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PROGRESS IN CONTROLLING ACID MINE WATER: A LITERATURE REVIEW

By Walter C. Lorenz

UNITED STATES DEPARTMENT OF THE INTERIOR
BUREAU OF MINES
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PROGRESS IN CONTROLLING ACID MINE WATER: A LITERATURE REVIEW[1]

by

Walter C. Lorenz[2]

INTRODUCTION AND SUMMARY

In connection with its renewed study seeking solutions to problems created by release of acid water from bituminous coal mines, the Bureau of Mines recently surveyed reports already written on the subject. This publication is based on that search.

The Problem

Poor distribution of water is evident on an ordinary geographic map of the United States. The more abundant supplies of surface water appear to be centered in the northeast, the southeast, and the central humid areas of the country. It is in the midst of this abundant surface water, in the Ohio River Valley, that most of the bituminous coal is mined. Varied industry has located in the valley to use the coal and the river. The coal is a source of power and raw material. The river provides transportation for raw and finished materials; equally important, it provides the water that is used for cooling and processing in manufacturing. It also serves as a vehicle for the disposal of waste.

Keeping the surface water in the Ohio River basin free of excessive domestic and industrial waste pollution has been a great problem. The Ohio River Valley Water Sanitation Commission, organized in 1948, has inspired progress in pollution control that has reversed a half-century trend of indiscriminate discharge of waste into the river and its tributaries.

The most serious pollution problem that continues in the Ohio River is the discharge of acid water from bituminous coal mines. The quantity of the potentially polluting water increases with rising coal production, but unlike most industrial and domestic waste it does not decrease when production has ceased or population has decreased. Acid drainage may continue for years after a mine has been abandoned. It is potentially very great because the total bituminous coal already mined in Pennsylvania and West Virginia represents only 9 or 10 percent of their reserves.

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[1] Work on manuscript completed May 1961.

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The chemical pollutants in acid mine water, including sulfuric acid and the acid salts of iron and other metals, are toxic to aquatic life. They destroy or reduce the natural alkalinity of streams, resulting in a permanent sulfate hardness both difficult and expensive to remove at water-treatment plants. The presence of the dissolved salts of iron and manganese imparts undesirable properties for many water users. As with other pollutants, the detrimental effects of mine-drainage pollution grow in importance with the water needs of the expanding population, especially in urban centers. Future needs for suitable domestic and industrial water must be met from various surface-water sources; the ground water supply will be inadequate.

The magnitude of the acid mine water problem in the Ohio River Valley can be visualized from an estimate made in 1942 by the U.S. Public Health Service (198).[3] It reported the sulfuric acid load in the river as 2.4 million tons per year, of which more than half drained from active and abandoned mines in Pennsylvania and northern West Virginia. From the same report, the figures for table 1 were taken to represent the acid load of the Allegheny and Monongahela Rivers.

TABLE 1. - Acid load of Allegheny and Monongahela Rivers in 1942

	Tons per year
Allegheny River.......	405,150
Monongahela River.....	920,656
Total..............	1,325,806

Acid is formed in coal mines from the pyritic material in coal, gob, and associated rock, in coal, and in coal-refuse storage when the pyrite contained in these various materials is exposed to the oxygen and moisture of the atmosphere. When the sulfuric acid and the acid salts of iron, formed from the pyrite, are dissolved by surface or ground water and carried to an adjacent watercourse, they become acid mine drainage and pollutants of connecting streams. Secondary reactions between sulfuric acid and the acid salts of iron, inorganic minerals, and organic materials in the mines, in coal storage and coal-refuse piles, and in the streams produce other chemicals often found with acid mine drainage.

Prior Research and Preventive Measures

Pollution of streams by acid mine water has been a problem of great concern to many individuals and organizations in the past 40 years. Many theories, investigations, and field experiments have been directed toward a solution.

Early studies, before and after World War I, were mainly concerned with identifying coal mine drainage as one source of acid in certain Pennsylvania streams. Methods were suggested for correcting the problem by treating with

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[3] Underlined number in parentheses refer to items in the bibliography at end of this report.

lime and recovering valuable byproducts. A neutralizing plant where byproducts were recovered was described by Campbell (48) and Tracy (194). Cost of treatment with lime was discussed by Handy (87) and Leitch (131). They recommended treating the water to neutralize it, as the only known method to correct pollution of streams by acid mine drainage.

A second phase in the progress toward a solution of the problem began with the studies and the recommendations made by Leitch and Yant, Bureau of Mines (132), on sealing abandoned coal mines. They were able to show from data collected that acid formation in three experimentally sealed mines did decrease over a period of more than 1 year. This information was used as a basis for an extensive mine-sealing program sponsored by the Federal Government during the 1930's, as a public works project, under the general supervision of the U.S. Public Health Service.

In addition to the work at the Bureau of Mines, research projects were carried out at West Virginia University, covering the cause and the extent of acid mine water in West Virginia; concurrent studies were made of results of mine-sealing programs in the State. The mine-sealing phase of abating stream pollution from acid mine water, which included both Federal and State programs, extended from about 1928 to World War II. The State-sponsored mine-sealing program in Pennsylvania started after World War II.

The next period, from about 1944 to the present, covered laboratory work on oxidation reactions, on methods of chemical analysis, and on the role of bacteria; it included laboratory and pilot work on the practicability of neutralizing acid water, on sealing abandoned coal mines, and on an engineering approach to a solution for the problem of acid mine water. The early work of this period, sponsored by Bituminous Coal Research, Inc., was carried out at West Virginia University. There, Hinkle and Koehler (93-95), Colmer and associates (58, 59), and Temple and associates (184-187) studied oxidation reactions, methods of chemical analysis, and the role of bacteria.

Soon after World War II, the Department of Health, Commonwealth of Pennsylvania, and later the National Coal Association and other coal producer organizations sponsored industrial fellowships at Mellon Institute for studies on acid mine water. Braley (37) investigated oxidation reactions, methods of analysis, and the practicability of neutralizing acid water and sealing abandoned coal mines, and advocated an engineering approach to a solution for the problem of acid mine water. Leathen and associates (111-120) studied the role of bacteria in bituminous coal mines and in the acid water drainage from the mines.

In 1955, the Ohio Department of Health, and later the Ohio Department of Natural Resources, sponsored studies on acid mine drainage in the State at the Ohio State University. The work at this institution was carried out by a team of scientists representing many skills (147). Oxidation of pyrite, formation of acid, and the role of bacteria are being studied in the laboratories; field experiments are made on mine sealing, neutralization, impoundments, and other engineering approaches.

Many studies have been made, and many reports have been published about acid mine drainage. While the various studies have contributed to a better understanding of the problem, areas of conflicting information and areas of limited subject matter knowledge exist.

Field applications designed to curb or stop pyrite oxidation are occasionally successful when most of the pyrite-containing material is submerged in water or is covered with earth. Except for an occasional natural flooding of an underground mine or earth sealing of a few refuse piles, most applications of this principle are found at strip mines. Similarly diversion of ground and surface water away from the mining is usually found at strip mines; a few experimental exceptions apply to underground mines or an occasional refuse pile.

Neutralization and various dilution projects have been advanced as treatments for acid drainage. The cost of lime, application difficulties, temporary nature of the treatment, and failure to remove objectional sulfates have led many investigators to conclude that neutralization cannot solve the problem but that it is useful and can be applied successfully in certain isolated cases (28, 34, 37, 40, 52, 127, 131). Some dilution projects are useful in controlling acid waterflow to streams, and streamflow control from flood-control dams has been reported capable of reducing overall acidity of a stream (110, 198). Many investigators agree that maintaining a proper ratio of acid mine water to streamflow will allow a stream to receive acid drainage and remain alkaline. They usually conclude that the dilution principle should be used where it is applicable, even though it does not solve the problem (37, 85, 105, 110, 160, 198).

The variations in terrain, in geological formation of coal and associated rock, in methods of mining, and in composition of pyritic materials contribute to the complexity of the problem. More must be known about the composition of the pyritic materials associated with coal, the mechanism of acid formation, and the control of chemical and bacterial oxidation reactions.

In the past, the Bureau of Mines has assisted the coal industry on many problems concerning acid mine water, including abatement of stream pollution from various mining wastes. Presently, the Bureau has reactivated a research project on the mechanics of reaction in the formation of acid in coal mines with a program designed to obtain the needed fundamental information.

SOURCES OF POLLUTION

Occurrence of Iron Sulfides

A natural chemical reaction, which takes place between the iron sulfides (pyrites) associated with coal and atmospheric oxygen and moisture, is responsible for the formation of the soluble acid sulfates. Some of the iron sulfides occur in the coalbed and others occur in the rock above and below the coal. Although marcasite and pyrite are often mentioned together, these sulfides, unless otherwise identified, are considered to be pyrite by many investigators. Yancey and Fraser (203), Sprunk and O'Donnell (175), Yancey (202), R. Theissen (189), G. Theissen (188), and Newhouse (153) have described the occurrence of pyritic material in binders or partings, in sulfur balls or niggerheads, in lenses, in veins or plates, and in finely disseminated particles or crystals. These forms in the coalbed are described in the following section.

Binders and Partings

Binders or partings are layers of shale that are parallel to the bedding planes of the coal, often continuous over large areas. These partings frequently contain pyrite and other minerals. A good example of this formation can be observed in the Pittsburgh seam.

Sulfur Balls

Sulfur balls are globular or irregular angular masses commonly found in many coalbeds. They are often mixtures of pyrite, clay, calcite, and other minerals, though occasionally they are siderite, limestone, or calcium sulfate. The balls may be distributed at random throughout the coal, or they may be concentrated in certain benches or layers in the bed.

Lenses

Lenses are circular or elliptical masses. They are possibly the most common of pyritic impurities in coal. They are usually thick in the center, gradually thinning to an outside edge. Common sizes range from one-half inch to 3 inches in thickness and about 1 foot across, although much larger ones are sometimes found. In some beds, small lenses occur at the same horizon along certain bedding planes. They may be almost edge to edge forming what appears to be a continuous sheet. In other cases the lenses are distributed randomly through the bed and may be found in any position, horizontal or vertical.

Veins or Plates

Veins or plates are thin streaks of pyrite, which fill joints, cleats, or fractures in many coalbeds. Pyrite in this form is probably secondary in origin and has been redeposited and recrystallized in the cracks and fractures after the coal was compacted; kaolinite and calcite are occasionally mixed with the pyrite.

Finely Disseminated Particles

A large part of the total pyritic sulfur in coal occurs in a finely disseminated form. The particle size of these crystals range from a fraction of a micron to 50 or more microns. The small crystals may be distributed evenly through the bed but are often concentrated in certain benches or layers. Thiessen (189) has shown by microscopic analysis of coals, starting at the bottom of the stratum and progressing upward every few inches, that seams just above the basic fire clay contain most of the pyritic material.

After the coal is mined, the foregoing materials, which contain pyrite, are often removed by handpicking or by mechanical action in a preparation plant. They constitute the accumulated refuse from coal mining. As this refuse is discarded either inside or outside a mine, the pyrite becomes exposed to natural oxidation and finally to natural leaching of the oxidation products by ground or surface water.

The most common pyritic materials usually associated with formation of acid are large sulfur balls, top and bottom coal, and rock above and below the coal seam. Of these, the more important sources are in the rock above and below the coal seam and in the top and bottom coal that is not mined but allowed to remain in place as roof and floor. In these places, pyritic materials are exposed to oxidation through upheaving, spalling, and roof falls, even after a mine has been abandoned.

Braley's data (37) from the analysis of three core drillings, taken for exploratory purposes in northern West Virginia, indicated how the sulfur content was distributed above, below, and through the Pittsburgh, the Sewickley, and the Waynesburg seams. The highest sulfur percentages were found in the shale below the Pittsburgh seam, in the 8-inch bottom and the 8-inch top coal of the seam, in the shale parting, and in the shale and the coal above the seam. Similar conditions and generally lower sulfur percentages exist for the Sewickley and the Waynesburg seam. Braley calculated that 8 inches of roof coal, containing about 2 percent sulfur, could produce about 45,500 tons of sulfuric acid per square mile of workings.

Temple and Koehler (187) examined and analyzed the roof strata that had been exposed by a fall in a northern West Virginia mine in the Pittsburgh seam. They found sulfur in varying amounts in the shales and the exposed coals from 0 to 25 feet above the seam. The exposed strata were coated with acid salts, identified as starkeyite and copiapite.

The examination of rock cover from core drillings, roof falls, and exposed overburden at strip mines has revealed that pyritic material exists many feet above the coal being mined. Even at 30 or more feet the rock often contains more sulfur than the coal. The disturbance of the cover or the overburden during mining exposes these pyritic materials to the air. The natural oxidation that then occurs is apparent in formations of white or yellow deposits of acid sulfates that often coat the exposed rock.

Oxidation of Iron Sulfides

The rock immediately above and below the coal seam often contains pyritic material as finely disseminated particles too small to be visible upon casual observation. Braley (37) described this pyrite as finely divided, black, amorphous material. Newhouse (153) reported minute grains that do not reflect light or etch with acids like single crystals but appear to be aggregates of crystals of submicroscopic size. Because of this small crystal size or because of other associated materials, the pyritic material in rock often oxidizes more rapidly than the various pyritic materials in the coalbed under the same exposure. Braley (25) reported an experiment to determine differences in oxidation rate between materials that he classified as yellow pyrite, marcasite, and black amorphous pyrite. Marcasite reacted 10 times as fast and black amorphous pyrite, 80 times as fast, as yellow pyrite.

