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Papers Presented Before The

# SEVENTH SYMPOSIUM on COAL MINE DRAINAGE RESEARCH

**NCA/BCR Coal Conference and Expo IV**

October 18-19-20, 1977

Kentucky Fair and Exposition Center

Louisville, Kentucky

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COUNCIL FOR SURFACE MINING AND
RECLAMATION RESEARCH IN APPALACHIA

THE COAL ASSOCIATION OF CANADA

*With Participation by the*

INTERNATIONAL COMMITTEE FOR COAL RESEARCH

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# PREFACE

The following pages contain the papers presented before the Seventh Symposium on Coal Mine Drainage Research during sessions on permits and regulations, formation and characteristics of mine drainage, abatement and treatment, and control of drainage from coal storage piles and coal cleaning refuse disposal sites. These papers were selected by the Program Committee to detail the most current work being conducted by some of the leading scientists, researchers, and technical representatives of government and industry. The content of the papers has not been edited, and the views expressed are entirely those of the authors.

The procedure of preprinting obviously places a great burden on the authors, and we are indebted to them for adhering to the strict publication timetable that had to be established. In those few cases where the authors found this timetable impossible to meet, the full text of the papers will be available as handouts at the Symposium or can be obtained by contacting the author.

The objective of the NCA/BCR Coal Conference and Expo IV is to publicize, discuss, and disseminate new information on all aspects of coal--from mining to utilization. These proceedings therefore have not been copyrighted; however, it should be noted that many of the processes described herein have been patented.

In addition to the National Coal Association and Bituminous Coal Research, Inc., this Conference was presented in cooperation with the International Committee for Coal Research, Federal Power Commission, Kentucky Coal Association, Tennessee Valley Authority, Federal Energy Administration, U.S. Department of Agriculture, U.S. Department of the Interior, Appalachian Regional Commission, U.S. Environmental Protection Agency, Energy Research and Development Administration, Coal Industry Advisory Committee on Water Quality, Council for Surface Mining and Reclamation Research in Appalachia, and The Coal Association of Canada. We gratefully acknowledge the assistance of the members of these cooperating organizations who served on the Program Committee and helped arrange the details of the Symposium.

The Seventh Symposium on Coal Mine Drainage Research is an integral part of the 1977 NCA/BCR Coal Conference and Expo IV. Other Symposiums included in this Conference are the Third Symposium on Coal Management Techniques, the Fourth Symposium on Coal Utilization, the Third Symposium on Underground Mining, the Third Symposium on Coal Preparation, and the Fifth Symposium on Surface Mining and Reclamation. Copies of the proceedings of each of the Symposiums can be purchased from National Coal Association, The Coal Building, 1130 Seventeenth Street, N.W., Washington, D.C. 20036. Instructions for ordering these publications, and the proceedings of the technical Symposiums conducted in the past, can be found on the inside back cover.

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# *PROGRAM*

SEVENTH SYMPOSIUM
on
COAL MINE DRAINAGE RESEARCH

October 18, 1977

SESSION TITLE: NPDES PERMITS--RECENT DEVELOPMENTS
Papers 1 to 2

October 19, 1977

SESSION TITLE: MINE DRAINAGE FORMATION AND CHARACTERISTICS
Papers 3 to 7

SESSION TITLE: MINE DRAINAGE ABATEMENT AND TREATMENT
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October 20, 1977

SESSION TITLE: CONTROL OF POLLUTION FROM COAL STORAGE PILES AND COAL CLEANING REFUSE
Papers 13 to 17

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# PRIORITY POLLUTANT EFFLUENT STANDARDS AND THE COAL INDUSTRY

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## S[illegible]ENT AGREEMENT

On June 7, 1977 in response to a law suit filed by several environmental groups, the Environmental Protection Agency signed a Settlement Agreement for the management of dangerous pollutants in industrial waste waters. Also signing that court order as an intervening defendant was the National Coal Association. With the establishment of this court consent degree, a broad program of action was initiated. Under the terms of this Settlement Agreement, filed in the United States District Court for the District of Columbia, EPA is required to develop effluent limitations guidelines, new source performance standards and pretreatment rules for 21 industries controlling the discharge of 65 chemicals and chemical classes believed to include the most dangerous substances commonly released into the environment. Coal Mining and Ore Mining are among the 21 industries scheduled for study. Some of the others included for study are Steam Electric Power Plants, Petroleum Refining, Nonferrous Metals Manufacturing, Organic and Inorganic Chemicals, Pulp and Paper, Plastics and Synthetic Materials, Miscellaneous Chemicals and the Electroplating Industry. Substances stipulated for study, in Appendix A of the Settlement Agreement, include organic compounds, such as pesticides, polychlorinated biphenyls, nitrosamines and inorganic substances such as asbestos and various metals.

The Settlement Agreement also mandates a schedule for the accomplishment of the program. Industries are to be studied in stages, over a period of years. Technical studies for the group of industries in the first stage were initiated October 13, 1977. The coal mining technical study (in the second group of industries) was initiated December 31, 1977 with a duration of one year. The scheduled deadline for proposing coal mining effluent limitations is September 30, 1978. Final rules for all industries must be published by December 31, 1979.

Criteria for the regulations were established in the court order. Briefly they are:

- Requiring the elimination of discharges of all pollutants if the agency determines that it is "technologically and economically achievable" for an industrial category.
- Identification of "the degree of effluent reduction attainable through the application of the best control measures and practice achievable".
- Consideration of the age of the facilities involved, the process employed and the cost of achieving such effluent reduction.
- Each industrial category must have specific standards for each of the 65 chemicals and chemical classes. However, "exclusion of point source categories and exclusion of substances from specific point source categories" is provided for in the Settlement Agreement. Adequate justification for exclusion must be provided based on criteria such as prior regulation or presence of a substance solely as a result of its presence in the intake water or existance of a substance in insignificant or non-toxic quantities.

In addition, it is stipulated that application of these regulations shall be accomplished by issuance or modification of NPDES permits. Achievement is required no later than June 30, 1983.

## AGENCY STRATEGY

In a letter to the National Resources Defense Council, Inc. (NRDC, the lead environmental group in the Settlement Agreement), on October 18, 1976, the strategy to be used for compliance with the Settlement Agreement was described by Mr. Beck, Deputy Assistant Administrator for Water Planning and Standards. The initial focus toward an Agency integrated regulatory program to manage discharges of dangerous pollutants was to identify those substances to be so regulated. Appendix A of the Settlement Agreement contains 65 chemicals and chemical classes. These various general parameters were further refined [illegible]e Office of Water Planning and Standards into a list of 129 specific compo[illegible] referred to as priority pollutants. Such a list permits this Office to conduct scientific studies of industrial discharges. This list of 129 priority pollutants, in an effort to satisfy the Settlement Agreement, contains every specific compound written in the agreement. Furthermore, where a group or class was written, specific compounds were chosen as best representatives of the group in order to facilitate practical and meaningful analysis of the industrial discharges. Some of the criteria used for selection of these compounds included frequency of occurance in water, availability of standards, frequency of production and chemical stability.

The Office of Water Planning and Standards' strategy is to integrate fully its regulatory programs under the Federal Water Pollution Control Act (the Act) into a program keyed to the effective control of hazardous pollutants discharged by industrial point sources. The strategy, as stipulated in the Settlement Agreement, will focus on regulating effluent discharges, industry by industry, rather than pollutant by pollutant. An industry-by-industry regulatory and study approach is considered most feasible for economic and technical work, health and environmental effects studies however, must logically be geared to individual or families of pollutants.

In order to meet the needs of the Settlement Agreement, a major effort is presently underway preparing a pollutant profile for the substances in Appendix A. This report will contain ecological and public health effects studies. In addition, the 8-months study shall provide a thorough review of the chemistry, toxicology, entry into the environment, fate and effects in the environment, production and use of the 65 substances. Information on such substances is to be supplied on: 1. monitoring, including sample considerations and analytical methods; 2. toxicological aspects including laboratory and field studies on aquatic and associated non-aquatic organisms and the acute and chronic effects on man and other mammals; 3. environmental fate and effects including the known environmental distribution of industrial and other discharges, the occurrence in natural waters, soils, drinking water supplies, and aquatic and non-aquatic organisms, the factors affecting the distribution of the substance in the environment, biological uptake and elimination, transportation paths and rates, as well as the expected distribution in the environment and the expected effects on aquatic and associated organisms including man; and 4. the production [illegible]e use of the substances including sources and quantities of discharges to wa[illegible]y industrial producers and users, municipalities, agriculture, and natural sources.

After this initial profile a more intensive study shall be conducted. The purpose of this study will be to develop information needed to close data gaps identified in the initial pollutant profiles for each of the 65 substances. The Agency will gather, develop and analyze scientific, technical, economic, cost, analytical and background information pertaining to the evaluation in the water environment of potential human-related or ecological-related hazards for the 65 substances identified in Appendix A of the Settlement Agreement which had not been addressed adequately by other means. The Agency will develop information on media distribution studies for the Settlement Agreement substances which will include geographical and quantitative identification of the pollutants in water, fish, wildlife, air, and on land; geographical and quantitative identification of importing, manufacturing, distribution, consumption, uses, disposal, and fate of the pollutants to the total environmental burden; and the identification of geographical and environmental areas of concern and the potential sources of each of the pollutants.

Within the Office of Water Planning and Standards, each of our four Divisions has specific and assigned responsibilities. The <u>Effluent Guidelines Division</u> is responsibile for the technology studies, for the investigation of a number of technology and process change options, for emphasis on technology demonstration and engineering analysis, for statistical survey design and data analysis, for consideration of indirect discharges and for issuing section 308 letters to obtain industrial information. The <u>Criteria and Standards Division</u> is responsible for health and environmental effects studies, for the development of specific criteria that will provide regulatory justification, for risk assessment and analysis to the extent feasible, for physical and background data as appropriate, and for the Federal interagency interface to obtain health and environmental effects information from other agencies. The <u>Monitoring and Data Support Division</u> is responsible for general studies of each pollutant including geographical and quantitative profiles of manufacturers and users, for a summary of losses to the environment, for an overall environmental risk assessment based upon amount released and environmental effects, for a data base associated with each industrial category, and for collecting available ambient water quality data to provide an overview of the magnitude and geographical extent of the problems. The <u>Office of Analysis and Evaluation</u> is responsible for economic studies including benefit analysis and analysis of the impact of the range of engineering cost, and preliminary economic analysis.

These economic studies will include increased emphasis toward benefit analysis. A clear description and evaluation of load reduction, health and water quality risk avoidance, and correlations between industry location and water qualtiy and/or health problems are contemplated. Analysis of various engineering cost estimates will be included to test sensitivity of conclusions, as well as to avoid the schedule problems posed by last-minute changes in technology and estimates of costs. A preliminary analysis will be conducted to establish ranges of acceptable, marginal and unacceptable costs associated with "control measures" identified by EGD. This will guide the Agency in developing treatment alternatives, as well as provide early warning that use of section 307(a) (directing the regulation of those substances determined to be toxic) may be needed. This will enable EPA to adjust its health and environmental effects studies to meet more stringent requirements of section 307(a).

The treatment technology studies, which have been a part of the Agency's regulatory efforts in the past, will include a number of technology and process change options to be fully investigated in such studies. Emphasis will be placed on technology demonstrations and engineering analysis. Where necessary, data collection will be accomplished through the use of section 308 of the Act which authorizes EPA to require dischargers to provide information needed for preparing effective regulations. EPA's resources within the Office of Research and Development and within the Regional Surveillance and Analysis Divisions will be used to spot check the section 308 responses. Statistical survey design and data analysis will be stressed. This will improve categorization and also the final effluent limits and standards. Consideration of the unique problems of indirect dischargers will be integrated into the study from the onset. Such factors as age, space incidental removal, user charges, and capital cost recovery will be explicitly addressed along with equity implications. As stated above, information will be factored into this program from the Agency's Office of Research and Development, Office of Toxic Substances, and the Office of Pesticide Programs.

The coal mining technology study has developed within the three phase strategy designed for the Effluent Guidelines Division. The (preliminary) screening phase was completed June, 1976. In this phase, a sampling program of the industry was done by the collection of samples of influent and effluent water, from 23 sites. Sites were selected with the advice and suggestions of representatives of Bituminous Coal Research and the National Coal Association. Samples were then analyzed for the presence or absence (and order of magnitude) of the 129 specific priority pollutants. To maintain consistant sampling and analytical procedures for all industries to be studied, the Agency has developed a sampling protocol and analytical methods to be used for screening for priority pollutants. This protocol represents the most current procedures for sampling and analysis of these specific substances. The purpose of phase two, the verification phase, shall be to sample and analyze with greater intensity, yielding quantitative analytical results for those pollutant parameters fou be present during the screening phase. The coal Mining, verification phase scheduled to begin Mid-September 1977. Regulation preparation is the third phase after each one year technical study.

In Summary, EPA's strategy is to: (1) integrate its control options for water quality constitutents of concern into one program; (2) initiate a series of health environmental, economic and technical studies to support the ranges of regulatory options; (3) complete health and environmental effects studies, pollutant by pollutant; (4) complete a general overview study; and (5) accomplish technical and economic studies, industry by industry, and place increased emphasis on statistics, benefit analysis, and technology demonstration. However, if a Best Available Technology Economically Achievable (BATEA) technology level is not deemed sufficient control, and the health/environmental risks are severe, section 307(a) (for toxics) will be used to require more stringent, environmentally protective controls. Section 307(b) and (c) would continue to control indirect dischargers, while section 311 would be used to control discharges related to spills. The water quality monitoring program will be used where possible as a feedback mechanism to determine the effectiveness of the final regulations over the long term. If more stringent controls are determined to be necessary, processes will be used to achieve the desired control.

To maintain control of the multiple activities and to ensure that the Agency's obligations according to the Settlement Agreement are met, a tracking system is being developed. The system will consist of a delineation of the significant milestones (tasks) of each study, i.e., technology, economic, health/environmental, and anaytical methods, contributing to the regulation development effort for each of the 21 industrial categories. Specific dates are assigned to the completion of these tasks, as well as to interim milestones important to either the completion of the task or necessary inputs to other tasks. Two criteria applied in the scheduling of these tasks are (1) that the requirements of the Settlement Agreement be met, and (2) that separate studies are timed so that they integrate their efforts at the proper points. These integration points have been identified and each study's schedule structured so that it will have progressed to that point and thus be prepared to effectively contribute to the overall program effort.

Operational components of this tracking system will include (regular) reports by the project officers on the status of their activities. These reports will be compared with the predetermined schedule necessary to meet all court deadlines. The reports and schedules will be computerized so that a computer printout will be sent to the Office of Analysis and Evaluation tracking officer.

Additional assurances that the Agency shall meet the ogligations of the Settlement Agreement, include periodic meetings with representatives of one of the environmental groups, NRDC. In these periodic meetings NRDC is briefed as to the progress and status of ongoing studies.

# REGULATION OF THE COAL MINING AND PREPARATION INDUSTRY

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## I. INTRODUCTION

The purpose of this paper is to describe the regulatory setting within which a major segment of the nation's coal industry operates. To a large extent this paper relies on information obtained during a recent study conducted by Hittman Associates, Inc., for the Appalachian Regional Commission (ARC). The Hittman report, entitled "Federal, State and Local Regulatory Powers Affecting Energy Processing and Related Development in the Appalachian Region,"[1] offers substantial insight into the relationship between existing regulatory practices and the operations of energy industries, the coal industry in particular. The Hittman study is a part of a comprehensive energy research program undertaken by ARC in order to understand economic, social and institutional factors. When taken together, these factors make up the context or environment within which Appalachian coal* is produced and consumed.

This paper attempts to build on the Hittman study by suggesting some of the implications of their results. It goes beyond the Hittman effort in that it identifies information which is crucial to the relationship between regulators and the regulated but which is not a part of the Hittman or other existing studies. The views expressed in this paper do not reflect the opinions or policies of the Appalachian Regional Commission, Appalachian states, the Federal Government or the MITRE Corporation.

The Hittman study is comprised of two distinct sections, each contained within a single volume. The first section identifies and describes all Federal, state and local regulatory powers in each of the 13 Appalachian states** which affect energy production, transportation and consumption. The second section analyzes the relationship between regulations and the energy industries in each of two case study areas, Indiana County in Pennsylvania and Pike County in Kentucky. For the purposes of description in the first section and analysis in the second, the study ca[illegible]zes regulations according to one of five phases of the energy flow chain---(1[illegible]lities development, (2) energy production, processing and conversion, (3) product distribution, (4) product use and (5) facility shut-down/reclamation. Information sources used in the study included reports conducted by private industry,

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*None of the analyses conducted under the ARC energy research program were limited to the energy resource--coal. However, the focus of each analysis was significantly influenced by the fact that the vast majority of Appalachia's energy base was coal.

**Alabama, Georgia, Kentucky, Maryland, Mississippi, New York, North Carolina, Ohio, Pennsylvania, South Carolina, Tennessee, Virginia and West Virginia.

government agencies, and private interest groups. Interviews were also conducted with officials of the energy industries and regulatory agencies. A limited survey was taken in preparing the second section to determine the minimum, maximum and average time entailed in acquiring specific Federal, state and local regulatory instruments such as permits and licenses.

The second section concludes with a description of eight distinct regulatory problems and with recommended mitigating measures for each. Problems were formulated from the analytical portion of the study; each problem is related to one or more issues pertaining to regulatory procedure or substance. The anticipated effectiveness of each measure in alleviating identified problems is also addressed as part of the conclusion.

While the focus of the Hittman study is broad to the extent that it exam[illegible] regulatory powers affecting all phases of the development of all energy reso[illegible] in each of 13 states, the focus of this paper is quite narrow. Our focus is [illegible]ed to the resource coal, and only to the phase of production (i.e., extraction and processing). Further, our attention is primarily limited to the voluntary compliance of coal operators with environmental health and safety regulations in Pennsylvania and Kentucky. Only tangential attention is given to enforcement policies and practices. While the regulatory approaches of Pennsylvania and Kentucky are significantly different and therefore interesting in their comparison, this paper does not advocate or imply that these approaches are representative of the full range of approaches available in the nation or in Appalachia, nor does it advocate or imply that the approach of any one state is "better" than that of another. Our purpose here is to identify and define problems in regulatory systems; each system is the composite of powers delegated to administrators at the Federal, state and local levels. Our purpose is also to suggest how these problems might be minimized or alleviated.

## II. REGULATORY POWERS, REGULATIONS, AND REGULATORY INSTRUMENTS.

The terms regulatory powers, regulations, and regulatory instruments are used in this paper to denote distinct elements of the regulatory process as a whole. The term regulatory powers refers to the authority vested in a specific executive branch agency by a state legislature or the Congress. Such powers permit and/or require action on the part of that agency pursuant to an objective of society. Regulatory powers tell agencies what they can or must do, but they rarely offer the specifics necessary for agencies to implement their authority.

Regulations are established primarily by a public agency under the authority vested in that agency by regulatory powers. Regulations specify, in such detail as will permit implementation, how agencies intend to proceed toward societal objectives. In essence, regulations prescribe behavior, that of the sponsoring agency as well as the agency's clientele (i.e., the public).

Regulatory instruments, such as permits, licenses, variances and certificates, are the most specific elements of the regulatory process. Their purpose is to demonstrate the compliance of past actions with regulations and/or to indicate how future actions will be in compliance. While agencies are not often exempt from demonstrating compliance with the regulations of other agencies, this paper is concerned only with the required use of regulatory instruments by the coal indu[illegible] For the purposes of this paper, we have restricted the definition of "public[illegible] the coal industry. In practice, of course, "public" refers to individuals an[illegible]terest groups as well as profit and non-profit corporations.

One additional distinction between these elements is of special importance. The content of, or action required by, each of the above elements may be either procedural or substantive in nature. The element is substantive when its provisions are directly related to a societal objective (e.g., surface mine reclamation). It is procedural when its provisions specify how past compliance or future compliance with a substantive requirement is to be demonstrated. While there is a considerable amount of overlap between the two provisions, the distinction is central to the analysis of regulatory systems as will become evident in this paper.

In its simplest form, a regulatory power is a contract between the legislative and executive branches of state and Federal government. It is primarily procedural in nature in that it permits and/or requires specific action on the part of the executive. In practice it is also substantive in that such powers usually express a broad societal objective that the executive is to attain through the use of its expanded authority. Regulations entail a relationship between the executive and the public. They are substantive in nature because they define specific behavior on the part of their clientele - the public, which is subject to sanction; consequently regulations may modify the action preferences of individuals or groups. Invariably, however, regulations limit the choice or discretion of groups or individuals.

Regulatory instruments are primarily mechanisms for communication between the regulator and the regulated. Because their purpose is to demonstrate compliance with specific regulations, instruments are procedural in nature and therefore do not directly modify the behavior of their clientele.

The regulation of individuals and of industries has become an extremely popular topic in recent years. One explanation behind the popularity of coal industry regulation is the need to increase coal production and consumption, thereby reducing oil imports. The distinction made in the preceeding discussion between elements of the regulatory process becomes central as we attempt to determine to what extent current regulatory practices limit coal production and consumption. The discussion is also important in determing how, in fact, each element of the regulatory process limits production and consumption. If, in the analysis of a state's regulatory process, it is determined that the procedure by which regulations are implemented limits the extraction and consumption of coal to an unjustifiable extent, then reformation of the procedure is called for without affecting the substance of regulations. On the other hand, if analysis indicates that it is the substance of regulations which limit, to an unacceptable degree, the extraction or consumption of coal, then modification of the substantive requirements of regulations is in order. Procedural changes are primarily organizational in nature; they modify the way in which regulatory requirements are administered, but such changes do not modify their content. Changes in the substance of regulations, however, require a political decision. When discussing modifications in the <u>substance</u> of coal industry regulations, a balancing of environmental, health and safety objectives against increased coal production and consumption is required. Such changes, in essence, modify the extent to which government limits the discretionary actions of industry.

## III. COSTS OF REGULATORY PROCEDURES.

The preceding discussion suggests the existence of two separate costs associated with the regulatory process. The first cost is that associated with actually doing what is required by regulations (i.e., the substantive cost). The second cost is that which is associated with the procedure of compliance. Procedural costs, which are somewhat more difficult to quantify than substantive costs, are the primary topic of this paper. Therefore, the remainder of our discussion will center around identifying those procedures for administrative review and approval* which delay the siting, construction and/or operation of coal mines and preparation facilities, thus resulting in increased costs to the operators. When combined, substantive and procedural costs may be considered as the total cost associated with the activities required of an operator to comply and demonstrate compliance with the regulatory process. Included among these costs are the following:

A. <u>Information repackaging and submittal</u>. This cost refers to the repackaging of similar information for submittal to various agencies, each with its own schedule and criteria for approval. Repackaging may be required by agencies at different levels (i.e., Federal, state, county or munici-

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*For example, the preparation of plans, reports, permit applications and sometimes litigation.

pal and in some cases, interstate), as well as to agencies of the same level of government.

B. Requirements for premature or overly finalized levels of detail. This refers to requirements by certain agencies of what many operators consider premature or overly finalized levels of engineering design detail and site specifics. Such information is often required in permit applications for operations which may be several years away.

