hawk Run discharge was pumped to the RBC building from a point sufficiently below the confluence to assure homogenization of the sources. Experiments were conducted using this mixture in order to study a "synthesized" natural mine water having characteristics different from the individual waters. Influent characteristics were determined as listed in Table 5. The flows of Mine Hole 1 and Hawk Run were nearly equal (25,000 m^3/d) and it was anticipated that each conservative constituent of the mixture in any section of the stream under consideration would be the mean of the concentrations of each constituent from the waters prior to mixing. This mass balance seemed to hold true for most of the parameters analyzed (Table 5), even though most are non-conservative.

Mass balance relationships were used to determine the extent of lateral mixing which occurred in the 50-m section below the confluence of the two streams. This information was needed to determine whether there was sufficient mixing in the reach so that the influent mixture pumped to the RBC units would be significantly different in quality from the individual waters. Experimental procedures and results of the study are presented in Appendix C. The experiment also was designed to determine whether backmixing of Mine Hole 1 discharge affected the quality at the point where mine drainage was being pumped from Hawk Run. Results of this work indicated that back-mixing was not occurring at this point and that the location of the feed line provided water representative of Hawk Run. Although the intake point in the combined stream (Hawk Run + Mine Hole 1) was not located far enough down-stream from the confluence to provide complete mixing, sufficient mixing did occur such that mine drainage influent differed in quality from either of the contributing flows.

EXPERIMENTAL APPARATUS AND PROCEDURES

Rotating Biological Contactors

Field studies were conducted with commercial RBC pilot units (Autotrol Corporation, Milwaukee, Wisconsin) equipped with 0.5-m and 2.0-m diameter discs (Figure 8). The 2.0-m RBC unit was not used in experiments at Crown, W. Va. because of shipment delays encountered. Each unit consisted of four stages of closely spaced and corrugated high-density polyethylene discs suspended on a shaft in a corrosion-proof trough. The troughs of the 0.5- and 2.0-m units were constructed of epoxy-coated aluminum and bitumastic-coated steel, respectively. The individual stages were separated by baffles. Flow through the stages of the 0.5-m unit was facilitated by a 2.5-cm diameter hole in each baffle. A serpentine flow pattern was formed in the 2.0-m unit by an arrangement of piping on the outside of stage compartments. A rotating bucket mechanism fed mine water from the influent chamber of each unit to stage compartments and thus controlled flow. Detailed information on the characteristics and design parameters of the experimental RBC units may be found in Appendix D.

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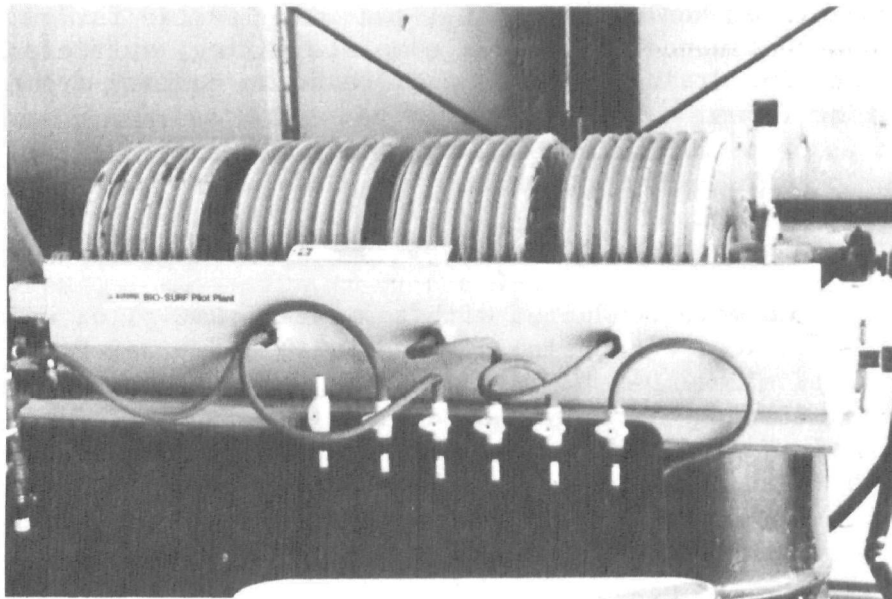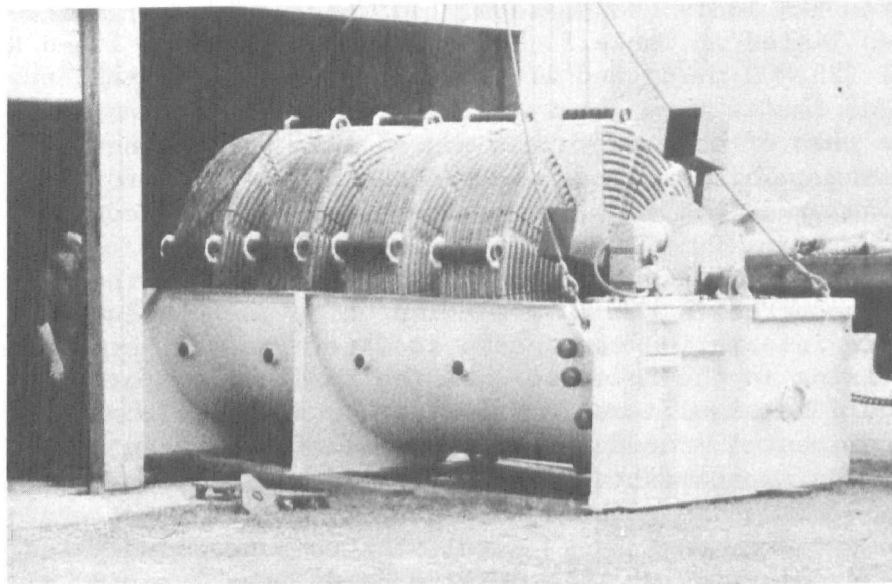
Figure 8. RBC units with disc diameters of 2.0 m (top) and
0.5 m (bottom) employed in field experiments.

Other Equipment

At each site, the RBC units were enclosed in a building for protection from the general environment. At the Crown Field site, mine water was continuously pumped to the pilot plant building as described by Wilmoth (73). Mine drainage flowed continuously during the respective study periods except for two occasions at Crown, W. Va. in which borehole pumping was interrupted. In these instances, mine water was stored prior to shutdown in a $10-m^3$ capacity tank to maintain flow over 48-hr periods. At Hollywood and Hawk Run, mine waters were delivered from the source by two 0.25-kw centrifugal pumps in connection with a 7.6-cm diameter foot valve and appropriate lengths of flexible polyethylene piping.

Flow rates were checked by collecting effluent samples for one minute in 3-ℓ and 100-ℓ containers, respectively, for the 0.5- and 2.0-m units. Water samples were collected manually or with portable automatic, discrete twenty-four bottle samplers (Manning model S-4040, Manning Environmental Corporation, Santa Cruz, Calif). Instruments were located on site for measurement of those constituents which required immediate determination [Fe(II), pH, temperature, and dissolved oxygen]. Temperature of the influent mine water was recorded continuously for experiments at Hawk Run, Pa. by use of a Linear Instruments model 261 chart recorder (Linear Instruments Corporation, Irvine, Calif.). Other analytical equipment was located either at the Crown Field Site or The Pennsylvania State University laboratories (see Appendix B).

Experimental Procedures

Mine water was mechanically pumped from each source to the feed chambers of the pilot units at a rate slightly greater than the desired 119 m^3/d. Excess flow from the feed chamber was discharged through an overflow pipe in order to maintain a constant liquid level of fresh mine water in the feed bucket chamber. The static level of mine water in the chamber and the number of feed buckets employed were determined in accordance with the desired flow rate.

All experiments were performed at an equivalent peripheral disc velocity of 19 m/min and a hydraulic loading of 0.16 m^3/d·m^2 in order to compare performance of the RBC units at each location. Attainment of a peripheral disc velocity of 19 m/min required 13 and 2.9 rpm for the 0.5- and 2.0-m units, respectively. The peripheral velocity of 19 m/min was selected on the basis of results in previous experiments on rotational effects for the RBC in Fe(II) oxidation (54). Where applicable, alteration of the standard hydraulic loading rate was made only after equilibrium data had been collected at a particular site and in the interest of improving performance (Hawk Run).

Treatment units were cleaned and disinfected prior to start-up at each location with 10-percent (v/v) HCl and 5-percent (w/w) sodium hydrosulfite-sodium bisulfite blend (Nalclean 2564, Nalco Chemical Co., Paulsboro, N.J.) for the 0.5- and 2.0-m units, respectively. Solutions were prepared with tap water, added to the troughs of each unit, and the discs were rotated for

one week. Start-up of the units began with the initiation of disc rotation and intake of mine water to the influent chamber. At no time during the field studies were mine waters seeded with bacteria.

Sampling

Water samples were collected from the influent line and from each stage compartment (see Appendix D for location of sampling lines). Sampling lines were flushed for one to two minutes prior to sample collection depending on the length of the hose. Water samples representative of influent mine water were initially collected from the feed chamber of each unit. Analyses of these samples were made to insure that no significant Fe(II) oxidation occurred in the feed chamber (less than 1 percent occurred) and that samples from each unit were similar in water quality for the parameters analyzed. The grab samples from influent and each stage of RBC units were either manually collected (two to five times per week) or automatically taken (twenty-four samples per day) depending on the particular experiment.

Premeasured plastic sampling squares affixed to the outer-most disc on each stage prior to start-up were carefully removed (one to three times per week) for appropriate chemical and microbiological analyses (Appendix B). This sampling schedule was employed both during start-up and during equilibrium Fe(II) oxidation periods which lasted a total of two to four months. Equilibrium conditions were considered to be the period during which Fe(II) oxidation efficiency was maximum and relatively constant. Following sufficient data collection at equilibrium, mine water feed was replaced, if available, with another source at the same location.

RESULTS

Start-Up

Performance of the 0.5-m RBC in the oxidation of Fe(II) was related to the source of mine drainage treated (Figure 9). At Hollywood, Pa., Fe(II) oxidation increased steadily after an initial 3-day lag period and exceeded 90 percent after 10 days of continuous operation. Fe(II) oxidation continued to increase steadily and an equilibrium point was reached in approximately 30 days. A similar pattern of Fe(II) oxidation was observed for the 2.0-m RBC except that equilibrium oxidation required approximately 35 days. A short lag in oxidation (3 days) with the 0.5-m unit occurred also in the initial treatment of combined Hawk Run and Mine Hole 1 drainage. By comparison to Proctor No. 2 oxidation, Fe(II) oxidation proceeded at a slightly slower rate following the lag period. Fe(II) oxidation approached 75 percent after 16 days and improved steadily thereafter until about 85 percent oxidation was reached in 40 days. The larger 2.0-m RBC required 50 days to reach an equilibrium level of oxidation. In treatment of Crown drainage, the 0.5-m RBC reached almost 8 percent oxidation within the first 3 days of continuous operation. During this period, pH increased from 4.5 (influent) to 6.0 (effluent). Concurrently, aluminum was continually being precipitated from solution and apparently onto disc surfaces. The effluent contained 43.1 percent less Al than the influent, presumably due to the lower solubility of Al at higher pH values (9). Following two days at
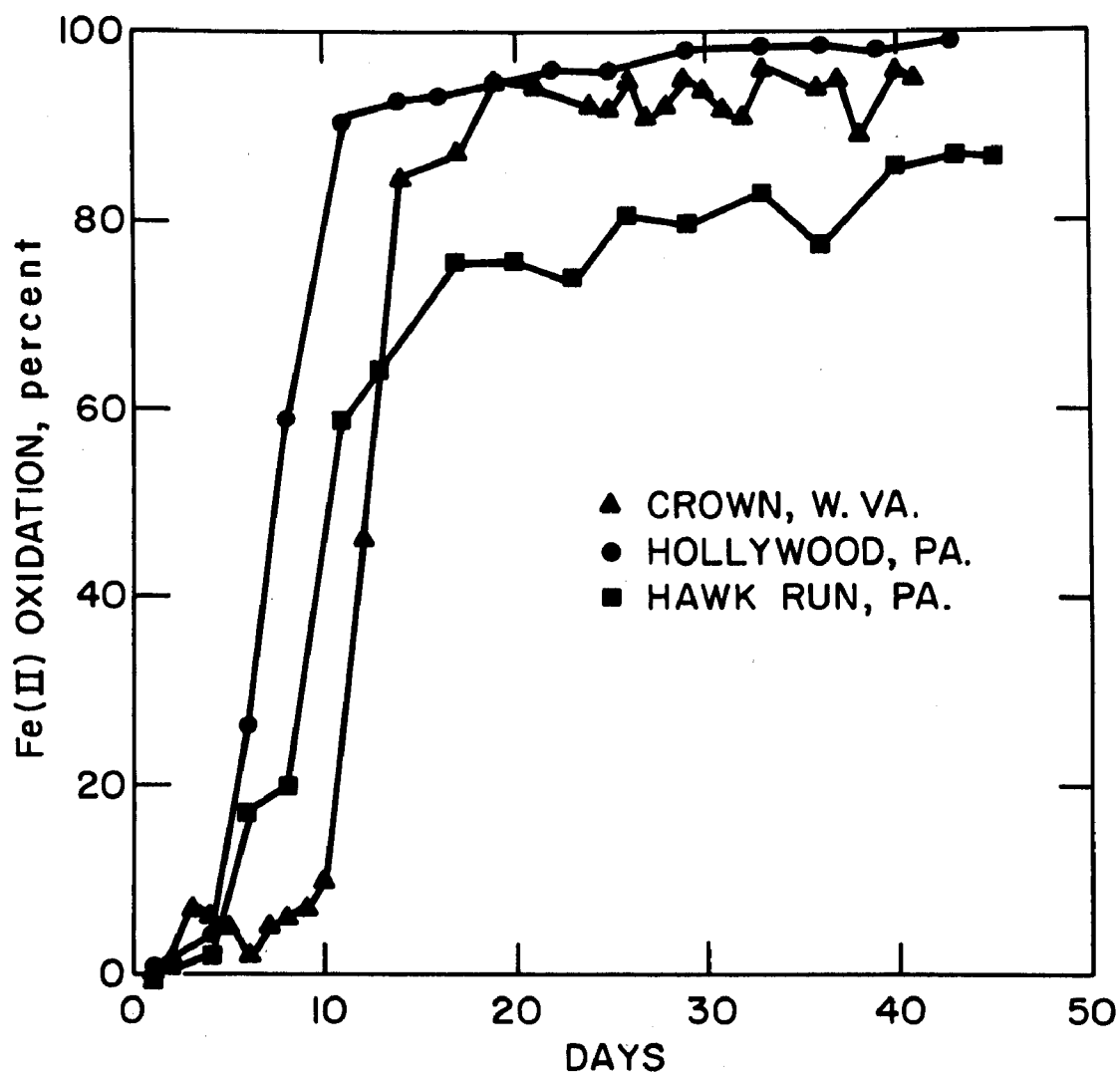
Figure 9.   Start-up and time required to obtain equilibrium Fe(II)
oxidation with the 0.5-m RBC in treatment of Crown mine
drainage at the Hollywood Proctor No. 2 mine water and
combination Hawk Run + MH 1 discharge.

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elevated pH and low effluent aluminum concentration, pH values of the effluent were comparable to influent values, and no change was observed in Al content in passage of mine water through the RBC. Fe(II) oxidation efficiency during this period was less than 2 percent. Thereafter, Fe(II) oxidation efficiency increased rapidly to an equilibrium level of 90 to 95 percent in 19 days.

Colonization of RBC discs by iron-oxidizing bacteria appeared to occur at approximately the same time during the treatment of influent mine water at Hollywood and Hawk Run (Figure 10). In contrast, bacterial densities on disc surfaces after 17 days treatment of Crown mine drainage were at least 1,000-fold greater than population densities developed on Hollywood and Hawk Run drainages for the same period of time. Nevertheless, Fe(II) oxidation performance for the RBC treating the various mine waters was not proportional to the populations of iron-oxidizing bacteria present on discs (Figure 9).

The inorganic salts-agar medium of Manning (51) was used to cultivate noniron-oxidizing microorganisms. Organisms recovered and examined by phase microscopic examination were found to be rod-shaped bacteria which would not be subcultured on the primary isolation medium or in a glucose-yeast extract medium and would not grow autotrophically in Fe(II) medium. On the primary isolation medium, colonies were nonpigmented, punctiform, and did not show any evidence of Fe(II) oxidation through deposition of brown Fe precipitates. It was suspected that the organisms were not nitrifying bacteria due to the excessively low pH of the medium (pH 3). Although the true nature of the noniron-oxidizing bacteria enumerated on the salts-agar medium could not be determined, they were presumed to be fastidious heterotrophs and will be referred to in this manner in all further discussions. A comparison of the development of heterotrophic and iron-oxidizing bacterial populations on disc surfaces with time at Hollywood revealed a much higher initial heterotrophic bacterial population per unit surface area (Figure 11). After 15 days, viable heterotrophic and chemolithotrophic bacterial numbers became parallel and the absolute density of heterotrophs exceeded that of the iron-oxidizing bacteria.

Equilibrium Conditions

The Fe(II) oxidation performance of the 0.5- and 2.0-m RBC units was compared for each drainage treated and related to corresponding mean influent mine water pH, temperature, and Fe(II) concentration (Table 6). The 0.5-m RBC performance was slightly superior to the prototype 2.0-m unit for the four mine waters treated. Hawk Run drainage contained the lowest mean influent Fe(II) and temperature and exhibited a greater variation in Fe(II) oxidation than did the other mine waters. Day-to-day variability in oxidation performance at a particular temperature was less than 5 percent for both units.

Changes in the dissolved oxygen concentration were observed as the water passed through each stage of the two RBC units (Table 7). With one exception, aeration created by turbulence during disc rotation and exposure to atmospheric oxygen resulted in a substantial increase in DO through the stages to near saturation levels in the final effluent. During treatment of
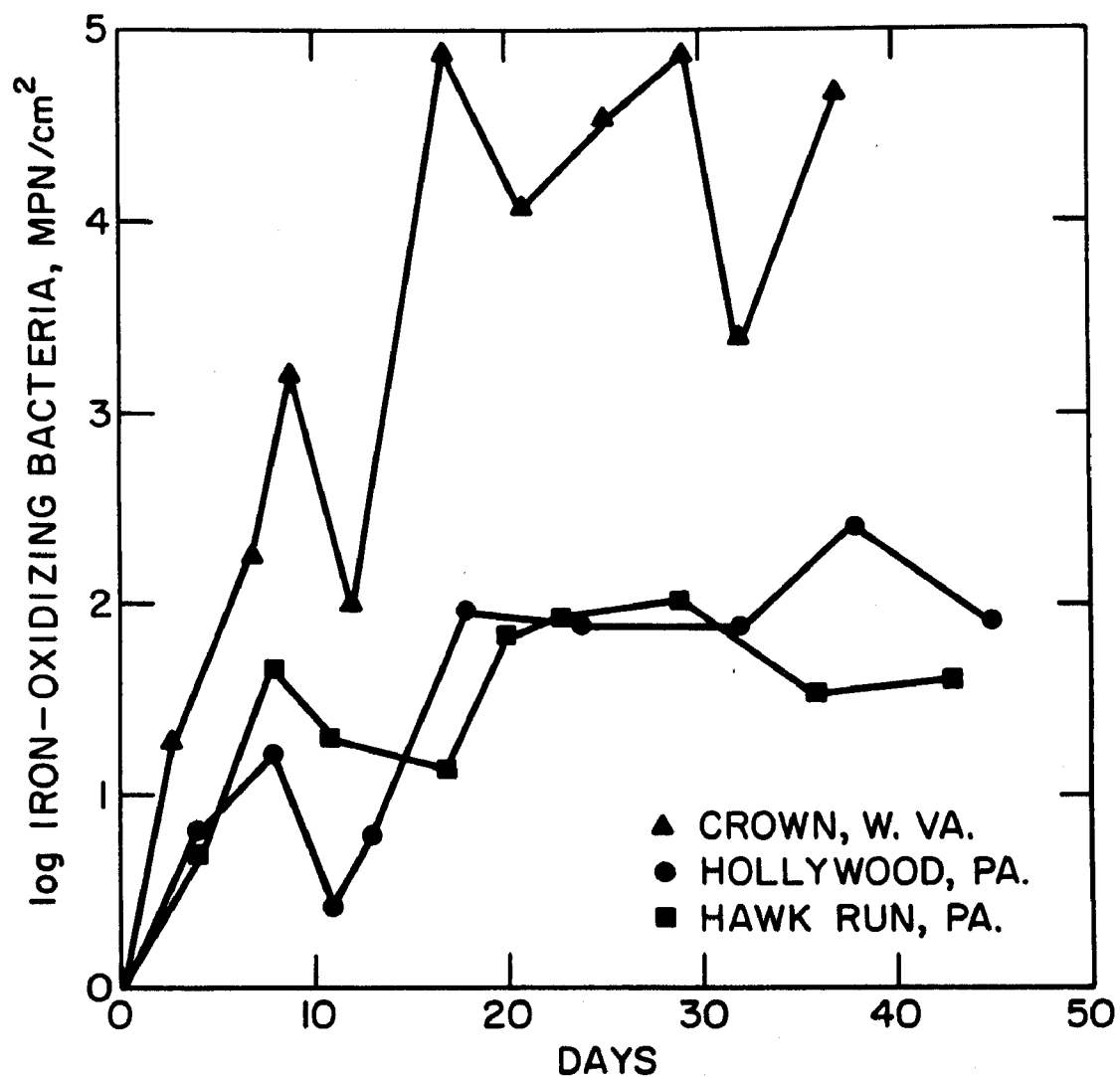
Figure 10. Iron-oxidizing bacteria at surface of 0.5-m RBC discs
for each mine drainage location. Data points represent
mean value for samples taken from influent-side disc of
all stages.
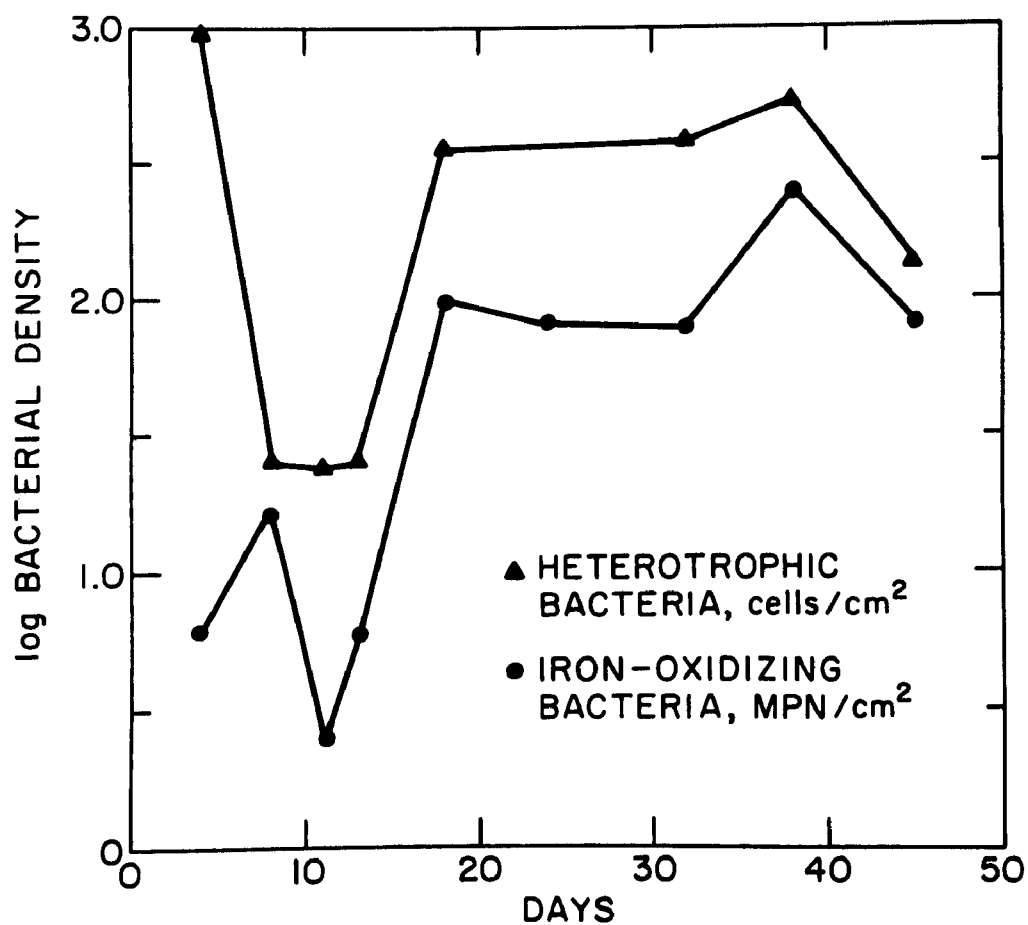
Figure 11. Iron-oxidizing and heterotrophic bacteria at surface
of 0.5-m RBC discs at Hollywood, Pa. Data points
represent mean value for samples taken from influent-
side disc of all stages.