Temple and Koehler (187) concluded that the two most important sources of pyritic material that contributed to acid formation were sulfur balls and roof strata. Of the two, roof strata showed more rapid oxidation and acid formation.

Intermediate steps of the natural oxidation of exposed pyritic material have often been identified as entities in dry, mined-out areas of many coal mines. These entities include melanterite, white to light-green crystals of ferrous sulfate; copiapite, yellow to brown crystals of ferric sulfate; halotrichite, white crystals of iron or magnesium aluminum sulfate; and alunogenite, white crystals of aluminum sulfate. Yellow amorphous masses also often formed in worked-out mine areas have been identified as basic hydrated ferric oxides or basic hydrated ferric sulfates.

The natural oxidation of pyritic material may be represented by the following chemical equations, which have been quoted by many investigators:

$$2FeS_2 + 7O_2 + 2H_2O = 2FeSO_4 + 2H_2SO_4 , \qquad (1)$$

$$FeS_2 + 3O_2 = FeSO_4 + SO_2 , \qquad (2)$$

$$FeS_2 + 7Fe_2(SO_4)_3 + 8H_2O \rightleftharpoons 15FeSO_4 + 8H_2SO_4 . \qquad (3)$$

Secondary reactions take place between ferrous sulfate, sulfuric acid and the compounds in nearby clays, limestones, sandstones, and various organic substances that are present in mines or streams to produce the variety of chemicals found in mine drainage. The supplemental reactions explain the existence of aluminum, manganese, calcium, magnesium, sodium, potassium, chlorates, nitrates, and silicates.

Studies have been made to determine a mechanism of acid formation in coal mines by atmospheric oxidation and by oxidation with micro-organisms. Several investigators described their experiments with atmospheric oxidation of pyritic materials (37, 45, 93, 147); other scientists reported on their investigations as to the role of sulfur- and iron-oxidizing bacteria in the formation of acid from pyritic material (58, 111-120, 184, 185).

Atmospheric Oxidation

Earlier investigators often reported that pyrite would oxidize after a specimen was exposed to oxygen in the atmosphere or oxygen in water. Stokes (181) stated that the amount of oxidation depended upon the time a specimen was exposed to either dry or moist air, or to water containing oxygen or other oxidizing agents in solution. Allen and Johnston (6) reported that it was well known that the sulfides of iron gradually oxidize when exposed to the atmosphere. Winchell (201) noted that oxidation is carried out by the action of descending meteoric water, free from dissolved solids but containing gases in solution, especially oxygen, nitrogen, and carbonic acid.

Downs (68), and Burke and Downs (45) were the first to verify experimentally the equations (1) and (2), using pyritic material associated with coal. Their tests were made on sulfur balls, containing about 90 percent FeS_2, in an apparatus designed to control oxygen, moisture, temperature, and solution concentration. Braley (37) confirmed this work in controlled oxidation experiments when he demonstrated that 1 mole of pyrite would react with dry air to form a mole of ferrous sulfate and a mole of sulfur dioxide, equation (2). In a similar fashion except for the use of wet instead of dry air, he showed that each mole of pyrite would oxidize to produce a mole of ferrous sulfate and a mole of sulfuric acid, equation (1). Temple and Koehler (187) verified equation (3) by mixing finely ground pyritic material in a solution of ferric sulfate. In this experiment, the ferric ion reacted rapidly with the pyrite to form ferrous sulfate and sulfuric acid.

Oxidation by Microorganisms

The reports written before and immediately after World War I usually contained the theoretical equation (1) for oxidation of pyrite. These authors assumed that the reaction proceeded without catalyzers, because previous investigators referred to atmospheric oxygen along with other chemical oxidizers in their studies of oxidizing pyrite and marcasite (1-4, 42, 82, 180, 181, 201).

The first reported observation that indicated that other substances may be present to accelerate the oxidation reaction arose from a study by Parr and Powell (154), on analysis of sulfur in coal. Fresh pulverized coal samples were inoculated with well-oxidized coal that was high in sulfates. At the end of an 88-day test, it was noted that soluble sulfates in the inoculated samples increased over those found in noninoculated ones. The explanation for this increase was a theory on the possible existence of bacteria or catalytic agent that accelerated the normal atmospheric oxidation of the sulfur in coal, after it had been mined. Apparently, no further work was carried out to identify or isolate bacteria or catalytic agents at that time. Davidson (65) in 1930 and Carpenter and Herndon (52) in 1933 conducted various experiments that confirmed Parr and Powell's theory. Duplicate pulverized coal samples were placed in distilled water, and half the samples were sterilized. Both sets were analyzed at intervals over an extended period of time. The data showed higner acid formation in the unsterilized samples. The conclusion was that at least part of the higher acidities could be attributed to bacteriological action. Their attempt to isolate the bacteria responsible for the acidity in the unsterilized samples was unsuccessful; a bacterium, which thrived at a pH of 2.9 to 3.1, was isolated from sources other than acid mine water and tentatively was identified as *Thiobacillus thiooxidans*.

In 1947 at West Virginia University, Colmer and Hinkle (58) reported conclusive evidence of the presence of a known sulfur-oxidizing bacterium, *Thiobacillus thiooxidans*, in acid mine water. Another bacterium that oxidized ferrous sulfate to ferric sulfate was isolated from the same acid water and identified as *Thiobacillus ferrooxidans* (59). Both organisms were found in every sample of acid mine water examined. Temple and associates (184-187) at West Virginia University reported that in addition to oxidizing ferrous to ferric iron, *Thiobacillus ferrooxidans* enhances acid formation from pyritic material. In the experiments made by Temple on oxidation of pyrite from a pulverized sulfur ball, *Thiobacillus ferrooxidans* produced a total acidity that was nearly double that reported for sterilized samples or for atmospheric oxidation only. Further confirmation of the role of bacteria in the formation of acid in coal mines was made at actual sites of acid formation in various underground mines. In each instance *Thiobacillus thiooxidans* and *Thiobacillus ferrooxidans* were identified and associated with the acid formation.

Leathen and associates (111-120), Mellon Institute, isolated Thiobacillus thiooxidans from every acid mine water sample they examined. In studies of the role of this bacterium in acid formation, various samples were inoculated with it, including museum-grade pyrite, museum-grade marcasite, sulfur ball material, and elemental sulfur. These experiments showed that the bacterium increased formation of acidity and sulfate from elemental sulfur. Only a slight increase in acidity and in sulfate was noted from bacterial action on museum-grade marcasite, and no increase was observed from the action on sulfur ball material on museum-grade pyrite. Similar experiments were conducted with the iron-oxidizing bacterium, Ferrobacillus ferrooxidans. In these studies, increases in acidity and in sulfate production from sulfur ball material that were 3 to 10 times greater than those obtained from sterile samples were observed. Substantial increases were found in acidity and in sulfate production from museum-grade marcasite but not from bacterial action on pyrite or elemental sulfur.

Moulton and associates (147), Ohio State University, also conducted studies on the role of microorganisms in the oxidation of pyritic materials. They used a pure culture of Ferrobacillus ferrooxidans and bacteria obtained from acid mine water. The rate of acid formation from pulverized pyrite and marcasite inoculated with bacteria was more than twice that of the sterile controls. Studies using a culture of the same bacteria in mine water showed greatly accelerated oxidation and precipitation of iron and a release of sulfuric acid. The starting pH value decreased from 3.5 to 2.8 or 2.6 after inoculating with the bacteria. While the presence of sulfur-oxidizing bacteria was demonstrated in acid mine water, these microorganisms apparently played no role in the formation of acid. Moulton postulated that the presence of sulfur as an intermediate product may account for their presence in the acid drainage.

Thiobacillus thiooxidans and Thiobacillus ferrooxidans were reported by Ashmead (16, 17) to be present in certain acid mine waters and coal mines in England. Bryner and Jameson (41) identified similar bacteria in acid water from copper mines in Utah.

The observations made at Ohio State University confirm the results of studies made at West Virginia University and at Mellon Institute. Bacteria carry out the oxidation of ferrous to ferric iron, and at present this is the only role that may be assigned them. The conclusions drawn by the various investigators, however, conflict. West Virginia and Ohio State University groups believe that bacteria play a significant, though not completely understood, role in the oxidation of pyritic materials, but the investigators at Mellon Institute have indicated that bacteria are not involved in the oxidation reaction to a major extent.

The research on oxidation of iron sulfides has been extensive. Much has been written on investigations concerning oxidizers, including atmospheric oxygen, and the acceleration of oxidation by an electric potential and by the action of bacteria. Only a few of the steps in the acid-producing oxidation reactions have been experimentally confirmed. The lack of information is noticeable with respect to basic aspects of acid formation; more accurate data would greatly assist better understanding of the mechanism.

MEASURES TO PREVENT POLLUTION

Neutralization of Acid Mine Water From Underground and Strip Mines

Many methods have been advanced as possible solutions to the acid mine water disposal problem. Often these suggested neutralizing the acid as it flowed from the mine before it entered the stream and recovering the valuable byproducts. The most noted example of developing this idea was the Calumet Neutralization Plant, which was operated intermittently from 1914 to 1920 by the H. C. Frick Coke Company. Campbell (48), and Tracy (194) described the construction and operation of the plant: (1) for sufficient treatment of mine water to permit its use in quenching coke; and (2) as a byproduct plant to produce a special oxide of iron, which was used in the removal of hydrogen sulfide from manufactured illuminating gas. The first operation was unsuccessful, as additional sulfate from neutralized water made the coke undesirable for metallurgical purposes. The second was unsuccessful because plant operation and maintenance costs became excessive. Because of these difficulties, the product became noncompetitive with a foreign product imported after World War I. The plant was shut down and dismantled in 1920.

Leitch (131), and Handy (87) recommended treating acid water to neutralize it as a logical method to alleviate the pollution of streams by acid mine drainage. Handy (87) presented the cost developed by the Melcroft Coal Co. for treating mine water with hydrated lime, together with an estimated cost for constructing and operating a 500,000-gallon-per-day treating plant.

Many ideas were presented between 1920 and 1930 for continuous neutralization of acid water discharging from a coal mine; some were even patented. Among those patented were plants designed to use marl or other porous calcium carbonates in specially constructed equipment placed at a point of water discharge (U. S. Patent Nos. 1,685,300 and 1,685,301). Kaplan (107) and Kaplan and Reger (108) proposed to neutralize the acid with various alkaline cyanides and recover valuable cyanide byproducts.

One of the common practices of this period was for mine operators to build boxes or flumes for lime or limestone near the mine entrance. The operator had been led to believe that this would provide ample neutralizing capacity and that the streams would soon clear. However, when no change was noted, either in the drainage or in the streams, the projects were soon abandoned. Generally the lime or limestone became coated with a yellow basic hydrated oxide of iron, hydrated ferric sulfate, or calcium sulfate, which retarded or stopped further neutralization.

Because the neutralization theory was so commonly accepted, various research groups made it one of their first projects for investigation. After comparing data from various experiments carried out by mine operators, Leitch (127) concluded, "It seems obvious that the cost of chemical neutralization of acid mine water must be calculated for individual mines, and these costs must also be considered an additional burden from which virtually nothing of material value can be returned to the operator. Chemical neutralization may cause increased hardness in direct proportion to the original acidity, possibly necessitating softening; and finally enough chemicals are said to remain in solution to cause foaming and priming in boilers." Carpenter and Herndon (52), after carefully considering many alkalis and byproducts, noted, "It is clearly evident that the treatment with the chemicals does not completely solve the problem since the sludge itself must be considered.... It is apparent that any attempt to treat the wastes on a large scale would be so expensive that unless some material of value could be produced it would be prohibitive. Since the materials in the water are mainly iron sulfates, and there are numerous other cheap sources of iron and sulfur, no great profit could be derived." In 1951, Braley (28, 34, 37) reported a pilot plant experiment in neutralizing acid mine drainage; his conclusions were, "Although acid mine drainage can be chemically treated with lime or other alkali to neutralize the acid, such a method is not practical or feasible because of the economic and other difficulties involved...hydrated lime might be used succesfully to neutralize casual pools of acid water found in coal workings, especially strippings, prior to the release of the water into drainage channels.... Calculations from the reactions...show that one pound of limestone is required to neutralize 0.98 pound of sulfuric acid. Thus, to neutralize the acid produced in the mines of Pennsylvania during 1 year would require the total annual production of limestone in that state, as reported for the year 1944."

While neutralizing acid water from existing mines presents an overwhelming problem in economics, limited treatment of water at mines has become commonplace. In clean-stream areas of Pennsylvania, an operator will usually neutralize casual pools before discharging to the stream. In Butler, Fayette, Mercer, and Venango Counties, Pa., a few strip mine operators treat the acid water as it drains or is pumped from their mines before it enters a clean stream.