C. Regulatory-induced uncertainties in timing. Uncertainty in timing and scheduling operations, especially in procurement of men and equipment, often occurs in cases where either no legal deadlines exist for responding to permit applications, or where one agency's approval or certification is necessary to obtain another agency's permit.

D. Permit resubmittals. When agencies have multi-module permit applica[illegible] and/or requirements such as the simultaneous issuance of all permits for a given operation, lead time delays have frequently resulted due to incomplete or improperly filed permit applications. This indicates some level of misunderstanding between operators and regulators.

E. Delays to initial activity. In many cases, operators cite procedural constraints to initial pre-construction activities until all permits from a given agency are issued. This is mostly a problem where the agency in question is vested with virtually all regulatory authority over coal operators.

F. Special conditions. Special conditions are often imposed on requests to modify permits which substantially alter the initial requirements upon which the timing and costs of planned site expansion were based (i.e., revision of barrier widths between entries in extending deep mining operations, and revision of slope and compaction requirements in expanding refuse disposal sites).

G. Jurisdictional overlapping. In certain instances, operators must meet standards imposed under different statutes which require inspections by different agencies which enforce their own requirements, such as in deep mine safety.

H. Data gathering and report preparation costs. In terms of personnel time and materials, operators are required to provide increasing amounts of information deemed necessary to evaluate compliance with substantive regulations. These costs do not include any construction, operation and maintenance costs for specific facilities; rather, they are limited to those costs associated with the preparation and submittal of required plans, reports and permit applications.

Each of the above procedural costs may be attributed in some ways to either of two related phenomena which characterize certain portions of regulation at the state and Federal levels. First, the duplication of requirements*, envolved from a national concern over the adequacy of state and local regulatory programs to protect public (and occupational) safety and health. Concern led to the enact[illegible] of legislation which mandated Federal oversight of most mining industry activ[illegible]

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*Four types of duplication of requirements were observed in another recent study. These were: (1) review duplication - when more than one agency has the responsibility to review the same plan or application for the same time; (2) permit duplication - when more than one agency requires a permit for the same facility or facet of operation; (3) cross compliance of plans and permits - when one or more agencies have regulations which must be complied with or another permit application or prior to approval of this permit; and (4) pyramiding of permits - when compliance with one agency's regulation required compliance with those of another agency which has overlapping jurisdiction (Green International, 1977[2]).

The sophistication of state environmental control programs has increased along with this expanding Federal role. Irrespective of the reasons behind the duplication of regulatory authority, the existence of distinct programs at the state and Federal levels has led to a number of administrative or regulatory bottlenecks. Such bottlenecks are complicated by the fact that programs vary in their emphasis and requirements. Thus, one may ask what, if any, level of duplication is necessary to provide a margin of safety to protect each narrowly defined area of public concern.

The second phenomenon is that of agency involvement in determining the specific means by which standards of performance are to be met. This phenomenon appears to have evolved from a desire to minimize the risk of structural failure or other technical deficiencies which might require the closing of a mine, refuse pile, or preparation plant. This phenomenon raises the issue of public (agency) involvement in private decision making. Specifically, should agencies' involvement be limited to requiring standards of performance (i.e., "results oriented" approach) or should that involvement extend to the approval of designs necessary to meet standards? In this paper, we assume that the operator should be afforded maximum flexibility to adjust to the dynamics of his industry and therefore we ask two questions. First, what level of engineering design detail is necessary to be provided in initial permit applications before receiving permission to construct each type of mining facility? Second, how can an operator be afforded maximum discretion and flexibility to adjust to the dynamics of operation without having to modify his initial plan or be subject to special conditions, while still meeting prescribed standards?

In order to address the phenomena of duplication and agency involvement which are also key issues, we will first present and describe the regulatory framework used in the two case study states that were examined in the Hittman study. Figures 1 and 2 illustrate, within the context of the energy flow chain described in Section I, supra, the agencies and their permit/enforcement responsibilities which regulate the coal mining and preparation industries in Pennsylvania and Kentucky. In Phase I, a distinction is made between permits required for underground and deep mines, and preparation plants. These flow charts were prepared after extensive telephone and personal conversations with numerous public and private officials late in 1976. Although cooperation was generally forthcoming, it must be noted that few public officials at any level of government demonstrated a good understanding of the regulatory process beyond their own authority. Permits for facilities sited on Federal lands were not included in these figures since very few coal facilities in these states are so located. For operations on Federal lands, requirements include an approval by the U.S. Geological Survey for the mining plan, and then a lease for mining on public lands by the Bureau of Land Management. The only other potential requirement is for a prospecting permit by the U.S. Forest Service if the prospective site is on Forest Service lands.

In comparing the two flow charts, it appears that the potential number of separate permits, licenses and certificates which may be required in each state for each type of facility is roughly equivalent. The actual number of such approvals which may be required will depend on the design characteristics and scheduling of the specific facility. The effluent sources of a mine, for example, may require separate permits for drainage points, refuse pile discharge and sediment basins. Similarly, separate air permits may be required for thermal dryers and access roads. It is conceivable that approval of all water effluent or air emission sources at a single facility could be obtained on a single permit. However, unless the state has NPDES* authority, the appropriate state water quality agency usually issues at least one similar permit of its own, in addition to certifying its concurrence before EPA issues the NPDES permit.

Another problem in determing the number of permits which may be required is that numerous planning modules such as those required to operate deep mines are

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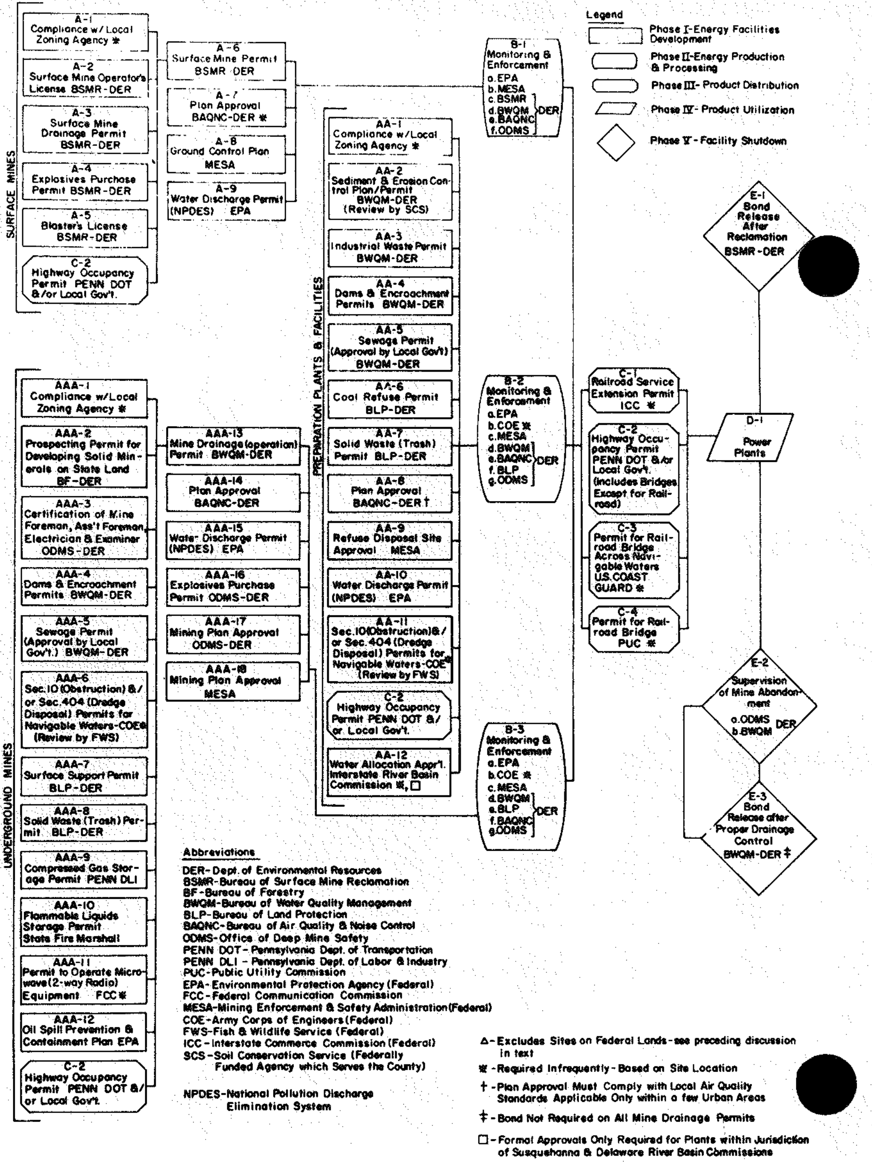
*The National Pollutant Discharge Elimination System (NPDES) is the basic enforcement tool provided within the 1972 Federal Water Pollution Control Act Amendments. This permit authority is fully transferable to state water quality agencies as long as certain enforcement standards and procedures are maintained.



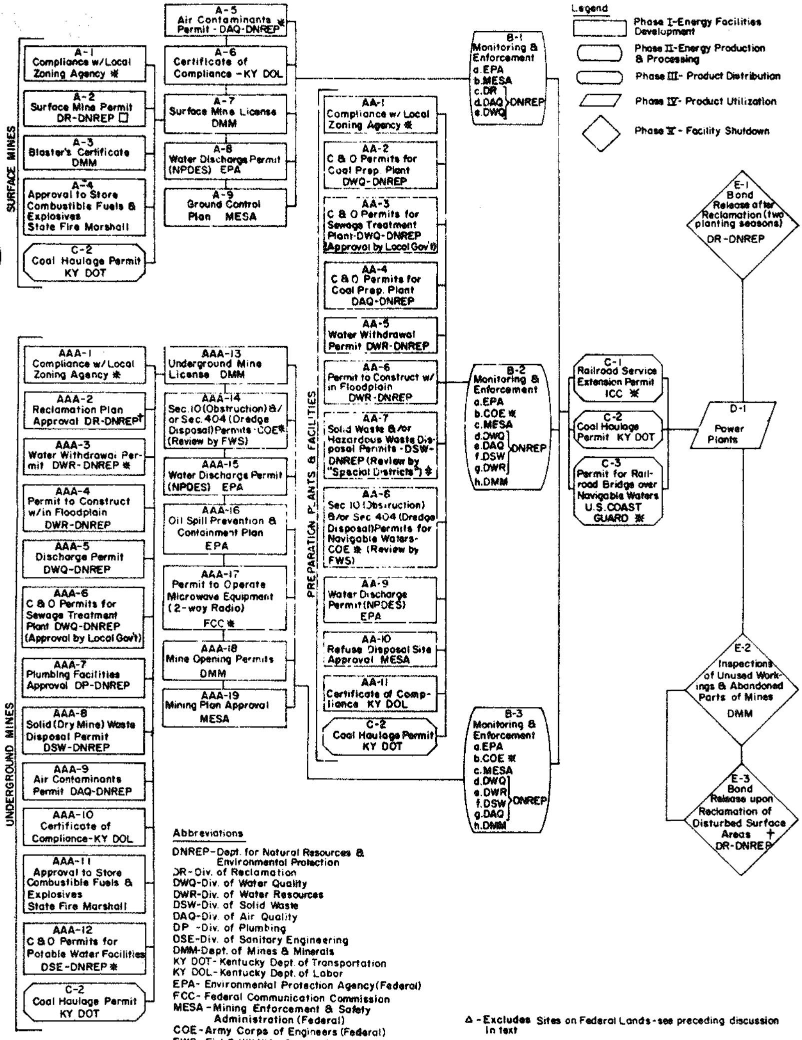
Abbreviations

DER-Dept. of Environmental Resources
BSMR-Bureau of Surface Mine Reclamation
BF-Bureau of Forestry
BWQM-Bureau of Water Quality Management
BLP-Bureau of Land Protection
BAQNC-Bureau of Air Quality & Noise Control
ODMS-Office of Deep Mine Safety
PENN DOT-Pennsylvania Dept. of Transportation
PENN DLI - Pennsylvania Dept. of Labor & Industry
PUC-Public Utility Commission
EPA-Environmental Protection Agency (Federal)
FCC-Federal Communication Commission
MESA-Mining Enforcement & Safety Administration (Federal)
COE-Army Corps of Engineers (Federal)
FWS-Fish & Wildlife Service (Federal)
ICC - Interstate Commerce Commission (Federal)
SCS - Soil Conservation Service (Federally Funded Agency which Serves the County)

NPDES-National Pollution Discharge Elimination System

Δ-Excludes Sites on Federal Lands-see preceding discussion in text
✻ -Required Infrequently - Based on Site Location
† -Plan Approval Must Comply with Local Air Quality Standards Applicable Only within a few Urban Areas
‡ -Bond Not Required on All Mine Drainage Permits
☐ -Formal Approvals Only Required for Plants within Jurisdiction of Susquehanna & Delaware River Basin Commissions

FIGURE 1 - PENNSYLVANIA FLOW CHART[3] Δ



Abbreviations

DNREP-Dept. for Natural Resources & Environmental Protection
DR-Div. of Reclamation
DWQ-Div. of Water Quality
DWR-Div. of Water Resources
DSW-Div. of Solid Waste
DAQ-Div. of Air Quality
DP -Div. of Plumbing
DSE-Div. of Sanitary Engineering
DMM-Dept. of Mines & Minerals
KY DOT- Kentucky Dept. of Transportation
KY DOL- Kentucky Dept. of Labor
EPA- Environmental Protection Agency (Federal)
FCC- Federal Communication Commission
MESA -Mining Enforcement & Safety Administration (Federal)
COE-Army Corps of Engineers (Federal)
FWS-Fish & Wildlife Service (Federal)
ICC -Interstate Commerce Commission (Federal)

NPDES -National Pollution Discharge Elimination System
C & O Construction & Operation

Δ -Excludes Sites on Federal Lands-see preceding discussion in text
✱ -Required Infrequently-Based on Site Location
† -Regulations for Enforcement Still Pending
✟ -KRS Sec.109 Provides for Local Collection or Disposal Districts - Exist Mainly in Urban Areas
☐ -Requires Prior Certification of Sediment and Erosion Control Plan and Post-Certification of Structures by Registered Engineer

FIGURE 2 - KENTUCKY FLOW CHART[3] Δ

often considered to be separate permits by operators, whether they involve one time filing (e.g., miner training, abandonment, or emergency medical programs) or periodic submittals (e.g., ventilation and roof support plans). Furthermore, when a facility expands its operations, the level of detail requested on a permit modification often amounts to a new permit application, even if it is not formally labelled as such by the agency.

While it is difficult to determine the exact number of distinct approvals required for a particular mine or preparation facility, it has been estimated that as many as 50 separate approvals are required in Pennsylvania[4]. Although this number may be higher than required for most operations, it is not altogether unheard of for large scale facilities. The approval times associated with a given operation and the effect of the permit process on scheduled production are more important factors than the actual number of permits which may be required. To determine a estimate of the average times required for approval of specific permits, questionnaires were distributed in the late summer of 1976 among individual operators through the major coal associations in the case study states. Questionnaire results are presented in Tables 1 and 2. While no claim is made that the number of responses is statistically valid,* it is felt that they represent "ballpark estimates" of permit approval times and the degree of variation between the states. One important comparison which can be made is the average total time between application for the first permit and the issuance of the last permit.** In months, these times were, for Kentucky: surface - 9.8, underground - 11.2; and for Pennsylvania: surface - 11.4, underground - 31.4. Permits for associated preparation plants generally required less time, although on a proportional basis to each type of mining operation. While these figures are reflective of the total elapsed time between the first permit application and last permit approval, they do not necessarily reflect the time required by regulatory agencies for processing. Nor do they indicate actual delays incurred by coal operators. Only through a comprehensive analysis of the activities of operators and regulators, is it possible to determine the nature and extent of financial, scheduling, or other problems resulting from delays.

On the average, the time required for NPDES approval is the greatest. It should be noted, however, that approval time of three years or more may have been caused, at least in part, by the fact that about 12,000 NPDES applications were filed between 1973 and last year. Additional factors include the lack of a uniform approach across EPA regions, until issuance of national guidelines for the mining industry in May 1976, the lack of an adequate staff to process the required paperwork, and numerous citizen appeals, especially on surface mine permits (EPA, 10/76)[5].

One probable reason for the approval time differences between the case study states appears to be internal agency policies regarding multiple permit applications. In Pennsylvania, most permitting functions are administered by the Department of Environmental Resources (DER). The DER has been granted complete authority over surface and deep mining operations as well as preparation facilities. As an administrative policy, DER has decided to issue all permits applicable to a given mine or preparation plant at the same time. In theory, this enables DER to foresee and therefore fully address all potential environmental problems in a comprehensive and timely fashion. To counter the problem of delays due to incomplete

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*Kentucky questionnaires were sent out just prior to the wildcat strike during the summer of 1976, which undoubtedly contributed to the relatively light response. However, interviews with operators in that state tend to confirm the approval time reported in the questionnaires.

**Average total time per operator was calculated from those questionnaire responses which cited approval times for at least the following major permits: surface mine permit from state agency, mining plan approval from MESA (if underground mine), plus the NPDES permit from EPA, for both surface and underground mines. The NPDES permit requires prior certification by the state water quality agency.

TABLE 1 - PENNSYLVANIA QUESTIONNAIRES[6]

| | | | | Approval Time Months/Operator | |
|---|---|---|---|---|---|
| | Surface | No. of Responses | Min. | Max. | Avg. |
| Mine Permits | -BSMR/Surface Mine Operator Lic. | 16 | 0.5 | 6.0 | 1.5 |
| | -BSMR/Surface Mine Drainage | 19 | 3.0 | 15.0 | 6.6 |
| | -BSMR/Surface Mine | 19 | 1.0 | 7.0 | 3.1 |
| | -BSMR/Explosives Purchase | 9 | 0.3 | 3.0 | 1.4 |
| | DER -BSMR/Blasters License | 6 | 1.0 | 2.5 | 2.6 |
| | -BWQ/Stream Encroachment | 6 | 0.5 | 6.0 | 2.9 |
| | -BWQ/Industrial Waste | 1 | 10.0 | 10.0 | 10.0 |
| | -BWQ/Solid Waste Mgt. | 2 | 6.0 | 13.0 | 8.3 |
| | -BLP/Coal Refuse | 4 | 4.0 | 12.0 | 7.0 |
| | Penn. DOT/Highway Occupancy | 6 | 0.3 | 2.0 | 0.7 |
| | EPA/Discharge (NPDES) | 6 | 5.0 | 52.0 | 18.8 |
| | MESA/Ground Control Plan | 9 | 1.0 | 3.0 | 1.5 |
| | Local Gov't./Sewage | 1 | 6.0 | 6.0 | 6.0 |
| | Avg. Total Time Per Operator | 20 | | | 11.4 |
| Prep. Plant Permits | -BWQ/Stream Encroachment | 4 | 3.0 | 13.0 | 5.5 |
| | -BWQ/Industrial Waste | 1 | 9.0 | 9.0 | 9.0 |
| | -BWQ/Solid Waste Mgt. | 3 | 1.0 | 9.0 | 9.0 |
| | -BWQ/Sewage | 1 | 6.0 | 6.0 | 6.0 |
| | -BWQ/Dams & Encroachment | 2 | 3.0 | 4.0 | 3.0 |
| | -BWQ/Erosion Control | 2 | 0.5 | 2.0 | 2.0 |
| | DER -BAQNC/Plan Approval | 2 | 1.0 | 1.0 | 1.0 |
| | -BAQNC/Operation | 1 | 2.0 | 2.0 | 2.0 |
| | -BLP/Coal Refuse | 3 | 6.0 | 9.0 | 7.0 |
| | -BSMR/Explosives Purchase | 3 | 1.0 | 1.5 | 1.2 |
| | -BWMR/Blasters License | 2 | 1.5 | 8.0 | 4.8 |
| | Penn. DOT/Highway Occupancy | 3 | 0.3 | 1.5 | 0.6 |
| | EPA/Discharge (NPDES) | 2 | 5.0 | 8.0 | 6.5 |
| | MESA/Refuse Disposal Site | 2 | 1.0 | 1.0 | 1.0 |
| | Local Gov't./Sewage | 1 | 6.0 | 6.0 | 6.0 |
| | Avg. Total Time per Operator | 2 | | | 6.3 |

TABLE 1 - PENNSYLVANIA QUESTIONNAIRES (Cont'd)[6]

| | Underground | Responses | Approval Time Months/Operator Min. | Max. | Avg. |
|---|---|---|---|---|---|
| Mine Permits | -BWQ/Op. or Mine Drainage | 13 | 2.0 | 48.0 | 11.6 |
| | -BWQ/Dams & Encroachment | 11 | 1.0 | 7.0 | 6.4 |
| | -BWQ/Sewage | 10 | 3.0 | 9.0 | 5.1 |
| | -BWQ/Erosion Control | 10 | 0.1 | 8.0 | 2.6 |
| | DER -BLP/Surface Support | 4 | 0.3 | 3.0 | 1.3 |
| | -BLP/Solid Waste (Trash) | 2 | 34.0 | 10.0 | 20.3 |
| | -ODOMS/Mining Plan Approval | 6 | 1.0 | 6.0 | 3.3 |
| | -ODOMS/Explosives Purchase | 6 | 0.5 | 3.0 | 1.2 |
| | -ODOMS/Blasters License | 2 | 1.0 | 2.0 | 1.5 |
| | Penn. DOT/Highway Occupancy | 7 | 0.3 | 15.0 | 4.5 |
| | Penn. DOLI/Compressed Gas Storage | 2 | 1.0 | 36.0 | 18.3 |
| | EPS/Discharge (NPDES) | 10 | 2.0 | 75.0 | 31.8 |
| | MESA/Mining Plan Approval | 7 | 2.3 | 12.0 | 3.6 |
| | MESA/Ventilation Plans | 13 | 1.0 | 14.0 | 3.9 |
| | MESA/Roof Control Plans | 11 | 0.5 | 10.0 | 3.9 |
| | COE/Const. in Nav. Waters | 1 | 3.5 | 3.5 | 3.5 |
| | COE/Discharge of Dredge & Fill Mat'ls | 2 | 5.0 | 25.0 | 15.0 |
| | Local Govt./Sewage | 4 | 0.3 | 9.0 | 2.8 |
| | Local Govt./Zoning Variance | 2 | 1.0 | 4.0 | 2.5 |
| | Avg. Total Time per Operator | 13 | | | 31.4 |
| Prep. Plant Permits | -BWQM/Dams & Encroachment | 1 | 5.0 | 5.0 | 5.0 |
| | -BWQM/Industrial Waste | 6 | 1.5 | 10.0 | 5.3 |
| | -BWQM/Sewage | 2 | 1.0 | 6.0 | 3.5 |
| | DER -BWQM/Erosion Control | 5 | 0.5 | 10.0 | 4.0 |
| | -BLP/Coal Refuse | 6 | 1.2 | 30.0 | 10.5 |
| | -BLP/Solid Waste (Trash) | 1 | 12.0 | 12.0 | 12.0 |
| | -BAQNC/Plan Approval | 2 | 2.0 | 15.0 | 8.5 |
| | -BAQNC/Operating | 2 | 1.5 | 15.0 | 5.3 |
| | Penn. DOT/Highway Occupancy | 1 | 1.5 | 1.5 | 1.5 |
| | EPA/Discharge (NPDES) | 4 | 12.0 | 66.0 | 41.8 |
| | MESA/Refuse Disposal Site | 8 | 1.0 | 8.0 | 2.5 |
| | COE/Discharge of Dredge & Fill | 1 | 5.0 | 5.0 | 5.0 |
| | Local Govt./Air Pollution | 2 | 0.3 | 12.0 | 6.1 |
| | Local Govt./Zoning Variance | 1 | 4.0 | 4.0 | 4.0 |
| | Avg. Total Time per Operator | 8 | | | 27 |

