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Studies of Limestone Treatment of Acid Mine Drainage

Part II

U.S. ENVIRONMENTAL PROTECTION AGENCY

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Studies of Limestone Treatment of Acid Mine Drainage

Part II

by

Bituminous Coal Research, Inc.

for the

Commonwealth of Pennsylvania
Department of Environmental Resources

and the

ENVIRONMENTAL PROTECTION AGENCY

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ABSTRACT

Laboratory studies were conducted with limestone as the neutralizing agent for coal mine water. Batch tests were used to determine the properties of limestone necessary for effective neutralization. Continuous flow tests were used to determine conditions required for an effective neutralization process.

The following variables are of importance for limestone to be an effective neutralizing agent: (a) particle size, (b) Ca and Mg content, and (c) surface area. Limestones having the smallest particle size commercially available were tested and found to be effective if criteria for variables other than particle size were met.

Data obtained with a small laboratory continuous flow test apparatus were used in determining operating conditions for a continuous treatment process for neutralizing mine water with limestone. An evaluation of this process indicated technical feasibility, advantages and disadvantages, and need for further study of certain aspects of this process.

The cost of treating coal mine water with the BCR limestone treatment process compares favorably with the published costs of treating mine water by other processes.

This report was submitted in fulfillment of Project Number 14010 EIZ under the joint sponsorship of the Water Quality Office of the Environmental Protection Agency, the Commonwealth of Pennsylvania, and Bituminous Coal Research, Inc.

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SECTION I

CONCLUSIONS

Studies on the limestone treatment of coal mine drainage have led to the following conclusions:

1. A process has been developed whereby coal mine drainage containing ferrous iron can be treated with limestone. This process results in complete neutralization of acidity and removal of iron to acceptable limits.

2. The BCR limestone treatment process consists of the following unit operations in sequence: (a) mine drainage holding or equalization, (b) adding pulverized limestone and mixing, (c) aerating, (d) slurry recirculation to the mixing area, (e) sludge settling, and (f) sludge dewatering and disposal.

3. The advantages of using limestone instead of lime are lower costs per unit weight of chemical reagent necessary to neutralize the same quantity and quality of coal mine drainage, fewer safety problems in handling a less reactive reagent, and a less harmful effect on the body of water receiving the effluent in case of accidental overtreatment. An additional advantage is a reduction in sludge volume and an increase in sludge solids content. In fact, the volume of sludge from limestone treatment can be as little as one-fifth that from lime treatment, and the solids content of the limestone sludge can be almost 15 times greater than that from treatment with lime. This reduction in sludge volume would mean that smaller settling basins would be required. This fact, by itself, may be sufficient reason for selecting limestone treatment over lime in areas where space is at a premium.

4. The major disadvantage of the process can be attributed to the slow rate of oxidation of ferrous iron at the relatively low pH attainable with limestone. Long detention times and, consequently, big tanks are required for mixing the mine water with limestone and for aerating until most of the ferrous iron has been oxidized. This would result in higher costs and inefficient mixing, diffusion of oxygen, and sparging of carbon dioxide. Other disadvantages of the process include the production of fine particles in the effluent, which do not settle rapidly and may require coagulant aids for their removal, and the questionable availability of finely divided limestone of the desired quality.

5. For use in a treatment operation, the particle size of the limestone should be 74 microns (200 mesh) and preferably smaller. In addition, the limestone should approach pure calcium carbonate in composition. Those stones which have a relatively low calcium content,

but which contain calcite and have a high surface area, are equally effective neutralizing agents. Magnesites are the least effective neutralizing agents, followed closely by dolomitic limestones.

6. Coal mine waters containing ferrous iron in quantities as great as 5,000 mg/l (such as those waters used for the technical and cost evaluations) present particular problems in treatment which have not been solved. Treatment of such waters would result in precipitation of calcium sulfate (gypsum) during treatment with resultant scaling problems on tanks, pipes, mixers, aerators, and pumps. Also, the volume of sludge would be greater than the volume of treated water obtained. These two problems are inherent in both limestone and lime treatment.

7. The cost of treating coal mine water with the BCR limestone process compares favorably with the published costs of treating mine water with other processes. Chemical costs for treating, using the BCR limestone process, were 5.0 to 5.8 cents per mg/l of acidity per 1,000,000 gallons. Total costs for treating coal mine discharges within the limits of quality normally encountered, ranged from 13.6 to 97.3 cents per 1,000 gallons of water. These costs include sludge disposal.

SECTION II

RECOMMENDATIONS

The following additional studies are recommended:

1. To optimize the BCR limestone treatment process, a pilot plant such as a field research unit or equivalent should be utilized as follows:

   a. Bench-scale tests were conducted with diffused air for aeration and sparging of carbon dioxide. Future studies should be directed toward use of more efficient mechanical aerators to determine if adequate sparging of carbon dioxide is accomplished with the mechanical-type aerator.

   b. Units permitting continuous build up of sludge should be employed to study the sludge to raw feed requirements to determine if smaller volumes of more concentrated sludge can be used to accomplish the required treatment.

   c. Further studies should be conducted on coal mine waters having sulfate concentrations of up to 20,000 mg/l, as formation of calcium sulfate would occur at these concentrations and would have a significant effect on the volume of sludge precipitated as well as result in problems of scaling on equipment such as mixers, aerators, etc.

   d. Tests should be conducted to determine the effect of coagulant aids on settling rates and volumes of sludge to possibly reduce the detention time in and, therefore, the size of the settling basins. The effect of coagulated sludge on sludge recycling should also be determined.

   e. Data obtained through this bench-scale study indicate sludge volume will be significantly lower than with lime treatment. This should be verified in large scale units and with more concentrated coal mine drainage.

2. The effect on cost of on-site grinding of coarse limestones to the desired size by such means as an autogeneous grinder should be studied and compared with the cost effect of using pulverized limestone.

3. Studies should be conducted on a scale as large as an actual treatment plant operation to determine the requirements and velocities necessary to provide adequate mixing and to prevent the deposition of solids.

4. Studies with a field research unit or equivalent pilot plant should incorporate the most recent information developed to increase the rate of ferrous iron oxidation in the coal mine water, such as by catalytic oxidation.

5. Although the emphasis during this study has been on treatment of waters containing iron in the ferrous state, the tests conducted on Thorn Run water, which contains iron principally in the ferric state, indicate that treatment of this type of water is less complicated, since the factors associated with the oxidation of ferrous iron are not present. A significant percentage of mine discharges are of the ferric iron type; therefore, it is recommended that additional laboratory studies be conducted to optimize the BCR limestone treatment process for this type of water. Practical application of the process to treatment of actual mine waters could, then, be brought about more quickly.

SECTION III

INTRODUCTION

This is the final and summary report on the Pennsylvania Department of Environmental Resources Project CR-75-A[1] activated November 10, 1969, with financial support from the Pennsylvania Coal Research Board and the Federal Water Quality Administration[2] through Grant 14010 EIZ to the Commonwealth of Pennsylvania. The project is based on work conducted on Pennsylvania Coal Research Board Project CR-75 activated July 1, 1967, with financial support from the Pennsylvania Coal Research Board, Bituminous Coal Research, Inc., and the United Mine Workers of America, and expanded February 7, 1968, with additional financial support through Grant WPRD 63-01-68 to the Commonwealth of Pennsylvania by the Federal Water Quality Administration. (1)[3]

Work on the project was conducted according to the BCR Research Program Proposal RPP-162R submitted to the Pennsylvania Coal Research Board on April 24, 1969, as revised in the Revision of Scope dated February 20, 1970, and submitted as a result of meetings between the sponsors and project personnel. The experimental work was conducted during the period November 10, 1969 to June 25, 1971.

Objectives

The overall, long-range objective of the program is to design and develop to pilot-plant stage an improved process for the control and prevention of pollution of waters by drainage from coal mines.

The objectives of the studies conducted in the period covered by this report were: (a) to improve and optimize the chemical techniques involved in the limestone treatment of coal mine drainage with emphasis placed on the evaluation of limestones and continuous flow tests, and (b) to utilize the information developed in these studies for both a technical evaluation and a cost evaluation of the BCR limestone process projected for full-scale operation.

Nature and Scope of the Problem

The occurrence of acid drainage associated with coal mining has been well documented. (2) In the Appalachian region alone, more than 5,000 miles of streams are adversely affected on a continuing basis by drainage resulting from the mining of coal. The coal industry is

[1] Formerly the Pennsylvania Coal Research Board Project CR-75-A.
[2] Currently the Water Quality Office of the Environmental Protection Agency (WQO, EPA).
[3] Numbers in parenthesis indicate references listed at end of report.

proceeding with a vigorous abatement program by constructing water treatment plants wherever polluting waters might be discharged from active mines into open streams. At the present time, there are over 200 mine water treatment plants built and operating in the state of Pennsylvania alone. Also, an additional 100 plants are in various stages of design and construction. (3)

In all but a few cases, lime neutralization, often in conjunction with aeration and settling ponds, is the type of treatment used. However, the relatively high cost of lime and the poor sludge quality (slow settling, large volumes, and low solids content) have stimulated work in the utilization of limestone. (4) The claimed advantages of limestone neutralization over lime neutralization are: (a) lower costs for chemical reagent, (b) decreased hazard to the operator handling a less reactive reagent, (c) little or no harmful effect on streams and stream life from an accidental overtreatment, and (d) potential for decreased sludge volume by an increased solids content in sludge.

Recent reports in the literature tend to confuse rather than clarify the issue of limestone treatment. One such report (5) describes the limestone treatment of a coal mine water containing iron principally in the ferric, Fe^{3+}, state and concludes that their studies resulted in successfully "treating mine waters of the wide range of acidity and iron normally encountered." The same report "recommended that, to effect maximum economics in treatment costs and in land conservation, consideration be given to the use of the limestone neutralization process wherever other treatment processes are now in use or contemplated."

Conversely, a more recent study concludes that "he who tries to treat large quantities of acid mine water containing high proportions of ferrous iron with a straight calcium carbonate neutralizer is likely to be in for some real interesting and expensive experiences." (6)

The key phrase is "ferrous iron." There are fundamental differences in treating water containing iron in the ferrous, Fe^{2+}, state and water containing iron in the ferric, Fe^{3+}, state. In the treatment of ferric iron waters, only neutralization is involved since the system has already attained equilibrium with respect to iron and, therefore, no further acid will be generated during treatment.

In contrast, the neutralization of ferrous iron waters also involves oxidation which, in turn, generates more acid. This can be represented by the following (unbalanced) reaction:

$$Fe^{2+} + O_2 + H_2O \rightarrow Fe(OH)_3 + H^+$$

If the oxidation proceeds slowly, acid is generated slowly, requiring further neutralization. With lime, an additional amount can be added, which raises the pH substantially and speeds up the oxidation, since a hundredfold increase in the rate of ferrous iron oxidation is reported per unit increase in pH. (7) On the other hand, an excess quantity of limestone will not raise the pH sufficiently high to increase the rate of ferrous iron oxidation, since limestone is only a weakly basic material.

The present program of laboratory investigation was designed to resolve some of the difference in results reported and to design a limestone treatment process that would be applicable to all types of mine waters.

Approach to the Problem and Research Procedure

A neutralization process for coal mine drainage entails a series of individual unit operations. One general concept of the limestone neutralization process is shown in Figure 1. The individual parts of the total system are: (a) holding tank, (b) pulverized limestone storage tank, (c) limestone feeder, (d) limestone reactor, (e) aerator, (f) settling tank, (g) optional sludge recirculation, (h) optional oxidation catalyst, and (i) optional coagulant aid.

For a mine water containing ferrous iron ($FeSO_4$) and free acid (H_2SO_4) the overall neutralization reaction using limestone ($CaCO_3$) and including oxidation can be represented in the following simplified manner:

$$3\ CaCO_3 + 2\ FeSO_4 + H_2SO_4 + 0.5\ O_2 + 2\ H_2O \rightarrow 3\ CaSO_4 + 2\ Fe(OH)_3 + 3\ CO_2$$

The products of this reaction are hydrated ferric hydroxide (yellow-boy), gypsum, and carbon dioxide gas which must be removed by sparging.

To develop and optimize a limestone neutralization process and thereby achieve the stated objectives of this program, work was conducted in the following categories:

Evaluation of Limestone--Preliminary experiments were conducted using limestones of various size consists and a number of synthetic and actual coal mine waters. Then, commercially available finely divided limestones were used in batch tests as neutralizing agents; it had been established (8) that, for use in a treatment operation, the particle size of the limestone should be 74 microns (200 mesh) and preferably smaller.

Sludge properties were measured from selected batch tests as part of the evaluation of these limestones.

Continuous Flow Experiments--Two actual coal mine waters were treated with limestone utilizing a small laboratory pilot plant to determine basic operating conditions required to neutralize acid mine drainage.

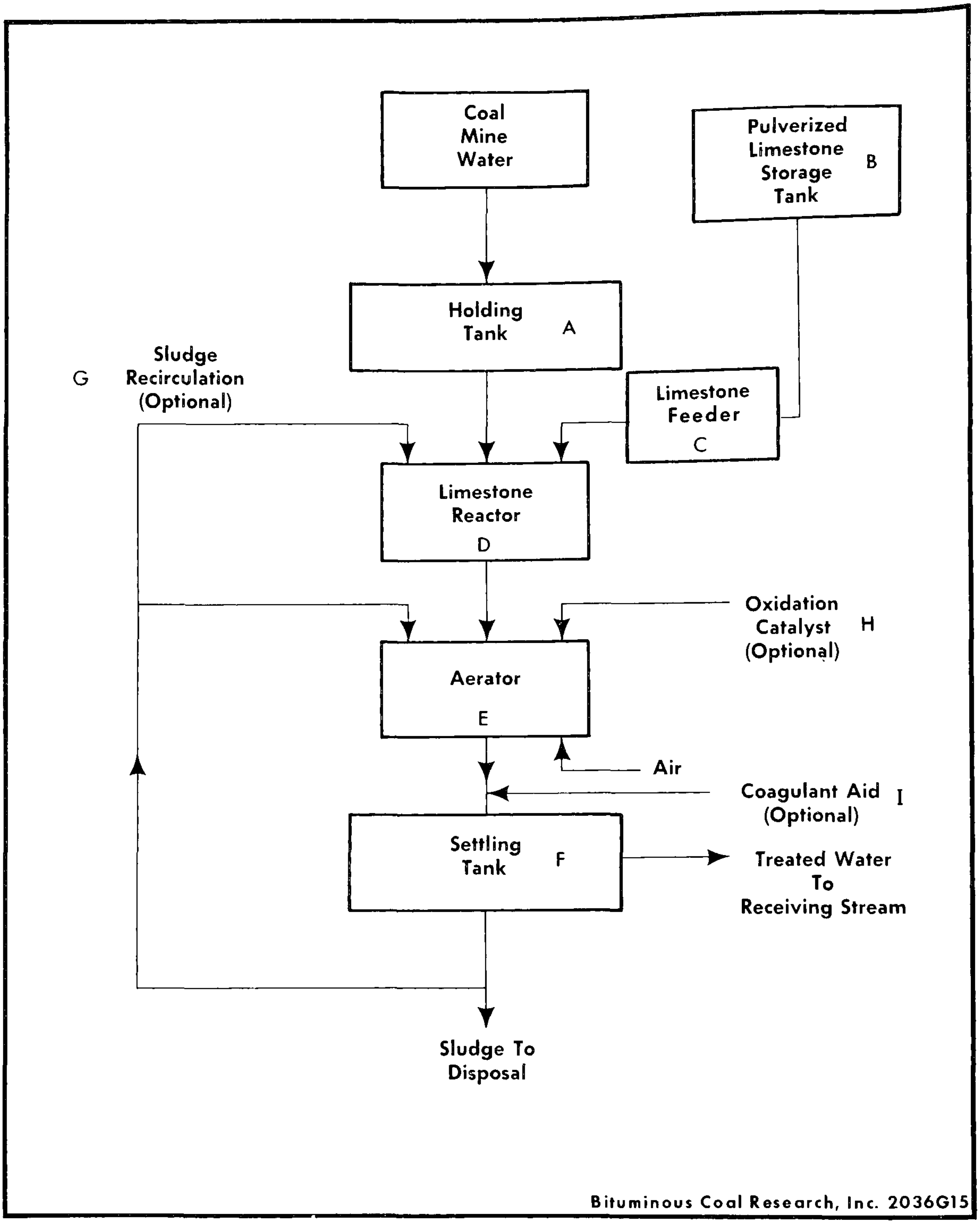

Figure 1. Flow Diagram of Conceptual Limestone Treatment Process

Properties of the sludges from selected experiments were measured as part of the evaluation of the effectiveness of continuous treatment.

Technical and Cost Evaluations--As the final phase of the project, information gained from the laboratory batch studies and continuous flow studies of the limestone treatment process was utilized in a technical and cost evaluation of the BCR limestone treatment process as projected for full-scale operation.

SECTION IV

DESCRIPTION OF PILOT PLANT

A continuous flow test apparatus was designed and constructed for use in evaluating the limestone neutralization process. This test apparatus was a modification of a unit originally designed and constructed for use on Pennsylvania Coal Research Board Project CR-75 conducted at BCR. (1) A photograph of the actual system is shown in Figure 2.

Materials and Equipment

Figure 3 is an artist's conception of the continuous flow system, indicating the location of the holding tanks, etc. The following paragraphs describe the equipment and the materials used in its construction.

Holding Tanks: The two Glascote glass-lined holding tanks each have bottom discharge and lids. The tanks have 90-gallon and 60-gallon capacities, for a total capacity of 150 gallons.

Sample Cooling and Circulating System: The Forma "Forma-Temp" portable cooler can maintain the sample at temperatures as low as 46 F. The cooler has a rated capacity of 4,000 Btu/hr. Circulation of the sample between the two holding tanks is accomplished by use of a Gorman-Rupp Model 11698, 5600 series, centrifugal pump, with a Gorman-Rupp Model 12500-21 oscillating pump used for priming.

Limestone Reactor: The stirred-tank reactor consists of a 60-gallon stainless steel tank equipped with four 3-inch stainless steel baffles. Stirring is accomplished by use of a "Lightnin" Model ND-1A, 1/4 horsepower, 1,750 rpm motor, 350 rpm propellor, portable mixer equipped with two 7.7-inch diameter "Super Pitch" propellors. All wetted parts of the mixer are of 304 stainless steel. The sample is transferred to the stirred-tank reactor from the holding tanks using a Gorman-Rupp Model 11698, 5600 Series centrifugal pump. The flow rate is controlled by a 1/2-inch Whitey Model 4558-316 stainless steel ball valve and is measured by a Brooks Model 1305 flowmeter. Compressed air can be introduced into this tank through a manifold consisting of four spherical gas diffuser stones (Fisher Scientific) mounted at the end of 3/16-inch stainless steel tubing. The diffuser stones are directly under the lower propellor two inches from the bottom of the tank and two inches from the propellor. The other propellor is mounted 15 inches above the lower propellor and 6 inches below the surface of the water when the tank has been filled to the 50-gallon level.

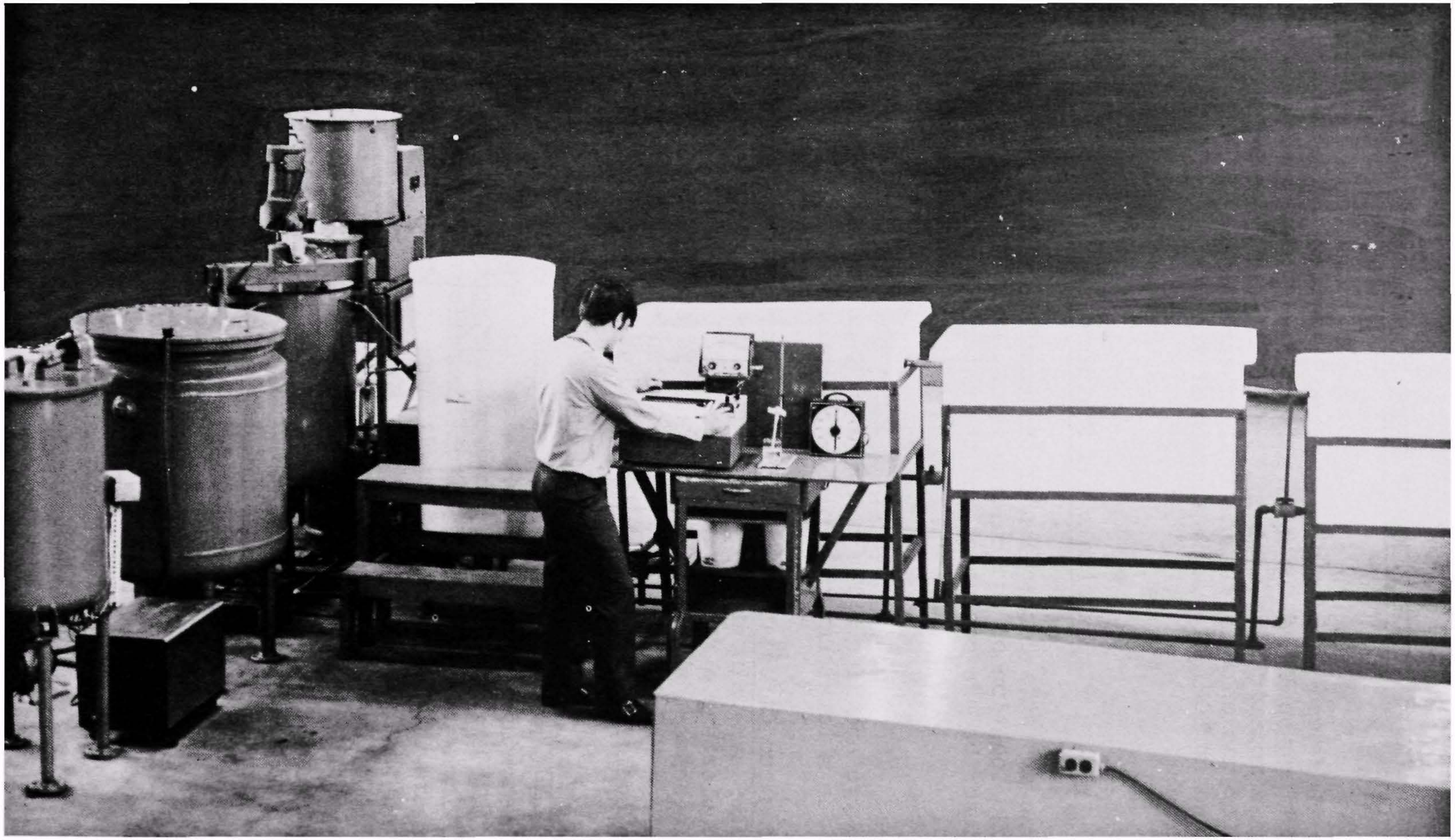

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Figure 2. General View of Continuous Flow System

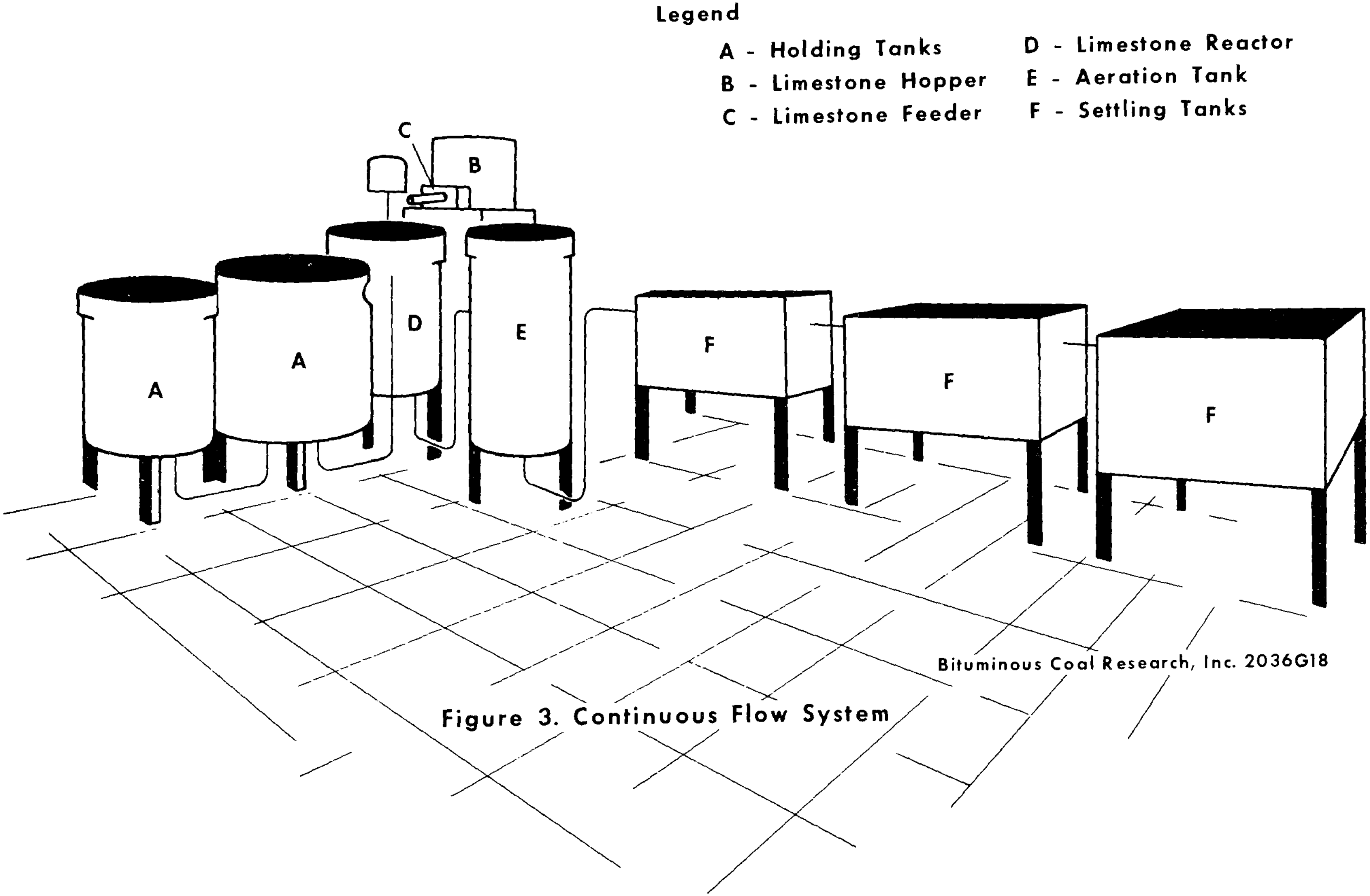

Figure 3. Continuous Flow System

Limestone Feeder: Pulverized limestone is fed to the reactor by a Vibra Screw feeder composed mainly of a 3-cu ft "Live Bin," a mechanical variable speed drive, a trough, and 1/4-inch diameter feed screw.

Aeration Tank: The polyethylene cylindrical tank has a capacity of 80 gallons and has an air manifold identical to the one mentioned above. The sample can be transferred to the aeration tank from the limestone reactor using a Gorman-Rupp Model 11698, 5600 Series centrifugal pump. The flow rate is controlled by a 1/2-inch Whitey Model 4558-316 stainless steel ball valve and is measured by a Brooks Model 1305 flowmeter.

Settling Tanks: Two 105-gallon polyethylene settling tanks are used to collect the sludge. A third 105-gallon polyethylene tank is available for storage of the sludge to be recirculated. The sample can be transferred to the settling tanks from the aeration tank using a Gorman-Rupp Model 11882-2, 200 series, centrifugal pump. The flow rate is controlled by a 1/2-inch Whitey Model 4558-316 stainless steel ball valve and is measured by a Brooks Model 1305 flowmeter. The sludge can flow by gravity from the first to the second and third settling tanks.

Piping: Piping is stainless steel, except for the large diameter flexible Tygon connectors between the settling tanks.

An auxiliary portable pumping system consists of a Gorman-Rupp Model 11698, 5600 Series centrifugal pump and a Gorman-Rupp Model 12500-21 oscillating pump. A second portable system, used primarily for recirculating sludge, consists of a Gorman-Rupp Model 11882-2, 200 Series centrifugal pump and a Gorman-Rupp Model 12500-21 oscillating pump.

Detention Time Study to Quantify Efficiency of Reactor

Studies using tracer techniques were initiated to determine the detention time in the limestone reactor. A solution of 570g of NaCl dissolved in 2 liters of tap water was added spontaneously to the stirred reactor tank which contained 50 gallons of tap water and which was operating at an inflow-outflow rate of 1.0 gallons per minute (gpm). Conductivity readings were taken at the reactor discharge at 30-second intervals for the first 2 minutes, every minute for the next 3 minutes, and then every 5 minutes. About 4 hours were required for the salt to pass through the reactor, as shown in Figure 4, by the conductivity returning to essentially the initial reading. Evidence of rapid mixing is also shown in this figure by the peak of the conductivity curve occurring 60 seconds after the addition of NaCl. The data were fitted to a probability density function (pdf). From this, the average detention time (the expected or mean value of the pdf) was 44.5 minutes. The theoretical detention

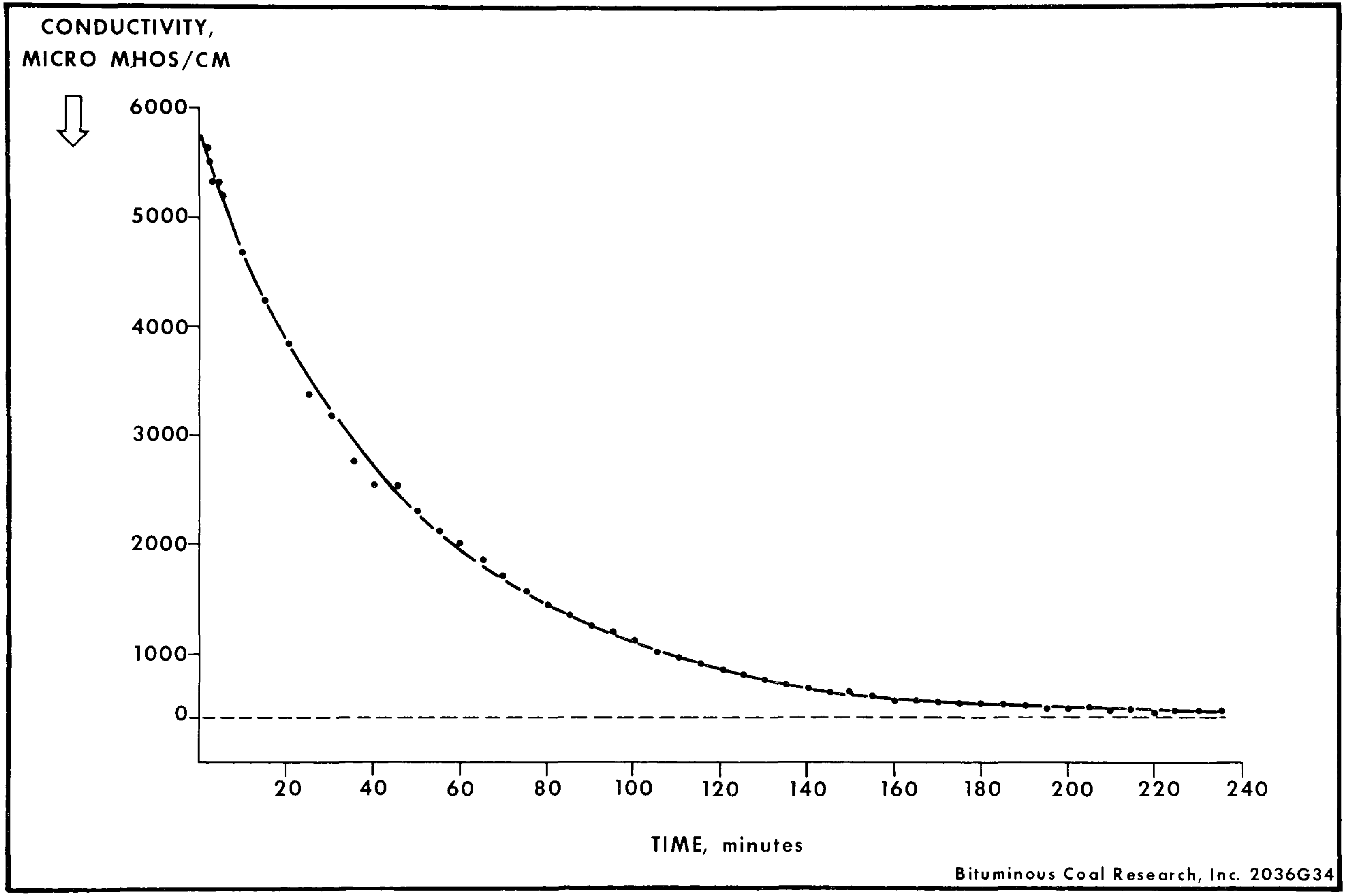

Figure 4. Detention Time Study—Limestone Reactor

time was 50 minutes (gallons of water in limestone reactor/flow rate, gpm). Therefore, the efficiency of the reactor (average detention time x 100/theoretical detention time) was 89.0 percent.

SECTION V

EXPERIMENTAL

General procedures, including apparatus and analytical procedures for evaluating the limestones and conducting the continuous flow experiments, are reported here.

Analytical Procedures

Both raw mine water and treated water samples were analyzed routinely for: (a) ferrous iron colorimetrically using o-phenanthroline, (b) cations, Si, Al, Fe, Ca, Mg, Mn, and Na, either by emission spectrographic techniques using a Jarrell Ash Model 78-000 1.5 meter Wadsworth grating spectrograph or by atomic absorption spectrophotometric techniques using an Instrumentation Laboratory Model IL-153 atomic absorption spectrophotometer, (c) acidity by adding hydrogen peroxide, boiling, cooling to room temperature, and titrating to pH 8.2, and (d) pH.

Evaluation of Limestones

Selected limestones were evaluated by consideration of (a) their physical and/or chemical properties and (b) their effectiveness in neutralizing coal mine water.

Materials

Tests were conducted with the 14 limestones which were used on Pennsylvania Coal Research Board Project CR-75. (1) These were procured as fairly coarse material and pulverized to the desired size.

A number of the suppliers of the 14 limestones were contacted to request information concerning rock dust and/or other finely divided grades of limestone which might be commercially available. Specific information solicited included: grades and quantities available, cost at the source and cost of delivery, chemical and sieve analyses, cost and method of grinding coarse fractions, and specifications for a rock dust grade. Bagged (80 lb) quantities of finely divided limestone were ordered, where available, for testing on this project.

Of the companies contacted, 11 responded and 9 of these supplied samples. Not all of the materials were specified as rock dust grade. The cost per ton of the materials f.o.b. shipping point ranged from $3.50 to $6.75 in bulk, from $5.50 to $10.00 bagged, usually in 80-lb bags. The cost of bagging the material was usually $2.50 per ton. Grinding costs, based on limited available data, were approximately $2.25 per ton. Average cost of delivery was $0.05 per ton per mile.

Hypothetically, 10 tons of limestone (bulk) at an initial cost of \$4.50 per ton delivered 35 miles would have a total cost of \$6.25 per ton, while bagged limestone at \$7.00 per ton delivered the same distance would have a total cost of \$8.75 per ton.

Chemical and Physical Properties of the Limestones

The chemical composition of the individual limestones was determined by conventional emission spectrographic techniques. Structure was determined by X-ray diffraction analyses utilizing a Picker Nuclear powder diffraction unit. Densities and surface areas of the limestones, where applicable, were determined, respectively, with a Beckman air pycnometer and either by the standard BET (Brunauer, Emmett, and Teller) technique using nitrogen as the adsorbate at liquid nitrogen temperatures or by a modified BET technique using a Micromeritics Model 2200 surface area analyzer.

Sampling the Finely Divided Limestones

The twelve finely divided limestones procured for use on this project arrived at BCR laboratories in 50 or 80 lb bags (in one case, in pails). In each case, the contents of one of the containers was piled in a cone (allowed to run down the apex of the cone equally in all directions to mix the sample) and spread in a circle to uniform thickness. The flat pile was marked into quarters and the two opposite quarters discarded. The process of piling, flattening, and rejecting two quarters was repeated (approximately five times) until the desired quantity was obtained and stored in glass jars. Samples for experimentation and analyses were taken from these glass jars.

Sieve Analyses of the Finely Divided Limestones

For the sieve analysis of each of the finely divided limestones, approximately 50.0g was weighed to an accuracy of at least 0.1 percent. The sieves selected were: Tyler mesh No. 20, 100, 200, and 400. Starting with the finest mesh sieve (No. 400), each sieve, with a solid pan at the bottom, was placed in a Ro-Tap Testing Sieve Shaker until less than 0.05g of material passed the particular sieve in one minute.

Synthetic Coal Mine Water

For these tests, fresh quantities of synthetic coal mine water were prepared as needed. Ferrous sulfate was added to deionized water to yield a solution containing 250 mg/l of Fe^{2+}. The pH of the solution was then adjusted to 3.0 by addition of sulfuric acid.

In some tests, dilute sulfuric acid (pH 3.0) was employed in place of the synthetic coal mine water.

Actual Coal Mine Waters

Most of the experiments with actual coal mine waters were conducted using a water designated South Greensburg, a discharge from an inactive drift mine in Westmoreland County, Pennsylvania. During these tests, the South Greensburg discharge contained from 69 to 98 mg/l of ferrous iron, from 140 to 199 mg/l of acidity as $CaCO_3$ equivalents, and had a pH of 4.9 to 6.1.

The remainder of the experiments were conducted with a water designated Thorn Run which is actually from a reservoir also in Westmoreland County, Pennsylvania, where a number of small discharges are impounded. During these tests, the Thorn Run discharge contained iron mostly in the ferric state (typically about 150 mg/l), only small amounts of ferrous iron, from 845 to 1,043 mg/l of acidity as $CaCO_3$ equivalents, and had a pH of 2.6 to 2.8.

General Procedure for Neutralization Reactions

Specified amounts of limestone were added to 1,500 ml of the water to be neutralized. The amount of limestone used was based on the acidity of the water. The mixture was stirred at a constant rate and aerated at a rate of 2,500 ml/min continuously for a 5-hour period. Aeration was carried out by bubbling air into the mixture through a gas diffuser at the bottom of the container. Changes in pH were recorded with time. The apparatus for conducting these experiments is shown in Figure 5. An Orion Model 401 meter with a Sargent/Jena combination electrode was used to measure pH and a Houston Instrument Omnigraphic T-Y recorder, Model HR-80, was employed to record changes in pH.

Neutralizing Efficiency of the Limestones

Evaluations of the limestones were based on consideration of the areas under the neutralization curves as compared to the areas under similar curves prepared using either BCR limestone No. 1809 or No. 2177. Relative areas under the neutralization curves were measured either by (a) copying the curves on relatively constant-weight paper and cutting out the area under each curve and weighing, or (b) using a planimeter. The limestones were also evaluated by comparing the neutralization curves with a composite neutralization curve of all results of past tests.