In Ohio, Indiana, Illinois, Kentucky, West Virginia, and Pennsylvania, mining operators often use a closed circuit, wash-water system at preparation plants. Dirt and other impurities, including iron sulfides and sulfates, are removed from the coal and are carried along with the wash water into a settling tank or pond. The overflow water, reused for washing coal, sometimes becomes acid and must be neutralized to prevent corrosion of the steel washing equipment. Many operators treat the acid water with lime slurry to a pH of 5.0 to 7.0 depending upon local requirements for protection of equipment and final disposition of the water.

Mine Sealing of Underground Mines

Crichton (61) describes various suggestions and remedies for solving the stream pollution problem with special emphasis on drainage from abandoned mines. He felt that the custom of neutralizing water containing acid mine drainage, then softening it for domestic and industrial use, only postpones the day when more drastic measures must be put into effect. These suggestions and remedies were proposed: (1) Sealing abandoned mines; (2) removing drainage from mines through pipes, ditches, or ducts to preselected downstream sites; (3) distilling the contaminated waters; (4) impounding fresh water for the purpose of dilution; and (5) stopping the mining of coal in certain areas. Crichton's proposals are still employed as preventive measures to control acid mine water. Collins (57) proposed treating water with lime for active mines and suggested sealing abandoned mines.

The term "mine sealing", as it has been discussed in many reports and papers, refers to closures of entrances, ventilating shafts, strata fractures, sinkholes, and other cracks or openings of underground mines with earth, rock, concrete blocks, concrete, brick, steel, or lumber. Since the term has become almost exclusively associated with underground mines, strip mine sealing will be discussed with strip mining under "Segregation and Sealing of Acid Forming Materials."

From 1914 to 1918, the expansion of the coal industry intensified the stream pollution problem from acid mine drainage (198), particularly from the bituminous coal areas of western Pennsylvania. The Allegheny River and its main tributary the Kiskiminetas River, and the Monongahela River and its main tributary the Youghiogneny River had become acid during some seasons of the year. The extent and magnitude of stream pollution from acid mine drainage has continued to increase where ever extensive mining has been practiced.

In 1924 the Bureau of Mines, recognizing a need, started one of the first research programs in the United States, designed to develop fundamental information on the formation of acid in coal mines. The Bureau had already been active in investigating corrosion problems arising from acid water in coal mines (14, 56, 76, 103) and in using analytical methods to determine the degree of acidity and the nature or composition of coal mine water (76, 172). Leitch (122-135) observed that many mines abandoned and caved or otherwise sealed were discharging water that was not acid or only slightly so. These abandoned mines were usually in areas or districts where the water flowing from adjacent open or active mines was acid. Because oxygen was necessary for acid formation, the sealing effect of the caving and the closing of entrances and other openings was concluded to be excluding oxygen from the mine. To confirm this, a series of tests, investigations, and field experiments was devoted exclusively to mine sealing.

In 1932, three mines were experimentally sealed, and the drainage was analyzed at regular intervals for more than a year. The acidity decreased thus demonstrating that the closing of entrances and other openings reduced or possibly stopped the formation of acid in mines by the exclusion of air. The seals were built with a water trap outlet designed to exclude air but not to prevent a normal flow of water from the mine.

Based on this work, the Bureau of Mines advocated sealing abandoned mines, not only to conserve natural resources but also to furnish employment in depressed areas. Instructions were prepared on constructing seals, methods of analysis for mine water, sampling procedures, and methods of measuring flow in small streams.

In 1933, an extensive mine sealing program was started by the Federal Government as Works Progress Administration, and Civil Works Administration projects. This program continued for several years in Ohio, Pennsylvania, West Virginia, Indiana, Illinois, Kentucky, Tennessee, Maryland, and Alabama; studies were conducted in Kansas and other States having coal mines. About $5.4 million was spent (198) on the program; the money was divided among the various States on the basis of relief fund requirements. The allotments were about 36 percent to Ohio, 28 percent to Pennsylvania, 22 percent to West Virginia; the remaining 14 percent was divided among the other States. The U.S. Public Health Service administered the program in cooperation with State and local health departments.

The data accumulated during the 1930's on existing active and abandoned mines, on acidity or alkalinity of the drainage from these mines, and on costs for sealing some of these mines have been used in various summaries to evaluate the effectiveness of the mine-sealing program (55, 97, 198). An estimated 28-percent reduction in acid load (198) in the Ohio River was attributed to sealing abandoned mines along the river and its tributaries.

Because the summaries were general evaluations of the effectiveness of the program, the value or lack of value of the various types of seals used was not appraised. As funds were not provided for maintenance of the seals at the completion of the program, no comprehensive evaluation can be made. Many times the seals consisted only of an earth dam or breast at each opening (105), intended to force enough water in the mine to exclude air. Often these seals failed or were removed because the acid water discharge had found a new opening. Many of the masonry seals have cracked (187) or fallen into disrepair. The deterioration of seals through vandalism, reopening of mines, and neglect has obliterated visual evidence of this program in many areas.

When the Federal program was terminated, most localities failed to continue sealing abandoned mines. The Pennsylvania mining law (198) provided for sealing abandoned mines but did not prescribe the method. Other States provided for closing or fencing to prevent entrance by abandoned mine openings.

In 1947 "The Coal Mine Sealing Act", passed in Pennsylvania (105), required operators to seal coal mines as they were abandoned, within certain prescribed time limits. The legislature also provided funds to defray costs of sealing abandoned mines not in possession of an operator.

Mine sealing to exclude air from underground mine areas has certain inherent, basic weaknesses. Crichton (61) stated, "Sealing the abandoned mines has been suggested, but this is impracticable in fractured ground. Where the ground can be thoroughly sealed, keeping out air and keeping the pyrites under water, oxidation will certainly be diminished." Brant and Moulton (40) explained, "Through the mining of coal, the roof strata lose their support, and if weakening and collapse of the roof strata take place, air courses may develop to render entirely ineffective a seal at the mine entry."

Since no critical evaluations had been made on the various mine sealing programs, Braley (29, 36, 37), Mellon Institute, experimentally sealed six isolated drift mines in Pennsylvania and carried out routine weekly examinations on each mine: (1) for change in oxygen content of the mine atmosphere after sealing, and (2) for the average daily output of acid on a yearly basis. The data collected over about 5 years, 1949-53, indicated that there was very little average change in oxygen concentration of the mine atmospheres or average acid load in the various drainages from the six mines.

At the same time, Braley also collected data after the Department of Mines, Commonwealth of Pennsylvania, had sealed the abandoned mines on Coal Run (a tributary of Casselman River), on Jacobs Creek, and on Indian Creek. The data collected indicated that there was no stream improvement because there was no average decrease in acidity as a result of sealing the abandoned mines. A deep mine, reached by a vertical shaft, was also sealed. As the water level rose in this mine, samples of the mine atmosphere were taken for oxygen determination as well as samples of the mine water for measurement of acidity. Data indicated a gradual decrease in oxygen until the mine was flooded. The mine drainage before sealing was alkaline, but became acid as it filled with water. After 7 to 10 months of overflow drainage, the water was again alkaline. Oxidation of pyritic material was concluded to be retarded or stopped when the coal seam was below surface drainage level and the mine became completely flooded with water.

In 1957, Moulton and associates (147), Ohio State University, questioned the effectiveness of the various mine-sealing programs because of conflicting information obtained by the various investigators. It was stated, "The question of efficacy of a mine sealing program is still a debatable one. There is no final proof, or disproof, at this point that seals will effectively prevent the formation of sulfuric acid." In an attempt to properly evaluate the mine-sealing program, a team of scientists from the university selected several mines in southern Ohio for further study.

Segregation and Sealing of Acid-Forming Material

Underground Mines

It has been demonstrated experimentally in the laboratory that acid formation from pyritic material can be decreased or stopped by decreasing or eliminating the presence of oxygen. Leitch, Yant, and Sayers (135), Burke and Downs (45), and Braley (37) studied the effects of varying oxygen concentration in test atmospheres. Leitch, Yant, and Sayers (135) and Braley (37) studied the effects of eliminating atmospheric oxidation by covering pyritic material with water, both in the laboratory and in the field. It has been further demonstrated in field experiments that sealing pyritic material with earth, as well as with water, can curtail or stop natural oxidation of the sulfides.

A coal waste fellowship was sponsored by the Western Pennsylvania Coal Operators Association at Mellon Institute from 1949 to 1954 to investigate spontaneous heating of coal refuse and to develop methods of preventing and of extinguishing refuse fires. Abatement of atmospheric pollution by preventing fires was the primary concern of this study, but the elimination of acid formation and acid water runoff was an important contribution. Hall and Nelson (86, 152), and Nelson (151) studied and reported sealing procedures that were used successfully by several coal companies. In general, these procedures included compacting the refuse in 2- or 3-foot layers with particular emphasis on compacting the edges; for extra protection, each layer of compacted refuse was sealed with clay. Sometimes layers of clay a foot or more in thickness were placed between each successive compacted layer of refuse, 2 to 4 feet in thickness; other layers were built from compacted refuse, up to 10 feet in thickness, and sealed with clay on the outer edge only. Edge sealing (86, 151, 152) is illustrated in figures 1-3.

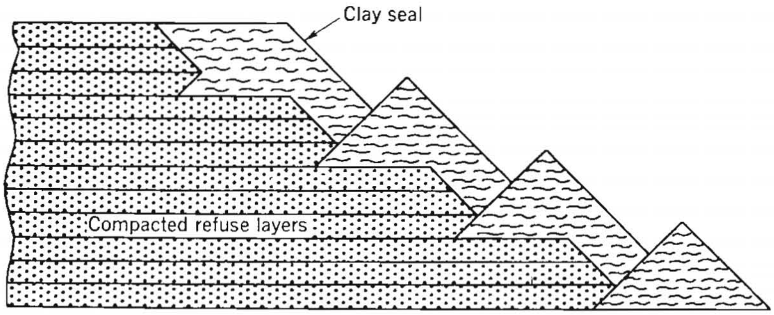

FIGURE 1. - Cross Section of Compacted Coal Refuse Sealed on the Edges With Uncompacted Clay.

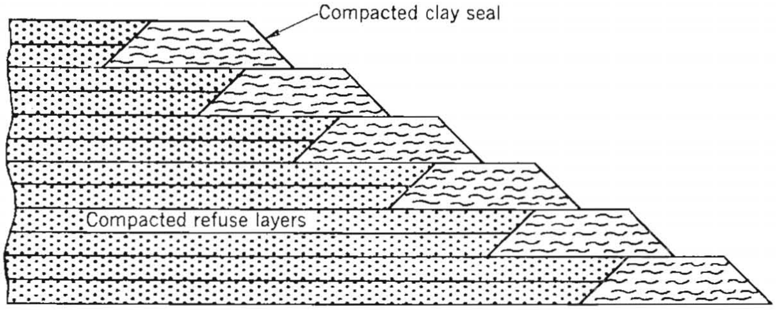

FIGURE 2. - Cross Section of Compacted Coal Refuse Sealed on the Edges With Compacted Clay.

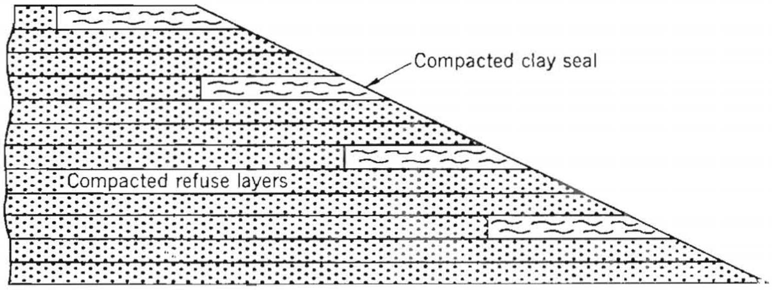

FIGURE 3. - Cross Section of Compacted Coal Refuse Partly Sealed on the Edges With Compacted Clay.

Refuse at the Cadogan mine of the Allegheny River Mining Co. near Kittanning, Pa., was sealed by placing layers of clay between compacted layers of refuse. Prevention of spontaneous combustion in the refuse required restriction of the thickness of the refuse layer to less than 4 feet, and about a foot of clay was placed between each layer of refuse. The edges of each refuse layer also were sealed with clay. Figure 4 is a view of this clay-sealed refuse, which is a storage for the coal waste at the Cadogan mine. At the Allegheny River Mining Co. Ringgold preparation plant, the sludge from the settling lagoons was used in conjunction with clay between layers of compacted refuse. The layer edges of the refuse at this plant also were covered with sludge and clay.

Many companies in the various coal-producing States follow a program of coal-refuse disposal by compacting and sealing the piles and controlling surface-water drainage from the disposal area. Strip mine operators often transfer refuse to the base of spoils piles to be covered with fresh-stripped spoil or transfer it to lagoons or final cuts to be covered and sealed by water.