TABLE 6. COMPARATIVE PERFORMANCE OF 0.5- and 2.0-M RBC UNITS AT EQUILIBRIUM Fe(II) OXIDATION FOR EACH MINE DRAINAGE TREATED

| | | Mean influent characteristics | | Fe(II) oxidation, percent | | | |
| | | | | 0.5-m RBC | | 2.0-m RBC | |
Mine Drainage	pH	Temp., °C	Fe(II), mg/ℓ	Mean	Std. dev.	Mean	Std. dev.
Crown (17)[a]	4.93	16.6	190	93.3	2.0	--[b]	--
RO brine (10)	2.38	23.9	356	97.7	1.1	--	--
Hollywood (8)	2.75	10.0	116	98.3	0.9	92.8	1.9
Mine Hole 1 (5)	3.92	9.9	70	84.7	1.4	76.9	0.3
Hawk Run (5)	3.23	3.9	32	75.3	7.6	72.3	4.1
Hawk Run (4) + MH 1	3.38	7.6	53	85.4	1.9	75.1	1.6

[a]Number of influent and effluent measurements applied to statistical determinations.

[b]RBC unit not examined for mine drainage listed.

TABLE 7. DISSOLVED OXYGEN IN MINE DRAINAGE INFLUENT AND INDIVIDUAL STAGE COMPARTMENTS
OF 0.5- AND 2.0-M RBC UNITS AT EQUILIBRIUM Fe(II) OXIDATION EFFICIENCY

	Mean dissolved oxygen, mg/ℓ									
	0.5-m RBC					2.0-m RBC				
Mine Drainage	Inf.	S1	S2	S3	Eff.	Inf.	S1	S2	S3	Eff.
Crown (10)[a]	2.4	5.9	7.0	7.7	8.2	--[b]	--	--	--	--
RO brine (6)	2.2	3.2	5.1	6.7	7.6	--	--	--	--	--
Hollywood (7)	1.9	6.4	8.4	9.4	9.8	2.9	5.5	7.1	8.3	9.1
Mine Hole (3)	2.4	6.8	8.0	8.5	9.2	1.2	5.8	7.1	8.1	9.4
Hawk Run (4)	11.7	10.8	10.6	10.5	10.9	11.9	11.0	11.1	11.1	11.4
Hawk Run (3) + MH 1	7.1	8.1	8.6	8.7	9.3	6.4	8.0	8.2	8.6	9.4

[a]Number of measurements applied to calculation of mean values.

[b]RBC unit not examined for mine drainage listed.

Hawk Run drainage, DO decreased slightly through the stages. The lower temperature mine water streams (Hawk Run and Hawk Run + MH 1) were initially higher in DO. The DO profiles were similar in both the 0.5- and 2.0-m RBC units.

Changes in the viable iron-oxidizing bacteria content of influent and effluent mine water were observed (Table 8). An increase was noted in iron-oxidizing bacterial numbers in the effluents of RBC units as compared to influent mine waters for the Crown RO brine, Mine Hole 1, and Hawk Run mine waters. The reverse situation occurred for the Hollywood mine drainage with both RBC field units and for the Hawk Run and combination drainages with the 2.0-m RBC unit. Heterotrophic bacteria were enumerated in influent and effluent mine drainage of the 0.5-m RBC at Hollywood. Mean influent and effluent populations at equilibrium Fe(II) oxidation were 340 and 540 cells/100 mℓ, respectively.

Effect of Temperature

The Hawk Run mine drainage exhibited the greatest fluctuation in temperature in comparison to the other five influent mine waters (0.4 to 9.8°C). During winter, influent and effluent mine water samples were automatically collected every hour over a 24-hr period for Mine Hole 1, Hawk Run, and combination Hawk Run and Mine Hole 1 drainages. Samples were analyzed for Fe(II) and the results were examined in relation to the continuous influent mine water temperature measurements. Since the RBC building was maintained at an ambient air temperature near the influent mine water temperature, variation in temperature as the mine water passed through the units was less than 1°C. Mine Hole 1 water temperature was constant at 10°C and Fe(II) oxidation was stable at 76.8 to 78.4 percent efficiency (Figure 12, top). Hawk Run + MH 1 mine water exhibited fluctuations in temperature which closely paralleled changes in Fe(II) oxidation (Figure 12, bottom). In the Hawk Run stream (Figure 13), Fe(II) oxidation lagged behind both a temperature decrease and increase. Both 0.5- and 2.0-m RBC units behaved similarly in Fe(II) oxidation with changes in temperature over a 24-hr period.

At Hawk Run, Pa. there existed good statistical correlation (1-percent confidence level) between Fe(II) oxidation efficiency and mine water temperature for the 0.5- and 2.0-m RBC units (Figure 14 and 15). A higher correlation was observed for the 0.5-m RBC (R = 0.853) than for the 2.0-m RBC (R = 0.668) due to an unexplained greater effect of temperature on Fe(II) oxidation in the smaller unit. The reverse situation was expected because the temperature of mine water effluent from the 0.5-m unit had increased slightly more than the temperature of the effluent from the 2.0-m RBC (0.9°C difference vs. 0.4°C difference).

Although the temperatures of Crown, W. Va. mine waters were higher than the temperature of Hollywood mine drainage, Fe(II) oxidation efficiency was not observed to be greater at the Crown site (Table 6). The temperatures of Hawk Run drainages were, at times, equivalent to the temperature of the Hollywood discharge; however, Fe(II) oxidation efficiency for field units in operation under equivalent conditions was 10 to 15 percent lower for the Hawk

TABLE 8. IRON-OXIDIZING BACTERIA IN MINE DRAINAGE INFLUENT AND EFFLUENT
OF 0.5- AND 2.0-M RBC UNITS AT EQUILIBRIUM Fe(II)
OXIDATION EFFICIENCY

Mine Drainage	Mean iron-oxidizing bacteria, MPN/100 mℓ		
	Influent	Effluent	
		0.5-m RBD	2.0-m RBC
Crown (5)[a]	290,000	160,000	--[b]
RO brine (4)	5,200	6,600	--
Hollywood (4)	3,300	990	1,900
Mine Hole 1 (3)	4,700	14,000	5,900
Hawk Run (4)	440	1,100	420
Hawk Run (3) + MH 1	200	310	110

[a]Number of measurements applied to calculation of mean values.

[b]RBC unit not examined for mine drainage listed.

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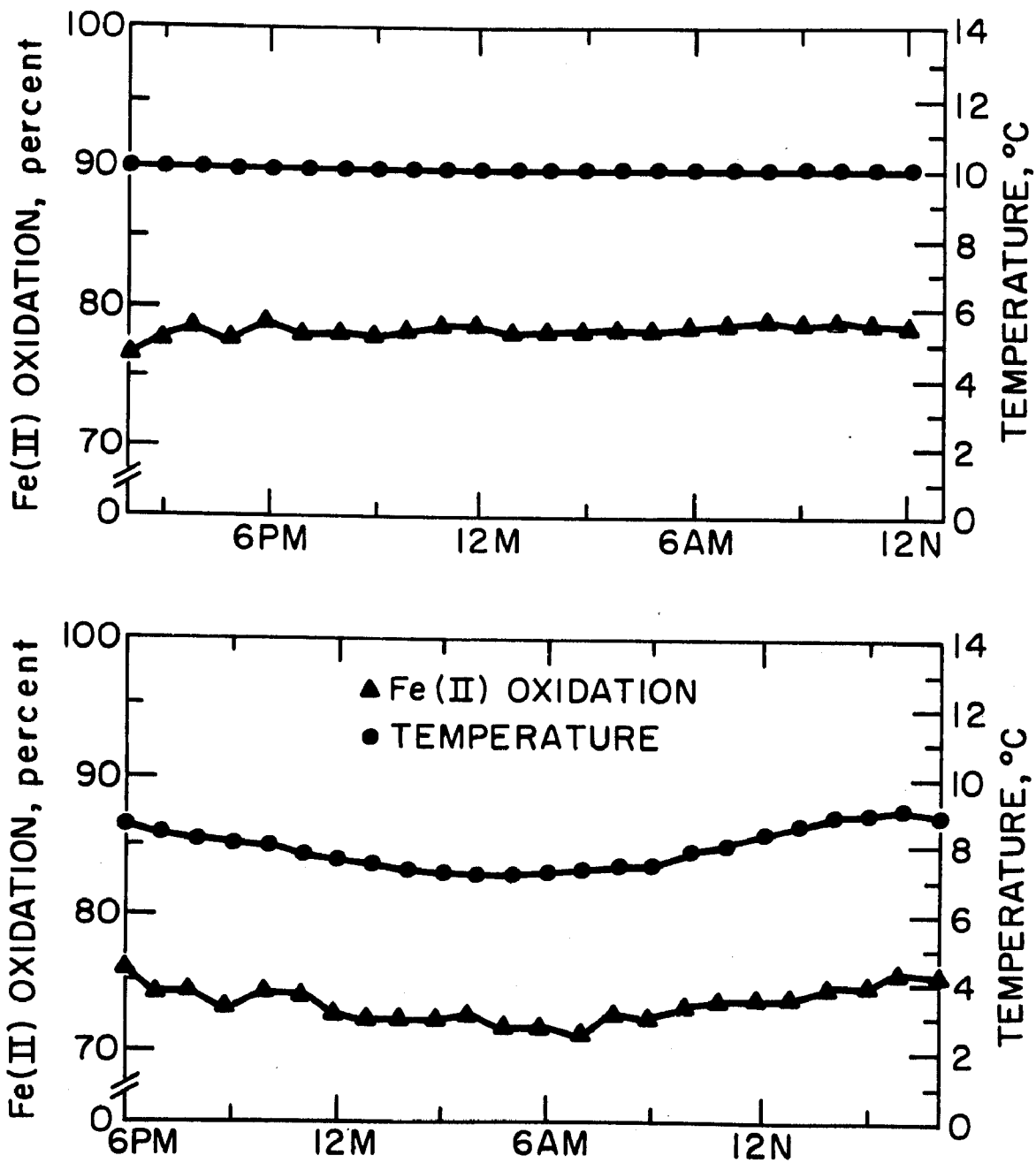
Figure 12.   Effect of mine drainage temperature fluctuations over
one 24-hr period on Fe(II) oxidation with 2.0-m RBC
in treatment of MH 1 discharge (top) and combination
Hawk Run and MH 1 drainage (bottom).
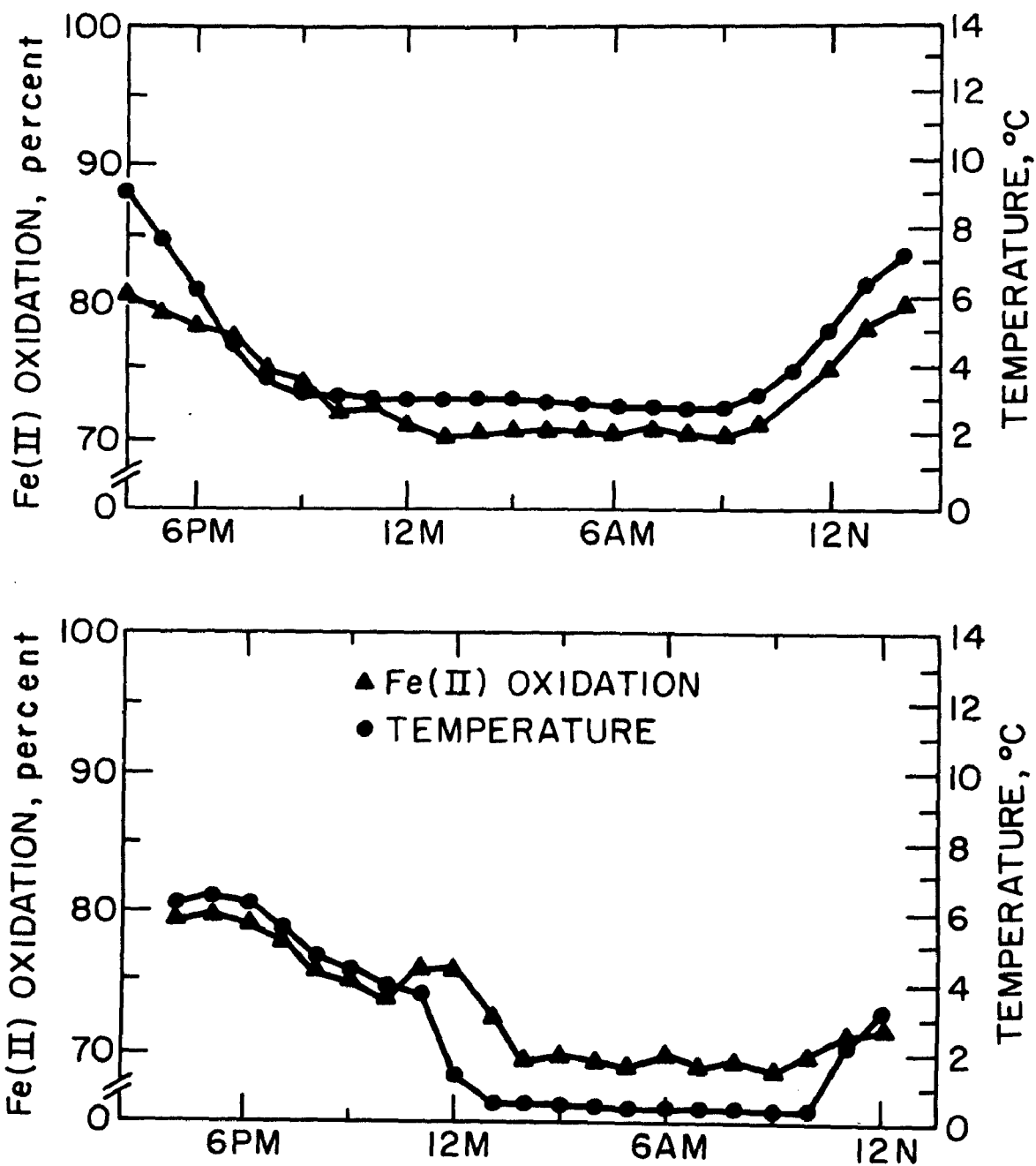
Figure 13. Effect of temperature fluctuations over one 24-hr period on Fe(II) oxidation with 2.0-m RBC in treatment of Hawk Run mine water.
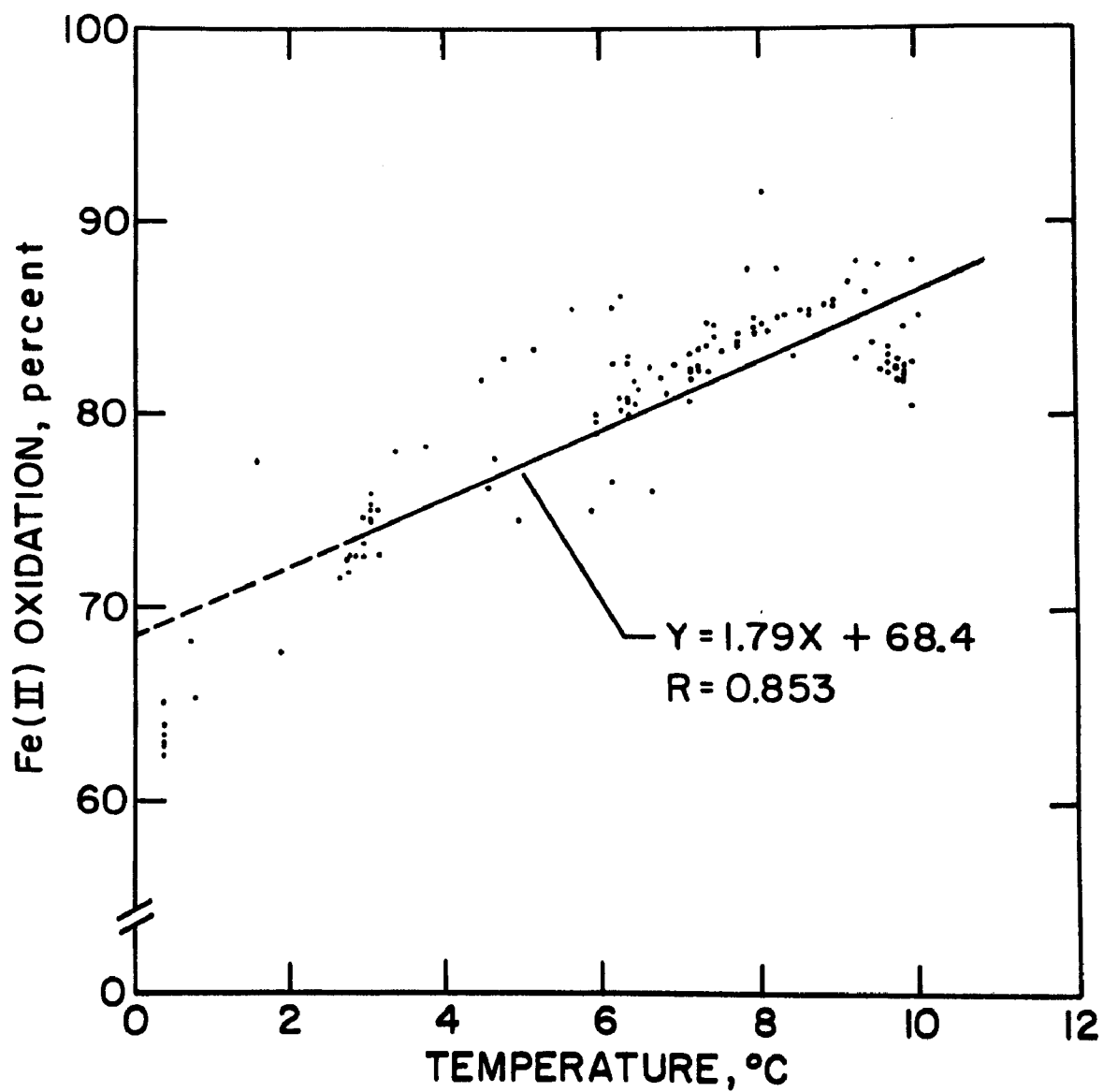
Figure 14. Effect of mine drainage temperature on Fe(II) oxidation for the 0.5-m RBC in treatment of mine waters at Hawk Run, Pa. Actual data collected within the temperature range of 0.4 to 10.3°C (inclusive).
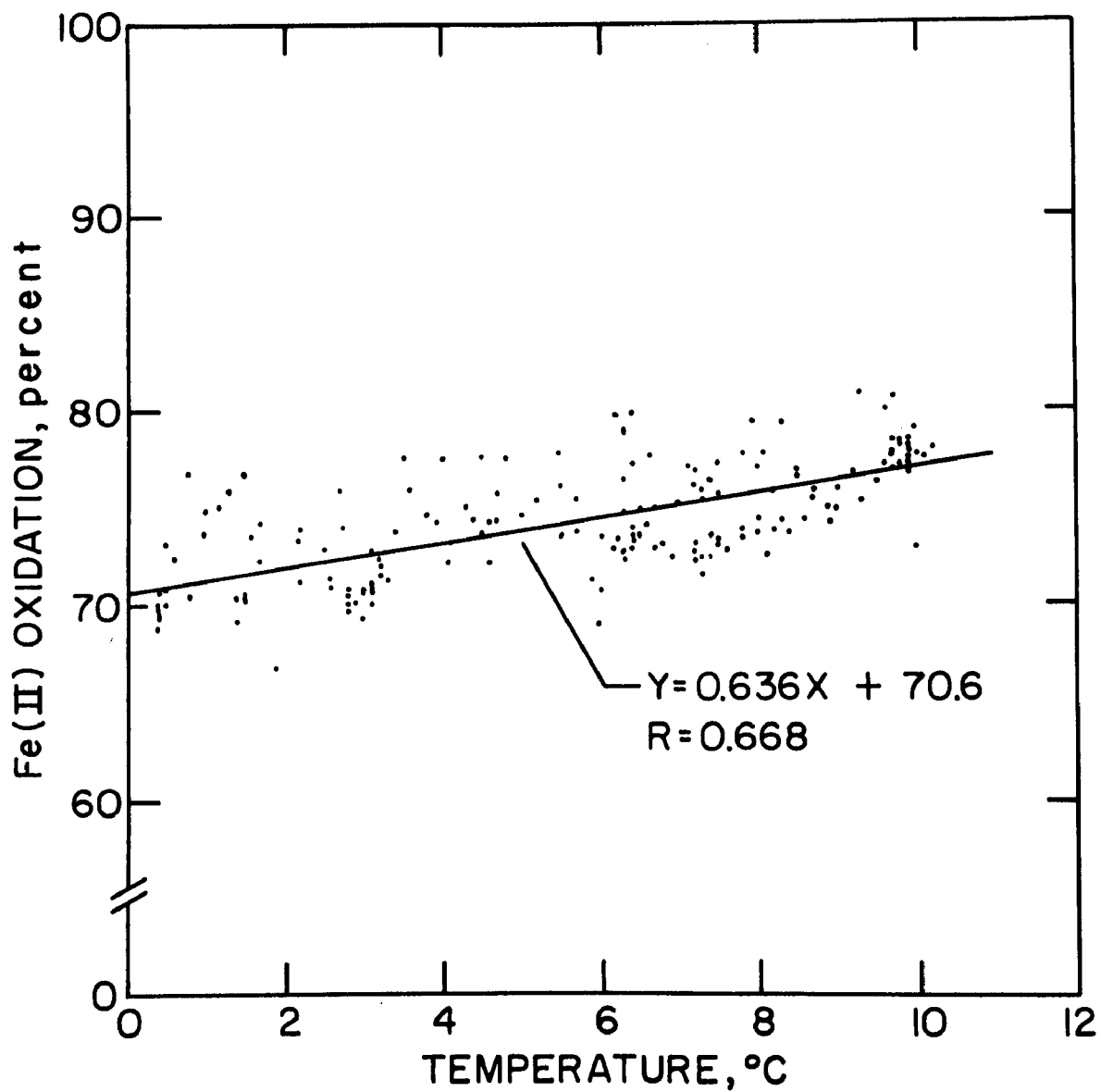
Figure 15. Effect of mine drainage temperature on Fe(II) oxidation for the 2.0-m RBC in treatment of mine waters at Hawk Run, Pa. Actual data collected within the temperature range of 0.4 to 10.3°C (inclusive).

Run drainages. Therefore, mine water temperature does not appear to be the principal reason for the lower Fe(II) oxidation efficiency at Hawk Run.

Effect of pH

Over the range of influent mine water pH values observed, including Crown, which fluctuated from pH 4.40 to 5.50, no effect of pH on Fe(II) oxidation performance was evident at each location with each RBC unit. Correlation of pH with Fe(II) oxidation revealed a coefficient (R) of less than 0.5 for each mine drainage examined.