The chemical composition, particle size, and crystalline structure of the limestones as well as the pH, ferrous iron content, and acidity of the mine water were also considered.

Effect of Particle Size

Ten experiments were conducted according to the general procedure. A single limestone, BCR No. 1809, was pulverized and neutralization curves prepared by adding 10 discrete particle size fractions each

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Figure 5. Apparatus for Neutralization of Coal Mine Water

of No. 1809 to synthetic coal mine water. The amount of limestone used was twice the stoichiometric amount based on the acidity of the water.

Studies with Actual Coal Mine Water

Fourteen limestones, pulverized and sieved to a narrow particle size range, 325 x 400 mesh (37 to 44 microns), were each used with the South Greensburg discharge. The amount of limestone used was twice the stoichiometric amount based on the acidity of this discharge. Neutralization curves were prepared according to the general procedure.

Studies with Dilute Sulfuric Acid

Two series of neutralization experiments were conducted using the 14 pulverized limestones. The amount of limestone was based on the acidity of the test water, in this case, dilute sulfuric acid (pH 3.0). In one series, the exact stoichiometric requirement of each of the 14 limestones was used to prepare neutralization curves according to the general procedure. In the next series, the same procedure was followed except for the use of twice the stoichiometric amount of each of the 14 limestones.

Studies with the Finely Divided Limestones

A representative sample of each of the 12 finely divided limestones was obtained. Neutralization curves were prepared with each limestone as received and with synthetic and two actual coal mine waters according to the general procedure. The amount of limestone used in each case was twice the stoichiometric amount based on acidity of the water. Each limestone was again tested after having been passed once through a pulverizing mill.

Continuous Flow Experiments

To determine basic operating conditions required to neutralize acid mine drainage with limestone, two actual coal mine waters were treated utilizing the small laboratory pilot plant which has been described in the previous section.

Actual Coal Mine Waters

Most of the experiments were conducted using the water designated the South Greensburg discharge. During the continuous flow tests, the South Greensburg discharge contained from 40 to 105 mg/l of ferrous iron, from 140 to 228 mg/l of acidity as $CaCO_3$ equivalents and had a pH of 4.6 to 5.6. The iron in this water was principally in the ferrous, Fe^{2+}, state.

A few experiments were conducted with the water designated the Thorn Run discharge. During these tests, the Thorn Run discharge contained 21 to 37 mg/l of ferrous iron, 995 to 1,049 mg/l of acidity as $CaCO_3$ equivalents and had a pH of 2.4 to 2.8. The iron in this water was principally in the ferric, Fe^{3+}, state. Total iron found in this water was typically about 150 mg/l.

General Procedure for Continuous Flow Tests

A sample of mine water was brought to the BCR laboratories and the continuous flow experiment conducted on the same day. The holding tanks and the limestone reactor were filled initially with 150 and 50 gallons, respectively, of this water. The appropriate amount of BCR No. 1809 limestone (of which 85 percent passed through a 200 mesh screen) was added and the mixture stirred for 50 minutes when the flow rate was 1.0 gpm or 100 minutes when the flow rate was 0.5 gpm.

After this initial period, the flow of coal mine water was adjusted to the specified rate, both from the holding tanks to the limestone reactor and from the limestone reactor to the aeration tank.

Limestone was then added at a specified constant rate based on acidity of the water.

Compressed air was fed into the aeration tank as it was being filled to the 50-gallon mark; aeration was continued and the level held at 50 gallons by pumping the aerated sample into the settling tank. Water remaining in the aeration tank at the end of the test was pumped into the settling tanks.

Aliquots (200 ml) were withdrawn periodically from the mixing tank, aeration tank, and the settling tanks; the pH, ferrous iron concentration, and, at times, the acidity were determined on each.

System of Nomenclature for Continuous Flow Tests

The continuous flow system was designed in a flexible manner to permit changes in the sequence of unit operations to be planned as part of the test program. It was necessary, therefore, to devise the following system of nomenclature for describing the numerous conditions and sequence of operations possible in these flow experiments.

The general procedure used for treating coal mine water with limestone utilizing the continuous flow pilot plant shown in Figure 3 has just been described. The sequence of unit operations specified in that description was (a) mixing the limestone and mine water in the limestone reactor followed by (b) aeration in a separate tank. The limestone reactor tank, which was also equipped to accomplish aeration and in which the limestone was always added, was designated tank No. 1. The aeration tank was designated tank No. 2. The numbered tanks are shown in Figure 6. Aeration in the selected tank was specified as "A"

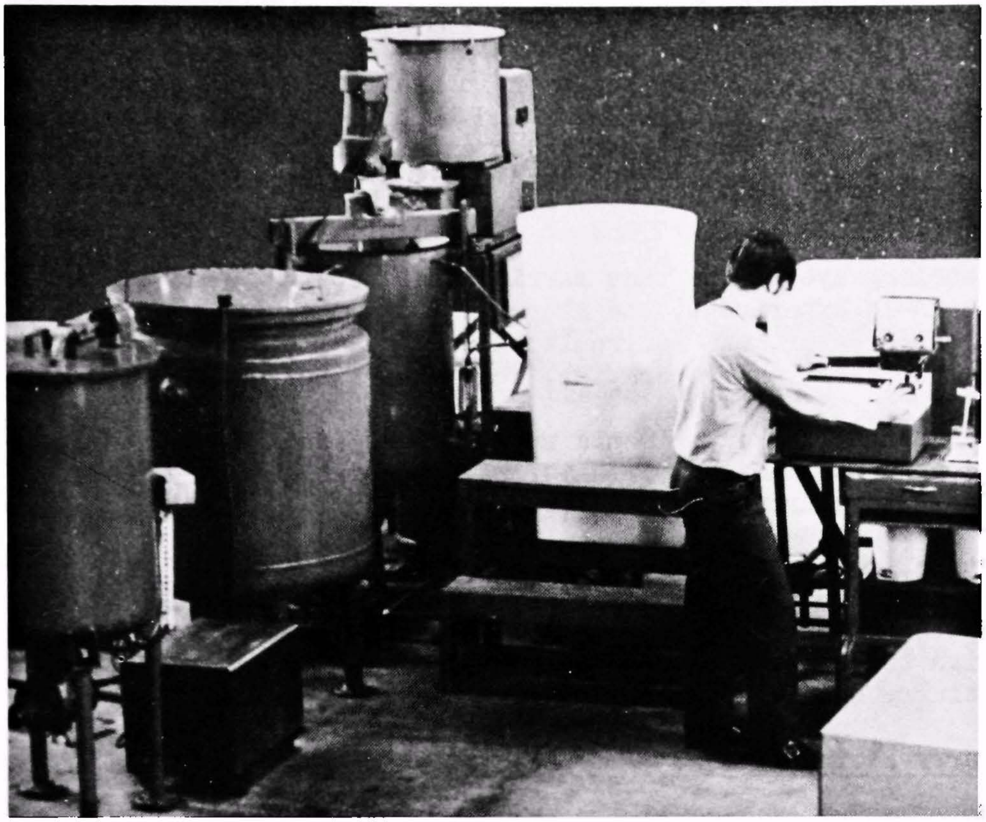

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Figure 6. Numbered Tanks for System of Nomenclature

and no aeration in the tank "N." The general procedure was then labeled 1N-2A, mixing the limestone and mine water with no aeration in tank No. 1 followed by aeration in tank No. 2. If aeration was accomplished first in tank No. 2 and then the aerated water mixed with limestone in the reactor, that experiment was labeled 2A-1N. In that manner, "2A" and "1N" were considered two distinct unit operations.

The labeling system was then carried one step further. If, in the sample 2A-1N experiment, the slurry, "(S)", the mixture of sludge and treated water, was recirculated and added to the raw mine water during the first unit operation, this experiment was labeled 2A(S)-1N.

In this manner the experiments were designed and labeled to include the various combinations of unit operations including the addition of recirculated slurry to one of two tanks.

Recirculation of the slurry (sludge plus treated water) resulting from this process only begins to simulate conditions of actual sludge recirculation. Neither time nor sufficient funds were available to redesign the continuous flow system once the necessity of recirculating this slurry became apparent.

<u>No Slurry Recirculation: Effect of Flow Rate and Amount of Limestone</u>

Flow rates of 0.5 and 1.0 gpm using twice (2X) and four times (4X) the stoichiometric amount of limestone based on acidity for each rate of flow were employed in experiments with the South Greensburg water.

<u>No Slurry Recirculation: Effect of Aeration and Sequence of Unit Operations</u>

Aeration was carried out in either or both tanks No. 1 and No. 2 and either before or after addition of limestone. In each of these experiments, the amount of limestone used was twice the stoichiometric amount based on the acidity of the coal mine water. The flow rate was 1.0 gpm in treatment of the South Greensburg water.

<u>Slurry Recirculation: Effect of Flow Rate and Aeration in Only One Tank</u>

In these experiments, slurry was recirculated as part of the treatment process. Slurry was added to either tank No. 1 or tank No. 2 at a rate of 0.5 gpm and the raw mine water, the South Greensburg discharge, treated at a rate of 0.5 gpm. Total flow into the settling tanks was then 1.0 gpm. Aeration was carried out in tank No. 2 only.

With the same conditions, this water was also treated at a flow rate of raw water of 1.0 gpm and slurry recirculated at 1.0 gpm. Total flow into the settling tanks was then 2.0 gpm.

Slurry Recirculation: Effect of Flow Rate and Aeration in Two Separate Tanks

Slurry was added to either tank No. 1 or No. 2 at a rate of 0.5 gpm and the raw mine water, the South Greensburg discharge, treated at a rate of 0.5 gpm for a total flow into the settling tanks of 1.0 gpm. Aeration was carried out simultaneously in both tank No. 1 and tank No. 2.

This same water was also treated using the same conditions except at a flow rate of 1.0 gpm of raw mine water and 1.0 gpm of recirculated slurry for a total flow of 2.0 gpm into the settling tanks.

Slurry Recirculation: Effect of 4X the Stoichiometric Amount of Limestone

In this series of experiments, the customary quantities of limestone (twice the stoichiometric amount based on acidity) were doubled and/or the slurry from the experiments with this greater quantity of limestone was recirculated. The South Greensburg discharge was again the water which was treated.

Slurry Recirculation: Effect of Amount Recirculated

Water from the South Greensburg discharge was treated with limestone and raw mine water:slurry ratios of 1:1, 3:2, and 3:1. In each case, the total flow of the treated water entering the settling tanks was held at 1.0 gpm. Aeration was carried out in tank No. 2 only.

The same water was treated at a rate of 0.5 gpm; the quantities of slurry recirculated were twice (1.0 gpm) that of the raw mine water. Total flow into the aeration tank was 1.5 gpm. Aeration was carried out in both tank No. 1 and tank No. 2.

Treatment of Thorn Run Water

For a cursory examination of treatment of a water containing iron principally in the ferric state, three experiments were conducted with Thorn Run water. In the first two, with flow rates of 1.0 and 2.0 gpm of raw mine water respectively, no slurry was recirculated. In the third experiment, slurry was recirculated; raw mine water was treated at a flow rate of 1.0 gpm and slurry recirculated at a flow rate of 1.0 gpm. Total flow into the settling tanks was then 2.0 gpm.

Sludge Properties

Volume, settling behavior, and solids content of sludge from selected batch experiments and continuous flow experiments were measured. Aliquots of 1,000 ml of combination sludge-treated water were taken at the end of a 5-hour batch experiment or at specified times during continuous flow experiments. The influence of the shape of the vessel on properties of the sludge, specifically on solids content, was also determined.

Sludge Volume and Settling Behavior

A well-mixed 1,000 ml sample of treated water containing sludge was placed in an Imhoff cone. Sludge volume was recorded at 5, 10, 15, 30, 45, and 60 minutes and 24 hours and was expressed as a percent of the 1,000 ml at 24 hours. A description of the settling behavior of the sludge was obtained by plotting the sludge volume with time.

Solids Content

From the Imhoff cone used in volume measurements, the water was siphoned off to the level of the settled sludge by means of a filter pump, Tygon tubing, and a Pasteur pipet. All water was then removed from the tubing and pipet, and about 2 ml of sludge was then drawn into the pipet. The sludge was placed into a preweighed beaker, weighed wet, and dried to constant weight at 105 C. Solids content was expressed as percent solids by weight in the sludge.

SECTION VI

RESULTS AND DISCUSSION OF LABORATORY STUDIES

Evaluation of Limestones

As part of the research program initiated at BCR to investigate the limestone treatment of coal mine drainage (1), an attempt was made to find which type of limestone would be most effective. As a result of that program, a method was established to evaluate the effectiveness of individual limestones as neutralizing agents for coal mine water. The evaluation resulted in certain conclusions concerning the limestones. For example, to be effective the stone must have a minimum particle size and relatively high calcium and low magnesium content, indicating finely divided calcites and ruling out dolomites and magnesites as neutralizing agents. The importance of a high surface area in some cases was also established. Fourteen limestones of varying origin, composition, and structure were used in that study.

These same 14 limestones were also used in part of this program to continue the evaluation of limestones as neutralizing agents for coal mine water and, therefore, the following data from the past program, Project CR-75, are included here to provide the necessary background information.

The results of the analyses of the 14 limestones by conventional emission spectrographic techniques are listed in Table 1. Structure determinations of the limestones by X-ray diffraction analyses are listed in Table 2. Density, as determined with an air pycnometer, and surface area, as determined either by a standard or modified BET technique, of each of these stones are listed in Table 3.

These 14 stones which had been received as fairly course material and pulverized to the desired size were used in studies (a) to optimize the particle size variable in limestone treatment, (b) to determine any relationship between the tests with synthetic coal mine water and the neutralization of an actual mine water, and (c) to attempt to simplify the test which had been established to evaluate limestones.

Twelve additional limestones were evaluated according to the procedures established in the above studies. These were received in a finely divided state, evaluated, pulverized further, and evaluated again.

Effect of Particle Size

Neutralization curves were prepared according to the general procedure with ten particle size fractions of BCR limestone No. 1809 and synthetic coal mine water. A composite of these neutralization curves is illustrated in Figure 7. The particle size in microns of each fraction is

TABLE 1. ANALYSES OF FOURTEEN LIMESTONES SELECTED FOR STUDY

BCR Sample No.	Spectrochemical Analyses, Mineral Samples Reported as Percent by Weight of Ignited Sample (900 C)									
	Loss on Ignition	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	TiO_2	Na_2O	K_2O	MnO_2
1462	48.4	3.90	1.24	1.46	80.0	11.5	0.03	<0.02	<0.1	<0.03
1337	46.5	1.40	<0.3	0.32	43.0	55.0	<0.03	0.02	<0.1	<0.03
1461	47.2	1.05	<0.3	0.30	45.0	53.0	<0.03	<0.02	<0.1	<0.03
1654	45.8	2.05	0.54	1.83	38.0	56.0	<0.03	<0.02	<0.1	<0.03
1352	42.6	8.00	2.75	1.08	30.0	56.0	0.11	0.08	0.87	<0.03
1364	30.4	28.5	10.7	3.70	4.20	46.5	0.50	0.70	2.25	0.07
1355	34.0	25.5	4.40	1.95	1.80	64.0	0.25	0.40	0.91	0.03
1362	36.1	10.6	2.17	12.8	3.80	69.0	0.12	0.03	0.20	0.37
2136	36.7	15.8	4.40	1.70	2.80	72.0	0.23	0.36	0.62	0.03
2135	34.6	19.5	6.10	2.70	2.40	66.0	0.27	0.33	1.50	0.03
1335	42.8	3.35	0.77	0.33	0.72	94.0	0.05	0.02	<0.1	<0.03
2145	41.7	5.00	1.69	0.88	1.48	90.0	0.07	0.03	<0.1	<0.03
1809	42.1	4.60	1.50	1.30	1.06	89.0	0.05	0.02	0.12	0.12
2177	42.7	1.41	0.42	<0.3	0.90	95.0	<0.03	0.02	<0.1	<0.03

TABLE 2. X-RAY ANALYSES OF FOURTEEN LIMESTONES

BCR Sample No.	Compounds Identified
1462	$MgCO_3$, $CaMg(CO_3)_2$
1337	$CaMg(CO_3)_2$
1461	$CaMg(CO_3)_2$
1654	$CaMg(CO_3)_2$, $CaCO_3$
1352	$CaMg(CO_3)_2$, $CaCO_3$
1364	$CaCO_3$, SiO_2, $[6SiO_2 \cdot Al_2O_3 \cdot 9MgO \cdot 7H_2O]$
1355	$CaCO_3$, SiO_2
1362	$CaCO_3$, SiO_2, αFe_2O_3, $Ca(MgFe)(CO_3)_2$
2136	$CaCO_3$, SiO_2
2135	$CaCO_3$, SiO_2
1335	$CaCO_3$
2145	$CaCO_3$, SiO_2
1809	$CaCO_3$, SiO_2
2177	$CaCO_3$

TABLE 3. DENSITY AND SURFACE AREA OF FOURTEEN LIMESTONES

BCR Sample No.	Density, D, g/ml	Surface Area, SA, m^2/g
1462	3.27	1.98‡
1337	2.74	0.62*
1461	2.94	1.11‡
1654	2.32	1.22*
1352	3.57	2.29‡
1364	2.87	2.13*
1355	2.63	2.94‡
1362	3.02	2.53‡
2136	2.46	5.39*, 5.13‡
2135	2.64	7.18‡
1335	2.70	0.88*
2145	2.59	2.05‡
1809	3.18	1.76*, 1.72‡
2177	2.54	1.17‡

* Standard BET

‡ Modified BET

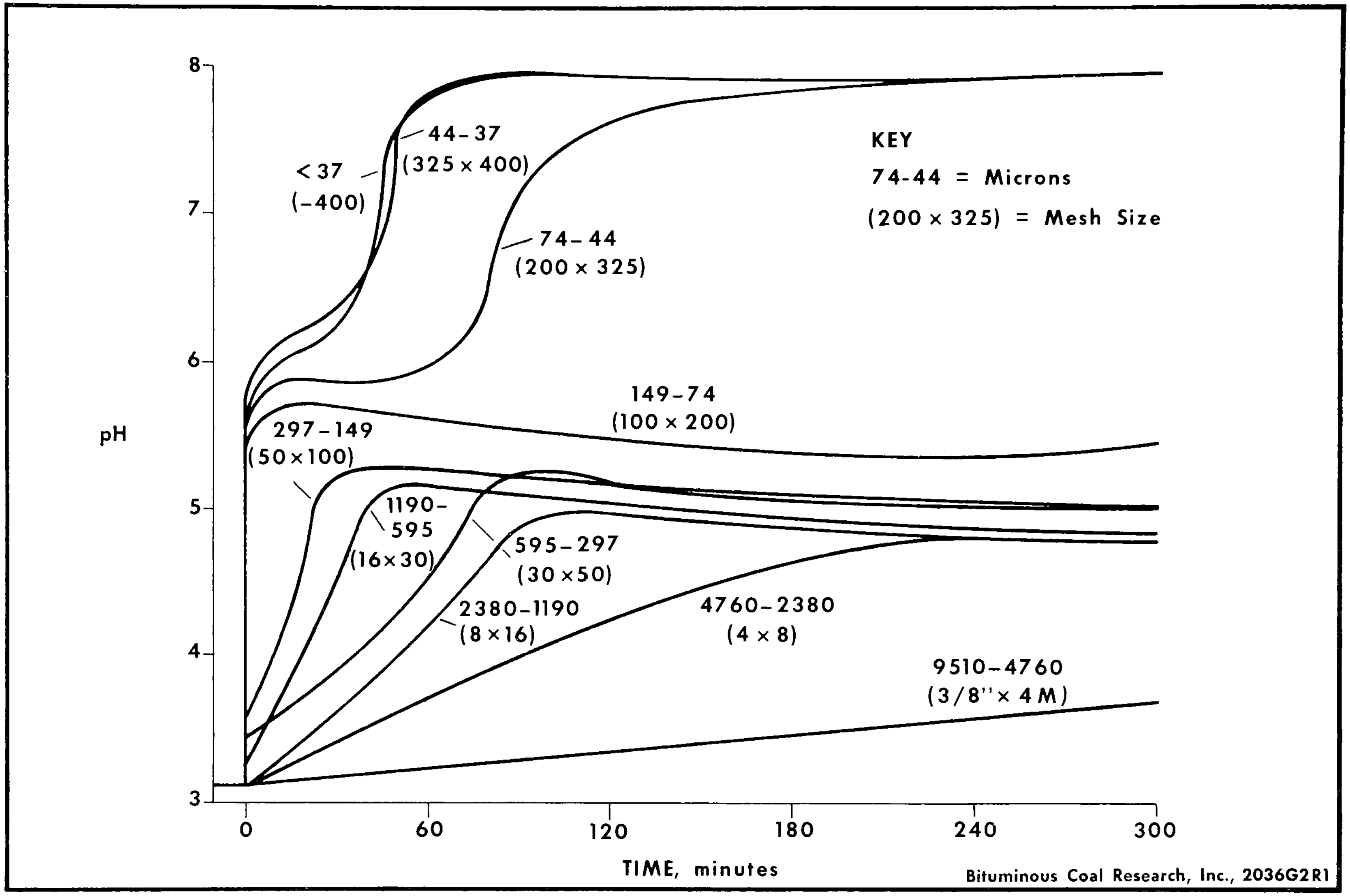


Figure 7. Effect of Particle Size of Limestone No. 1809 on Neutralization of Synthetic Coal Mine Water

listed on the appropriate curve with the corresponding mesh size shown in parentheses. The two largest size fractions, 4,760 to 9,510 microns and 2,380 to 4,760 microns, were relatively undisturbed by the mixing action and remained on the bottom of the beaker throughout the test. Size fractions between 74 to 2,380 microns effected essentially the same response--an initial increase of 2 to 3 pH units. After about 90 minutes, the pH was slightly higher for the finer size fractions. As indicated in Figure 7, the response from size fractions below 74 microns was significantly different. An immediate increase to about pH 6 was observed followed by a further, less rapid increase to approximately pH 8. This series of experiments led to the choice of the 37 to 44 micron (325 x 400 mesh) fractions for all further experiments with the 14 limestones.

Studies with Actual Coal Mine Water

Neutralization experiments were conducted according to the general procedure with 14 limestones and the South Greensburg discharge. The results are presented in Table 4. The second column in this table contains the relative weights of the papers which were cut to include only the areas under the 14 neutralization curves. The weight of blank papers is presented in the third column. The size of the blanks was arbitrarily chosen but was identical for a particular series of tests. The weights of the blanks indicated that the weights of equal sizes of paper were essentially the same.

On the basis of the results as listed in Table 4, on the visual observations of the 14 neutralization curves, and on comparison of these curves with the model curves in Figure 8, limestones No. 2135, 1335, 2136, 1809, 2145, and 2177 were judged to be effective limestones to neutralize this actual coal mine water. Figure 8 shows the composite curves resulting from the past evaluations of limestones with synthetic coal mine water and has been presented before as Figure 12 on page 47 of Reference 1. From the past studies, area A on this figure represents the curves produced by effective limestones; areas B and C represent those from ineffective limestones.

In Table 5, the limestones are listed in order of increasing effectiveness based on these tests, with limestone No. 2177 being the most effective. The relative effectiveness of the 14 limestones, as a result of these tests with the South Greensburg water, is compared to the relative effectiveness from tests conducted in the past with synthetic coal mine water. Relative areas under the neutralization curves with the synthetic systems were obtained by integration. The relative areas with the South Greensburg coal mine water were obtained by the cut and weigh method. Agreement between results of the tests with synthetic coal mine water and the results of the tests with the actual coal mine water was good. This is shown in Table 5 by the similarities in relative effectiveness of each limestone in both tests. Both the

TABLE 4. EVALUATION OF LIMESTONES WITH SOUTH GREENSBURG COAL MINE WATER

BCR Sample No.	Relative Area under Curve	Weight of Paper-blank, gm
1462	16	1.2686
1461	19	1.2332
1337	25	1.2677
1654	26	1.2630
1352	36	1.2777
1364	44	1.2677
1355	55	1.2567
1362	62	1.2561
2135	70	1.2687
1335	78	1.2904
2136	79	1.2777
1809	84	1.2572
2145	97	1.2801
2177	100	1.2740
	Mean	1.2670

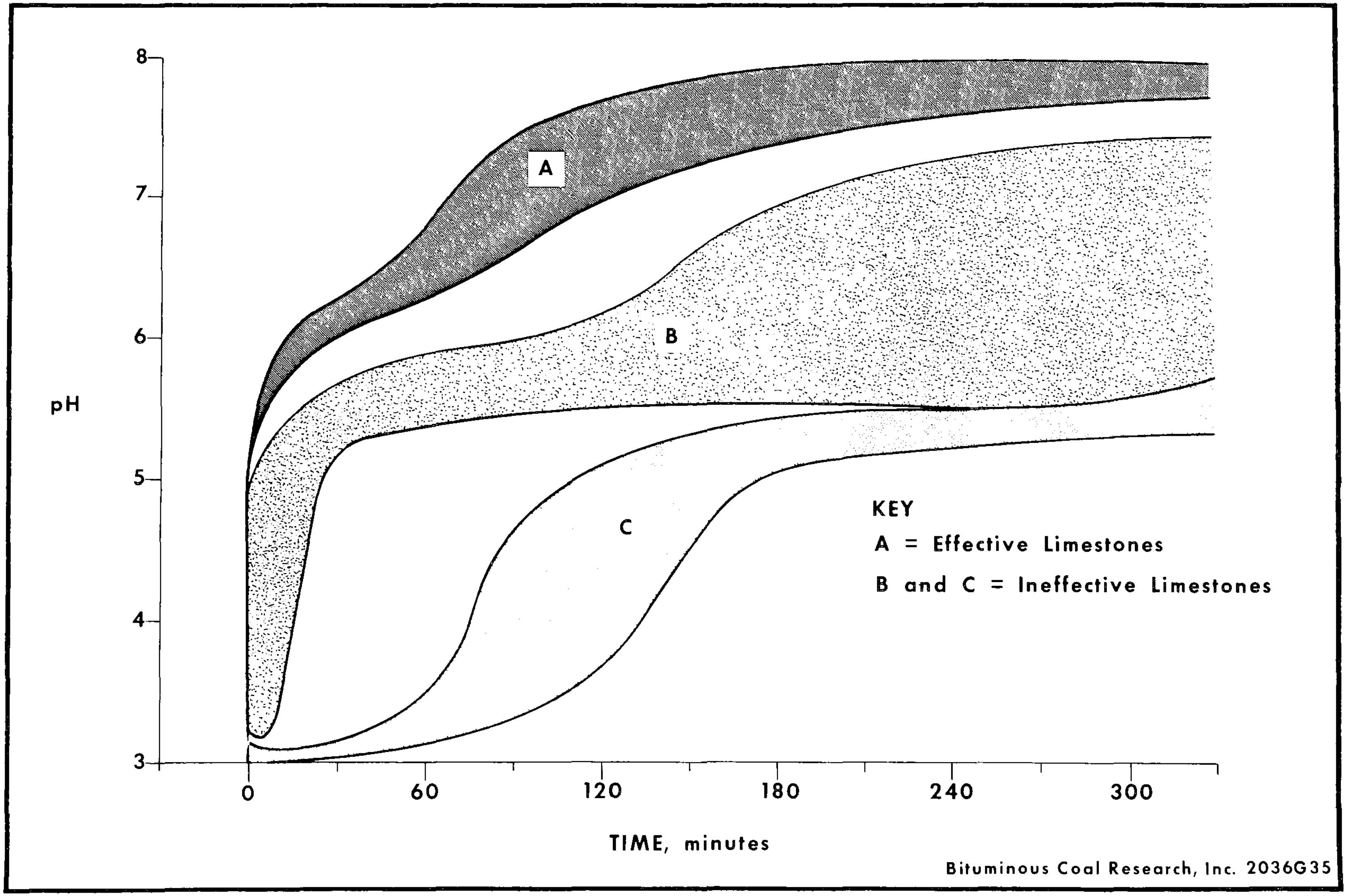


Figure 8. Model Curve for Judging Effectiveness of Limestones I

TABLE 5. RELATIVE EFFECTIVENESS OF LIMESTONES WITH SYNTHETIC AND SOUTH GREENSBURG COAL MINE WATER

Relative Effectiveness	Synthetic Coal Mine Water	South Greensburg Water
14	1462	1462
13	1337	1461
12	1461	1337
11	1654	1654
10	1352	1352
9	1364	1364
8	1355	1355
7	1362	1362
6	2136	2135
5	2135	1335
4	1335	2136
3	2145	1809
2	1809	2145
1	2177	2177

synthetic and the South Greensburg waters contained iron principally in the ferrous state and, therefore, treatment of these waters involved oxidation as well as neutralization with limestone.

Studies with Dilute Sulfuric Acid

As part of a study to simplify the test to evaluate limestones, dilute sulfuric acid was used in place of the synthetic or actual coal mine waters employed in earlier studies; the neutralization tests were conducted according to the general procedure. The results of experiments with twice the stoichiometric amount of each of the 14 limestones are presented in Table 6. The relative areas under the neutralization curves, as measured by the cut and weigh method, are presented in the second column in this table. The pH values at the times specified were taken from the neutralization curves and are listed in the last columns. Comparison of the results in Table 6 with the results of tests with 14 limestones and the South Greensburg water (Table 4) shows smaller differences in the areas under the neutralization curves when dilute sulfuric acid was used.

The results of neutralization experiments with the exact stoichiometric amount of each of the 14 limestones and dilute sulfuric acid are presented in Table 7. Relative areas under the neutralization curves were measured either by the cut and weigh method or with a planimeter and are presented in the second column in this table. The pH values at the times specified are listed in the last columns. From this table, some of the limestones judged from past tests to be effective neutralizing agents, for example No. 2135 and 2136, were among the least effective stones. With the exact stoichiometric amount of limestone, the amount of impurities in the stones, specifically the presence of inert SiO_2, is an important factor. The stones which were not effective (Table 7) contain significant quantities of SiO_2, with the exception of No. 1462 which is principally a magnesite, $MgCO_3$, and for that reason was the least effective of the 14.

In only two cases, with limestones No. 1809 and 2177, did the pH reach a value of 6 after 60 minutes as indicated by the data in Table 7. Even with the effective limestones, after 300 minutes the pH value was not much greater than 6.

A comparison of the relative effectiveness of the 14 limestones from tests with (a) synthetic coal mine water, (b) South Greensburg water, (c) dilute sulfuric acid using twice the stoichiometric amount of limestone, and (d) dilute sulfuric acid with the exact stoichiometric requirement of limestone is presented in Table 8. The limestones are listed in order of increasing reactivity, the most reactive being No. 2177. In all columns but the last, limestones in positions 1 through 6 were the effective stones; those in positions 7 through 14 were not effective as neutralizing agents.

TABLE 6. EVALUATION OF LIMESTONES WITH DILUTE SULFURIC ACID AND TWICE THE STOICHIOMETRIC AMOUNT OF LIMESTONE

Sample No.	Relative Area under Curve	pH after 30 min	pH after 60 min	pH after 300 min
1462	7	3.2	3.2	3.5
1654	61	5.1	5.8	6.6
1461	63	5.0	6.0	6.6
1337	67	5.4	6.3	6.8
1355	74	5.1	6.5	7.3
1352	76	6.4	6.7	7.2
1364	77	6.0	6.7	7.4
1362	87	6.8	7.2	7.7
2136	90	7.0	7.3	7.8
2135	91	7.0	7.3	7.7
2145	92	7.3	7.5	7.9
1335	93	7.2	7.5	7.8
1809	99	7.4	7.7	8.0
2177	100	7.7	7.8	8.0

TABLE 7. EVALUATION OF LIMESTONE WITH DILUTE SULFURIC ACID AND THE EXACT STOICHIOMETRIC AMOUNT OF LIMESTONE

BCR Sample Number	Relative Area under Curve: Cut and Weigh	Relative Area under Curve: Planimeter	Spectrochemical Analysis Percent of Ignited (900 C) Sample: SiO_2	pH Attained after: 30 min	pH Attained after: 60 min	pH Attained after: 300 min
1462	4	4	3.9	3.0	3.1	3.2
1364	14	14	28.5	3.4	3.5	3.5
1355	19	19	25.5	3.5	3.7	3.7
2135	22	22	19.5	3.7	3.8	3.8
2136	30	30	15.8	4.0	4.1	4.1
1362	31	31	10.6	3.8	4.0	4.3
1654	42	42	2.0	3.5	3.7	4.5
1461	48	49	1.1	3.4	3.7	6.0
1352	56	57	8.0	3.7	4.1	6.0
1337	65	64	1.4	3.5	4.0	6.4
1335	65	66	3.4	4.5	4.7	5.8
2145	75	77	5.0	4.5	5.2	6.3
1809	98	96	4.6	5.2	6.2	7.0
2177	100	100	1.4	5.9	6.3	6.9

TABLE 8. RELATIVE EFFECTIVENESS OF LIMESTONES WITH SYNTHETIC AND SOUTH GREENSBURG COAL MINE WATERS AND WITH DILUTE SULFURIC ACID

Relative Effectiveness	Synthetic Coal Mine Water*	South Greensburg Water*	Dilute Sulfuric Acid*	Dilute Sulfuric Acid‡
14	1462	1462	1462	1462
13	1337	1461	1654	1364
12	1461	1337	1461	1355
11	1654	1654	1337	2135
10	1352	1352	1355	2136
9	1364	1364	1352	1362
8	1355	1355	1364	1654
7	1362	1362	1362	1461
6	2136	2135	2136	1352
5	2135	1335	2135	1337
4	1335	2136	2145	1335
3	2145	1809	1335	2145
2	1809	2145	1809	1809
1	2177	2177	2177	2177

* Twice the stoichiometric amount of limestone employed.

‡ The exact stoichiometric amount of limestone employed.

With the exact stoichiometric amount of limestone and dilute sulfuric acid, the differences in reactivity of the 14 limestones were amplified compared to the other tests, but the effect of the presence of inert materials in the stones was such that there was poor agreement with the results of the other tests. There was better agreement between the results with the synthetic and South Greensburg waters than with dilute sulfuric acid (2X) and the South Greensburg water. The test had been simplified by the use of dilute sulfuric acid, but the results seemed less meaningful in relation to the neutralization of coal mine water. Therefore, no further tests were made with dilute sulfuric acid as the test water.

Both the cut and weigh method and the planimeter were used to obtain the data in Table 7 on relative areas under the neutralization curves. One study (9) reports the relative standard deviation for obtaining the area under a curve using a planimeter as 4.06 percent compared to 1.74 percent by the cut and weigh method, the latter being the more precise. The same study, though, reports the time required for the planimeter method to be half that of the cut and weigh method. The planimeter was used for all measurements given hereafter in this report.

Recommended Test Method

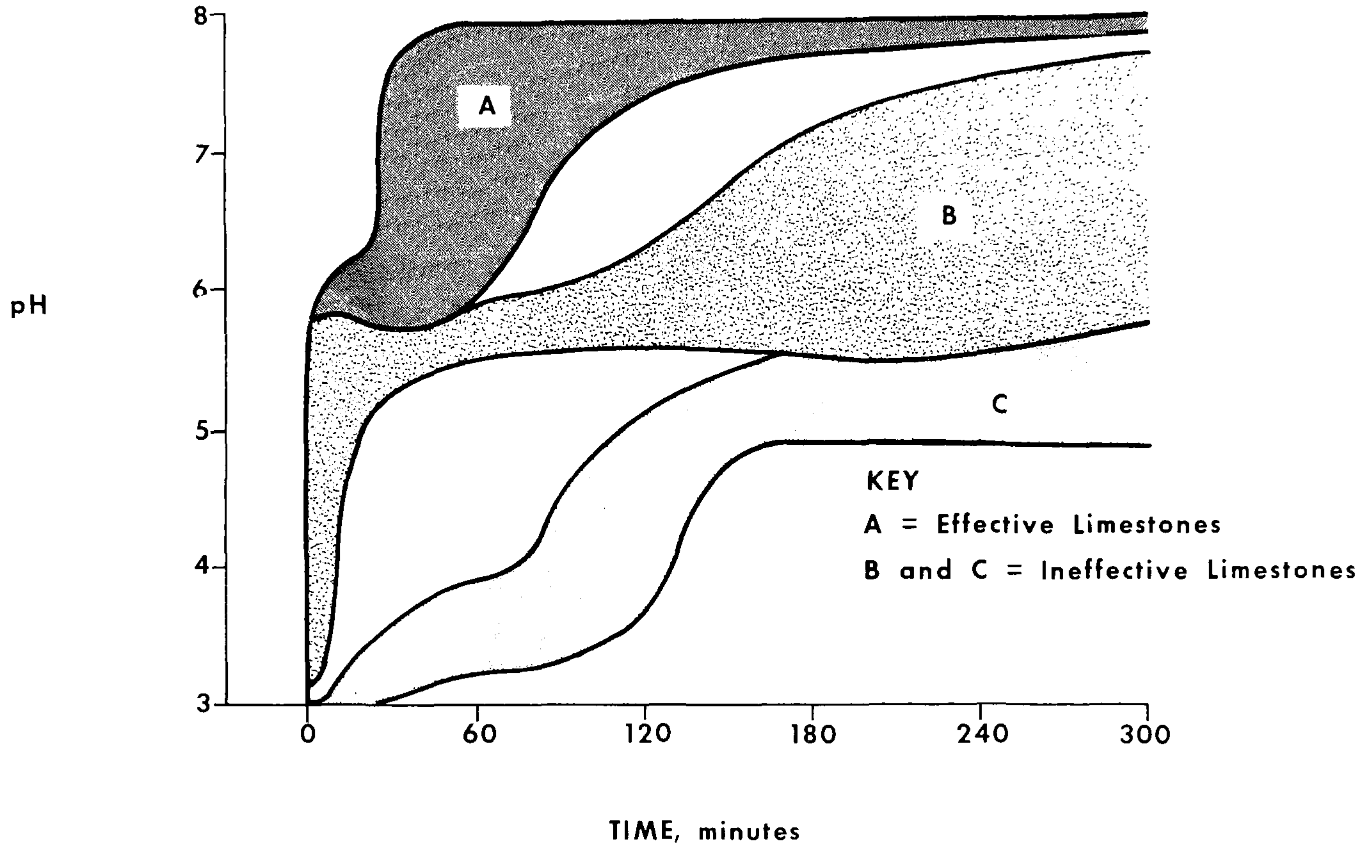
With the data available, the following test is recommended to evaluate limestones as potential neutralizing agents for coal mine water:

Finely divided (37 to 44 microns, 325 x 400 mesh) limestone should be added and air introduced to a solution of synthetic coal mine water at pH 3.0, containing from 200 to 250 mg/l of Fe^{2+} added as ferrous sulfate; this solution should be stirred and aerated continuously for a 5-hour period and the changes in pH recorded with time. The amount of limestone added should be twice the stoichiometric amount based on the acidity of the synthetic coal mine water and based on the assumption that the stone consists of pure $CaCO_3$. Air should be bubbled into the solution through a gas diffuser at the bottom of the container. The aeration should be maintained throughout the reaction at a rate of 2,500 ml/min.