## TABLE 2 - KENTUCKY QUESTIONNAIRES[6]

| | | | No. of Responses | Approval Time Months/Operator | | |
|---|---|---|---|---|---|---|
| | | Surface | | Min. | Max. | Avg. |
| Mine Permits | | DMM/Surface Mine Lic. | 7 | 0.3 | 1.5 | 0.7 |
| | | DNREP-DR/Surface Mine | 6 | 1.0 | 3.0 | 1.9 |
| | | Ky. DOT/Coal Haulage | 7 | 0.2 | 0.8 | 0.4 |
| | | Ky. DOL/Certif. of Compliance (WCD) | 5 | 0.3 | 1.5 | 1.0 |
| | | Fire Marshall/Hazardous Materials | 1 | 0.5 | 0.5 | 0.5 |
| | | EPA/Discharge (NPDES) | 5 | 1.0 | 24.0 | 8.1 |
| | | MESA/Ground Control Plan | 6 | 0.5 | 2.5 | 1.2 |
| | | Avg. Total Time per Operator | 6 | | | 9.8 |
| Prep. Plant Permits | DNR EP | -DWQ/Const.$^+$ Op. Prep Plant | 4 | 0.3 | 3.5 | 1.8 |
| | | -DWQ/Sewage Treatment | 3 | 2.0 | 2.5 | 2.2 |
| | | -DWQ/Dry Refuse Disposal | 2 | 1.5 | 2.0 | 1.8 |
| | | -DWR/Water Withdrawal | 3 | 0.3 | 1.0 | 1.0 |
| | | -DWR/Const. in Floodplain | 1 | 1.0 | 1.0 | 1.0 |
| | | EPA/Discharge (NPDES) | 5 | 0.9 | 24.0 | 7.5 |
| | | MESA/Refuse Disposal Site | 6 | 1.0 | 3.0 | 2.0 |
| | | COE/Const. in Nav. Waters | 1 | 3.0 | 3.0 | 3.0 |
| | | Avg. Total Time per Operator | 3 | | | 6.3 |
| | | Underground | | | | |
| Mine Permits | | DMM/Underground Mine Lic. | 5 | 0.3 | 2.0 | 0.9 |
| | | DMM/Initial Mine Opening | 3 | 0.3 | 2.0 | 1.3 |
| | | DMM/Add'l Mine Opening | 3 | 0.3 | 1.0 | 0.6 |
| | DNR EP | -DR/Approval of Recl. Plan | 3 | 1.0 | 3.0 | 2.0 |
| | | -DWQ/Water Discharge | 3 | 2.0 | 6.0 | 3.3 |
| | | -DWQ/Sewage Treatment | 3 | 1.5 | 4.0 | 2.5 |
| | | -DWQ/Dry Refuse (Waste) Disposal | 2 | 2.0 | 2.0 | 2.0 |
| | | -DWR/Water Withdrawal | 1 | 1.0 | 1.0 | 1.0 |
| | | -DWR/Const. w/in Floodplain | 2 | 1.0 | 2.5 | 1.7 |
| | | Ky. DOT/Coal Haulage | 5 | 0.3 | 1.0 | 0.6 |
| | | Ky. DOL/Certif. of Complicance (WCD) | 3 | 0.3 | 1.5 | 0.9 |
| | | EPS/Discharge (NPDES) | 5 | 2.0 | 24.0 | 9.4 |
| | | MESA/Mining Plain | 5 | 0.3 | 2.5 | 1.4 |
| | | MESA/Ventilation Plan | 5 | 0.3 | 4.0 | 1.5 |
| | | MESA/Roof Control Plans | 5 | 0.3 | 2.5 | 1.2 |
| | | COE/Const. in Nav. Waters | 1 | 3.0 | 3.0 | 3.0 |
| | | Avg. Total Time per Operator | 5 | | | 11.2 |
| p. nt Permits | DNR EP | -DWQ/Const.$^+$ Op. Prep. Plant | 3 | 2.0 | 6.0 | 3.3 |
| | | -DWQ/Sewage Treatment | 2 | 1.5 | 2.0 | 1.7 |
| | | -DWQ/Dry Refuse Disposal | 2 | 2.0 | 2.0 | 2.0 |
| | | -DWR/Water Withdrawal | 1 | 1.0 | 1.0 | 1.0 |
| | | -DWR/Const. in Floodplain | 1 | 1.0 | 1.0 | 1.0 |
| | | -DAQ/Air Quality | 3 | 3.0 | 6.0 | 5.0 |
| | | EPA/Discharge (NPDES) | 4 | 2.0 | 24.0 | 8.7 |
| | | MESA/Refuse Disposal Site | 4 | 1.0 | 5.0 | 2.5 |
| | | COE/Const. in Nav. Waters | 1 | 3.0 | 3.0 | 3.0 |
| | | Avg. Total Time per Operator | 4 | | | 9.5 |

## QUESTIONNAIRE ABBREVIATIONS - PENNSYLVANIA[6]

DER - Department of Environmental Resources
BSMR - Bureau of Surface Mine Reclamation
BWQ - Bureau of Water Quality
BLP - Bureau of Land Protection
BAQNC - Bureau of Air Quality and Noise Control
BF - Bureau of Forestry
ODSM - Office of Deep Mine Safety
Penn. DOT - Pennsylvania Department of Transportation
Penn. DOLI - Pennsylvania Department of Labor and Industry
EPA - Environment Protection Agency
COE - Army Corps of Engineers
ICC - Interstate Commerce Commission
Lic. - license
Mgt. - management
Gov't. - government
Const. - construct
Nav. - navigable
Mat'ls - materials
NPDES - National Pollution Discharge Elimination System

## QUESTIONNAIRE ABBREVIATIONS - KENTUCKY[6]

DMM - Department of Mines and Minerals
DNREP - Department for Natural Resources and Environment Protection
Ky. DOT - Kentucky Department of Transportation
Ky. DOL - Kentucky Department of Labor
WCD - Workmen's Compensation Division
DR - Division of Reclamation
EPA - Environmental Protection Agency
MESA - Mining Enforcement and Safety Administration
DWQ - Division of Water Quality
DWR - Division of Water Resources
COE - Army Corps of Engineers
NPDES - National Pollution Discharge Elimination System
Certif. - certificate
Mat'l - material
Const. - construct
Op. - operate
Nav. - navigable
Add'l - additional
Rec'l - reclamation
w/ - with
Lic. - license

inaccurately filed applications, last year DER adopted the policy of informing the applicant within five days as to the completeness of his application package (i.e., inclusive of all required permit applications). An older Department policy has been to respond with approval or denial of permit applications within 60 days. However, DER officials indicate that this goal is not always met; many operators contend that meeting of the goal is the exception rather than the rule. The DER permits are generally issued at the Bureau level by field personnel called regional directors. One of the director's functions is to meet with all of his program managers (regional personnel responsible for water quality, air quality, solid waste, etc.) and the permit applicant to determine the latter's needs and the approval requirements of his proposed operation. A common problem in this area arises when the applicant wishes to begin certain activities such as pre-construction site clearing, without having to wait for the issuance of all permits, especially the detailed mine drain[illegible] or "operating" permit. While such a "variance" in its all-at-once permit is[illegible]ce policy may be obtained at one of the coordinating meetings chaired by the regional director, many operators claim that in practice this seldom occurs. One option for the operator is to hand-carry an application to Harrisburg and directly appeal for a variance based on special circumstances. However, operators may be reluctant to do this, given the necessity of dealing with the regional office in the future.

Kentucky, by contrast, has divided the responsibility for overseeing the coal industry. Miner health and safety for all types of operations is regulated by the Department of Mines and Minerals, which also licenses both surface and deep mines. However, most permit authority, especially involving environmental controls, is vested in the Department for Natural Resources and Environmental Protection (DNREP) which provides day-to-day oversight of surface mining and related operations. The DNREP has a "divisionalized" permit process in which each division appears to have significant autonomy in issuing permits. Circulation of permit applications for review among the divisions is commonplace, but individual permits are issued for specific activities without awaiting concurrent approval of permits outstanding in other divisions. Furthermore, if all water discharges and sewage treatment facilities appear on one permit to the Division of Water Quality, combined approval may be obtained following a review by the Division of Sanitary Engineering and the Division of Plumbing. The latter two divisions issue separate permits primarily when individual facilities are emplaced on existing sites.

Between the two states, Kentucky's Division of Reclamation is the only entity which has a prescribed statutory deadline for reviewing and responding to permit applications - currently 30 days. Most other permits are estimated by DNREP officials to take 30 to 45 days for action. Current practice is for DNREP to issue all permits from Frankfort, based upon site investigation reports from its regional officials.

In comparing permit practices within two states, each with somewhat distinctive problems in regulating coal development, one must be careful in drawing any conclusions based solely upon the time required to obtain permit approvals. Just as a relatively lengthy review process does not necessarily indicate thoroughness or quality of review, neither does a relatively brief review process indicate a coordinated, streamlined and effective approval route. Two more important charac[illegible]istics of an effective permit process might be the rate of compliance with the [illegible]tance of regulations (without necessitating mine closure), while maintaining [illegible] maximum feasible operator discretion as to how compliance is to be achieved. This involves much subjective judgment in comparing operations subject to different regulatory requirements and would entail a major study in itself. However, a description of specific regulatory problems which occurred in the case study states may be useful in more clearly depicting the problems of effectively regulating the coal industry.

## IV REGULATORY PROBLEMS

The following problems describe in detail those costs identified in Section III.

- Mine drainage.

To contain acid mine drainage, long a major pollution source in the Appalachian Region, mining operations are now controlled by more regulations than ever before. Regulatory problems in this environmental area are illustrated by a Pennsylvania case where an operator wanted to put down a new shaft as an extension to an existing underground mine. In theory, this would have required modification of the existing mine drainage permit or the issuance of a new drainage permit* by DER's Bureau of Water Quality Management. However, the Bureau indicated that a new sediment and erosion control plan was required. The Bureau's policy is to require prior approval of such a plan from the Soil Conservation Service (SCS) a Federally funded agency serving the county. Before granting approval, the SCS requested details regarding the exact design and location of all prospective facilities, such as the bathhouse, powderhouse, stream culverts, bridges, etc. While [illegible] operator would have had to plan and design such facilities at some point, the pr[illegible]vision of this level of detail before he has the certainty of permission even to put down a shaft imposes two burdens. The first involves added difficulty in scheduling men and equipment to perform construction activities in a timely fashion. The second involves the operator locking himself into a specific site layout perhaps five years or more before actual production begins, enhancing the possibility of requesting several permit modifications downstream.

By contrast, Kentucky does not require any permit specifically to control mine drainage from deep mines. In fact, the Division of Water Quality in DNREP only requires a permit from deep mining operations when there is a preparation facility present, as potential discharge from the latter is felt to pose a greater threat to water quality. However, the Division has authority to require operators to abate deep mine drainage, and does so when such a water problem is cited. In any event, all deep mines are required to have NPDES permits from the U.S. EPA, which must first be certified by the appropriate state agency.

- Coal refuse disposal.

Coal refuse piles have been and remain major sources of pollution runoff and leaching, in addition to being safety hazards, especially when used as impoundments. Regulations which affect refuse disposal, however, differ greatly in the case study states. Until a few years ago, prevention of refuse pile runoff in most states consisted mainly of excavating a collection ditch or detainment pond to capture water percolating through the pile as well as preventing contamination by adjacent surface runoff. Presently, in Kentucky, the Division of Water Quality approves refuse piles in conjunction with the preparation facility via a single permit application (modelled after EPA's NPDES permit application). In it, specifications must be provided for plant discharge limits and for overflow ponds and other containment facilities for ancillary areas of sufficient capacity to handle runoff under emergency conditions. Other state and Federal permits may be required at the preparation facility based on site specifics, but the only other permit always required for the refuse pile itself (from a safety standpoint) is from the U.S. Mining Enforcement and Safety Administration (MESA).

In Pennsylvania, however, the permit process for refuse pile maintenance best illustrates two regulatory issues: the phenomena, briefly mentioned before, of permit pyramiding; and the problem of legal exemptions vis-a-vis practical enfo[illegible]ment. Regarding the first issue, DER's Bureau of Land Protection requires a two-stage approval for refuse piles. Phase I consists of the submittal of extensive geological and pollution monitoring data to determine soil stability and related

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*All deep mines in Pennsylvania require a mine drainage permit from DER. This is a highly detailed 26 module form which serves as an operating permit for environmental (as opposed to health and safety) purposes. Recently, the state Environmental Hearing Board held that public notice must be made weekly for four weeks (i.e., by newspaper) to precede the filing of new mine drainage permit applications, thus adding an additional month to the permit process.

factors. Phase II permits construction at the site following approval of far more detailed engineering designs, but only when all other pending DER permits are ready to be issued. In the case described here, the site design included construction of a headwall to divert a small stream from reaching the refuse pile, thus requiring a dams and encroachment permit from DER, Bureau of Water Quality Management. At the same time, the plan to channelize water percolating within the pile to prevent pollution runoff (as is encouraged by the Bureau) effectively created a discharge source for which an industrial waste permit was required; this in turn produced a point source discharge for which an NPDES permit from EPA was also required. Finally, a sediment and erosion control permit had to be obtained from DER upon review by the SCS, as well as the disposal site approval issued by MESA.

In addition to the total number of permits potentially required, one major diff[illegible] between refuse pile maintenance in the two states is the requirement for channeling or otherwise collecting refuse pile runoff which must then receive treatment of neutralization, aeration and sedimentation which may or may not result in separate facilities from the preparation plant slurry pond, depending upon site logistics. At issue is DER Regulation Section 97-32 and 34, which specifically exempt operators from treating seasonal flow from refuse piles. Operators contend that required collection of refuse pile runoff and subsequent treatment as discharge effectively negates this exemption.

o     <u>Mine health and safety</u>.

This problem arises, primarily, when agencies at both the state and Federal level have responsibility over a single area of concern such as deep mine safety. In such cases, operators may be required to comply with certain legal provisions which require the cooperation, or at least acquiescence, of one of the agencies. One such case involved MESA regulations which require artificial roof support (e.g., cabs and canopies) in new and existing deep mines. These regulations have been opposed at times not only by operators, but also by miners and state regulatory officials as well. In particular, the retrofit of cabs and canopies for face equipment has been considered unsafe at times, especially in low seams or those with uneven surfaces where clearance between the equipment and the roof is uncertain. Fatalities have occurred in some cases where the retrofitted canopy was declared to have been a contributing factor[7]. In one case, Kentucky's Department of Mines and Minerals approved the removal of canopies which MESA had just ordered installed. This case highlights the occasional difficulty an operator may be placed in when subject to two different statutes and enforcement agencies. Although such a situation has arisen only in relation to deep mining, similar jurisdictional problems <u>may</u> occur under Federal control over surface mining unless adequate provisions are made within the law for coordinated Federal-state enforcement as in the case of air and water pollution control.

o     <u>Data gathering and plan/report preparation</u>.

One operator of two deep mines producing slightly over one million tons per year conducted an in-house study on the most readily quantifiable categories of substantive and procedural costs. This study estimates the costs of personnel time, material and miscellaneous expenses incurred in the gathering of data, preparation [illegible] submittal of all Federal plans, reports and permit applications required by law. [illegible]e requirements are expressly not included. The study is confined to the post-1960 period and focuses primarily on the requirements of MESA and EPA, although the costs of preparing additional Federal research questionnaires have also been included. The results indicate that an average of about $400,000 per year is the total cost of gathering the data, preparing the required documents performing related administrative functions and also some substantive costs of regulations. For EPA requirements, the primary cost was attributed to the NPDES discharge monitoring reports which require periodic submittal. However, far more significant in terms of total costs were the various plans and reports required by MESA, accounting for well over 90% of the total cost.

Before describing in greater detail the elements contained within the $400,000 figure, it is necessary to note that the figure represents the best guess estimate of only one coal operator. Neither the industry, through its trade associations, nor the Federal Government has undertaken a comprehensive assessment of either the substantive or procedural costs of coal mine regulation. In our efforts to corroborate or refute the $400,000 fiugure, we have contacted numerous Federal officials, in the BOM and in the MESA. During these conversations, officials exhibited a wide range of opinion regarding regulatory costs. Some felt the figure was outrageously high while others felt it to be low. While the majority of those contacted felt that a figure of $25,000 to $200,000 was more reflective of operators' procedural costs, no consensus of opinion could be reached. Because neither the coal industry nor the Federal Government has undertaken a comprehensive assessment of the costs of regulation and because the figure of $400,000 stands uncorrobated by industry or the agencies responsible for coal industry regulation, we, the authors of thi[illegible] paper, offer the figure without endorsement for the use of our readers at the[illegible]cretion.

Although the list of elements contained within the $400,000 cost figure is too extensive to list in its entirety, some of the more prominant MESA submittals include: periodic (usually six months) ventilation and roof support plans, fan stoppage plans, cleanup program, firefighting and evacuation plans, miner training and retraining plans, conditions in active working place forms, records of certified and qualified personnel, circuit breaker test records, respirable dust reports for each miner, approvals for mining near oil and gas wells, refuse disposal plan and updates, black lung x-rays, daily roof bolt test records, examination record of mine ventilation equipment, bleeder system evaluation reports, search for smoking materials plan, mine foreman daily reports, and pre-shift and on-shift examination reports for violations and hazardous conditions.

It must be said that many of these plans and record keeping requirements should be prepared simply to operate a safe and orderly mine regardless of their usefulness in determining regulatory compliance. Also, substantive regulatory costs, as in the taking of x-rays and maintaining respirable dust report, are clearly intermingled with procedural costs, at least in the case of MESA requirements. Furthermore, many of these are one time submittals, although periodic updates may be frequent and/or extensive. However, several instances have been cited where periodic requirements such as roof control plans are re-prepared with little additional substance merely to fulfill a requirement. Most if not all of these plans and reports may be considered useful and perhaps necessary; nevertheless, one may question how much these extensive record keeping and reporting requirements actually contribute to mine health and safety, as opposed to occupying key mine personnel with functions only indirectly involved with maintaining safe conditions. Given the frequency of MESA inspections, the basic issue remains: How "results-oriented" should an enforcement agency be, in this case with respect to the demonstrated maintenance of safe working conditions? The threat of certain closure until unsafe mine conditions are corrected still remains the most effective enforcement tool available.

## V. CONCLUSIONS AND RECOMMENDATIONS

In the preceding section of this paper, several regulatory bottlenecks and potential bottlenecks were cited from the year-long Hittman study. Based on th[illegible] in-depth comparison of regulatory powers in two case study areas and on numerous interviews with officials of public and private organizations throughout Appalachia, the following conclusions can be drawn:

o Major differences exist in the procedures and substance by which the coal industry is regulated from state-to-state. These differences have been minimized to a fair extent by growing Federal involvement, especially in the areas of mine health and safety and water pollution control. Greater similarities are expected over time, due to the passage of the Federal surface mining and reclamation law.

o The growth of procedural costs has paralleled the growth of substantive costs associated with coal industry regulation. However, the nature of procedural costs is such that initiatives to modify and coordinate administrative oversight roles may offer a more effective regulatory process without requiring the sacrifice of environmental integrity.

o The greatest impacts of regulatory procedures are basically twofold. First, there has been a general lengthening of lead times necessary prior to initial operation. This is attributed to agency policies such as requiring all permits for a given facility to be issued prior to beginning any activity. Second, additional uncertainty has been created for the operator, not only in the scheduling of men and equipment before production, but also in terms of expanding operations, since the conditions under which permit modifications are granted frequently entail substantive changes.

o A related procedural problem is the trend toward more extensive and detailed reports, permits, plans and record keeping as required by numerous agencies. In theory, such requirements are supposed to minimize the likelihood of regulators suspending mining operations for future non-compliance or hazardous conditions. However, in practice this trend departs from the idea of regulations as being "results-oriented," and in some cases it may result in premature and/or overly finalized levels of engineering design detail at the time of application.

o Jurisdictional overlapping, between and within governmental levels, contributes to most regulatory problems, and particularly to procedural costs. However, statutory provisions and organizational priorities often preclude inter-agency mechanisms to coordinate regulatory functions.

The circumstances described in the above conclusion, if left unaddressed, may continue to impede, albeit to an undetermined extent, future coal development. Therefore, the following recommendations are presented for the consideraion of policy-makers at the Federal and state levels.

1. Phasing of Approvals. This approach addresses the problem of permit requirements which entail what some operators consider premature or overly finalized levels of design detail, which in turn contributes to lead time delays. States with multi-moduled permit applications and agency policies calling for the approval of all permit applications at the same time should carefully review their procedures to determine what information is really necessary to approve each phase of development. As long as the proposed location of the mine itself is considered ecologically acceptable and safe to public (e.g., not of such a steep slope or in such proximity to an adjoining community as to pose probable hazards) then preliminary activities might reasonably be permitted without the formal approval to commence operation. Phase 1 activities might include installation of a bridge for site access, pre-construction site clearing, the laying down of haulage roads, soil stability analyses for refuse site selection, and limited construction for items such as sediment detention facilities. Phase 2 approval of full construction should require only those levels of design details needed to ensure the use of proper mining and control techniques. Standardized best mining or control practices under various geologic or topographical conditions (similar to those identified by the Bureau of Land Management for operations on Federal lands) would be useful as a means of commiting the operator to proper measures without the time and expense of providing over-finalized details in the application. Since the operational standards would remain unchanged, [illegible] a "results-oriented" approach could be accomplished without compromising on environmental integrity.

2. Master Permit-By-Industry. While addressing the same regulatory problems as the first approach, this concept would additionally address one of the main causes of regulatory bottlenecks, that of jurisdictional overlapping. Since the environmental problems of the coal industry are distinct from other extractive industries such as oil and gas, one possibility is to require within a single document, all permits, licenses, certificates and other approvals now issued at the state level. Although in theory this might be just as applicable for Federal agencies, the similarity of ecological conditions and the scale of operations at the state level would render the latter as a more feasible level of government for this approach. It would be most feasible in states like Pennsylvania which already have

consolidated the majority of their functions affecting the coal industry into one department.

Under this approach, individual "functional" permits (e.g., sediment and erosion, industrial waste, mine drainage, dams and encroachment, mining plan approval, etc.) would become detailed modules within a master permit application. Slightly modified master permit applications would be available for each type of facility within an industry series (i.e., surface mines, deep mines and preparation plants for the coal industry series). Permits legally required by agencies other than the primary state regulatory agencies, such as for highway occupancy or for labor certification, could still be included within the master application. However, the issuance of multi-agency approvals, would require some coordination to assure timely review and approval. This could be the job of a permit coordination office as an independent office within the state executive.