Changes in pH occurred in the mine water at each stage of the RBC (Figure 16). When influent mine water was above pH 3.0, a mine water buffering system resulted in decreasing individual stage and effluent pH values to near pH 3. On the other hand, when influent mine water pH was below 3.0 (RO brine and Hollywood mine drainage), individual stage and effluent pH values increased to values near pH 3. Observations of pH characteristics were seen to be independent of the RBC studied. These occurrences are consistent with the nature of iron chemistry which is discussed in Section 8.

Effect of Influent Fe(II)

Influent Fe(II) content for all mine drainages ranged from a low of 27 mg/ℓ for the Hawk Run stream to a high of 433 mg/ℓ for the concentrated RO brine. The Hollywood mine drainage exhibited the greatest fluctuation in influent Fe(II) concentration and a decrease in influent Fe(II) resulted in a subsequent increase in oxidation efficiency (Figure 17). For the limited data collected, a correlation (R) of -0.838 and -0.832 was observed for the 0.5- and 2.0-m units, respectively (significant at the 1-percent confidence level). The 0.5-m RBC was less affected by increased influent Fe(II) than the 2.0-m unit. Influent Fe(II) did not fluctuate as greatly at the other treatment sites and minor fluctuations showed poor correlation with efficiency (not significant at the 5-percent level).

Kinetics of Fe(II) Oxidation

Although several mine water characteristics varied in magnitude for each drainage, Fe(II) oxidation followed a concentration dependent, first-order relationship with time in all instances. The straight line, semi-logarithmic reactions depicted for the 0.5- and 2.0-m RBC units are illustrated in Figures 18 and 19, respectively.

The slopes of these lines (k values) indicated the rate of Fe(II) removal in accordance with first order kinetics:

$$F_t = F_o e^{-kt} \qquad (6.1)$$
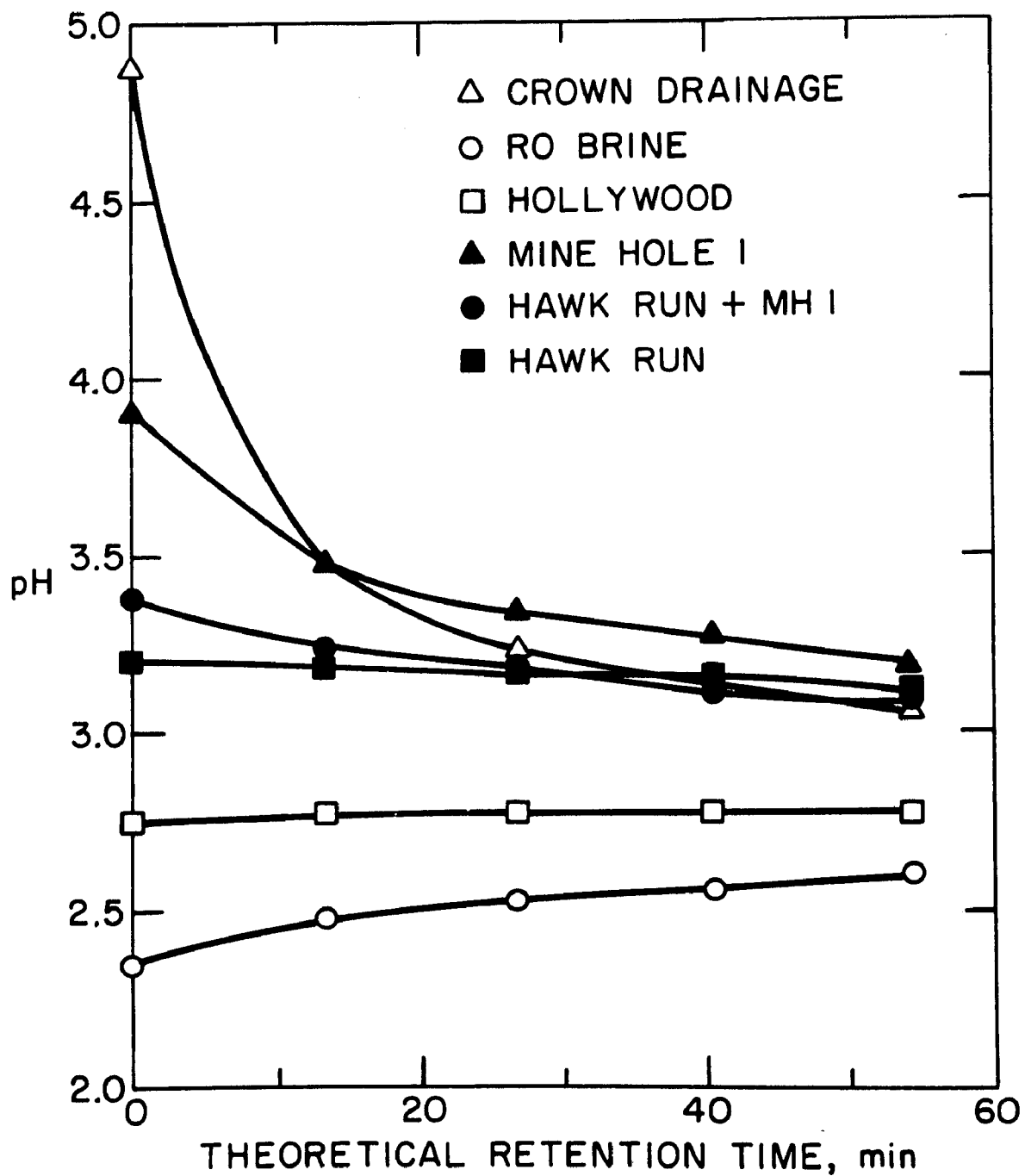
Figure 16. Changes in mine water pH with retention time in the
0.5-m RBC. Each data point represents the mean of
four to seventeen observations.
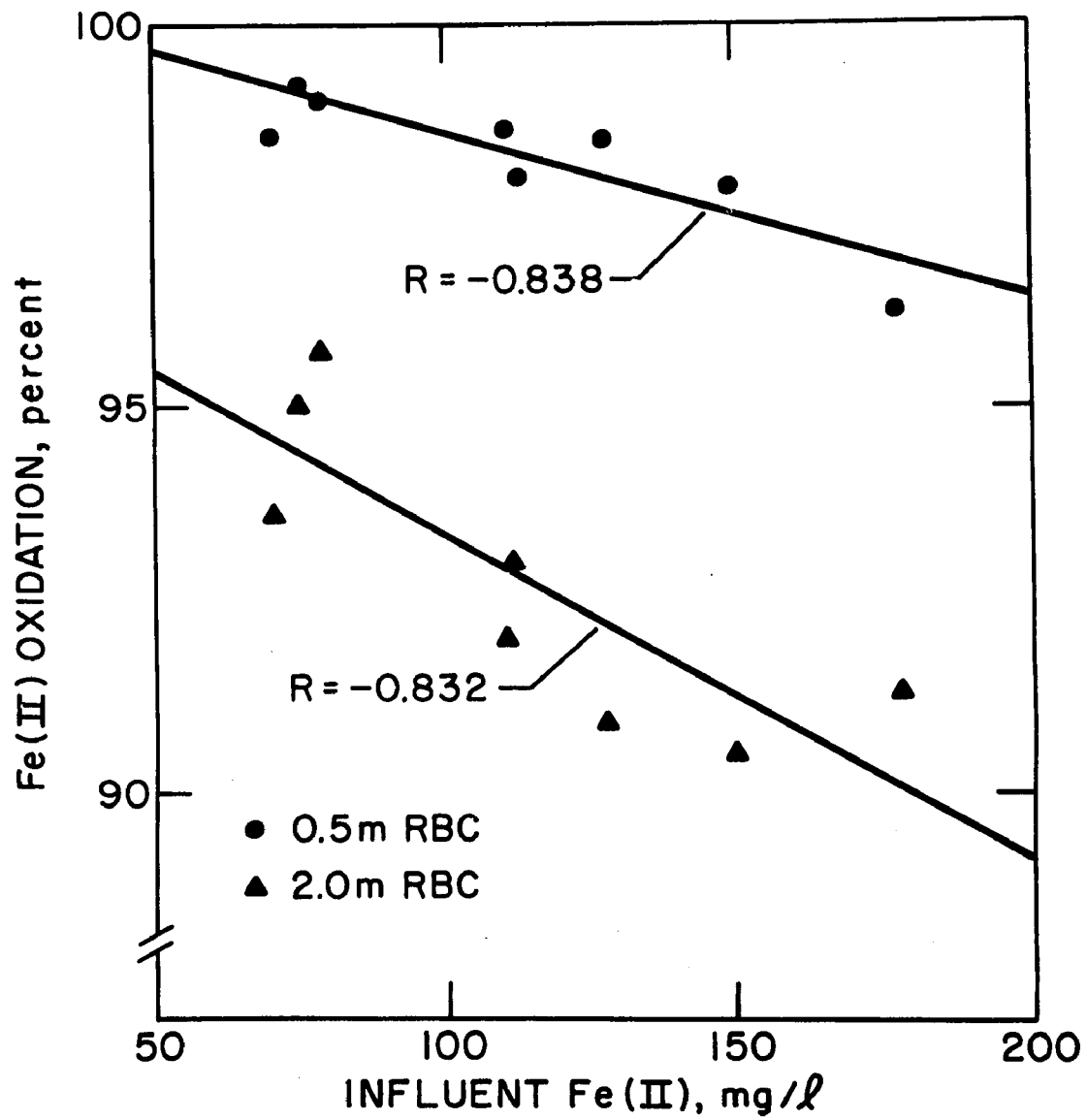
Figure 17. Effect of influent Fe(II) concentration on Fe(II)
oxidation efficiency in treatment of Hollywood
mine drainage.
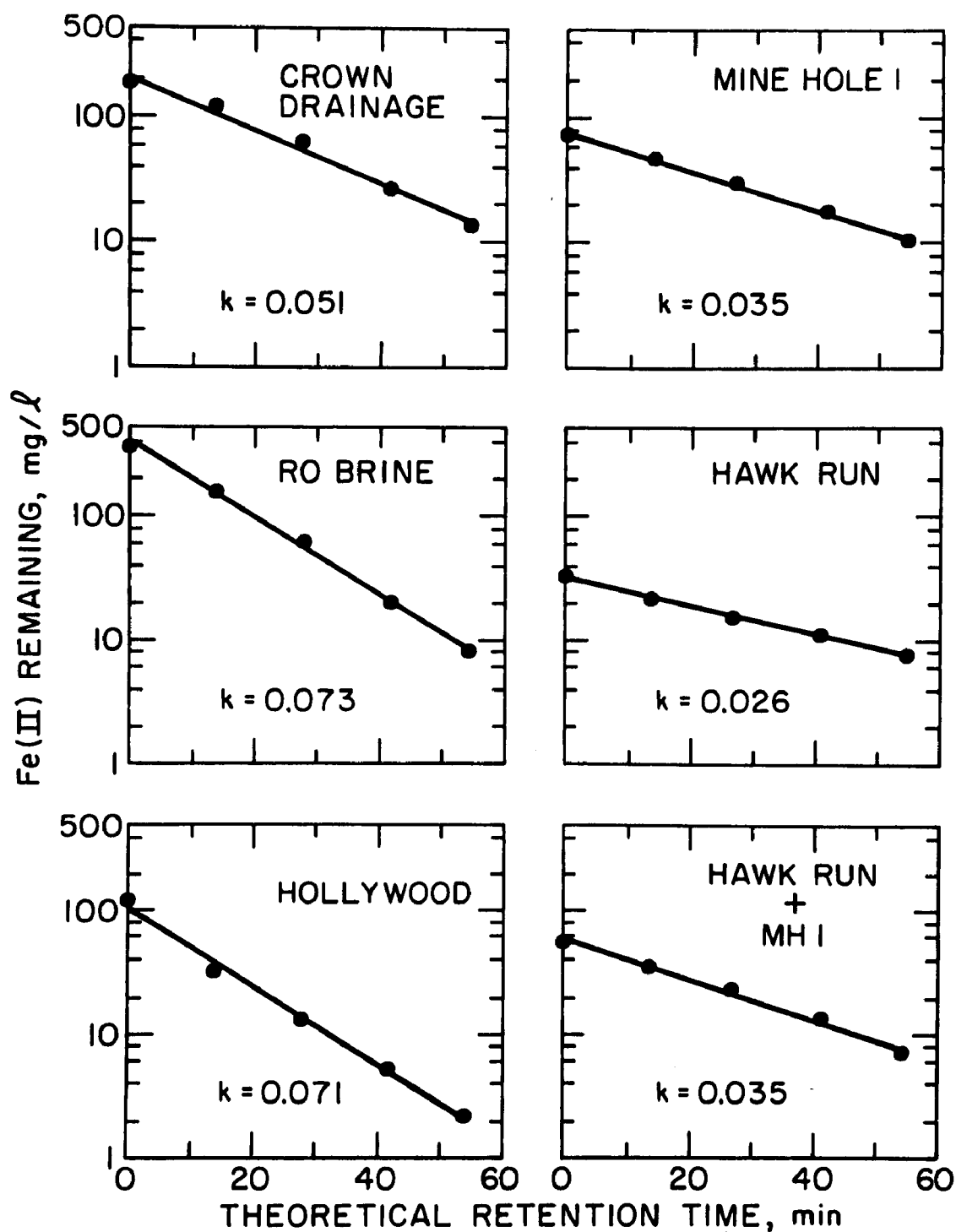
Figure 18. Kinetics of Fe(II) oxidation with the 0.5-m RBC showing values of k (Base e). Each stage data point represents the mean of four to seventeen observations.
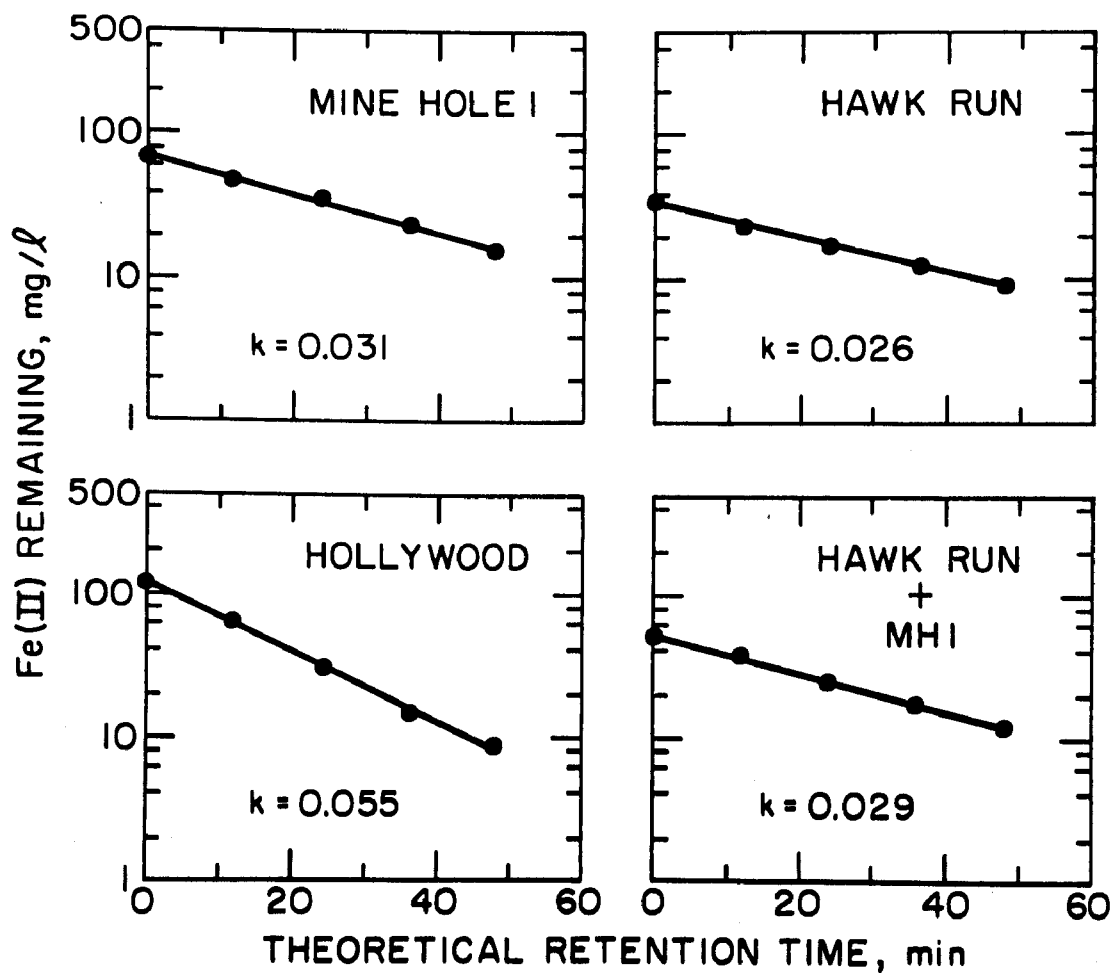
Figure 19. Kinetics of Fe(II) oxidation with the 2.0-m RBC showing values of k (Base e). Each stage data point represents the mean of four to eight observations.

where

$$F_t \quad = \quad \text{Fe(II) concentration at time, } t, \text{ mg/}\ell$$

$$F_o \quad = \quad \text{initial Fe(II) concentration, mg/}\ell$$

$$t \quad = \quad \text{theoretical liquid retention time, min, and}$$

$$k \quad = \quad \text{decay coefficient (base e) for Fe(II), min}^{-1}$$

Equation (6.1) can be made more useful by taking the natural logarithm of both sides and letting $Y = \ell n\, F_t$ and $a = \ell n\, F_o$:

$$Y \quad = \quad -kt + a \qquad\qquad (6.2)$$

Values for the decay rate shown in Figures 18 and 19 were obtained from Equation (6.2) by solving for the unknown, k. A similar decay rate (k = 0.054) was observed in previous studies (54) in treatment of Hollywood mine drainage with the 0.5-m RBC at a hydraulic loading equivalent to that used in this study.

Effect of Hydraulic Loading

The lower Fe(II) oxidation observed for the mine waters treated at Hawk Run, Pa. prompted attempts to improve oxidation efficiencies to the levels observed at other locations. After reaching equilibrium Fe(II) oxidation in treatment of Mine Hole 1 discharge at a hydraulic loading of 0.16 $m^3/d \cdot m^2$ with RBC field units, the hydraulic loading was decreased to 0.11 $m^3/d \cdot m^2$, allowed to reach equilibrium, and decreased again to 0.08 $m^3/d \cdot m^2$. Decreases in hydraulic loading resulted in corresponding increases in Fe(II) oxidation efficiency (Table 9). A hydraulic loading of 0.08 $m^3/d \cdot m^2$ allowed a sufficient increase in residence time in the trough of each RBC unit to obtain Fe(II) oxidation efficiencies similar to that normally observed at double the hydraulic loading applied at the other mine water treatment locations (Table 6).

Effect of Unanticipated Shutdown

After approximately 50 days of continuous operation of the 2.0-m RBC at Hollywood, Pa., malfunction of the drive motor which activates disc rotation occurred. Mine water was permitted to flow continuously through the unit; however, only 35 percent of the disc surface area remained wetted. Consequently, it was possible to observe the effect of a temporary shutdown on the operation of the biological process. During this period (4 days), Fe(II) oxidation efficiency decreased from 95.0 to 1.5 percent and DO levels in the trough of the unit decreased from 7.6 mg/ℓ just prior to shutdown to 0.5 mg/ℓ at the quiescent condition. Following this period, repair of the motor was completed and passage of mine water equivalent to one tank volume (4.6 m^3) resulted in a return of Fe(II) oxidation efficiency to 85.0 percent. Some desiccation, presumably injurious to the iron-oxidizing bacteria, was visibly apparent at the disc surfaces exposed to the air. Interior surfaces between discs, however, which provide the majority of available surface area,

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TABLE 9.   EFFECT OF HYDRAULIC LOADING ON Fe(II) OXIDATION EFFICIENCY WITH
THE 0.5- AND 2.0-M RBC UNITS IN TREATMENT OF MINE HOLE 1 DISCHARGE

| Hydraulic | Fe(II) oxidation, percent | | | |
| loading, $m^3/d \cdot m^2$ | 0.5-m RBC | | 2.0-m RBC | |
	Mean	Std. dev.	Mean	Std. dev.
0.08 (4)[a]	96.8	2.2	94.4	1.1
0.11 (4)	91.7	1.3	83.9	0.6
0.16 (5)	84.7	2.7	76.9	2.3

[a]Number of analyses applied to statistical determinations.

may protect the bacteria from evaporation of water from solids.

Following six days of renewed operation of the 2.0-m RBC at a Fe(II) oxidation of 85.0 to 86.0 percent, drive motor malfunction recurred. At this time, mine water flow was interrupted and the troughs of both units drained, thereby exposing the entire disc ensemble to the atmosphere. The units remained in this condition without disc rotation for 8 days. When a new drive motor was installed on the larger unit (the original motor was defective), flow was returned to both units and disc rotation was restored. After processing 0.14 and 4.6 m^3 (one tank volume) of mine water in the 0.5- and 2.0-m RBC units, respectively, Fe(II) oxidation efficiency was estimated at 71.7 percent for the smaller RBC and 70.0 percent for the larger unit. Five days later and prior to the final shutdown at the Hollywood facility, Fe(II) oxidation efficiencies of 93.5 and 84.3 percent were reached for the 0.5- and 2.0-m units respectively. Under the limited conditions observed in the field, it appeared that the unit supporting an established biomass active in Fe(II) transformation may be expected to recover oxidative capacity readily.

Characteristics of Biological Film

Solids formed on disc surfaces of the 0.5- and 2.0-m RBC units were examined at equilibrium Fe(II) oxidation for all mine waters treated. At Hollywood, Pa., (Figure 20, top) and Crown, W. Va., disc solids consisted of a bright orange surface layer and a darker inner layer. Solids were translucent and gelatinous, particularly on discs at stages close to the influent end of the RBC. The gelatinous outer layer was not seen on the disc surfaces during treatment of mine waters at Hawk Run, Pa. (Figure 20, bottom).

Solids thickness on stage 1 discs of the 0.5-m RBC treating first Crown mine drainage and later RO brine was approximately 2 and 3 mm, respectively. At Hollywood, stage 1 disc solids attained a maximum thickness of 2 mm with the 0.5-m RBC and 1 mm with the 2.0-m RBC. During equilibrium Fe(II) oxidation at Hawk Run, Pa., stage 1 solids had a maximum thickness of 1 mm for the 0.5-m RBC and 0.5 mm in thickness for the 2.0-m unit. The thickness of solids on discs visibly decreased in the direction of flow of mine water through both the 0.5- and 2.0-m units with all mine drainages treated. Differences in solids thickness at various stages of treatment were less evident with the high Fe(II)-containing RO brine and the outer gelatinous layer prevailed on the latter stages of the RBC to a greater extent than when Crown or Hollywood mine drainages were treated.

Microscopic observation of solids, previously freed of iron (see Appendix B), under phase-contrast optics indicated the presence of a gelatinous matrix with embedded bacteria (zoogloeae) (Figure 21). The matrix was more readily perceived in samples taken from RBC units at Hollywood and Crown, although zoogloeal aggregates were observed in Hawk Run solids, especially in samples retrieved from stage 1.