A composite curve including results from all past tests should be used to judge the results of this test. Such a curve is presented in Figure 9. The curve from an effective limestone would be located in area A of Figure 9; curves from ineffective limestones would be located in areas B or C. Finally, the test should be repeated with the coal mine water to be treated and with the selected limestone.

Evaluation of Finely Divided Limestones

Twelve samples of finely divided limestones were procured for use on this project and are listed in Table 9. These were requested from the



Bituminous Coal Research., Inc. 2036G17

Figure 9. Model Curve for Judging Effectiveness of Limestones II

TABLE 9. ANALYSES OF TWELVE FINELY DIVIDED LIMESTONES

Spectrochemical Analyses, Mineral Samples
Reported as Percent by Weight
of Ignited Sample (900 C)

BCR Sample Number	Source	CaO	MgO	SiO_2	Al_2O_3	Fe_2O_3	Loss On Ignition	X-ray Analyses: Compounds Identified
2501	South Dakota	93	0.64	4.15	1.12	0.46	42.3	
2501-P	South Dakota	93	0.72	3.85	1.17	0.33	42.2	$CaCO_3$; SiO_2
2502	South Dakota	90	1.12	5.80	1.50	0.55	41.5	
2502-P	South Dakota	90	1.15	6.00	1.53	0.53	41.4	$CaCO_3$; SiO_2
2503	South Dakota	90	0.88	6.20	1.57	0.59	41.3	
2503-P	South Dakota	90	0.94	6.05	1.70	0.62	41.3	$CaCO_3$; SiO_2
2504	Ohio	55	42.0	2.10	0.41	0.28	46.5	
2504-P	Ohio	53	43.0	2.40	0.48	0.24	46.1	$CaMg(CO_3)_2$
2522	Pennsylvania	87	0.91	7.30	2.15	1.32	40.4	
2522-P	Pennsylvania	85	1.16	7.30	2.55	1.35	40.5	$CaCO_3$; SiO_2
2523	Pennsylvania	84	9.80	3.30	1.35	0.48	43.2	
2523-P	Pennsylvania	86	7.80	3.00	1.13	0.37	43.1	$CaCO_3$; $CaMg(CO_3)_2$
2544	New York	96	1.45	1.40	0.20	0.37	43.5	
2544-P	New York	95	1.55	1.20	0.23	0.28	43.4	$CaCO_3$
2545	West Virginia	97	0.58	1.15	0.33	0.16	43.2	
2545-P	West Virginia	96	0.75	1.15	0.35	0.21	42.9	$CaCO_3$
2547A	Michigan	95	1.00	1.53	0.59	0.44	43.2	
2547A-P	Michigan	94	1.80	1.95	0.61	0.54	43.0	$CaCO_3$
2547B	Michigan	93	1.28	3.30	1.27	0.60	42.9	
2547B-P	Michigan	91	2.55	3.30	0.99	0.59	42.6	$CaCO_3$
2576	Pennsylvania	41	24.5	23.0	2.15	6.80	35.0	
2576-P	Pennsylvania	44	23.0	20.0	1.90	6.20	34.8	$CaCO_3$; SiO_2; $CaMg(CO_3)_2$; $Ca(OH)_2$
2577	Kentucky	93	2.68	2.73	0.51	0.43	42.8	
2577-P	Kentucky	88	4.35	4.00	0.69	0.93	41.6	$CaCO_3$; SiO_2; $CaMg(CO_3)_2$

companies supplying the limestones for the studies under Pennsylvania Coal Research Board Project CR-75. Of the 12, two were dolomitic limestones; the remainder were high calcium limestones.

The finely divided limestones were first tested and analyzed for particle size and chemical composition as received. In addition, each one was passed once through a pulverizing mill; in Table 9 the pulverized samples are indicated by the suffix "P." Tests and analyses were repeated with crystalline structure by X-ray diffraction also being determined on the pulverized materials. The chemical composition and crystalline structure are included in Table 9.

The complete particle size analyses for each of the limestones as received are listed in Table 10; those for the stones pulverized once are in Table 11. The mesh size listed on the containers in which the limestones were received was the determining factor in choosing the size of screens used in these analyses.

Screen analyses for as-received and pulverized stones are listed in Table 12. Specifications for rock dust require that 70 percent of the material pass through a 200 mesh screen. Only 7 of the 12 limestones, as received, met this standard. After pulverizing once (designated "P"), all met this standard.

The percent moisture of each limestone as received and dried to constant weight at 105 C is listed in Table 13. The amount of moisture was not judged to be significant.

Neutralization curves were prepared for batch experiments by testing each limestone, both as received and after pulverizing once, with synthetic coal mine water and two actual coal mine waters, the South Greensburg and Thorn Run discharges. During these experiments, the synthetic coal mine water contained from 196 to 252 mg/l of ferrous iron, Fe^{2+}, from 481 to 497 mg/l of acidity as $CaCO_3$ equivalents, and had a pH of 2.9 to 3.0. The South Greensburg discharge contained from 69 to 98 mg/l of ferrous iron, from 140 to 199 mg/l of acidity as $CaCO_3$ equivalents, and had a pH of 4.9 to 6.1. The Thorn Run discharge contained from 10 to 23 mg/l of ferrous iron, from 845 to 1,043 mg/l of acidity as $CaCO_3$ equivalents, and had a pH of 2.6 to 2.8.

Data from the neutralization curves are listed in the following tables: limestone No. 2501 and 2501-P, Table 14; limestone No. 2502 and 2502-P, Table 15; limestone No. 2503 and 2503-P, Table 16; limestone No. 2504 and 2504-P, Table 17; limestone No. 2522 and 2522-P, Table 18; limestone No. 2523 and 2523-P, Table 19; limestone No. 2544 and 2544-P, Table 20; limestone No. 2545 and 2545-P, Table 21; limestone No. 2547A

TABLE 10. PARTICLE SIZE ANALYSES OF TWELVE FINELY DIVIDED LIMESTONES "AS RECEIVED"

Tyler Mesh	No. 2501				No. 2502				No. 2503				No. 2504			
	I	II	III	IV	I	II	III	IV	I	II	III	IV	I	II	III	IV
20	23.7	47.6	47.6	52.4	26.2	52.6	52.6	47.4	0.0	0.0	0.0	100.0	0.0	0.0	0.0	100.0
100	21.5	43.2	90.8	9.2	11.1	22.3	74.9	25.1	0.9	1.8	1.8	98.2	0.3	0.6	0.6	99.4
200	2.3	4.6	95.4	4.6	2.2	4.4	79.3	20.7	3.0	6.0	7.8	92.2	5.3	10.6	11.2	88.8
400	0.7	1.4	96.8	3.2	2.0	4.0	83.3	16.7	8.4	16.9	24.7	75.3	11.5	23.0	34.2	65.8
Pan	1.6	3.2	100.0	--	8.3	16.7	100.0	--	37.5	75.3	100.0	--	32.8	65.7	99.9	--
Total	49.8	100.0	--	--	49.8	100.0	--	--	49.8	100.0	--	--	49.9	99.9	--	--

Tyler Mesh	No. 2522				No. 2523				No. 2544				No. 2545			
	I	II	III	IV	I	II	III	IV	I	II	III	IV	I	II	III	IV
20	0.0	0.0	0.0	100.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0	100.0	0.1	0.2	0.2	99.8
100	14.2	28.5	28.5	71.5	1.6	3.2	3.2	96.8	1.9	3.8	3.8	96.2	4.2	8.4	8.6	91.4
200	7.0	14.0	42.5	57.5	10.1	20.2	23.4	76.6	4.9	9.8	13.6	86.4	10.3	20.7	29.3	70.7
400	3.9	7.8	50.3	49.7	9.2	18.4	41.8	58.2	5.9	11.8	25.4	74.6	8.5	17.1	46.4	53.6
Pan	24.7	49.6	99.9	--	29.1	58.2	100.0	--	37.1	74.5	99.9	--	26.7	53.6	100.0	--
Total	49.8	99.9	--	--	50.0	100.0	--	--	49.8	99.9	--	--	49.8	100.0	--	--

Tyler Mesh	No. 2547A				No. 2547B				No. 2576				No. 2577			
	I	II	III	IV	I	II	III	IV	I	II	III	IV	I	II	III	IV
20	0.1	0.2	0.2	99.8	38.1	76.6	76.6	23.4	0.0	0.0	0.0	100.0	0.0	0.0	0.0	100.0
100	0.1	0.2	0.4	99.6	5.9	11.9	88.5	11.5	9.5	18.6	18.6	81.4	1.6	3.2	3.2	96.8
200	0.4	0.8	1.2	98.8	1.1	2.2	90.7	9.3	13.5	26.5	45.1	54.9	8.9	17.9	21.1	78.9
400	1.2	2.4	3.6	96.4	1.1	2.2	92.9	7.1	13.2	25.9	71.0	29.0	8.4	16.9	38.0	62.0
Pan	47.8	96.4	100.0	--	3.5	7.0	99.9	--	14.8	29.0	100.0	--	30.8	62.0	100.0	--
Total	49.6	100.0	--	--	49.7	99.9	--	--	51.0	100.0	--	--	49.7	100.0	--	--

I = Weight on sieves, grams

II = Percent by weight on sieves

III = Total percentage on each sieve

IV = Total percentage passing each sieve

TABLE 11. PARTICLE SIZE ANALYSES OF TWELVE FINELY DIVIDED LIMESTONES (AFTER PULVERIZING)

Tyler Mesh	No. 2501-P				No. 2502-P				No. 2503-P				No. 2504-P			
	I	II	III	IV	I	II	III	IV	I	II	III	IV	I	II	III	IV
20	0.0	0.0	0.0	100.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0	100.0
100	0.4	0.8	0.8	99.2	0.4	0.8	0.8	99.2	0.1	0.2	0.2	99.8	0.0	0.0	0.0	100.0
200	3.1	6.2	7.0	93.0	2.9	5.8	6.6	93.4	0.7	1.4	1.6	98.4	1.1	2.2	2.2	97.8
400	8.7	17.4	24.4	75.6	6.6	13.2	19.8	80.2	3.9	7.8	9.4	90.6	8.0	16.1	18.3	81.7
Pan	37.7	75.6	100.0	--	40.2	80.2	100.0	--	45.2	90.6	100.0	--	40.6	81.7	100.0	--
Total	49.9	100.0	--	--	50.1	100.0	--	--	49.9	100.0	--	--	49.7	100.0	--	--

Tyler Mesh	No. 2522-P				No. 2523-P				No. 2544-P				No. 2545-P			
	I	II	III	IV	I	II	III	IV	I	II	III	IV	I	II	III	IV
20	0.0	0.0	0.0	100.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0	100.0
100	0.4	0.8	0.8	99.2	0.1	0.2	0.2	99.8	0.0	0.0	0.0	100.0	0.1	0.2	0.2	99.8
200	1.5	3.0	3.8	96.2	2.5	5.0	5.2	94.8	0.6	1.2	1.2	98.8	1.1	2.2	2.4	97.6
400	3.7	7.4	11.2	88.8	8.0	16.1	21.3	78.7	4.0	8.0	9.2	90.8	5.3	10.6	13.0	87.0
Pan	44.1	88.7	99.9	--	39.2	78.7	100.0	--	45.1	90.7	99.9	--	43.3	86.9	99.9	--
Total	49.7	99.9	--	--	49.8	100.0	--	--	49.7	99.9	--	--	49.8	99.9	--	--

Tyler Mesh	No. 2547-A-P				No. 2547-B-P				No. 2576-P				No. 2577-P			
	I	II	III	IV	I	II	III	IV	I	II	III	IV	I	II	III	IV
20	0.0	0.0	0.0	100.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0	100.0
100	0.1	0.2	0.2	99.8	0.3	0.6	0.6	99.4	0.2	0.4	0.4	99.6	0.0	0.0	0.0	100.0
200	0.7	1.4	1.6	98.4	2.4	4.8	5.4	94.6	3.7	7.4	7.8	92.2	1.1	2.2	2.2	97.8
400	1.4	2.8	4.4	95.6	6.8	13.7	19.1	80.9	10.4	20.9	28.7	71.3	3.7	7.6	9.8	90.2
Pan	47.6	95.6	100.0	--	40.1	80.8	99.9	--	35.5	71.3	100.0	--	44.2	90.2	100.0	--
Total	49.8	100.0	--	--	49.6	99.9	--	--	49.8	100.0	--	--	49.0	100.0	--	--

I = Weight on sieves, grams

II = Percent by weight on sieves

III = Total percentage on each sieve

IV = Total percentage passing each sieve

TABLE 12. PARTICLE SIZE ANALYSES OF TWELVE FINELY DIVIDED LIMESTONES AS RECEIVED AND PULVERIZED - PERCENT PASSING 200 MESH

BCR Sample Number	Percent Passing 200 Mesh	BCR Sample Number	Percent Passing 200 Mesh
2501	4.6	2501-P	93.0
2502	20.7	2502-P	93.4
2503	92.2	2503-P	98.4
2504	88.8	2504-P	97.8
2522	57.5	2522-P	96.2
2523	76.6	2523-P	94.8
2544	86.4	2544-P	98.8
2545	70.7	2545-P	97.6
2547A	98.8	2547A-P	98.4
2547B	9.3	2547B-P	94.6
2576	54.9	2576-P	92.2
2577	78.9	2577-P	97.8

TABLE 13. MOISTURE CONTENT OF TWELVE FINELY DIVIDED LIMESTONES

BCR Sample No.	Moisture (105 C) Percent
2501	0.23
2502	0.04
2503	0.42
2504	0.16
2522	0.07
2523	0.45
2544	0.27
2545	0.00
2547A	0.44
2547B	0.07
2576	0.03
2577	0.13

TABLE 14. NEUTRALIZATION DATA FOR LIMESTONE NO. 2501 AND 2501-P

	Synthetic		South Greensburg		Thorn Run	
	2501	2501-P	2501	2501-P	2501	2501-P
Experiment No.	396-31	396-71	396-50	396-93	396-47	396-83
Fe^{2+}, mg/l						
0 min	225	243	75	92	17	15
15	225	183	72	86	22	15
30	221	106	69	82	21	15
45	213	69	72	76	21	15
60	211	47	67	63	21	14
120	192	6	65	39	21	13
180	193	6	65	22	21	11
240	180	6	64	14	--	11
300	177	6	47	11	--	7
24 hr	114	1	41	2	17	1
pH						
0 min	3.0	3.0	5.5	5.0	2.8	2.8
15	4.8	6.0	6.2	6.5	3.4	5.5
30	5.4	6.0	6.0	6.5	3.8	6.1
45	5.4	5.9	5.9	6.5	4.3	6.3
60	5.3	5.8	5.8	6.5	4.4	6.5
120	5.2	7.2	5.6	6.5	4.4	7.1
180	5.1	7.7	5.4	6.5	4.4	7.4
240	5.0	7.8	5.4	6.5	4.5	7.5
300	5.0	7.9	5.3	6.7	4.6	7.6
Initial Acidity, mg/l	497	487	141	195	940	845
Final Acidity, mg/l (24 hr)	273	-13	117	-1	107	-4

TABLE 15. NEUTRALIZATION DATA FOR LIMESTONE NO. 2502 AND 2502-P

	Synthetic		South Greensburg		Thorn Run	
	2502	2502-P	2502	2502-P	2502	2502-P
Experiment No.	396-34	396-72	396-48	396-58	396-94	396-84
Fe^{2+}, mg/l						
0 min	231	241	74	91	17	14
15	211	177	69	75	21	15
30	207	106	71	67	18	15
45	206	70	66	55	19	15
60	199	48	63	32	17	14
120	182	6	64	7	11	14
180	177	5	61	7	11	13
240	176	5	61	3	12	11
300	173	5	46	3	8	7
24 hr	133	1	40	3	1	3
pH						
0 min	3.0	3.0	5.8	5.0	2.8	2.8
15	5.5	5.9	6.4	6.4	3.2	5.4
30	5.4	5.8	6.2	6.4	3.3	6.0
45	5.4	5.8	6.1	6.4	3.4	6.3
60	5.4	5.8	6.0	6.4	3.6	6.5
120	5.3	7.3	5.7	7.0	4.0	7.0
180	5.2	7.7	5.6	7.6	4.1	7.3
240	5.2	7.8	5.4	7.7	4.2	7.4
300	5.1	7.8	5.4	7.7	4.2	7.5
Initial Acidity, mg/l	497	487	154	195	1005	845
Final Acidity, mg/l (24 hr)	264	-18	103	-9	110	4

TABLE 16. NEUTRALIZATION DATA FOR LIMESTONE NO. 2503 AND 2503-P

	Synthetic		South Greensburg		Thorn Run	
	2503	2503-P	2503	2503-P	2503	2503-P
Experiment No.	396-36	396-73	396-49	396-95	396-57	396-85
Fe^{2+}, mg/l						
0 min	227	242	69	95	19	14
15	151	133	57	87	19	14
30	101	67	50	81	24	16
45	72	13	41	72	22	14
60	15	10	21	67	23	13
120	6	9	10	37	23	13
180	5	6	8	10	22	12
240	5	6	6	9	23	9
300	5	9	3	9	16	9
24 hr	1	1	1	1	2	2
pH						
0 min	3.0	3.0	6.1	5.0	2.8	2.8
15	6.0	6.0	6.4	6.6	3.2	6.0
30	5.9	6.0	6.3	6.6	3.3	6.4
45	5.9	6.2	6.3	6.6	3.4	6.6
60	5.9	7.3	6.3	6.6	3.6	6.9
120	7.6	7.8	6.5	6.4	4.0	7.4
180	7.8	7.9	7.2	6.5	4.1	7.6
240	7.9	7.9	7.6	6.8	4.2	7.7
300	7.9	8.0	7.7	7.2	4.2	7.7
Initial Acidity, mg/l	497	487	154	198	1005	880
Final Acidity, mg/l (24 hr)	-25	-19	-7	-5	359	0

TABLE 17. NEUTRALIZATION DATA FOR LIMESTONE NO. 2504 AND 2504-P

	Synthetic		South Greensburg		Thorn Run	
	2504	2504-P	2504	2504-P	2504	2504-P
Experiment No.	396-38	396-74	396-51	396-96	396-62	396-87
Fe^{2+}, mg/l						
0 min	218	242	71	97	19	15
15	212	236	70	91	17	17
30	212	228	73	90	18	19
45	212	224	67	87	18	19
60	207	221	52	87	19	18
120	207	213	54	90	21	17
180	220	207	52	90	19	17
240	204	199	54	96	19	14
300	201	149	51	57	15	15
24 hr	102	110	49	52	3	1
pH						
0 min	2.9	3.0	5.6	5.0	2.8	2.8
15	3.6	4.8	6.3	5.5	3.0	3.2
30	3.8	5.3	6.1	5.6	3.1	3.2
45	3.9	5.3	5.8	5.6	3.1	3.2
60	5.0	5.3	5.8	5.5	3.1	3.3
120	5.3	5.3	5.6	5.4	3.7	4.3
180	5.3	5.3	5.5	5.3	4.2	4.4
240	5.3	5.3	5.4	5.3	4.3	4.5
300	5.3	5.3	5.4	5.2	4.5	4.5
Initial Acidity, mg/l	497	487	140	198	1043	880
Final Acidity, mg/l (24 hr)	245	200	112	152	49	54

TABLE 18. NEUTRALIZATION DATA FOR LIMESTONE NO. 2522 AND 2522-P

	Synthetic		South Greensburg		Thorn Run	
	2522	2522-P	2522	2522-P	2522	2522-P
Experiment No.	396-40	396-75	396-52	396-97	396-63	396-87
Fe^{2+}, mg/l						
0 min	218	236	72	92	14	13
15	156	130	69	88	21	20
30	123	52	60	77	21	17
45	101	13	60	68	21	18
60	87	11	42	60	21	17
120	60	11	31	23	17	15
180	48	10	25	12	9	12
240	39	8	18	10	9	11
300	33	7	11	7	9	15
24 hr	12	1	1	1	1	2
pH						
0 min	2.9	3.0	5.3	4.9	2.8	2.8
15	6.0	6.0	6.4	6.6	4.8	6.2
30	5.8	6.0	6.4	6.6	5.2	6.5
45	5.6	6.4	6.3	6.6	5.5	6.8
60	5.6	7.5	6.3	6.6	5.7	7.0
120	5.4	7.8	6.2	6.6	6.0	7.4
180	5.3	7.9	6.2	6.7	6.2	7.6
240	5.3	7.9	6.1	7.2	6.5	7.6
300	5.3	8.0	6.1	7.5	6.7	7.7
Initial Acidity, mg/l	497	487	140	191	1043	912
Final Acidity, mg/l (24 hr)	22	-26	109	8	12	-9

TABLE 19. NEUTRALIZATION DATA FOR LIMESTONE NO. 2523 AND 2523-P

	Synthetic		South Greensburg		Thorn Run	
	2523	2523-P	2523	2523-P	2523	2523-P
Experiment No.	396-39	396-76	396-53	396-98	396-64	396-88
Fe^{3+}, mg/l						
0 min	196	234	73	91	13	13
15	149	132	65	80	14	18
30	87	52	56	74	14	17
45	68	32	55	60	15	17
60	57	23	37	25	12	15
120	23	12	28	22	11	12
180	13	11	23	13	6	11
240	11	8	17	5	6	7
300	11	8	11	6	6	7
24 hr	1	1	1	1	1	3
pH						
0 min	2.9	3.0	5.3	4.9	2.8	2.8
15	6.0	5.9	6.6	6.4	4.9	5.8
30	5.9	5.8	6.6	6.4	5.4	6.2
45	5.8	5.8	6.5	6.4	5.7	6.4
60	5.7	5.9	6.5	6.4	5.9	6.5
120	5.7	7.3	6.4	6.3	6.3	7.0
180	6.5	7.6	6.3	6.4	6.5	7.3
240	7.4	7.8	6.3	6.5	6.8	7.5
300	7.6	7.8	6.3	6.7	7.1	7.6
Initial Acidity, mg/l	497	487	140	191	1043	912
Final Acidity, mg/l (24 hr)	487	-15	107	0	11	-10

TABLE 20. NEUTRALIZATION DATA FOR LIMESTONE NO. 2544 AND 2544-P

	Synthetic		South Greensburg		Thorn Run	
	2544	2544-P	2544	2544-P	2544	2544-P
Experiment No.	396-41	396-77	396-54	406-1	396-65	396-89
Fe^{2+}, mg/l						
0 min	223	233	71	92	13	22
15	154	155	67	82	16	23
30	87	84	65	78	13	21
45	21	13	58	71	10	16
60	13	10	31	65	6	16
120	6	7	25	60	6	12
180	5	7	11	13	5	9
240	5	7	6	5	5	7
300	5	7	5	8	5	7
24 hr	1	1	1	5	2	2
pH						
0 min	2.9	3.0	5.1	5.0	2.8	2.8
15	6.0	6.0	6.4	6.6	5.9	6.0
30	5.9	6.0	6.4	6.6	6.4	6.3
45	5.9	6.1	6.4	6.6	6.6	6.5
60	6.2	7.4	6.4	6.5	6.8	6.5
120	7.8	7.8	6.4	6.5	7.4	7.2
180	7.9	7.9	6.4	6.6	7.6	7.4
240	8.0	7.9	6.6	6.9	7.6	7.6
300	8.0	8.0	6.8	7.4	7.7	7.6
Initial Acidity, mg/l	497	487	153	199	1043	889
Final Acidity, mg/l (24 hr)	-12	-12	7	-16	-1	-4

TABLE 21. NEUTRALIZATION DATA FOR LIMESTONE NO. 2545 AND 2545-P

	Synthetic		So. Greensburg		Thorn Run	
	2545	2545-P	2545	2545-P	2545	2545-P
Experiment No.	396-42	396-78	396-55	406-2	396-66	396-90
Fe^{2+}, mg/l						
0 min	217	230	70	96	13	23
15	128	83	59	77	13	21
30	73	13	47	68	12	17
45	34	13	40	52	8	17
60	16	11	17	43	8	17
120	6	10	12	7	7	16
180	6	8	6	6	4	11
240	6	7	6	5	3	7
300	5	7	6	6	4	8
24 hr	1	1	1	3	1	5
pH						
0 min	2.9	3.0	5.1	5.0	2.8	2.8
15	6.0	6.1	6.4	6.6	5.8	6.5
30	5.8	7.7	6.4	6.6	6.1	6.8
45	5.8	7.8	6.4	6.6	6.3	7.1
60	5.8	7.8	6.4	6.6	6.4	7.3
120	7.2	7.8	6.4	7.1	6.8	7.5
180	7.6	7.8	6.4	7.6	7.2	7.6
240	7.7	7.8	6.7	7.7	7.4	7.6
300	7.8	7.8	7.0	7.7	7.5	7.7
Initial Acidity, mg/l	497	487	153	199	1004	889
Final Acidity, mg/l (24 hr)	-2	-21	6	-11	3	-1

TABLE 22. NEUTRALIZATION DATA FOR LIMESTONE NO. 2547A AND 2547A-P

	Synthetic		South Greensburg		Thorn Run	
	2547A	2547A-P	2547A	2547A-P	2547A	2547A-P
Experiment No.	396-44	396-81	396-60	406-3	396-67	396-91
Fe^{2+}, mg/l						
0 min	219	233	76	87	15	23
15	97	127	69	79	9	21
30	11	11	59	63	6	17
45	11	11	47	59	7	15
60	7	9	8	48	8	13
120	8	8	4	7	5	12
180	8	9	8	5	5	9
240	8	9	4	4	5	9
300	7	9	4	4	5	9
24 hr	1	3	1	1	1	1
pH						
0 min	3.0	3.0	5.0	4.9	2.8	2.7
15	6.1	6.1	6.5	6.8	6.9	6.6
30	6.6	6.5	6.6	6.8	7.3	7.0
45	7.9	7.8	6.6	6.7	7.5	7.2
60	8.1	7.9	6.7	6.7	7.5	7.3
120	8.1	8.0	7.7	7.4	7.7	7.5
180	8.1	8.0	7.8	7.8	7.7	7.6
240	8.1	8.0	7.8	7.9	7.7	7.6
300	8.1	8.1	7.9	8.0	7.7	7.6
Initial Acidity, mg/l	495	481	153	197	1004	1009
Final Acidity, mg/l	2	-30	-7	-16	7	-9

TABLE 23. NEUTRALIZATION DATA FOR LIMESTONE NO. 2547B AND 2547B-P

	Synthetic		South Greensburg		Thorn Run	
	2547B	2547B-P	2547B	2547B-P	2547B	2547B-P
Experiment No.	396-68	396-82	396-61	406-4	396-69	396-92
Fe^{2+}, mg/l						
0 min	241	235	74	85	16	23
15	235	129	73	77	16	26
30	231	56	72	65	16	26
45	233	14	74	62	16	25
60	235	14	73	57	17	17
120	235	10	76	20	17	13
180	237	11	62	7	17	11
240	243	11	59	3	17	10
300	182	18	59	3	17	9
24 hr	173	3	57	1	6	2
pH						
0 min	3.0	3.0	5.0	4.9	2.7	2.7
15	3.6	5.9	5.3	6.5	3.1	6.0
30	3.9	5.9	5.3	6.5	3.1	6.3
45	4.1	6.0	5.4	6.5	3.3	6.5
60	4.2	7.2	5.4	6.5	3.4	6.6
120	4.8	7.8	5.4	6.4	4.2	7.2
180	4.8	7.9	5.3	6.6	4.2	7.4
240	4.7	7.9	5.2	7.0	4.2	7.5
300	4.6	7.9	5.2	7.3	4.3	7.5
Initial Acidity, mg/l	495	481	153	199	988	1009
Final Acidity mg/l (24 hr)	421	-15	145	-9	310	-11

TABLE 24. NEUTRALIZATION DATA FOR LIMESTONE NO. 2576 AND 2576-P

	Synthetic		So. Greensburg		Thorn Run	
	2576	2576-P	2576	2576-P	2576	2576-P
Experiment No.	406-15	406-17	406-27	406-28	406-33	406-30
Fe^{2+}, mg/l						
0 min	255	248	89	95	10	10
15	247	247	88	95	17	27
30	247	243	90	94	18	23
45	249	237	85	95	19	21
60	248	237	87	91	21	22
120	247	232	81	89	23	18
180	244	215	88	87	40	18
240	245	196	89	86	41	12
300	238	188	90	85	46	8
24 hr	177	110	77	68	3	3
pH						
0 min	3.0	3.0	5.0	5.0	2.6	2.7
15	4.0	5.5	5.2	6.0	2.6	3.0
30	4.3	5.0	5.2	6.0	2.8	3.0
45	4.9	5.5	5.2	6.0	2.8	3.1
60	5.2	5.4	5.2	5.9	2.9	3.2
120	5.2	5.4	5.2	5.6	3.0	4.0
180	5.2	5.3	5.2	5.5	3.0	4.3
240	5.2	5.2	5.2	5.4	3.1	4.3
300	5.2	5.2	5.1	5.3	3.2	4.4
Initial Acidity, mg/l	484	484	182	184	998	889
Final Acidity, mg/l (24 hr)	315	216	180	150	354	300

TABLE 25. NEUTRALIZATION DATA FOR LIMESTONE NO. 2577 AND 2577-P

	Synthetic		So. Greensburg		Thorn Run	
	2577	2577-P	2577	2577-P	2577	2577-P
Experiment No.	406-16	406-18	406-26	406-29	406-34	406-31
Fe^{2+}, mg/l						
0 min	252	248	88	98	10	10
15	88	123	77	82	11	12
30	60	57	66	70	12	12
45	32	23	60	56	11	11
60	23	20	49	45	10	10
120	17	13	13	20	6	8
180	15	12	6	17	27	7
240	13	11	8	16	23	7
300	13	1	6	14	24	7
24 hr	1	1	1	1	1	2
pH						
0 min	3.0	3.0	5.0	5.0	2.6	2.7
15	6.0	6.0	6.5	6.4	5.3	5.9
30	5.8	6.0	6.5	6.4	5.6	6.2
45	5.8	7.1	6.5	6.4	5.7	6.4
60	6.0	7.8	6.4	6.4	5.8	6.6
120	7.4	7.8	6.5	6.6	6.2	7.0
180	7.6	7.8	6.6	7.2	6.5	7.2
240	7.7	7.8	6.8	7.4	6.6	7.4
300	7.8	7.8	7.3	7.5	6.8	7.4
Initial Acidity, mg/l	484	484	182	184	998	889
Final Acidity, mg/l (24 hr)	-14	-16	-3	0	4	2

and 2547A-P, Table 22; limestone No. 2547B and 2547B-P, Table 23; limestone No. 2576 and 2576-P, Table 24; and limestone No. 2577 and 2577-P, Table 25. Ferrous iron and pH versus time are shown, as well as initial and final acidity of the coal mine water.

From these data, the dolomitic limestones, No. 2504 and 2576 were ineffective as neutralizing agents even after having been pulverized further (see No. 2504-P and 2576-P, Tables 17 and 24). The others, all essentially high calcium limestones, performed with varying degrees of effectiveness. The areas under the individual neutralization curves relative to that of limestone No. 1809, which has been used most in mine drainage studies at BCR, are presented in Table 26. Limestone No. 1809 is from the same source as, and is similar to, No. 2522-P. The difference in performance between 2522-P and 1809 with the South Greensburg water (See Table 26) is attributed to differences in quality of the discharge when each test was conducted.

The effect of particle size of the limestones on neutralization can be seen in Figures 10, 11, and 12. The percent of limestone "as-received" passing 200 mesh (from Table 12) is plotted against the relative areas under the neutralization curves (from Table 26) for the synthetic coal mine water, Figure 10; the South Greensburg water, Figure 11; and the Thorn Run water, Figure 12. In all cases, effectiveness of the limestones increased with the smaller particle size fractions.

The effect of further pulverizing the limestones (and, therefore, the effect of particle size) can also be seen in the following neutralization curves: the finely divided limestones with synthetic coal mine water, Figures 13 and 14; with South Greensburg water, Figures 15 and 16; and with Thorn Run water, Figures 17 and 18. The first of the two sets of curves with each type of water represents limestones as-received; the second set of curves, limestones after pulverization When the pulverized limestones were used, the neutralization curves of 10 of the 12 limestones became more similar, since the particle size of the stone was made more similar.

The dolomitic limestones, No. 2504 and 2576, were no more effective neutralizing agents even after the particle size was reduced substantially by pulverization.

It is significant that in no case were any special precautions necessary in handling the limestones during pulverization, analyses, and testing. The lesser reactivity of the limestones with mine water (as compared to that of lime) is a distinct advantage to those who will handle this chemical reagent.

In summary, the performance of the best of the finely divided limestones in these batch neutralization experiments was similar to that of limestone No. 1809. Particle size, again, was determined to be a most significant factor. The possibility of using these limestones, which are commercially available in a finely divided state, in a

TABLE 26. RELATIVE AREA UNDER NEUTRALIZATION CURVES TWELVE FINELY DIVIDED LIMESTONES WITH SYNTHETIC AND TWO ACTUAL COAL MINE WATERS

Limestone Number	Synthetic	South Greensburg	Thorn Run
2501	45	27	31
2502	48	33	21
2503	90	88	88
2504	43	29	19
2522	52	55	70
2523	73	63	77
2544	95	68	98
2545	86	68	90
2547A	104	110	106
2547B	32	15	22
2576	44	7	1
2577	89	76	75
2501-P	88	67	93
2502-P	87	99	91
2503-P	97	75	99
2504-P	47	17	24
2522-P	98	83	100
2523-P	88	66	92
2544-P	97	78	96
2545-P	101	103	103
2547A-P	103	112	103
2547B-P	96	77	95
2576-P	50	28	20
2577-P	99	89	91
1809	100	100	100

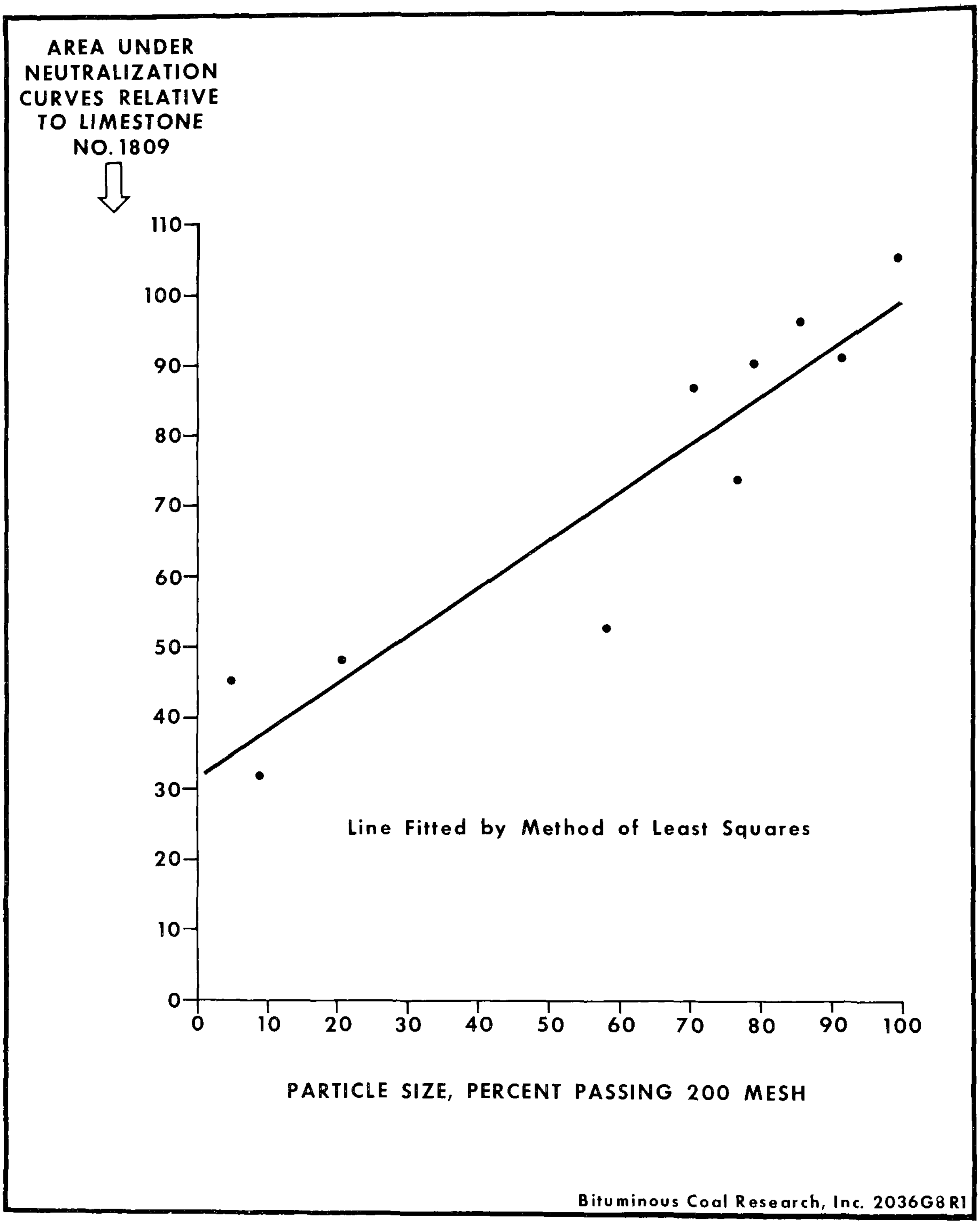


Figure 10. Effect of Particle Size of Limestones on Neutralization of Synthetic Coal Mine Water