At a minimum, a permit coordination office should identify all of the Federal, state, interstate, county and municipal regulations which must be complied with for a given activity, as well as the appropriate contact points within each agency. Furthermore, if such coordinators served in a separate non-regulatory agency, they could facilitate agency reviews and approvals by acting as ombudsmen for operator complaints as well as an inter-agency arbiter and counsel on jurisdictional disputes. Experience with part-time permit coordinators within regulatory agencies indicates that they are unlikely to be able to perform all of the above functions, due to their other duties as well as their primary responsibilities.

One major concern of operators over this approach would be the possible delay of certain activities until all approvals are granted, or the cessation of operation due to a violation in one permit module. In developing such a master permit system, care must be taken to incorporate much of the first approach in terms of the phasing of permit approvals to allow certain activities to be performed before others. Mine health and safety aspects would certainly entail separate inspection and enforcement provisions from those modules concerned with environmental aspects. However, approval of state mining plans could still be incorporated with the master application, perhaps as a Phase 2 approval.

As new Federal legislation increasingly provides for state coordination and, in many cases, assumption of Federal enforcement authority, there is a greater need to consolidate state permit activities to minimize paperwork and confusion. The specifics of this approach would necessarily have to be tailored to each state's institutions and coal-related problems. A more common alternative often sought is a legal deadline for permit responses, yet, in many cases these deadlines lead to permit rejection based on insufficient time and personnel for proper evaluation. If the basic components of a master permit application are adopted, arbitrary deadlines (as opposed to agency guidelines for approval) would become an unnecessary mechanism to achieve a streamlined but effective review and approval procedure.

3. Areawide Approach to NPDES and NEPA. Although the previous recommendation may be more applicable to state than it is to Federal agencies, some consolidation of Federal requirements is desirable. This is especially true with respect to the National Environmental Policy Act (NEPA) and the NPDES permit administered by EPA  Presently, NEPA requires that an Environmental Impact Statement ( be prepared by Federal agencies in cases where their actions may "significantly affect the environment." With respect to new electric power plants, EPA often considers the issuance of an NPDES permit such an action. The environmental impacts which may result from coal mines and preparation facilities differ substantially from those which may result from electric utility plants. Whereas the impact of utilities is primarily on air quality, the impact of mines is primarily on water quality; water pollution from a utility is thermal in nature while water pollution from a mine is chemical. Because the impact of mines is primarily chemical and because mines are usually concentrated in greater numbers within a given geographic area than are utilities, the cumulative effects of mines on water quality are likely to be greater than those of utilities. Therefore, while the issuance of individual NPDES permits may result in limited environmental impacts, the issuance of numerous

NPDES permits results in very significant, cumulative impacts.

As of this writing, new source effuent standards have been promulgated by EPA for coal preparation facilities but not for the coal mines, which remain subject to existing source effluent standards. Without a formal definition as to what constitutes a new coal mining source, the drafting of an EIS in conjunction with the issuance of an NPDES permit is not required, since legally this does not constitute a new Federal action. In many cases, however, the existence of new preparation facilities within close proximity to "existing" coal mines makes it difficult to address their respective environmental impacts in isolation, particularly since NPDES issuance for either one directly affects the other. Current NPDES policy requires the submittal of environmental data. While this may suffice in some cases, often an E[illegible]nmental Impact Assessment (EIA) is requested of the operator by EPA. This, [illegible]y cases, provides the data to support EPA's Environmental Appraisal which d[illegible]ents EPA's decision to issue a negative declaration (i.e., no significant impact is anticipated) in lieu of preparing a full EIS. In cases where significant impacts are anticipated, a decision is made instead to prepare an EIS. Clearly, once new source standards for coal mines are promulgated, this process will become more complex in terms of the number of individual sources which will require either an EIS or an EIA. This will be further complicated by the fact that the impacts of individual mines may be limited, but the cumulative impacts of numerous mines concentrated in areas such as watersheds may be very significant.

The use of an areawide approach to the issuance of NPDES permits may simplify the EIS process in relation to NPDES issuance and provide a more effective management tool. This would entail the preparation of an areawide EIS based on a discernible geographic area such as a watershed. Its main purpose would be to broadly classify tracts within the total area based on their relative ecological sensitivity[8]. The classification scheme would indicate where specific water quality and mining-related problems exist and would alleviate two regulatory problems. First, it would enhance certainty in the permit process by providing guidance to the operator in advance as to which areas are the most environmentally sensitive. For example, the total land area could be delineated into three categories, including areas where permits might be granted with minimal delay, areas where problems exist but specified or additional control techniques may be deemed acceptable, and areas where environmental problems are severe and thus limited or no mining activity may be permitted without a separate EIS on each proposed facility. Second, this approach would facilitate the processing of large numbers of permits; Region III alone anticipates 300-400 new coal mining permits per year in the near-term. The EIS, of necessity, would also require projections on anticipated levels of mining in order to establish threshold criteria upon which variations in effluent limitations and/or approved control techniques would be based. The areawide approach would not only alleviate existing regulatory problems, it would also enable regulatory authorities to consider the cumulative effect of mines within a given geographic area.

Numerous uncertainties of such an approach remain to be worked out before it can be successfully adopted. Two prominent ones include: how EPA can fairly and adequately consider non-coal effluents within an area in prescribing effluent limitation strategies for the coal industry; and, how far ahead can or should such an EI[illegible]roject future mining activities? Nevertheless, the benefits of adopting an [illegible]de approach appear well worth the attempt, in terms of reducing permit uncer[illegible]y for the operator as well as enhancing broader concern for environmental impacts in compliance with NEPA goals and requirements.

## VI. SUMMARY

This paper has described the existing relationship between coal mine an preparation plant operators and the regulators of such facilities at the state and Federal levels. By presenting examples of this relationship, drawn from a recent study, the paper has attempted to describe how the instruments of regulation (e.g., permits, licenses, and certificates) affect coal industry operators. Although we have not been able to quantify, in terms of exact time or dollars, the effect of such instruments upon the industry, it is certainly possible to conclude that the instruments themselves and their required use tend to limit the discretion of the operator. As operators' discretion is limited so is their ability to respond to changes in the market. Thus, it can be said that existing regulatory procedures which are required of the coal industry entail a certain degree of time delay which translates into additional administrative expense to the operator as well as lost marketing opportunities. Partly in recognition of this problem Congress provided a mechanism for state jurisdiction and control consistent with minimum Federal standards as established in the Surface Mining Control and Reclamation Act of 1977. This effectively reduces the potential for additional duplication of control in an area important to the coal industry. One primary area for consolidating Federal/state roles is in the design, construction and operation of coal refuse piles. Similar to the procedures soon to be employed for surface mines, MESA might be authorized to approve a particular state's requirements covering refuse piles which would avoid the current information repackaging and dual inspections. However, as is the case of deep mining, legislative modification must precede any such consolidation of regulatory practices. Greater coordination of Federal and state roles is an objective which should be pursued, as well as a review of existing requirements in the regulation of the coal mining and preparation industry.

## REFERENCES

1. Hittman Associates, Inc., Federal, State and Local Regulatory Powers Affecting Energy Processing and Related Development in the Appalachian Region; 3 vols.; prepared under Contract 76-82 for the Appalachian Regional Commission, February 1977.

2. Green International, Inc., Improving Coal Productivity by Regulatory Integration, Phase I; 3 vols.; prepared for the U.S. Energy Research and Development Administration (Morgantown Research Center), October 1976 (draft).

3. Op. Cit., Hittman Associates, Inc.; Vol. II, pp. IV 298-299.

4. H.E. Steinman, Chief Engineer, Coal Division, Jones S. Laughlin Steel Corp., "Opening A New Mine Requires Everyone's Permission." A paper presented at Off-the-Record Meeting AIME, Pittsburgh Section, November 1, 1974.

5. Raymond C. George, EPA Region III, Remarks before the NCA/BCR Coal Conference and Expo III, Louisville, Kentucky, October 20, 1976, "Panel: Problems in Permit Granting and Administration."

6. Op. Cit., Hittman Associates, Inc.; Vol. II, pp. IV 245-248.

7. Kentucky Coal Journal, June 1976.

8. Robert Blasak, Environmental Engineer, EIS Preparation Section, EPA Region III, Personal Communication dated August 12, 1977.

# ACID GENERATION WITHIN A SPOIL PROFILE: PRELIMINARY EXPERIMENTAL RESULTS

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## Introduction

Strip mining for coal in Appalachia breaks up many continuous, underground [illegible] strata containing pyrite and exposes them to the atmosphere for varying periods. When this fractured rock is exposed to oxygen ($O_2$), pyrite is oxidized to soluble acid or subsequent reaction products, which are readily leached--either directly by rain or indirectly by flowing or seeping water--thereby, creating acid drainage. Under unsaturated conditions, oxidation products diffuse along water films to a region of more rapid flow or condense water from surrounding air, accumulating in pendular rings at contact points (Ahmad, 1975). Infiltrating water or a rising water table may intercept these, resulting in periodic flushing of acid products from spoil banks.

Pyrite in rock strata is usually found in a coarse-grained stable form or in a fine-grained (framboidal) reactive form (Caruccio, 1975). The rate of acid-producing reaction is a function of oxygen concentration, temperature, degree of surface saturation with water and pH of the contact solution (Ahmad, 1975).

Current concerted efforts towards energy self-sufficiency virtually ensure that our shallow coal deposits will be strip mined. Strip mining will cause considerable changes in the amount, distribution, and quality of water in mined areas. Unless proper precautions are taken, a great deal of damage will probably occur to water quality as a result of acid drainage and excess of eroded sediment. Modern methods of mining and reclamation attempt to minimize such detrimental effects by isolating acid producing materials deep within a spoil bank, regrading to the original contour, and rapid revegetation (Grim and Hill, 1974). However, it is not yet known whether these precautions will fully prevent, or merely delay, the long-term acid drainage problem.

To obtain information on acid drainage potential of a recently reclaimed strip mine spoil, the study reported here was initiated. The purpose was to explore physical and chemical processes that affect the quality and quantity of water on reclaimed areas in Appalachia. This paper presents preliminary results.

## Methods and Materials

Two large caissons filled with spoil material were used in this study. The caissons, representing two halves of a continuous 6 m field profile, were 2.4 m in diameter and 3.6 m deep. They were made of corrugated galvanized steel and were coated inside with acid resistant NEXON. Caisson 1 was "topsoiled" with 50 cm of [illegible] material, and in caisson 2, 40 cm of acid shale was placed beneath 240 cm of [illegible] spoil. These procedures simulated standard field practices of topsoiling and of burying acid materials during reclamation of strip mined land in Pennsylvania. At the bottom of each caisson 60 cm of sand was placed surrounding a central screened well casing to facilitate drainage and to prevent piping into the well.

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Note: Although trade names are mentioned in this publication for the purpose of providing a specific information, this does not constitute an endorsement of the product by the U.S. Department of Agriculture over other products not mentioned.

Besides the central well, the caissons were instrumented with access tubes for moisture and density measurements, temperature sensors, tensiometers, lysimeters to catch leachate effluent, and $O_2$ diffusion tubes to measure $O_2$ concentrations within the spoil (Figure 1). Table 1 lists the location and types of instrumentation in both caissons.

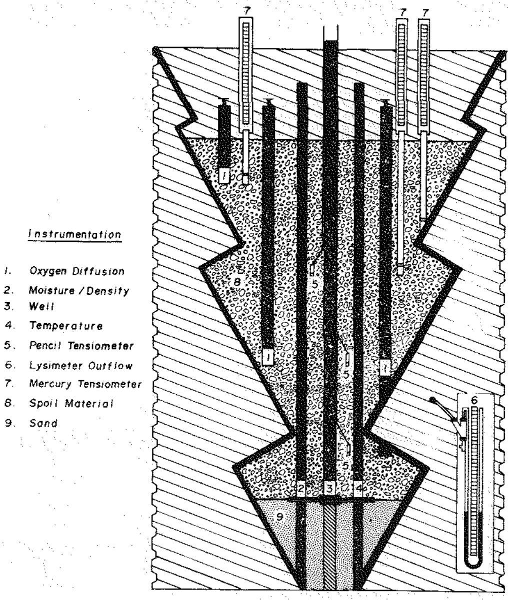

Figure 1. Caisson instrumentation description.

The field profile chosen for study in the caissons was taken from a recently strip-mined and reclaimed site near Kylertown, Pa., and the spoil sampled was that found over the Lower Kittanning, B-coal seam. The upper part of this profile (1.5 m) in an adjacent exploratory pit was described in detail and its hydraulic, chemical, and morphologic properties were compared with properties of other profiles in adjacent areas by Pedersen (1977).

The spoil was excavated in 30-cm increments with a backhoe, transferred [illegible] large boxes, and transported to a research facility where it was placed by ha[illegible] in the caissons, duplicating the field order. A 15 kg sample from each box w[illegible] used for analyses of particle size, physical and chemical properties.

Profile hydraulic properties like moisture characteristic, were determined on <2 mm fraction of spoil (uncorrected). Calculated values were then multiplied by a factor equal to the fractional amount of material <2 mm in a given sample. Measured specific retention values (ElBoushi, 1966) for spoil fractions >2 mm were then added as a constant (corrected). The Green and Corey (1971) model, matched at experimental values of saturated hydraulic conductivity (Pedersen, 1977), was used to calculate relationships between hydraulic conductivity and water content from corrected and uncorrected values of moisture characteristic for both caissons.

Table 1. Location of instruments[1] caisson 1 and 2

| Location | | |
|---|---|---|
| Caisson 1 | Caisson 2 | Type |
| (cm) | | |
| 0 | 0 | Old surface |
| 18 | 31 | New surface |
| 30 | 38 | L, Tr, D, TC(2) |
| 61 | 69 | L, Tg, TC(2) |
| 90 | 98 | Tr |
| 122 | 130 | L, Tp, D, TC(2) |
| 183 | 191 | L, Tp, TC(1) |
| 244 | 252 | L, Tp, D, TC(2) |
| 274 | 282 | L, TC(1) |
| 274 | 282 | Bottom of spoil |
| 274 | 282 | Top of screen and sand |
| 335 | 343 | Bottom, well casing, access tubes |

[1] L = lysimeter; Tr = mercury tensiometer; D = diffusion chamber; TC = thermocouple; Tg = gage tensiometer; Tp = pencil tensiometer.

Changes in moisture content and density were determined using neutron and gamma probes, respectively. Temperature changes were monitored with copper-constantan thermocouples, and $O_2$ concentrations were measured periodically with an $O_2$ analyzer in diffusion tubes. Organic C was determined by a Walkley Black method (Allison, 1965). Total S was determined by a high temperature combustion, while standard tests (ASTM, 1971) were used to determine sulfate, pyritic and organic S in each layer of the spoil.

To determine leaching potential of the reassembled profile, a 10-kg subsample of each excavated layer was placed in a 20 cm diameter PVC cylinder and leached with 1000 ml of water. The leachate was filtered and on the filtrate pH was determined with a glass electrode, total acidity was determined by hot titration with 0.02N NaOH in the presence of phenolphthalein (APHA, 1965), and electrical conductivity was determined with a dip cell and Wheatstone bridge circuit. Filtrate cations Ca and Mg were determined by atomic absorption spectrophotometry, and $SO_4$ was determined indirectly by barium absorption spectrophotometry (Borden and McCormick, 1970). Values for Ca, Mg, total acidity and $SO_4$ were all expressed in parts per million (ppm) $CaCO_3$ equivalent. It has been found that hardness (taken as Ca + Mg) plus total acidity frequently approximates the $SO_4$ content in effluents from stripmine spoils (Morth et al., 1972; Agnew and Corbett, 1969).[1]

Rainwater needed for application to the caissons was collected from the roof of the research facility and stored in large tanks. During the application water

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[1] Expressing $SO_4$ in ppm $CaCO_3$ equivalent could be misleading, since at pH 3 a considerable fraction of $SO_4$ is in the form of $HSO_4^-$. However, since the difference between $SO_4$ in ppm and $SO_4$ in ppm $CaCO_3$ equivalent is very minor (a factor of 1.04), $SO_4$ and total hardness may still be compared.

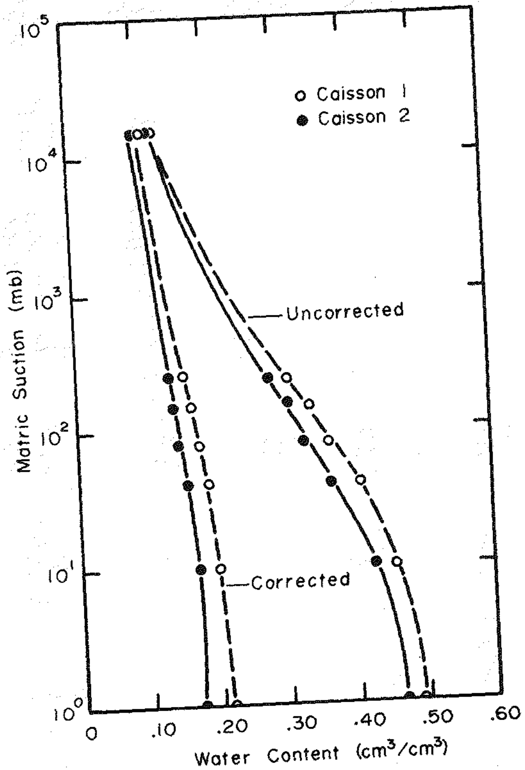

Figure 2. Moisture characteristics for caisson 1 and [illegible]

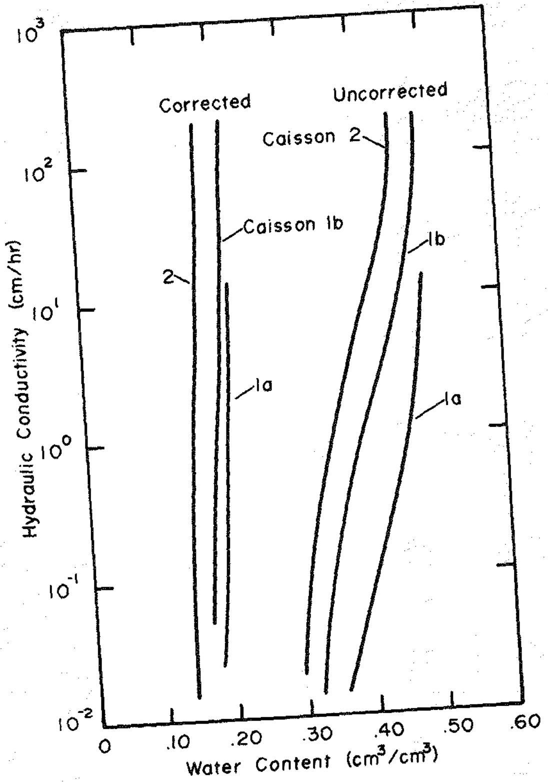

Figure 3. Matched hydraulic conductivity as a function of water cont[illegible] 1a- matched at K = 13.1 cm/hr; 1b- an[illegible]tched at K = 189 cm/hr.

ponded on the soil surface in topsoiled caisson 1 when water at 30 cm/hr was applied for 92 minutes. No ponding was noted on spoil alone in caisson 2 even when water at 189 cm/hr was applied, so water application was discontinued after 16 min. The total amounts applied were 46- and 50 cm of water to caissons 1 and 2, respectively.

## Results and Discussion

Most major coal-producing states in the eastern United States now require that acid producing materials be buried and regraded areas be covered with previously salvaged topsoil. Handling and turning over of fractured rock materials during reclamation reexposes additional pyrite to the atmosphere. The general coarseness of rockfill enhances air movement into and within the stockpiled spoil and may also [illegible] localized water flows within a spoil bank through discrete channels and fissures, unlike the wetting front type of movement prevalent in natural soil.

When rock strata are shattered during mining, resulting particle size distributions may cause uncontrolled seepage, piping, and internal erosion. Covering the spoil surface with topsoil may also contribute to internal erosion as well as to "fingering." Fingering is caused by wetting front instability at the soil-spoil interface during a rain that results in discrete "fingers" of water moving into the underlying rockfill, carrying high concentrations of sediment into the profile. Such movement may provide a transport mechanism for Fe- and S- oxidizing bacteria associated with the sediment, which may initiate or enhance microbial oxidation within a profile. Because of its finer texture, topsoil covering the spoil material may seal the surface after a rain, thus decreasing the $O_2$ supply needed to oxidize the pyrite. However, this beneficial effect may be offset by an increased tendency for the sealed surface to erode and expose underlying spoil.

Preliminary results (Rogowski and Jacoby, 1977) indicated that infiltration rate was much higher on spoil alone (>189 cm/hr) in caisson 2 than on spoil covered with topsoil (<30 cm/hr) in caisson 1. After application of water, material in caisson 1 settled less (18 cm) than material in caisson 2 (31 cm). In general, below a 1 m depth, moisture, density, and temperature distribution data suggested movement of water within the spoil in discrete channels and fissures rather than as a continuous wetting front. Water retention averaged 12 to 15% of the amount applied and most of the drainable water (3/4) arrived at the 3 m deep water table within an hour after it was first applied.

Figure 2 shows water content as a function of matric suction and Figure 3 shows hydraulic conductivity as a function of water content for composite profiles of caissons 1 and 2. Curves for the "corrected" values suggested that very small changes in water content may cause very large changes in hydraulic conductivity and water flux. Observed values support these conclusions particularly for caisson 2 and illustrate why flushing of acid products from spoil banks is a common occurrence. Rapid initial infiltration and rapid transmission of applied water in caisson profiles was followed by a slow redistribution of retained water (Figure 4). Consequently, chemical analyses of leachates should be similar to the analyses of effluents flushed out by rain from spoil banks.

In caisson 1 the soil layer held more water for a longer period of time than underlying spoil material. Water was released from this layer at a very slow rate suggesting a different leaching pattern on topsoiled materials. In caisson 2, the infiltration rate never exceeded infiltration capacity, even when water was applied at 189 cm/hr. Consequently, the infiltration and redistribution profiles for caisson 2 (Figure 4) reflect a continuous increase in water content with depth culminating in the water table at about 200 cm. The profiles may represent a more nearly normal pattern for leaching effluents flushed by rain from spoil banks.