Glass cover slips attached to disc surfaces from stage 1 of the 2.0-m RBC prior to start-up at Hawk Run were removed at various intervals and
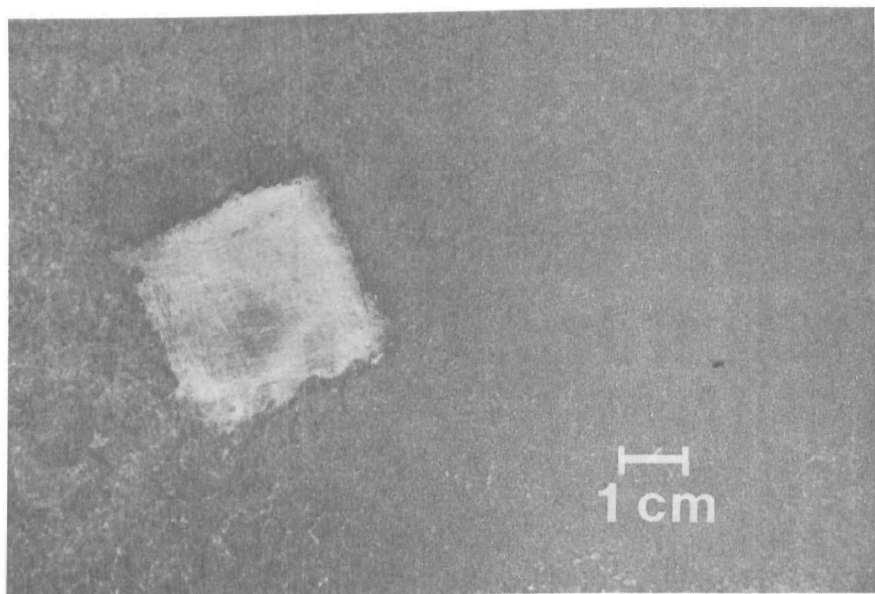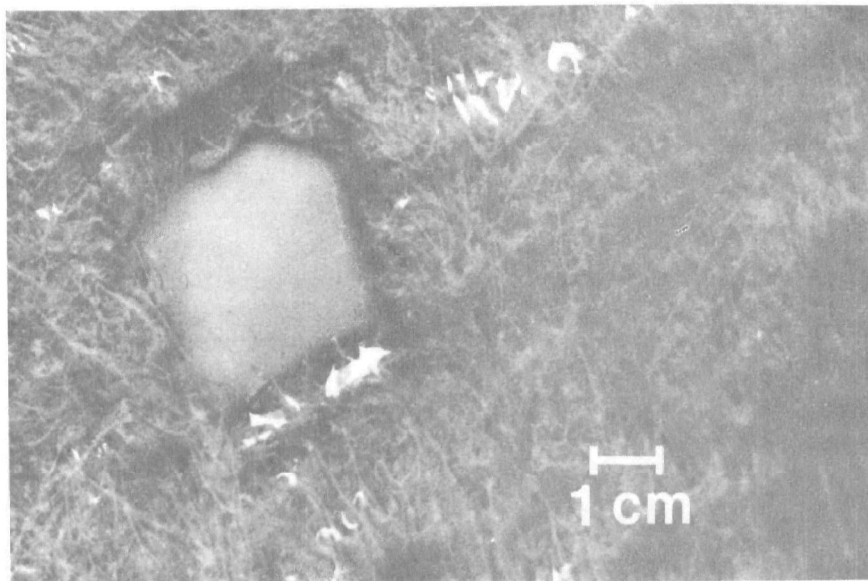
Figure 20. Solids formation on stage 1 discs of 0.5-m RBC in treatment
of mine drainage at Hollywood, Pa. (top) and Hawk Run, Pa.
(bottom). Cut-away sections reveal thickness of solids layer.
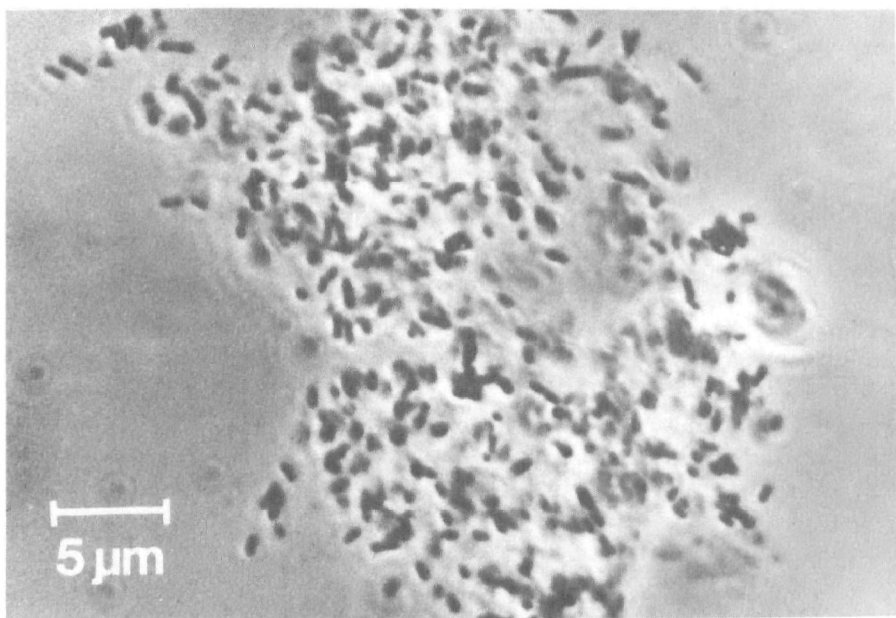
Figure 21. Phase-contrast photomicrograph showing bacteria embedded
in gelatinous matrix (zoogloea) from stage 1 of 0.5-m RBC
in treatment of mine drainage at Hollywood, Pa.

prepared for observation under the scanning electron microscope (SEM) (see Appendix B). Straight and curved bacilli were the only microbiological forms detected in observation of the iron-free samples. Observations by the SEM of a specimen prepared from a solids sample taken after 54 days of RBC mine drainage treatment clearly demonstrated bacterial cells in a slime layer (Figure 22, top). It was apparent, however, that the extensive preparation required prior to SEM analysis (fixation in OsO_4, alcohol drying, and critical point drying) resulted in the loss of many cells from specimens. Microorganisms recovered on 0.4-μm Nucleopore polycarbonate filters (General Electric Corp., Pleasanton, Calif.) from the influent mine drainage (Figure 22, bottom) were similar in morphology to those samples from disc solids observed under the SEM.

Certain chemical and microbiological characteristics of disc solids taken from the 0.5- and 2.0-m RBC units at equilibrium Fe(II) oxidation are given for each mine drainage in Tables 10 and 11, respectively. The dry weight of total solids and total Fe and Al per unit surface area (mg/cm^2) was highest on discs of the 0.5-m RBC which treated RO brine (Table 10). Iron-oxidizing bacterial densities were similar for the Crown mine drainage and RO brine even though influent Fe(II) content and corresponding Fe(II) oxidation efficiency were higher in treatment of the RO brine. Similarly, iron-oxidizing bacterial densities on disc surfaces were lower in treatment of Hollywood mine drainage as compared to the drainages of Hawk Run, even though efficiency of Fe(II) oxidation was higher at Hollywood at equivalent flow and disc rotation. A similar relationship existed for the 2.0-m RBC (Table 11). Approximately double the weight of total solids and total Fe per unit surface area formed on discs of the 0.5-m RBC in treatment of RO brine in comparison with other drainages. Similar relationships developed with the 2.0-m RBC although no data on this unit are available for Crown mine water treatment. The larger solids mass obtained in treatment of RO brine most probably relates to the high ferrous iron present in the influent brine.

Solids on disc surfaces of the 0.5- and 2.0-m RBC units contained a very low percentage of Al regardless of the source of mine drainage. Total Fe and Al comprised approximately 25 to 50 and 0.05 to 0.1 percent, respectively, of total disc solids dry weight for both RBC units. The Hollywood Proctor No. 2 mine drainage contained a much higher Al content than the drainages at Hawk Run (see Section 6) which probably accounts for the higher Al content in solids formed on Proctor No. 2 mine drainage. The relationship appeared to hold for both the 0.5- and 2.0-m RBC, although total solids content was higher for the 0.5-m RBC.

Disc solids characteristics presented in Tables 10 and 11 are tabulated for the influent-side disc of each individual stage (Tables 12 and 15). A general decrease per stage was observed in weight per unit disc surface area for each chemical characteristic (total solids, total Fe, and Al) (Tables 13, 14, and 15). Iron-oxidizing bacterial densities exhibited a greater variation in disc solids from stage to stage than chemical characteristics, although similar trends were apparent for both the 0.5- and 2.0-m RBC units (Table 12).
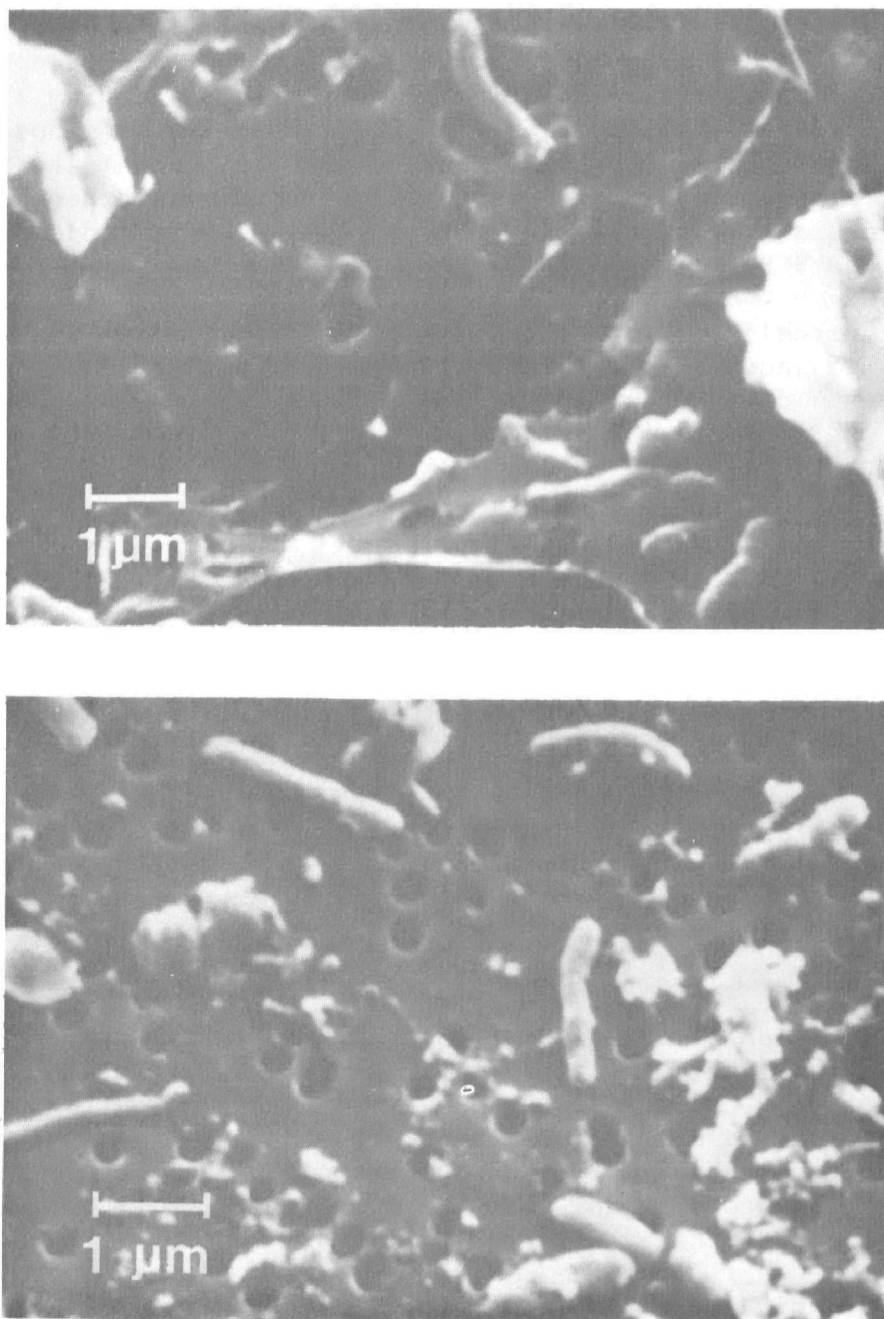
Figure 22.   Scanning electron micrographs. Top: Glass cover slips
             removed from stage 1 disc of 2.0-m RBC after 54 days of
             continuous treatment at Hawk Run. Bottom: Microorganisms
             filtered from Hawk Run mine water onto a 0.40-μm diameter
             filter.   Iron solubilized by addition of 1-percent oxalic
             acid to prepare samples for observation of microorganisms.

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TABLE 10. CHARACTERISTICS OF SOLIDS AT SURFACE OF
DISCS IN 0.5-m RBC[a]

Mine Drainage	Iron-oxidizing bacteria, MPN/cm^2	Total solids, mg/cm^2	Total iron, mg/cm^2	Aluminum, mg/cm^2
Crown (5)[b]	15,000	20.9	7.7	0.026
RO brine	3,800	45.3	14.9	0.029
Hollywood (4)	64	19.2	10.2	0.024
Mine Hole 1 (3)	220	22.2	4.0	0.009
Hawk Run (4)	290	21.2	5.0	0.011
Hawk Run (3) + MH 1	70	16.7	7.9	0.013

[a]Samples collected from influent-side disc of each stage of RBC during equilibrium Fe(II) oxidation.

[b]Number of analyses used to calculate mean values.

TABLE 11. CHARACTERISTICS OF SOLIDS AT SURFACE OF
DISCS IN 2.0-m RBC[a]

Mine Drainage	Iron-oxidizing bacteria, MPN/cm^2	Total solids, mg/cm^2	Total iron, mg/cm^2	Aluminum, mg/cm^2
Hollywood (4)[b]	51	10.6	4.7	0.021
Mine Hole 1 (3)	1,200	12.6	3.1	0.011
Hawk Run (4)	82	13.9	3.2	0.010
Hawk Run (3) + 1	410	11.2	3.3	0.012

[a]Samples collected from influent-side disc of each stage of RBC during equilibrium Fe(II) oxidation.

[b]Number of analyses used to calculate mean values.

TABLE 12. IRON-OXIDIZING BACTERIAL DENSITIES OF DISC SOLIDS AT EACH STAGE OF THE 0.5- AND 2.0-M RBC[a]

Mine Drainage	Iron-oxidizing bacteria, MPN/cm^2							
	0.5-m RBC				2.0-m RBC			
	S1	S2	S3	S4	S1	S2	S3	S4
Crown (5)[b]	25,000	12,000	11,000	17,000	--[c]	--	--	--
RO brine (4)	510	3,100	10,000	12,000	--	--	--	--
Hollywood (4)	150	60	58	33	91	77	38	26
Mine Hole 1 (3)	450	310	91	190	850	1,600	640	950
Hawk Run (4)	300	430	220	240	94	56	74	120
Hawk Run (3) + MH 1	72	77	62	69	650	220	420	450

[a]Samples collected from influent-side disc of each stage of RBC during equilibrium Fe(II) oxidation.

[b]Number of analyses for each stage used to calculate mean values.

[c]RBC unit not examined for mine drainage listed.

TABLE 13. TOTAL SOLIDS CONTENT OF DISC SOLIDS AT EACH STAGE OF THE 0.5- AND 2.0-M RBC[a]

Mine Drainage	Total solids dry weight, mg/cm^2							
	0.5-m RBC				2.0-m RBC			
	S1	S2	S3	S4	S1	S2	S3	S4
Crown (5)[b]	20.6	22.3	17.5	9.9	--[c]	--	--	--
RO brine (4)	81.3	40.5	34.0	26.8	--	--	--	--
Hollywood (4)	30.8	22.6	13.6	10.0	13.4	14.3	8.4	6.2
Mine Hole 1 (3)	31.7	19.8	17.9	19.4	10.4	13.4	14.7	12.0
Hawk Run (4)	24.8	23.7	21.4	14.8	13.7	14.8	13.3	13.6
Hawk Run (3) + MH 1	18.9	19.7	15.9	12.1	14.6	12.6	8.3	9.1

[a]Samples collected from influent-side disc of each stage of RBC during equilibrium Fe(II) oxidation.

[b]Number of analyses for each stage used to calculate mean values.

[c]RBC unit not examined for mine drainage listed.

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TABLE 14. TOTAL IRON CONTENT OF DISC SOLIDS AT EACH STAGE OF THE 0.5- AND 2.0-M RBC[a]

| Mine | Total iron, mg/cm^2 | | | | | | | |
| Drainage | 0.5-m RBC | | | | 2.0-m RBC | | | |
	S1	S2	S3	S4	S1	S2	S3	S4
Crown (5)[b]	11.8	8.1	7.1	3.6	--[c]	--	--	--
RO brine (4)	14.1	19.9	13.5	11.9	--	--	--	--
Hollywood (4)	10.8	17.9	5.7	6.2	5.1	6.6	5.1	2.1
Mine Hole 1 (3)	4.0	4.2	4.3	3.7	1.8	3.9	3.5	2.7
Hawk Run (4)	4.5	7.2	4.8	3.5	3.9	4.8	3.1	1.0
Hawk Run (4) + MH 1	18.1	7.0	4.9	1.5	3.0	3.6	3.2	3.2

[a]Samples collected from influent-side disc of each stage of RBC during equilibrium Fe(II) oxidation.

[b]Number of analyses for each stage used to calculate mean values.

[c]RBC unit not examined for mine drainage listed.

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TABLE 15. ALUMINUM CONTENT OF DISC SOLIDS AT EACH STAGE OF THE 0.5 and 2.0-M RBC[a]

Mine Drainage	Aluminum, mg/cm^2							
	0.5-m RBC				2.0-m RBC			
	S1	S2	S3	S4	S1	S2	S3	S4
Crown (5)[b]	0.047	0.024	0.017	0.017	--[c]	--	--	--
RO brine (4)	0.045	0.028	0.022	0.029	--	--	--	--
Hollywood (4)	0.025	0.027	0.022	0.023	0.024	0.022	0.022	0.017
Mine Hole 1 (3)	0.010	0.010	0.010	0.008	0.007	0.016	0.011	0.012
Hawk Run (4)	0.011	0.011	0.011	0.010	0.010	0.010	0.010	0.009
Hawk Run (3) + MH 1	0.027	0.008	0.007	0.010	0.007	0.010	0.025	0.006

[a] Samples collected from influent-side disc of each stage of RBC during equilibrium Fe(II) oxidation.

[b] Number of analyses for each stage used to calculate mean values.

[c] RBC unit not examined for mine drainage listed.

Hydraulic Characteristics of RBC

In order to characterize the hydraulic efficiency of the RBC, a concentrated tracer solution (1.0 g/ℓ LiCl) was added instantaneously to one feed bucket of each RBC unit just prior to discharge into stage 1. The volume of tracer solution added to the 2.0-m RBC unit was proportionately larger on the basis of trough volume. Samples collected from each stage and effluent at specified time intervals were analyzed for lithium and the results were used to construct plots of Li recovered versus time (Figure 23). Samples collected from stage 1 within 30 seconds of tracer addition revealed peak Li content. Higher Li concentrations were recovered from stage 1 of the 0.5-m RBC (Figure 23, top) than from the same stage of the 2.0-m RBC (Figure 23, bottom) which suggested more short-circuiting of flow to subsequent stages for the larger sized RBC. Time for 50 percent of tracer to pass through the tank (mean retention time) was nearly identical to the theoretical retention times calculated on the basis of flow and trough volume for the respective units (Table 16). Although RBC units were sized for equivalent hydraulic loading (flow per unit disc surface area) for all experiments described in this study, different ratios of surface area-to-trough volume for the units (Table D-1) resulted in different theoretical retention times. Villemonte and Rohlich (68) described certain dimensionless ratios which may be employed to evaluate the hydraulic efficiency of continuous flow reactors. Application of these indices to the results of tracer addition revealed near ideal dispersion of reactor contents in individual stages of each unit, some short-circuiting between individual stage compartments, and overall flow through the tank which approached "plug flow" conditions (Table 16).

Analysis of total Fe and Al in influent and effluent of RBC units at Hollywood and Hawk Run indicated that approximately 10 percent of influent total Fe and Al was continually being deposited on disc and trough surfaces. Mass balance calculations for total Fe and Al in influent and effluent mine water and on disc surfaces suggested that approximately 5 percent of the total influent Fe was continually being deposited in the trough with the remainder accumulating on disc surfaces. Following shutdown at the Hollywood Facility, total solids deposited in the trough of the 0.5-m and 2.0-m RBC units were found to have reduced the liquid volume of the trough by 14 percent (19 liters) and 1.5 percent (57 liters), respectively. The 2.0-m RBC was equipped with four perforated tubes attached to the periphery of disc surfaces of each stage to aid in turbulence and the prevention of solids deposition in the reactor compartments (see description of tubes in Appendix D). The 0.5-m unit, however, did not provide means of controlling solids deposition except for the turbulence created by disc rotation.

COST ANALYSIS

Estimated Costs

Costs were estimated for Fe(II) oxidation with the RBC for mine drainage flows of 500 and 5,000 m^3/d (Table 17). Costs for pumping, neutralization, and solids handling were not listed. Only unit process costs were included in the estimates. Cost estimates were quoted by Autotrol Corporation, one of several manufacturers of RBC equipment. Equipment needs were
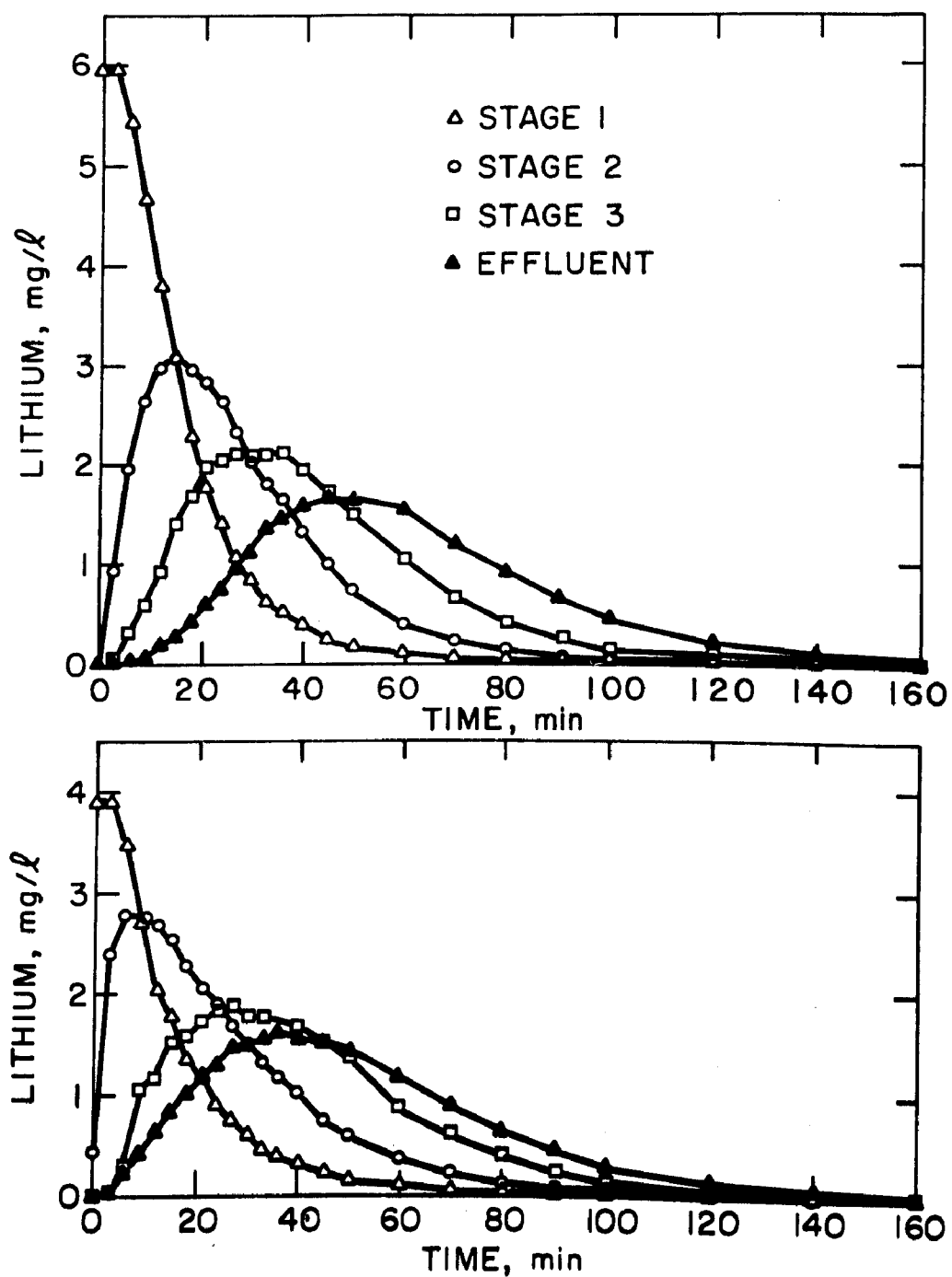
Figure 23. Recovery of tracer in each state of RBC field units.
Top: 0.29 g Li added to influent of 0.5-m RBC at
flow rate of 3.4 m^3/d; Bottom: 8.2 g Li added to
influent of 2.0-m RBC flow rate of 115 m^3/d.