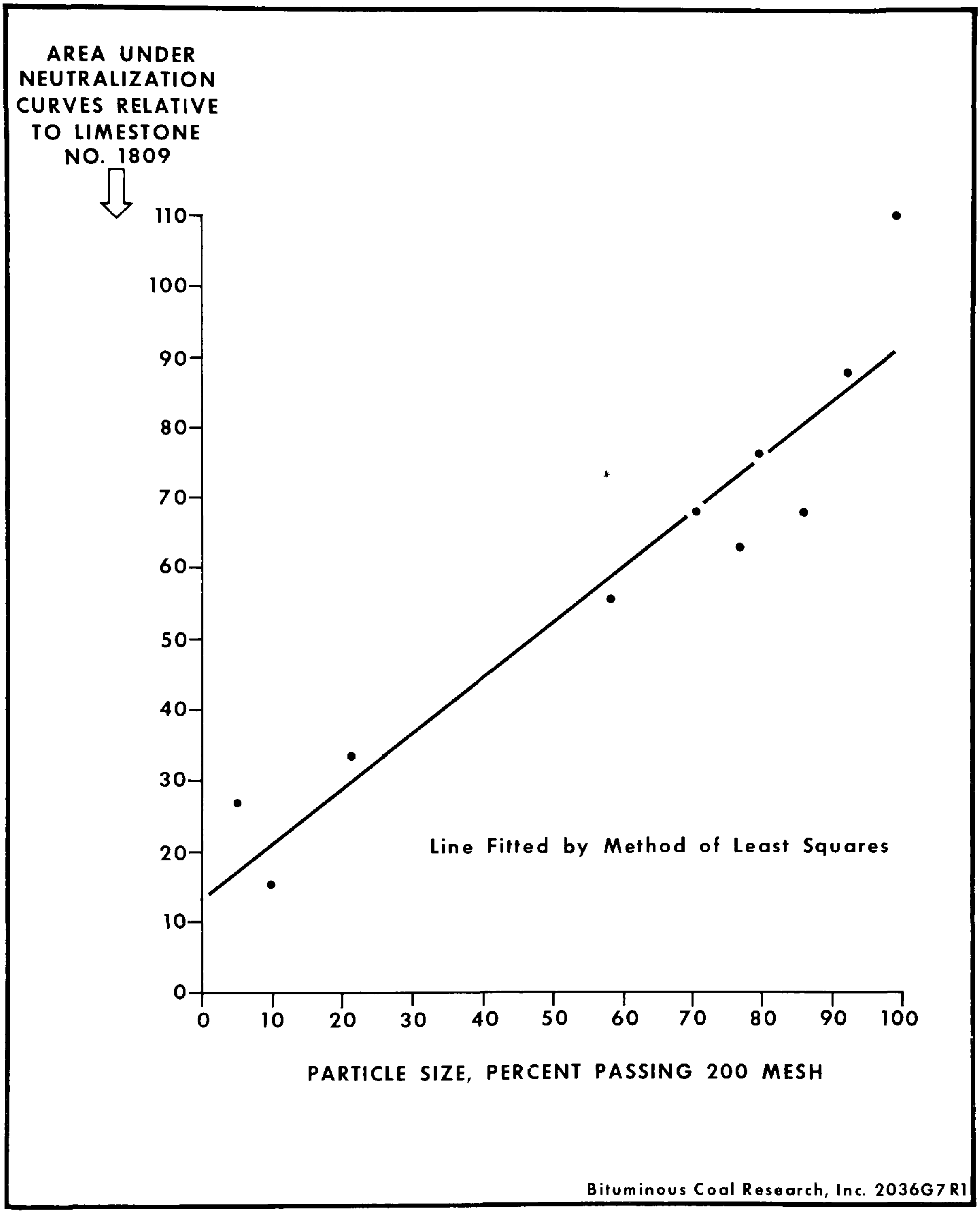


Figure 11. Effect of Particle Size of Limestones on Neutralization of South Greensburg Coal Mine Water

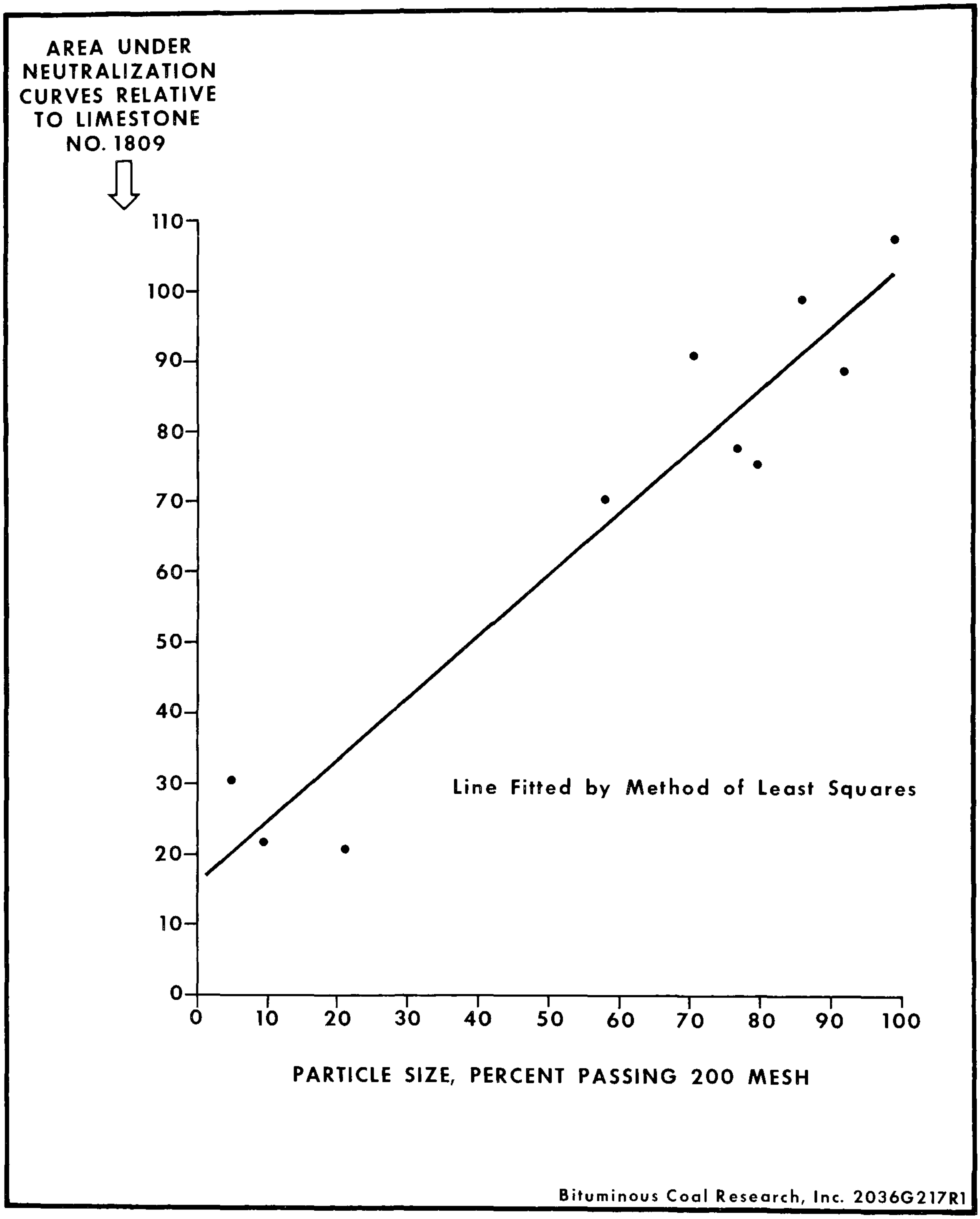


Figure 12. Effect of Particle Size of Limestones on Neutralization of Thorn Run Coal Mine Water

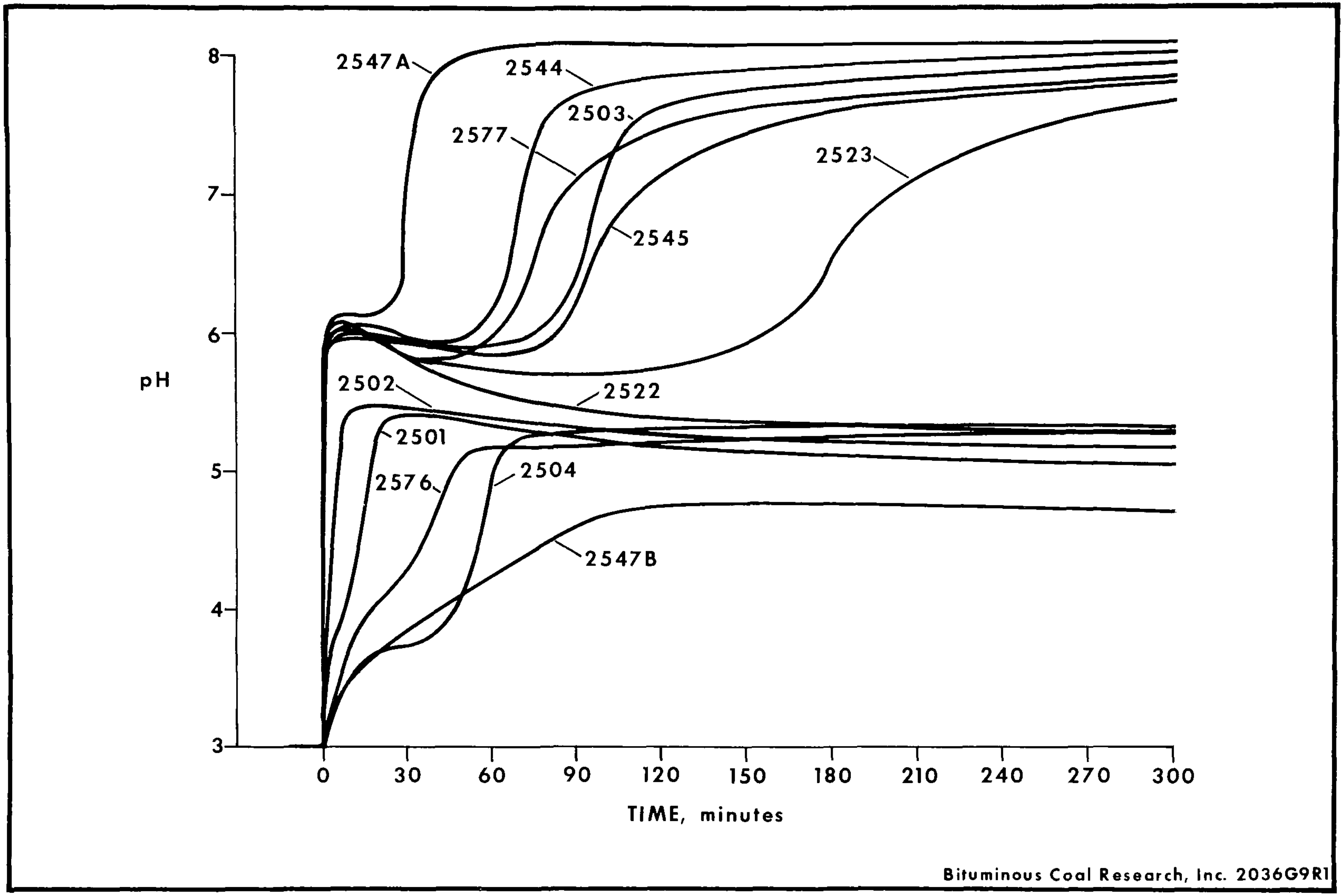


Figure 13. Neutralization of Synthetic Coal Mine Water with Finely Divided Limestones "As Received"

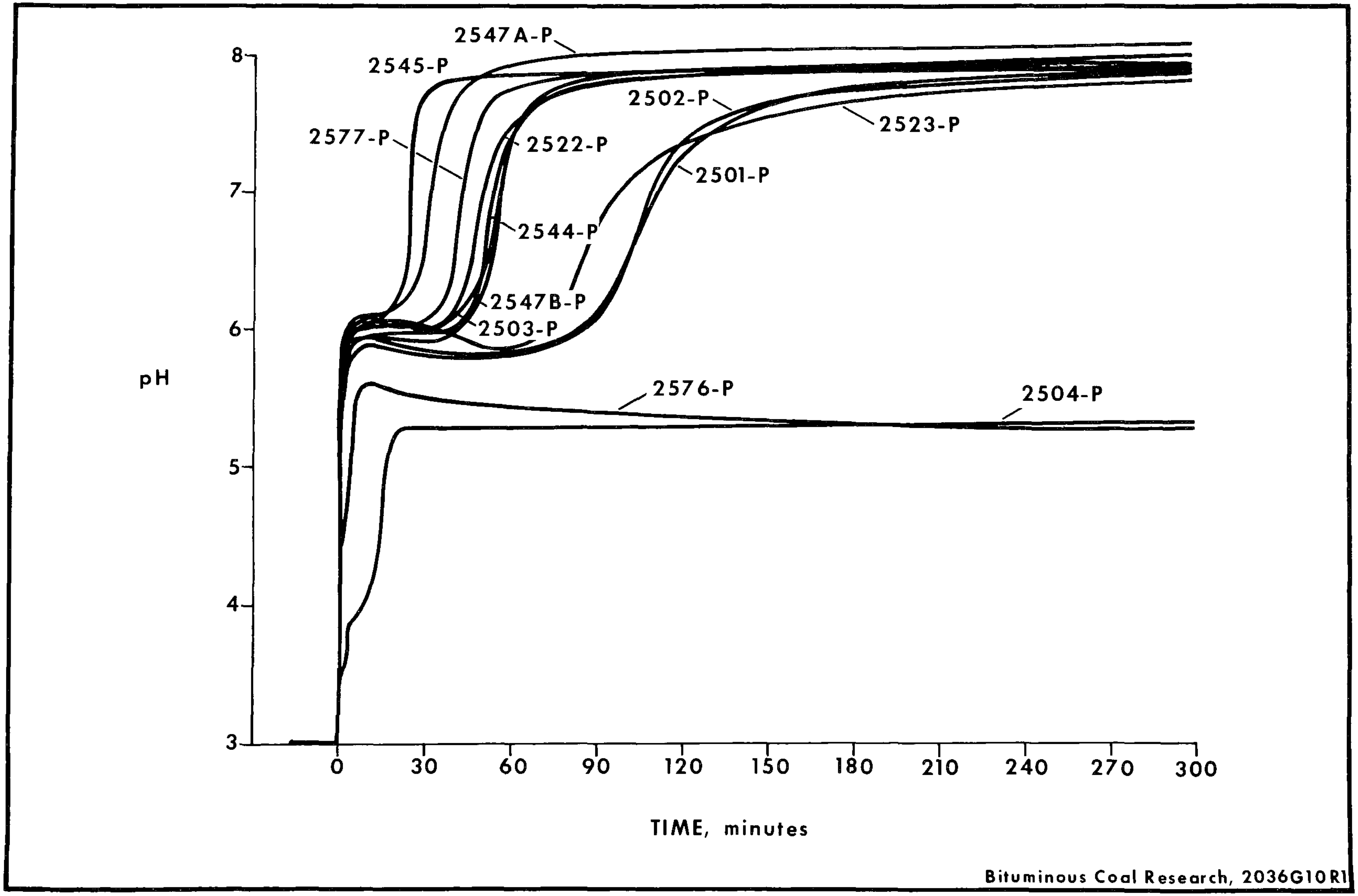


Figure 14. Neutralization of Synthetic Coal Mine Water with Finely Divided Limestones (After Pulverizing)

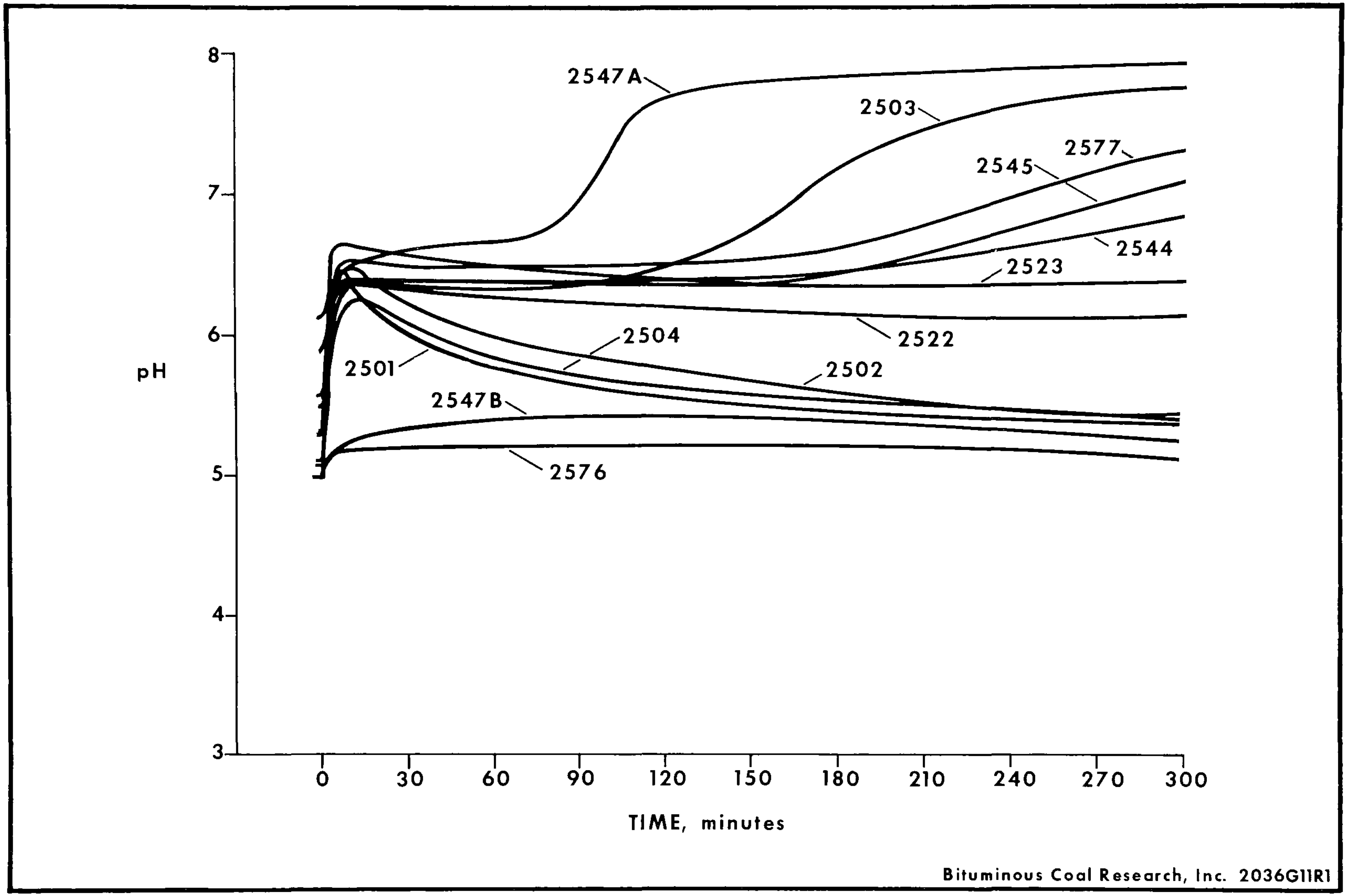


Figure 15. Neutralization of South Greensburg Coal Mine Water with Finely Divided Limestones "As Received"

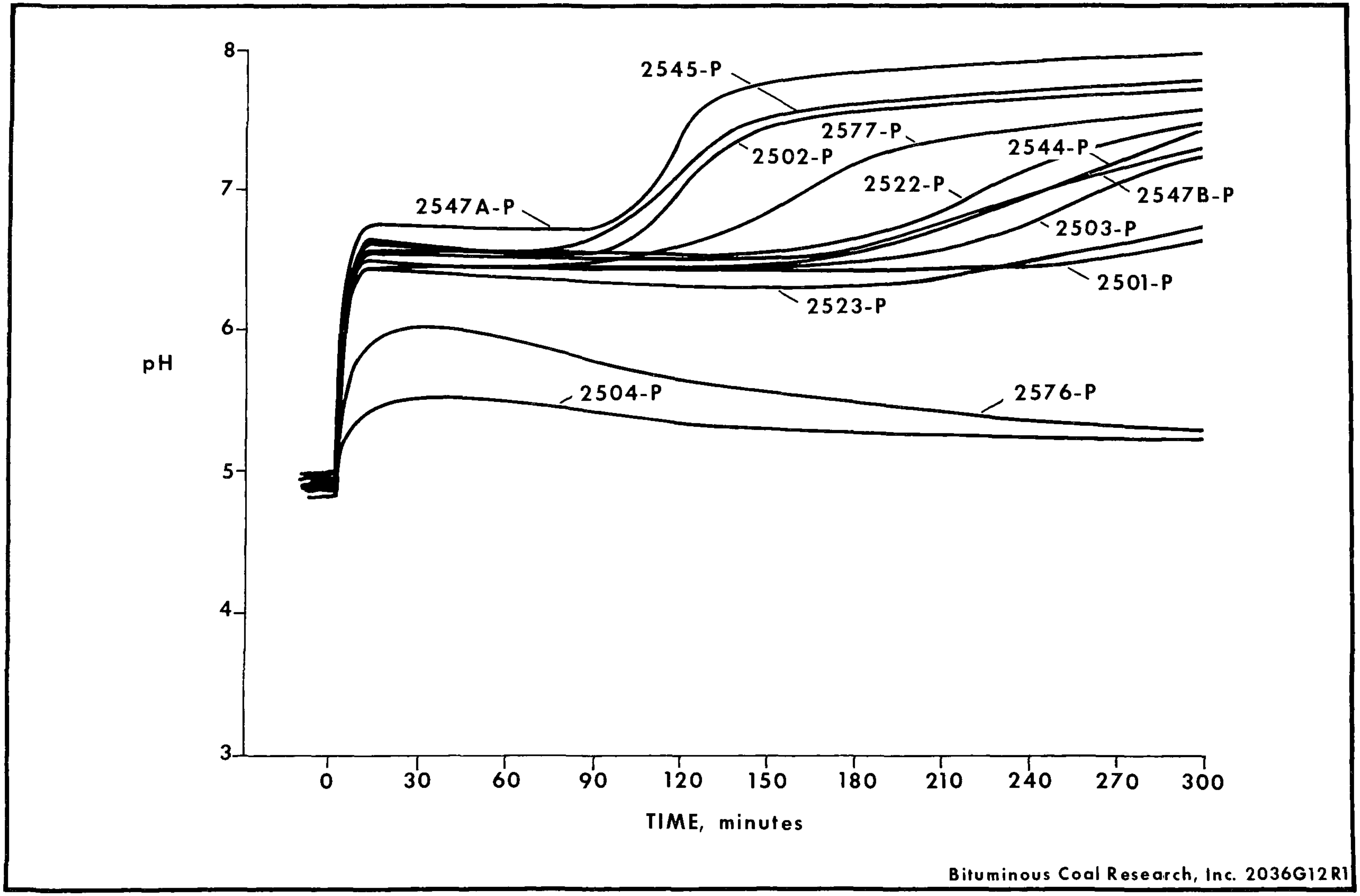


Figure 16. Neutralization of South Greensburg Coal Mine Water with Finely Divided Limestones (After Pulverizing)

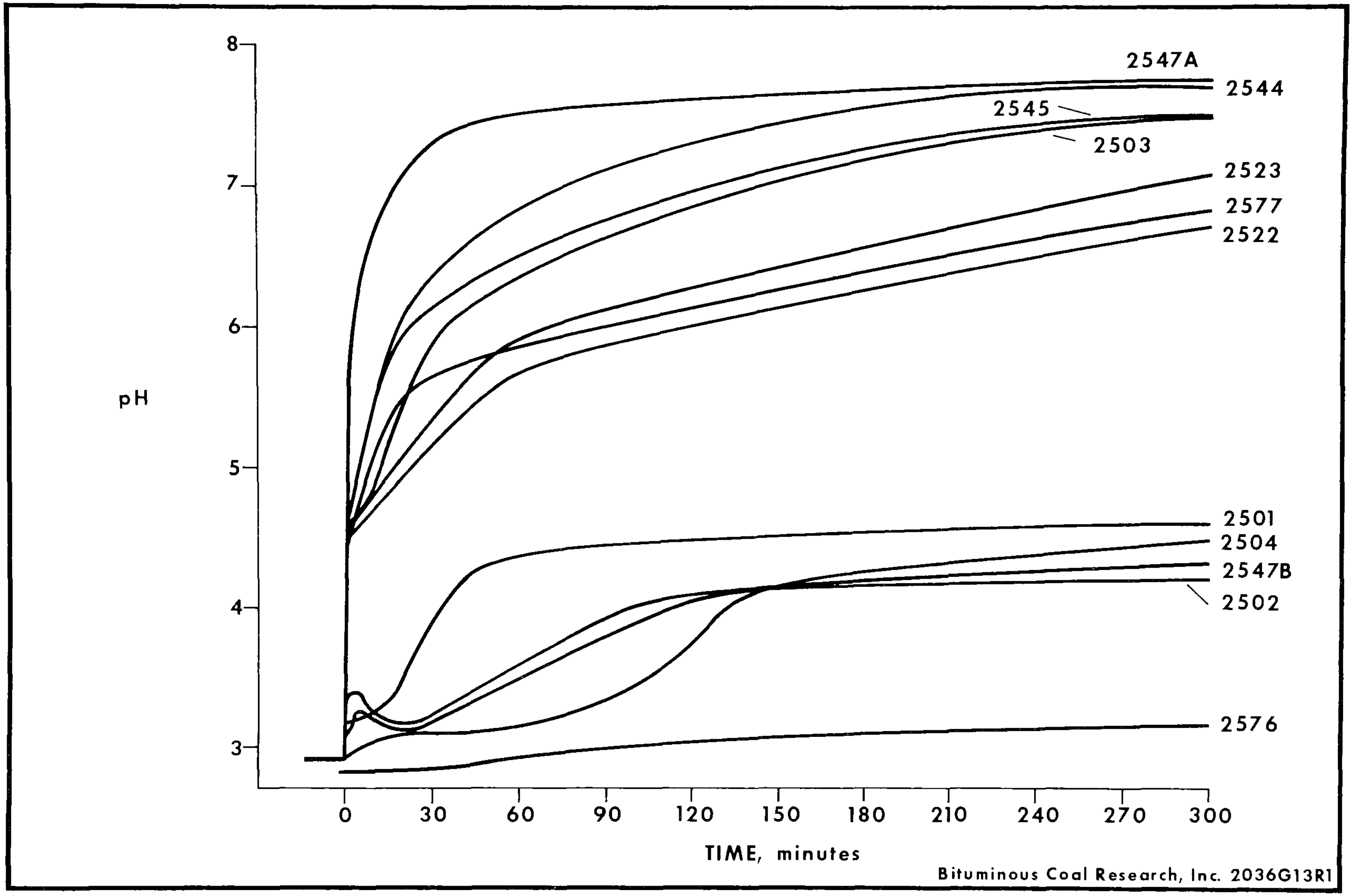


Figure 17. Neutralization of Thorn Run Coal Mine Water with Finely Divided Limestones "As Received"

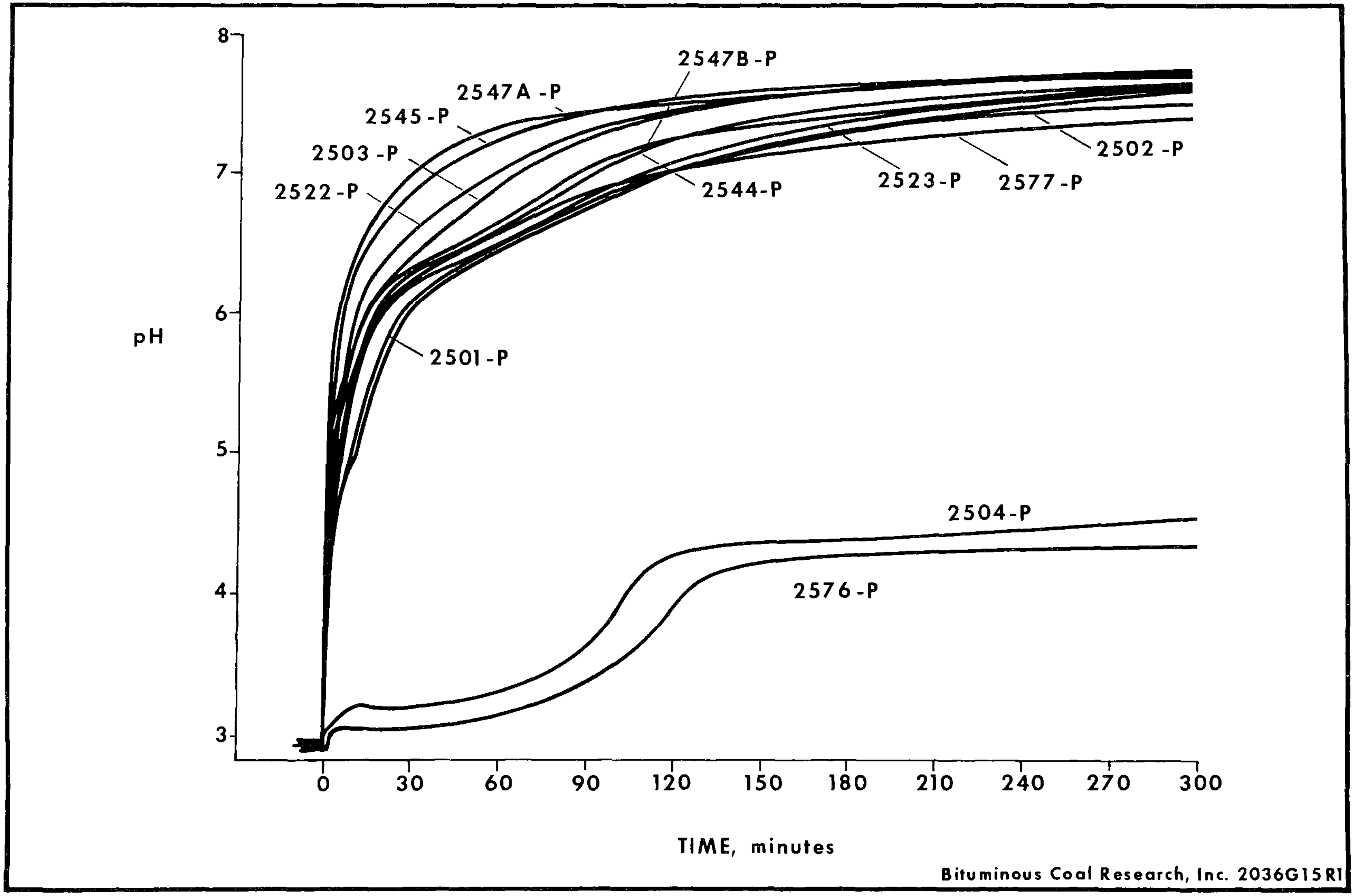


Figure 18. Neutralization of Thorn Run Coal Mine Water with Finely Divided Limestone (After Pulverizing)

treatment process depends on the results of the studies to optimize the treatment process utilizing the continuous flow system.

Evaluation of Five Additional Materials

Five additional materials were received, but were less completely evaluated than the 12 limestones. These included aragonite, siderite, and three waste materials. All contained water and were dried prior to testing and analyses. The data from tests with synthetic coal mine water are presented in Table 27. The aragonite, the orthorhombic form of $CaCO_3$, No. 1549, was as effective a neutralizing agent as calcite, (the rhombohedral, most abundant form). Siderite, No. 2578, which is essentially $FeCO_3$, had little or no effect on neutralization. The remaining three materials were described as principally limestones but were waste products from the manufacture of asbestos products. Two of them, No. 2603 and 2604, exhibited properties similar to each other, including neutralizing effectiveness. The third, No. 2605, was judged to be ineffective.

Sludge Properties

Properties of sludge formed during selected batch experiments with the finely divided limestones were measured and are presented in Table 28. Synthetic and two actual coal mine waters, the South Greensburg and Thorn Run discharges, were employed in these tests.

Synthetic Coal Mine Water--A complete description of the neutralization portion of each experiment with synthetic coal mine water has previously been presented in the following tables:

Experiment No.	Table No.
396-40	18
396-75	18
406-16	25
406-18	25

As presented in Table 28, sludge volumes ranged from 0.8 to 1.6 percent; solids content of the sludge ranged from 4.2 to 13.4 percent. Experiments No. 406-16-1 and 406-16-2 were conducted to check reproducibility. These identical experiments produced reasonably comparable results. Experiment No. 406-16-3 was also identical to No. 406-16-1 and No. 406-16-2, but in this experiment the sludge was "aged" for 48 hours before putting it in the Imhoff cone. A lower sludge volume and a substantially higher solids content resulted. In general, the more effective iron removal resulted in a greater volume of sludge. Relatively effective limestones were used in each of these

TABLE 27. EVALUATION OF FIVE ADDITIONAL MATERIALS WITH SYNTHETIC COAL MINE WATER

BCR Sample Number	Description	Spectrochemical Analyses, Mineral Samples Reported as Percent by Weight of Ignited Sample (900 C)						X-ray Analyses	Area Under Neutralization Curve Relative to No. 1809	Percent Moisture 105 C
		CaO	MgO	SiO_2	Al_2O_3	Fe_2O_3	Loss on Ignition	Compounds Identified		
1549	Aragonite	95	1.98	1.37	0.34	0.38	43.6	Calcite; Aragonite	102	--
2578	Siderite	4.9	4.55	16.3	5.60	67.0	29.1	$FeCO_3$; SiO_2	0.1	--
2603	Waste	80	14.4	3.0	0.98	1.10	45.2	--	111	52.90
2604	Waste	82	9.0	4.7	0.88	2.50	44.5	--	111	53.57
2605	Waste	40	45.0	10.3	3.05	1.16	30.1	--	64	33.53

TABLE 28. PROPERTIES OF SLUDGE FORMED IN BATCH NEUTRALIZATION EXPERIMENTS

Experiment Number	Limestone Number	Volume of Sludge, ml 5 min	10 min	15 min	30 min	45 min	60 min	24 hr	Sludge Volume Percent 24 hr	Solids Content Percent 24 hr	Fe^{2+}, mg/l Initial	Final
A - Synthetic Coal Mine Water												
396-40	2522	0.3	1.2	2.5	5.5	6.5	7.0	8.0	0.8	9.1	218	33
396-75	2522-P	3.0	10.5	12.0	12.5	12.0	12.0	13.0	1.3	4.2	236	7
406-16-1	2577	6.0	15.0	17.0	16.5	16.0	16.0	15.5	1.6	6.3	252	17
406-16-2	2577	5.5	11.0	12.0	12.0	12.0	12.0	12.0	1.2	8.1	252	15*
406-16-3	2577	3.5	7.5	11.0	12.0	11.5	11.5	11.5	1.2	13.4	252	13‡
406-18	2577-P	15.0	18.0	18.0	17.5	17.0	16.5	15.5	1.6	10.1	248	1
B - South Greensburg Coal Mine Water												
406-27	2576	0.1	0.1	0.1	0.1	0.1	0.1	0.8	0.1	4.7	89	89
406-28	2576-P	0.2	0.2	0.2	0.3	0.3	0.4	1.9	0.2	8.9	95	85
406-26	2577	0.1	0.2	0.2	0.5	1.3	2.2	7.0	0.7	6.4	88	6
406-29	2577-P	0.1	0.1	0.2	0.4	0.9	1.8	5.5	0.6	7.6	98	14
C - Thorn Run Coal Mine Water												
406-33	2576	0.9	1.1	1.2	1.3	1.3	1.2	1.1	0.1	48.8	10	46‡
406-30	2576-P	0.6	3.0	3.2	4.0	4.5	4.5	4.6	0.5	26.0	10	8‡
406-34	2577	0.5	15.0	39.0	33.0	26.0	25.0	22.0	2.2	12.5	10	24+
406-31	2577-P	0.2	1.4	7.0	30.0	25.0	24.0	21.8	2.2	11.4	10	7+

* - To check reproducibility
‡ - Sludge aged for 48 hours
** - Final acidity > 300 ppm
+ - Final acidity < 5 ppm

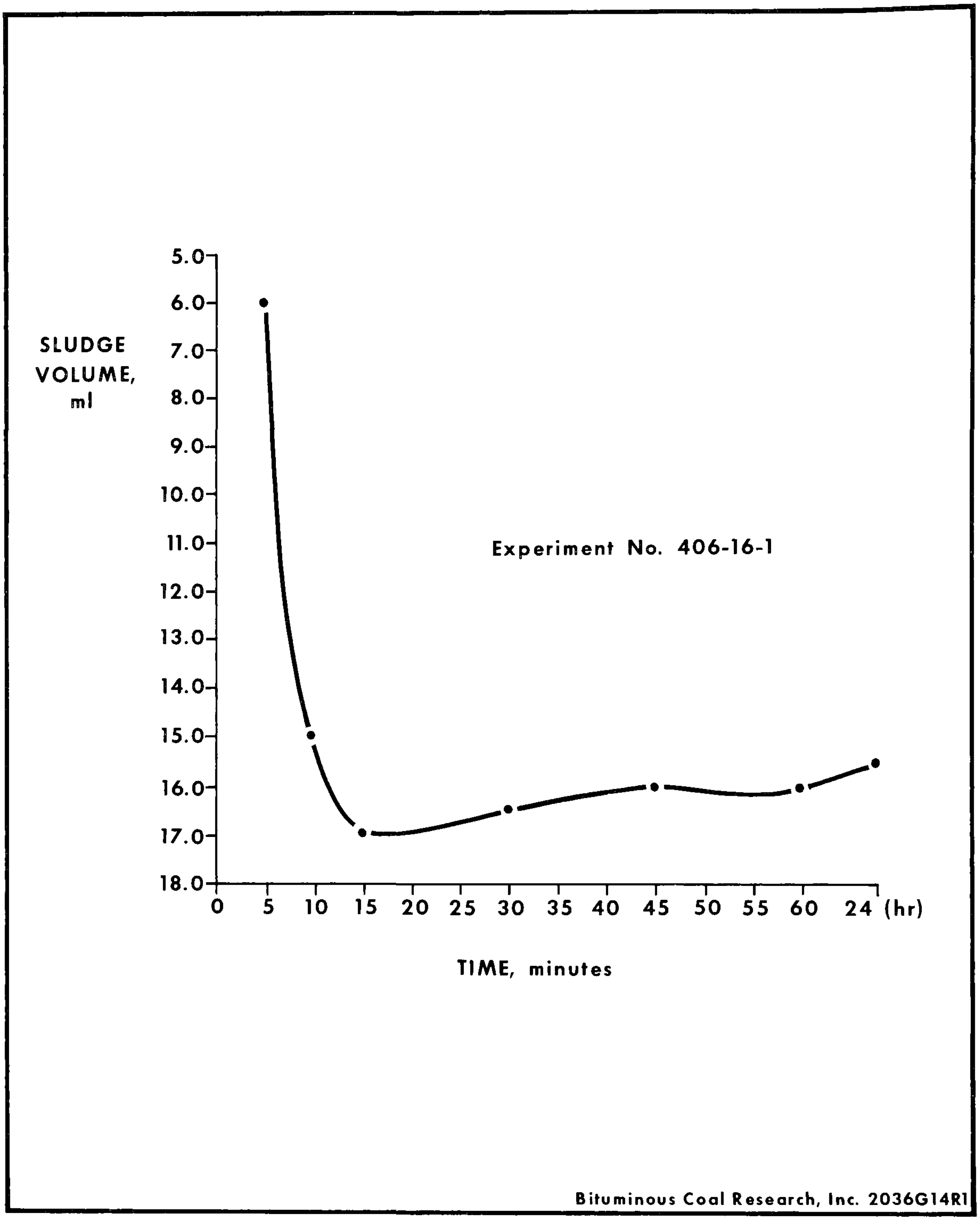


Figure 19. Settling Behavior of Sludge

experiments. Limestone No. 2522-P is from the same source as, and should be reasonably identical to, No. 1809 which has been used exclusively in the continuous flow experiments.