Figure 5 shows particle size distributions for topsoil, spoil, acid shale and sand layers. Original density distributions and density distributions after water application are shown in Figure 6. Soil adjacent to smooth surfaces (such as

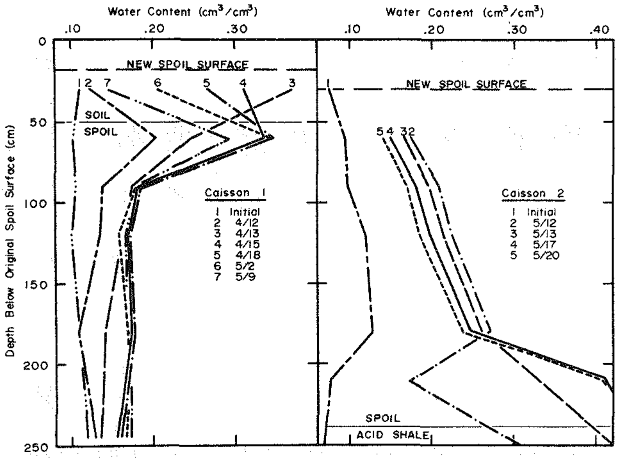

Figure 4. Experimental water redistribution profiles for caisson 1 and 2.

access tubes), cracks and fissures is generally (Cedergren, 1967) more susceptible to piping. Although substantial settlement in both caissons would suggest increased profile density, generally lower measured values of "New" density in Figure 6 reflect the effects of piping and internal erosion. The susceptibility of material to internal erosion is given by a piping ratio. Piping ratio ($P_r$) is usually written (Cedergren, 1967, p. 175),

$$P_r = D_{15}(\text{of filter})/D_{85}(\text{of soil}) < 5 \qquad (1)$$

where $D_{15}$ and $D_{85}$ represent the 15 and 85 percentage particle-size (percent passing), respectively. Comparisons of particle-size in Figure 5 indicate that *both topsoil and spoil materials were very susceptible to piping*, with piping ratios above 5, whereas, the sand layer (as intended) acted as a good filter. The results show that a considerable sediment transport and rearrangement of internal geometry is possible within the spoil because of infiltrating water. This change in internal geometry may contribute to new surfaces being exposed to oxidation by air and to leaching by infiltrating water. We may speculate that internal sediment translocation, particularly translocation of sediment derived from a topsoil, may lead to the formation of internal filter at some level within a profile and a possible renovation of acid effluents percolating from overlying parts of the profile. Thus, comparisons of piping ratios for different materials used in reclamation could result in better and more efficient use of available spoils.

Temperature profiles in Table 2 reflect the ambient conditions and water movement into the spoil rather than the true temperature profiles, as found in the field. However, warmer temperatures in caisson 2 were more conducive to acid formation. Results in Table 3 lead to a similar conclusion. Rapid diffusion of $O_2$ into the coarse spoil profile (caisson 2) favored acid generation as compared with

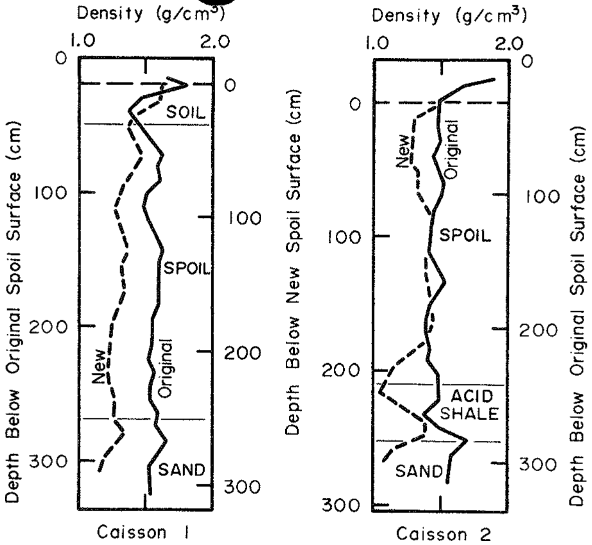

Figure 6. Caisson profile density before (original) and following (new) water application.

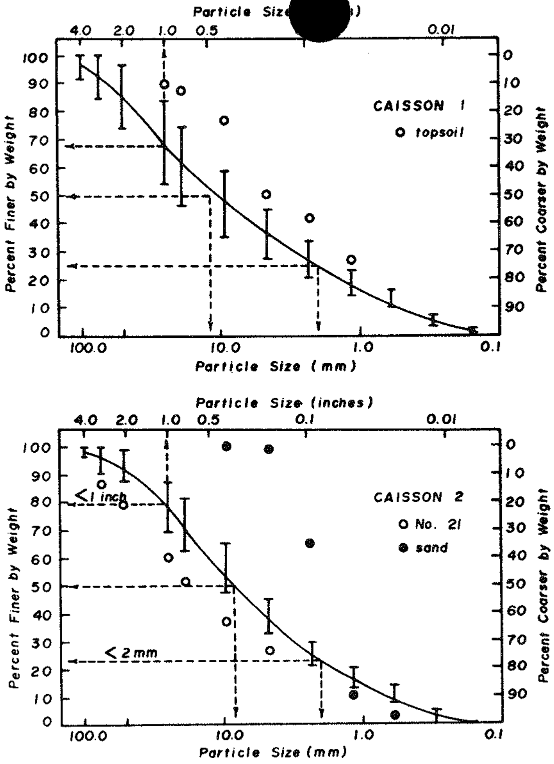

Figure 5. Particle-size analysis of caisson materials.

a topsoiled profile in caisson 1 where $O_2$ concentration slowly recovered to pre-application levels.

Table 2. Temperature profiles for selected times and depths following water[1/] application on caisson 1 and 2

| | Depth below original surface (cm) | | | | | |
|---|---|---|---|---|---|---|
| Time | 30 | 61 | 122 | 183 | 244 | 274 |
| (min) | | | (Temperature, °C) | | | |
| | | | Caisson 1 | | | |
| 0 | 9.6 | 7.0 | 6.9 | 6.6 | 6.4 | 6.0 |
| 20 | 10.8 | 5.8 | 5.6 | 5.9 | 5.1 | 4.5 |
| 50 | 14.2 | 10.9 | 5.7 | 5.5 | 5.2 | 5.9 |
| 200 | 16.7 | 11.4 | 6.2 | 5.6 | 6.1 | 6.3 |
| 740 | 16.4 | 12.2 | 7.5 | 6.8 | 7.4 | 7.1 |
| 1280 | 14.3 | 12.1 | 8.2 | 6.5 | 8.4 | 9.4 |
| 2060 | 17.4 | 14.4 | 10.6 | 9.9 | 10.0 | 10.9 |
| 3620 | 15.8 | 15.6 | 12.9 | 11.9 | 13.0 | 13.1 |
| | | | Caisson 2 | | | |
| | 38 | 69 | 130 | 191 | 252 | 282 |
| 0 | 12.4 | 12.9 | 13.4 | 13.3 | 12.4 | 11.7 |
| 54 | 14.2 | 13.8 | 13.6 | 13.4 | 12.5 | 11.8 |
| 124 | 17.4 | 14.2 | 14.0 | 13.7 | 13.3 | 12.4 |
| 244 | 21.2 | 14.8 | 14.2 | 13.8 | 12.6 | 11.7 |
| 424 | 20.4 | 14.9 | 14.3 | 14.2 | 14.0 | 13.3 |
| 544 | 17.6 | 14.7 | 14.2 | 13.9 | 14.3 | 13.5 |
| 664 | 16.4 | 14.8 | 14.6 | 14.5 | 14.8 | 13.7 |
| 1024 | 13.6 | 14.2 | 14.5 | 14.4 | 14.8 | 14.5 |
| 1324 | 15.1 | 13.5 | 13.7 | 13.2 | 14.5 | 14.8 |
| 2404 | 13.2 | 13.7 | 13.7 | 14.0 | 15.7 | 15.1 |

[1/] On caisson 1 water at 23.5°C was applied at 11:40 EST on 4/12/77, on caisson 2 water at 15.6°C was applied at 9:56 EST 5/12/77.

Results of organic C determination are shown in Table 4. Pedersen (1977) found that in undisturbed soil profiles adjacent to a mined area, organic C rapidly decreased to less than 1% below a 10 cm depth. Except for the topsoil, values expected for the spoil should be also less than 1% organic C. Values shown in Table 4 would, therefore, seem to indicate some additional source of carbon wi[illegible] the spoil. Quite possibly, this additional source of carbon could be either finely divided coal or organic shale material often present in the spoil prof[illegible] Still higher values of organic C were observed (Pedersen, 1977) when a combustion furnace was used, suggesting perhaps incomplete oxidation of carbon bearing fragments in the Walkley-Black procedure. Apparently alternate procedures to determine organic C in stripmine spoil need to be investigated.

Except for the dark acid shale material in caisson 2, S contents did not seem excessive in any of the layers (Figure 7). The topsoil layer in caisson 1 and acid shale layer in caisson 2 represented the extremes. Somewhat more sulfate S in caisson 1 spoil reflected more effective weathering in the topmost layers of this

Table 3. Oxygen ($O_2$) concentration for selected times after application of water

| | Caisson 1, Depth (cm) | | | | Caisson 2, Depth (cm) | | |
|---|---|---|---|---|---|---|---|
| Time | 30 | 122 | 244 | Time | 38 | 130 | 252 |
| (days) | | (% $O_2$) | | (days) | | (% $O_2$) | |
| 0 | 14.8 | 8.4 | 12.9 | 0 | 17.1 | 9.8 | 11.3 |
| 1 | 1.9 | 5.7 | 6.7 | 1 | 19.8 | 19.0 | -[1] |
| 6 | 2.1 | 4.0 | 11.4 | 5 | 16.9 | 17.7 | - |
| [illegible] | 4.7 | 4.5 | 10.5 | 8 | 18.0 | 18.8 | 17.7 |
| [illegible] | 8.1 | 7.7 | 4.2 | 14 | 20.8 | 19.6 | 20.5 |

[1] Water table above $O_2$ diffusion chamber.

Table 4. Percent Carbon[1] (C) and Organic Matter[2] (OM) on caisson 1 and 2 spoil

| Depth | C | OM |
|---|---|---|
| (cm) | % | % |
| | Caisson 1 | |
| 0 | 2.3 | 4.4 |
| 51 | 2.0 | 3.8 |
| 74 | 2.3 | 4.3 |
| 91 | 2.5 | 4.9 |
| 112 | 2.7 | 5.1 |
| 132 | 2.4 | 4.7 |
| 155 | 2.2 | 4.2 |
| 183 | 2.6 | 5.0 |
| 208 | 2.2 | 4.2 |
| 229 | 2.3 | 4.4 |
| 252 | 2.4 | 4.5 |
| | Caisson 2 | |
| 0 | 2.4 | 4.7 |
| 28 | 2.3 | 4.3 |
| 48 | 1.8 | 3.5 |
| 69 | 2.1 | 4.1 |
| 91 | 2.2 | 4.3 |
| 117 | 2.4 | 4.6 |
| 144 | 2.4 | 4.6 |
| 168 | 2.4 | 4.7 |
| 189 | 2.7 | 5.2 |
| 215 | 2.6 | 5.0 |
| 245 | 3.5 | 6.8 |

[1] Walkley Black, Allison (1965).

[2] Organic Matter taken as 1.9 C.

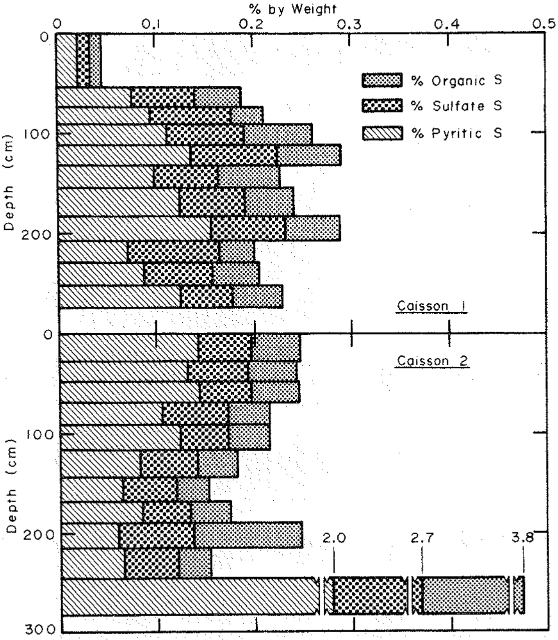

Figure 7. Forms of sulfur present in the caisson profiles by layer.

profile. In general, topsoil content of total S was about 20% of total S in spoil material, which in turn represented only about 6% of that found in black shale.

Table 5 shows electrical conductivity, sum of total acidity, and hardness as well as sulfate content in laboratory leachates from each layer, while Table 6 shows average sediment concentration, electrical conductivity, sum of total acidity, and hardness along with sulfate content in effluents from selected depths after water application.

Based on sediment data, internal erosion in caisson 2 (spoil alone) seemed much less severe. However, since the spoil in caisson 2 settled more than spoil-soil combination in caisson 1 it could be argued that in caisson 2 larger ero[illegible] particles were being trapped by the wire mesh covering lysimeters and were ne[illegible] sampled in effluent. Actual sediment load inside caisson 2 could thus be muc[illegible] greater.

Further comparisons between results in Tables 5 and 6 indicated that in laboratory leachate samples values of $SO_4$ were about 88% of the sum of total acidity and hardness, as compared with 68% for the caisson effluents. When estimating hardness in effluents from spoil materials under field conditions, inclusion of other ions, like Al, Fe, and Mn (besides Ca and Mg) should perhaps also be considered (ASTM, 1971). Thus, comparison of the electrical conductivity or $SO_4$ values shows both to be about one and a half times as large in the effluent (Table 6) as in the leachates (Table 5), suggesting a higher salt content in the

Table 5. Values of electrical conductivity (EC), sum of total acidity and Ca + Mg hardness (Total), and sulfate ($SO_4$) for 22 layers of reconstructed spoil profile

| Depth | EC | Total | $SO_4$ | Depth | EC | Total | $SO_4$ |
|---|---|---|---|---|---|---|---|
| (cm) | (μmhos) | (ppm $CaCO_3$ equivalent) | | (cm) | (μmhos) | (ppm $CaCO_3$ equivalent) | |
| | | Caisson 1 | | | | Caisson 2 | |
| 51 | 410 | 256 | 44 | 28 | 905 | 653 | 555 |
| [illegible] | 285 | 104 | 131 | 48 | 820 | 601 | 510 |
| [illegible] | 740 | 492 | 444 | 69 | 900 | 675 | 545 |
| [illegible] | 800 | 485 | 439 | 91 | 2000 | 1216 | 1044 |
| 132 | 995 | 689 | 593 | 117 | 280 | 109 | 140 |
| 155 | 660 | 336 | 329 | 144 | 1280 | 958 | 745 |
| 183 | 620 | 361 | 340 | 168 | 660 | 421 | 385 |
| 208 | 445 | 207 | 225 | 189 | 845 | 596 | 485 |
| 229 | 3400 | 2883 | 2742 | 215 | 2050 | 1710 | 1669 |
| 252 | 998 | 727 | 594 | 245 | 1100 | 778 | 640 |
| 274 | 870 | 593 | 485 | 282 | 6000 | 5480 | 6740 |

Table 6. Average sediment concentration, electrical conductivity (EC), sum of total acidity and Ca + Mg hardness (Total), and sulfate ($SO_4$) contents in effluent from selected depths

| Depth | Sediment Concentration | EC | Total | $SO_4$ |
|---|---|---|---|---|
| (cm) | (ppm) | (μmhos) | (ppm $CaCO_3$ equivalent) | |
| | | Caisson 1 | | |
| 30 | 38627 | 61 | 12 | 58 |
| 61 | 23660 | 134 | 137 | 43 |
| 122 | 4918 | 1780 | 2129 | 1587 |
| 183 | 2508 | 2716 | 3736 | 2769 |
| 244 | 2175 | 3313 | 4204 | 3412 |
| 274 | - | 7500 | 12295 | 9787 |
| 335 (well) | 48 | 2475 | 2996 | 2091 |
| | | Caisson 2 | | |
| [illegible] | 7828 | 630 | 454 | 82 |
| [illegible] | 1160 | 2490 | 2712 | 2087 |
| [illegible] | 4446 | 1175 | 1177 | 786 |
| 191 | 2212 | 1200 | 1037 | 811 |
| 252 | 842 | 3134 | 3575 | 2593 |
| 282 | 491 | 3367 | 3445 | 2863 |
| 343 (well) | 231 | 2733 | 2981 | 2079 |

former. At the same time average electrical conductivity and $SO_4$ content of the effluent seemed to be higher in caisson 2 suggesting, as expected, greater acid generation within the spoil alone as compared to spoil covered with topsoil.

Quality of rainwater as compared with water used in laboratory studies (Table 7) may introduce some variation into field results. Data listed in Table 7 show differences between April (caisson 1) and May (caisson 2) precipitation, mainly in the electrical conductivity and $SO_4$ values. However, in terms of overall variability these differences are not likely to be significant.

Table 7. Values of pH, electrical conductivity, total acidity, Ca, Mg, and $SO_4$ for leaching water and for rainwater applied to caissons 1 and 2

| | Leaching water | Rainwater | |
|---|---|---|---|
| | | Caisson 1 | Caisson 2 |
| pH | 4.5 | 5.6 | 5.7 |
| Electrical conductivity (μmhos) | 1.4 | 13 | 25 |
| Total acidity (ppm $CaCO_3$ equiv.) | 17 | 25 | 29 |
| Ca (ppm $CaCO_3$ equiv.) | 0 | 10 | 11 |
| Mg (ppm $CaCO_3$ equiv.) | 0 | 0.2 | 0.8 |
| $SO_4$ (ppm $CaCO_3$ equiv.) | 5 | 5 | 15 |

Figures 8 and 9 compare Ca, Mg, $SO_4$, and total acidity values in leachates from the separate layers with the values of the same parameters in effluents from selected depths after the application of water. The same type of comparison for pH values is shown in Figure 10. Each change of slope represents a sampling point. Hence, for "Original" portion of graph a break in slope represents each successive layer that was leached in the laboratory. Similarly for the "1st run" portion of the graph each break in slope represents depth of the lysimeter from which a given effluent originated. Analyses of laboratory leachates tell us what each component layer may contribute to the cumulative effluent. However, combined cumulative field effluents can be quite different. The results shown bring into question the advisability of leaching each component layer separately as compared to leaching of a composite column.

Comparison of Ca, Mg, $SO_4$, and total acidity for the caisson profiles (Figures 8 and 9) performed on laboratory leachates and caisson effluents shows order of magnitude differences (factor of 10) between the effluent (1st run) and the leachates (Original) in caisson 1 and general similarity in caisson 2. The large surge of acid products expected from leaching of acid shale in caisson 2 was not found, although generally profile effluent was considerably more acid than the effluent reaching the water table in caisson 1.

The quality of water reaching the water table on stripmined and reclaime[illegible]d is of considerable interest to regulatory agencies. Figure 10 shows that in caisson 1, pH values at the water table approximated those of the original rai[illegible] Samples of effluent from the well were essentially sediment free (Table 6) but with a fairly high dissolved salt content, although the salt content in the well effluent samples decreased sharply from that of the layer above. Whether these data will be duplicated in ensuing runs, and to what extent they are a result of topsoil cover and sand layer is not known. Since the particle size distribution of the sand layer was chosen to control piping, we may speculate that internal erosion of topsoil created a soil filter within a spoil profile at the sand-spoil interface. This filter could be instrumental in improving quality of water reaching the water table.

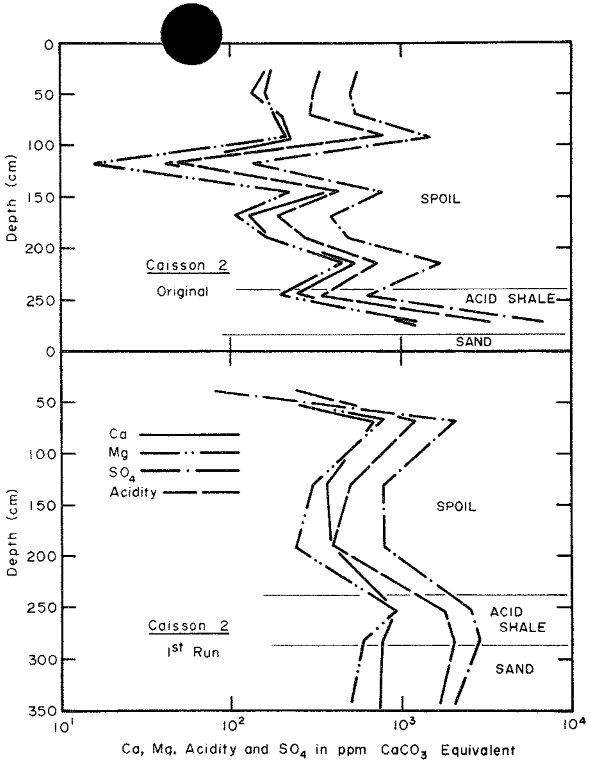

Figure 9. Comparison of Ca, Mg, $SO_4$ and Total Acidity values in laboratory leachates for individual layers with values in effluents from selected depths.

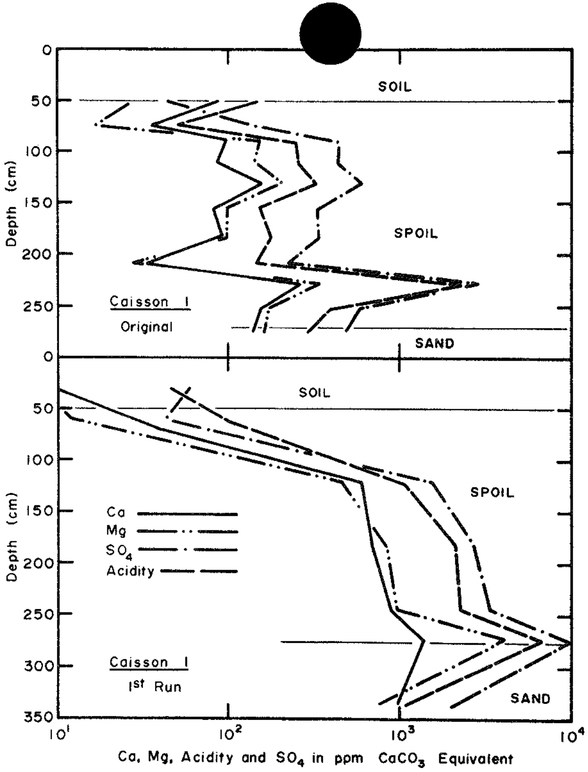

Figure 8. Comparison of Ca, Mg, $SO_4$ and Total Acidity values in laboratory leachates for individual layers with values in effluents from selected depths.

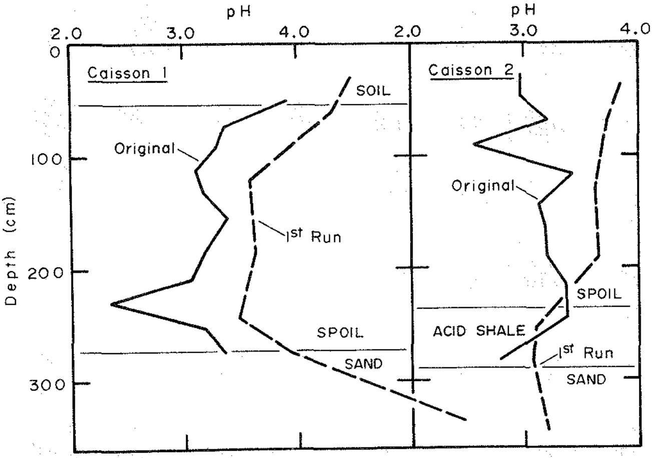

Figure 10. Comparison of pH values in laboratory leachates for individual layers with values in effluents from selected depths.