TABLE 16. HYDRAULIC CHARACTERISTICS OF 0.5- AND 2.0-M RBC UNITS

Para-meter	Lithium, mg/ℓ							
	0.5-m RBC				2.0-m RBC			
	S1	S2	S3	S4	S1	S2	S3	S4
t_p	3	15	36	47	3	6	27	37
t_{10}	1.9	8.1	17.3	28.9	1.8	5.1	15.0	20.1
t_{50}	10.3	23.5	39.2	56.8	10.4	20.5	38.1	49.4
t_{90}	33.9	54.3	77.0	98.7	36.1	53.4	76.3	96.5
T	13.6	27.2	40.8	54.4	12.0	24.0	36.0	48.0
$\dfrac{t_p}{T}$	0.22	0.55	0.88	0.86	0.25	0.25	0.75	0.77
$\dfrac{t_{90}}{t_{10}}$	17.8	6.7	4.5	3.4	20.1	10.5	5.1	4.8
$\dfrac{t_{50}}{T}$	0.76	0.86	0.96	1.04	0.87	0.85	1.06	1.03

$^a t_p$ = time for peak tracer concentration to pass through tank.

t_{10} = time for 10 percent of tracer to pass through tank.

t_{50} = time for 50 percent of tracer to pass through tank.

t_{90} = time for 90 percent of tracer to pass through tank.

T = theoretical retention time (trough volume/flow rate).

$\dfrac{t_p}{T}$: Measures average short-circuiting, dead spaces, and effective tank volume. It is 1.0 for ideal settling and zero for ideal mixing.

$\dfrac{t_{90}}{t_{10}}$: Measures dispersion. It is 1.0 for ideal settling and 21.9 for ideal mixing.

$\dfrac{t_{50}}{T}$: It is 1.0 for ideal settling and 0.693 for ideal mixing.

TABLE 17. ESTIMATED COSTS FOR Fe(II) OXIDATION WITH
ROTATING BIOLOGICAL CONTACTORS[a]

Item	Estimated costs at design flow of: 500 m^3/d	Estimated costs at design flow of: 5,000 m^3/d
Initial cost		
RBC shafts with drive package	46,285	375,030
Enclosures (fiberglass)	7,880	63,040
Concrete basins (installed)[b]	12,000	64,000
Freight and installation	8,100	59,800
Total	$ 74,265	$ 561,870
Annual amortization cost[c]	$ 7,009	$ 53,035
Annual operating cost		
Electrical (5¢/kwh)[d]	1,964	26,147
Maintenance[e]	1,086	8,729
Personnel ($9/hr)	225	675
Total	$ 3,275	$ 35,551
Cost per cubic meter treated, ¢/m^3		
Amortization	3.8	2.9
Operating	1.8	1.9

[a]Basis: Influent Fe(II)   =   250 mg/ℓ
Oxidation efficiency = 95 percent
Hydraulic loading = 0.16 $m^3/d \cdot m^2$
Commercial rates quoted by Autotrol Corporation, 25 June 1978.

[b]Installed cost = $325/$m^3$ of concrete

[c]Seven percent interest amortized over 20 years (capital recovery factor = 0.09439).

[d]Drive motors rated at 4.5 and 60 kw, total, for the small and large facilities, respectively.

[e]Two percent of the cost of RBC shafts plus one percent of enclosure and freight + installation costs.

sized on the basis of surface area required for obtaining the hydraulic loading normally used in this study (0.16 $m^3/d \cdot m^2$). Normal large-scale application of the RBC would employ 3.6-m diameter discs. Autotrol Corporation recommended use of 2.0-m discs because of the greater mass density of iron solids in comparison to solids adhered to disc surfaces in organic wastewater treatment.

Costs per cubic meter treated for the 500 and 5,000 m^3/d installations were estimated at 3.8 and 2.9¢, respectively, for amortization of capital expenditures and 1.8 and 1.9¢, respectively, for operation and maintenance. The larger facility may realize an economy of scale in comparison of amortized cost estimates per cubic meter treated for the two design flows. The comparable operating costs were due, primarily, to the constant electrical cost per kwh applied to the estimates for both installations.

Cost Comparison

Costs for Fe(II) oxidation by conventional chemical oxidation were estimated for design flows equivalent to those used in cost estimates for the RBC (Table 18). Estimates were obtained with the aid of current equipment manufacturer literature and information contained in publications by Mihok (52) and Doyle et al. (22) which described mine drainage pollution control costs. Required aeration basin volume was determined for each flow rate by use of a design retention time of 90 min. Wilmoth et al. (74) found retention times in aeration basins used in six chemical mine drainage treatment plants to range from 10 to 370 min.

For both design flows, amortized capital costs were estimated to be less than one-half those estimated for the RBC. Operating costs were almost double those of the RBC estimates. Total costs per cubic meter treated were lower, however, for the conventional process in use today for mine drainage Fe(II) oxidation. In simply comparing total unit process costs, the lower unit costs estimated for electricity, maintenance, and personnel with the RBC do not compensate for higher capital cost of equipment and installation. The overall economics would favor the RBC method only when electrical power costs double the value used in the estimates.

Direct comparison of the RBC and conventional chemical oxidation methods may not provide a true comparison of total estimated treatment costs. The process chosen for the Fe(II) oxidation may change equipment and chemical needs for other required processes and these modifications could change the overall economics. Several advantages have been cited for oxidation systems which precede neutralization. Use of limestone has proved to be feasible and lower in cost than lime when mine water iron exists as Fe(III) (72). Limestone has been reported to be impractical for neutralization when mine water Fe(II) is greater than 100 mg/ℓ because the pH cannot be elevated to levels high enough to stimulate rapid chemical Fe(II) oxidation (47). Fe(II) .oxidation, if performed prior to neutralization, would allow use of limestone. Over-treatment would not be likely with limestone treatment because pH values above 8 are not attainable. Process control would be simpler when neutralization follows Fe(II) oxidation because addition of excess neutralizing chemical would not be necessary to account for acidity production from post

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TABLE 18. ESTIMATED COSTS FOR Fe(II) OXIDATION BY
CONVENTIONAL CHEMICAL OXYGENATION WITH MECHANICAL AERATORS[a]

Item	Estimated costs at design flow of: 500 m^3/d	Estimated costs at design flow of: 5,000 m^3/d
Initial cost		
Mechanical aerators	7,000	55,000
Concrete basins (installed)[b]	12,000	64,000
Freight and installation	3,000	20,000
Total	$ 22,000	$ 139,000
Annual amortization cost[c]	$ 2,100	$ 13,100
Annual operating cost		
Electrical (5¢/kwh)[d]	3,270	41,640
Maintenance[e]	1,958	14,912
Personnel[f]	1,050	8,250
Total	$ 6,278	$ 64,802
Cost per cubic meter treated, ¢/m^3		
Amortization	1.1	0.7
Operating	3.4	3.5

[a]Basis: Influent Fe(II) = 250 mg/ℓ; influent pH = 7.5
          Theoretical design retention time = 90 min
          Commercial rates estimated for 1978.

[b]Installed cost = $325/$m^3$ of concrete.

[c]Seven percent interest amortized over 20 years (capital recovery factor = 0.09439).

[d]Mechanical aerators rated at 7.5 and 95 kw, total, for small and large facilities, respectively.

[e]Ten percent of aerator capital cost plus one percent of freight and installation plus aerator replacement by use of sinking fund at five percent over aerator life of 7 years (factor = 0.12282).

[f]Fifteen percent of aerator capital cost.

Fe(II) oxidation and hydrolysis. Lovell (47) observed better sludge settleability for limestone treatment in comparison to hydrated lime. These considerations may be more important in choosing a method for Fe(II) oxidation than a simple comparison of costs for the unit process alone.

Within the precision of treatment costs estimates, it appeared that total costs for the RBC system would be similar to costs for a well designed chemical oxidation process. The RBC system was estimated to be a more capital intensive process, while the chemical oxidation method was found to be more energy intensive and higher in total operating costs.

Costs estimated for the two Fe(II) oxidation systems were based on liberal use of design safety factors. Sufficient cost savings may be accrued with the conventional method by use of clay-lined ponds in place of concrete basins. In addition, smaller size basins would be required for the oxidation system by elevating pH prior to oxidation to values above the lower limit for current effluent discharge regulations. In this way, it would be possible to take advantage of the more rapid oxidation rates which would result (see Figure 3). Holland et al. (35) indicated that a pH of 10.5 was desired to assure complete and rapid Fe(II) oxidation by chemical oxygenation. Studies by Wilmoth (73) and Lovell (47) showed elevation of mine water pH to a value of 8 was adequate for efficient oxidation. The additional dosage of neutralizing chemical required to attain these pH values may offset its potential savings.

For the RBC system, capital and operating costs may be lowered by use of larger diameter disc assemblies. The RBC equipment recommended by Autotrol Corp. and used in estimating costs included 2.0-m discs in place of their conventional full-scale equipment (3.6-m diameter discs). Other suppliers of RBC devices manufacture mechanically supported disc assemblies. The 3.6-m assemblies available from these manufacturers may be suitable for use in a mine drainage treatment application and should result in lower total costs. For example, a smaller number of RBC shafts, enclosures, and concrete basins would be required in order to provide the desired hydraulic loading for application to a 5,000 m^3/d design flow and their use may save an estimated $200,000 in total initial costs.

BENCH-SCALE STUDIES

INTRODUCTION

Bench-scale RBC experiments permitted examination of the effect on Fe(II) oxidation efficiency of supplementation or alteration of mine drainage feed which could not be conveniently achieved in field studies. At the Crown field site, two identical 15-cm diameter RBC units (Figure 24, top), constructed and described in previous studies (54), were fed mine drainage having a natural pH range of 4.05 to 5.74. One unit was supplemented with 0.25N H_2SO_4 to lower the pH to 2.8 to 3.4. Schnaitman et al. (56) observed stimulation of Fe(II) oxidation by T. ferrooxidans at this pH range. The remaining unit received natural, unadjusted pH mine drainage and served as a control.

Miniaturized versions of RBC field units with discs measuring 10 cm in diameter were constructed and operated under controlled environment conditions (Figure 24, bottom). Synthetic mine drainage was used as the main feed source for the two identical units in order to provide more control over mine drainage variables of temperature, ionic concentration, pH, and microorganism content. One RBC received a supplement of natural mine drainage (5 percent of total flow) to examine the effect on Fe(II) oxidation of constituents in drainage not present in synthetic mine water.

For both bench-scale studies, Fe(II) oxidation, viable iron-oxidizing bacteria density both in mine water and on disc surfaces, and other parameters of interest were analyzed throughout the length of the study (see Appendix B).

MINE WATER CHARACTERISTICS

The Crown drainage was used as mine water feed to the 15-cm RBC units. Mine water was analyzed during the period of study for selected physical, chemical, and microbiological parameters (Table 19). Mine water temperature was somewhat higher than that measured in field studies. The difference was apparently due to the slow velocity of travel of mine water through the small diameter tubing. Other characteristics of the mine water used in the bench-scale work were similar to those observed for the mine water during field studies (Table 3).

Synthetic mine water applied in controlled laboratory experiments was produced by dissolving reagents in deionized water (Table 20). Fe(II) content and pH of the synthetic mixture were measured regularly (five to
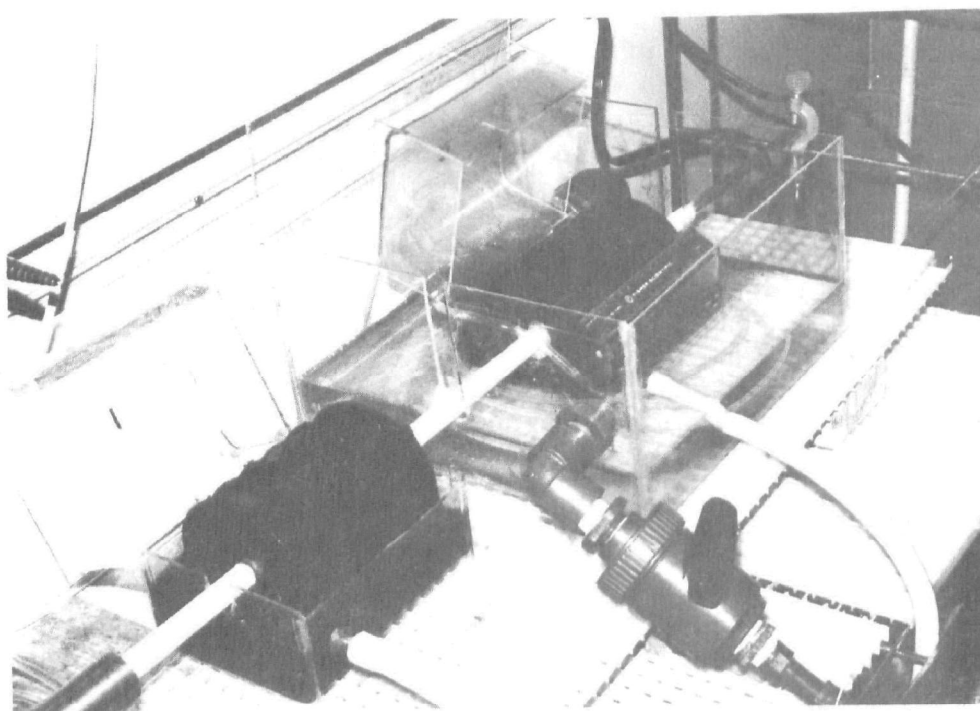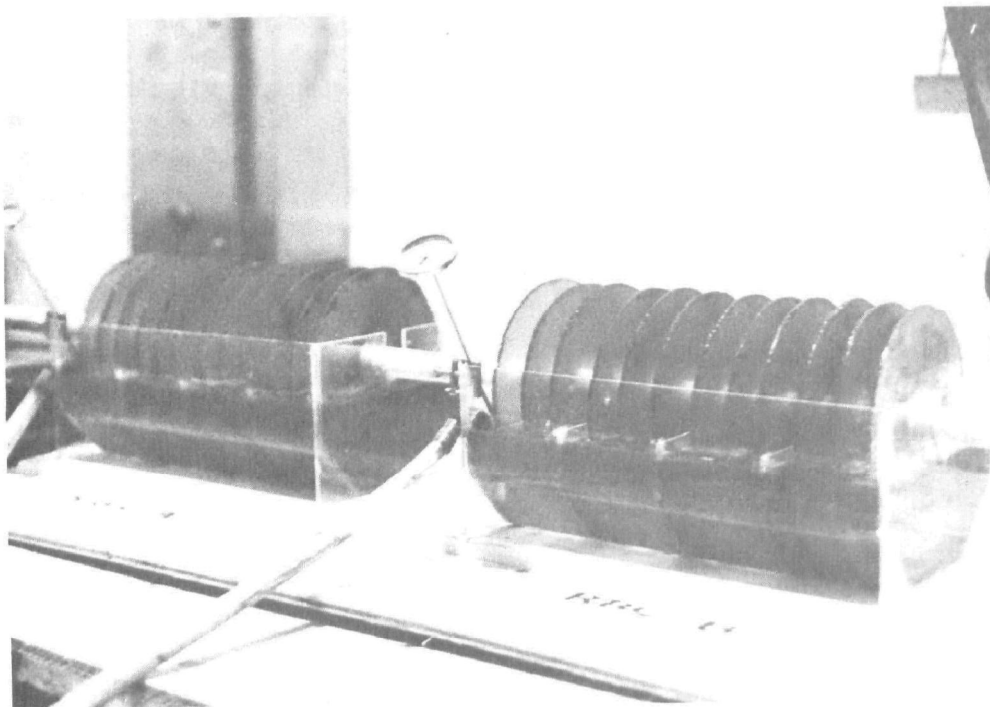
Figure 24.   Bench-scale RBC units. Top: Experimental 15-cm diameter
units used in pH studies at Crown, W. Va. Bottom: 10-cm
units used in laboratory studies on the supplementation
of natural mine drainage to synthetic mine water feed.

TABLE 19. CHARACTERISTICS OF ACID MINE DRAINAGE EMPLOYED IN BENCH-SCALE
EXPERIMENTS AT THE U.S. EPA CROWN FIELD SITE NEAR MORGANTOWN, W. VA.[a]

Parameter	Unsupplemented mine drainage		Acidified mine drainage	
	Mean	Std. dev.	Mean	Std. dev.
Temp., °C (21)[b]	19.2	2.7	19.3	2.5
pH (21)	4.34	--	2.95	--
Fe(II), mg/l (21)	182	35	181	35
Fe(III), mg/l (11)	36	50	35	44
Iron-oxidizing (11) bacteria, MPN/100 ml	3,000	13	6,500	21

[a]Samples were collected from May 24 to June 22, 1977.

[b]Number of analyses applied to statistical determinations.

TABLE 20. COMPOSITION OF SYNTHETIC MINE DRAINAGE FEED SOLUTION
EMPLOYED IN LABORATORY STUDIES

Constituent	Intended final ionic concentration
$FeSO_4 \cdot 7H_2O$	250 mg/ℓ Fe(II)
$CaCl_2$	50 mg/ℓ Ca
$MgSO_4 \cdot 7H_2O$	50 mg/ℓ Mg
$Al_2(SO_4)_3 \cdot 18H_2O$	25 mg/ℓ Al
$MnSO_4 \cdot H_2O$	5 mg/ℓ Mn
$(NH_4)_2SO_4$	1 mg/ℓ NH_3-N
K_2HPO_4	0.5 mg/ℓ PO_4
H_2SO_4	to pH 3

seven times per week). A final pH of 2.8 to 3.2 was desired to reflect a typical acid mine drainage pH and was maintained approximately 85 percent of the time. Fe(II) concentrations were maintained at a mean value of 233 mg/ℓ and a standard deviation of 17 mg/ℓ. Hollywood mine drainage served as the natural mine drainage supplement (Table 4). Iron-oxidizing bacterial populations were monitored for each container of drainage (15 liters) collected weekly by sampling and analyzing just prior to use and at the point of exhaustion of the feed. These analyses were performed to check the accuracy of dilution into synthetic mine water. The mean iron-oxidizing bacteria in drainages were found to be 2,100 MPN/100 mℓ. The calculated mean density of iron-oxidizing bacteria following dilution was 100 MPN/100 mℓ.

EXPERIMENTAL APPARATUS AND PROCEDURES

Crown, West Virginia

The two 15-cm diameter RBC units were constructed from acrylic plastic and designed to conform to a surface area-to-trough volume ratio similar to commercial field units (see Appendix D). Peripheral disc velocity was equivalent to that used in field studies (19 m/min) and rotation (38 rpm) was maintained by a small gear-reduced electric motor. Hydraulic loading to the units was the same as normally used in field studies (0.16 m^3/d·m^2) and mine water was applied to each unit with a Gorman-Rupp model 7128 dual head metering pump at the rate of 100 mℓ/min per channel. A small amount of 0.25N H_2SO_4 (approximately 1 mℓ/min) was injected into the feed line of one unit with the aid of a Beckman model 746 metering pump.

Laboratory

The two identical 10-cm diameter RBC units were constructed from acrylic plastic and scaled to the 15-cm RBC units, but were equipped with only two stages (see Appendix D). Peripheral disc velocity was maintained at 19 m/min (57 rpm) with an electric motor.

Synthetic mine drainage flow was provided by a system (Figure 25) of laboratory pumps (two Sage model 375A four channel tubing pumps, and one Pharmacia model P-3 three channel peristaltic pump) which metered separate concentrated solutions of inorganic salts, $FeSO_4 \cdot 7H_2O$, and 0.1N H_2SO_4 along with deionized water prepared by continuous feed of tap water through a commercial laboratory RO unit (Millipore Corporation, Bedford, Mass.). Final mine water flows (10 mℓ/min) were equivalent to a hydraulic loading to each unit of 0.16 m^3/d·m^2. The controlled temperature room which housed the RBC units and the feed solutions was maintained at approximately 10°C during the period of study (44 days).

Extra pump channels allowed separate metering of Hollywood drainage to both RBC units for initial start-up and to one RBC for supplementation of synthetic feed. At start-up, the units received approximately 1 mℓ/min of Hollywood drainage to produce a population of microorganisms on RBC disc surfaces. After 14 days, significant Fe(II) oxidation occurred (greater than 80 percent) and mine drainage feed was replaced with the synthetic mixture and the flow rate increased to 10 mℓ/min. Following a period of initial
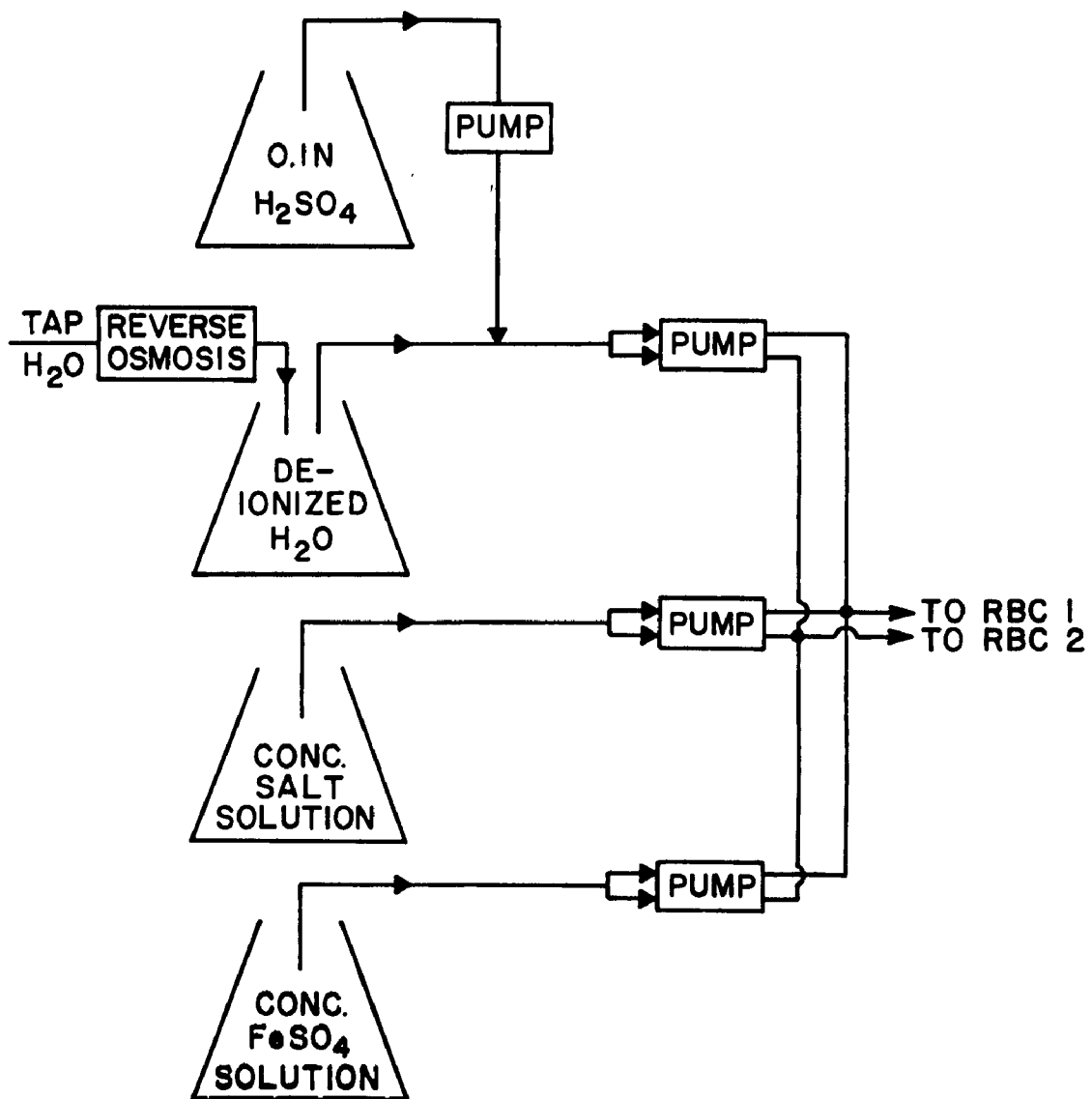
Figure 25. Apparatus and concentrated solutions employed in continuous metering of synthetic mine drainage to 10-cm bench-scale RBC units.

acclimation to synthetic feed (24 days), one unit was fed Hollywood drainage at 5 percent of total feed while the other unit received no supplement and served as a control.