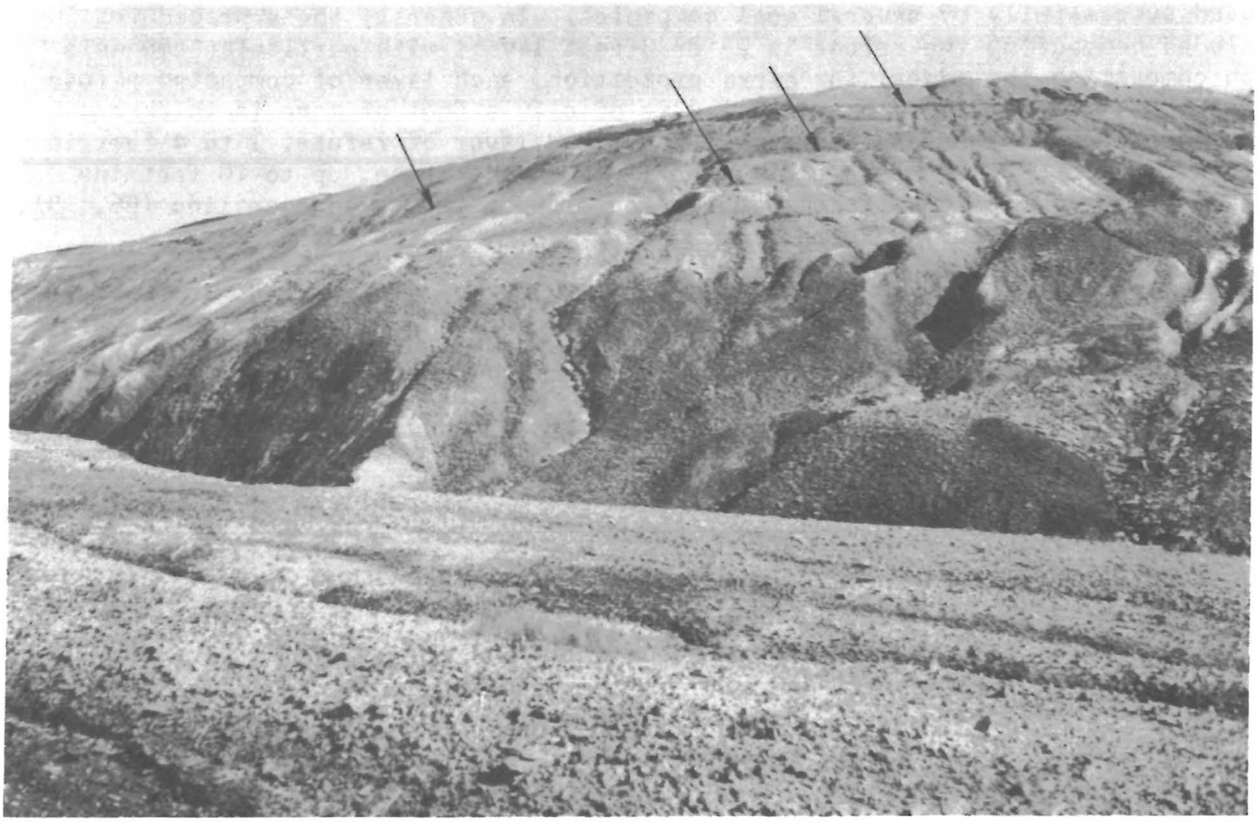

FIGURE 4. - Coal Refuse Sealing at the Cadogan Mine. Refuse layers can be identified by parallel line effect in the pile, as indicated by arrows.

Coal refuse was used in many mining areas as road-building material because of its low cost and its compacting properties. Mine operators, farmers, and local property owners sometimes used it for driveways, lanes, and other access roads. In some States, township and county road commissioners used it on the various highways under their jurisdiction. The practice had become so widespread in a few mining areas that the stream pollution problems from acid mine drainage increased after each rain. Because of the many undesirable conditions resulting from the use of refuse on roads, many road commissioners and property owners have discontinued its use. The old refuse roads are being sealed by covering with earth, crushed limestone, or black top in many places, including roads on coal mine properties.

Strip Mines

When known measures are used to prevent the formation of acid and acid water runoff at strip mines, the entire operation, including abandonment, can be accomplished with minimum pollution to the local stream systems. One of the most important measures is the segregation and sealing of acid-forming materials. The procedures are simple and add but little to the costs of digging and backfilling if a routine is established at the beginning of the operation and is continued throughout. Braley (30, 32, 37), Pennsylvania Department of Health (160), Jones (105), and others have recommended the following procedures for minimum acid formation at strip mines: (1) As the overburden is removed and piled to conform to the contour of the strips, the acid-forming refuse is separated and placed at the base of the spoil pile. (2) The final bit of loose overburden on the exposed block of coal is separated and cleaned away by bulldozing and hand sweeping. (3) The backfill, which is started with the opening of the next succeeding cut, covers all waste. (4) A final step after abandonment to seal the mine is either to grade overburden to cover the pit and highwall area or to construct earth dams to hold water and flood the final cut. Figure 5, a sketch of a hypothetical strip mine, indicates a mine-sealing procedure that can be followed to bury refuse with earth. Figure 6 illustrates completed grading and reclamation for an abandoned coal-stripping operation near Kent, Pa. Figure 7 is a view of the restoration of land to contour at a strip mine east of Greensburg, Pa.

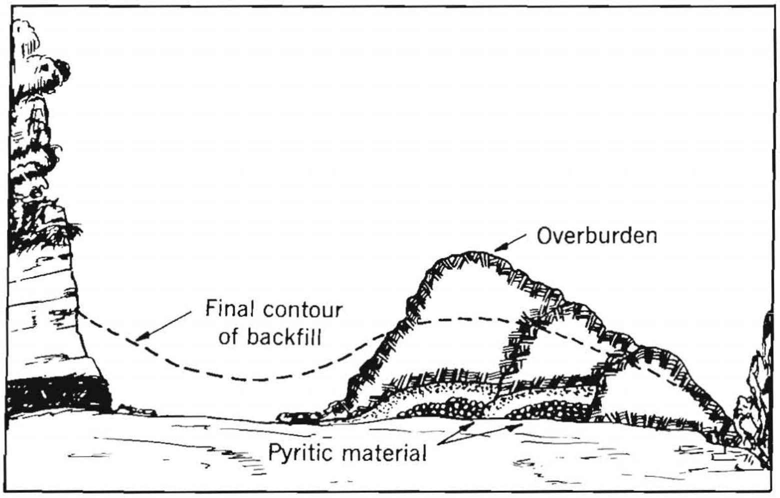

FIGURE 5. - Sketch of Strip Mine Sealing Method. Pyritic material is covered with spoil.

Sealing of abandoned strip mines probably started in Indiana during the Federal Government mine-sealing program in 1933; Indiana sponsored a continuation program from 1933 to 1940. The method used was to construct an earth dam or dams across the final cut between the highwall and adjacent spoil pile to hold and raise the water level above the coal seam and adjacent pyritic material. This impounding of water has often been successful in sealing the pyritic material found in coal and associated strata against further oxidation and formation.

In Indiana, the strip mine ponds, usually acid to start with, often become neutral or alkaline within 2 to 4 years after they are formed. This change in acidity is a natural reaction brought about between the acid water, the surrounding soil, and the diluting and neutralizing effect of entering ground and surface water, after the pyrite material has been sealed to stop further oxidation and acid formation. Similar conditions exist in a few strip mines in other States where bituminous coal is mined.

In the calcareous areas found in Illinois, West Virginia, and other States, the impounded water in a final strip mine cut often remains alkaline because early acid formation has been neutralized by the carbonates in the soil. If these mines are sealed shortly after abandonment the water drainage will continue alkaline. Figure 8 is a view of an alkaline pond in Harrison County, W. Va., where spoil has been restored to a natural contour around the pond and then planted to alfalfa.

FIGURE 6. - Abandoned Coal-Stripping Operation Near Kent, Pa. Backfilling, grading, and reclamation conform to Pennsylvania laws.

FIGURE 7. - Land Restoration to Contour at Abandoned Coal-Stripping Operation Near Greensburg, Pa. Restored land planted to corn. Previous highwall follows tree line in background.

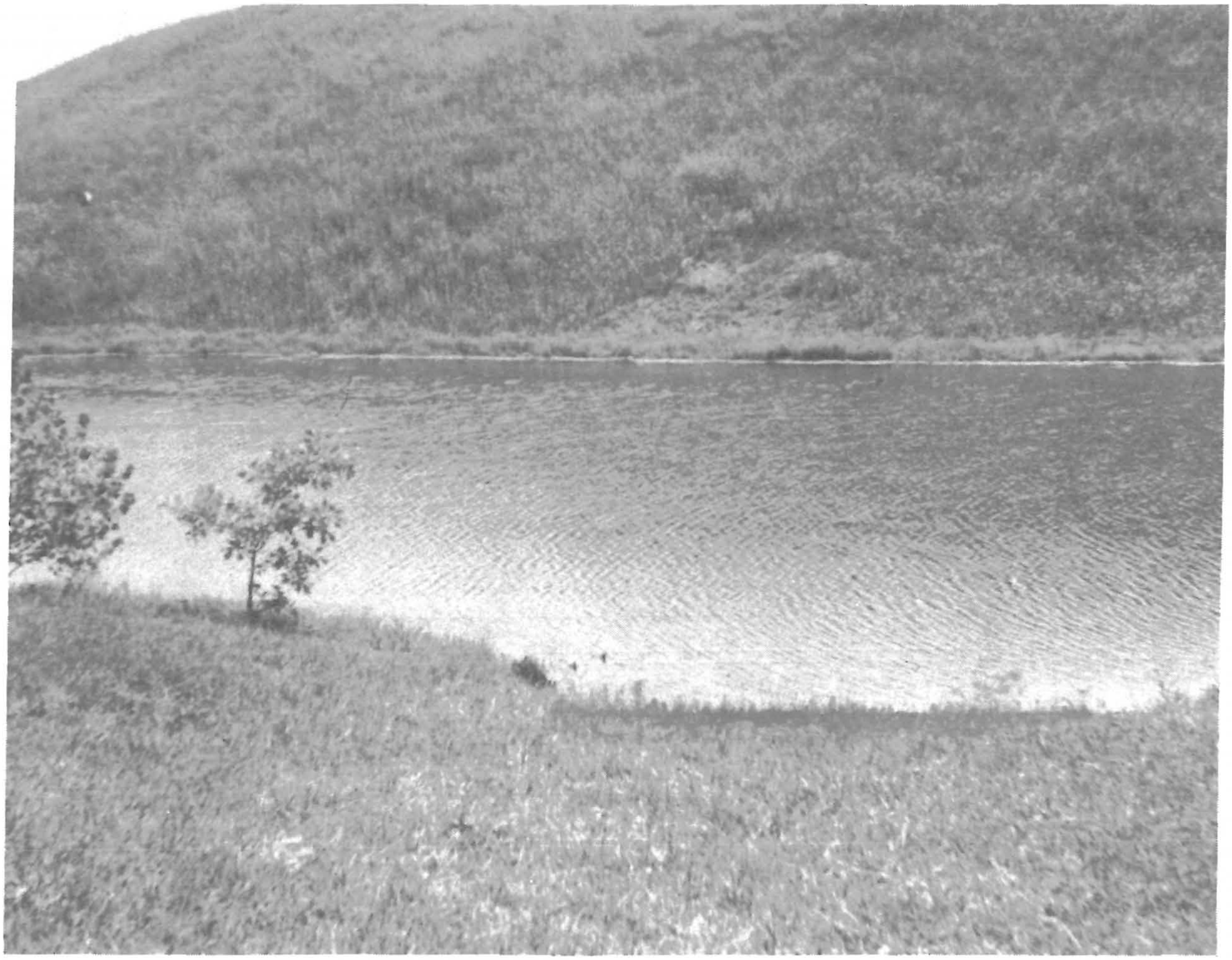

FIGURE 8. - Alkaline Pond in Harrison County, W. Va. Spoil has been restored to a natural contour around the pond and then planted to alfalfa.

The sealing failures in strip mine impoundments were traced by most investigators either to earth dams that were inadequate to impound enough water to cover exposed potential acid-producing material or to toxic overburden that cannot be covered and sealed. Sandstone overburden and overburden composed of acid-producing shales are most commonly associated with acid strip mine ponds. Figure 9 is a view of acid sandstone spoil and an acid pond at a strip mine in Williamson County, Ill. Figure 10 is a view of acid shale spoil and an acid pond at an abandoned strip mine Mahoning County, Ohio.