Table 8. Comparison of means ($\bar{x}$) and coefficients of variation (CV)[1/] for total acidity, Ca, Mg, $SO_4$ and electrical conductivity (EC) for laboratory leachates (Original) and for effluents (1st run) from caissons 1 and 2

| Analysis | Total Acidity | | Ca | | Mg | | $SO_4$ | | EC | |
|---|---|---|---|---|---|---|---|---|---|---|
| | $\bar{x}$ | CV% | $\bar{x}$ | CV% | $\bar{x}$ | CV% | $\bar{x}$ | CV% | $\bar{x}$ | CV% |
| | | | ppm $CaCO_3$ equivalent | | | | | | µmhos | |
| | | | | | Caisson 1 | | | | | |
| Original | 241 | 17 | 95 | 13 | 94 | 21 | 360 | 17 | 741 | 10 |
| 1st run | 787 | 27 | 278 | 36 | 239 | 48 | 963 | 31 | 1135 | 26 |
| | | | | | Caisson 2 | | | | | |
| Original | 377 | 17 | 210 | 16 | 182 | 20 | 709 | 15 | 1123 | 11 |
| 1st run | 877 | 12 | 482 | 12 | 392 | 13 | 1077 | 18 | 1811 | 8 |

[1/] Log-normal distributions were assumed.

On closer inspection there seemed to be some differences among pH and other water quality parameters for the two caissons in Figures 8, 9 and 10 as well as in Tables 5 and 6. Table 8 shows some pertinent statistics obtained by lumping together values for different layer leachates or different depth effluents in each caisson. Graphing of limited data (not shown) suggested a log-normal distribution function for these water quality parameters. Assuming a log-normal distribution, an average 20% coefficient of variation seemed to describe well most of the spoil water quality data. The results showed that concentrations were consistantly higher in caisson 2 than in caisson 1. At first glance effluent data (1st run) (Figures 8 and 9) seemed less variable than the leachate results (Original). However, results in Table 8 indicated that for caisson 1 effluent data (1st run) varied more than leachate data (Original) while for caisson 2, except for $SO_4$ data, effluent data (Original) varied less. Considering the heterogeneity of spoil materials, the encountered degree of variation does not seem to be excessive.

## Conclusions

Preliminary results after initial water application to two caissons filled with mine spoil showed a much higher infiltration rate and settling on spoil alone than on spoil covered with soil. Considerable piping and internal erosion tended to transport large amounts of soil material deep into spoil profiles. Temperature profiles reflected water movement, while $O_2$ concentration values decreased when soil covered the spoil surface. Determination of organic C in spoil materials, using conventional methods seemed questionable. Although S contents within a spoil profile undoubtedly were related to acid generation, the highest S content (acid shale, caisson 2) did not seem to generate exceptionally high acid effluent. Apparently adequate topsoil cover (caisson 1) improved the quality of water reaching the water table. Possibly, piping and erosion could have created an internal filter and the results suggest that under controlled field conditions a similar filter may form. Since topsoil cover seemed to reduce substantially oxygen diffusion, less oxidation and acid generation with depth might be expected on soil reclaimed according a new Pennsylvania law. The study results showed that organic C and leaching analyses of individual layers might not truly reflect the field situation. Organic C may often be contaminated with coal or organic shale fragments, while a cumulative profile effluent seemed to contain considerably higher concentration of salts than combined leachates from the individual layers.

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## References

Agnew, A. F. and D. M. Corbett. 1969. Hydrology and chemistry of coal-mine drainage in Indiana. 157th National Meeting, Amer. Chem. Soc., Division of Fuel Chemistry, Minneapolis, Minnesota. Symposium on pollution control in fuel combustion, processing. Preprints. Vol. 13 (2):137-149. Library, Bituminous Coal Research, Inc., Monroeville, Pa. 15146.

Ahmad, M. V. 1975. Coal mining and its effect on water quality. In R. A. Deju (ed.) Extraction of Minerals and Energy: Today's Dilemmas. Science Publishers, Inc., Ann Arbor, Michigan.

Allison, L. E. 1965. Organic carbon. In C. A. Black (ed.) Methods of Soil Analysis Part 2. Amer. Soc. of Agron., Madison Wisconsin.

APHA. 1965. Standard methods for examination of water and wastewater. Am. Publ. Health Assoc., Inc., New York, N. Y.

ASTM. 1971. Standard methods of coal analysis. Am. Soc. for Testing Materials, Philadelphia, Pa.

Borden, F. Y. and L. H. McCormick. 1970. An indirect method for the measurement of sulfate by barium absorption spectrophotometry. Soil Sci. Soc. Am. Proc. (34):705-706.

Caruccio, F. T. 1975. Estimating the acid potential of coal mine refuse. In M. J. Chadwick and G. T. Goodman (ed.) The Ecology of Resource Degradation and Renewal. Blackwell Scientific Publications.

Cedergren, H. R. 1967. Seepage, drainage, and flow nets. John Wiley and Sons, Inc., New York, N. Y.

ElBoushi, I. M. 1966. Geologic interpretations of recharge through coarse gra[illegible] and broken rock. Unpublished Ph.D. Thesis. Stanford University, Stanford, California.

Green, R. E. and J. C. Corey. 1971. Calculation of hydraulic conductivity: A further evaluation of some predictive methods. Soil Sci. Soc. Am. Proc. (35):3-8.

Grim, E. C. and R. D. Hill. October 1974. Environmental protection in surface mining of coal. Environmental Protection Technology Series, EPA-670/2-74-093.

Morth, A. H., E. E. Smith, and K. S. Shumate. November 1972. Pyritic systems: A mathematical model. Environmental Protection Technology Series, EPA-R2-72-002.

Pedersen, T. A. 1977. Comparison of morphological, chemical and physical properties of minesoils and contiguous natural soils. Unpublished M.S. Thesis. The Pennsylvania State University, University Park, Pennsylvania.

Rogowski, A. S. and E. L. Jacoby, Jr. 1977. Water movement through Kylertown strip mine spoil. 1977 ASAE Summer Meeting, North Carolina State University, Raleigh, North Carolina, Paper No. 77-2057. Submitted for publication in 1977 Transactions of the ASAE.

# TIME AS A FACTOR IN ACID MINE DRAINAGE POLLUTION

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## I. INTRODUCTION

### A. Background of the Problem

In order to meet the future energy requirements of the United States a greater emphasis will be placed on coal exploitation. The bituminous coal field of Appalachia is one area that will be further developed to supply a portion of the coal needs of America. In this area, which contains many near surface seams of coal, strip mining will be a common mining process whereby large quantities of rock are stripped away, exposing the coal which is subsequently mined. During the strip mining process large quantities of rock are disrupted and the associated minerals are exposed to the atmosphere to be subjected to physical and chemical weathering processes.

One group of minerals, the iron disulfides, commonly occur as marcasite and pyrite in the coal and overlying strata. Upon exposure to the atmosphere these minerals oxidize in a humid environment to form hydrous iron sulfates, which are readily dissolved in water to produce acidic drainages. The following equations summarize the chemical reactions that are involved in the disulfide oxidation and the conversion of the weathering products to acidity.

$$2FeS_2 + 2H_2O + 7O_2 = 2Fe^{++} + 4SO_4^{=} + 4H^+ \qquad (1)$$

$$2Fe^{++} + \tfrac{1}{2}O_2 + 2H^+ \rightleftharpoons 2Fe^{+++} + H_2O \qquad (2)$$

$$2Fe^{+++} + 6H_2O \rightleftharpoons 2Fe(OH)_3 + 6H^+ \qquad (3)$$

$$FeS_2 + 14Fe^{+++} + 8H_2O \rightleftharpoons 15Fe^{++} + 2SO_4^{=} + 16H^+ \qquad (4)$$

(Stumm and Morgan, 1970)

The stoichiometry of equation (1) indicates that two moles of pyrite ($FeS_2$) oxidize to release four moles of acidity (as $H^+$). The ferrous iron is further oxidized to ferric iron and hydrous ferric oxides with an additional release of four moles of acidity. These relations show that four moles of acidity are produced for each mole of pyrite that is oxidized under humid conditions. Singer and Stumm (1970) have also shown that the ferric iron can be reduced by pyrite to generate additional ferrous iron and acidity in accord with equation (4). The rates of all these reactions are increased by iron bacteria which serve as catalysts and can accelerate the reactions by a factor as large as $10^6$ (Singer and Stumm, 1970).

Within a particular mine site the overburden may also contain calcareous materials which can react with water to produce alkalinity. These reactions are summarized by the following equations:

$$CaCO_3 + H_2O \rightleftharpoons Ca^{++} + HCO_3^- + OH^- \qquad (5)$$

$$HCO_3^- + H_2O \rightleftharpoons H_2CO_3 + OH^- \qquad (6)$$

(Garrels and Christ, 1965)

However, unlike the acid reactions, the alkalinity reactions are limited by the solubility of calcium carbonate in water. As a result the concentration of alkalinity that can be generated by the overburden has a maximum value for a given partial pressure of carbon dioxide. These chemical relationships of alkalinity and acidity are time dependent and the length of time that an acid material is permitted to weather before being contacted by water or the length of contact time between alkaline material and water determines to a large extent the amount of acidity and alkalinity that can be produced within the backfilled overburden of a strip mine.

In the following discussions we assume that infiltrating waters contact the alkaline producing material before contacting the acid material. Obviously, the solubility of carbonate material, and hence the neutralizing capacity, would be much greater in an acidic environment. However, as shown in equations (1) through (4) large concentrations of iron are placed in solution during the acid forming reactions. The solubility of these metals is pH dependent and they remain in so[illegible]tion as long as acid conditions prevail. If the acid drainage were to come in co[illegible]tact with a neutralizing medium, the iron would precipitate onto the surface and armor the neutralizing mineral against further chemical reaction. This would eventually render the neutralizing material inert and destroy its alkaline production potential. Thus to protect and preserve the neutralizing capability of calcareous minerals, the alkaline producing strata must be placed hydrologically antecedent of the acid producing material. The following discussions assume that the placement of alkaline and acid materials would be in this order and that infiltrating waters develop alkalinity before flowing in contact with acid producers.

### B. Factors Affecting Acid Mine Drainage

Caruccio (1968) showed that the degree of acidity of mine drainages in western Pennsylvania was a function of (1) the calcium carbonate content of the strata, (2) the pH of the ground water, (3) the mode of occurrence of the iron disulfide and (4) the neutralizing and buffering capacity of the ground water. A recent study based in eastern Kentucky produced similar results (Caruccio, Geidel and Sewell, 1976; Caruccio and Geidel, 1976; and Caruccio et al, 1977).

The presence of calcium carbonate in the overburden determines to some extent the amount of alkalinity that infiltrating waters have before coming in contact with the acidic material. If the alkaline material is placed before the acid producing material in a ground water flow path then the infiltrating waters have the opportunity to develop some alkalinity which may effectively or partly neutralize the acidity produced by the toxic materials.

The pH of the ground water determines the viability of the various catalyzing bacteria and the solubility of the heavy metals. In the absence of calcareous material, the pH of the natural ground water could be less than 5.5 which would be conducive to the survival of the iron bacteria and enhance acid production. In addition, the solubility of iron is increased and in accord with equation (4) the production of acidity increases, which in turn places more iron in solution and the mechanism becomes self-propagating.

One of the important factors in the formation of acid mine drainage is the pyrite morphology. Caruccio (1968, 1973) and Caruccio et al (1977) found a strong association between the occurrence of acid mine drainage and a combination of py[illegible] morphology and ground water geochemistry. Previous studies have shown that the pyrite occurring in coals and associated strata has a variety of forms which have been described as (1) massive, plant replacements, (2) mossy-pitted (marcasite?), (3) euhedral grains, (4) cleat coats and (5) framboidal. The framboidal pyrite is composed of particles which are extremely fine grained ($< 1\ \mu$) and because of the large surface area afforded by the fine granularity is the most reactive of all the pyrite types.

Another factor in acid mine drainage formation is the geochemistry of the natural waters. Acid waters emerging from a mine interior blend and interact with the natural waters that have not been in contact with the toxic material. The quality of the mixing waters and the degree of neutralization and buffering that can take place determines to a large extent the ultimate quality of the mine drainage emanating from a mine.

Interestingly, the geochemistry of the natural water and the occurrence of framboidal pyrite, both of which control the drainage quality, have been related to the depositional environment of the coal seam. Highly buffered-neutralizing waters originating in coals having a relative paucity of framboidal pyrite have been associated with rocks deposited in a fresh-water paleoenvironment. On the other hand waters with low specific conductances and little if any neutralizing or buffering capacities were found to emanate from coals having an abundance of framboidal pyrite and were associated with rocks deposited in a marine-brackish water paleo[illegible]onment (Caruccio et al, 1977).

Several other factors determining mine drainage quality are the dissolution of clay minerals and the cation exchange capacity of the materials in the overburden (Geidel, 1976). In a study utilizing shales collected from eastern Kentucky and West Virginia, she found that the dissolution of aluminum silicate minerals taking place during the weathering process liberates hydroxide to produce alkalinity in accord with equation (7).

$$Al_2Si_2O_5\ (OH)_4 + 5H_2O = 2Al^{+++} + 2H_4SiO_4\ (aq.) + 6\ OH^- \qquad (7)$$

(Gardner, 1970)

This additional alkalinity is also available to neutralize acidity and can be generated through the decomposition of some shales.

Geidel (1976) also found the cation exchange capacity to be an important factor when the overburden is comprised primarily of shales. The associated clay minerals can exchange interlayer and surface cations with cations (including $H^+$) in the drainage. This enhances the weathering of the minerals and serves to neutralize the acidity during the times when the hydrogen ions penetrate the clay crystal lattice and replace cations such as calcium, sodium, potassium, iron and aluminum.

The replacement of cations in the clays with $H^+$ also weakens the mineral ionic bonds and allows the silicate groups in the structure to be removed as silicic acid. As the clay minerals expand in this process, more surface area is exposed to provide more cations for effective exchange, which enhances the weathering process.

## II. TIME AS A FACTOR IN ACID MINE DRAINAGE PRODUCTION

### A. General Considerations

All of the factors discussed above are dependent upon the availability of water. In addition, it is not only the quantity or quality of the ground or surface water coming in contact with the rocks but equally as important, the frequency or time interval between the times that the rocks are wetted.

In most reclaimed mine sites the high permeability of the backfilled material [illegible]ts the water table from mounding to the shallow horizons. Thus during p[illegible]s of infiltrating rainfall or the spring thaw, percolating water will pass over the masses of various rock types and rinse the weathering products from the surfaces. After the wetting front passes through a particular horizon, the water retained by capillary forces in contact with the rock surfaces forms micro environments of chemical reactivity leading toward alkalinity or acidity production. These chemical systems remain intact until they are flushed through the system by a new wetting front and replaced by fresh water that is retained to start the chemical process anew. We maintain that the length of time between flushings (or rinsing) determines to a large extent the quality of mine drainage. This is based primarily upon two weathering characteristics.

First, in the generation of alkalinity, water coming in contact with calcium carbonate quickly becomes saturated with respect to the carbonate-bicarbonate equilibria and for all intents and purposes the amount of alkalinity available for neutralization becomes fixed during the early stages of water percolation through the backfilled material. The factors leading toward carbonate solubility include the pH of the infiltrating waters, the partial pressure of carbon dioxide and the surface area of reactivity.

However, most of the alkalinity produced is generated during the initial chemical reactions and the rate of reactivity declines with time. Once the carbonate-bicarbonate equilibria are achieved in the infiltrating waters additional contact with calcium carbonate does not increase the alkalinity of the system (the maximum value is about 700 mg/l as $CaCO_3$). Thus regardless of the amount of calcium carbonate present in the strata, the solubility of the carbonate, and hence the alkalinity of the system, is limited by the geochemical conditions leading toward e[illegible]librium conditions.

In the second weathering consideration, and unlike the alkalinity production, the generation of acidity through the dissolution of hydrous iron sulfates (the weathering products of pyrite) in water is not limited by solubility considerations. As long as oxygen is available and the weathering products can accumulate in the micro-geochemical environments the oxidation process continues indefinitely. As in all geochemical systems a solubility limit will eventually arrest the oxidation reaction but in the iron sulfate dissolution reactions the solubility limit is orders of magnitude greater than that of the calcium carbonate system. Thus in the acid producing systems the concentrations of acidity increase with time.

## B. Laboratory Experiments and Results

### 1. Initial survey

In a preliminary study, coal and rock core samples collected from areas of western Pennsylvania were crushed, split and riffled into portions that were analyzed for total sulfur contents, cast into polished pellets for reflected light microscopy and subjected to simulated weathering conditions.

In the simulated weathering studies the crushed samples were weighed and placed in inert plastic boxes whereby a constant flow of humidified air passed over the sample. Other than the normal oxidation processes the samples were not altered or chemically treated. At selected intervals the sample was covered with deionized water, drained and the effluent analyzed for volume, pH, conductivity, temperature, acidity and/or alkalinity. The concentrations of acidity or alkalinity (in mg/l as $CaCO_3$) were adjusted by the volume of effluent to obtain milligrams of acidity or alkalinity produced (in milligrams). Multiplying this value by the ratio of the weight of the sample to 100 grams, the acid or alkaline production potential was expressed as milligrams of acid or alkalinity produced per 100 grams of sample. These data were then plotted as cumulative acidity or alkalinity produced per 100 grams of sample for a particular time interval.

In almost every case we noticed that the cumulative acidity trends curved upward with time, indicating increased acid production; whereas the cumulative alkalinity curves were invariably straight lines. These anomalous relationships l[illegible] us to believe that the acid-alkaline production potentials were time dependent [illegible] related to the frequency of flushing or rinsing with water.

### 2. Variability in time of flushing intervals

As further proof of this notion, and in another study we leached some samples (including shales and sandstones) every other day for the first four weeks and then once a week for the next several weeks. Indeed a distinct difference appeared in the acid and alkaline samples. In the following discussions typical examples will be used to illustrate the trends that were routinely ascertained.

Within the samples that produced alkalinity a unique set of relationships commonly emerged. Regardless of the flushing interval alkalinity, specific conductance, sulfate and pH remained constant after the first week or so of flushing (Figure 1). These trends indicated that the alkalinity reactions were attaining near equilibrium conditions within the time between each flushing. On a daily basis the alkalinity and specific conductance produced remained relatively constant (Figure 1).

In a separate but related study the pH of deionized water was monitored through time as pulverized limestone was added to the solution. The water was circulated around a combination electrode by air bubbles and a change in pH from 5.05 to 8.8 took place in less than one minute after the limestone was added to the beaker. This further supports the findings that equilibrium conditions were quickly attained in a carbonate-bicarbonate aqueous system.

[illegible]n contrast, in the acid producing systems, as the leaching intervals were v[illegible]ed, the amount of acidity produced varied accordingly. When the flushing interval was extended, the amount of acidity produced increased (Figure 2).

During the first 25 days the samples were rinsed every two or three days and produced mildly acidic leachates (1 - 4 mgs of acid/100 grams of sample). When the flushing interval was extended (beyond 25 days) the amount of acidity in the effluent increased (4 - 11 mgs of acid/100 grams of sample). The specific conductance values reflected similar trends and indicated that the oxidation of pyrite continued during the interval between flushings and that equilibrium conditions were not attained. As seen in Figure 2, when the time period between flushings was extended the amount of acidity increased with attendant increases in specific conductance reflecting greater concentration of dissolved ions and hence, increased chemical reactivity.

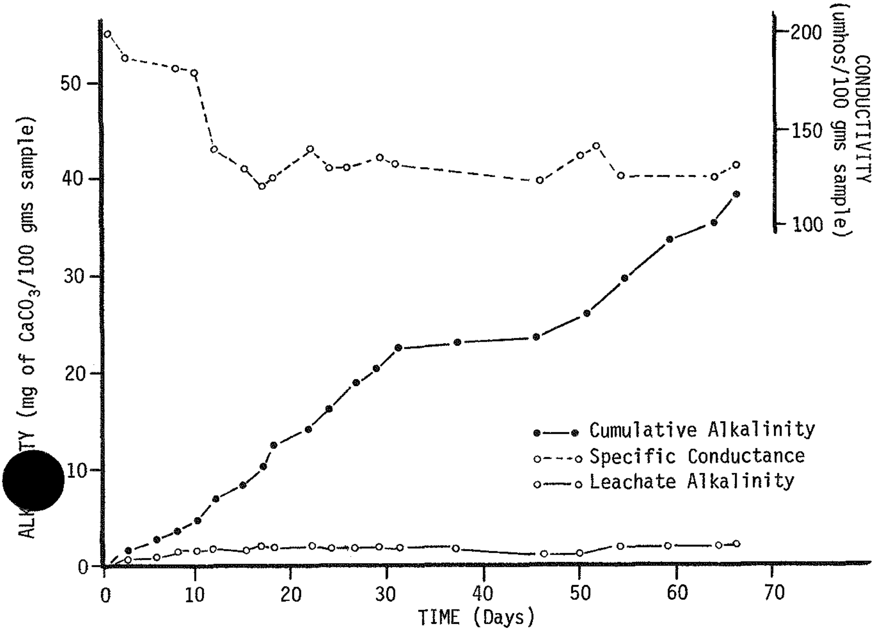

Figure 1. Plot of Alkalinity, Cumulative Alkalinity, and Specific Conductance for a Typical Shale Sample.

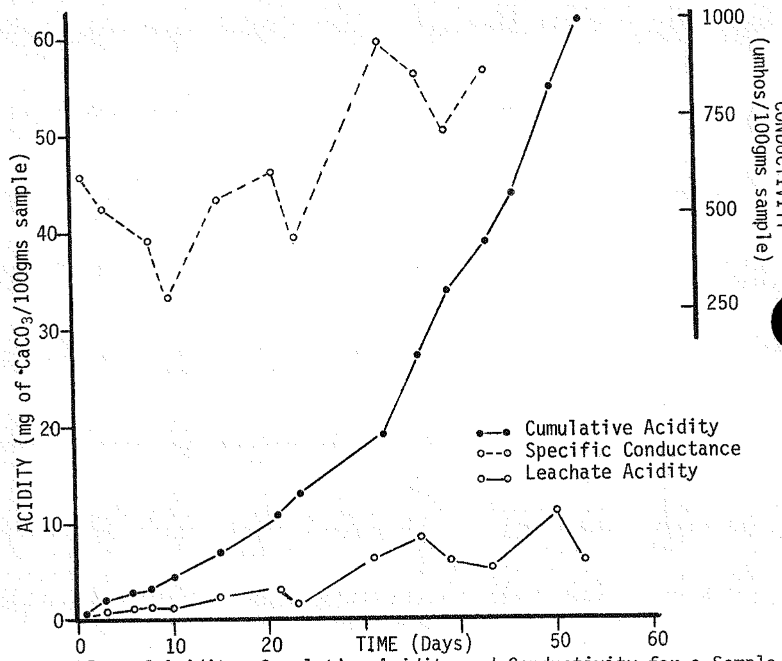

Figure 2. Plot of Acidity, Cumulative Acidity and Conductivity for a Sample.

### 3. Variability in Frequency of Flushing Intervals

In this phase of the study samples of gray shales and limestones were crushed and riffled into three portions. The first portion of each rock type was leached once a day, the second portion was leached twice a week and the third, once every ten days. All results were adjusted to a common base of milligrams of alkalinity produced per 100 grams of sample and compared; an example of which is illustrated in Figure 3.

The results of this study showed that a definite relationship exists between the frequency of flushing and the amount of cumulative alkalinity produced. As would be expected, when the alkalinity from one flushing is added to each preceding value, the greater the frequency of flushing the greater the cumulative alkalinity. Thus the greater the frequency of flushing the greater the alkalinity produced.