RESULTS

Adjustment of pH of Natural Mine Water

The 15-cm RBC (RBC A) which received natural Crown mine drainage behaved similarly to the 0.5-m RBC pilot unit in establishing Fe(II) oxidation (Figure 26). Three days after start-up, Fe(II) oxidation efficiency was approximately 6 percent in the bench-scale unit and mine water effluent pH increased to 6.55. Thereafter, effluent pH was below 4 and oxidation efficiency increased steadily to above 90 percent after 13 days. RBC B, which received mine drainage acidified with H_2SO_4 to a mean pH of 2.95, did not exhibit the rapid onset of Fe(II) oxidation demonstrated by RBC A (Figure 26). After 26 days of continuous operation, both units achieved an equilibrium Fe(II) oxidation efficiency of 95.3 to 99.2 percent.

Iron-oxidizing bacterial densities and total solids content on disc surfaces were compared for the two RBC units (Figure 27). Initially, iron-oxidizing bacterial numbers on disc surfaces were lower for RBC B. After 20 days, however, iron-oxidizing bacterial densities were nearly equal and the efficiency of Fe(II) oxidation was greater than 80 percent in both units. RBC B had a lower total disc solids dry weight during the 30-day period.

Supplementation of Synthetic Mine Water with Natural Mine Drainage

Initial acclimation of two bench-scale 10-cm RBC units to pH 3 synthetic mine drainage (24 days) revealed a maximum Fe(II) oxidation efficiency of 49.4 and 40.6 percent after 17 days of operation in a controlled (10°C) room (Figure 28). Following this period, oxidation efficiency decreased steadily. Just prior to supplementation with natural mine drainage, Fe(II) oxidation in the two units was 19.8 and 28.6 percent. The difference observed in oxidation with the two identical units at the time of Fe(II) analysis apparently was due to chance because Fe(II) concentrations fluctuated between the units.

On the 26th day of continuous synthetic mine drainage feed, one unit (RBC 1) was supplemented with natural mine drainage (5 percent). Fe(II) oxidation efficiency increased over 20 percent after 1 day and continued to increase thereafter. The control unit (RBC 2) was consistently less efficient than the unit which received mine drainage supplement. Twelve days after initiation of mine drainage supplement, samples were periodically collected for enumeration of iron-oxidizing bacteria in influent and effluent mine water and on disc surfaces (Table 21). Iron-oxidizing bacteria were not detected in the synthetic mine drainage, but a mean MPN of 1,100 cells/100 ml were recovered in the effluent. A higher effluent iron-oxidizing bacterial density was observed for the RBC which received mine drainage supplement. Iron-oxidizing bacterial populations on stage 1 and 2 discs were higher, however, for the unit which received synthetic feed (RBC 2), possibly reflecting the higher proportion of solids-associated bacteria on RBC 2 which
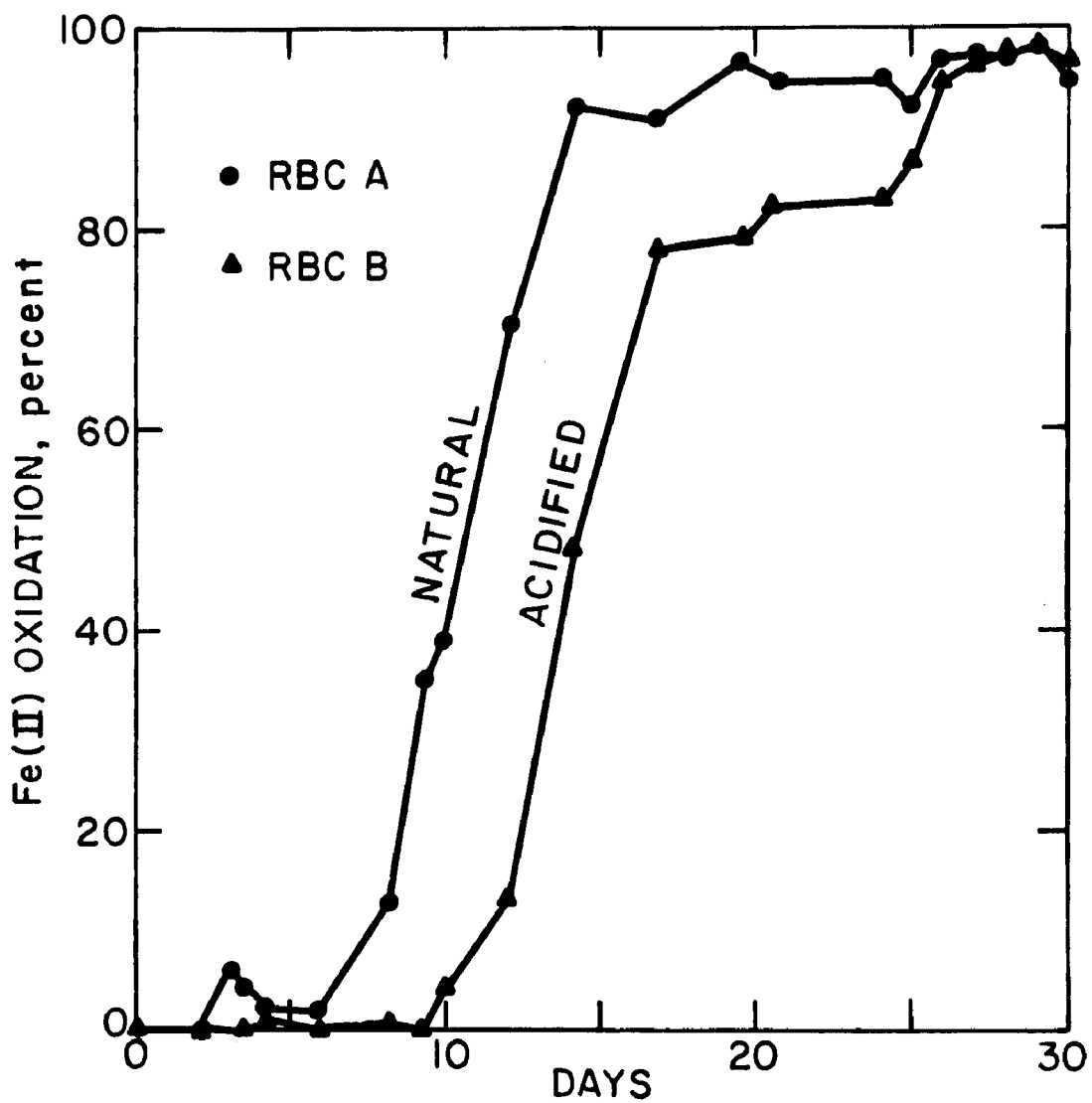
Figure 26. Fe(II) oxidation in 15-cm RBC units operated on Crown mine
drainage with a natural pH range of 4.05 to 5.74 (RBC A)
and acidified to pH 3 (RBC B).
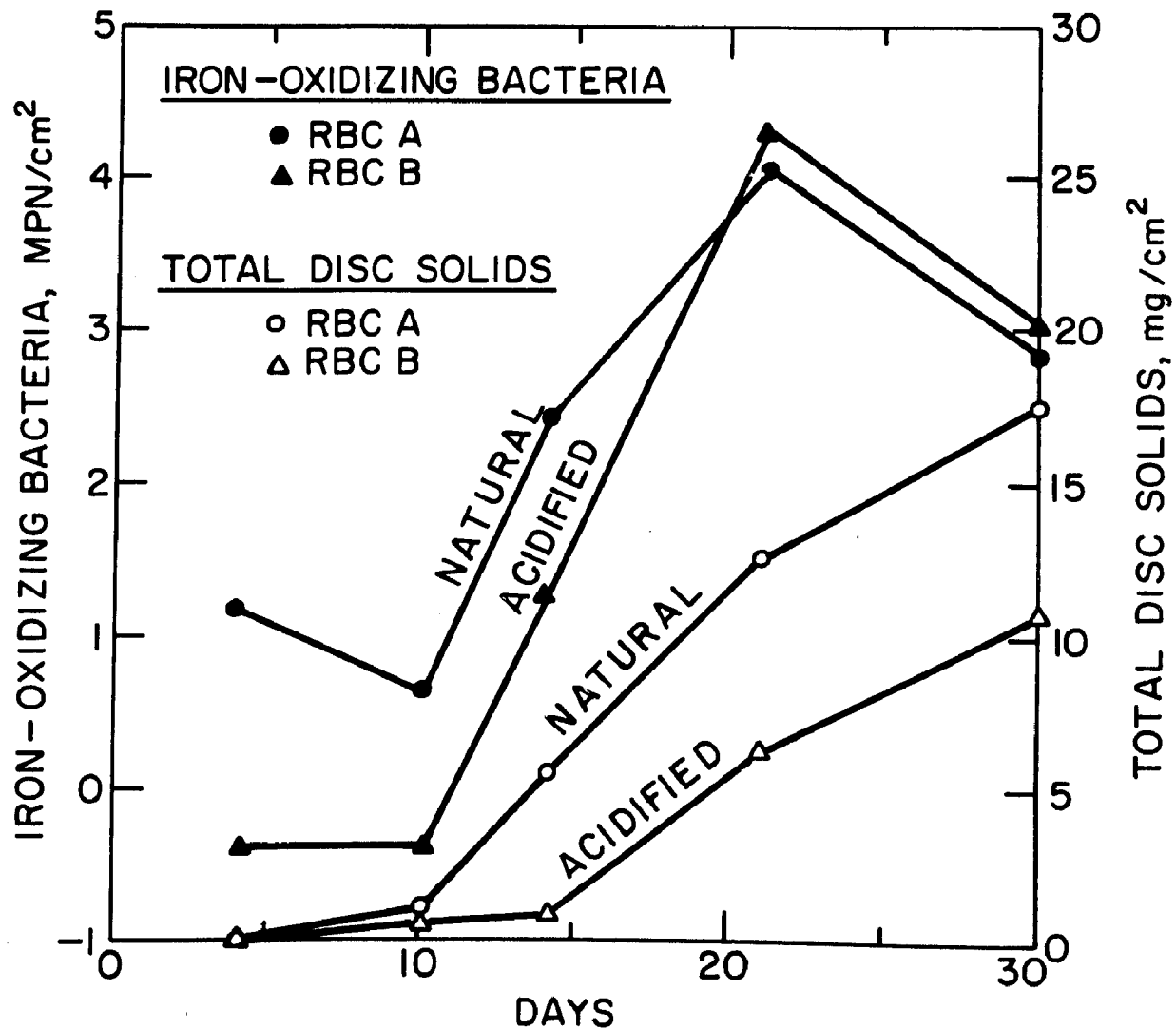
Figure 27. Iron-oxidizing bacterial densities at surface of discs and
total disc solids dry weight. Bench-scale (15-cm) RBC
units in treatment of Crown drainage with a natural pH
range of 4.05 to 5.74 (RBC A) and an adjusted pH of 3
(RBC B).
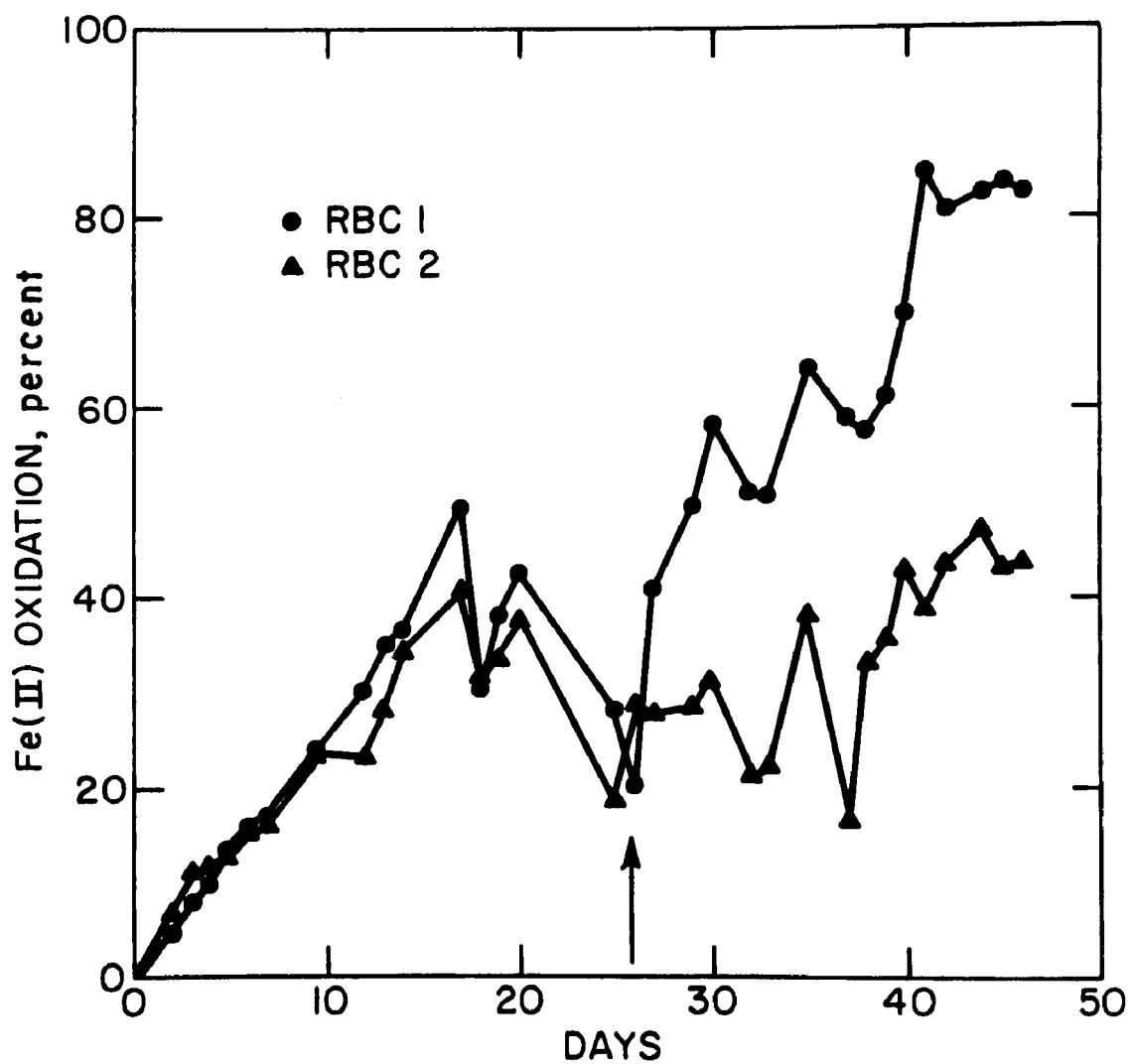
Figure 28. Fe(II) oxidation in bench-scale (10-cm) RBC units in
treatment of synthetic mine water at 10°C and initial
pH of 3. Arrow denotes point of addition of 5 percent
Hollywood mine drainage to RBC 1.

TABLE 21. IRON-OXIDIZING BACTERIA IN INFLUENT AND EFFLUENT MINE WATER
AND DISC SOLIDS OF 10-CM RBC UNITS IN TREATMENT OF SYNTHETIC
MINE WATER SUPPLEMENTED WITH HOLLYWOOD MINE DRAINAGE
(RBC 1) AND UNSUPPLEMENTED (RBC 2).

| | Iron-oxidizing bacteria[a] | |
Sample	RBC 1 (supplemented)	RBC 2 (no supplement)
Mine water, MPN/100 mℓ		
Influent	38	ND[b]
Effluent	3,200	1,100
Disc solids, MPN/cm^2		
Stage 1	420	470
Stage 2	230	710

[a]Each analysis represents the mean of three determinations.

[b]None detected.

must have become established by adsorption of the bacterial inoculum to the feed rather than continuous adsorption of cells from the influent. In order to preserve sufficient active solids on disc surfaces of the small 10-cm units only very small areas (4 cm^2) on the discs could be sampled for solids. The limited solids which could be collected from the surfaces of discs contributed to inaccuracies in bacterial enumeration of solids.

SECTION 8

DISCUSSION

ROLE OF RBC IN MINE DRAINAGE TREATMENT

The RBC is not intended to provide complete treatment of acid mine drainage. The function of the RBC is to achieve effective oxidation of Fe(II) through microbial action. Neutralization of RBC effluent and separation of precipitated iron solids would be necessary in order to produce a water suitable for stream-release. Several investigators have reported advantageous use of limestone in place of lime for neutralization of acid mine drainage (33, 47, 72, 73). It was concluded, however, that chemical oxidation of Fe(II) would not be feasible for mine drainage treatment when limestone was applied as the neutralizing chemical. The time required for sufficient Fe(II) oxidation was reported to be extremely long because the pH values attainable with limestone were not sufficiently high to promote rapid oxidation. Application of the RBC to oxidation of Fe(II) prior to mine drainage neutralization would allow the use of limestone for effluent pH adjustment.

A flow diagram of a proposed acid mine drainage treatment process is presented in Figure 29. Lovell (47) suggested that preneutralization-Fe(II) oxidation systems should produce an effluent Fe(II) concentration below 10 mg/ℓ. He observed that agitation during neutralization provided further Fe(II) oxidation which produced undetectable Fe(II) content in the final effluent. Detailed design of the proposed treatment system may require bench-scale studies to evaluate Fe(II) oxidation in neutralization of low Fe(II) (less than 10 mg/ℓ) acid water to simulate treatment of RBC effluent.

Fe(II) oxidation efficiencies in RBC treatment of mine waters at Hawk Run, Pa. were observed to be lower than those for mine drainage treated at the other two locations under similar temperature, pH, and RBC operating conditions. The mine waters at Hawk Run, however, were usually lower in Fe(II) content. Therefore, Fe(II) concentration of Hawk Run RBC effluents was similar to Fe(II) in RBC effluents for the other two locations [about 10 mg/ℓ Fe(II)]. If observed lower efficiencies are not due to lower initial Fe(II) content, it may then be desirable to conduct pilot or bench-scale studies at the actual mine drainage site in preparation for full-scale design. Obviously, these studies could not be performed to obtain design information prior to mining because the actual mine drainage may not be available. It may be possible to obtain mine water from a nearby mine, if available, although care must be exercised in application of results. The results of any small scale RBC studies should be used with caution.

INFLUENT
ACID MINE DRAINAGE

Fe(II) OXIDATION

ROTATING BIOLOGICAL CONTACTOR

NEUTRALIZATION

LIMESTONE

CLARIFICATION

SEDIMENTATION
POND OR BASIN

SLUDGE
HANDLING
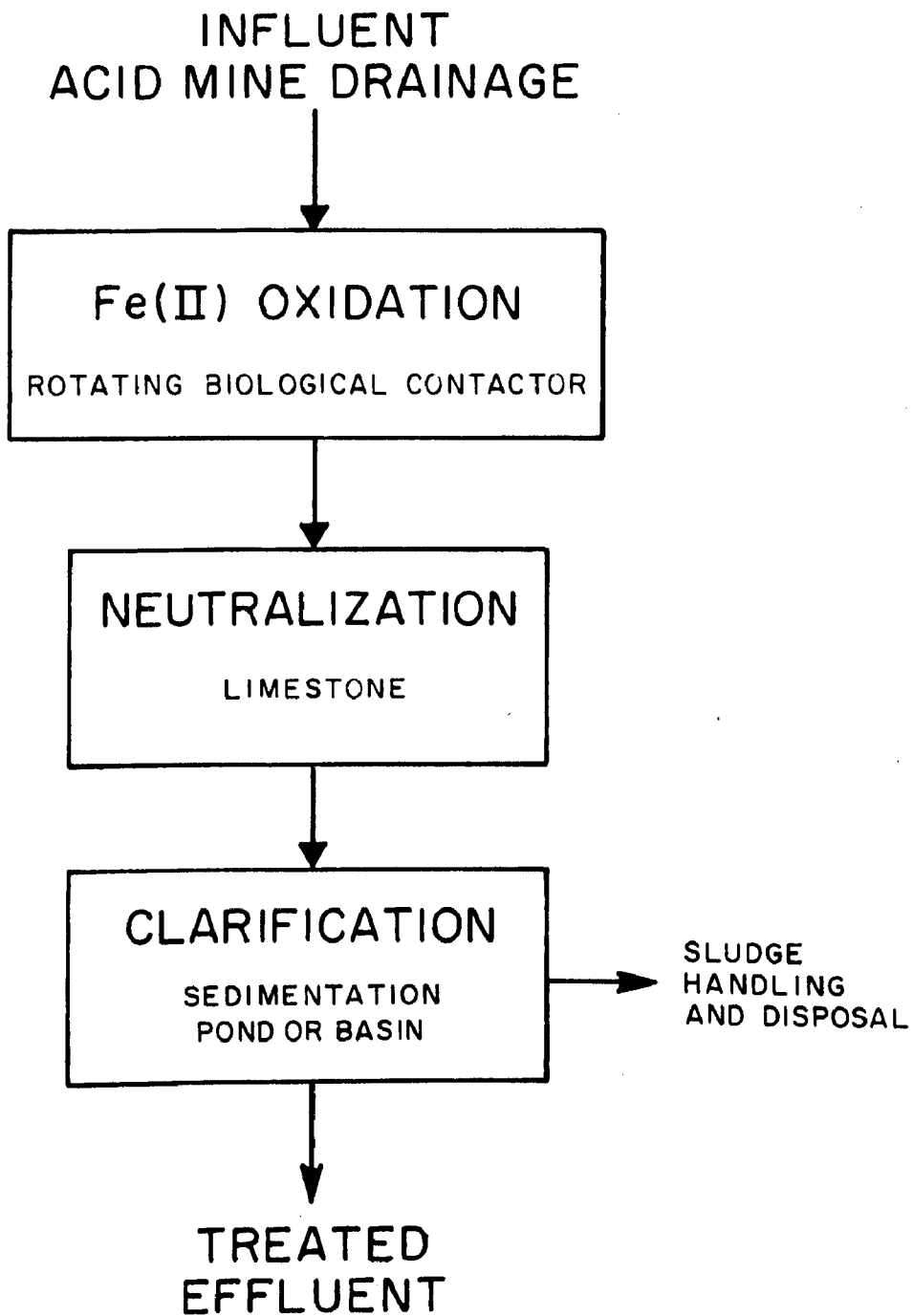AND DISPOSAL

TREATED
EFFLUENT

Figure 29. Proposed treatment process for acid mine drainage.

RELATIONSHIP OF TEMPERATURE TO Fe(II) OXIDATION

A microbial population which mediated continuous Fe(II) oxidation at temperatures outside the range reported to be optimum for pure cultures of the iron-oxidizing bacterium, Thiobacillus ferrooxidans, developed on disc surfaces of RBC units in field experiments with natural mine drainage. Silverman and Lundgren (59) reported maximum growth and Fe(II) oxidation of Ferrobacillus ferrooxidans (T. ferrooxidans) at 28 and 37°C, respectively; values representative of the warmer region of the mesophilic temperature range. Field RBC units developed populations of iron-oxidizing bacteria which, in all probability, included strains of T. ferrooxidans. Mine water temperatures as low as 0.4°C did not inhibit Fe(II) oxidation in field RBC units, although Fe(II) oxidation efficiency was reduced by 10 to 20 percent from that obtained in treatment of the same mine water at 10°C. These mine waters are well within the psychrophilic temperature range for micro-organisms and the results are at least suggestive of the activity of psychrotrophic iron-oxidizing bacteria in the mine water environment.