The settling behavior of these sludges can be described by a curve from experiment No. 406-16-1 as presented in Figure 19. The absence of a boundary during settling prevented the measurement of settling rates in the customary manner.

Limestone versus Lime Neutralization--Experiment No. 396-75 was repeated (synthetic coal mine water with limestone No. 2522-P). Initially the synthetic coal mine water contained 230 mg/l of Fe^{2+}, 487 mg/l of acidity as $CaCO_3$, and had a pH of 3.0. After the standard 5-hour batch experiment, the limestone-treated water contained 1 mg/l of Fe^{2+}, minus 20 mg/l of acidity of $CaCO_3$ (denoting alkalinity), and had a pH of 8.0.

Another 1,500 ml portion of the synthetic coal mine water was treated with 1.1 times the stoichiometric amount of lime, $Ca(OH)_2$, based on acidity. The solution was aerated for 30 minutes while being stirred at the same rate as in the limestone batch experiments. At the end of this time the lime-treated water contained 1 mg/l of Fe^{2+}, minus 28 mg/l of acidity as $CaCO_3$ (denoting alkalinity) and had a pH of 7.6.

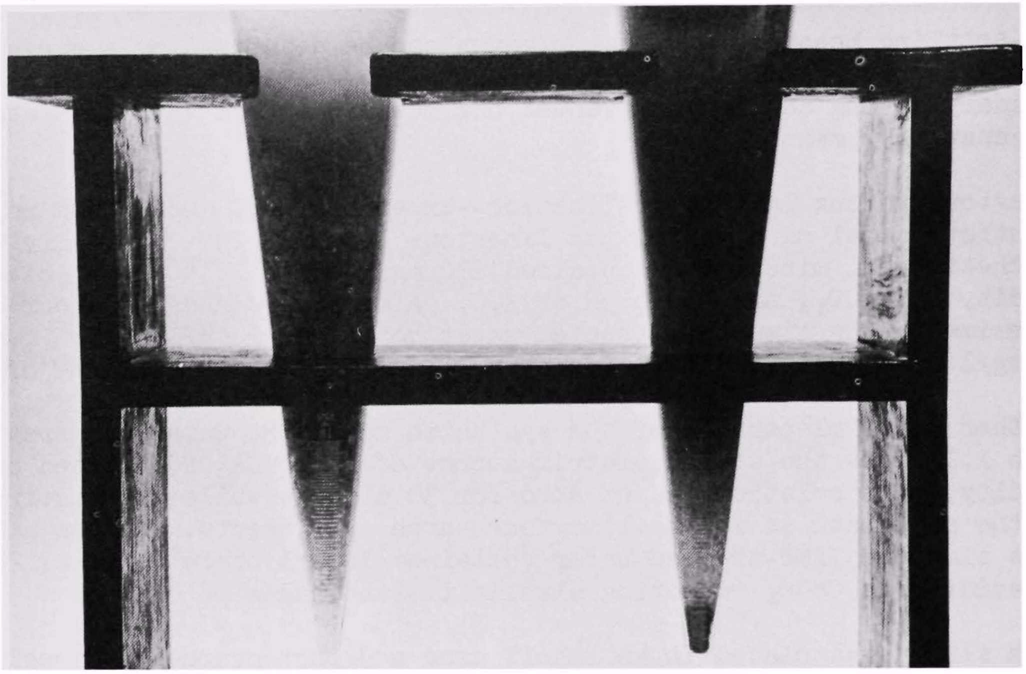
Each slurry was placed in an Imhoff cone and photographed at specific time intervals. After 5 minutes (See Figure 20), some of the more granular particles (probably limestone) had already settled in the Imhoff cone on the right. The lime-treated material in the cone on the left had not yet begun to settle. After 30 minutes (same figure), the bulk of the limestone sludge (cone on the right) had already settled. The water above the sludge was uniformly cloudy (and yellow) at all depths in the cone. The absence of any definite boundary (other than the almost immediate settling of the granular material at the bottom) as the sludge settled is evident in this figure. The sludge from lime treatment (cone on the left) can be seen settling much more slowly with the typical definite boundary between sludge and clear water on top. The atypical settling rate curves can be attributed to the absence of definite boundaries between limestone sludge and supernatant liquid during settling. Figure 19 described settling behavior in a qualitative sense but was not meant to be a settling rate curve.

The next figure, No. 21, shows the settling of both sludges after 1 hour and 1 week. The water above the limestone sludge is still somewhat hazy after 1 hour. After 1 week, the water above each sludge was clear. At the end of this time the volume of the sludge from limestone treatment was 1.2 percent; that from lime treatment was 6.8 percent. The volume of sludge from lime treatment was greater than five times that from limestone treatment.

The solids content of the sludge from limestone treatment was 8.9 percent; that from lime treatment was 0.6 percent. Solid content of the limestone sludge was almost 15 times greater than that from treatment

Five Minutes (2036P8)

Lime Limestone



Thirty Minutes (2036P3)

Lime Limestone

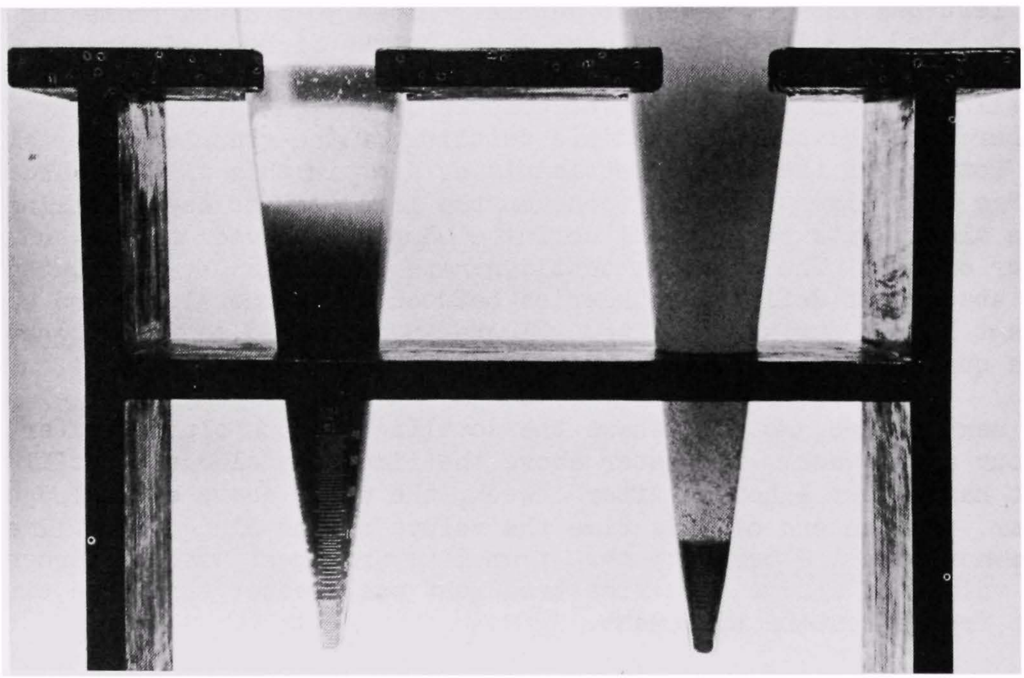
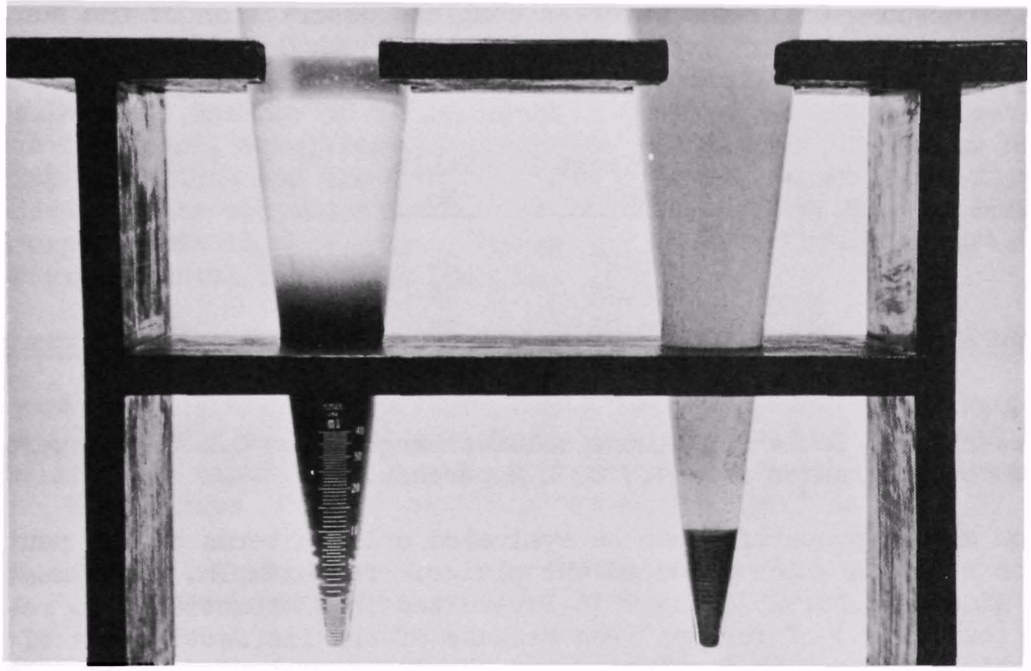


Figure 20. Lime versus Limestone Sludge after Settling for Five Minutes and Thirty Minutes

One Hour (2036P4)

Lime Limestone



One Week (2036P9)

Lime Limestone

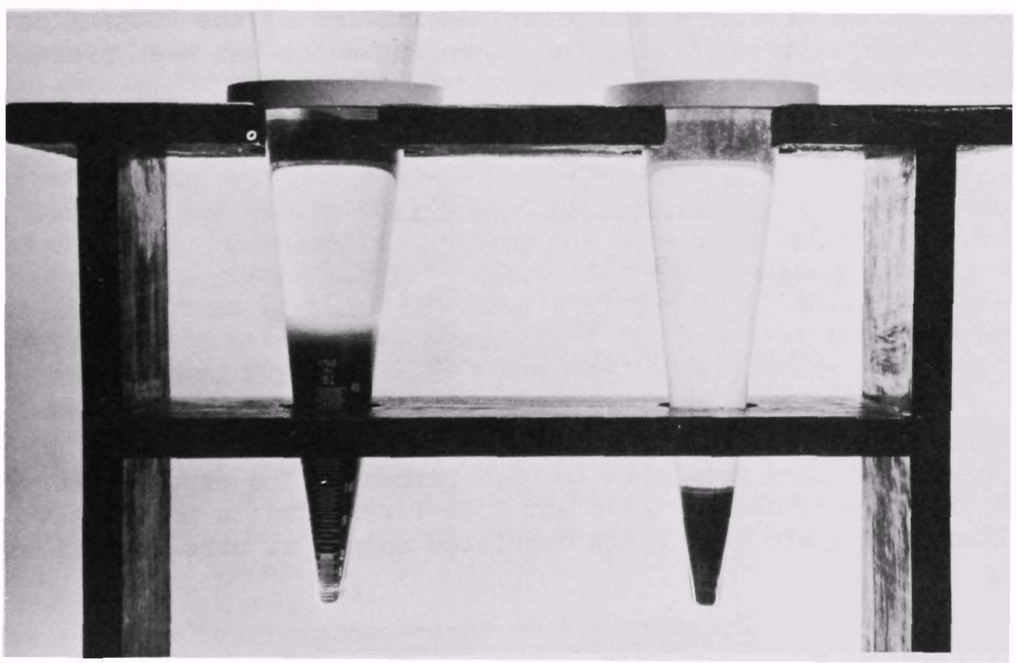


Figure 21. Lime versus Limestone Sludge after Settling for One Hour and One Week

with lime. The quality of the original water being treated was identical in both cases.

South Greensburg Coal Mine Water--A complete description of the neutralization portion of each experiment with the South Greensburg water has been presented in the following tables:

Experiment No.	Table No.
406-27	24
406-28	24
406-26	25
406-29	25

As presented in Table 28, sludge volumes ranged from 0.1 to 0.7 percent; solids content ranged from 4.7 to 8.9 percent.

Data on sludge properties can be evaluated only in terms of the neutralization reaction which produced the sludge. For example, experiments using limestone No. 2576 and 2576-P resulted in substantially no removal (oxidation) of ferrous iron because of the ineffectiveness of the dolomitic limestone in increasing the pH of the coal mine water. In these instances, properties of sludge containing very little material other than limestone are being measured.

Thorn Run Coal Mine Water--A complete description of the neutralization portion of each experiment with the Thorn Run water has been presented in the following tables:

Experiment No.	Table No.
406-33	24
406-30	24
406-34	25
406-31	25

As presented in Table 28, sludge volumes ranged from 0.1 to 2.2 percent; solids content ranged from 11.4 to 48.8 percent. The experiments with the dolomitic limestone No. 2576 and 2576-P resulted in ineffective neutralization; again the sludge consisted mainly of unreacted limestone.

Continuous Flow Experiments

The laboratory pilot plant described in a previous section was utilized to optimize the continuous treatment of acid mine drainage with limestone. Tests were conducted with two actual mine waters--the South Greensburg discharge which contained iron principally in the ferrous,

Fe^{2+}, state, and the Thorn Run discharge which contained iron principally in the ferric, Fe^{3+}, state. BCR limestone No. 1809 (minus 325 mesh), since the evaluation of limestones had shown it to be one of the most effective neutralizing agents, was employed in all cases. Variables studied were the amount of limestone, flow rate, aeration, order of mixing and aeration (sequence of unit operations), and sludge recirculation. Because of the numerous conditions studied in continuous treatment, involving primarily the sequence of the mixing and aerating operations and the specific tank to which recirculated slurry was added, a thorough understanding of the nomenclature used to describe these experiments is necessary. The system of nomenclature is detailed in the experimental section on page 22.

No Slurry Recirculation: Effect of Flow Rate and Amount of Limestone

Flow rates of 0.5 and 1.0 gpm each, using twice (2X) and four times (4X) the stoichiometric amount of limestone, were employed in four 1N-2A continuous flow experiments involving treatment of South Greensburg water. The results of these experiments are presented in Table 29.

Although the pH of the raw mine water increased, essentially no decrease in the Fe^{2+} concentration was observed during the initial 50-minute batch mixing period in the limestone reactor.

The decrease in both pH and Fe^{2+} concentration after 30 minutes in the settling tank under quiescent conditions without aeration indicates that oxidation of Fe^{2+} was still occurring after treatment in all cases. In at least one case, (Experiment No. 402-5), however, the Fe^{2+} concentration in the settling tank reached a value of 30 mg/l within 24 hours, and did not decrease further over an additional 3-day period.

Doubling the amount of limestone employed had a more pronounced effect on the efficiency of iron removal than did halving the flow rate, i.e., doubling the theoretical detention time in the limestone reactor to 100 minutes. For example, halving the flow rate resulted in a 1.17-fold increase in percentage Fe^{2+} removed during treatment at both the 2X and 4X limestone levels. Doubling the amount of limestone led to a nearly 3-fold increase in percentage Fe^{2+} removed; the actual percentage increases were 2.95 and 2.94 times the initial values at flow rates of 0.5 and 1.0 gpm, respectively. The nearly perfect agreement between these factors in each case may be fortuitous, especially since in some instances the experimental conditions necessitated operating the limestone feeder near its lower limit. In fact, for the test with 2X limestone and a flow rate of 0.5 gpm, the calculated feed rate could be attained only by operating the feeder on a 5-minute on-off cycle.

The increased effectiveness of iron removal when 4X limestone was used probably cannot be attributed to the slightly higher pH as compared to the test with 2X limestone (See Table 29). One possibility is that some Fe^{2+} was adsorbed on the surface of the excess limestone.

TABLE 29. EFFECT OF FLOW RATE AND AMOUNT OF LIMESTONE ON CONTINUOUS FLOW TREATMENT OF SOUTH GREENSBURG COAL MINE WATER NO SLURRY RECIRCULATED

Conditions of Experiment* Experiment No.	1N-2A 402-5 2X limestone, 1.0 gal/min‡		1N-2A 402-4 2X limestone, 0.5 gal/min‡		1N-2A 402-6 4X limestone, 1.0 gal/min‡		1N-2A 402-7 4X limestone, 0.5 gal/min‡	
Sampling Point	pH	Fe^{2+}†	pH	Fe^{2+}†	pH	Fe^{2+}†	pH	Fe^{2+}†
Raw mine water	5.2	84	5.5	82	5.5	66	5.6	63
Limestone reactor effluent after batch mixing period	6.2	82	6.4	82	6.5	64	6.7	58
Aeration tank effluent after:								
Initial filling period	6.6	78	6.6	71	6.5	--	6.8	35
60 min flow after filling was completed	6.6	70	6.6	66	6.8	40	6.8	30
Contents of settling tank 30 min after flow ceased	6.2	69	6.4	65	6.5	31	6.6	24
Percent Fe^{2+} removed during treatment**	18		21		53		62	

* Limestone reactor = 1; Aeration tank = 2; No aeration in the tank specified = N; Aeration in the tank specified = A. Therefore, 1A-2A specifies a limestone reactor to aeration tank sequence with aeration carried out in both tanks.

† All Fe^{2+} concentrations are expressed as milligrams per liter (mg/l).

** Based on analyses of samples from settling tank 30 min after flow ceased.

‡ Detention time at 1.0 gal/min = 50 min; at 0.5 gal/min = 100 min

The most significant fact is that iron removals achieved in each of the four experiments can not be considered satisfactory. The results indicate that, at least for this particular coal mine water, simple "one pass" limestone treatment with aeration is not feasible using limited amounts of limestone and retention times. This finding is in agreement with our earlier observations (1) regarding continuous flow limestone neutralization of coal mine water containing iron principally in the ferrous state.

No Slurry Recirculation: Effect of Aeration and Sequence of Unit Operations

In most of the following experiments the sequence of operations as described in the general procedure was not followed. This variation necessitated the system of nomenclature used to illustrate the experimental conditions in each test. Twice the stoichiometric amount of limestone was employed in this series of tests.

Aeration was carried out before and/or after addition of limestone in eight experiments. The South Greensburg water was treated at a rate of flow of 1.0 gpm in each case. The results of these experiments are summarized in Table 30. That the results are reproducible can be seen by the results of duplicate experiments listed in this table. Duplicate experiments were conducted at random in all other series of experiments but are not included in this report. They, too, showed that the results of these experiments are, in fact, reproducible.

Experiments 1N-2A. Two identical experiments were conducted using these conditions. This is essentially the general procedure followed in past experiments. Ferrous iron was removed as effectively as in past tests.

Experiment 1A-2N. No advantage was gained by aerating and mixing with limestone at the same time.

Experiments 1A-2A. Two identical experiments were conducted. No advantage was gained in removal of iron by aerating and mixing with limestone followed by another aeration step. Final pH (after 24 hr) was slightly higher than with no second aeration step.

Experiments 2A-1A. In two identical experiments, the mine water was aerated prior to and during mixing with limestone. The percentage of ferrous iron removed was essentially double that of the other experiments reported here. (See last line, Table 30.)

Experiment 2A-1N. Again the mine water was aerated prior to mixing with limestone; this time, though, there was no aeration during the second step, mixing with limestone. The percentage of ferrous iron removal was still substantially doubled by the preaeration step even without subsequent aeration.

TABLE 30. EFFECT OF AERATION AND SEQUENCE OF UNIT OPERATIONS ON CONTINUOUS FLOW TREATMENT OF SOUTH GREENSBURG COAL MINE WATER

Conditions of Experiment*	1N-2A		1N-2A		1A-2N		1A-2A		1A-2A		2A-1A		2A-1A		2A-1N	
Experiment No.	402-8		402-17		402-9		402-11		402-12		402-14		402-16		402-15	
Sampling Point	pH	Fe^{2+} ‡	pH	Fe^{2+} ‡	pH	Fe^{2+} ‡	pH	Fe^{2+} ‡	pH	Fe^{2+} ‡	pH	Fe^{2+} ‡	pH	Fe^{2+} ‡	pH	Fe^{2+} ‡
Raw mine water	5.0	91	5.2	72	5.1	82	5.4	58	5.2	40	5.2	64	5.0	73	5.2	73
Tank used in "first unit operation" after batch mixing period	6.2	86	6.4	68	6.6	70	6.8	50	6.5	30	6.1	62	5.5	74	5.8	73
Effluent from "second unit operation" after:																
Initial filling period before start to flow	6.5	78	6.8	69	6.5	74	6.8	48	6.6	32	6.7	51	6.4	64	6.7	64
60 min after start of flow conditions	6.6	80	6.8	68	6.6	79	6.8	40	6.7	29	6.6	42	6.7	48	6.5	56
Contents of settling tank 24 hr after flow ceased	6.1	59	6.3	39**	6.5	55	6.7	37	6.7	27	6.4	20	6.4	22	6.3	27
Percent Fe^{2+} removed during treatment	35		46		33		36		32		69		70		63	

* Limestone reactor = 1; Aeration tank = 2; No aeration in the tank specified = N; Aeration in the tank specified = A. Therefore, 1A-2A specifies a limestone reactor to aenation tank sequence with aeration carried out in both tanks.

‡ All Fe^{2+} concentrations are expressed as milligrams per liter (mg/l).

** Contents of settling tank after week end (approximately 64 hr).

In none of the experiments described above was the iron removal satisfactory; therefore, the acidity value was not determined for this series.

An improvement, however, was seen in iron removal by the data from experiments involving an aeration step prior to mixing the mine water with limestone. The experiments with and without the preaeration step are compared in Figure 22.

<u>Slurry Recirculation: Effect of Flow Rate and Aeration in Only One Tank</u>

The results of the first series of experiments designed to examine the effect of slurry recirculation on pH, iron content, and acidity are summarized in Table 31. The pH of the South Greensburg discharge, used in almost all of the slurry recirculation experiments, ranged from 5.0 to 5.3; the ferrous iron concentration ranged from 61 to 90 mg/l, and the acidity value as $CaCO_3$ equivalents ranged from 140 to 184 mg/l. The raw water was treated at a flow rate of 0.5 gpm. Slurry from a previous experiment was stirred and the entire mass (sludge + treated water) added to the tank specified at a rate of 0.5 gpm. In each test, twice the stoichiometric amount of limestone was employed.

Experiment 1N-2A(S). In a typical experiment, 85 percent of the ferrous iron was removed compared to 35 percent ferrous iron removed during a similar experiment without slurry recirculation. Little or no residual acidity was found in the effluent.

Experiment 1N(S)-2A. Adding the slurry to the first unit operation resulted in slightly improved ferrous iron removal--92 percent as compared to 85 percent in the previous experiment 1N-2A(S).

Experiment 2A-1N(S). Aerating the raw mine water followed by mixing with slurry and limestone gave results similar to the previous experiment 1N(S)-2A. These were the two most effective treatments in this series.

Experiment 2A(S)-1N. Less effective treatment was obtained from this experiment in which the slurry was added to the raw mine water while aerating, followed by mixing with limestone.

In general, recirculation of slurry improved the effectiveness of limestone treatment as shown by pH and percent ferrous iron removed from the raw coal mine water. Residual acidity in the effluent in this series of experiments was negligible. (See Table 30, this report, for a comparison with similar experiments involving no slurry recirculation.)

In the next experiments, with slurry recirculation and aeration in only one tank, the raw water was treated and the slurry added to the tank specified, both at 1.0 gpm. The results of these experiments are summarized in Table 32. Also included in this table for comparison are

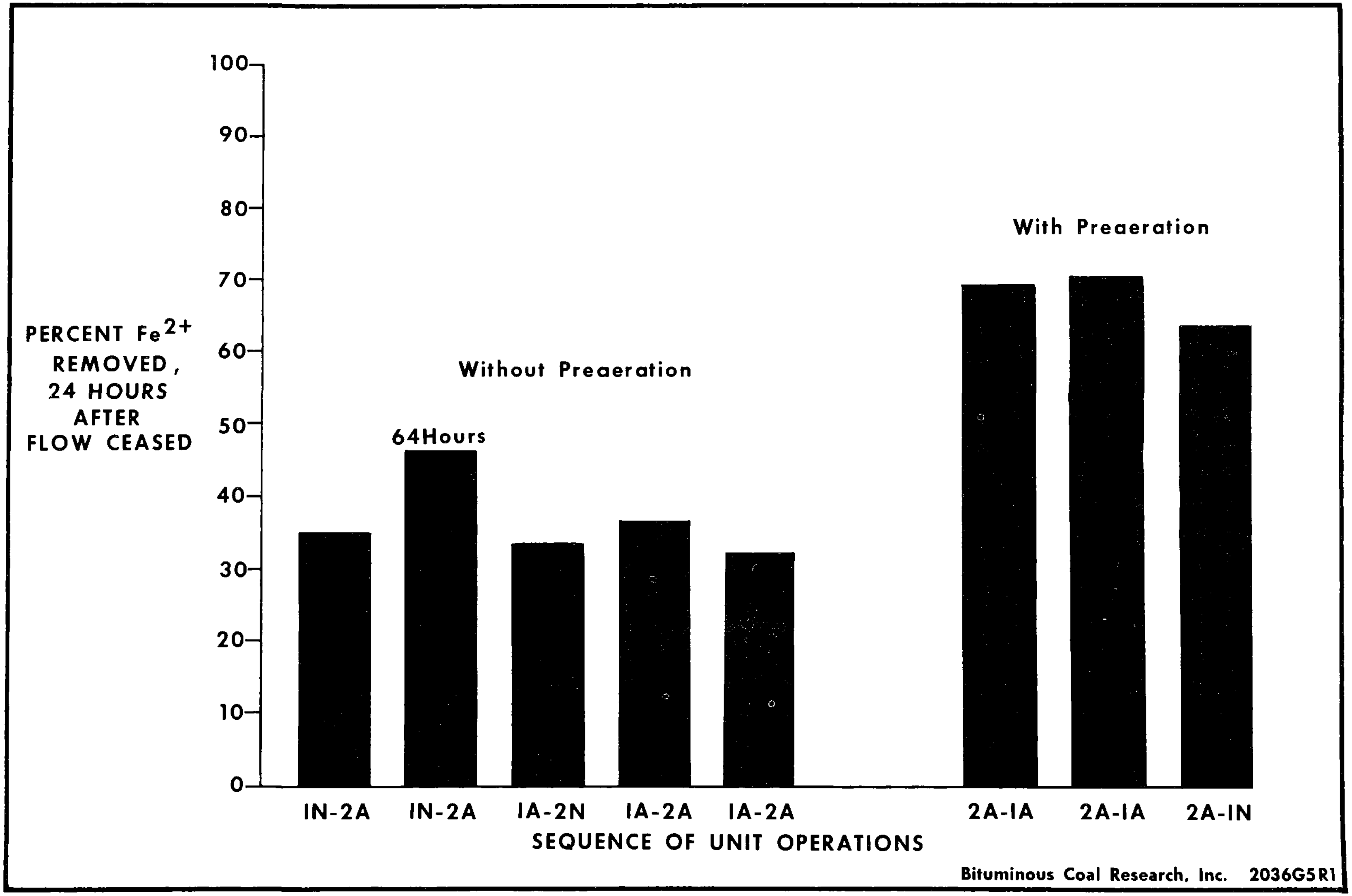


Figure 22. Effect of Aeration and Sequence of Unit Operations on Continuous Flow Treatment of South Greensburg Coal Mine Water

TABLE 31. EFFECT OF SLURRY RECIRCULATION AND AERATION IN ONE TANK ON CONTINUOUS FLOW TREATMENT OF SOUTH GREENSBURG COAL MINE WATER

Conditions of Experiment* Experiment No.	1N-2A(S) 402-34		1N(S)-2A 402-21		2A-1N(S) 402-32		2A(S)-1N 402-29	
Sampling Point	pH	Fe^{2+} ‡	pH	Fe^{2+} ‡	pH	Fe^{2+} ‡	pH	Fe^{2+} ‡
Raw mine water	5.2	75	5.2	79	5.0	88	5.1	81
Tank used in "first unit operation" after batch mixing period	6.3	75	6.5	48	5.4	82	6.4	36
Effluent from "second unit operation" after:								
Initial filling period before start of flow	6.9	31	6.9	46	6.8	28	6.6	31
60 min after start of flow conditions	6.9	26	6.6	36	6.7	23	6.6	33
Contents of settling tank 24 hr after flow ceased	6.4	11	6.5	6	6.6	6	6.2	16
Percent Fe^{2+} removed during treatment	85		92		93		80	
Acidity‡ of contents of settling tank 24 hr after flow ceased	+2		+6		-7		+16	

* Limestone reactor = 1; Aeration tank = 2; No aeration in the tank specified = N. Aeration in the tank specified = A; Recirculated slurry added to the tank specified = (S). Therefore, 1N(S)-2A specifies a limestone reactor to aeration tank sequence with slurry added to the limestone reactor and aeration only in the aeration tank.

‡ All Fe^{2+} concentrations and acidity (as CaCO equivalents) expressed as milligrams per liter (mg/l).

TABLE 32. EFFECT OF FLOW RATE AND AERATION IN ONE TANK ON CONTINUOUS FLOW TREATMENT OF SOUTH GREENSBURG COAL MINE WATER

Conditions of Experiments*	Experiment Number	Total Flow Rate gpm†	Initial			Final			Percent Fe^{2+} Removed
			pH	Fe^{2+}‡	Acidity‡	pH	Fe^{2+}‡	Acidity‡	
1N-2A(S)	402-65	2.0	4.8	99	199	6.3	22	30	78
	402-34	1.0**	5.2	75	144	6.4	11	2	85
1N(S)-2A	402-66	2.0	4.9	91	199	6.4	23	25	75
	402-67	2.0	4.9	91	202	6.4	34	32	63
	402-21	1.0**	5.2	79	159	6.5	6	6	92
2A-1N(S)	402-71	2.0	4.9	74	200	6.1	37	16	50
	402-32	1.0**	5.0	88	162	6.6	6	-7	93

*See Table 31 for labeling system.

**Experiments at 1.0 gal/min were first described in Table 31.

‡All Fe^{2+} concentrations and acidity (as $CaCO_3$ equivalents) expressed as milligrams per liter (mg/l).

†Detention time at 2.0 gal/min = 25 min; at 1.0 gal/min = 50 min

the results from the experiments with the same sequence of operations but a flow rate of raw water and slurry of 0.5 gpm each (See Table 31). In all cases, the lower flow rate of 0.5 gpm and, therefore, longer detention (reaction) times resulted in a lower level of Fe^{2+} remaining in the treated water (effluent); at a flow rate of 1.0 gpm, the lowest level of Fe^{2+} attained in the effluent was 22 mg/l (experiment No. 402-65, a 1N-2A(S) experiment). A pH greater than 6.0 was always realized along with a very low level of acidity. The most satisfactory treatment occurred when the flow rate was 0.5 gpm.

Slurry Recirculation: Effect of Flow Rate and Aeration in Two Tanks

The second series of experiments with slurry recirculation was conducted to examine the effect of aeration during two unit operations. The South Greensburg water was treated at a rate of flow of 0.5 gpm and the slurry added to the tank specified at a rate of flow of 0.5 gpm. In each test, twice the stoichiometric amount of limestone was employed. The results are summarized in Table 33.

Experiment 1A-2A(S). Aerating while mixing the raw mine water with limestone in the limestone reactor, and aerating again while mixing the recirculated slurry with raw mine water containing limestone in the aeration tank, resulted in the most effective treatment with limestone thus far. Only 4 mg/l (5 percent) of ferrous iron remained, with no residual acidity in the effluent.

Experiment 1A(S)-2A. Introducing the slurry to the first unit operation in this experiment gave results comparable to those achieved in the previous experiment 1A-2A(S).

Experiment 2A-1A(S). The treatment conditions specified in this experiment also resulted in effective treatment.

Experiment 2A(S)-1A. The conditions specified in this experiment resulted in slightly less effective treatment than the other three experiments in this series. Even with the less effective treatment, ferrous iron concentration in the effluent was only 7 mg/l. There was a slight (+22 mg/l) residual acidity.

Aeration during two unit operations along with recirculation of slurry has resulted in the most effective treatment thus far. This double aeration might be acceptable as part of a treatment process since it would effect a reduction in the holding times required in the limestone reactor and aeration tanks.

In the next experiments with slurry recirculation and aeration in two tanks, the raw water was treated and the slurry recirculated at a rate of flow of 1.0 gpm each. Detention time at 2.0 gpm flow was 25 min. The results are summarized in Table 34. Also included in this table for comparison are the results from the experiments with the

TABLE 33. EFFECT OF SLURRY RECIRCULATION AND AERATION IN TWO TANKS ON CONTINUOUS FLOW TREATMENT OF SOUTH GREENSBURG COAL MINE WATER

Conditions of Experiment* / Experiment No.	1A-2A(S) 402-39**		1A(S)-2A 402-38**		2A-1A(S) 402-36**		2A(S)-1A 402-37**	
Sampling Point	pH	Fe^{2+} ‡	pH	Fe^{2+} ‡	pH	Fe^{2+} ‡	pH	Fe^{2+} ‡
Raw mine water	5.1	76	5.2	77	5.1	74	5.3	74
Tank used in "first unit operation" after batch mixing period	6.6	67	6.7	27	6.1	74	6.6	30
Effluent from "second unit operation" after:								
Initial filling period before start of flow	6.7	19	6.7	20	6.8	25	6.7	26
60 min after start of flow conditions	6.7	15	6.7	17	6.8	22	6.8	21
Contents of settling tank 24 hr after flow ceased	6.6	4	6.6	4	6.4	6	6.4	7
Percent Fe^{2+} removed during treatment	95		95		92		90	
Acidity‡ of contents of settling tank 24 hr after flow ceased	-3		+7		-2		+22	

* See Table 31 for labeling system.

‡ All Fe^{2+} concentrations and acidity (as $CaCO_3$ equivalents) expressed as milligrams per liter (mg/l).

** Detention time = 50 min

TABLE 34. EFFECT OF FLOW RATE AND AERATION IN TWO TANKS ON CONTINUOUS FLOW TREATMENT OF SOUTH GREENSBURG COAL MINE WATER

Conditions of Experiment*	Experiment Number	Total Flow Rate gpm‡	Initial			Final		
			pH	Fe^{2+} ‡	Acidity‡	pH	Fe^{2+} ‡	Acidity‡
1A-2A(S)	402-68	2.0	4.9	100	198	6.4	20	20
	402-69	2.0	4.9	100	205	6.3	11	4
	402-74	2.0	5.0	101	209	6.5	17	5
	402-39	1.0**	5.1	76	146	6.6	4	-3
1A(S)-2A	402-70	2.0	4.9	101	203	6.2	6	62
	402-75	2.0	4.8	103	210	6.4	19	-1
	402-38	1.0**	5.2	77	146	6.6	4	7
2A-1A(S)	402-73	2.0	4.9	84	210	6.0	21	21
	402-36	1.0**	5.1	74	160	6.4	6	-2
2A(S)-1A	402-76	2.0	4.9	100	218	6.3	9	11
	402-37	1.0**	5.3	74	148	6.4	7	22

*See Table 31 for labeling system.

**Experiments at 1.0 gal/min were first described in Table 33.

‡All Fe^{2+} concentrations and acidity (as $CaCO_3$ equivalents) expressed as milligrams per liter (mg/l).

‡Detention time at 2.0 gal/min = 25 min; at 1.0 gal/min = 50 min

same sequence of operations but a flow rate of raw water and slurry of 0.5 gpm each for a detention time of 50 min (See Table 33). Again, in almost all cases the lower flow rate of 0.5 gpm and, therefore, longer detention (reaction) times resulted in a lower level of Fe^{2+} remaining in the effluent; at a flow rate of 1.0 gpm, a level of Fe^{2+} of as low as 6 mg/l was attained (experiment No. 402-70, a 1A(S)-2A experiment). Conditions 2A(S)-1A (experiment No. 402-76) also resulted in a low level (9 mg/l) of Fe^{2+} in the effluent. A low level of acidity and a pH of at least 6.0 were always attained.

Slurry Recirculation: Effect of 4X the Stoichiometric Amounts of Limestone

In the third series of slurry recirculation experiments, the effect of aerating during one unit operation, adding four times (4X) the stoichiometric amount of limestone based on acidity, and/or using recirculated slurry produced during a 4X limestone experiment was examined. The rate of flow of the treated water and the slurry was each 0.5 gpm for a total flow of 1.0 gpm. The results are summarized in Table 35.

Experiments 1N(S)-2A and 2A(S)-1N. In these experiments, four times the stoichiometric amount of limestone based on acidity was used. The recirculated slurry was produced from previous experiments with twice the stoichiometric amount of limestone. In both cases, the ferrous iron content in the effluent was at the lowest point attained with any experiments utilizing the continuous flow system. The excess amount of limestone is apparent from the negative acidity values, denoting alkalinity. The excess limestone was beneficial, even more so than in previous experiments involving no slurry recirculation (See experiments No. 402-6 and 402-7, Table 29).

Experiments 1N(S)-2A and 2A-1N(S). In both these experiments, twice the stoichiometric amount of limestone was used, but the slurry recirculated was from experiments with four times the stoichiometric amount of limestone. In the 1N(S)-2A experiment, iron removal was satisfactory and the residual acidity in the effluent only slight. In the 2A-1N(S) experiment, however, only 82 percent of the ferrous iron was removed; the residual acidity in the effluent was still +109 mg/l. This was the only experiment in this series in which the slurry was added to the second unit operation; therefore, the need is clear for introducing the slurry as early as possible in the treatment process to achieve maximum benefit from sludge recirculation where aeration is not carried out in both tanks.

Experiment 2A(S)-1N. In this experiment, (a) limestone was added at a rate of four times the stoichiometric amount, and (b) the slurry recirculated was that from an experiment with four times the stoichiometric amount of limestone. Under what may be described as extraordinary conditions, essentially all (99 percent) of the ferrous iron was removed. The negative acidity of the effluent denotes alkalinity.

TABLE 35. EFFECT OF SLURRY RECIRCULATION AND 4X THE STOICHIOMETRIC AMOUNT OF LIMESTONE ON CONTINUOUS FLOW TREATMENT OF SOUTH GREENSBURG COAL MINE WATER

Conditions of Experiment*	1N(S)-2A†		1N(S)-2A**		2A(S)-1N†		2A-1N(S)**		2A(S)-1N#	
Experiment No.	402-22		402-25		402-23		402-26		402-24	
Sampling Point	pH	Fe^{2+} ‡	pH	Fe^{2+} ‡	pH	Fe^{2+} ‡	pH	Fe^{2+} ‡	pH	Fe^{2+} ‡
Raw mine water	5.1	90	5.0	84	5.0	81	5.1	79	5.0	79
Tank from "first unit operation" after batch mixing period	6.5	51	6.6	38	6.6	45	5.6	81	6.6	31
Effluent from "second unit operation" after:										
Initial filling period before start of flow	6.8	42	6.7	25	6.7	31	6.6	36	6.8	21
60 min after start of flow conditions	6.8	39	6.7	23	6.7	22	6.7	31	6.8	14
Contents of settling tank 24 hr after flow ceased	7.0	1	6.5	3	6.6	3	6.4	14	7.0	1
Percent Fe^{2+} removed during treatment	99		96		96		82		99	
Acidity‡ of contents of settling tank 24 hr after flow ceased	-191		+10		-109		+109		-115	

* See Table 31 for labeling system.
† 4X limestone.
** 2X limestone with slurry from 4X limestone experiment.
\# 4X limestone with slurry from 4X limestone experiment.
‡ All Fe^{2+} concentrations and acidity (as $CaCO_3$ equivalents) expressed as milligrams per liter (mg/l).