When the daily alkalinity and conductivity values are plotted against time (Figures 4 and 5) it is readily apparent that the concentrations of daily alkaline productions are relatively similar. This fully supports the belief that alkalinity limits are reached in short periods of time and that the maximum alkalinity is available within a one day period.

In contrast, however, as was shown by the results depicted in Figure 2, the concentration of acidity increases with the time between flushing and continues to increase indefinitely.

## III. SUMMARY AND CONCLUSIONS

The degree of acidity in coal mine drainage is a function of a balance between the amount of acidity produced and the alkalinity production potentials. The acidity is derived primarily by the oxidation of reactive pyrite and the subsequent

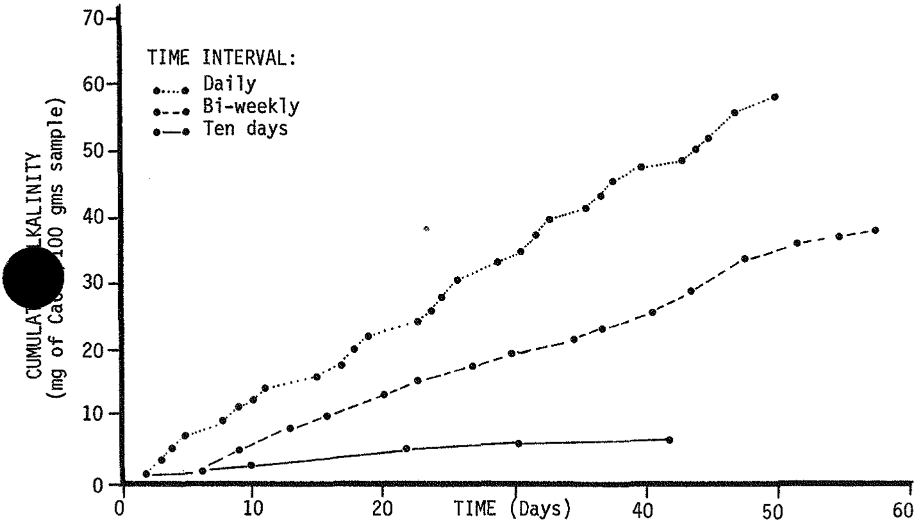

Figure 3. Plot of Cumulative Alkalinity of Samples Leached at Various Time Intervals.

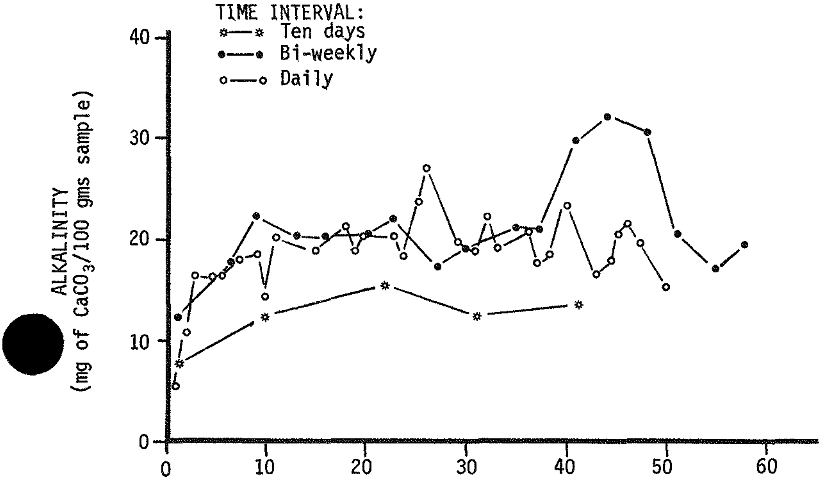

Figure 4. Plot of the Alkalinity of Samples Leached at Various Time Intervals.

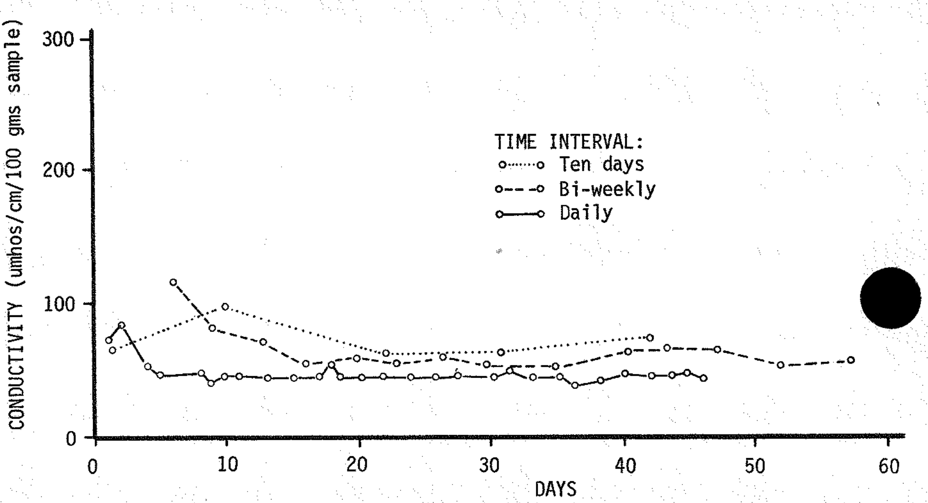

Figure 5. Plot of the Specific Conductance of Samples Leached at Various Time Intervals.

dissolution and hydrolysis of the weathering products. The alkalinity, on the other hand, is produced by a dissolution reaction between calcium carbonate and water. The kinetics of both systems are markedly different and the concentrations of acid or alkalinity are time dependent. In the following geochemical system we assume that the material producing alkalinity is hydrologically antecedent of the acid producing material.

Recent simulated weathering tests of acid and alkaline producing rocks showed that the rates of reactions of the two systems were markedly different. The amount of acidity produced by frequent flushings produced less acid than flushings which were done at longer time intervals. Thus, we found that frequent flushings commonly produced mildly acidic leachates.

Alkalinity production, however, is limited by the solubility of calcium carbonate in water which, at a given partial pressure of carbon dioxide, has a maximum neutralizing potential. Recent laboratory tests relating the change of pH of leachates to contact time with limestone showed that the solubility limit of carbonate was approached in less than one minute by an asymptotic relationship that decreased with time. In addition we found that calcareous material released limited concentrations of alkalinity that were constant for the time periods used in this study.

To emphasize how these findings can be used to explain the occurrence of acid mine drainage in some situations, a comparison of the alkalinity and acidity production potentials of the samples used in Figures 1 and 2 can be made for various flushing intervals.

Assuming for the moment that in a backfilled mine the shales producing the alkalinity in Figure 1 overlie the coarse grained sandstones producing the acidity in Figure 2. As long as a continual flushing exists, as in the first ten days, the amount of alkalinity (in this case about 2 mgs/100 grams of sample) exceeds and neutralizes the amount of acidity produced (about 1 mg/100 grams of sample), constraining the iron solubility and bacterial action which serves to inhibit acid production. If the interval of time between flushings were to increase, as in the 40-50 day period, the amount of alkalinity which remains constant, would now be overwhelmed by increased concentrations of acidity (about 5 - 11 mgs/100 grams of sample) and the system would now produce acid drainages. At this stage the solubility of iron increases which adds to the acid production and the environment becomes conducive to the iron bacteria which catalyze the reactions and compound the acid problem.

Under most natural systems the concentrations of alkalinity may be much greater than those used in this study, but then too, so would the concentrations of acidity. However, the relationships between acidity and alkalinity production potentials and [illegible] time interval between flushings as outlined in this paper should still hold [illegible]e.

These relationships suggest that the length of time between flushing intervals is critical to the prevention of acidic drainages in strip mines that contain potentially neutralizing material. Regardless of the time interval of flushing, the maximum alkalinity produced by calcareous material in the section is rapidly achieved and remains relatively constant. Subsequently, frequent flushings of acidic material prevent the accumulation of oxidation products and produce mildly acidic drainages that can be neutralized by the available alkalinity. On the other hand, seldom flushings solubilize larger concentrations of oxidation products producing strongly acidic solutions which overwhelm the available alkalinity and produce acid mine drainage. This may partially explain why the deep burial of acid material below water levels (in addition to the oxygen exclusion principle) prevents acid mine drainage production.

Under some circumstances, where mine drainages alternate between acid and neutral qualities in response to changes in climatic conditions, the time between flushing mechanism may also be used to explain the variation in mine drainage chemistry and the occurrence of acid mine drainage.

## REFERENCES CITED

Caruccio, F. T. (1968) An evaluation of factors affecting acid mine drainage production and the groundwater interactions in selected areas of western Pennsylvania. *Preprints of Papers Presented Before the Second Symposium on Coal Mine Drainage Research*. pp. 107-152, Bituminous Coal Research, 350 Hochberg Road, Monroeville, Pennsylvania 15146.

Caruccio, F. T. (1973) Estimating the Acid Production Potential of Coal Mine Refuse: *The Ecology of Resource Degradation and Renewal*, Edited by Chadwick and Goodman, Blackwell Scientific Publications.

Caruccio, F. T., Geidel, G. and Sewell, J. M. (1976) The character of drainage as function of the occurrence of framboidal pyrite and ground water quality in eastern Kentucky. *Preprints of Papers Presented Before the Sixth Symposium on Coal Mine Drainage Research*. Louisville, Kentucky.

Caruccio, F. T. and Geidel, G. (1976) Geochemical factors affecting coal mine drainage quality: *The Reclamation of Drastically Disturbed Lands*. (in press), American Society of Agronomy.

Caruccio, F. T., Ferm, J., Horne, J., Geidel, G. and Baganz, B. (1977) Paleoenvironment of coal and its relation to drainage quality. EPA-600/7-77-067, National Technical Information Service, Springfield, Virginia 22161.

Gardner, L. R. (1970) A chemical model for the origin of gibbsite from kaolinite. American Mineralogist, vol. 55, p. 1380-1389.

Garrels, R. M. and Christ, C. L. (1965) *Solutions, Minerals, and Equilibria*. Harper and Row, New York, N.Y.

Geidel, G. (1976) A laboratory study of the effect of carboniferous shales from the Pocahontas basin (eastern Kentucky - West Virginia) on acid mine drainage and water quality: Unpublished Master's thesis, University of South Carolina, Columbia, South Carolina, 101 p.

Singer, P. C. and Stumm, W. (1970) Acid mine drainage: the rate determining step. Science, vol. 167, pp. 1121-1125.

Stumm, W. and Morgan, J. J. (1970) *Aquatic Chemistry*, Wiley-Interscience, New York, N.Y.

# ENVIRONMENTAL POLLUTION BY TRACE ELEMENTS IN COAL PREPARATION WASTES*

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## INTRODUCTION

Coal is gaining new strength as the world searches for more energy. Coal is [illegible] a very clean fuel, however. Many of its problems can be traced back to its [illegible]c composition, i.e., a sedimentary formation of combustible, organic material containing inorganic rock and mineral matter. When mined, additional inorganic material which surrounds the coal seam may be taken as coal seams are stripped as rapidly and as economically as possible. From an environmental viewpoint, the mineral matter in coal produces undesirable gaseous and particulate pollutants which escape into the atmosphere when the coal is burned. To reduce these problems, about one-half of all the coal mined in the U. S. is cleaned or prepared near the mine to remove some of the heavier, unwanted, mineral matter from the lighter coal.[1] The prepared coal that is sent to the power plant is cleaner and thus produces less air contamination when burned than if it were not cleaned. The coal preparation waste left behind, however, is not always innocuous. The choice appears to be between possible terrestrial pollution from coal preparation wastes and obvious atmospheric pollution if these same materials were burned in the coal.

Coal preparation wastes contain a broad array of accessory or trace elements.[2] Some elements, such as iron, sulfur, aluminum, silicon, potassium, calcium, magnesium, titanium and sodium are present near or above the one percent level.[2] These elements form the major mineral species, such as pyrite, clays, quartz, calcite, and rutile. Almost all the other elements are present in much lesser amounts.[2] The chemistry of the various trace elements in the coal waste structure is less well understood than it is in coal itself where, for all the years of study, the subject of minor and trace element chemistry and associations is still debated. In any waste pile, however, each element will have some propensity to be leached and thereby carried into the aquatic environment. Investigators in several laboratories throughout the country are working at trying to understand how the elements are associated in coal and coal wastes, and thereby what their leaching propensity might be, but, until this is accomplished, the most enlightening information about element levels in waste-pile drainages appears to be the drainages themselves.

Trace or accessory elements are beginning to be recognized as serious waterborne contaminants. The concern about elements in coal waste drainage stems from the sensitivity of plant and animal life to them. All elements can be tolerated at some level, but many cause mortality at even very low levels. For example, it has been reported that as little as 400 ppm of Fe or Al ions in soils can result in the mortality of plants, and that fish kills may be caused by concentrations of these ions as low as 0.5 ppm.[3,4] In acid environments, such as exist in the drainages [illegible] coal waste piles, it is not unreasonable to expect the levels of some elements [illegible]ecome this high or higher and thus threaten animal and plant life.

Data on element leaching from coal waste are found to be somewhat restricted.[2] Generally, less than a dozen elements have been studied. Almost all are considered major elements. Other than the acidity-producing ability (measured by leachate acidity and pH) of coal waste, few parameters have been studied which can help predict the behavior of elements in the environment. Not even the percentages of elements that can be leached appear to be known. In short, the environmental

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* Work performed under the auspices of the United States Energy Research and Development Administration and Environmental Protection Agency.

behavior of the elements in coal waste piles is very poorly understood.

Through 1975, only a few authors had studied the levels of elements found in the drainage from coal waste piles.[2] Typically these elements have been those readily measured with atomic absorption, namely Fe, Al, Mn, Ca and Mg. Additional ions less frequently reported, but measured by this technique are Na, K, Zn, Ni and Cu. Very scant quantitative data are available for P, B, Mo, Cl and Pb. Other parameters frequently determined for refuse drainage are pH, sulfate ion and total solids, while total acidity and conductivity are less often measured.

The little quantitative data available support what those who have seen the run-off from coal waste piles would have guessed: the aqueous drainage from coal refuse usually contains considerable dissolved mineral or inorganic matter. For drainages from coal waste piles in Pennsylvania, West Virginia, Kentucky, Indian and Illinois where the pH was below 3, dissolved iron levels are almost always we above 500 ppm and sulfate ions above 1500 ppm.[5] Some Pennsylvania coal waste effluents have been found to have greater than 4% sulfate ion, while some Illinois drainages have over 1% dissolved iron.[5] The highest ion concentrations are generally found in the most acidic drainages.[3, 5] Certainly these elemental ion levels are cause for concern, considering the sensitivity of plant and animal life to many of them.

Recognizing the need to understand the chemistry of environmentally harmful trace elements released in the drainage of coal preparation wastes and the need to develop control technology for removing or recovering the elements of environmental or economic interest, EPA and ERDA, through an interagency agreement, initiated a program at Los Alamos Scientific Laboratory in 1975 to study these problems. The data reported in the technical sections of this paper were obtained as part of that project.

## MATERIAL COMPOSITION

The coal preparation waste that we have studied came from the southern part of the Illinois Basin. This basin, which includes Illinois, Indiana, and western Kentucky, is one of the major coal mining areas of the U. S. The coal in this area is highly mineralized, especially with pyrite, which is quite sensitive to oxidation and yields sulfuric acid and soluble iron. The waste material studied is representative of the average daily production of waste produced by a coal preparation plant which cleans over 10,000 tons of coal per day. The mineral content is given in Table I.

The mineral composition of the waste studied fits well into the range typically found in the Illinois Basin.[6] (Some values like pyrite and marcasite and gypsum may be a little high when the major element content below is considered.) Silica (19%) and aluminosilicates (39%) are the dominant minerals, while pyrite (17%) and surprisingly marcasite (12%) comprise a major portion of the remainder. Residual coal comprises most of the unaccountable material (11%). This sample did have a surprisingly low calcite value. This could lower the inherent acid neutralizing ability of the waste material. Other than this, this material should leach like much of the other coal preparation wastes from this region.

The major elements in the coal waste studied are those which make up the minerals discussed above. A listing is given in Table II. Some trace elements which are potentially hazardous are given in Table III. All these elements are typical of the values found in this area of the Illinois Basin.[6]

### TABLE I

MINERAL CONTENT OF AN ILLINOIS-BASIN COAL PREPARATION WASTE

| Mineral | Wt. % |
|---|---|
| Illite | 11.7 |
| Kaolinite | 7.8 |
| [illegible]her Clays | 19.5 |
| [illegible]rtz | 19.2 |
| Pyrite | 17.2 |
| Marcasite | 12.4 |
| Gypsum | 1.2 |
| Calcite | 0.0 |

### TABLE II

MAJOR INORGANIC ELEMENTS IN AN ILLINOIS-BASIN COAL PREPARATION WASTE

| Element | Wt. % |
|---|---|
| Si | 13.6 |
| Fe | 11.0 |
| Al | 5.1 |
| K | 1.1 |
| Ti | 0.35 |
| Mg | 0.23 |
| Na | 0.16 |
| Ca | 0.09 |

### TABLE III

SOME TRACE ELEMENTS IN AN ILLINOIS-BASIN COAL PREPARATION WASTE

| Element | PPM |
|---|---|
| Mn | 147 |
| Zn | 124 |
| As | 94 |
| V | 86 |
| Cr | 77 |
| Ni | 71 |
| Cu | 51 |
| Pb | 34 |
| Co | 30 |
| Be | 2.8 |
| Cd | 0.7 |

## STATIC LEACHING STUDIES

Static leaching techniques offer a rapid method for determining the effects of experimental parameters. However, these techniques only roughly approximate the actual environmental conditions encountered. We have used this technique to study time, temperature, particle size, oxygen and pH effects on the element leaching from coal waste materials. A few examples are presented below.

Crushed (-3/8") or powdered (-20 mesh) waste (50 g) was added to 250 ml of leachate (distilled water or dilute sulfuric acid) contained in a 500-ml erlenmeyer flask. The flask was either stoppered or fitted with a modified stopper designed to allow air into the flask while retaining the contents. Heating, when desired, was provided by a variac-controlled heating mantle. The completed flask assembly was inserted into a shaking apparatus that was used to agitate the sample during the experiment. After the completion of the leach period, the sample was removed from the shaker, and the leachate and residue were separated by vacuum filtration. The residue was rinsed with distilled water and the filtrate added to the leachate.

The leachate was tested for pH and then acidified with 6N nitric acid(to prevent precipitate formation) and made up to 250 ml. Aliquots from this were used to [illegible]rmine total solids and elemental ion concentrations.

Selected results for a series of experiments covering waste size and oxygen presence for times up to 8 weeks are given in Figure 1. Illinois-Basin coal waste produces an immediate drop in pH, reaching a value of 2.5 within a contact time of just 10 minutes (Figure 1A). This value continues to drop steadily in the presence of air and is still dropping when it reaches 1.8 in 50 days. In the absence of air, pH rises. (The initial pH drop probably reflects the presence of oxygen in the unpurged, but stoppered flasks.) Presumably, the chemical system is equilibrating through reactions which consume or tie up hydrogen ions. The depletion of

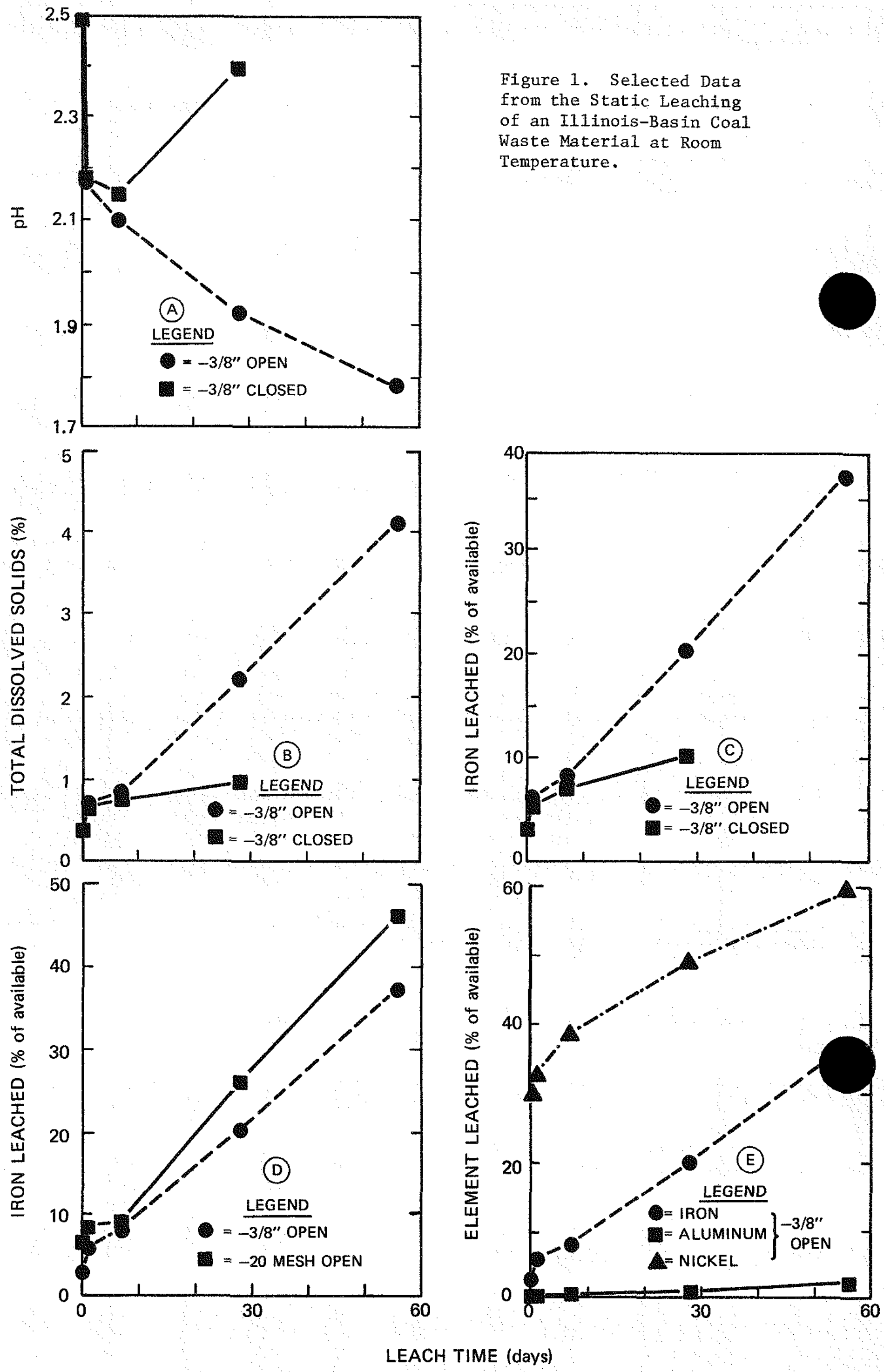

Figure 1. Selected Data from the Static Leaching of an Illinois-Basin Coal Waste Material at Room Temperature.

oxygen is dramatically demonstrated by the formation of a vacuum in the stoppered flasks.