Discrepancies in chemolithotrophic activity by pure and mixed cultures in respect to environmental temperatures have been noted elsewhere. Sharma and Ahlert (57) distinguished between nitrification by pure cultures and in soils, streams, and treatment plants. It was recognized that nitrification in natural environments and treatment plants can proceed at temperatures below that recorded as minimal for nitrogen transformations by pure cultures in the laboratory. Duddles et al. (22) observed 90 percent efficiency for nitrification with a full-scale fixed-film biological tower at wastewater temperatures as low as 4°C. Ammonia and nitrite oxidation serve as energy yielding reactions for autotrophic bacteria of the genera Nitrosomonas and Nitrobacter, respectively. A variety of microorganisms, both heterotrophic and autotrophic, however, may contribute to nitrification. Similarly, other microorganisms in addition to the autotrophic bacterium, T. ferrooxidans, may promote Fe(II) oxidation in acid mine waters. The discrepancy between characteristics of laboratory cultures of T. ferrooxidans and biological Fe(II) oxidation in mixed culture suggests the possibility of strain differences.

RELATIONSHIP OF pH TO Fe(II) OXIDATION

Schnaitman et al. (56) observed the optimum pH for microbial Fe(II) oxidation to be 3.0, with activity substantially reduced below pH 2.5 and above 3.8. Influent mine water pH values as high as 5.50 and as low as 2.16 did not retard Fe(II) oxidation in field and laboratory RBC units. It appeared that Fe(II) oxidation at equilibrium and subsequent hydrolysis of Fe(III) caused the pH in the RBC reactor to buffer nearer to the pH values reported as optimum for microbial Fe(II) oxidation. The observation is explainable by a simplified view of Fe(II) oxidation [Equation (8.1)] and Fe(III) hydrolysis [Equation (8.2)].

$$Fe^{2+} + \frac{1}{4} O_2 + H^+ = Fe^{3+} + \frac{1}{2} H_2O \qquad (8.1)$$

$$Fe^{3+} + 3H_2O = Fe(OH)_3(s) + 3H^+ \qquad (8.2)$$
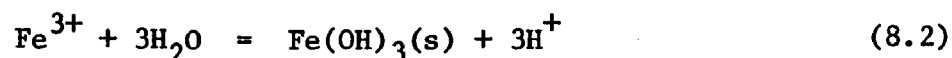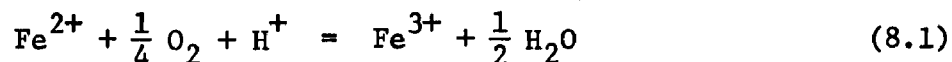
It may be observed from the preceding equations that Fe(II) oxidation consumes one mole of H^+ for every mole of Fe(II) oxidized and should result in an increase in pH. In contrast, subsequent hydrolysis of Fe(III) results in production of three moles of H^+ for every mole of Fe(III) hydrolyzed which would lead to a lower pH. Thermodynamic equilibria indicate that a large percentage of Fe(III) would be hydrolyzed only at initial pH values above about pH 3 (see Section 4). Therefore, when influent mine water is above pH 3, oxidation and hydrolysis would produce a net decrease in pH. Theoretically, one mole of H^+ would be consumed and three moles of H^+ would be produced for each mole of Fe(II) oxidized and mole of Fe(III) hydrolyzed. This possible explanation would account for the lowering of pH observed for the Crown mine drainage in passage through the RBC unit (see Figure 16). On the other hand, when the influent is below approximately pH 3, relatively little hydrolysis would occur and Fe(II) oxidation would produce a net slight increase in pH (though slight considering pH is a log function and 3 is near the end of the scale). Because Fe(II) oxidation is more important in comparison to Fe(III) hydrolysis at these pH values, one mole of H^+ would be consumed for every mole of Fe(II) oxidized and the pH would rise, as observed in Hollywood mine drainage and Crown RO brine. As suggested in Section 3, several complexes of Fe(II) and Fe(III) are possible in acid mine waters and these may affect hydrogen ion activity. Also, acid mine drainage may be a potent solvent for many minerals, depending largely on the geology and hydrology of the drainage area, and dissolved constituents may react with H^+.

SYNTHETIC VERSUS NATURAL MINE DRAINAGE

The difference between RBC performance in Fe(II) oxidation when synthetic mine water is treated in the presence and absence of natural mine drainage appears to demonstrate the importance of some natural stimulatory constituent in mine drainage (qualitative or quantitative microbial characteristics, growth factor, detoxicant, etc.) which was not present in synthetic feed. Although it may appear that the absence of indigenous microorganisms would preclude treatment of a specific wastewater by a biological treatment process, foreign organisms acclimated to the treatment of certain industrial wastewaters, particularly those from chemical manufacture, have been inoculated and, if necessary, nutrient supplemented, to permit a biological purification to take place. Multiplication of iron-oxidizing bacteria, initially established in bench-scale RBC units treating mine water, was demonstrated, although rates of Fe(II) oxidation were slower without mine drainage supplement which provided a continuous inoculum of bacteria. Possibly, a combination of adsorption of mine water bacteria onto discs and synthesis of new cells accelerate Fe(II) oxidation with the RBC.

DEVELOPMENT OF SOLIDS ON RBC DISC SURFACES

Inspection of RBC solids from disc surfaces at all field locations revealed two distinct layers (Figure 30); an inner dark brown layer and an orange-brown outer layer which may or may not be gelatinous. Atmospheric oxygen must dissolve in the mine water film on discs during rotation and, subsequently, penetrate the solids layers along with soluble Fe(II) and other essential nutrients for growth of microorganisms (CO_2, N, P, and trace elements). In addition, diffusible waste products leave the film and collect
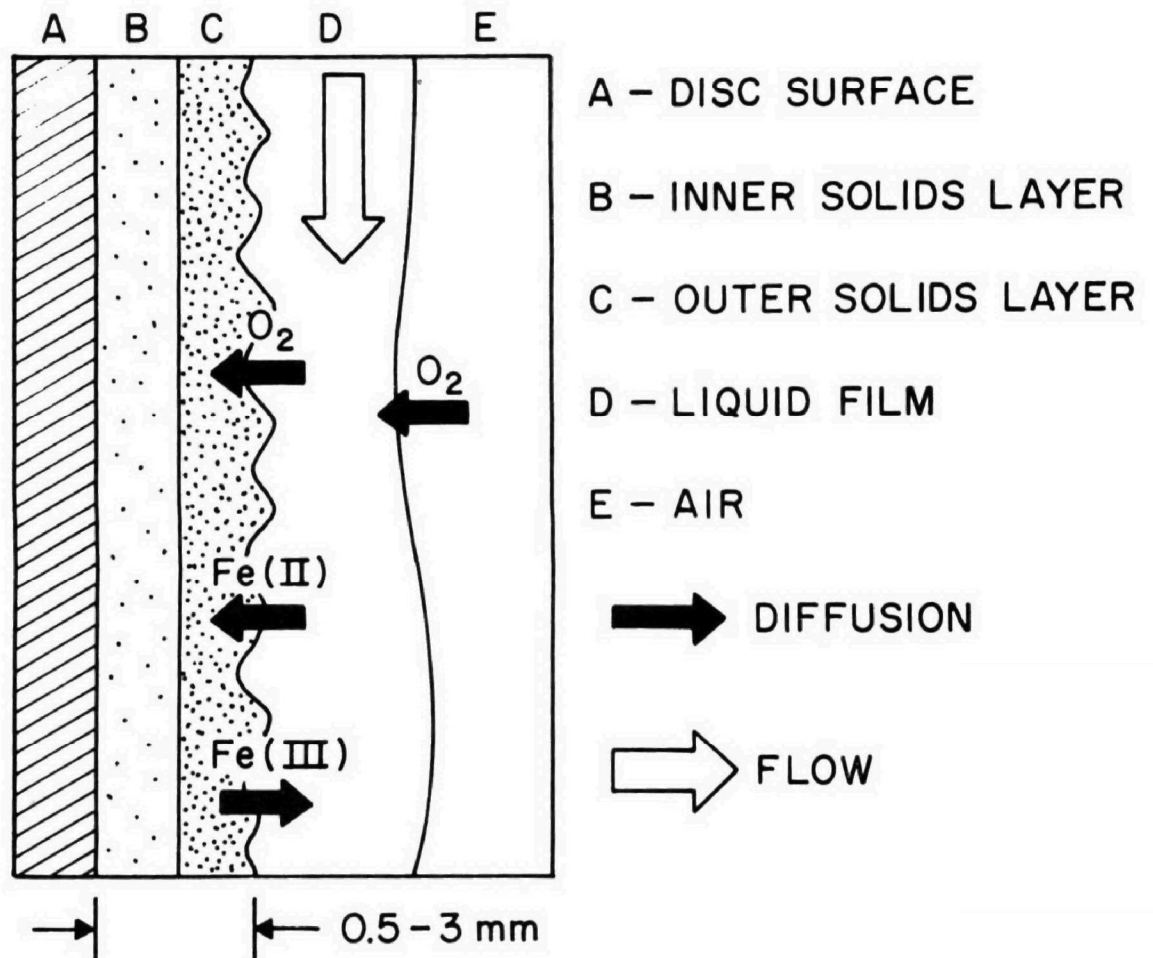
Figure 30. Functions of RBC disc surface, disc solids, liquid
           film, and atmosphere in mine water treatment.

in the water. Antonie (4) reported solids buildup on RBC discs reached a maximum in as little as one week in treatment of domestic wastewater. The time to reach equilibrium disc solids weight was reported by Olem and Unz (54) in Fe(II) oxidation experiments with the RBC to be approximately five months. Periodic cleaning of the discs did not appear necessary. Hoehn and Ray (34) examined the structure and function of the solids layer which developed in fixed-film treatment of domestic wastewater. These organic films were unlike the primarily inorganic disc solids reported herein.

Langmuir and Wittemore (45) described the relationship between age of Fe(III) deposits in mine drainage streams and certain characteristics of precipitates. Fresh amorphous Fe(III) precipitates are typically light brown, orange, or yellow in color, depending on exact composition, and have maximum solubility in comparison to aged Fe(III) deposits which may be partially or totally crystalline in composition, darker brown, and have a much lower solubility. It appeared that the solids which initially developed on disc surfaces of field RBC units did not slough off and become replaced as quickly as occurs in treatment of many organic wastes with the RBC (4). In time, Fe(III) deposits may age and appear at the surface of discs as dense, dark brown, impure oxyhydroxides. Bacterial colonization and activity in this layer is probably minimal. The added weight of the coating may place additional stress on structural capacity of discs.

A gelatinous surface covering was not observed for RBC treatment of any of the mine waters examined at the Hawk Run facility. At mine water temperatures similar to the Hollywood mine drainage (10°C), Fe(II) oxidation efficiencies were still 10 to 15 percent lower at Hawk Run than at other sites. Fe(II) concentrations were relatively low for the Hawk Run mine waters (under 100 mg/ℓ); however, the Hollywood drainage was at times as low in Fe(II), and still Fe(II) oxidation greater than that observed at Hawk Run was noted. This observation may suggest that the iron-oxidizing bacterial population was sufficiently high at Hollywood prior to onset of lower Fe(II) levels and permitted the high efficiencies to continue at the lower Fe(II) concentrations. Estimates of iron-oxidizing bacterial densities revealed no difference in cells per unit surface area for the Hawk Run drainage as compared to that of Hollywood. Absence of a thick gelatinous surface coating was readily apparent in RBC treatment of mine drainage at Hawk Run as compared to other locations. A fibrous (gelatinous) surface layer may provide more surface area for improved O_2 transfer due to its shaggy nature and thus may increase effective disc surface area.

COMPARISON OF DIFFERENT SIZE RBC UNITS

The 0.5-m RBC performance was slightly superior in Fe(II) oxidation efficiency compared to the prototype unit under all conditions. Lower mine water temperatures, however, did not seem to affect the performance of the larger unit as greatly as the smaller RBC. There does exist a sizeable difference in available surface area for the two RBC units (Table 22). Design RBC hydraulic loadings calculated in this report were based solely on disc surface area, although, the smaller RBC unit had a greater proportion of the total surface area due to the troughs than the prototype and full-scale units. Olem and Unz (54) observed similar viable iron-oxidizing

TABLE 22. COMPARISON OF AVAILABLE SURFACE AREA FOR DIFFERENT SIZE
RBC UNITS

| RBC unit | Disc diameter | Surface area, m^2 | | Portion of total surface area due to trough, percent |
		Disc	Trough[a]	
Bench-scale	15 cm	0.438	0.10	19.1
Pilot-scale	0.5 m	21.8	2.14	8.9
Prototype	2.0 m	738.1	18.8	2.5
Full-scale	3.6 m	9,290	50	0.5

[a]Available trough area was calculated from dimensions of bench-scale and field RBC units and estimated for full-scale RBC by use of one 7.6-m shaft placed in a contoured basin.

bacterial densities in comparison of trough and disc surfaces of the same stage. Therefore, calculation of the effective surface area of small diameter RBC units should include the trough surfaces. It is likely that if the units had been sized on the basis of trough surface area, closer agreement would have been obtained in Fe(II) oxidation performance with the large and small RBC units.

Trough surface area of the pilot unit should be included in design of the RBC. Only on this basis may the procedures described by Olem and Unz (54) be used with confidence. The method uses the Fe(II) loading in terms of grams of Fe(II) applied per day per square meter of available surface area. ʼThe loading is calculated using the influent Fe(II) concentration (mg/ℓ) and a design mine water flow (m^3/d). This information will allow determination of required disc area when a desired effluent Fe(II) content is chosen.

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CHEMICAL EQUILIBRIA OF IRON

Calculations for constructing the solubility diagrams for $Fe(OH)_3(s)$ and $Fe(OH)_2(s)$ are summarized below according to equilibrium constants at 25°C (Table A-1).

Fe(III) - $Fe(OH)_3(s)$ Solubility Diagram

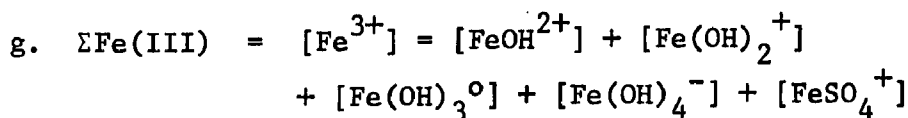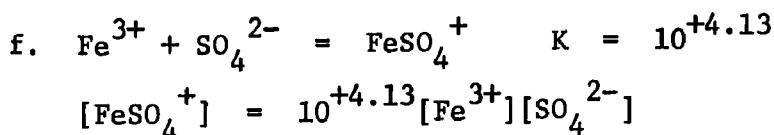a. $Fe(OH)_3(s) = Fe^{3+} + 3OH^-$ $\quad K = 10^{-37.1}$

$[Fe^{3+}] = 10^{+4.90}[H^+]^3$

b. $Fe^{3+} + H_2O = FeOH^{2+} + H^+$ $\quad K = 10^{-2.17}$

$[FeOH^{2+}] = 10^{-2.17}[Fe^{3+}]/[H^+]$

c. $Fe^{3+} + 2H_2O = Fe(OH)_2^+ + 2H^+$ $\quad K = 10^{-7.17}$

$[Fe(OH)_2^+] = 10^{-7.17}[Fe^{3+}]/[H^+]^2$

d. $Fe^{3+} + 3H_2O = Fe(OH)_3^{\,o}(aq) + 3H^+$ $\quad K = 10^{-13.70}$

$[Fe(OH)_3^{\,o}] = 10^{-13.70}[Fe^{3+}]/[H^+]^3$

e. $Fe^{3+} + 4H_2O = Fe(OH)_4^- + 4H^+$ $\quad K = 10^{-21.88}$

$[Fe(OH)_4^-] = 10^{-21.88}[Fe^{3+}]/[H^+]^4$

f. $Fe^{3+} + SO_4^{2-} = FeSO_4^+$ $\quad K = 10^{+4.13}$

$[FeSO_4^+] = 10^{+4.13}[Fe^{3+}][SO_4^{2-}]$

g. $\Sigma Fe(III) = [Fe^{3+}] = [FeOH^{2+}] + [Fe(OH)_2^+]$
$+ [Fe(OH)_3^{\,o}] + [Fe(OH)_4^-] + [FeSO_4^+]$
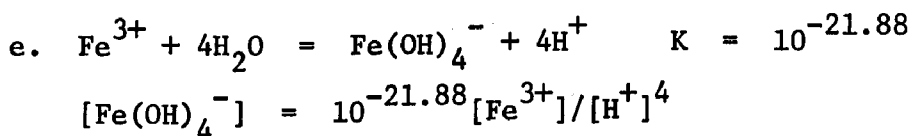
TABLE A-1. CHEMICAL EQUILIBRIUM DESCRIBING SOLUBILITY AND COMPLEXATION OF Fe(II) AND Fe(III)

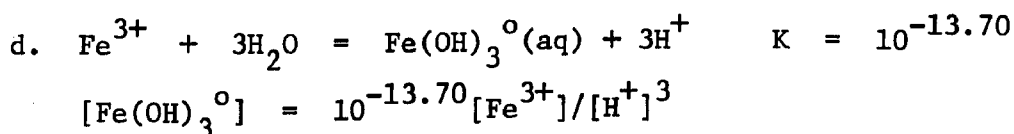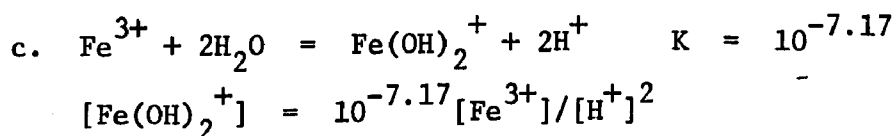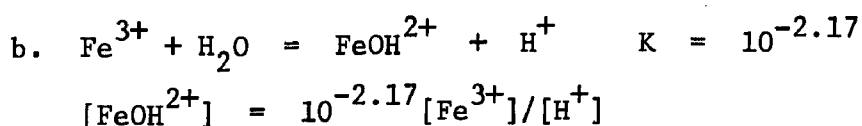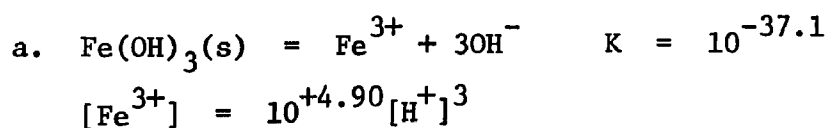| Reaction	Equilibrium constant at 25°C	Reference
$Fe(OH)_2(s) = Fe^{2+} + 2OH^-$	$10^{-15.1}$	(9)
$Fe^{2+} + H_2O = FeOH^+ + H^+$	$10^{-10.11}$	(76)
$Fe^{2+} + 2H_2O = Fe(OH)_2^{\,o}(aq) + 2H^+$	$10^{-19.66}$	(76)
$Fe^{2+} + 3H_2O = Fe(OH)_3^- + 3H^+$	$10^{-31.97}$	(76)
$Fe^{2+} + SO_4^{2-} = FeSO_4^{\,o}(aq)$	$10^{+2.20}$	(69)
$Fe(OH)_3(s) = Fe^{3+} + 3OH^-$	$10^{-37.1}$	(45)
$Fe^{3+} + H_2O = FeOH^{2+} + H^+$	$10^{-2.17}$	(69)
$Fe^{3+} + 2H_2O = Fe(OH)_2^+ + 2H^+$	$10^{-7.17}$	(69)
$Fe^{3+} + 3H_2O = Fe(OH)_3^{\,o}(aq) + 3H^+$	$10^{-13.70}$	(44)
$Fe^{3+} + 4H_2O = Fe(OH)_4^- + 4H^+$	$10^{-21.88}$	(44)
$Fe^{3+} + SO_4^2 = FeSO_4^+$	$10^{+4.13}$	(69)

h. $\Sigma SO_4 = [FeSO_4^+] + [SO_4^{2-}]$

$$= 10^{-1.98}(1000 \text{ mg/}\ell)$$

i. For each pH, $[Fe^{3+}]$ and each Fe(III)-OH complex are calculated. The two remaining equations, which contain two unknowns ($FeSO_4^+$ and SO_4^{2-}), are then solved simultaneously.

Fe(II) - Fe(OH)$_2$(s) Solubility Diagram

a. $Fe(OH)_2(s) = Fe^{2+} + 2OH^-$ $K = 10^{-15.1}$

$$[Fe^{2+}] = 10^{+12.9}[H^+]$$

b. $Fe^{2+} + H_2O = FeOH^+ + H^+$ $K = 10^{-10.11}$

$$[FeOH^+] = 10^{-10.11}[Fe^{2+}]/[H^+]$$

c. $Fe^{2+} + 2H_2O = Fe(OH)_2^o(aq) + 2H^+$ $K = 10^{-19.66}$

$$[Fe(OH)_2^o] = 10^{-19.66}[Fe^{2+}]/[H^+]^2$$

d. $Fe^{2+} + 3H_2O = Fe(OH)_3^- + 3H^+$ $K = 10^{-31.97}$

$$[Fe(OH)_3^-] = 10^{-31.97}[Fe^{2+}]/[H^+]^3$$

e. $Fe^{2+} + SO_4^2 = FeSO_4^o(aq)$ $K = 10^{+2.20}$

$$[FeSO_4^o] = 10^{+2.20}[Fe^{2+}][SO_4^{2-}]$$

f. $\Sigma Fe(II) = [Fe^{2+}] + [FeOH^+] = [Fe(OH)_2^o]$

$$+ [Fe(OH)_3^-] + [FeSO_4^o]$$

g. $\Sigma SO_4 = [FeSO_4^o] + [SO_4^{2-}]$

h. For each pH, $[Fe^{2+}]$ and each Fe(II)-OH complex are calculated. The two remaining equations which contain two unknowns ($FeSO_4^o$ and SO_4^{2-}) are then solved simultaneously.

APPENDIX B

ANALYTICAL PROCEDURES

WATER SAMPLES

Temperatures

An electric thermometer with a stainless steel probe (YSI model 43TD, Yellow Springs Instrument Co., Inc., Yellow Springs, Ohio) was used for in situ temperature measurements.

pH

Measurements of pH were determined with an Orion model 801 digital pH/mv meter (Orion Research Inc., Cambridge, Mass.).

Fe(II)

A dichromate titration procedure for Fe(II) was followed according to procedures described by Lachman and Lovell (42) and is presented below.

Reagents--
    a. Phosphoric-sulfuric acid mixture. Concentrated H_2SO_4 and concentrated H_3PO_4 (150 mℓ each) are added to 700 mℓ distilled water.

    b. Diphenylamine indicator. Barium diphenylamine sulfonate (0.32 g) is dissolved in 100 mℓ distilled water. Sodium sulfate (0.500 g) is then added and the $BaSO_4$ precipitate is filtered. The filtrate is the indicator.

    c. 0.01 N potassium dichromate $(K_2Cr_2O_7)$.

Procedure--
    a. The sample (25 mℓ) is pipetted into a flask.

    b. Acid mixture (10 mℓ) is added to sample.

    c. Two drops of diphenylamine indicator is added.

    d. Titration with $K_2Cr_2O_7$ is performed to a purple endpoint.

Calculations--

$$Fe(II), mg/\ell = C \times P \times 2,234$$

where

$$C = m\ell\ K_2Cr_2O_7\ used,\ and$$

$$N = normality\ of\ K_2Cr_2O_7$$

Fe(III)

Fe(III) was considered the difference between total Fe and Fe(II). Total Fe was determined using a Perkin-Elmer model 403 and 305A atomic absorption spectrophotometer (Perkin-Elmer Corp., Norwalk, Conn.) at Crown, W. Va. and The Pennsylvania State University, respectively. Samples were acidified prior to analysis with 50 percent HCl.