Inhibitor: Research and Application in Underground Mines

In the various sealing programs conducted at coal mines, acid formation was often curtailed or stopped when the pyritic material was covered with either water or earth. This principle of sealing or blanketing pyrite to exclude oxygen has led to theories on the possible use of chemical inhibitors or coatings to provide a similar blanketing effect. For example, introducing

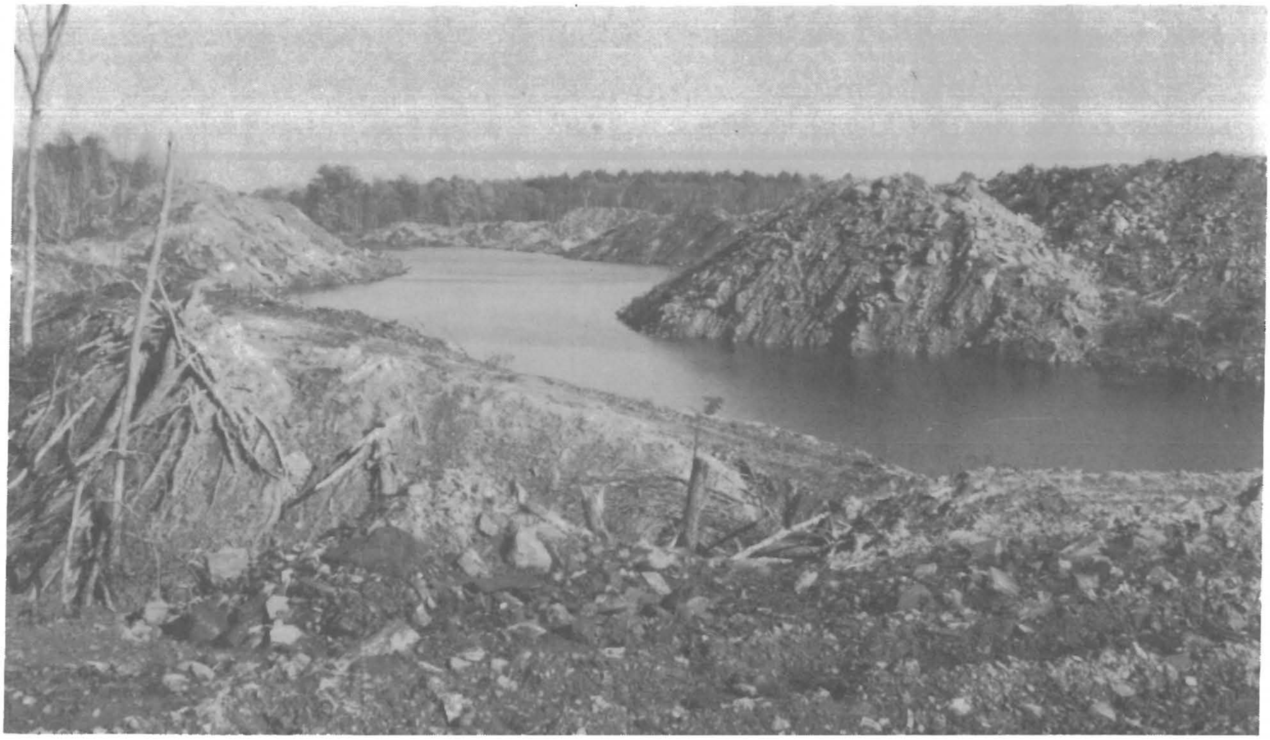

FIGURE 9. - Acid Pond in Williamson County, Ill. Spoil is predominantly sandstone.

FIGURE 10. - Acid Pond in Mahoning County, Ohio. Spoil is predominantly acid shale and clay.

small concentrations of a chemical either to create a film over the metal or to induce passivity by inhibiting the anodic or cathodic portions of the normal corrosion reaction can control corrosion of metals.

Experience with the use of chemicals to inhibit oxidation of pyritic material in coal mines has been meager. Burke and Downs (45) noted that the presence of insoluble sulfates decreased or inhibited the oxidation rate of their pyrite sample. Other than this observation, apparently no further work was reported on the inhibiting effect of insoluble sulfates. Patrick (156) supervised laboratory experiments at Johns Hopkins University on the use of chromates to inhibit oxidation of pyrite, assuming that pyrite would display an electrochemical behavior similar to that of iron. No field experiments were made using chromates, but limited applications were conducted using various phosphates. Beçause of application difficulites, the experiments were discontinued. Braley (37) conducted laboratory experiments with phosphates, chromates, and various alkalies; at the same time he made field tests with ammonia gas. His observations were that the chromates and phosphates acted as an alkali or neutralizing agent rather than as an inhibitor, and that even though inhibitors may be available the practical application of these chemicals to all areas of a coal mine presented an unsurmountable obstacle to their use.

In experiments to inhibit the growth of acid-forming bacteria, conducted at coal mines, Temple and Koehler (187) sprayed acriflavine on a roof section, intermittently over a 6-week period. During the spraying period, no acid was formed, and no bacteria were detected; after the spraying was stopped, the area became acid and bacteria reappeared.

The use of chemical inhibitors or coatings has been unsuccessful in underground mines. Lack of knowledge of methods of application and suitable chemicals as inhibitors has restricted progress.

Control of Drainage

Underground Mines

When acid forms from oxidation of pyritic materials, the reaction requires only a small amount of water; the moisture in the atmosphere is usually enough. The soluble acid salts remain harmlessly in place, where formed, until enough water collects to dissolve them. This collected water becomes acid mine drainage and a pollutant of streams when it flows or is pumped out of the mines. A measure has been proposed to remove this acid from mine drainage by collecting and pumping the water from the mine before it has had an opportunity to contact soluble acid salts.

The studies made by Braley (30, 32, 35-37) of methods to decrease acid formation in strip pits led to further consideration of a possible engineering approach to the problem in underground mines. Such an approach to control drainage included aboveground systems to prevent entrance of surface water, whenever possible; at the same time it included designs for impervious underground sumps to store fresh alkaline water for frequent pumping to the surface.

The water would be fed to these sumps by ditches and pipes, which would collect it at the coal face or other points of water entrance, thus preventing contact between the entering water and the acid salts that had been formed on exposed pyritic material in the mine. Because natural ground water is usually alkaline, Braley (37) stated, "The best system of mine drainage is the system that takes the water out by the shortest and most rapid route and does not allow the water to form pools in the mine, except for strategically located sumps where it can collect without leaching acid and from which it can be pumped most conveniently."

Two notable experiments are presently being conducted in underground mines to test the value of the frequent water-discharge principle and other recommended drainage-control measures. Both mines are in or near Greene County, Pa., on the Dunkard Creek watershed. Dunkard Creek has been classified as a clean stream by the Pennsylvania Sanitary Water Board in accordance with provisions of the Clean Stream Act of 1945. Braley (33) has described the program conducted by the Christopher Coal Co., a subsidiary of the Consolidation Coal Corp., at its Humphrey Mines near Mt. Morris, Pa.; Steinman (177) has described the Jones and Laughlin Steel Corp. program at its Vesta-Shannopin mines in the same general area. Both mines conducted closely controlled programs which adhere to the recommended practices of the Pennsylvania Sanitary Water Board for discharge of mine water to a clean stream.

Strip Mines

Methods for mine water drainage controls can be readily tested at strip mines. Because the mines are often small and stripping uncovers the coal and rock strata, the various applied measures are in the open for better observation and study. Because of this arrangement, the principles for frequent discharge of water, rapid drainage, minimum pooling, and the handling of surface drainage from areas outside the mine can be practiced under carefully regulated conditions; the immediate and long-range benefits can be readily noted. Figure 11 is a sketch illustrating these various drainage-control principles at a strip mine.

The studies conducted in Pennsylvania from 1949 to 1953 have contributed to a better understanding of acid formation and of practical engineering methods available to decrease stream pollution from acid mine water. Investigations made by Braley (30, 32, 33, 35-37) for the Sanitary Water Board, Jones (105), and the Commonwealth of Pennsylvania (159-161) have outlined practical methods as follows:

1. Keep strip pits dry at all times.
    a. Surface water must be excluded as much as possible by providing diversion ditches above the highwall.
    b. Ground water and any surface water that collects in the pit must be removed rapidly and continuously by pumping or through a free-flowing drainage system.

c. Pooling of water should be held to a minimum needed for pump operation. The water should never overflow from pools into the general pit area during active mining.

2. Segregate and bury all pyritic material in the bottom of the open pits under impervious material. This prevents oxidation.

3. Backfill the pits in such a manner that all coal refuse is buried in the bottom, and the exposed coal in the highwall is covered with compacted spoil. The contour of the grading and backfill must encourage positive drainage of surface water away from the immediate area at all times.

4. An additional control for too rapid runoff of surface water from spoils piles, contour backfill, and similar areas can be accomplished by planting trees, shrubs, or grasses on the bare ground.

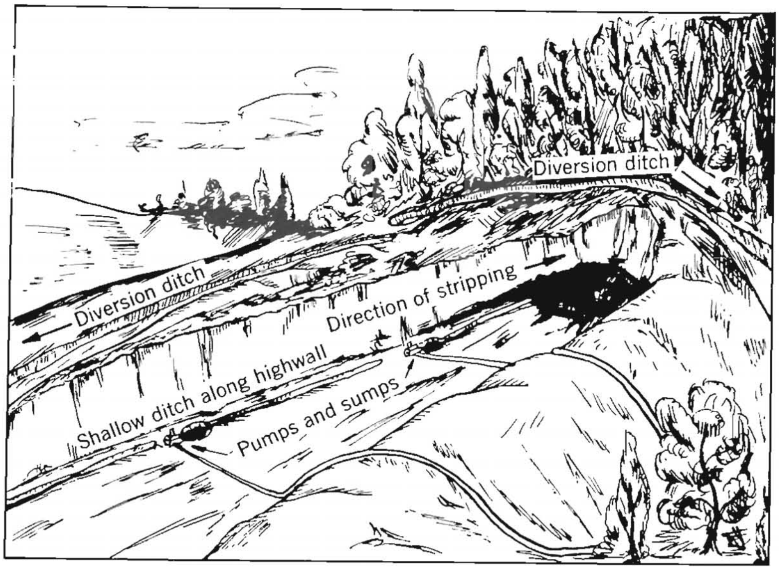

FIGURE 11. - Sketch of Strip Mine Drainage Control Measures for Surface and Ground Water.

Ponds

The ponds used by coal operators are generally artificial bodies of water formed in a depressed area near a mine or a preparation plant. They are often built to conform to the characteristics of the local terrain. In hilly or rolling land, an earth dam may be built between the high points in a valleylike area to impound water; in flat land, a depression may be dug and the earth banked around the hole to create a pond of the size and depth desired. At a strip mine, an earth dam may be built between the highwall and the spoil bank in a final cut. The impounding of mine drainage has occasionally been considered a preventive measure in controlling stream pollution from acid mine water or other waterborne coal mine wastes. The ponds have been used for these purposes:

1. To regulate drainage flow, over a 24-hour period, from a coal mine to a stream after once-a-day, offpeak pumping from underground workings.

2. To regulate acid waterflow to a local stream by retaining the water in the pond during a time of drought or low flow and then releasing it at flood or high flow.

3. To slow down drainage flow from a mine or neutralizing plant to facilitate the settling of insoluble iron compounds or calcium sludges before discharging the water to a stream.

4. To provide reservoir capacity for preparation plants and storage space for the water discharged from the washing operation in closed-circuit water systems.

5. To slow down waste water effluent from a preparation plant to remove coal and refuse fines before returning the water to a local stream.

An application of regulated acid water flow to a local stream was described by Gross and Lee (85) in 1951. A levee had been built around coal refuse piles to impound surface water runoff on the Peabody Coal Co. properties near Kincaid, Ill. The acid water was released from this impoundment through various control-valving mechanisms to the Sangamon River at a predetermined dilution rate of 1 to 50. The quantity of water that was reported to be released was based upon riverflow rates calculated from continuous gaging records.

Flood and Low-Flow-Control Reservoirs for Acid Water Dilution

The intensive urban and industrial development of the Ohio River basin (110) has provided economic justification for the multiple-purpose reservoirs needed as aids in solving many water-use problems. The most important of these problems include navigation, floods, hydroelectric power production, domestic and industrial water supplies, waste disposal, recreation, and fish and wildlife conservation.

Low-flow regulation is the reservoir's most valuable function in relation to stream betterment and pollution abatement activities. The detrimental effects to a stream of sewage, industrial wastes, and acid coal mine drainage are more pronounced during low streamflow than during more normal flow or floods. For this reason, an application of flow regulation has been advocated (198) as a remedial measure to abate pollution of streams of the Ohio River basin from various wastes, including acid mine drainage.

Flood and low-flow regulation reservoirs impound water when an excess is available and store it for controlled release during subsequent low flow (110). The value of this type of control lies in the ability to dilute the wastes at times when natural stream flow is insufficient. Flow regulation, which is not acceptable as a substitute for waste treatment, does supplement it through dilution. It does not reduce the quantity or quality of wastes, particularily acid mine drainage, but merely dilutes this waste. No amount of reservoir operation can make an alkaline or neutral stream of one whose average quality is acid.

The operation of the Tygart River reservoir (110, 198) is an example of the beneficial effects that can be realized from low-flow regulation in the reduction of stream hardness from pollution by mine drainage. Table 2, estimated and compiled by the Corps of Engineers (110), illustrates possible beneficial effects of dilution in the Monongahela River during the drought of 1930-34.

TABLE 2. - Tygart River reservoir effect of low-water regulation, 1930-34

Month (average 1930-34)	Hardness,[1] parts per million			Discharge,[1] cubic feet per second		
	Natural	Regulated	Change	Natural	Regulated	Change
January	97	97	0	15,800	15,800	0
February	81	81	0	15,800	15,800	0
March	75	75	0	27,200	27,200	0
April	89	93	[2] 4	20,500	19,600	[2] 900
May	105	114	[2] 9	16,300	15,700	[2] 600
June	146	152	[2] 6	5,100	4,900	[2] 200
July	160	146	14	4,600	4,900	300
August	188	158	30	5,400	5,700	300
September	158	127	31	4,600	5,000	400
October	200	169	31	2,800	3,100	300
November	197	158	39	5,600	5,900	300
December	129	127	2	13,500	13,600	100
Average	136	125	11	11,400	11,400	0

[1] Effect of flood control operation disregarded because of its relatively small effect on monthly average discharges and consequently on monthly average hardness.