Even with the excess amount of limestone used in the experiments, there would have been no harmful effect on the stream receiving this effluent. The pH remained at 7 or less under conditions which simulated an accidental overtreatment.

Slurry Recirculation: Effect of Volume Recirculated

In this series of experiments, the amount (volume) of slurry recirculated and mixed with the raw mine water was varied. The South Greensburg water was treated and the slurry recirculated each at a rate of flow of 0.5 gpm each. The results are summarized in Table 36. Experiment No. 402-21 from Table 31 is included for comparison.

Experiments 1N(S)-2A. In two experiments, the amount (volume) of sludge recirculated and mixed with raw mine water was reduced from the customary 1:1 ratio of raw water to slurry, as in past experiments, to 3:2 to 3:1. In these experiments the slurry was introduced into the limestone reactor tank. There is a direct relationship between the amount (volume) of slurry used and the effectiveness of ferrous iron removal and neutralization, as evidenced by acidity. This can be seen in Table 36 and in Figure 23. As the amount of slurry mixed with the raw mine water is increased, there is a corresponding decrease in ferrous iron concentration and acidity in the effluent. For maximum benefit in the treatment of this particular water, it was necessary to add a volume of slurry at least equal to the volume of mine water being treated.

The amount of slurry recirculated in the next series was twice that of the raw water. Again, the South Greensburg water was treated at a rate of flow of 0.5 gpm and the slurry recirculated at 1.0 gpm. Data from these four experiments are summarized in Table 37. Treatment, as judged by pH, Fe^{2+} and acidity, was most effective in all cases. The combination of long detention time and greater volume of slurry than used in past experiments resulted in negative acidities, denoting alkalinity in all cases.

Limestone Treatment of Thorn Run Coal Mine Water

In the first two experiments, no slurry was recirculated through the system during treatment. The raw mine water had a pH of 2.8 and contained the following (in mg/l): Fe^{2+}, 21; acidity, 995; Fe_T, 138; Al, 72; Mn, 11; Ca, 135; Mg, 58; and Si, 19.

In the first experiment the water was treated at a rate of 1.0 gpm. The results of this experiment, No. 402-88, are summarized in Table 38. The effluent had a pH of 6.2 and contained the following (in mg/l): Fe^{2+}, 3; acidity, -85 (alkalinity); Fe_T, 5; Al, < 2; Mn, 11; Ca, 590; Mg, 70; and Si, 18. Treatment was most effective.

TABLE 36. EFFECT OF THE VOLUME OF SLURRY RECIRCULATED ON CONTINUOUS FLOW TREATMENT OF SOUTH GREENSBURG COAL MINE WATER

Conditions of Experiment* / Experimental No. / Raw Mine Water: Slurry Ratio	1N(S)-2A / 402-41 / 3:1		1N(S)-2A / 402-42 / 3:2		1N(S)-2A / 402-21 / 1:1	
Sampling Point	pH	Fe^{2+}‡	pH	Fe^{2+}‡	pH	Fe^{2+}‡
Raw mine water	5.1	61	5.0	71	5.2	79
Tank from "first unit operation" after batch mixing period	6.4	49	6.6	41	6.5	48
Effluent from "second unit operation" after:						
Initial filling period before start of flow	6.8	49	6.8	36	6.9	46
60 min after start of flow conditions	6.7	40	6.8	36	6.6	36
Contents of settling tank 24 hr after flow ceased	6.5	31	6.4	15	6.5	6
Percent Fe^{2+} removed during treatment	49		79		92	
Acidity‡ of contents of settling tank 24 hr after flow ceased	+46		+22		+ 6	

*See Table 31 for labeling system.
‡All Fe^{2+} concentrations and acidity (as $CaCO_3$ equivalents) expressed as milligrams per liter (mg/l).

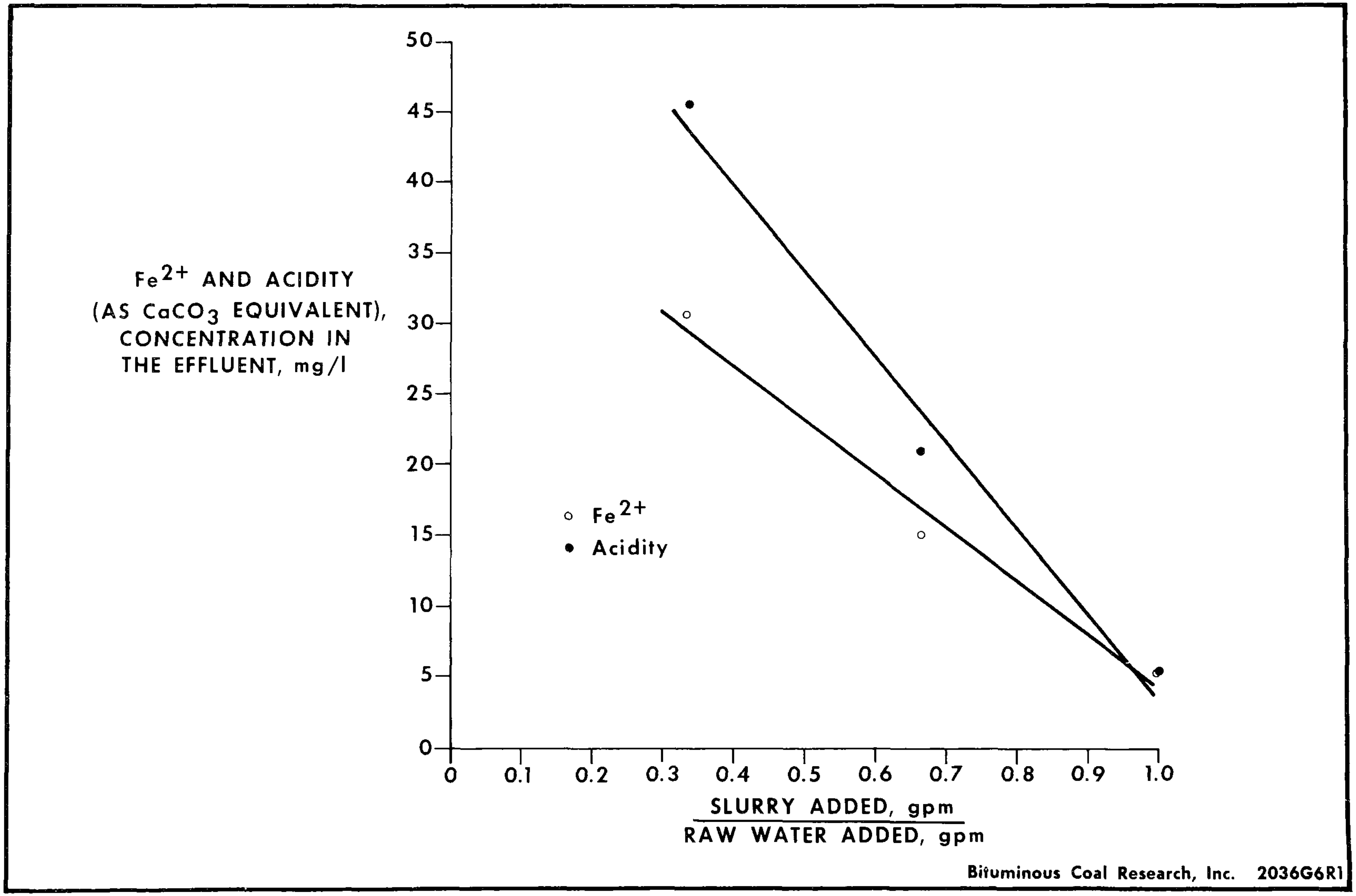


Figure 23. Effect of Volume of Slurry Recirculated on Continuous Flow Treatment of South Greensburg Coal Mine Water

TABLE 37. EFFECT OF VOLUME OF SLURRY RECIRCULATED ON CONTINUOUS FLOW TREATMENT OF SOUTH GREENSBURG COAL MINE WATER

Conditions of Experiment*	Experiment Number	Raw Water Flow Rate, gpm	Recirculated Slurry, gpm	Initial			Final		
				pH	Fe^{2+}‡	Acidity‡	pH	Fe^{2+}‡	Acidity‡
1A(S)-2A	402-77	0.5	1.0	4.8	73	228	6.3	7	-2
1A(S)-2A	402-78	0.5	1.0	4.7	100	225	6.6	1	-23
1A-2A(S)	402-79	0.5	1.0	4.7	105	225	7.0	1	-21
2A-1A(S)	402-80	0.5	1.0	4.6	90	221	6.7	7	-21

*See Table 31 for labeling system.

‡All Fe^{2+} concentrations and acidity (as $CaCO_3$ equivalents) are expressed as milligrams per liter (mg/l).

TABLE 38. CONTINUOUS FLOW TREATMENT OF THORN RUN COAL MINE WATER

Conditions of Experiment*	Experiment Number	Raw Water Flow Rate, gpm	Recirculated Slurry gpm	Initial			Final		
				pH	Fe^{2+}‡	Acidity‡	pH	Fe^{2+}‡	Acidity‡
2A-1N	402-88	1.0	none	2.8	21	995	6.2	3	-85
2A-1N	402-89	2.0	none	2.5	37	998	5.2	9	-50
2A-1N(S)	402-90	1.0	1.0	2.4	34	1049	7.1	4	-15

*See Table 31 for labeling system.

‡All Fe^{2+} concentrations and acidity (as $CaCO_3$ equivalents) are expressed as milligrams per liter (mg/l).

In the second experiment, (No. 402-89) the flow rate was increased to 2.0 gpm. The acidity was again negative, denoting alkalinity, and the Fe^{2+} concentration was at a low level; however, final pH was only 5.2. Detention times in this experiment would be only 25 minutes (2.0 gpm, 50 gallon reactor tank).

In the final experiment (No. 402-90), slurry was recirculated. The flow of water being treated and the slurry being recirculated were each 1.0 gpm. The effluent at a pH of 7.1, 4 mg/l of Fe^{2+} and a negative acidity reflects this as the most effective treatment.

Sludge Properties

Properties of sludge formed during selected continuous flow experiments with the South Greensburg and Thorn Run waters were measured. These experiments involved both slurry recirculation and no slurry recirculation.

South Greensburg Coal Mine Water: No Slurry Recirculation--No. 402-85 was a typical 2A-1A experiment with the South Greensburg water involving no slurry recirculation. That this experiment resulted in essentially ineffective neutralization and ferrous iron removal can be seen by the data in Table 39, particularly the residual 73 mg/l of Fe^{2+} at the end of the experiment (See No. 402-85-2). After 8 days, residual Fe^{2+} was about 1 mg/l. These data were used in Figure 24 to show the effect of aging of sludge on solids content. Generally, solids content increased with aging. There seemed to be a difference in solids content depending on whether the sludge was allowed to "age" in the settling tanks or in the Imhoff cone (See No. 402-85-6). A relatively large decrease in solids content of the sludge was effected by aerating a portion of the sludge again 15 days after the experiment (See No. 402-85-5).

Thorn Run Coal Mine Water: No Slurry Recirculation--Experiments No. 402-88 and 402-89 have been described in Table 38. The data on sludges from these experiments are listed in Table 39. Again, as in Table 28, which summarizes the data from the batch experiments with Thorn Run and the finely divided limestones, the data show the relatively high solids content of the sludge from treatment of this water with limestone, even though no slurry was recirculated in any of these experiments with the Thorn Run coal mine water.

South Greensburg Coal Mine Water: Slurry Recirculation--Experiment No. 402-80 has been described in Table 37. The data on sludge from this experiment, as listed in Table 40, show about the same solids content as a sludge prepared in an experiment in which slurry was not recirculated (See, for example, experiment No. 402-85-2, Table 39).

No. 402-87-7 was a 2A-1N(S) experiment. Sludge solids content, as listed in Table 40, was 6.5 percent and increased to 7.3 percent after aging the sludge for 24 hours.

TABLE 39. PROPERTIES OF SLUDGE FORMED IN CONTINUOUS FLOW EXPERIMENTS WITH NO SLURRY RECIRCULATED

Experiment Number	Volume of Sludge, ml 5 min	10 min	15 min	30 min	45 min	60 min	24 hr	Sludge Volume Percent 24 hr	Solids Content Percent 24 hr	Experimental* Conditions	Comments
A. South Greensburg Coal Mine Water											
402-85-2	0.3	1.3	2.5	3.0	3.5	4.0	5.0	0.5	6.0	2A-1A	73 mg/l residual Fe^{2+}
402-85-3	0.0	0.0	0.1	0.7	1.5	2.5	3.5	0.4	7.3	2A-1A	After 1 day, 41 mg/l residual Fe^{2+}
402-85-4	0.0	0.0	0.3	1.5	2.7	5.0	5.0	0.5	9.0	2A-1A	After 8 days, 1 mg/l residual Fe^{2+}
402-85-5	8.5	9.5	9.8	10.0	10.5	10.5	11.0	1.1	9.2	2A-1A	After 15 days
402-58-5	0.5	6.0	11.0	11.0	11.0	11.5	13.0	1.3	6.3	2A-1A	Same as above; after aeration
402-85-6	--	--	--	--	--	--	10.0	1.0	9.9	2A-1A	After 17 days
402-85-6	--	--	--	--	--	--	10.0	1.0	8.2	2A-1A	Same as above; in cone over weekend
B. Thorn Run Coal Mine Water											
402-88-2	0.5	1.0	23.0	17.0	17.0	17.0	17.0	1.7	10.6	2A-1N	
402-89-3	0.4	10.0	13.0	12.0	12.0	12.0	12.0	1.2	10.0	2A-1N	

* See Table 31 for labeling system

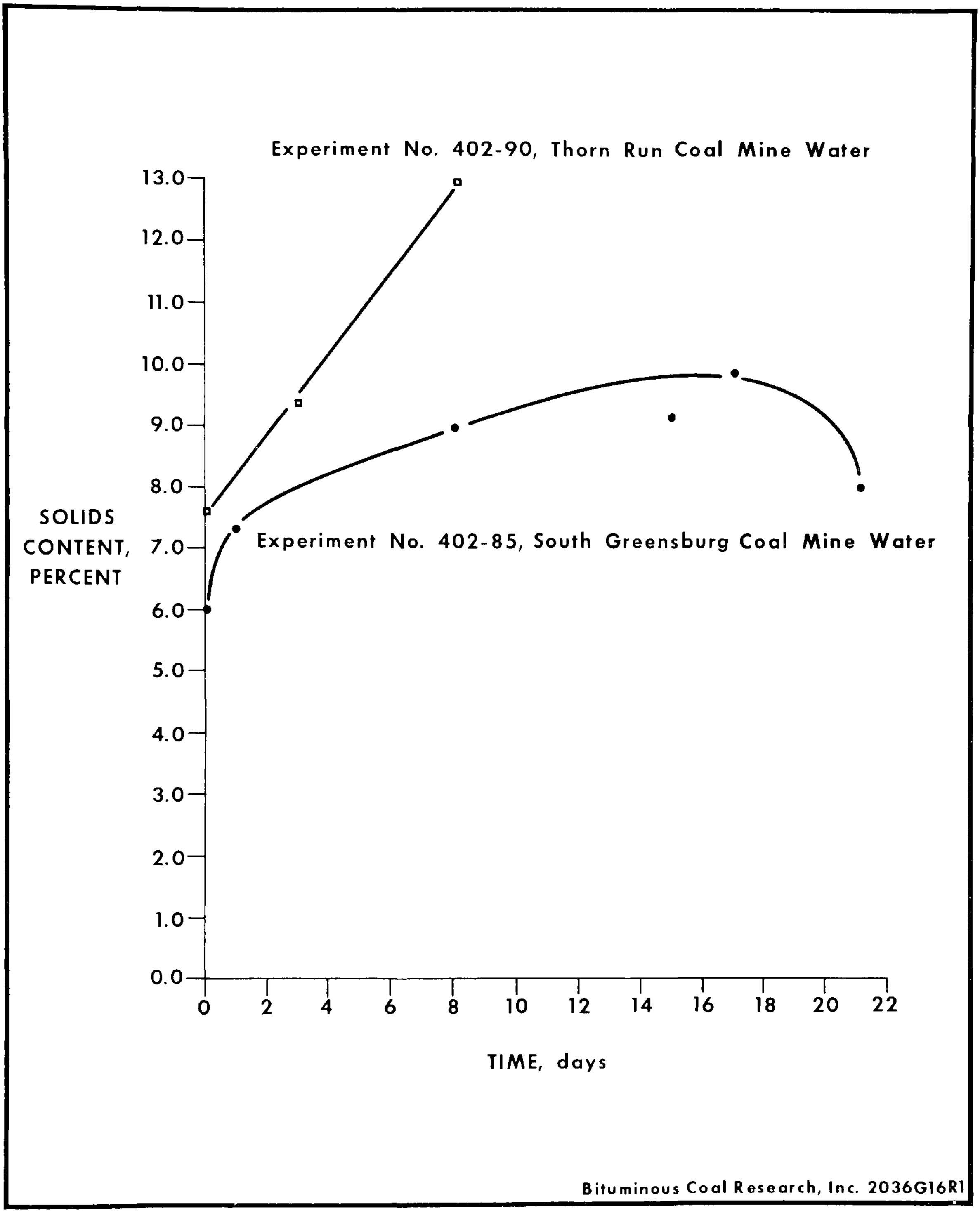


Figure 24. Effect of Aging on Solids Content of Sludge Formed in Continuous Flow Experiments

TABLE 40. PROPERTIES OF SLUDGE FORMED IN CONTINUOUS FLOW EXPERIMENTS WITH RECIRCULATED SLURRY

Experiment Number	Volume of Sludge, ml: 5 min	10 min	15 min	30 min	45 min	60 min	24 hr	Sludge Volume Percent 24 hr	Solids Content Percent 24 hr	Experimental Conditions*	Comments
A--South Greensburg Coal Mine Water											
402-80-7	1.6	2.0	2.5	3.0	3.5	4.0	3.6	0.4	6.6	2A-1A(S)	2:1 Slurry:raw water ratio
402-87-7	0.0	0.1	0.4	0.8	1.0	1.0	3.5	0.4	6.5	2A-IN(S)	
402-87-8	0.0	0.0	0.0	0.1	0.4	0.6	1.5	0.2	7.3	2A-IN(S)	Same as 87-7, but 24 hr later
B--Thorn Run Coal Mine Water											
402-90-8	0.1	0.3	8.5	11.0	10.0	10.0	10.0	1.0	7.6	2A-IN(S)	
402-90-8	0.1	3.0	10.0	9.0	8.5	9.0	10.0	1.0	5.9	2A-IN(S)	Same as 90-8, aerated 2 hr
402-90-9	--	--	--	--	--	--	--	--	9.4	2A-IN(S)	After 3 days
402-90-10	7.0	10.0	12.0	12.0	12.0	12.0	12.0	1.2	13.0	2A-IN(S)	After 8 days

* See Table 31 for labeling system

Thorn Run Coal Mine Water: Slurry Recirculation--Experiment No. 402-90 has been described in Table 38. Properties of the sludge from this experiment are listed in Table 40. Again, aerating the sample resulted in a decrease in the solids content of the sludge (See experiment No. 402-90-8). The effect of aging the sludge was noted and the information plotted on Figure 24 along with the effect of aging the South Greensburg sludge from experiment No. 402-85. A solids content of this sludge of 13.0 percent after 8 days is one of the highest of this series and can be considered quite desirable.

Effect of Shape of Vessel on Sludge Settling--It has been mentioned that, in experiment No. 402-85 described in Table 39 and Figure 24, there seemed to be a difference in solids content whether the sludge "aged" in the settling tanks or in the Imhoff cone as shown by No. 402-85-6. To further examine this effect of shape of vessel on solids content, we conducted the standard 2A-1N(S) continuous flow experiment, No. 402-95-8, with the South Greensburg coal mine water. Ferrous iron and acidity were relatively low and pH was 6.4 at the end of this experiment. We then placed 1,000 ml aliquots of the slurry containing sludge and treated water in the following vessels: round-bottom flask, beaker, Erlenmeyer flask, graduated cylinder, polyethylene round bottle, and Imhoff cone. The solids content of sludge in each vessel is listed in Table 41. Those vessels which have sloping sides resulted in a solids content of about 7 percent. Those which have perpendicular sides and relatively flat bottoms resulted in a solids content of from 3 to 4 percent, the polyethylene bottle being the single exception.

TABLE 41. EFFECT OF SHAPE OF VESSEL ON SOLIDS CONTENT OF SLUDGE

Experiment Number	Experimental Conditions*	Solids Content, Percent, 24 hr	Shape and Size of Vessel
402-95-8	2A-1N(S)	7.3	Round bottom flask, 2000 ml
402-95-8	2A-1N(S)	3.1	Beaker, 2000 ml
402-95-8	2A-1N(S)	3.6	Erlenmeyer flask, 2000 ml
402-95-8	2A-1N(S)	3.9	Graduated Cylinder, 1000 ml
402-95-8	2A-1N(S)	6.6	Polyethylene Bottle, round, 2 gal
402-95-8	2A-1N(S)	7.4	Imhoff cone, 1000 ml
402-95-8	2A-1N(S)	7.4	Imhoff cone, 1000 ml, to check reproducibility

*See Table 31 for labeling system

SECTION VII

EVALUATION OF BCR LIMESTONE TREATMENT PROCESS

The following discussion of the projected full-scale operation of the BCR limestone treatment process is based on the laboratory studies described in the previous section. The discussion of the application of this process centers only on the limestone treatment of coal mine drainage containing ferrous iron since most of the laboratory studies have been conducted using synthetic coal mine water, which is essentially a solution of ferrous sulfate, and also with the South Greensburg discharge, an actual coal mine drainage containing iron principally in the ferrous state.

The laboratory studies have (a) demonstrated the feasibility of this treatment process using laboratory-scale pilot-plant apparatus, (b) delineated the individual operations and sequence of operations necessary for adequate treatment, and (c) established basic information pertinent to engineering design of full-scale treatment plants. Based on the results of these studies, a report was prepared (10) relating experimental results to engineering design of full-scale treatment plants. For these engineering evaluations, flows of 0.1, 1.0, and 7.0 million gallons per day (mgd) were chosen and data developed for construction and operation of plants to treat discharges having these flows. The sponsors of this project then chose WQO, EPA Class I mine drainage as the quality of mine water to be used in the evaluations, since that type of mine drainage would present the greatest problems in treatment. The Class I mine drainage has the following range in quality:

pH	2 - 4.5
Acidity, mg/l (as $CaCO_3$)	1,000 - 15,000
Ferrous iron, mg/l	500 - 10,000
Ferric iron, mg/l	0
Aluminum, mg/l	0 - 2,000
Sulfate, mg/l	1,000 - 20,000

In addition to the Class I mine drainage, the South Greensburg discharge used in the laboratory studies and having an estimated flow of 4.0 mgd was also considered for this evaluation. This water has the following average quality:

Acidity, mg/l (as $CaCO_3$)	190
Ferrous iron, mg/l	90
Ferric iron, mg/l	0
Aluminum, mg/l	8
Sulfate, mg/l	1,200

Further experimentation will be necessary to determine the optimum ratio of sludge (concentrated solids) to raw mine water for this process. In the laboratory studies described in the previous sections, slurry (sludge plus treated water) rather than sludge, was recirculated due to the nature of the pilot plant. In this section which attempts to project the results of the laboratory studies to full scale treatment plants, the more familiar term "sludge" will be used for the recirculated material. Process materials balances based on the laboratory studies will, therefore, include the additional water carried along with the sludge. Recognition is given to the necessity of concentrating the solids to be recirculated in an actual system. The need for further study in this area will be apparent.

Description of Individual Treatment Units

The essential treatment units for the BCR limestone treatment process for a full-scale plant are, in flow-through sequence: holding lagoon, reactor tank, aeration tank, settling basin, and sludge dewatering basin. Major equipment components of the process include a mixer, mechanical aerators, limestone storage facilities and feeder, and sludge pumps. A summary discussion of the design parameters and process units employed by the proposed limestone treatment method follows.

A holding or equalization lagoon is the first operation unit. It should be designed to provide a detention period of 12 hours for the flow of mine water. The principal function of this unit is to level out fluctuations in the flow of mine water and thus provide a continuous supply of water to be treated during periods of intermittent pumping from the mine. Incidentally, this lagoon also serves to level out fluctuations in raw water quality and thus produce a narrow range of acidity in the mine water supplied to the reactor tank. Based on the laboratory studies, the rate of limestone feed to the process should be adjusted to provide a limestone to acidity ratio of 2:1. Flow metering of the holding lagoon effluent in conjunction with grab sample analyses for acidity is necessary for setting the rate of limestone feed. The frequency of sampling required will depend upon the degree of variation in mine water quality for each particular installation.

Provision for bulk storage of limestone at the treatment plant site is recommended with a minimum of 4 days storage capacity. It was assumed for this evaluation that an acceptable grade of pulverized limestone, comparable to the quality determined from past studies (1) to be effective for treatment, can be supplied to the plant site. The cost advantage or disadvantage of pulverizing limestone on-site must be determined for each particular installation and involves economic considerations beyond the scope of this study. Necessary provisions should be made to reduce the dust problem associated with unloading bulk trucks. Vibratory-type feeders are recommended for controlling the rate of limestone feed to the process. "Live" bins are also recommended.

The second treatment unit is the reactor tank, where pulverized limestone and recirculated sludge are mixed with the coal mine drainage for a period of 60 minutes based on the total combined flow of raw water and recirculated sludge. Laboratory studies have shown that optimum treatment efficiencies are obtained when the mine water and limestone feed are mixed with an equal volume of previously formed sludge in the reactor tank. This unit must be equipped with a mixer capable of maintaining a complete mix of the tank contents. Intimate contact of the limestone and recirculated sludge with mine water constituents is essential to initiate the neutralization reaction. While the volume of the reactor tank is fixed by the required detention period, the dimensional design must be coordinated with the sizing of the mixer to ensure adequate mixing.

An aeration tank sized to provide a 60-minute detention period is recommended. In the laboratory studies, diffused air was used to successfully oxidize ferrous iron. A diffused air system, however, is probably not practical for a plant-scale aeration tank, and floating mechanical aerators are recommended for the actual process application. Aeration equipment and tank configuration must complement each other to function as an efficient unit for providing complete mixing and sufficient transfer of oxygen from the atmosphere to the water. In addition, adequate sparging action must be produced to cause the release of carbon dioxide and, therefore, an increase in pH. The aeration tank effluent should be provided with a continuous pH monitoring system to indicate the completeness of the neutralization reaction.

Settling basins with a 12-hour detention period are recommended. The design of these basins should include an influent trough which will reduce the influent approach velocity and distribute the flow across the width of the basin. Provisions should also be made in these basins to reduce the possibility of short-circuiting, which would result in unsettled sludge spilling into the receiving stream.

The sludge removal system must be capable of removing the settled solids with a minimum of turbulence, so that the effective volume and retention time of the settling basin is not reduced. Sludge from the settling basin will be pumped to a sludge recirculation well. From this point, it will be recycled to the reactor tank or wasted to sludge dewatering ponds. Dewatering ponds should be located in proximity to the treatment facilities to further concentrate the waste solids prior to disposal. Ultimate disposal of the concentrated solids will be accomplished by removal from the site by tank truck. The supernatant from the dewatering ponds will be decanted to the receiving stream.

Flow Schematics, Unit Designs, and Material Balances

The plant flow schematics and unit designs presented in Figures 25 through 27 inclusive and material balances presented in Figures 30 through 38 inclusive are based on limestone treatment of Class I coal mine drainage by the BCR process at 0.1, 1.0, and 7.0 mgd flow rates.

For the purposes of this study, the following three cases of the Class I mine drainage have been used to develop the flow schematics, unit designs, and material balances:

Case A:	Acidity, mg/l (as $CaCO_3$)	1,000
	Ferrous iron, mg/l	500
	Ferric iron, mg/l	0
	Aluminum, mg/l	0
	Sulfate, mg/l	1,000
Case B:	Acidity, mg/l (as $CaCO_3$)	8,000
	Ferrous iron, mg/l	5,000
	Ferric iron, mg/l	0
	Aluminum, mg/l	500
	Sulfate, mg/l	10,000
Case C:	Acidity, mg/l (as $CaCO_3$)	15,000
	Ferrous iron, mg/l	10,000
	Ferric iron, mg/l	0
	Aluminum, mg/l	2,000
	Sulfate, mg/l	20,000

In addition to the data for the Class I coal mine drainage cases discussed above, a plant flow schematic and unit designs and a material balance for treating South Greensburg coal mine drainage at a 4.0 mgd flow rate have been presented in Figures 28 and 39. A proposed plant layout and hydraulic profile for the same discharge is shown in Figure 29. The average quality of the South Greensburg coal mine water is shown on page 104.

The following assumptions were made for the purpose of completing the plant design data and material balances:

The limestone requirement is twice the stoichiometric amount based on acidity.

A recirculated sludge to coal mine drainage feed ratio of 1:1 is required. (Actually, a 1:1 ratio of slurry to coal mine drainage. See laboratory studies.)

Twenty-five percent of the limestone feed remains unreacted in the sludge.

All but 7 mg/l of the initial iron present is precipitated in the sludge as ferric hydroxide.

All of the initial aluminum is precipitated in the sludge as aluminum hydroxide.

Calcium sulfate (gypsum) is not precipitated in the sludge.

Sludge solids content is five percent.

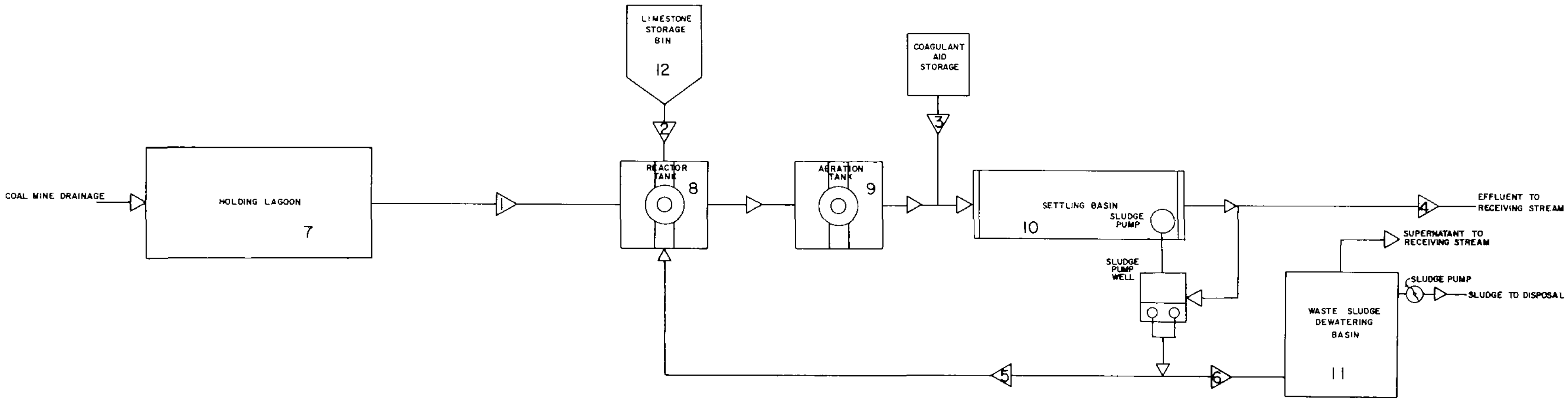
Sludge specific gravity is 1.05.

Most of the above were determined from the laboratory studies, with the following exceptions: The experimental data on treatment of the South Greensburg water did not indicate the formation of gypsum. However, with treatment of Class I mine drainages, it is expected that the solubility product of calcium sulfate will be exceeded and gypsum will, in fact, be precipitated in the sludge. Nevertheless, the formation of gypsum was ignored, since it could not be determined from the laboratory studies where the gypsum would precipitate. Also formation of this material in the mixing and aeration tanks could result in coating of equipment and loss of efficiency of that equipment--all considered beyond the scope of this study. Furthermore, it was apparent that the recommended studies with waters resembling Class I discharges would be necessary to obtain data which could be used for plant design and material balances and which would include formation of gypsum.

Summary Technical Evaluation of the Process

Based on the laboratory studies and on consideration of the individual treatment units, flow schematics, unit designs, and material balances, the following is a summary evaluation of the BCR limestone treatment process as it applies to plant scale treatment of coal mine drainage.

A holding lagoon capacity corresponding to twelve hours retention is necessary to ensure a constant quantity of mine water during periods of intermittent pumping from the mine and to level out raw water quality.