Aluminum

Acidified samples were analyzed for Al using a Perkin-Elmer model 403 and atomic absorption spectrophotometer at Crown, W. Va. and The Pennsylvania State University, respectively.

Dissolved Oxygen

DO was determined in situ with a YSI model 54B oxygen meter and probe. Measurements of the DO of feed well contents were considered representative of influent mine water DO.

Ammonia Nitrogen

NH_3-N was determined colorimetrically with the aid of a Technicon Autoanalyzer II (Technicon Industrial Systems, Tarrytown, N.Y.) and was based on the procedure in Standard Methods for the Examination of Water and Wastewater (63).

Organic Nitrogen

Org-N was considered the difference between NH_3-N and total Kjeldahl nitrogen (TKN). TKN was determined colorimetrically using a Technicon Autoanalyzer II according to an automated version of the procedures in Standard Methods.

Nitrate plus Nitrate Nitrogen

$(NO_2 + NO_3)$-N was measured colorimetrically by the cadmium reduction method (63) using a Technicon Autoanalyzer II. Samples received preliminary cation exchange treatment and neutralization to pH 7.

Total Phosphorus

The stannous chloride method with persulfate digestion (63) was employed for determination of total P.

Iron-oxidizing Bacteria

The most probable number (MPN) of iron-oxidizing bacteria in mine waters was estimated with a combination multiple tube and microtitre plate procedure. An inorganic salts culture medium was employed which contained 1,500 mℓ Fe(II) (Table B-1). Five, 1.0-m portions of mine water were added to tubes which contained 2.0 mℓ of culture media. Five, 0.1-mℓ aliquots of a serial dilution of mine water were transferred to a presteril-ized plastic microtitre plate (Cooke Engineering Co., Alexandria, Va.) which contained 0.2 mℓ of culture media per well. Plates were covered with plastic film and presterilized plastic lids and incubated with tubes at 28°C for three weeks. The number of wells per dilution giving positive results, as evidenced by the appearance of an orange color, was recorded and used to calculate the MPN per 100 mℓ (63).

Heterotrophic Bacteria

Enumeration of heterotrophic bacteria was based on an adaptation of the membrane filter technique for coliform bacteria (63) using an iron salts and purified agar culture medium (51) (Table B-2). Mine water samples (0.01, 0.1, 1, 10, and 50 mℓ) were each filtered through a 0.45 μm membrane filter (Millipore Corp., Bedford, Mass.) and placed in a 47-mm petri plate (Millipore Corp.) which was one-half full of culture media. Plates were incubated at 28°C for two weeks. The number of plates which contained 30 to 300 colonies was used to calculate the number of cells of heterotrophic bacteria per 100 mℓ of original sample.

Lithium

Following addition of lithium chloride (LiCl) as a hydraulic tracer (see Section 6), Li was measured with a Perkin-Elmer model 305A atomic absorption spectrophotometer.

DISC SOLIDS SAMPLES

Premeasured plastic sampling tabs attached to disc surfaces prior to start-up were removed from discs and placed in sterile containers. Sterile distilled water, previously adjusted to pH 3 with H_2SO_4, was added to the container. The contents were then mechanically homogenized for two minutes and apportioned for appropriate microbiological and chemical analyses.

Total Solids Dry Weight

Total disc solids were quantitated using 10 to 25 mℓ portions of the original homogenized sample. Samples were dried overnight at 103°C, cooled in a desiccator, and weighed.

TABLE B-1. CULTURE MEDIUM USED TO RECOVER IRON-OXIDIZING BACTERIA FROM MINE WATER AND RBC DISC SOLIDS

Constituent	Concentration, g/ℓ
$(NH_4)_2SO_4$	0.15
KCl	0.15
K_2HPO_4	0.15
$MgSO_4 \cdot 7H_2O$	3.36
$CaCl_2$	0.97
$Al_2(SO_4)_3 \cdot 18H_2O$	2.25
$MnSO_4 \cdot H_2O$	0.12
$FeSO_4 \cdot 7H_2O$[a]	7.46

[a]Iron source added separately, then medium adjusted to pH 3.0 with 1N H_2SO_4 and sterilized by passage through 0.20-μm membrane filter (Millipore Corp.)

TABLE B-2. CULTURE MEDIUM USED TO RECOVER HETEROTROPHIC BACTERIA FROM MINE WATER AND RBC DISC SOLIDS[a] (51)

Solution	Constituent	Concentration, g/ℓ
A[b]	$FeSO_4 \cdot 7H_2O$	33.4
B[c]	$(NH_4)_2SO_4$	6.0
	KCl	0.2
	$MgSO_4 \cdot 7H_2O$	1.0
	$Ca(NO_3)_2$	0.02
C[d]	Purified Agar L28[e]	7.0

[a]Solution B was added to C at room temperature and gently mixed. Then solution A was added to the combination and mixed well.

[b]Solution A (300 mℓ) was adjusted to pH 2.5 with 6M H_2SO_4 and sterilized by passage through a 0.20-μm membrane filter (Millipore Corp.).

[c]Solution B (550 mℓ) was adjusted to pH 3.0 with 6 M H_2SO_4 and autoclaved at 121°C for 15 min.

[d]A suspension of agar (150 mℓ) was soaked for 15 min and autoclaved at 121°C for 15 min.

[e]Flow Laboratories, Rockville, Md.

Total Iron

Total Fe in disc solids was determined with the aid of a Perkin-Elmer model 305A atomic absorption spectrophotometer using dilute samples which had been dissolved in 50-percent HCl.

Aluminum

A Perkin-Elmer model 305A atomic absorption spectrophotometer was used to determine Al concentration using acidified solutions of disc solids samples.

Iron-oxidizing Bacteria

Iron-oxidizing bacterial densities in disc solids were estimated using the procedure outlined previously for their enumeration in mine water.

Heterotrophic Bacteria

The enumeration of heterotrophic bacteria in disc solids was performed using the procedure previously described for their determination in mine water.

MICROSCOPY

Phase-contrast Microscopy

Living cells were observed and photographed by preparation of glass slide wet mounts under a Zeiss Standard Universal microscope with 35-mm camera (Carl Zeiss, Oberkochen/Wuert., West Germany).

Scanning Electron Microscopy

Glass cover slips were attached to clean discs on the first stage of the 2.0-m RBC unit prior to start-up at Hawk Run, Pa. The samples were removed at various intervals and prepared for observation under the SEM. For initial preparation, samples were dipped in a one-percent solution of osmium tetroxide (OsO_4) in Kellenberger buffer (38) and then exposed to OsO_4 vapors for 1.5 hours. Fixed samples were dehydrated by successive soakings in 25, 50, 75, 95, and 100 percent ethyl alcohol, transferred to fresh 100 percent alcohol, and then dried with a Pelco model H critical point dryer (Ted Pella Co., Tustin, Calif.). Dried samples received a sputter coating of gold and were placed in a desiccator for future observation under an ISI Super IIIA scanning electron microscope with 35-mm camera (International Scientific Instruments, Inc., Santa Clara, Calif.).

Membrane filters recovered microorganisms from mine water and received the same preparation prior to viewing under the SEM as did glass cover slips. Nucleopore brand polycarbonate filters which contained 0.4-μm pores were used as suggested by Todd and Kerr (64).

APPENDIX C

MIXING CHARACTERISTICS OF MINE DRAINAGE STREAMS
AT HAWK RUN, PA

The extent of lateral mixing which occurred in the 50-m section below the confluence of Hawk Run and Mine Hole 1 was evaluated to determine whether there was sufficient mixing in the reach so that the influent mixture pumped to the RBC units would be significantly different in quality from the individual waters to represent a third type of drainage. Also determined was whether backmixing of Mine Hole 1 discharge affected the water quality at the point where mine drainage was being pumped from Hawk Run. Stations were established at eleven points downstream from the confluence and four points upstream (Figure C-1). Water samples were collected from each station at three equally spaced point across the stream. Measurements of Fe(II) concentration were taken at each of these points (Table C-1). Fe(II) is not a conservative substance; however, Fe(II) concentrations were equal for stations 1 and 2, which covered approximately the same distance as was investigated in the analysis of mixing. Therefore, Fe(II) was considered within the reach under study.

Fe(II) concentrations across the stream at station 3 were similar; therefore, backmixing did not affect the mine water quality at the intake line for Hawk Run. Fe(II) measurements for station 12 (Hawk Run + 1 intake) indicated that complete mixing had not yet occurred. Complete mixing was evident at some location downstream from the intake for the combined stream at either station 14, 15, or beyond.
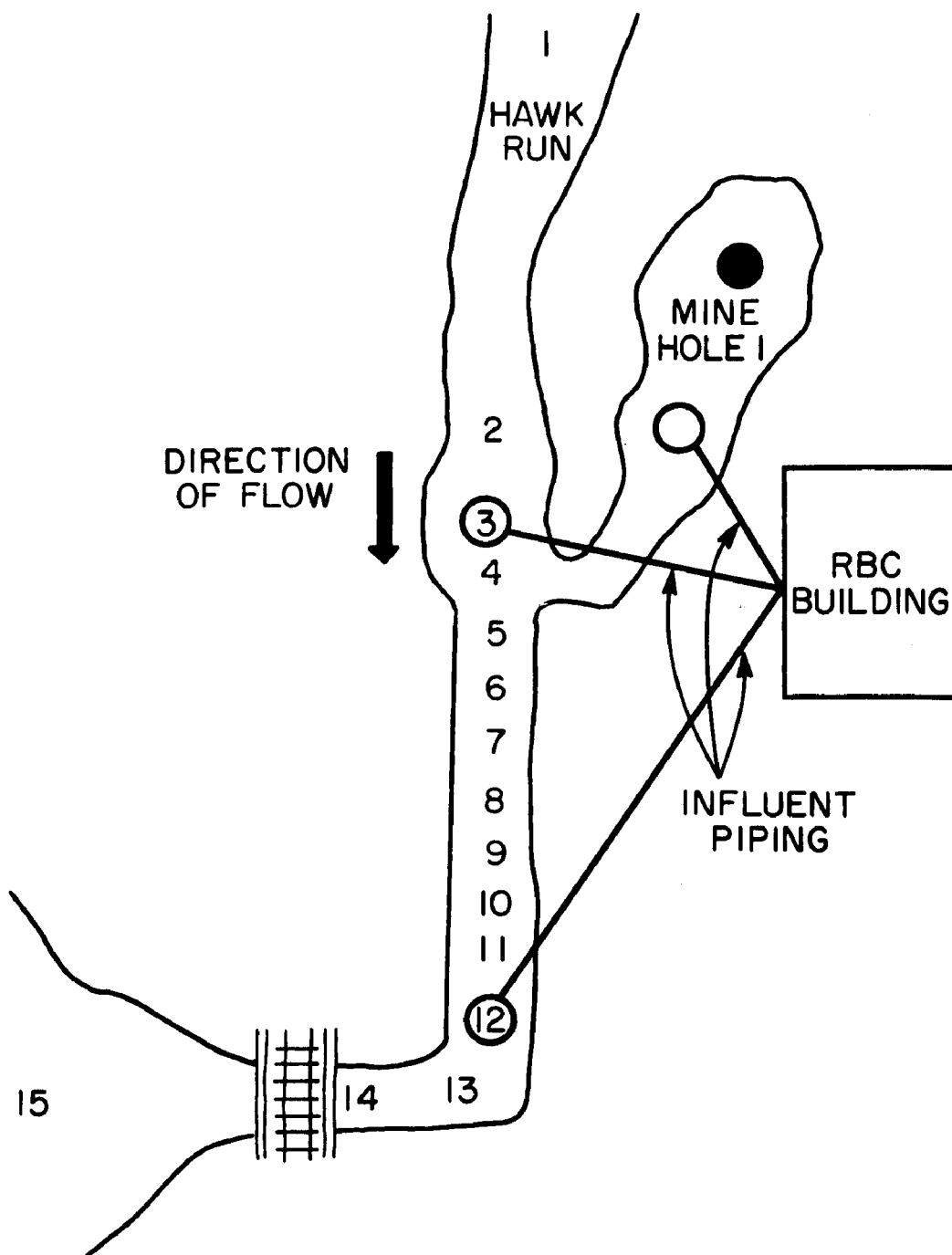
Figure C-1. Schematic of mine drainage streams at Hawk Run, Pa.,
showing locations of sampling stations and mine
water feed lines.

TABLE C-1. MINE WATER Fe(II) CONCENTRATIONS AT STATIONS
ON STREAMS AT HAWK RUN, PA.[a]

Station[b]	Fe(II) concentration, mg/ℓ		
	Left	Middle	Right[c]
1	--	31	--
2	--	31	--
3	32	32	31
4	32	32	53
5	31	34	57
6	34	57	53
7	31	55	45
8	32	47	45
9	32	44	45
10	31	40	44
11	32	36	44
12	32	36	40
13	34	35	40
14	38	38	40
15	38	37	40

[a]Fe(II) concentration of mine hole 1 = 57 mg/ℓ.

[b]See Figure C-1 for location of stations.

[c]Corresponds to side of Hawk Run Stream where RBC units were located.

APPENDIX D

CHARACTERISTICS OF EXPERIMENTAL RBC UNITS

The RBC field units used in this study were commercial devices equipped with 0.5-m and 2.0-m diameter discs (Autotrol Corporation, Milwaukee, Wisc.) designed specifically for experimental pilot plant use. Bench-scale RBC units were designed to scale from pilot units, except the 10-cm unit, which was equipped with only two stages instead of the normal four (Table D-1).

DRIVE SYSTEM

Disc rotation for the 10-cm, 15-cm, and 0.5-m units was supplied by 93, 47, and 186 watt, respectively, 115 v, single phase, gear-reduced motors. Discs of the 2.0-m RBC were rotated by a 0.746 kw, 230/460 v, three phase, variable speed motor. All RBC units were equipped with sprocket and chain drive systems.

FLOW PATTERN

An influent chamber and bucket feed system supplied a constant flow of mine water to the stages of the RBC field units. Flow through each stage was formed in a serpentine pattern for the 2.0-m RBC and by a 2.5-cm diameter hole in each baffle for the 0.5-m unit (Figure D-1). Flow was metered to the bench-scale units and influent feed chambers were not used. Flow through the stages of bench-scale units was facilitated by small holes between baffles in a fashion similar to the 0.5-m field RBC.

RBC CONSTRUCTION

Trough and disc material used in construction of bench-scale units were acrylic plastic. Corrosion-resistant aluminum and steel were used for the 0.5- and 2.0-m RBC troughs, respectively. Disc construction material for commercial RBC units was composed of vacuum-formed, 1-mm thick, high-density polyethylene which was heat-welded, shaped in a honeycomb configuration, and stacked on square corrosion-resistant steel shafts. CPVC tubing served as shafts for both bench-scale units.

The 2.0-m RBC was equipped with four perforated tubes attached to the periphery of discs on each stage and spaced at 90° intervals. Each 0.5-m length of PVC pipe was 7.6 cm in diameter and contained approximately ten 2.5-cm diameter holes which release air below the liquid surface and apply mine water to the discs during rotation out of the liquid. The tubes were designed in this manner to improve turbulence and minimize solids deposition in the reactor compartment.

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TABLE D-1. DESIGN AND NORMAL OPERATIONAL PARAMETERS OF RBC EXPERIMENTAL
UNITS

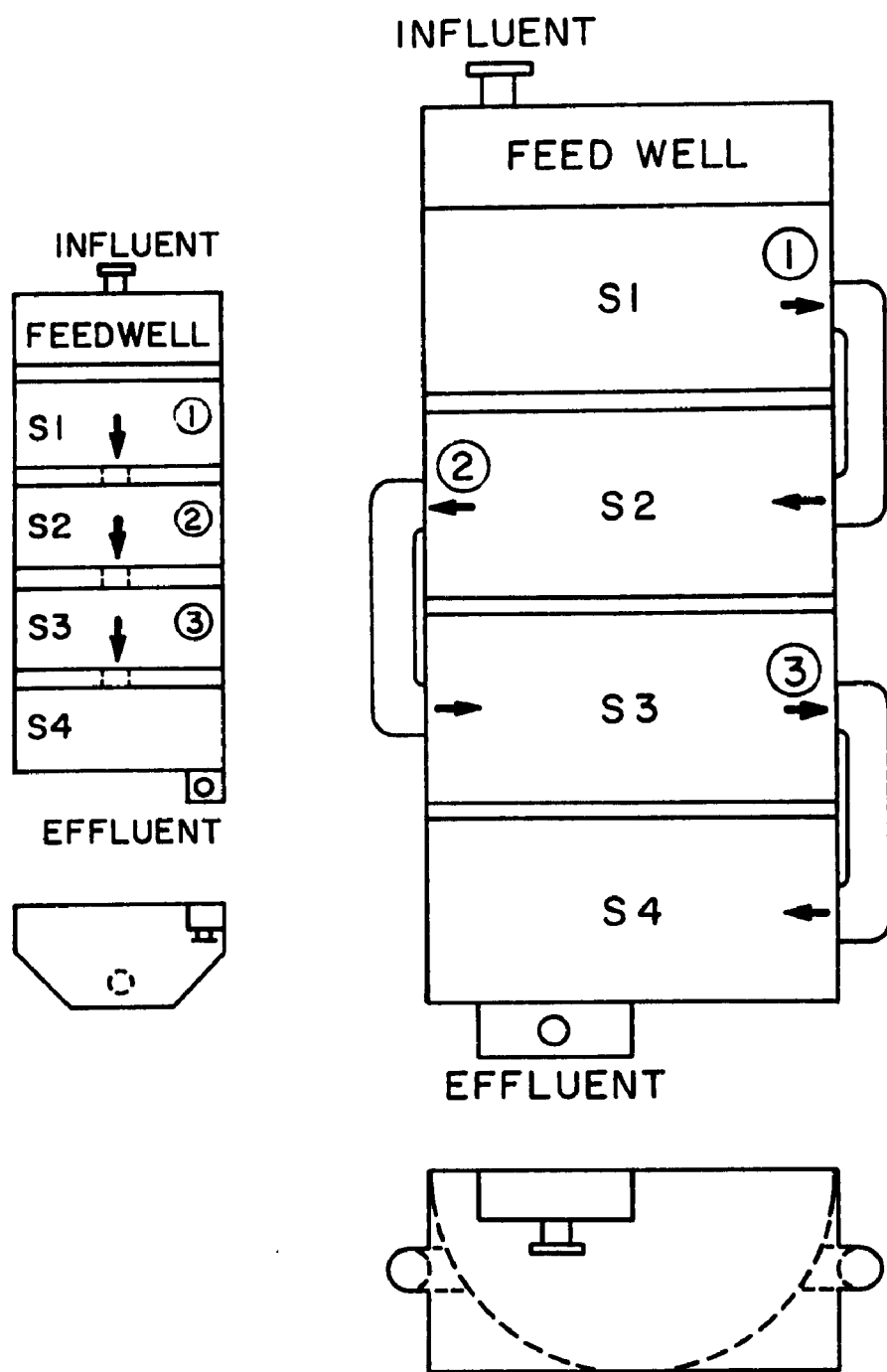| Parameter	10-cm Bench-scale RBC unit	15-cm Bench-scale RBC unit	0.5-m Pilot RBC unit	2.0-m Prototype RBC unit
Number of stages				
Disc diameter, m	0.10	0.15	0.5	2.0
Disc surface area, m^2	0.090	0.438	21.8	738.1
Trough volume, liters	0.60	3.0	140	3,800
Surface-to-volume ratio, m^2/m^3	157	146	156	194
Disc rotation				
Revolutions per min	57	38	13	2.9
Peripheral velocity, m/min	19	19	19	19
Hydraulic				
Flow rate, m^3/d	0.014	0.072	3.41	115
Loading, $m^3/d \cdot m^2$	0.16	0.16	0.16	0.16

Figure D-1. Plan and side view showing flow pattern and stage sampling locations for trough of 0.5-m RBC (left) and 2.0-m RBC (right). Drawing is not to scale.

APPENDIX E

FORMULAS FOR STATISTICAL ANALYSIS

MEAN $\bar{X}$ AND $\bar{Y}$

$$\bar{X} = \frac{\sum\limits_{i=1}^{N} X_i}{N} \qquad \text{and} \qquad \bar{Y} = \frac{\sum\limits_{i=1}^{N} Y_i}{N}$$

where X_i, Y_i = values of datum point, i, and

$\qquad$ N $\quad$ = total number of data points.

MEAN pH

$$\text{Mean pH} = \frac{\sum\limits_{i=1}^{N} pH_i}{N}$$

where pH_i = value of datum point, i.

MEAN BACTERIAL POPULATIONS

$$\text{Mean Bact.} = \text{antilog} \left[\frac{\sum\limits_{i=1}^{N} \log bact._i}{N} \right]$$

where $bact._i$ = value of datum point, i.

STANDARD DEVIATION

$$\text{Std. Dev.} = \left[\frac{\sum\limits_{i=1}^{N} X_i^2 - \left[\dfrac{\sum\limits_{i=1}^{N} X_i}{N}\right]^2}{N-1} \right]$$

LINEAR REGRESSION EQUATION

$$\bar{Y} = m\bar{X} + b$$

SLOPE OF THE REGRESSION LINE, (m)

$$m = \frac{\dfrac{\sum\limits_{i=1}^{N} X_i Y_i}{N} - \bar{X}\,\bar{Y}}{\sigma_x^2}$$

where $\sigma_x^2 = \dfrac{\sum\limits_{i=1}^{N} X_i^2}{N} - \bar{X}^2$ = variance of X values.

ORDINATE INTERCEPT OF THE REGRESSION LINE, (b)

$$b = \bar{Y} - m\bar{X}$$

CORRELATION COEFFICIENT, (R)

$$R = \frac{\dfrac{\sum\limits_{i=1}^{N} X_i Y_i}{N} - \bar{X}\,\bar{Y}}{\sigma_x \sigma_y}$$

where $\sigma_y^2 = \dfrac{\sum\limits_{i=1}^{N} Y_i^2}{N} - \bar{Y}^2$ = variance of Y values.

STUDENT'S t-TEST FOR SIGNIFICANCE OF CORRELATION COEFFICIENT

$$t = \frac{R}{\left[\dfrac{1 - R^2}{N - 2}\right]^{1/2}}$$

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

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15. SUPPLEMENTARY NOTES

16. ABSTRACT   Pilot scale (0.5-m diameter) and prototype (2.0-m diameter) rotating biological contactors (RBC) were investigated for oxidation of ferrous Fe(II) iron contained in six heterogeneous mine waters located at three coal mining sites in Pennsylvania and West Virginia. Continuous biological oxidation of Fe(II) and Fe(III) was accomplished at natural mine water temperatures as low as 0.4°C at Hawk Run, Pa. and as high as 29°C at Crown, W. Va. Reduction of Fe(II) oxidation efficiency at 0.4°C amounted to 10 to 20 percent of that achieved at 10°C. Oxidation efficiency was above 80 percent at mine water temperatures of 10 to 29°C. Microbiological oxidation with the 0.5-m RBC was unaffected at influent mine water pH values in the range of 2.18 to 5.50 (Crown, W. Va.). Fe(II) oxidation was an average 10 percent less efficient for a mine water treated under similar operating conditions with the 2.0-m than with the 0.5-m RBC. The observed decrease may be due to nonmicrobiological factors such as increased short-circuiting, lower residence time, and a smaller effective surface area which may be increased through proper design. Costs for Fe(II) oxidation with the RBC were estimated to be about twice the amortized capital costs and one-half the operating costs compared to a conventional chemical oxidation process. Neutralization of RBC effluent and separation of precipitated iron solids is required to produce water of suitable quality for stream-release. Both iron-oxidizing and heterotrophic bacteria existed in a gelatinous matrix present on disc surfaces of RBC units operating at Hollywood, Pa.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Bacteria, Biological Treatment, Cost Comparison, Iron, Oxidation, Water Pollution Control	Acid Mine Drainage Autotrophic Bacteria Coal Mine Drainage Ferric Iron Ferrous Iron Iron-oxidizing Bacteria Rotating Biological Contactor Treatment Processes	13B

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