[2] Denotes increase in hardness and decrease in discharge during storage period.

The reservoir on the Tygart River, a Monongahela River tributary, is operated in the primary interest of flood control during the winter and early spring and for flood control and low-flow regulation on a seasonal basis during the late spring, summer, and fall. The operation is designed to insure a minimum flow of 340 cubic feet per second in the Monongahela River at Dam No. 8 under the most severe drought conditions of record (110). Similar benefits have been noted from reservoirs and low-flow regulations on the Allegheny River and its tributaries.

Acid Water Diversion

Acid mine drainage makes water difficult and expensive to treat for most domestic and commercial, and some industrial, water supply purposes. Chemical treatments that neutralize and remove the acid, the acid salts, and the nonacid sulfates are operations that add to the overall water treatment costs. Occasionally the water authority in a coal-mining region has been able to eliminate some of these costs by diverting as much of the acid mine drainage as possible to a watershed away from a public water supply reservoir. Examples of this preventive measure for diversion of acid mine drainage from public water supply areas to less sensitive ones are found in western Pennsylvania.

Diversion of Acid Water by Pumping.--Westmoreland County Sanitary District impounds acid mine water in a tributary to Beaver Run about 10 miles north of Greensburg, Pa., and automatically pumps it to the Turtle Creek Watershed. This preventive measure protects the Beaver Run Reservoir by removing up to 1 million gallons per day of acid mine drainage from the Beaver Run Watershed.

Diversion of Acid Water by Draining.--In 1925, the Supreme Court of Pennsylvania directed a lower court to restrain the Sagamore Coal Co., the Melcroft Coal Co., and others from discharging any drainage of acid mine waters into the waters of Indian Creek or its tributaries above the dam of the Mountain Water Supply Co. in Fayette County, Pa. To comply with the court order, the various coal companies constructed a flume and a tunnel to drain the acid water around the reservoir to a point below the dam.

CONCLUSIONS

The research and industrial applications summarized in this circular show that a great deal of work has been done toward bringing the acid mine water problem under control. From the research surveyed, it is evident that the coal industry has been offered many practical tools toward diminishing pollution, particularily where there is strip mining. It is encouraging to note that the coal industry has applied many of the useful control measures and at the same time has done much to improve its housekeeping in relation to waste disposal.

Although excellent work has been done in the laboratory and in the field, it is also apparent that much remains to be done. The review of research shows that there are still many areas of conflicting thought, particularily as to the mechanism of acid formation and the control of the chemical and the bacterial reactions involved. Reviewing fieldwork shows that many practical questions have been given only provisional answers. There are also many questions where the best answer is an educated guess. In fieldwork more information is needed in identifying and disposing of acid-forming materials, in sealing of coal mines, and in control of ground and surface water in abandoned mines.

The application of current knowledge is important, but further research is vital. New guidelines are needed for successful solutions to the problem. To assist in finding answers for the knotty acid mine water problem, the Bureau of Mines has begun a research program designed to obtain fundamental information on the formation of acid in coal mines.

BIBLIOGRAPHY

1. ALEXANDER, L. J. Control of Iron and Sulfur Organisms by Super-Chlorination and De-Chlorination. Jour. Am. Water Works Assoc., vol. 32, 1940, pp. 1137-1146.

2. _____. Control of Iron and Sulfur Organisms by Super-Chlorination and De-Chlorination. Jour. Am. Water Works Assoc., vol. 36, 1944, pp. 1349-1355.

3. ALLEN, E. T., AND CRENSHAW, J. L. The Stokes Method for the Determination of Pyrite and Marcasite. Am. Jour. Sci., vol. 38, 1914, pp. 371-392.

4. _____. Effect of Temperature and Acidity in the Formation of Marcasite (FeS_2), and Wurtzite (ZnS): A Contribution to the Genesis of Unstable Forms: A Microscope Study by H. E. Mervin. Am. Jour. Sci., vol. 38, 1914, pp. 393-431.

5. ALLEN, E. T., CRENSHAW, J. L., AND JOHNSTON, J. The Mineral Sulfides of Iron: With Crystallography Study by E. S. Larsen. Am. Jour. Sci., vol. 33, 1912, pp. 169-236.

6. ALLEN, E. T., AND JOHNSTON, J. The Exact Determination of Sulfur in Pyrite and Marcasite. Ind. Eng. Chem., vol. 2, 1910, pp. 196-203.

7. AMERICAN PUBLIC HEALTH ASSOCIATION. Standard Methods for the Examination of Water, Sewage, and Industrial Wastes. 10th ed., 1955, 522 pp.

8. ANDERSON, H. V., AND CHESLEY, K. G. X-ray Analysis of Slate. Am. Jour. Sci., vol. 22, 1931, pp. 103-112.

9. _____. X-ray Study of the Transformation of Marcasite Into Pyrite. Am. Jour. Sci., vol. 148, 1933, pp. 315-324.

10. AQUINO, D. I. Studies on the Sulfur Oxidizing Bacteria. Univ. Philippines Nat. and Applied Sci. Bull. 2, 1932, pp. 309-339.

11. ARDEN, T. V. The Hydrolysis of Ferric Iron in Sulfate Solution. Jour. Chem. Soc., No. 2, 1951, pp. 350-363.

12. ASH, S. H. Buried Valley of the Susquehanna River, Anthracite Region of Pennsylvania. Bureau of Mines Bull. 494, 1950, 27 pp.

13. _____. Water Problem in the Pennsylvania Anthracite Mining Region. Bureau of Mines Inf. Circ. 7175, 1941, 11 pp.

14. ASH, S. H., FELEGY, E. W., KENNEDY, D. O., AND MILLER, P. S. Acid Mine-Drainage Problems, Anthracite Region of Pennsylvania. Bureau of Mines Bull. 508, 1951, 72 pp.

15. ASH, S. H., HOWER, C. S., KENNEDY, D. O., AND LESSER, W. H. Mine Pumping Plants, Anthracite Region of Pennsylvania. Bureau of Mines Bull. 531, 1953, 151 pp.

16. ASHMEAD, D. The Influence of Bacteria in the Formation of Acid Mine Waters. Colliery Guardian, vol. 190, 1955, pp. 694-698.

17. _____. The Influence of Bacteria in the Formation of Acid Mine Waters (Part 2). Colliery Guardian, vol. 192, 1956. pp. 483-486.

18. BACH, H. The Disposal of Coal Mine Liquid Wastes. Proc. Inst. Bituminous Coal, 3d Internat. Conf., 1931, vol. 2, pp. 946-956.

19. BAIN, G. W. Pyrite Oxidation. Econ. Geol., vol. 30, 1935, pp. 166-169.

20. BERGEY's Manual of Determinative Bacteriology. Williams and Wilkins, Baltimore, Md., 7th ed., 1957, 1094 pp.

21. BIRHARZ, O. W. Experiences with Acid Mine Water Drainage in Tri-State Field. Trans. AIME., vol. 181, 1949, pp. 282-291.

22. BLAKELY, A. G. Chemistry in Coal Mining. Coal Age, vol. 10, 1916, pp. 296-302.

23. BRALEY, S. A. Acid Drainage From Coal Mines. Min. Eng., vol. 3, 1951, pp. 703-707.

24. _____. Acid Mine-Drainage I. The Problem. Mechanization, vol. 18, No. 1, 1954, pp. 87-89.

25. _____. Acid Mine-Drainage II. Sources. Mechanization, vol. 18, No. 2, 1954, pp. 113-115.

26. _____. Acid Mine-Drainage III. Sampling and Analysis. Mechanization, vol. 18, No. 3, 1954, pp. 96-98.

27. _____. Acid Mine-Drainage IV. Composition and Flow. Mechanization, vol. 18, No. 4, 1954, pp. 137-138.

28. _____. Acid Mine-Drainage V. Control of Mine Acid. Mechanization, vol. 18, No. 5, 1954, pp. 97-98.

29. _____. Acid Mine-Drainage VI. Control of Oxidation. Mechanization, vol. 18, No. 6, 1954, pp. 105-107.

30. _____. Acid Mine-Drainage VII. Strip Mines. Mechanization, vol. 18, No. 8, 1954, pp. 101-103.

31. _____. Evaluation of Mine Drainage Water. Min. Eng., vol. 9, 1957, pp. 76-78.

32. BRALEY, S. A. Experimental Strip Mines Show No Stream Pollution. Min. Cong. Jour., vol. 38, 1952, pp. 50-67.

33. _____. Mine Acid Control. A New Approach. Coal Age, vol. 62, 1957, pp. 68-69.

34. _____. A Pilot Plant Study of the Neutralization of Acid Drainage From Bituminous Coal Mines. Commonwealth of Pennsylvania, Dept. of Health, Ind. Fellowship No. 326-B, 1951, 14 pp.

35. _____. Research on Acid Mine Water. Trans. Coal Min. Inst. of America. December 1952, 10 pp.

36. _____. Special Summary Report on Mine Acid Control. Commonwealth of Pennsylvania, Dept. of Health, Ind. Fellowship No. 326-B-6, 1952, 22 pp.

37. _____. Summary Report of Commonwealth of Pennsylvania, Dept. of Health, Ind. Fellowship No. 326-B, (1-7 incl.), 1954, 279 pp.

38. _____. Truth and Fallacy About Acid Coal Mine Drainage. Min. Eng., vol. 8, 1956, pp. 314-318.

39. BRANT, R. A., AND FOSTER, W. R. Magnesian Halotrichite From Vinton County, Ohio. Ohio Jour. Sci., vol. 59, 1959, pp. 187-192.

40. BRANT, R. A., AND MOULTON, E. Q. Acid Mine Drainage Manual. Eng. Experiment Sta. Ohio State Univ. Bull. 179, 1960, 40 pp.

41. BRYNER, L. C., AND JAMESON, A. K. Microorganisms in Leaching Sulfide Minerals. Jour. Bact., vol. 6, 1958, pp. 281-287.

42. BUEHLER, H. A., AND GOTTSCHALK, V. H. Oxidation of Sulfides. Econ. Geol., vol. 5, 1910, pp. 28-35.

43. BUERGER, M. J. The Crystal Structure of Marcasite. Am. Miner., vol. 16, 1931, pp. 361-395.

44. _____. The Pyrite-Marcasite Relationship. Am. Miner., vol. 19, 1934, pp. 37-61.

45. BURKE, S. P., AND DOWNS, W. R. Oxidation of Pyritic Sulfur in Coal Mines. Trans. AIME., vol. 130, 1938, pp. 425-444.

46. BUTLIN, K. R., SELWYN, S. C., AND WAKERLY, D. S. Sulphide Production From Sulphate Enriched Sewage Sludges. Jour. Applied Bact., vol. 19, 1956, pp. 3-15.

47. CAMPBELL, E. P., HOWES, W., AND ODE, W. H. Salts in tne Tri-State Mill Waters: Their Ill Effect on the Flotation of Blends and Their Removal. Bureau of Mines Rept. of Investigations 3149, 1932, 24 pp.

48. CAMPBELL, J. R. Mine Water and Its Treatment. Min. Cong. Jour., 1924, pp. 42-46.

49. CARPENTER, L. V. Pollution in the Monongahela River Basin and its Effect on Water Supplies. West Virginia Univ. Eng. Experiment Sta. Tech. Bull. 2, 1928, 9 pp.

50. _____. Wanted: More Research on Acid Mine Waters. Coal Age, vol. 35, 1930, pp. 406.

51. CARPENTER, L. V., AND DAVIDSON, A. H. Developments in the Treatment of Acid Mine Drainage. Proc. West Virginia Acad. Sci., vol. 4, 1930, pp. 93-99.

52. CARPENTER, L. V., AND HERNDON, L. K. Acid Mine Drainage From Bituminous Coal Mines. West Virginia Univ. Eng. Experiment Sta. Res. Bull. 10, 1933, 38 pp.

53. _____. Report on Pollution Survey of the Cheat River Basin. Spec. Rep. West Virginia Water Comm., 1929, 46 pp.

54. CHANCE, E. M. Use of Mine Water as Boiler Feed. Coal Age, vol. 11, 1917, pp. 600-601.

55. CHAPMAN, C. L. Progress in Mine Sealing. West Virginia Univ. Eng. Experiment Sta. Tech. Bull. 11, 1938, pp. 79-85.

56. CLARK, H. H., AND ILSLEY, L. C. Action of Acid Mine Water on the Insulation of Electric Conductors. Bureau of Mines Tech. Paper 58, 1913, 26 pp.

57. COLLINS, C. P. Pollution of Water Supplies by Coal Mines Drainage. Eng. News-Record, vol. 91, 1923, pp. 638.

58. COLMER, A. R., AND HINKLE, M. E. The Role of Microorganisms in Acid Mine Water. Science, vol. 106, 1947, pp. 253-356.