TABULATION OF PLANT FLOWS & UNIT DESIGN BASIS FOR 0.1 MGD TREATMENT PLANT

CASE NO.	LINE LOCATION	1	2	3	4	5	6	7	8	9	10	11	12
	TREATMENT PLANT INFLUENT CONDITIONS	HOLDING LAGOON EFFLUENT GPD	LIMESTONE FEED LB/DAY	COAGULANT AID FEED LB/DAY	PLANT EFFLUENT GPD	RECIRCULATED SLUDGE GPD	WASTE SLUDGE GPD	HOLDING LAGOON	REACTOR TANK	AERATION TANK	SETTLING BASIN	WASTE SLUDGE DEWATERING BASIN	LIMESTONE STORAGE BIN
A	ACIDITY 1,000 MG/L FERROUS IRON 500 MG/L ALUMINUM 0 MG/L SULFATE 1,000 MG/L	100,000	1,670	0.8	97,300	100,000	2,750	50' LG x 30' W x 10' SWD	12' LG x 12' W x 8' SWD	12' LG. x 12' W x 8' SWD	95' LG. x 45' W x 9' SWD	75' LG. x 46' W x 10' SWD	110 FT^3
B	ACIDITY 8,000 MG/L FERROUS IRON 5,000 MG/L ALUMINUM 1,500 MG/L SULFATE 10,000 MG/L	100,000	13,300	0.8	71,500	100,000	28,500	50' LG. x 30' W x 10' SWD	12' LG. x 12' W x 8' SWD	12' LG. x 12' W x 8' SWD	98' LG. x 45' W x 9' SWD	190' LG. x 105' W x 10' SWD	890 FT^3
C	ACIDITY 15,000 MG/L FERROUS IRON 10,000 MG/L ALUMINUM 2,000 MG/L SULFATE 20,000 MG/L	100,000	25,000	0.8	38,300	100,000	61,700	50' LG. x 30' W x 10' SWD	12' LG. x 12' W x 8' SWD	12' LG. x 12' W x 8' SWD	105' LG. x 46' W x 9' SWD	300' LG. x 150' W x 10' SWD	1,670 FT^3

LEGEND

LG. - LENGTH
W - WIDTH
SWD - SIDE WATER DEPTH

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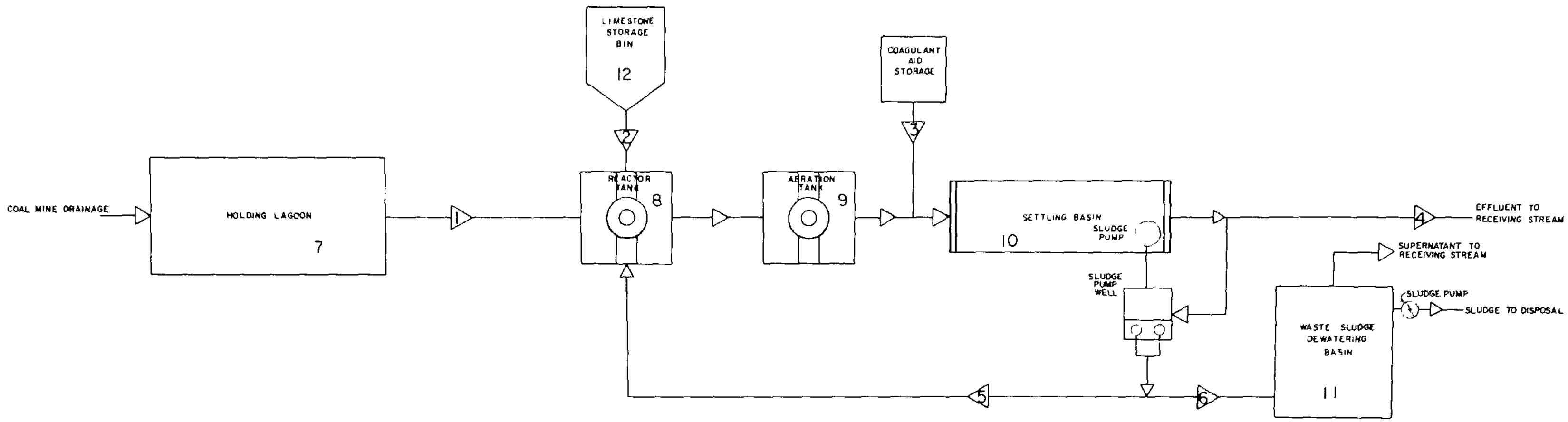
Figure 25. Plant Flow Schematic, Plant Flows and Unit Design Basis for 0.1 mgd Limestone Treatment Plant for Class I Coal Mine Drainage



TABULATION OF PLANT FLOWS & UNIT DESIGN BASIS FOR 1 0 MGD TREATMENT PLANT

CASE NO.	LINE LOCATION / TREATMENT PLANT INFLUENT CONDITIONS	1 HOLDING LAGOON EFFLUENT GPD	2 LIMESTONE FEED LB/DAY	3 COAGULANT AID FEED LB/DAY	4 PLANT EFFLUENT GPD	5 RECIRCULATED SLUDGE GPD	6 WASTE SLUDGE GPD	7 HOLDING LAGOON	8 REACTOR TANK	9 AERATION TANK	10 SETTLING BASIN	11 WASTE SLUDGE DEWATERING BASIN	12 LIMESTONE STORAGE BIN
A	ACIDITY 1,000 MG/L FERROUS IRON 500 MG/L ALUMINUM 0 MG/L SULFATE 1,000 MG/L	1,000,000	16,700	8 3	973,000	1,000,000	27,500	125'LG x 70'W x 10'SWD	40'LG x 20'W x 14'SWD	30'LG x 30'W x 12'SWD	230'LG x 90'W x 9'SWD	175'LG x 100'W x 12'SWD	1,110 FT^3
B	ACIDITY 8,000 MG/L FERROUS IRON 5,000 MG/L ALUMINUM 1,500 MG/L SULFATE 10,000 MG/L	1,000,000	133,000	8.3	715,000	1,000,000	285,000	125'LG. x 70'W x 10'SWD	40'LG x 20'W x 14'SWD	30'LG. x 30'W x 12'SWD	245'LG x 95'W x 9'SWD	515'LG x 270'W x 12'SWD	8,900 FT^3
C	ACIDITY 15,000 MG/L FERROUS IRON 10,000 MG/L ALUMINUM 2,000 MG/L SULFATE 20,000 MG/L	1,000,000	250,000	8 3	383,000	1,000,000	617,000	125'LG. x 70'W x 10'SWD	40'LG. x 20'W x 14'SWD	30'LG. x 30'W x 12'SWD	264'LG x 100'W x 9'SWD	750'LG x 385'W x 12'SWD	16,680 FT^3

LEGEND

LG - LENGTH
W - WIDTH
SWD - SIDE WATER DEPTH

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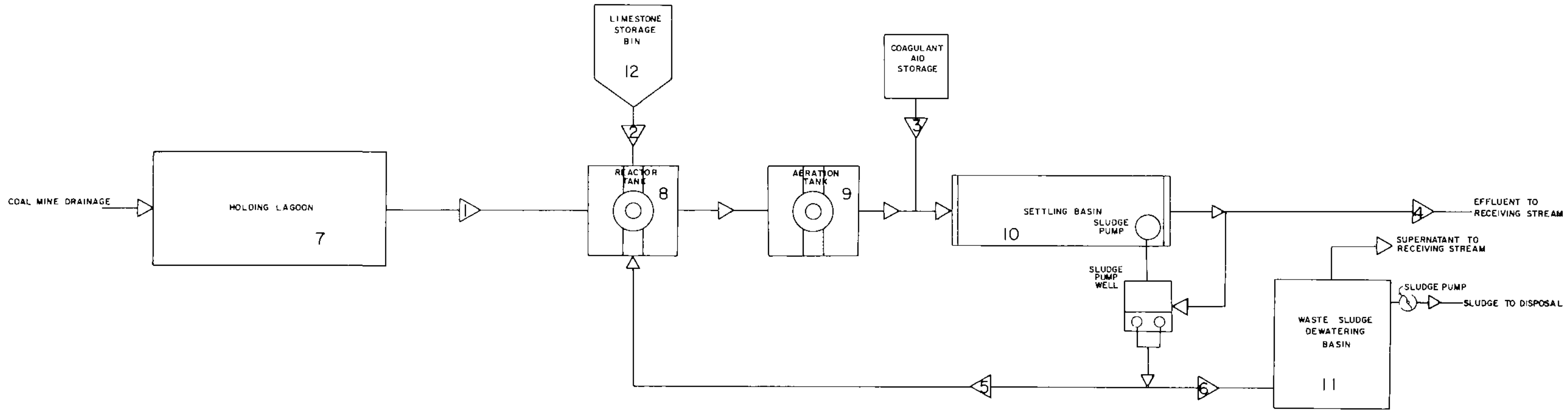
Figure 26. Plant Flow Schematic, Plant Flows and Unit Design Basis for 1.0 mgd Limestone Treatment Plant for Class I Coal Mine Drainage



TABULATION OF PLANT FLOWS & UNIT DESIGN BASIS FOR 70 MGD TREATMENT PLANT

CASE NO.	LINE LOCATION	1	2	3	4	5	6	7	8	9	10	11	12
	TREATMENT PLANT INFLUENT CONDITIONS	HOLDING LAGOON EFFLUENT GPD	LIMESTONE FEED LB/DAY	COAGULANT AID FEED LB/DAY	PLANT EFFLUENT GPD	RECIRCULATED SLUDGE GPD	WASTE SLUDGE GPD	HOLDING LAGOON	REACTOR TANK	AERATION TANK	SETTLING BASIN	WASTE SLUDGE DEWATERING BASIN	LIMESTONE STORAGE BIN
A	ACIDITY 1,000 MG/L FERROUS IRON 500 MG/L ALUMINUM 0 MG/L SULFATE 1,000 MG/L	7,000,000	117,000	58	6,810,000	7,000,000	192,000	310'LG. x 160'W x 10'SWD	115'LG. x 46'W x 15'SWD	130'LG. x 45'W x 14'SWD	550'LG. x 200'W x 10'SWD	400'LG. x 200'W x 12'SWD	7,780 FT^3
B	ACIDITY 8,000 MG/L FERROUS IRON 5,000 MG/L ALUMINUM 1,500 MG/L SULFATE 10,000 MG/L	7,000,000	934,000	58	5,000,000	7,000,000	2,000,000	310'LG. x 160'W x 10'SWD	115'LG. x 46'W x 15'SWD	130'LG x 45'W x 14'SWD	590'LG. x 210'W x 10'SWD	1200'LG x 600'W x 14'SWD	62,270 FT^3
C	ACIDITY 15,000 MG/L FERROUS IRON 10,000 MG/L ALUMINUM 2,000 MG/L SULFATE 20,000 MG/L	7,000,000	1,750,000	58	2,680,000	7,000,000	4,320,000	310'LG x 160'W x 10'SWD	115'LG x 46'W x 15'SWD	130'LG x 45'W x 14'SWD	650'LG x 230'W x 10'SWD	1760'LG x 900'W x 15'SWD	116,760 FT^3

LEGEND

LG - LENGTH
W - WIDTH
SWD - SIDE WATER DEPTH

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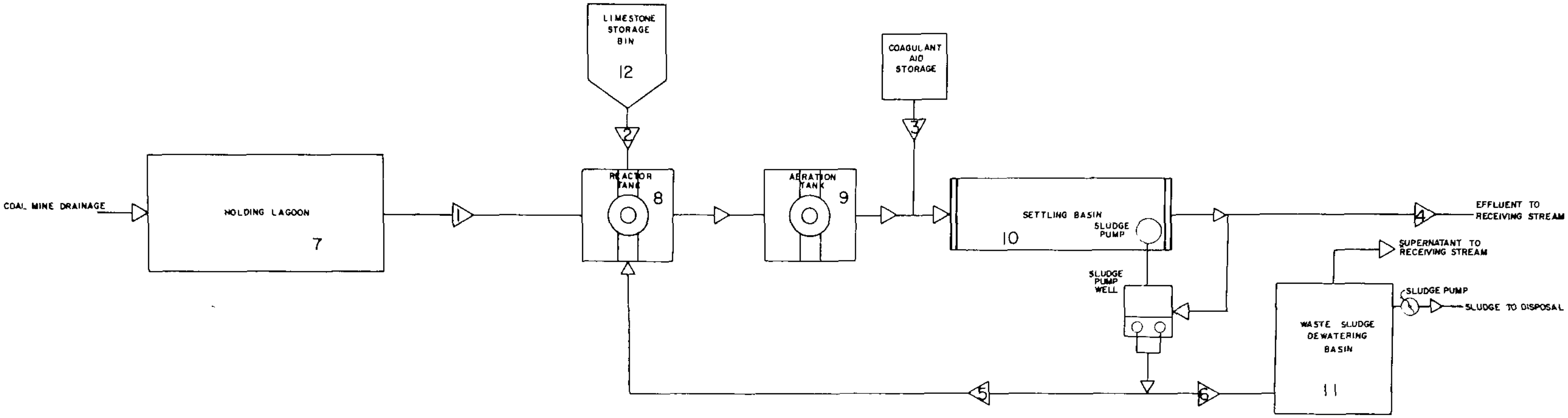
Figure 27. Plant Flow Schematic, Plant Flows and Unit Design Basis for 7.0 mgd Limestone Treatment Plant for Class I Coal Mine Drainage



TABULATION OF PLANT FLOWS & UNIT DESIGN BASIS FOR 4.0 MGD TREATMENT PLANT

LINE LOCATION	1	2	3	4	5	6	7	8	9	10	11	12
TREATMENT PLANT INFLUENT CONDITIONS	HOLDING LAGOON EFFLUENT GPD	LIMESTONE FEED LB/DAY	COAGULANT AID FEED LB/DAY	PLANT EFFLUENT GPD	RECIRCULATED SLUDGE GPD	WASTE SLUDGE GPD	HOLDING LAGOON	REACTOR TANK	AERATION TANK	SETTLING BASIN	WASTE SLUDGE DEWATERING BASIN	LIMESTONE STORAGE BIN
ACIDITY 190 MG/L FERROUS IRON 90 MG/L ALUMINUM 8 MG/L SULFATE 1200 MG/L	4,000,000	12,700	33.4	3,980,000	4,000,000	21,200	250'LG x 130'W x 10' SWD	70'LG x 35'W x 14'SWD	70'LG x 35'W x 14' SWD	420' LG x 145 W x 10' SWD	176'LG x 98'W x 10' SWD	850 FT³

LEGEND

LG - LENGTH
W - WIDTH
SWD - SIDE WATER DEPTH

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Figure 28. Plant Flow Schematic, Plant Flows and Unit Design Basis for 4.0 mgd Limestone Treatment Plant for South Greensburg Coal Mine Drainage

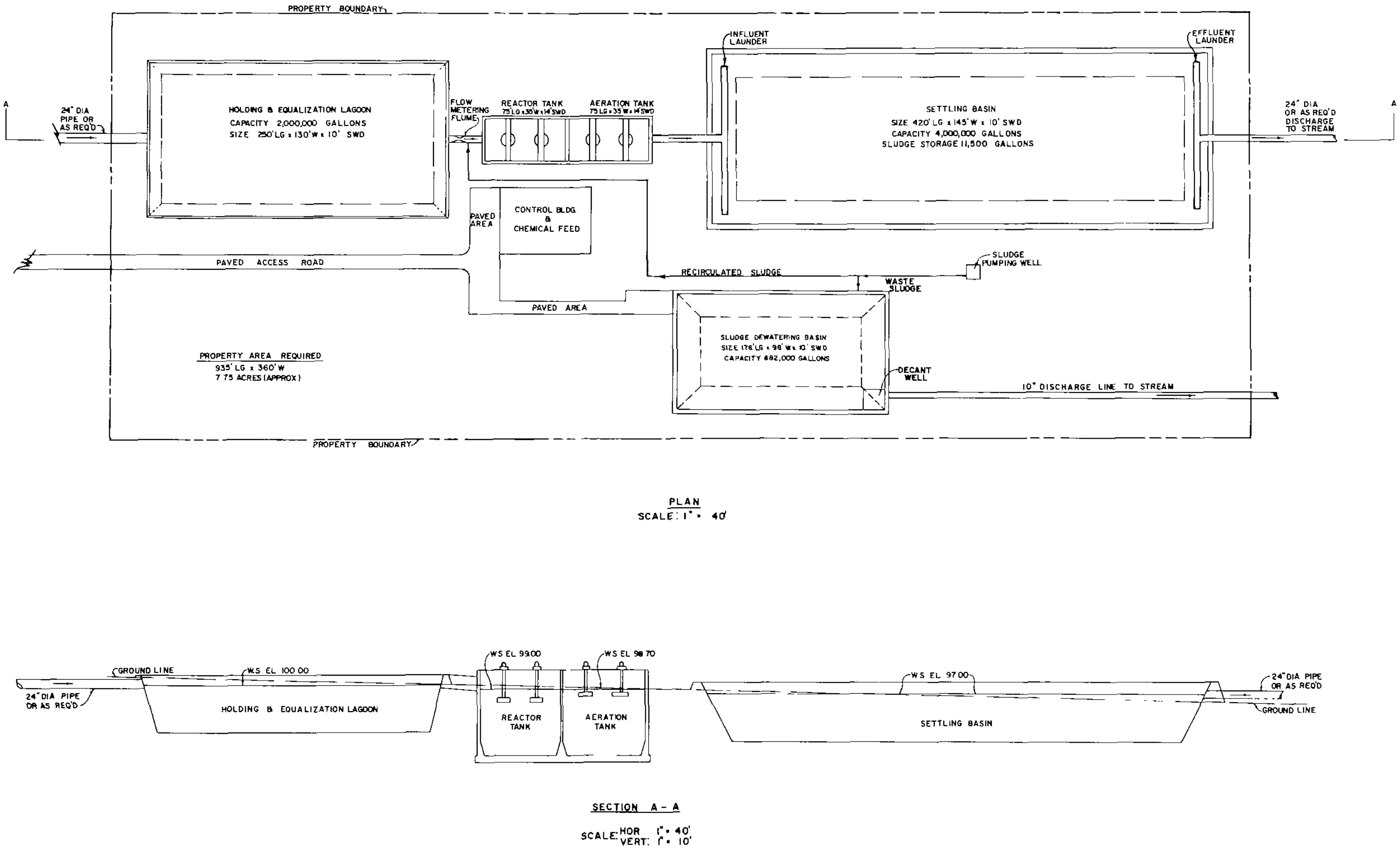

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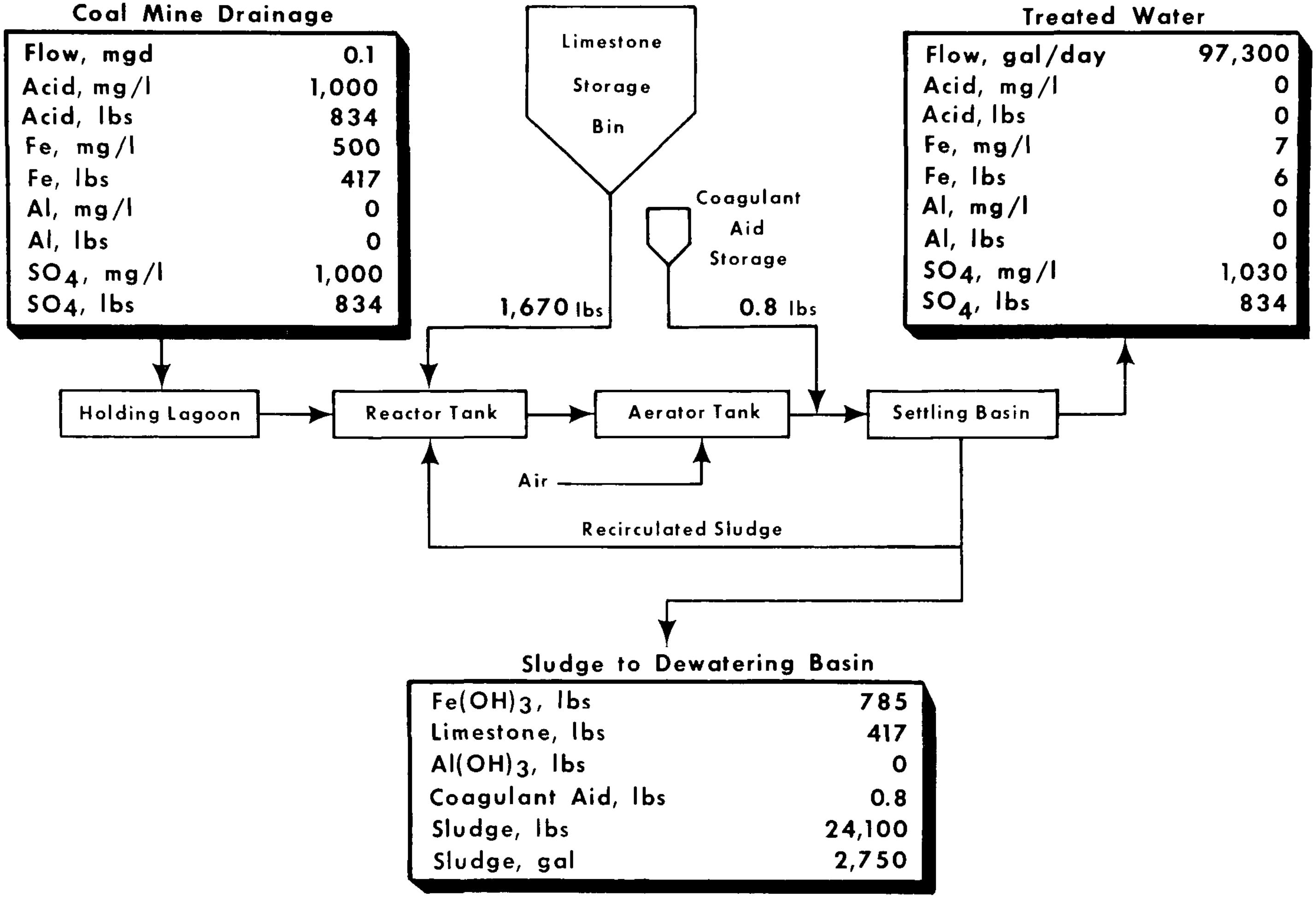
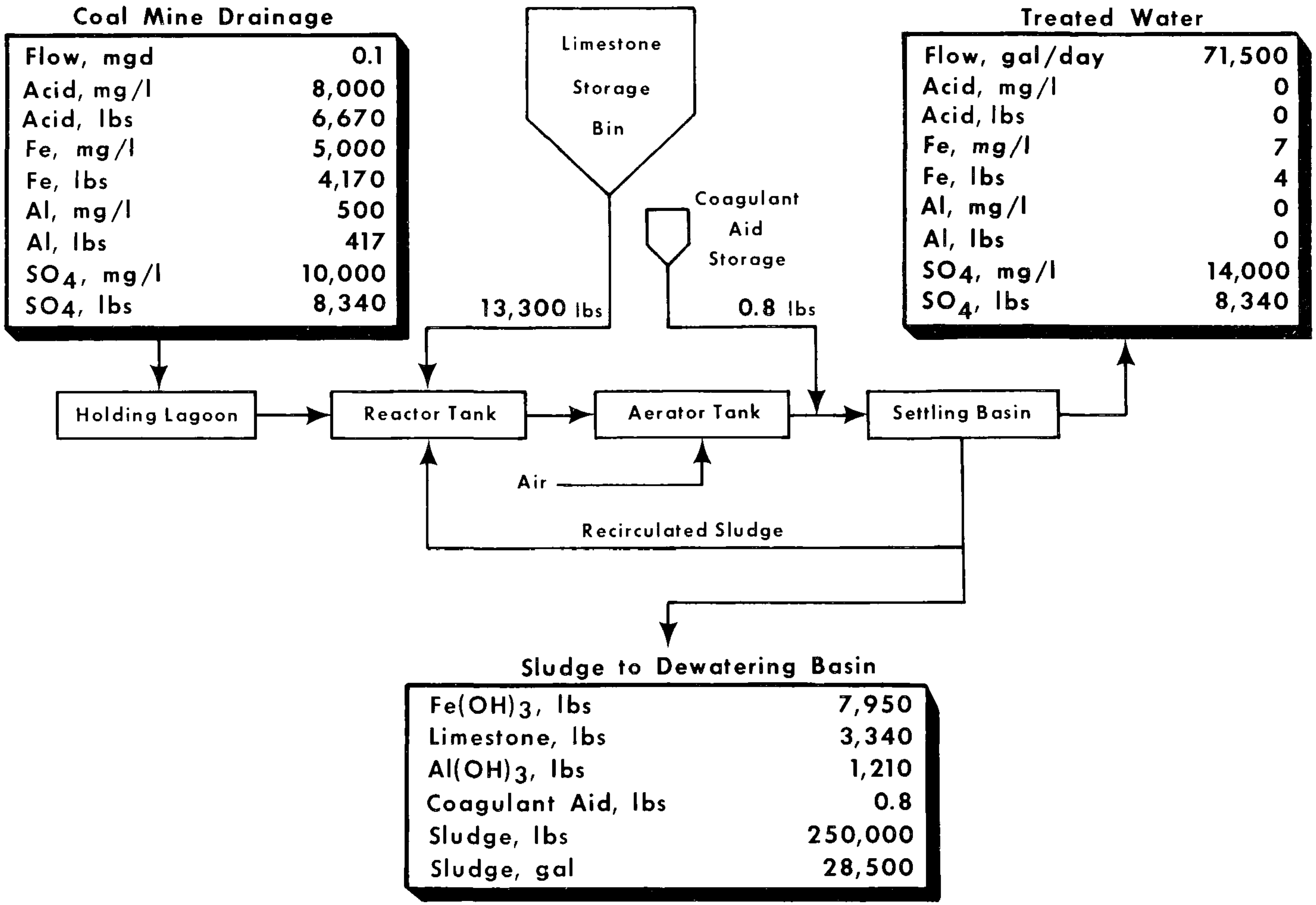
Figure 29. Plant Layout and Hydraulic Profile for 4.0 mgd Limestone Treatment Plant for South Greensburg Coal Mine Drainage



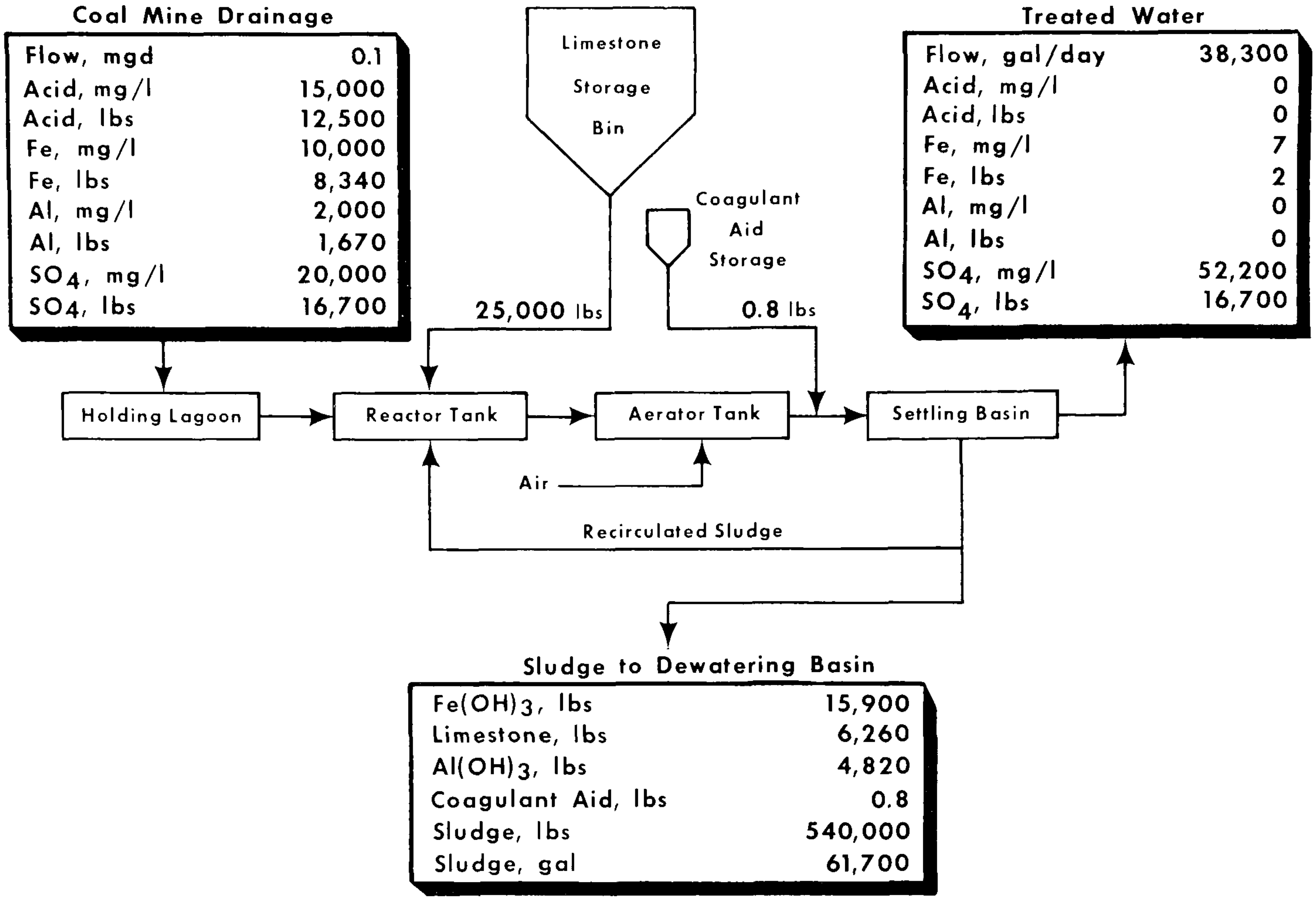
Bituminous Coal Research, Inc. 2036G24

Figure 30. Material Balance for Limestone Treatment of Class I, Case A Coal Mine Drainage at 0.1 mgd Flow Rate



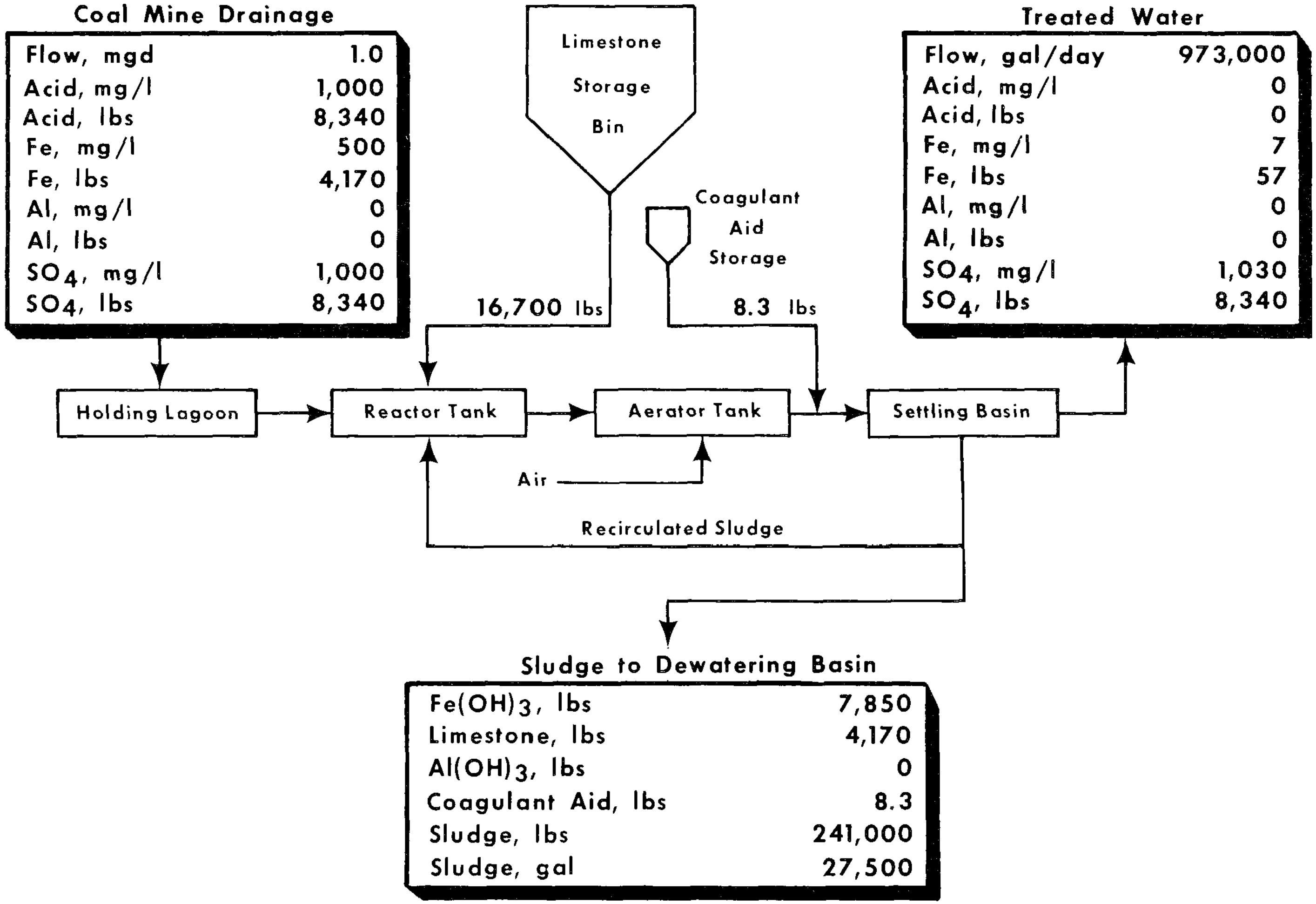
Bituminous Coal Research, Inc. 2036G25

Figure 31. Material Balance for Limestone Treatment of Class I, Case B Coal Mine Drainage at 0.1 mgd Flow Rate



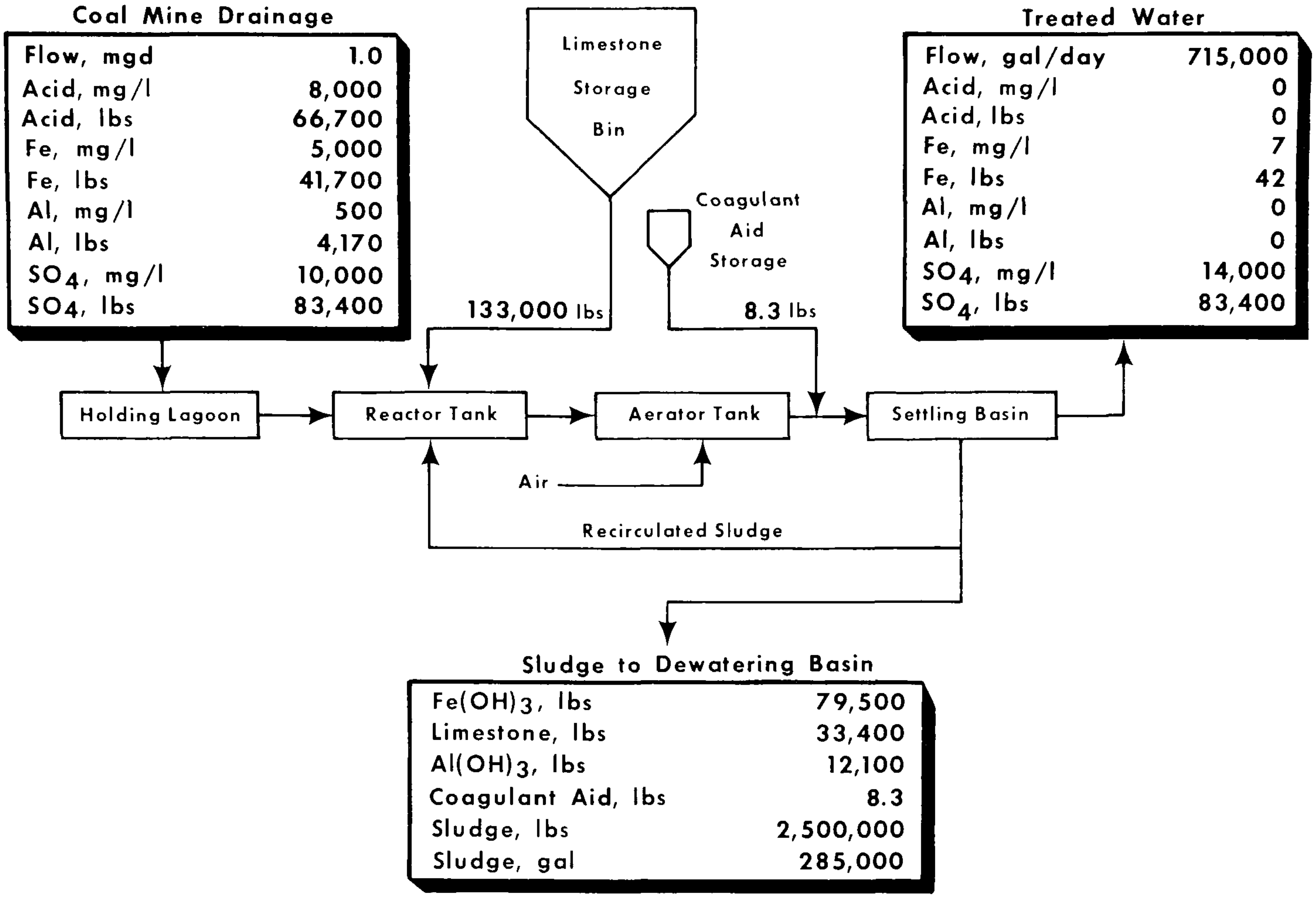
Bituminous Coal Research, Inc. 2036G26

Figure 32. Material Balance for Limestone Treatment of Class I, Case C Coal Mine Drainage at 0.1 mgd Flow Rate



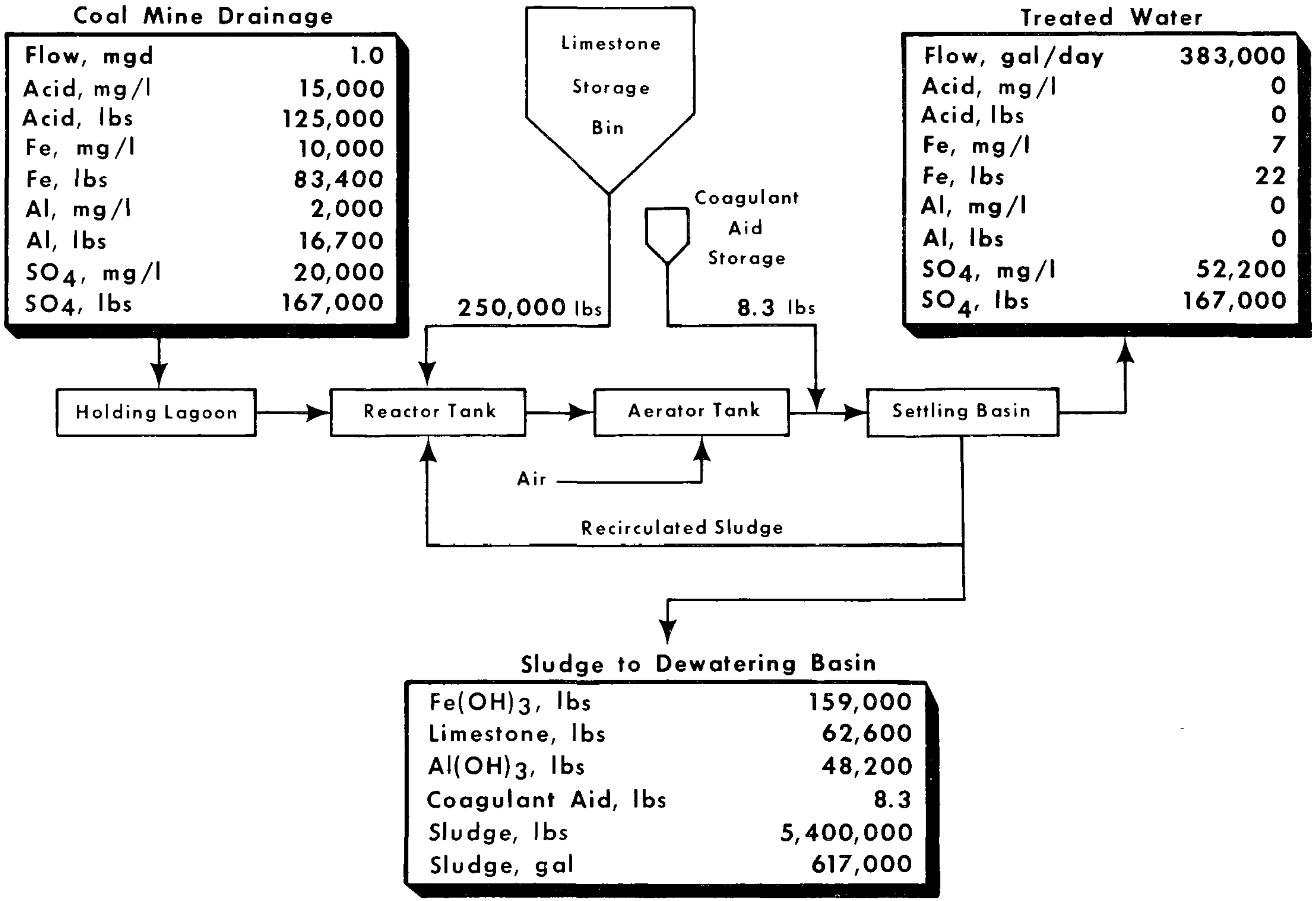
Bituminous Coal Research, Inc. 2036G27

Figure 33. Material Balance for Limestone Treatment of Class I, Case A Coal Mine Drainage at 1.0 mgd Flow Rate



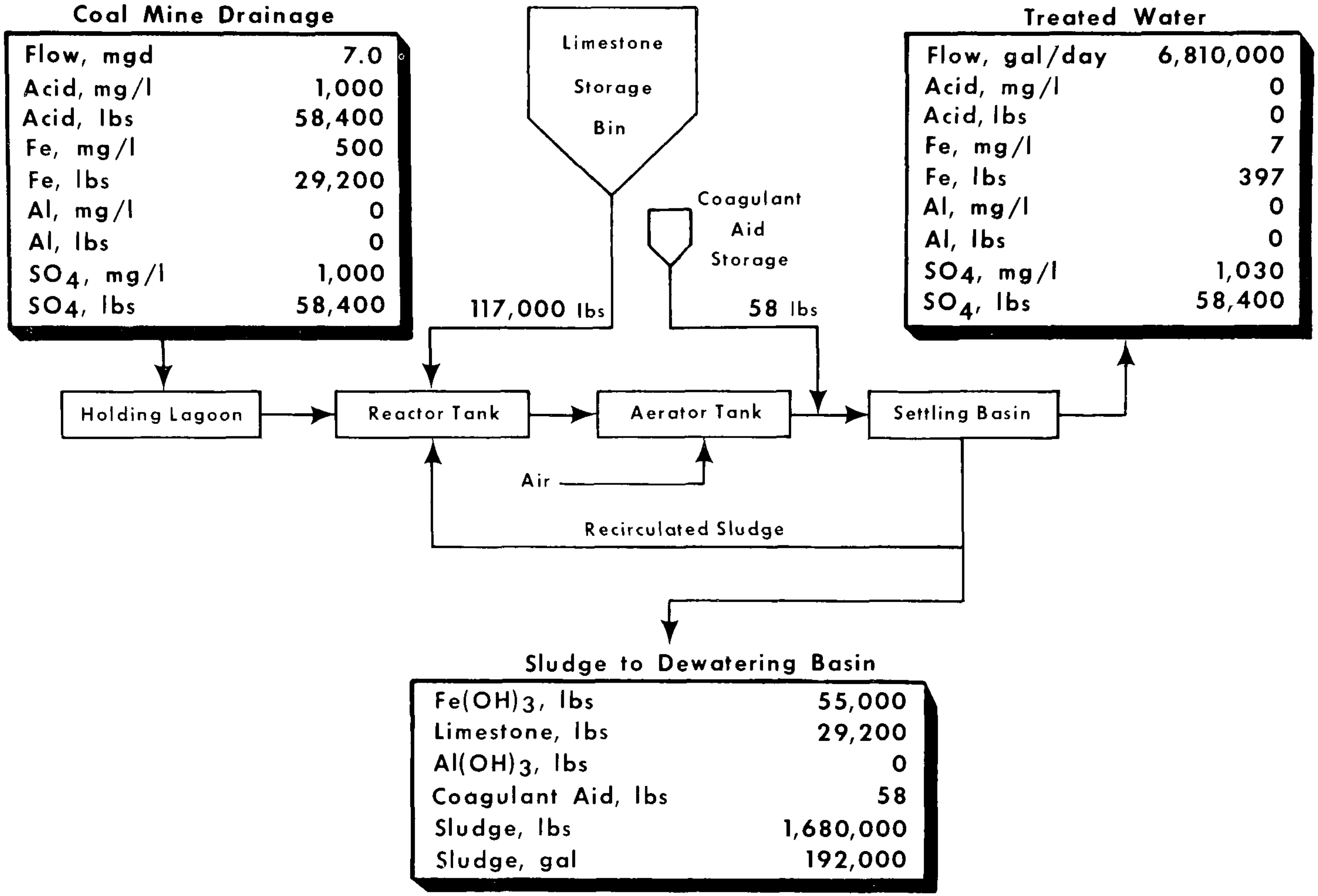
Bituminous Coal Research, Inc. 2036G28

Figure 34. Material Balance for Limestone Treatment of Class I, Case B Coal Mine Drainage at 1.0 mgd Flow Rate