59. COLMER, A. R., TEMPLE, K. L., AND HINKLE, M. E. An Iron-Oxidizing Bacterium From the Acid Drainage of Some Bituminous Coal Mines. Jour. Bact., vol. 59, 1950, pp. 317-328.

60. CRICHTON, A. B. Disposal of Drainage From Coal Mines. Trans. Am. Soc. Civil Eng., vol. 92, 1928, pp. 1332-1342.

61. _____. Mine Drainage Stream Pollution. Min. Eng., vol. 4, 1923, pp. 147-148.

62. _____. Mine Drainage Stream Pollution. Trans. AIME., vol. 69, 1923, pp. 434-446.

63. _____. Relation of Drainage From Mines to Stream Pollution. Min. Cong. Jour., vol. 12, 1926, pp. 418-420.

64. CRICHTON, A. B. What Shall Be Done About the Growing Evil of the Pollution of Streams by Mine Drainage. Coal Age, vol. 23, 1923, pp. 447-451.

65. DAVIDSON, A. H. Studies on Acid Drainage From Bituminous Coal Mines. West Virginia Univ. Eng. Thesis, 1931, 79 pp.

66. DEXTER, G. M. Municipal Water Needs Versus Strip Coal Mining. AIME Tech. Pub. 2570-F, 1949, pp. 37-58.

67. DOSS, B. Melnikovite. Mineral Magazine, vol. 16, 1911-1913, p. 364.

68. DOWNS, W. R. The Natural Oxidation of Pyrite Sulfur in Coal. West Virginia Univ. Master's Thesis, 1936, 85 pp.

69. DOWNS, W. S. A Survey of Culverts in West Virginia. West Virginia Univ. Eng. Experiment Sta. Res. Bull. 13, 1934, 68 pp.

70. DRAKE, C. F. Effect of Acid Mine Drainage on River Water Supply. Jour. Am. Water Works Assoc., vol. 23, 1931, pp. 1474-1494.

71. _____. Water-Purification Problems in Mining and Manufacturing Districts. Jour. Am. Water Works Assoc., vol. 23, 1931, pp. 1261-1271.

72. DRAKELY, T. J. The Influence of Iron Pyrites on the Oxidation of Coal. Jour. Chem. Soc., vol. 109, 1916, pp. 723-733.

73. EAVENSON, H. N. Run-off and Mine Drainage. Trans. AIME., vol. 66, 1921, pp. 624-635.

74. _____. Stream Pollution - Again an Issue in Pennsylvania as Administration Backs Drastic Program. Coal Age, vol. 40, 1935, pp. 195-196.

75. EILERTS, C. K., SMITH, R. V., ARCHER, F. G., BURMAN, L. M., GREEN, F., AND HAMONTRE, H. C. Field and Laboratory Tests of Sodium Chromates and Alkalies for Controlling Corrosion in Gas-Condensate Wells. Corrosion, vol. 6, 1950, pp. 131-136.

76. FELEGY, E. W., JOHNSON, L. H., AND WESTFIELD, J. Acid Mine Water in the Anthracite Region of Pennsylvania. Bureau of Mines Tech. Paper 710, 1948, 49 pp.

77. FELLOWS, P. A. Sealing Projects Sharply Reduce Stream Pollution From Abandoned Mines. Coal Age, vol. 42, 1937, pp. 158-161.

78. FOSTER, W. D., AND FEICHT, F. L. Minerology of Concretions from Pittsburgh Coal Seam With Special Reference to Analcite. Am. Miner., vol. 31, 1946, pp. 357-364.

79. FRANCIS, W. Coal: Its Formation and Composition. Edward Arnold Publishers, Ltd., London, 1954, 567 pp.

80. GALLIHER, E. E. The Sulfur Cycle in Sediments. Jour. of Sedimentary Petrol., vol. 3, No. 9, 1933, pp. 51-63.

81. GIDLEY, L. P. Treatment of Acid Mine Drainage. West Virginia Univ. Chem. Thesis, 1928, 72 pp.

82. GOTTSCHALK, F. A., AND BUEHLER, H. A. Oxidation of Pyrite II. Econ. Geol., vol. 7, 1912, pp. 12-34.

83. GRAVES, H. S. The Control of Stream Pollution. Am. Forests, vol. 46, 1940, pp. 113-114, 141.

84. GRAWE, O. R. Pyrites Deposits of Missouri. Missouri Geol. Survey and Water Res., vol. 30, 1945, 482 pp.

85. GROSS, C. D., AND LEE, C. Collection and Treatment of Acid Runoff From Coal-Gob-Pile-Storage-Areas. Proc. 6th Ann. Purdue Univ. Ind. Waste Conf., 1951, pp. 10-21.

86. HALL, E. P., AND NELSON, W. L. A Proposed Seal for Hillside Coal Refuse Piles. Mechanization, vol. 16, No. 8, 1952, pp. 119-124.

87. HANDY, J. O. Mine Water Purification. Min. Cong. Jour., vol. 12, 1926, pp. 421-422.

88. HEBLEY, H. F. Preventing Stream Pollution. Min. Cong. Jour., vol. 9, 1957, pp. 82-86.

89. _____. Stream Pollution by Coal Mine Wastes. Min. Eng., vol. 5, 1953, pp. 404-412.

90. HERNDON, L. K. Survey of Mine Drainage in the West Fork Basin. West Virginia Univ. Eng. Experiment Sta. Tech. Bull. 4, 1931, 27 pp.

91. HERNDON, L. K., AND HODGE, W. W. West Virginia Coal Seams and Their Drainage. West Virginia Univ. Eng. Experiment Sta. Res. Bull. 14, 1946, 43 pp.

92. HINKLE, M. E., AND KOEHLER, W. A. The Action of Certain Microorganisms in Acid Mine Water Drainage. AIME Tech. Pub. 2381, 1948, 5 pp.

93. _____. Investigations on Coal Mine Drainage. West Virginia Univ. Eng. Experiment Sta., Bituminous Coal Research, Inc., Fellowship Ann. Rept., 1944.

94. _____. Investigations on Coal Mine Drainage. West Virginia Univ. Eng. Experiment Sta., Bituminous Coal Research, Inc., Fellowship Ann. Rept., 1945.

95. _____. Investigations on Coal Mine Drainage. West Virginia Univ. Eng. Experiment Sta., Bituminous Coal Research, Inc., Fellowship Ann. Rept., 1946.

96. HODGE, W. W. The Effect of Coal Mine Drainage on West Virginia Rivers and Water Supplies. West Virginia Univ. Eng. Experiment Sta. Res. Bull. 9, 1937, 26 pp.

97. _____. The Effect of Coal Mine Drainage on West Virginia Rivers and Water Supplies. West Virginia Univ. Experiment Sta. Res. Bull. 18, 1938, 28 pp.

98. HODGE, W. W., AND NIEHAUS, E. J. Ohio River Water in the Wheeling District and Its Treatment for Use in Boilers. West Virginia Univ. Eng. Experiment Sta. Tech. Bull. 15, 1936, 28 pp.

99. HOFFERT, J. R. Acid Mine Drainage. Ind. Eng. Chem., vol. 39, 1947, pp. 642-646.

100. HOLLIS, M. D. Water Pollution Abatement in the United States. Sew. Ind. Wastes, vol. 23, 1951, pp. 89-94.

101. JENSEN, M. L. Sulfur Isotopes and the Origin of Sandstone-Type Uranium Deposits. Econ. Geol., vol. 53, 1958, pp. 598-616.

102. JOFFE, J. S. Preliminary Studies on the Isolation of Sulfur-Oxidizing Bacteria From Sulfur-floats-soil Compost. Soil Sci., vol. 13, 1922, p. 161.

103. JOHNSON, L. H. Treatment of Acid Mine Water for Breaker Use in the Anthracite Region of Pennsylvania. Bureau of Mines Inf. Circ. 7382, 1946, 14 pp.

104. JONES, D. C. Acid Mine Drainage: Its Control Reduces Stream Pollution. Part I. Mechanization, vol. 15, No. 10, 1951, pp. 85, 87, 88, 91.

105. _____. Acid Mine Drainage: Its Control Reduces Stream Pollution. Part II. Mechanization, vol. 15, No. 11, 1951, pp. 130, 132, 135, 136.

106. JOSEPH, J. M. Microbiological Study of Acid Mine Waters: Preliminary Report. Ohio Jour. Sci., vol. 53, 1953, pp. 123-127.

107. KAPLAN, B. B. The Recovery of Marketable By-products From Acid Mine Water. Proc. West Virginia Acad. Sci., vol. 4, 1930, pp. 90-92.

108. KAPLAN, B. B., AND REGER, D. B. Process of Purifying Water. U. S. Pat. 1,878,525, 1932.

109. KOPP, O. C., AND KERR, P. F. Differential Thermal Analysis of Pyrite and Marcasite. Am. Miner., vol. 43, 1958, pp. 1079-1097.

110. LANDENBERGER, E. W. Multiple-Purpose Reservoirs and Pollution Control Benefits. Ohio River Valley Water Sanitation Commission, 1953, 31 pp.

111. LEATHEN, W. W. Bacteriologic Aspects of Bituminous Coal Mine Effluents. Proc. Pennsylvania Acad. Sci., vol. 27, 1953, pp. 37-44.

112. LEATHEN, W. W., AND BRALEY, S. A. Bacterial Activity on Sulfuritic Constituents Associated With Coal. Bact. Proc., 1950, p. 21.

113. _____. The Effect of Iron-Oxidizing Bacteria on Certain Sulfuritic Constituents of Bituminous Coal. Bact. Proc., 1951, p. 21.

114. _____. A New Iron-Oxidizing Bacterium: *Ferrobacillus ferrooxidans*. Bact. Proc., 1954, p. 44.

115. LEATHEN, W. W., BRALEY, S. A., AND McINTYRE, L. D. The Role of Bacteria in the Formation of Acid From Certain Sulfuritic Constituents Associated With Bituminous Coal. I. *Thiobacillus thiooxidans.* Applied Microbiol., vol. 1, 1953, pp. 61-64.

116. _____. The Role of Bacteria in the Formation of Acid From Certain Sulfuritic Constituents Associated With Bituminous Coal. II. Ferrous Iron Oxidizing Bacteria. Applied Microbiol., vol. 1, 1953, pp. 65-68.

117. LEATHEN, W. W., KINSEL, N. A., AND BRALEY, S. A. *Ferrobacillus ferrooxidans*: A Chemosynthetic Autotrophic Bacterium. Jour. Bact., vol. 72, 1956, pp. 700-704.

118. _____. A Solid Medium for the Study of *Ferrobacillus ferrooxidans*. Bact. Proc., 1955, p. 46.

119. LEATHEN, W. W., AND MADISON, K. M. The Oxidation of Ferrous Iron by Bacteria Found in Acid Mine Water. Bact. Proc., 1949, p. 64.

120. LEATHEN, W. W., McINTYRE, L. D., AND BRALEY, S. A. A Medium for the Study of the Bacterial Oxidation of Ferrous Iron. Science, vol. 114, 1951, pp. 280-281.

121. LEAVER, E. S., AND THURSTON, R. V. Ferric Sulfate and Sulfuric Acid From Sulfur Dioxide and Air. Bureau of Mines Rept. of Investigations 2556, 1923, 5 pp.

122. LEITCH, R. D. The Acidity of Bennett Branch of Sinnemahoning Creek, Pa., During Low Water. Bureau of Mines Rept. of Investigations 3097, 1931, 6 pp.

123. _____. The Acidity of Black Lick, Two Lick, and Yellow Creeks, Pennsylvania, During Low Water in 1930. Bureau of Mines Rept. of Investigations 3102, 1931, 7 pp.

124. _____. Acidity of Drainage From High Pyritic Coal Areas in Pennsylvania. Bureau of Mines Rept. of Investigations 3146, 1932, 15 pp.

125. _____. The Acidity of Several Pennsylvania Streams During Low Water. Bureau of Mines Rept. of Investigations 3119, 1931, 10 pp.

126. LEITCH, R. D. A General Review of the United States Bureau of Mines Stream-Pollution Investigations. Bureau of Mines Rept. of Investigations 3098, 1931, 7 pp.

127. _____. Mine-Water Neutralization Costs, Sealing, Impounding, and Effects of Pennsylvania Stream Pollution-Prevention Act. Proc. Coal Min. Inst. America, No. 51, 1938, pp. 1-9.

128. _____. Observations on Acid Mine Drainage in Western Pennsylvania. Bureau of Mines Rept. of Investigations 2889, 1928, 18 pp.

129. _____. Observations on Acid Mine Drainage in Western Pennsylvania. Min. Cong. Jour., vol. 14, 1928, pp. 835-839, 848.

130. _____. Sealing of Coal Mines Will Reduce the Acidity of Their Effluent Waters. Coal Age, vol 40, 1935, pp. 323-326.

131. _____. Stream Pollution by Acid Mine Drainage. Bureau of Mines Rept. of Investigations 2725, 1926, 7 pp.

132. LEITCH, R. D., AND YANT, W. P. A Comparison of the Acidity of Waters From Some Active and Abandoned Coal Mines. Bureau of Mines Rept. of Investigations 2895, 1928, 8 pp.