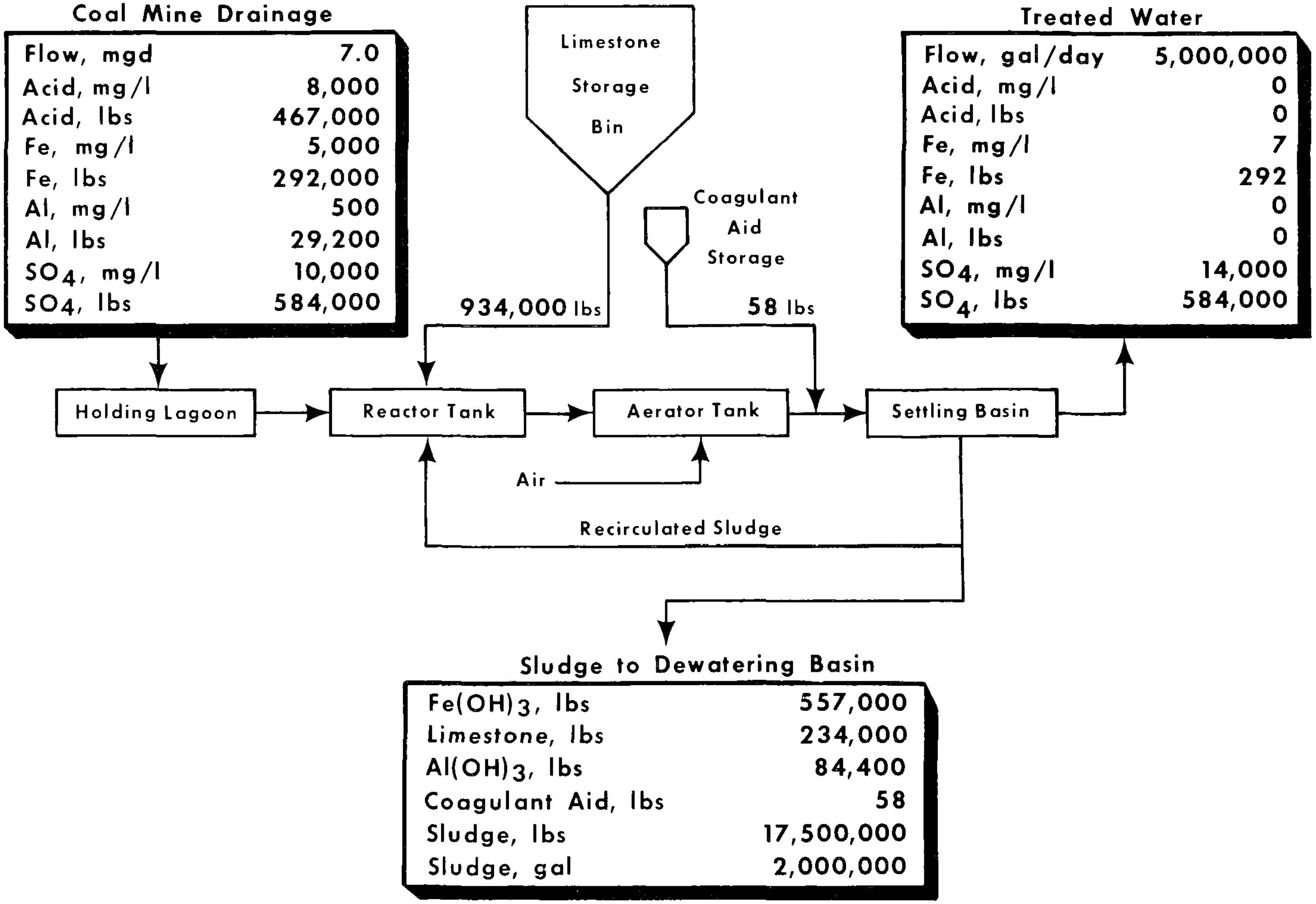
Bituminous Coal Research, Inc. 2036G29

Figure 35. Material Balance for Limestone Treatment of Class I, Case C Coal Mine Drainage at 1.0 mgd Flow Rate



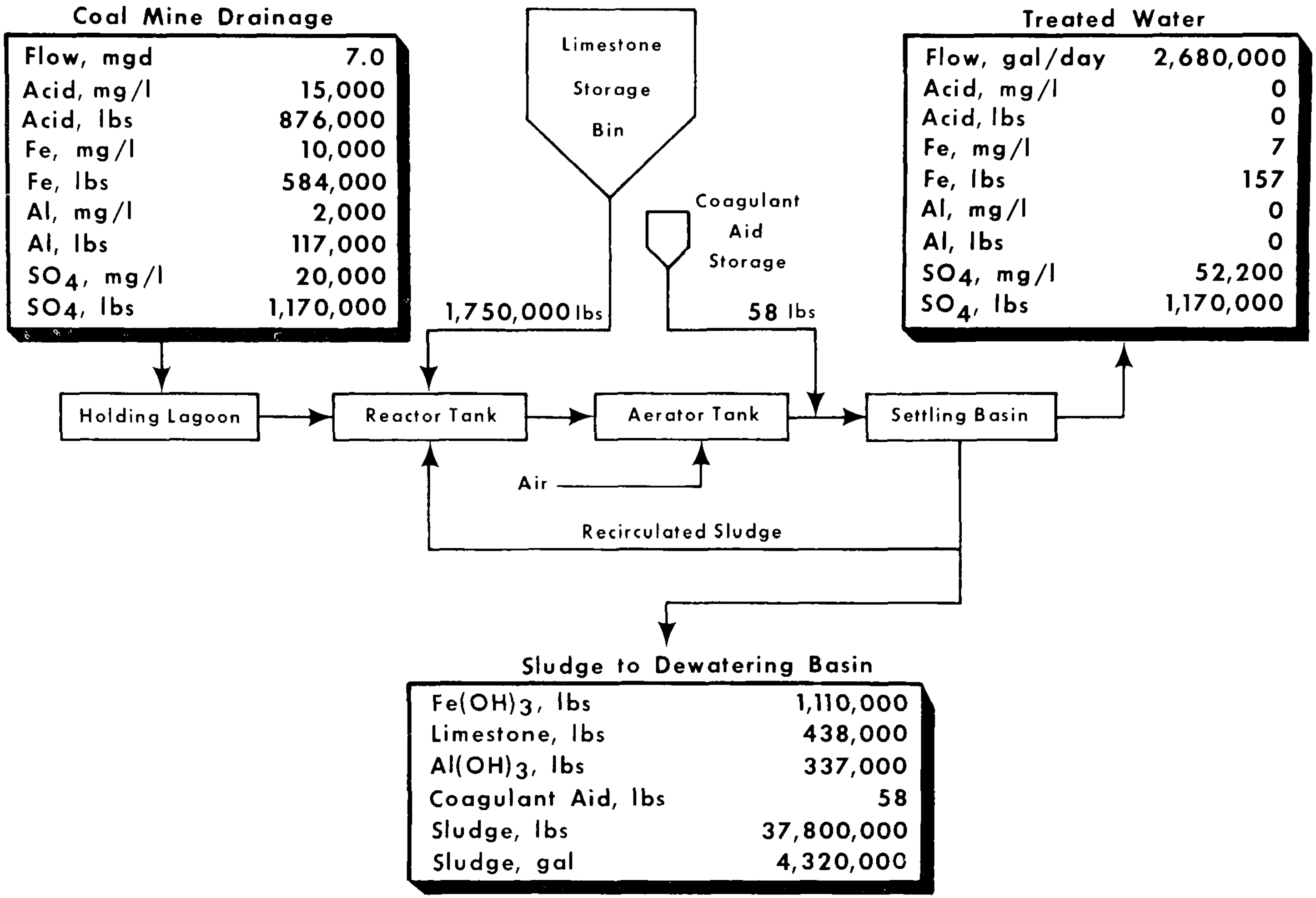
Bituminous Coal Research, Inc. 2036G30

Figure 36. Material Balance for Limestone Treatment Class I, Case A Coal Mine Drainage at 7.0 mgd Flow Rate



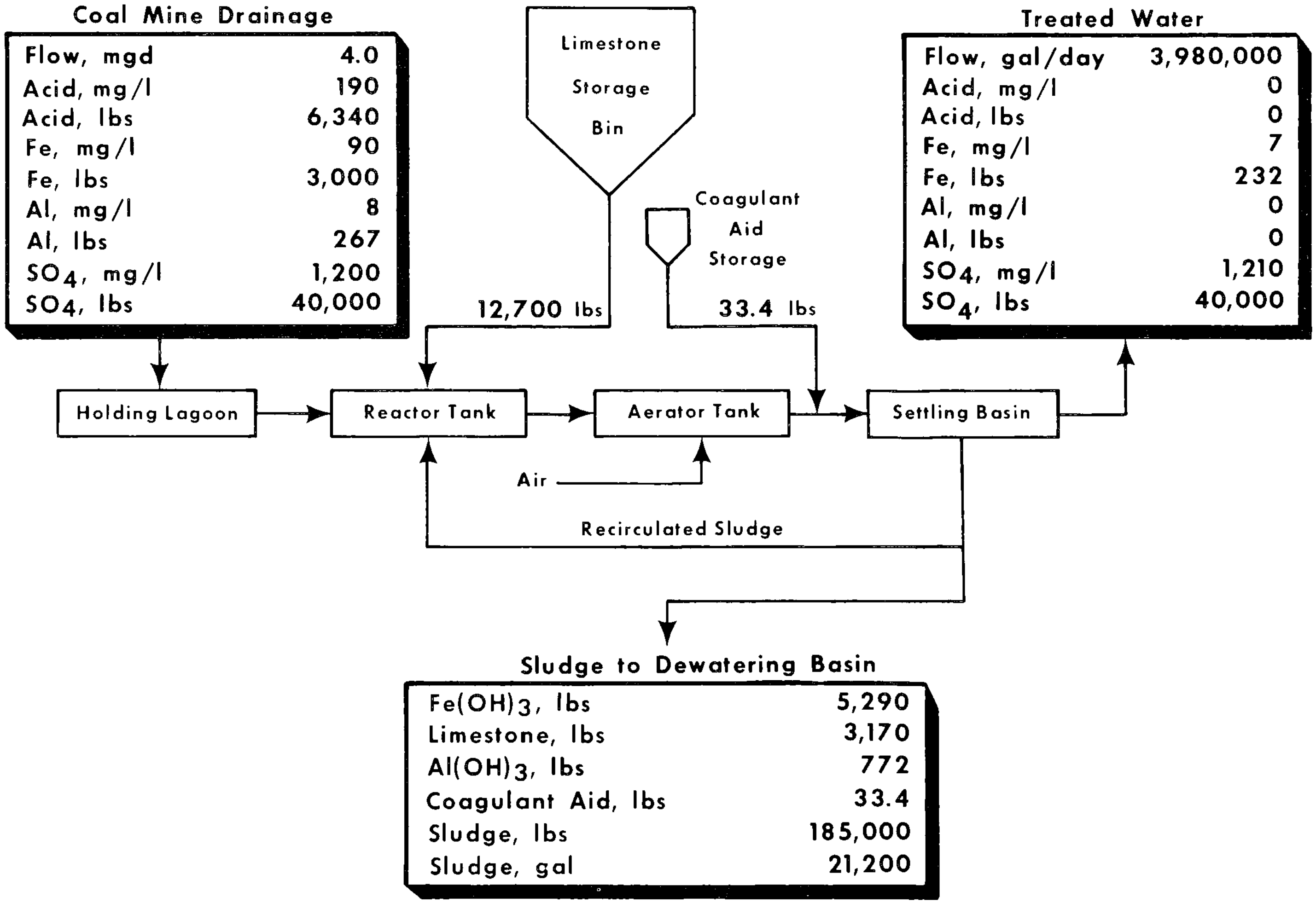
Bituminous Coal Research, Inc. 2036G31

Figure 37. Material Balance for Limestone Treatment of Class I, Case B Coal Mine Drainage at 7.0 mgd Flow Rate



Bituminous Coal Research, Inc. 2036G32

Figure 38. Material Balance for Limestone Treatment of Class I, Case C Coal Mine Drainage at 7.0 mgd Flow Rate



Bituminous Coal Research, Inc. 2036G33

Figure 39. Material Balance for Limestone Treatment of South Greensburg Coal Mine Drainage at 4.0 mgd Flow Rate

Manual control procedures for regulating the feed rate of limestone based on the acid loading of the raw water are required by the process.

No insurmountable problems are anticipated with the on-site handling of pulverized limestone. Major considerations would include dust control during unloading, and preventing moisture contact with the stored material. Vibratory-type feeders can be utilized for limestone addition to the process.

Deposition of solids, particularly calcium sulfate, occurring in either the reactor tank or the aeration tank would pose an operational problem detrimental to process efficiency. The necessarily large tanks, due to the 60-minute detention time and the high solids content, impose critical design conditions for mixing and aeration. With high flows such as 7 mgd and high acid loadings, such as Case B and Case C of Class I as described, it is very unlikely that efficient mixing could be attained in the necessarily large reaction and aeration tanks required.

Settled sludge in earthen basins, as the result of any treatment process, does not present a condition conducive to its efficient removal on a continuous flow basis. Handling large volumes of sludge, as required by recycling in this limestone treatment process, increases the problem.

As a result of the technical evaluation of the process, it has been demonstrated that treatment of coal mine drainages such as the South Greensburg water or the lower acid limits of Class I discharge (such as Case A as described) is not only technically feasible, (as has been established by the laboratory studies), but can be accomplished with practical systems. Treatment of those waters having high flow rates and high acid loadings (Case B and Case C) present particular problems which have not been solved by this study. However, those waters are not typical of coal mine drainage and can be considered rare, particularly considering the concentration of iron. An examination of four reports (11, 12, 13, 14), which included analyses of coal mine discharges in an area covering greater than 1,700 square miles in Ohio and Pennsylvania, revealed that none of the discharges reported approached the levels of acidity and iron described by Case B and Case C This was also true in another report (15) describing the quality of one creek in West Virginia which contributed 25 percent of the acid loading to a basin containing an area of 384 square miles. In only a few instances were discharges having the quality of Case A, Class I described in these reports.

One of the problems presented by using the BCR limestone treatment process can be considered a result of the 60-minute detention time due to the relative insolubility of the limestone and the resultant sluggishness of the ferrous iron oxidation reaction. Studies which should result in enhancing the rate of oxidation of ferrous iron by using an activated carbon catalyst are already underway at BCR (EPA Project No. 14010 GYH titled "Oxidation of Ferrous Iron in Coal Mine Water with Activated Carbon Catalysts"). These studies should offer a practical solution to reducing the detention time necessary for the oxidation of ferrous iron, thereby allowing smaller tanks to be used with corresponding greater efficiency in mixing.

The BCR limestone process should be studied on a larger scale since the bench scale studies have not sufficiently defined the following:

(a) the mixing requirements in the reactor tank,

(b) the effect on cost of grinding coarse limestone versus the use of pulverized limestone,

(c) the effect of using mechancial aerators,

(d) the sludge recirculation ratio in an equilibrium condition and the effect of sludge properties such as solids content, alkalinity, etc. on process efficiency.

(e) the effect on the system of treating coal mine drainages having sulfate concentrations of up to 20,000 mg/l with resultant precipitation of gypsum,

(f) the effect of coagulant aids on settling properties and on recycled sludge, and

(g) the effect of more concentrated coal mine drainage on sludge volume.

Cost Evaluation of the Process

The development of cost data for construction and operation of full-scale mine drainage treatment plants to treat Class I coal mine drainage is difficult because of the wide range of flow and quality conditions included in Class I. Furthermore, treatment plant costs will vary due to the availability of suitable land, soil conditions, and topography of the site. For the cost analysis, it has been assumed that sufficient land is available to construct the treatment units, the topography of the proposed plant site is relatively level, the proposed site does not have a high water table, the depth to bedrock at the proposed plant site is a minimum of 10 feet, and soil at the proposed plant site contains a high clay content. In addition, it has been assumed that the proposed holding basin could be constructed with a water surface elevation sufficient to produce a gravity flow condition through the plant complex; therefore, the only pumping requirements would be for recirculation and wasting of sludge.

The treatment facility designed to treat coal mine drainage containing ferrous iron, using limestone as the neutralizing agent, consists of the following unit operations, in flow-through sequence: (a) holding or equalization lagoon; (b) reactor tank; (c) aeration tank; (d) settling basin, and (e) sludge dewatering basin.

The cost evaluation has been based upon the sequence of treatment units outlined above and the plant operation procedures and assumptions described in the following text. The coal mine drainage is conveyed to an earthen holding lagoon providing a 12-hour retention of the coal mine water. The holding lagoon design is based upon a 2-foot freeboard and 1:1 sidewall slope with riprap on the upper sidewalls. To permit monitoring and sampling of the holding basin overflow, an open concrete flume connects between the holding basin and reactor tank. The pulverized limestone and recirculated sludge is added in the reactor tank and is mixed with the coal mine drainage for a period of 60 minutes. Reinforced concrete reactor tanks eliminate the erosion problems of earthen basins caused by mixing action. The reactor tanks are built with vertical walls and a 4-foot freeboard.

Effluent from the reactor tank flows to the aeration tank where mixing, aeration and sparging of carbon dioxide are accomplished by mechanical surface aerators. The aeration tanks are sized for a 60-minute detention period, for the total flow rate to the unit. The aeration tanks are constructed of reinforced concrete. The aerators are mechanical surface aeration units which ensure continuous mixing. The aerator is secured with guy wires or supported by structural steel members spanning the tank walls.

The aeration tank effluent flows into the settling basin, providing a 12-hour detention period based upon the flow rate to the settling basin. The settling basin is provided with an influent distribution trough and weir and designed to minimize the possibility of short circuiting. The earthen basins are constructed of well-compacted clay-type soil to reduce leakage. In addition, the earthen settling basins are constructed with a minimum of 2 feet freeboard, a minimum inside wall slope of 2:1 and riprap on the upper sidewalls to prevent erosion by the surface wave action. An open channel as the treated water enters the receiving stream permits visual observation and continuous pH monitoring of the effluent. The sludge from the settling basins is pumped from the settling basin to the sludge pump well.

The sludge removal system has been designed to use portable floating surface pumps secured to the basin crest by guy wires. Recirculated sludge is pumped at a rate equal to the plant influent to the reactor tank. The remainder of the settled solids is pumped by the waste sludge pumps to the earthen sludge dewatering basins for additional concentration and disposal. All pumping systems include a standby pumping unit to be used during maintenance or breakdown of an operating pump.

The construction costs for the sludge dewatering facilities are based on the assumption that the basins can be located adjacent to the treatment complex and do not reflect the costs of pumping sludge through a long pipeline. The supernatant from the dewatering basin is discharged to the receiving stream. A concrete sump with pumps and appurtenances to pump the concentrated sludge from the dewatering basin provides a means for transfer of the sludge to tank trucks for ultimate disposal. The dewatering basins have the capacity to hold a 3-month sludge accumulation.

The design of the limestone treatment process units is based on single unit operation and does not reflect the capital costs if duplicate units are required.

Bulk storage of pulverized limestone is provided at the plant site to provide a minimum of 4 days storage. It is assumed that the limestone would be delivered to the plant site by pneumatic unloading trucks. The limestone storage bins are equipped with level indicators, limestone feeders, and dust collectors. The limestone feeders are installed in duplicate to reduce the possibility of plant shutdown due to mechanical equipment failure and to permit routine maintenance on the equipment. This equipment should be located near the reactor tank to reduce the distance required to convey the limestone. A control building is required at the plant site to house the plant services, administration facilities, and chemical feed systems. The plant services and administration section of the control building should contain (a) an office for the plant operator; (b) a central control panel from which the treatment plant operations would be monitored; (c) laboratory facilities for water quality analysis and chemical dosage controls; (d) main motor control center, and (e) maintenance shop. The chemical feed equipment section of the control building contains the limestone and coagulant aid feed equipment.

A paved access roadway should be constructed to the plant site to ensure delivery of the chemicals to the plant during all weather conditions.

The operation and control of the proposed coal mine drainage treatment complex is based upon the coal mine water flow rate and acidity concentration of the specific discharge to be treated. The holding basin effluent flow should be continuously and automatically metered. Acidity concentration at this point in the process must be manually sampled and analyzed to determine the quality of limestone feed. In addition, the pH should be continuously and automatically monitored by pH probes located between the aeration tank and settling basin and in the treated water discharge channel. The recirculated sludge flow should be automatically regulated by the plant influent flow rate at the ratio of 1:1.

Tables 42 through 45 inclusive are breakdowns of the capital costs for construction of treatment plants for the flow rates and cases of water

TABLE 42
ESTIMATE OF CAPITAL COST FOR LIMESTONE
TREATMENT PLANT TO TREAT
CLASS I COAL MINE DRAINAGE 0.1 MGD FLOW RATE

	CASE A*	CASE B*	CASE C*
1. SITE PREPARATION			
a. Clearing & Grubbing	$ 300.00	$ 400.00	$ 500.00
2. STRUCTURES			
a. Holding Lagoon	3,750.00	3,750.00	3,750.00
b. Reactor Tank	3,300.00	3,300.00	3,300.00
c. Aeration Tank	3,300.00	3,300.00	3,300.00
d. Settling Basin	7,860.00	9,790.00	10,500.00
e. Sludge Dewatering Basin	8,400.00	38,850.00	105,000.00
f. Sludge Pump Well	3,000.00	4,250.00	5,500.00
3. CONTROL BUILDING	30,000.00	30,000.00	30,000.00
4. MECHANICAL EQUIPMENT			
a. Mixers	2,625.00	2,625.00	2,625.00
b. Aerators	3,750.00	3,750.00	7,500.00
c. Sludge Recirculation Pumps	3,900.00	3,900.00	3,900.00
d. Waste Sludge Pumps	1,950.00	1,950.00	1,950.00
e. Settling Basin Sludge Pumps	4,550.00	4,550.00	4,550.00
5. CHEMICAL FEED EQUIPMENT	3,500.00	6,000.00	10,900.00
6. MECHANICAL PIPING	12,000.00	13,000.00	15,000.00
7. CONTROL EQUIPMENT	5,000.00	5,000.00	5,000.00
8. ACCESS ROADWAY	2,500.00	2,500.00	2,500.00
9. FINAL GRADING	2,000.00	2,000.00	2,000.00
10. ELECTRICAL	10,000.00	10,500.00	11,000.00
11. CONTINGENCIES	11,090.00	14,415,00	22,735.00
12. ENGINEERING	7,500.00	9,420.00	15,060.00
TOTAL CAPITAL COSTS	$130,275.00	$173,250.00	$266,570.00

* See page 106 for description.

TABLE 43
ESTIMATE OF CAPITAL COST FOR LIMESTONE
TREATMENT PLANT TO TREAT
CLASS I COAL MINE DRAINAGE AT 1.0 MGD FLOW RATE

		CASE A*	CASE B*	CASE C *
1.	SITE PREPARATION			
	a. Clearing & Grubbing	$ 750.00	$ 825.00	$ 920.00
2.	STRUCTURES			
	a. Holding Lagoon	20,900.00	20,900.00	20,900.00
	b. Reactor Tank	16,500.00	16,500.00	16,500.00
	c. Aeration Tank	15,750.00	15,750.00	15,750.00
	d. Settling Basin	45,250.00	49,800.00	57,000.00
	e. Sludge Dewatering Basin	47,750.00	380,000.00	790,000.00
	f. Sludge Pump Well	5,500.00	6,300.00	7,500.00
3.	CONTROL BUILDING	48,000.00	48,000.00	48,000.00
4.	MECHANICAL EQUIPMENT			
	a. Mixers	9,750.00	9,750.00	9,750.00
	b. Aerators	12,750.00	15,750.00	18,000.00
	c. Sludge Recirculation Pumps	4,250.00	4,250.00	4,250.00
	d. Waste Sludge Pumps	1,950.00	2,550.00	3,000.00
	e. Settling Basin Sludge Pumps	4,850.00	6,000.00	6,850.00
5.	CHEMICAL FEED EQUIPMENT	10,500.00	26,000.00	44,500.00
6.	MECHANICAL PIPING	25,000.00	27,500.00	29,000.00
7.	CONTROL EQUIPMENT	12,000.00	12,000.00	12,000.00
8.	ACCESS ROADWAY	2,500.00	2,500.00	2,500.00
9.	FINAL GRADING	4,000.00	4,000.00	4,000.00
10.	ELECTRICAL	15,000.00	16,000.00	17,000.00
11.	CONTINGENCIES	29,790.00	60,395.00	78,180.00
12.	ENGINEERING	19,260.00	39,960.00	52,560.00
	TOTAL CAPITAL COSTS	$352,000.00	$764,730.00	$1,238,160.00

* See page 106 for description.

TABLE 44
ESTIMATE OF CAPITAL COST FOR LIMESTONE
TREATMENT PLANT TO TREAT
CLASS I COAL MINE DRAINAGE AT 7.0 MGD FLOW RATE

		CASE A*	CASE B*	CASE C*
1.	SITE PREPARATION			
	a. Clearing & Grubbing	$ 1,200.00	$ 1,500.00	$ 1,800.00
2.	STRUCTURES			
	a. Holding Lagoon	115,500.00	115,500.00	115,500.00
	b. Reactor Tank	65,900.00	65,900.00	65,900.00
	c. Aeration Tank	87,900.00	87,900.00	87,900.00
	d. Settling Basin	256,000.00	290,000.00	350,000.00
	e. Sludge Dewatering Basin	230,000.00	2,260,000.00	5,250,000.00
	f. Sludge Pump Well	16,500.00	18,750.00	20,000.00
3.	CONTROL BUILDING	64,000.00	64,000.00	64,000.00
4.	MECHANICAL EQUIPMENT			
	a. Mixers	63,000.00	63,000.00	63,000.00
	b. Aerators	59,000.00	150,000.00	225,000.00
	c. Sludge Recirculation Pumps	19,750.00	19,750.00	19,750.00
	d. Waste Sludge Pumps	3,900.00	8,250.00	13,900.00
	e. Settling Basin Sludge Pumps	20,750.00	22,800.00	26,400.00
5.	CHEMICAL FEED EQUIPMENT	25,500.00	132,500.00	247,500.00
6.	MECHANICAL PIPING	58,000.00	64,000.00	70,000.00
7.	CONTROL EQUIPMENT	35,000.00	35,000.00	35,000.00
8.	ACCESS ROADWAY	2,500.00	2,500.00	2,500.00
9.	FINAL GRADING	9,250.00	9,500.00	10,000.00
10.	ELECTRICAL	36,000.00	37,500.00	40,000.00
11.	CONTINGENCIES	115,350.00	269,900.00	452,710.00
12.	ENGINEERING	76,200.00	117,900.00	298,920.00
	TOTAL CAPITAL COSTS	$1,361,200.00	$3,896,150.00	$7,459,780.00

* See page 106 for description.

TABLE 45. ESTIMATE OF CAPITAL COST FOR LIMESTONE TREATMENT PLANT TO TREAT SOUTH GREENSBURG COAL MINE DRAINAGE AT 4.0 MGD FLOW RATE

1.	SITE PREPARATION	
	a. Clearing & Grubbing	$ 500.00
2.	STRUCTURES	
	a. Holding Lagoon	76,000.00
	b. Reactor Tank	43,200.00
	c. Aeration Tank	43,200.00
	d. Settling Basin	118,500.00
	e. Sludge Dewatering Basin	35,000.00
	f. Sludge Pump Well	12,000.00
3.	CONTROL BUILDING	48,000.00
4.	MECHANICAL EQUIPMENT	
	a. Mixers	25,500.00
	b. Aerators	31,000.00
	c. Sludge Recirculation Pumps	11,250.00
	d. Waste Sludge Pumps	1,950.00
	e. Settling Basin Sludge Pumps	11,250.00
5.	CHEMICAL FEED EQUIPMENT	6,000.00
6.	MECHANICAL PIPING	40,000.00
7.	CONTROL EQUIPMENT	24,000.00
8.	ACCESS ROADWAY	2,500.00
9.	FINAL GRADING	6,000.00
10.	ELECTRICAL	30,000.00
11.	CONTINGENCIES	56,150.00
12.	ENGINEERING	36,960.00
	TOTAL CAPITAL COSTS	658,960.00

TABLE 46. BASIS FOR ESTIMATED COSTS OF LIMESTONE TREATMENT OF COAL MINE DRAINAGE PRESENTED IN TABLE 42, TABLE 43, TABLE 44, AND TABLE 45

1. CAPITAL COSTS
The capital costs are amortized for twenty (20) years at six (6) percent interest

2. LABOR

a. 0.1 MGD Treatment Plant:

1 Operator	@ $ 7,500	=	$ 7,500.00
1 Part Time Laborer	@ $ 3,000	=	3,000.00
			$10,500.00

b. 1.0 MGD Treatment Plant:

1 Operator	@ $ 8,000	=	$ 8,000.00
1 Laborer	@ $ 6,000	=	6,000.00
			$14,000.00

c. 7.0 MGD Treatment Plant:

1 Operator	@ $10,000	=	$10,000.00
2 Laborers	@ $ 7,500	=	15,000.00
			$25,000.00

d. 4.0 MGD Treatment Plant:

1 Operator	@ $10,000	=	$10,000.00
1 Laborer	@ $ 7,500	=	7,500.00
			$17,500.00

3. LIMESTONE
(Pulverized limestone delivered to plant site by bulk trucks.)

0 to 10 tons/yr	-	$7.00 per ton
10 to 20 tons/yr	-	$6.50 per ton
Greater than 20 tons/yr	-	$6.00 per ton

4. COAGULANT AID
$2.00 per pound

5. POWER

a. 0.1 MGD Treatment Plant: $85.00 per horsepower per year

b. 1.0 MGD Treatment Plant: $80.00 per horsepower per year

c. 7.0 MGD Treatment Plant: $75.00 per horsepower per year

d. 4.0 MGD Treatment Plant: $80.00 per horsepower per year

6. MAINTENANCE AND REPAIRS

a. 0.1 MGD Treatment Plant: $ 3,000 per year

b. 1.0 MGD Treatment Plant: $ 5,000 per year

c. 7.0 MGD Treatment Plant: $10,000 per year

d. 4.0 MGD Treatment Plant: $ 8,000 per year

7. CONTINGENCIES
One percent of construction costs

8. SLUDGE DISPOSAL COST
$10.00 per 1,000 gallons

TABLE 47. ESTIMATED COSTS OF LIMESTONE TREATMENT OF WQO, EPA CLASS I CASE A COAL MINE DRAINAGE.* ALL COSTS REPORTED AS CENTS PER 1,000 GALLONS OF WATER TREATED

Plant Capacity (MGD)	Capital Cost	Labor	Limestone	Coagulant Aid	Power	Maintenance & Repairs	Contingencies	Sludge Disposal Cost	Total Costs	Accumulation Of Sludge In 1 Yr.-Acre-Ft.
0.1	31.1	28.8	5.8	1.7	6.9	8.0	3.6	11.4	97.3	1.3
1.0	8.4	3.8	5.8	1.7	1.9	1.4	1.0	11.3	35.3	12.8
7.0	4.6	1.0	5.0	1.7	2.0	0.3	0.5	11.4	26.5	89.7

* See page 106 for description.

TABLE 48. ESTIMATED COSTS OF LIMESTONE TREATMENT OF WQO, EPA CLASS I CASE B COAL MINE DRAINAGE.* ALL COSTS REPORTED AS CENTS PER 1,000 GALLONS OF WATER TREATED

Plant Capacity (MGD)	Capital Cost	Labor	Limestone	Coagulant Aid	Power	Maintenance & Repairs	Contingencies	Sludge Disposal Cost	Total Costs	Accumulation Of Sludge In 1 Yr.-Acre-Ft.
0.1	41.4	28.8	43.8	1.7	6.9	8.0	4.7	118.7	254.0	13.3
1.0	18.3	3.8	40.5	1.7	2.9	1.4	2.0	118.9	189.5	133.1
7.0	13.3	1.0	40.0	1.7	2.7	0.3	1.5	118.5	179.0	929.4

* See page 106 for description.

TABLE 49. ESTIMATED COSTS OF LIMESTONE TREATMENT OF WQO, EPA CLASS I CASE C COAL MINE DRAINAGE.* ALL COSTS REPORTED AS CENTS PER 1,000 GALLONS OF WATER TREATED

Plant Capacity (MGD)	Capital Cost	Labor	Limestone	Coagulant Aid	Power	Maintenance & Repairs	Contingencies	Sludge Disposal Cost	Total Costs	Accumulation of Sludge In 1 Yr.-Acre-Ft.
0.1	63.9	28.8	81.0	1.7	8.1	8.0	7.3	256.8	455.6	28.7
1.0	29.6	3.8	75.0	1.7	3.8	1.4	3.4	256.8	375.5	287.8
7.0	25.4	1.0	75.0	1.7	3.6	0.3	2.9	257.3	367.2	2,011.9

* See page 106 for description.

TABLE 50. ESTIMATED COSTS OF LIMESTONE TREATMENT OF SOUTH GREENSBURG COAL MINE DRAINAGE. ALL COSTS REPORTED AS CENTS PER 1,000 GALLONS OF WATER TREATED

Plant Capacity (MGD)	Capital Cost	Labor	Limestone	Coagulant Aid	Power	Maintenance & Repairs	Contingencies	Sludge Disposal Cost	Total Costs	Accumulation of Sludge In 1 Yr.-Acre-Ft.
4.0	3.9	1.2	1.1	1.7	2.3	0.5	0.4	2.5	13.6	11.1

TABLE 51. COMPARISON OF COSTS FOR TREATING COAL MINE DRAINAGE

Source	Acidity, mg/l	Chemical Costs: Cents per 1,000 gal	Chemical Costs: Cents per mg/l acidity 1,000,000 gal	Total Costs, Cents per 1,000 gal
This report:				
Case A, 0.1 mgd	1,000	5.8	5.8	97.3
1.0 "	"	5.8	5.8	35.3
7.0 "	"	5.0	5.0	26.5
Case B, 0.1 mgd	8,000	43.8	5.5	254.0
1.0 "	"	40.5	5.1	189.5
7.0 "	"	40.0	5.0	179.0
Case C, 0.1 mgd	15,000	254.0	5.4	455.6
1.0 "	"	189.5	5.0	375.5
7.0 "	"	179.5	5.0	367.2
South Greensburg 4.0 mgd	190	1.1	5.8	13.6
Corsaro, et al (Ref. No. 16)				
0.9 mgd	1,400	11.5	8.2	33.0
2.7 mgd	650	5.5	8.5	19.95
Calhoun (Ref. No. 17) ~ 200 gal/day	360	~ 1	2.8	~ 6*
Wilmoth et al (Ref. No. 18)				
7.5 cfs	466	4.7	1.0	Not reported
Johns-Manville (Ref. No. 19)				
1.5 mgd	367	1.2	-	15

* Includes only chemical cost, power, maintenance, and labor.

quality previously described. A summary of the procedures used to determine the plant operating costs presented in Tables 47 through 50 inclusive are listed in Table 46.

The costs presented in Tables 47 through 50 have been summarized and compared to other published costs (16, 17, 18, 19) in Table 51. As indicated previously, waters of the quality of Case B and Case C of the Class I discharge are the exception, and the high costs for treating these waters may not, in fact, have much meaning.

Corsaro et al (16) treated a mine water containing approximately 1,400 mg/l of acidity and having a flow of 0.9 mgd with lime for a total treatment cost of 33.0 cents per 1,000 gal. This can be compared with treatment of Case A (1,000 mg/l) at 1.0 mgd with limestone, for which the total cost for treatment was 35.3 cents per 1,000 gal (See Table 47). These costs include 1.7 cents per 1,000 gal for coagulant aid, and it is noted that no coagulant aid was used in the lime treatment study. In the same study (16), chemical costs were higher for treatment with lime than with limestone and ranged from 7.5 to 9.4 cents per mg/l of acidity per 1,000,000 gallons for lime treatment compared to 5.0 to 5.8 for limestone treatment from this study.

Calhoun (17) and Wilmoth and Hill (18) reported cost of limestone for treating mine waters containing ferric iron of 2.8 and 1.0 cents per mg/l acidity per 1,000,000 gallons, respectively, as compared to 5.0 to 5.8 from this study. Neither reported complete total costs.

A recent Johns-Manville study (19) reports the lowest total cost for treating mine water with limestone as 15 cents compared to 13.6 cents reported here for treating the South Greensburg water.

In summary, chemical costs and total costs for the BCR limestone process for treatment of coal mine drainage, particularly the more-difficult-to-treat drainages containing ferrous iron, compare favorably to costs of treatment using other neutralization processes.

SECTION VIII

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* * * * *

A significant objective of this project was to investigate practical means of abating mine drainage pollution. Such research projects, intended to assist in the prevention of water pollution by industry, are required by Section 6b of the Water Pollution Control Act, as amended. This project of EPA was conducted under the direction of the Pollution Control Analysis Section, Ernst P. Hall, Chief, Dr. James M. Shackelford, Project Manager, Ronald D. Hill, Project Officer.

SECTION IX

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Laboratory studies were conducted with limestone as the neutralizing agent for coal mine water. Batch tests were used to determine the properties of limestone necessary for effective neutralization. Continuous flow tests were used to determine conditions required for an effective neutralization process.

The following variables are of importance for limestone to be an effective neutralizing agent: (a) particle size, (b) Ca and Mg content, and (c) surface area. Limestones having the smallest particle size commercially available were tested and found to be effective if criteria for variables other than particle size were met.

Data obtained with a small laboratory continuous flow test apparatus were used in determining operating conditions for a continuous treatment process for neutralizing mine water with limestone. An evaluation of this process indicated technical feasibility, advantages and disadvantages, and need for further study of certain aspects of this process.

The cost of treating coal mine water with the BCR limestone treatment process compares favorably with the published costs of treating mine water by other processes.
(Ford - Bituminous Coal Research, Inc.)

Abstractor C. T. Ford   *Institution* Bituminous Coal Research, Inc.

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