133. _____. Sealing Old Workings Prevents Acid Formation and Saves Pipes and Streams. Coal Age, vol. 35, 1930, pp. 78-80.

134. LEITCH, R. D., YANT, W. P., AND SAYERS, R. R. Character of Drainage From Mines in the Thick Freeport Coal Bed, Pa. Bureau of Mines Rept. of Investigations 3193, 1932, 29 pp.

135. _____. Effect of Sealing on Acidity of Mine Drainage. Bureau of Mines Rept. of Investigations 2994, 1930, 11 pp.

136. LEPP, H. The Synthesis and Probable Geologic Significance of Melnikovite. Econ. Geol., vol. 52, 1957, pp. 528-535.

137. LEWIS, W. M., AND PETERS, C. Coal Mine Slag Drainage. Ind. Wastes., vol. 1, 1956, pp. 145-147.

138. MAIZE, R. History and Progress Made in Mine Sealing to Reduce the Flow of Acid Water Into the Streams of the Commonwealth of Pennsylvania. Proc. Coal Min. Inst. America, No. 66, 1952, pp. 128-141.

139. MAPSTONE, G. E. The Weathering of Pyrite. Chem. and Ind., vol. 73, No. 20, 1954, pp. 577-578.

140. MASON, W. C. Will Neutralize Mine Water With Marl Before Pumping It to Surface. Coal Age, vol. 22, 1922, pp. 201-202.

141. McKINNEY, R. E. Microbiological Process Report. II Aerobic Precess. Applied Microbiol., vol. 5, 1957, pp. 167-174.

142. MELLOR, J. W. A Comprehensive Treatise on Inorganic and Theoretical Chemistry. vol. 14, pt. 3, Longmans, Green Co., New York, N. Y., 1947, pp. 1-418.

143. MORGAN, L. S. Acidity and Hardness at Monongahela River Plants. Eng. News-Record, vol. 106, 1931, p. 850.

144. _____. Investigation on Treatment and Disposal of Acid Industrial Wastes. Jour. Sewage Works, vol. 14, 1942, pp. 404-409.

145. _____. Stream Pollution in Southwestern Pennsylvania. Jour. Am. Water Works Assoc., vol. 38, 1946, pp. 713-716.

146. MOSES, H. E. Pennsylvania's Clean Stream Program. Jour. Am. Water Works Assoc., vol. 42, 1950, pp. 146-150.

147. MOULTON, E. Q., BAKER, R. F., BRANT, R. A., COSENS, K. W., LUCAS, J. R., McFADDEN, G. H., RANDLES, C. I., SHEETS, W. D., AND SMITH, E. E. The Acid Mine-Drainage Problem in Ohio. Including an Annotated Bibliography of 538 References. Eng. Experiment Sta. Ohio State Univ. Bull. 166, 1957, 158 pp.

148. MURDOCK, G. R. Industrial Wastes. Ind. Eng. Chem., vol. 45, 1953, pp. 101A-103A.

149. MURDOCK, W. J. Effects of Strip Mining on Water Supply. Jour. Am. Water Works Assoc., vol. 39, 1947, pp. 760-769.

150. NELSON, H. W., SNOW, R. D., AND KEYES, D. B. Oxidation of Pyritic Sulfur in Bituminous Coal. Ind. Eng. Chem., vol. 25, 1933, pp. 1355-1358.

151. NELSON, W. L. The disposal of Coal Refuse. Air Pollution Control Assoc., Pittsburgh, Pa. Tech. Co-ordinating Comm. Report T-4-1, 1954, 41 pp.

152. NELSON, W. L., AND HALL, E. P. A Proposed Sealed Circular Coal Refuse Piles. Mechanization, vol. 16, No. 12, 1952, pp. 85-89.

153. NEWHOUSE, W. H. Some Forms of Iron Sulfide Occurring in Coal and Other Sedimentary Rocks. Jour. Geol., vol. 35, 1927, pp. 73-83.

154. PARR, W. W., AND POWELL, A. R. A Study of the Forms in Whicn Sulfur Occurs in Coal. Univ. of Illinois Eng. Experiment Sta. Bull. 111, 1919, 66 pp.

155. PARSONS, J. W. A Biological Approach to the Study and Control of Acid Mine Pollution. Jour. Tennessee Acad. Sci., vol. 27, 1952, pp. 304-309.

156. PATRICK, W. A., AND McCOLLUM, F. W. Acid Mine Drainage Problems. Press releases from the Johns Hopkins Univ., 1955.

157. PAUL, J. W. Sealing Abandoned Coal Mines in Pennsylvania. Dept. of Health, Sanitary Water Board, 1935, 12 pp.

158. PAUL, J. W. Treating Bituminous Coal Mines to Reduce Acid Drainage. AIME. Tech. Pub. 628, 1935, 17 pp.

159. PENNSYLVANIA, COMMONWEALTH OF. Coal Mine Drainage. Dept. of Health, Bureau Sanitation Eng. Bull. 104, 1951, 24 pp.

160. _____. Control of Acid Drainage From Coal Mines. Dept. of Health, Sanitary Water Board, 1952, 28 pp.

161. _____. Experimental Rules and Regulations for the Operation and Maintenance of Strip Mines to Prevent Pollution of the Waters of the Commonwealth. Dept. of Health, Sanitary Water Board, 1952, 12 pp.

162. POWELL, A. R. The Analysis of Sulfur Forms in Coal. Bureau of Mines Tech. Paper 254, 1921, 21 pp.

163. READ, T. T. The Oxidation of Pyrite. Econ. Geol., vol. 2, 1907, p. 505.

164. REEDY, J. H., AND MACHIN, J. S. The Oxidation of Ferrous Sulfate to Ferric Sulfate by Means of Air. Ind. Eng. Chem., vol. 15, 1923, pp. 1271-1272.

165. REID, K. A. Pollution of Streams From Mining Operations. Trans. North America Wildlife Conf., vol. 1, 1936, pp. 544-550.

166. RIDGWAY, R. H. Pyrites. General Information. Bureau of Mines Inf. Circ. 6523, 1931, 26 pp.

167. RILEY, C. F. Reclamation of Coal Strip-Mined Lands With Reference to Wildlife Plantings. Jour. Wildlife Magazine, vol. 21, 1957, pp. 402-413.

168. RITTER, R. E., AND BROWN, C. F. Leaching of Mine Wastes. Proc. West Virginia Acad. Sci., vol. 21, 1949, pp. 66-67.

169. RUBEY, W. W. Lithologic Studies of Fine-Grained Upper Cretaceous Sedimentary Rocks of the Black Hills Region. Shorter Contributions to General Geology Geol. Survey Prof. Paper 165A, 1930, pp. 1-54.

170. SAYERS, R. R., YANT, W. P., AND LEITCH, R. D. A General Review of the Bureau of Mines Stream Pollution Investigation. Trans. AIME., vol. 94, 1931, pp. 137-150.

171. SEARLES, R. M. Stream Pollution and the Mining Industry. Min. Cong. Jour., vol. 24, 1938, pp. 43-46, 61.

172. SELVIG, W. A., AND RATLIFF, W. C. Nature of Acid Water From Coal Mines and Determination of Acidity. Ind. Eng. Chem., vol. 14, 1922, pp. 125-127.

173. SNYDER, R. H. Effects of Coal Strip Mining Upon Water Supplies. Jour. Am. Water Works Assoc., vol. 39, 1947, pp. 751-769.

174. SPENCER, K. A. Pyrite Recovery From Coal Mine Refuse. Am. Min. Cong. Yearbook, 1940, pp. 97-104.

175. SPRUNK, G. C., AND O'DONNELL, H. J. Mineral Matter in Coal. Bureau of Mines Tech. Paper 648, 1942, 67 pp.

176. STARKEY, R. L. Concerning the Carbon and Nitrogen Nutrition of Thiobacillus thiooxidans. An Autotrophic Bacterium Oxidizing Sulfur Under Acid Conditions. Jour. Bact., vol. 10, 1925, pp. 165-195.

177. STEINMAN, H. E. An Operators Approach to Mine Water Drainage Problems and Stream Pollution. Min. Cong. Jour., vol. 46, 1960, pp. 70-73.

178. STEVENSON, W. L. Restriction of Stream Pollution. Min. Cong. Jour., vol. 12, 1926, pp. 423-425, 469.

179. STEWARD, A. H. Stream Pollution Control in Pennsylvania. Jour. Sewage Works, vol. 17, 1945, pp. 586-593.

180. STOKES, H. N. Experiments on the Action of Various Solution on Pyrite and Marcasite. Econ. Geol., vol. 2, 1907, pp. 14-23.

181. _____. On Pyrite and Marcasite. Geol. Survey Bull. 186, 1901, 50 pp.

182. STREETER, H. W. Surveys for Stream Pollution Control. Proc. Am. Soc. Civil Eng., vol. 64, 1938, pp. 5-21.

183. STROM, K. M. Land-Locked Waters and the Deposition of Black Muds. Recent Marine Sediments. Am. Assoc. Petrol. Geol., 1939, pp. 356-372.

184. TEMPLE, K. L., AND COLMER, A. R. The Autotrophic Oxidation of Iron by a New Bacterium: Thiobacillus ferrooxidans. Jour. Bact., vol. 62, 1951, pp. 605-611.

185. _____. The Formation of Acid Mine Drainage. Min. Eng., vol. 3, 1951, pp. 1090-1092.

186. TEMPLE, K. L., AND DELCHAMPS, E. W. Autotrophic Bacteria and the Formation of Acid in Bituminous Coal Mines. Applied Microbiol., vol. 1, 1953, pp. 255-258.

187. TEMPLE, K. L., AND KOEHLER, W. A. Drainage From Bituminous Coal Mines. West Virginia Univ. Eng. Experiment Sta. Res. Bull. 25, 1954, 35 pp.

188. THIESSEN, G. Forms of Sulfur in Coal. Chap. 12 in Chemistry of Coal Utilization, John Wiley and Sons, Inc., New York, N. Y., 1945, pp. 425-449.

189. THIESSEN, R. Occurrence and Origin of Finely Disseminated Sulfur Compounds in Coal. Trans. AIME., vol. 63, 1920, pp. 913-951.

190. THIMANN, K. V. The Life of Bacteria, Their Growth, Metabolism, Relationship. The Macmillan Co., New York, N. Y., 1955, 459 pp.

191. TISDALE, E. S. Water Pollution Control in West Virginia. West Virginia Univ. Eng. Experiment Sta. Tech. Bull. 8, 1936, pp. 126-132.

192. TISDALE, E. S., AND LYON, E. W. Acid Mine Drainage Control on Upper Ohio River Tributaries. Jour. Am. Water Works Assoc., vol. 27, 1935, pp. 1186-1198.

193. _____. Mine Sealing Program on Ohio River Watershed. Jour. Am. Water Works Assoc., vol. 26, 1934, pp. 1843-1852.

194. TRACY, L. D. Mine Water Neutralization at the Calumet Mine. Trans. AIME., vol. 66, 1921, pp. 609-623.

195. _____. Six Tons of Ferric Hydrate Secured Daily From Water at a Connelsville Mine. Coal Age, vol. 18, 1921, pp. 13-16.

196. TRAX, E. C. Acid Waters in Western Pennsylvania. Eng. News-Record, vol. 64, 1910, p. 362.

197. _____. A Quarter Century of Progress in the Purification of Acid Waters. West Virginia Univ. Eng. Experiment Sta. Tech. Bull. 6, 1933, pp. 5-19.

198. U.S. PUBLIC HEALTH SERVICE. Supplement "C," Acid Mine Drainage Studies, 1942, 68 pp.

199. WAKSMAN, S. A., AND JOFFEE, J. S. Microorganisms Concerned in the Oxidation of Sulfur in the Soil. II. Thiobacillus thiooxidans. A New Sulfur-Oxidizing Organism Isolated From the Soil. Jour. Bact., vol. 7, 1922, pp. 239-256.

200. WATSON, K. S. Coal Mining: Stream Pollution Culprit. Eng. News-Record, vol. 145, 1950, pp. 41-42.

201. WINCHELL, A. N. The Oxidation of Pyrite. Econ. Geol., vol. 2, 1907, pp. 290-294.

202. YANCEY, H. F. Some Chemical Data on Coal Pyrite. Chem. Met. Eng., vol. 22, 1920, pp. 105-109.

203. YANCEY, H. F., AND FRASER, T. The Distribution of the Forms of Sulfur in the Coal Bed. Univ. of Illinois Eng. Experiment Sta. Bull. 125, 1921, 94 pp.

204. YOUNG, C. M. The Chemistry of Mine Water. Coal Age, vol. 10, 1916, pp. 704-707.

205. _____. Pollution of River Water in the Pittsburgh District. Jour. Am. Water Works Assoc., vol. 8, 1921, pp. 201-217.

206. ZOBELL, C. E. Occurrence and Activity of Bacteria in Marine Sediments. Recent Marine Sediments. Am. Assoc. Petrol. Geol., 1939, pp. 416-427.

207. ZOBELL, C. E., AND RITTENBERG, S. C. Sulfate-Reducing Bacteria in Marine Sediments. Jour. Marine Res., vol. 7, 1948, pp. 602-617.