The total dissolved solids in the leachate increases dramatically as the coal waste is shaken in air (Figure 1B). The data here are for a 5-to-1 water-waste ratio and reflect that after 50 days the leachate contains 4% dissolved solids and is increasing approximately 0.07% every day. In the absence of air only minor increases occur.

Very similar results to those for the dissolved solids are observed for iron, which reiterates the sensitivity of this element to oxygen (Figure 1C). The strong leaching power of highly contaminated and acidic leachate with dissolved air is readily apparent when it is seen that 40% of all the iron available is leached from th[illegible]l waste in 60 days.

Particle size is also important in coal waste leaching. This is reflected by the nearly 20% increase in iron leached from -20 mesh waste over that from -3/8" waste (Figure 1D). With the trend towards the processing of finer material through the preparation plant (80% of the waste in this plant was minus 2 inches), waste pile leaching will become more severe.

Not all elements behave like iron, which starts out at a relatively low level of solubility and rapidly increases with time (Figure 1E). Aluminum, a major constituent of clays and feldspars, is and remains quite insoluble. Nickel, an element whose mineral association is not known, on the other hand, is much more soluble than iron. Indeed, a wide range of element solubilities might be expected.

An experiment to determine the solubility of a variety of elements in coal waste was conducted on -20 mesh waste under room temperature, open air conditions. Not entirely surprising, the elements which were present in the highest concentrations in the leachate were generally those that were also present in the greatest amount in the bulk material (compare the "amount leached" data in Table IV with the data in Tables II and III). When the percentage of material present in the bulk material that is leached is considered, a very different picture takes shape.

Calcium occurs in a very soluble form in this Illinois-Basin coal waste (see the "% leached" data in Table IV). This is consistent with the presence of gypsum. Cobalt, nickel, zinc, cadmium, and manganese also occur in relatively soluble forms. Frequently thought to occur as sulfides, they do not appear to be related to the bulk of the iron which occurs as pyrite and marcasite and is less soluble. The similarity of vanadium and chromium to the clay elements, aluminum and potassium, suggests that these elements may substitute for aluminum in the clay structure. Titanium is quite insoluble, as would be expected if it occurred as titanium dioxide. This particular compound has been observed in the waste, using an electron microprobe. More conclusive elemental leaching behavior and mineral associations will arise as more data become available. Static leaching experiments will provide a rapid method for providing much of that data.

## COLUMN LEACHING STUDIES

[illegible]ynamic column leaching experiments provide a laboratory technique to answer a[illegible] criticism of the static leaching methods, i.e., they more nearly approximate real-life conditions. On the other hand, dynamic experiments are somewhat more difficult to control, are time consuming, and rarely provide time-dependent, percentage-of-element-leached type data without resorting to mathematical gymnastics. In spite of these difficulties, column leaching experiments provide quite useful information which can be of use to understand how waste piles behave under leaching conditions and to indicate the types of methods that might be necessary to control waste pile leaching.

Crushed waste samples (1500 g) were mixed and carefully loaded (to insure uniform distribution) into a glass column 70 cm long and 4.6 cm in diameter. This

## TABLE IV

## ELEMENTS RELEASED FROM AN ILLINOIS-BASIN COAL WASTE DURING 4 DAYS OF AQUEOUS LEACHING(a)

| Element | Amount Leached (µg/g of Waste)(b) | Element | % of Total Element Leached |
|---|---|---|---|
| Fe | 16400 | Ca | 79 |
| Ca | 680 | Co | 60 |
| Al | 570 | Ni | 46 |
| Mg | 216 | Zn | 42 |
| K | 90 | Cd | 35 |
| Na | 74 | Mn | 28 |
| Zn | 48 | Fe | 14 |
| Mn | 40 | As | 9 |
| Ni | 31 | Mg | 9 |
| Co | 18 | Cu | 7 |
| As | 7 | Be | 6 |
| Cu | 4 | Na | 5 |
| Ti | <2 | V | <3 |
| V | <2 | Cr | 1 |
| Cr | 1 | Al | 1 |
| Be | 0.2 | Pb | <1 |
| Cd | 0.2 | K | 0.8 |
| Pb | <0.2 | Ti | <0.1 |

(a) -20 mesh waste opened to air at room temperature

(b) Also aqueous level if 1 g of waste is leached with 1 g of water

column had previously been drawn at the bottom to provide a small (7 cm) orifice. An overflow tube (7 cm) was provided at the top. Particle retention was insured by placing 5 cm of glass wool at the top and bottom of the column. Distilled water, which had been equilibrated with air and had a 100 cm pressure head was meter[illegible] upwards through the column to prevent plugging. Flow rates were generally a[illegible] 45 ml/hr. During experiments where air was passed through the column, the lea[illegible]te was removed through the bottom orifice and air blown (280 ℓ/hr) upwards.

Leachate samples (35 ml or 100 ml) were collected periodically, their pH determined, and then acidified with 10 volume percent of 6N nitric acid. These acidified samples were then analyzed for total dissolved solids and inorganic elements and the data corrected for dilution.

Data for pH and iron concentration levels in a leachate when water flows continuously through a coal waste column are shown in Figure 2. (A much more comprehensive compilation will appear in the annual report of this project.) The low initial pH value (1.7) is much like the value observed in the static experiments above. The shape of the pH-volume curve reminds one of a weak-acid titration curve. Here the inflection point occurs around 3000 ml or nearly 6 times the volume of water (500 ml) needed to cover the coal waste. The early rise in pH suggests that a moderate amount of acidic material is originally present and that more is not readily formed with the influx of fresh water.

The initial iron content (over 10000 ppm) in leachate from coal waste is high (Figure 2). The level falls off extremely fast and is only a few hundred ppm after 3 liters has passed through the 1500 g mass. The level eventually drops to 10-25 p[illegible] remains constant after 10 liters have been collected. It would appear that o[illegible] certain amount of soluble iron is initially present, that this is flushed out, and that additional soluble iron does not form rapidly.

The iron behavior in the continuous flow system is dramatically different from that in the static system. (Compare the -3/8" open system data in Figure 1C with that in Figure 2, using 1 liter of volume as being approximately equal to 1 day of time.) The failure of significant amounts of soluble iron to form in the flowing system suggests the absence of the proper conditions in this system to oxidize pyrite. The importance of oxygen and ferric ions as factors in the oxidation of pyrite has long been recognized.[7] Astronomical increases in oxidation of pyrite by iron bacteria have also been observed.[7] In general, the rate-determining step, oxidation of ferrous ion to ferric ion, occurs more rapidly at higher pH.[7] Thus, pH does not appear to be a factor. Silica and clays, on the other hand, can catalyze the reaction.[7] All in all, it appears that removing the pyrite oxidation products from the vicinity of the pyrite and minimizing contact with contaminated water reduces the overall contamination by pyrite oxidation.

Data for pH and iron concentration levels in a leachate when the water flow is periodically interrupted and air is blown through the waste are shown in Figure 3. The first parts of the curves (until the interruption for air) are like those in the continuous leach experiments (Figure 2). After air is blown through the column for 1 day, however, the pH drops upon resumption of leaching and the iron concentration doubles (285 ppm rises to 550 ppm). As the leaching continues, these parameters return to approximately the same values as those expected if no interruption had occurred. When air is blown through the column for 7 days, the drop in pH becomes much more pronounced, and the iron concentration increases 12-fold (78 ppm rises to 1000 ppm).

Too little data are available for a solid explanation about the behavior of the discontinuous leaching system. Two plausible explanations for the increases in acid and iron concentration, however, are increased oxygen transport and mini-static/equilibrium leaching sites. Since the waste never became dry during either air-flow period, small "ponds" of contaminated leachate could have formed. Unlike the flowing water with its relatively fixed amount of oxygen, these little "ponds" could easily supply their oxygen content to the reaction site and readily be replenished by the passing air.

The discontinuous leaching of coal waste indicates serious potential problems that might occur during the disposal of coal waste. Waste materials are generally discarded wet or damp. This should be a condition highly suitable for pyrite oxidation. Also wastes discarded in the midwest and east receive substantial amounts of rain before they are covered. These generally drain but remain damp for long periods. Again oxidation should be prevalent. Good disposal procedures may need to include considerations dealing with moisture content, spreading area, and time delay before covering in order to minimize acid and leachable iron production.

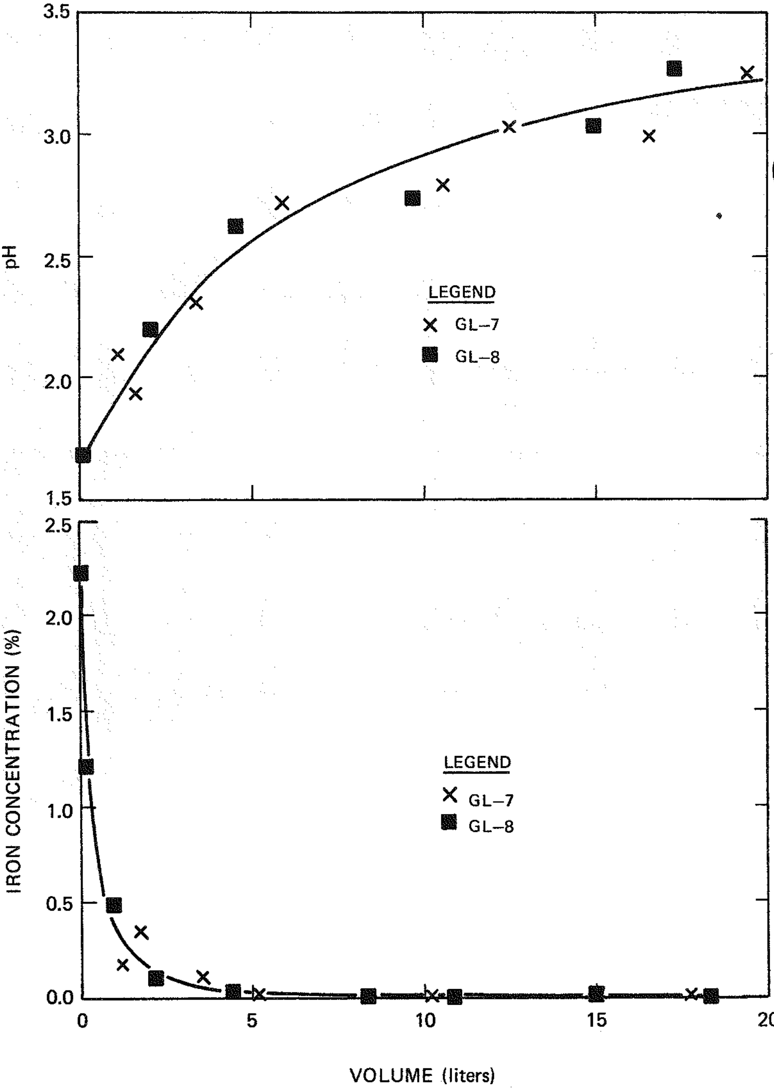

Figure 2. pH and Iron Concentration Changes as Water Passes Continuously through an Illinois-Basin Coal Waste.

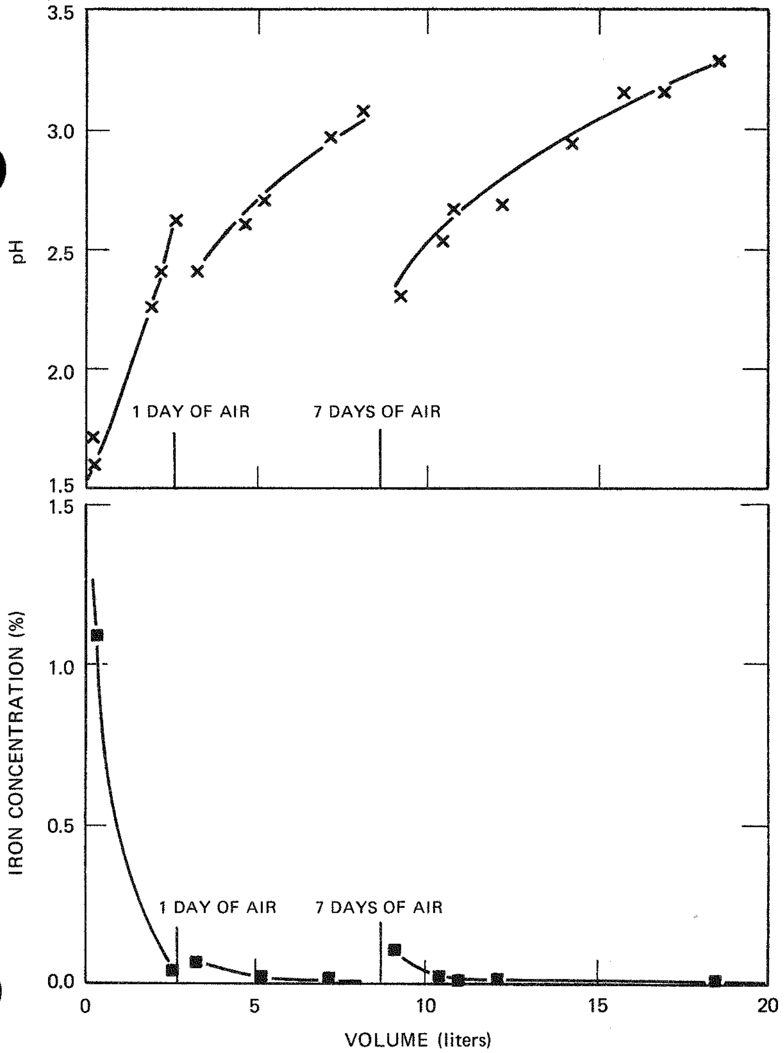

Figure 3. pH and Iron Concentration Changes as Water Passes Discontinuously through an Illinois-Basin Coal Waste.

## SUMMARY

Coal preparation waste contains a multitude of leachable elements. Data for 18 elements are presented here. Generally these elements occur in the waste leachates at levels related to their occurrence in the waste. Closer inspection reveals, however, that some elements are much more leachable than others. Thus, for Illinois-Basin waste iron is found to be present in waste leachate in high amounts, but this amount represents only a small percentage of the total iron in the waste. Cobalt and nickel, on the other hand, are not very plentiful in the waste, but are highly leachable. Aluminum, a major constituent of clays in the waste, is very poorly leached.

Oxygen availability is a prime factor in the production of soluble iron which is readily flushed from the waste. Particle size is less important. Under d[illegible] conditions and with plenty of air, pyrite oxidizes rapidly. This latter situ[illegible] poses a problem for the plant operator, as coal preparation wastes are discard[illegible] damp and remain so via rainstorms for long periods before they are covered.

## REFERENCES

1. National Academy of Sciences, "Underground Disposal of Coal Mines Wastes," Report to the National Science Foundation, Washington, DC (1975).
2. Wewerka, E. M.; Williams, J. M.; Wanek, P. L; and Olsen, J. D., "Environmental Contamination from Trace Elements in Coal Preparation Wastes-A Literature Review and Assessment," EPA-600/7-76-007 (1976).
3. Massey, H. F. and Barnhisel, R. I., "Copper, Nickel, and Zinc Released from Acid Coal Mine Spoil Materials of Eastern Kentucky," Soil Sci. 113 (3), 207-12 (1972).
4. Lowry, G. L., "Some Physicochemical Properties of Weathering Coal Spoils and Their Influence on the Growth of Pine Seedlings." University Microfilms (Ann Arbor, MI), Order No. 61-4968; Dissertation Abstracts 22, 1774-5 (1961).
5. Martin, J. F., "Quality of Effluents from Coal Refuse Piles," Pap. Symp. Mine Prep. Plant Refuse Disposal, 1st, Louisville, KY, Oct. 22-4, 1974, pp. 26-37.
6. Ruch, R. R.; Gluskoter, H. J.; and Shimp, N. F., "Occurrence and Distribution of Potentially Volatile Trace Elements in Coal," EPA-650/2-74-054 (1974).
7. Singer, P.C.; and Stumm, W., "Acid Mine Drainage: Rate-Determining Step," Science, 167, 1121 (1970).

# ACID LAKE RENOVATION

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## Introduction

A major environmental concern with surface mining is acid maine drainage (AMD). [illegible]der to eliminate AMD various states strengthened their water quality laws and regulations. The more stringent water quality standards dictated that some action be taken concerning acid water impoundments. There have been two basic approaches about the fate of an acid lake. The most prevelant approach (at least in Kentucky) has been to drain and/or fill the existing depression the lake occupied. A second alternative has been to renovate the acid lake. Acid lakes have been considered liabilities in reclaimed areas. The renovation or reclamation of an acid lake presents an opportunity to turn this liability into an asset. People have long realized the value of good lakes, but many people have often failed to appreciate an acid lake as an "out of balance" resource. This paper is an attempt to explore the latter alternative and examine some case studies as a means of evaluation.

## Methods

The lakes under investigation are located in Muhlenberg County, Kentucky on Peabody Coal Company's River Queen Mine (Figs. 1-4). These lakes were created during surface mining for coal (No. 11 and 12 seams) in 1967-68. Extensive field investigations of the five acid lake watersheds were used to identify problem areas (acid spoil, gob areas, etc.) in each watershed. Water quality data that were obtained on each particular lake included pH, acidity and alkalinity (Table 1). When feasible, water samples were taken from each major drainage occurring within the watershed. These drainages produced runoff only after prolonged precipitation had occurred. These data from the subwatersheds (pH and acidity) were used to isolate problem areas within each lake's watershed. Adjacent watersheds with "surplus" alkalinity or buffering capacity were investigated to explore the possibility of diverting water and hence alkalinity into the existing acid lakes. Diversion work to bring additional water into a watershed was only feasible for lake No. 5.

Lakes 1, 2, 3 and 5 were treated using 44.8 metric tons/hectare (20 tons/acre) of agricultural limestone on the problem areas within the watershed of each lake. Where extensive waste coal and gob areas existed some limited grading was performed to cover these extremely toxic areas and thereby eliminating that source of AMD. Lake No. 5 required the most grading work due to its larger watershed (Table 1). Each lake's water (except 5) was treated using agricultural limestone applied from a truck with a blower attachment. The limestone was blown over the lake surface [illegible]ll as the shoreline. All lakes with the exception of No. 2 and No. 4 had [illegible] diversion work in addition to spoil and water treatment. Areas that were sparsely vegetated or regraded were planted with grasses and legumes and/or trees to stabilize the spoil material.

## Results

All the lakes included in this study were originally in an extremely acidic condition (Table 1). After treatment with limestone, all lakes (except 5) attained state water quality standards (pH 6.0) within 6 months (Table 2). Water in lake No. 5 was not treated directly, but by improvement of the watershed, incoming water over a long time period (18 months) neutralized the entrapped acid water

Table 1. Physical and chemical aspects of the five acid lakes under study on River Queen Mine, Muhlenberg County, Kentucky 1973-1977.

| LAKE | DATE OF SAMPLE | pH | mg/1 ACIDITY | mg/1 ALKALINITY | mg/1 TOTAL IRON | SIZE* | WATERSHED* | DEPTH** MAXIMUM | DEPTH** AVERAGE |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 9/13/73 | 3.9 | 46 | 0 | .8 | 0.80 | 14 | 3.7 | 3.0 |
| 2 | 9/13/73 | 4.3 | 14 | 0 | .05 | 0.65 | 3.6 | 2.4 | 1.5 |
| 2 | 3/01/73 | 6.2 | 4 | 4 | --- | 0.65 | 3.6 | 2.4 | 1.5 |
| 3 | 11/8/72 | 3.6 | 256 | 0 | --- | 0.45 | 10 | 3.7 | 2.4 |
| 3 | 6/24/73 | 3.8 | 114 | 0 | --- | 0.45 | 10 | 3.7 | 2.4 |
| 3 | 9/14/73 | 3.0 | 198 | 0 | --- | 0.45 | 10 | 3.7 | 2.4 |
| 4 | 11/8/72 | 3.6 | 266 | 0 | 10.5 | 0.40 | 4.6 | 2.4 | 1.7 |
| 4 | 9/14/73 | 3.2 | 104 | 0 | --- | 0.40 | 4.6 | 2.4 | 1.7 |
| 5 | 4/27/73 | 3.3 | 238 | 0 | --- | 6.60 | 57.5 | 9.1 | 5.0 |
| 5 | 12/5/73 | 3.3 | 355 | 0 | --- | 6.60 | 57.5 | 9.1 | 5.0 |
| 5 | 10/31/75 | 6.2 | 11.7 | 50.4 | --- | 6.60 | 57.5 | 9.1 | 5.0 |
| 1 | 8/30/76 | 7.6 | 2.0 | 42 | .15 | 0.80 | 14 | 3.7 | 3.0 |
| 2 | 8/30/76 | 8.1 | 1.0 | 26 | .05 | 0.65 | 3.6 | 2.4 | 1.5 |
| 3 | 8/30/76 | 7.0 | 1.0 | 12 | .05 | 0.45 | 10 | 3.7 | 2.4 |
| 4 | 8/30/76 | 6.9 | 2.0 | 22 | --- | 6.60 | 57.5 | 9.1 | 5.0 |
| 1 | 7/13/77 | 7.6 | 0 | 48 | .17 | 0.80 | 14 | 3.7 | 3.0 |
| 2 | 7/13/77 | 8.8 | 0 | 26 | .08 | 0.65 | 3.6 | 2.4 | 1.5 |
| 3 | 7/13/77 | 7.2 | 0 | 20 | .25 | 0.45 | 10 | 3.7 | 2.4 |
| 4 | 7/13/77 | 6.7 | 0 | 18 | .20 | 0.40 | 4.6 | 2.4 | 1.7 |
| 5 | 7/13/77 | 6.9 | 0 | 46 | .07 | 6.60 | 57.5 | 9.1 | 5.0 |

*Hectares
**Meters

(Table 2).

Immediate positive results were noted in impoundment No. 2. This was due to the small size of both its watershed and capacity, low initial acidity and good access. The other lakes had higher acidity levels, poorer access, and thereby required longer times for neutralization.

Table 2. Length of time required for lakes to attain pH 6.0 or greater after water treatment or land modification.

| LAKE NO. | INITIAL pH | TIME REQUIRED UNTIL pH 6.0 | CURRENT* pH |
|---|---|---|---|
| [illegible] | 3.9 | 3 months | 7.6 |
| 2 | 4.3 | 7 days | 8.8 |
| 3 | 3.0 | 3 months | 7.2 |
| 4 | 3.2 | 6 months | 6.7 |
| 5 | 3.3 | 18 months | 6.9 |

*July 13, 1977

From an economic viewpoint reclaiming acid lakes proved advantageous. The cost of renovating never exceeded the estimated cost of draining or filling. In fact expenditures ranged from approximately equal to 1/10 of projected draining or filling costs (Table 3).

Table 3. Estimated cost of renovating acid lakes of River Queen Mine, Muhlenberg County, Kentucky.

| | COST $ | | | | |
|---|---|---|---|---|---|
| LAKE | LIMESTONE* | GRADING | TOTAL | vs. | DRAINING OR BACKFILLING |
| 1 | 1300 | 300 | 1600 | | 2000 |
| 2 | 400 | | 400 | | 4000 |
| 3 | 1500 | 200 | 1700 | | 2000 |
| 4 | 500 | 200 | 700 | | 4000 |
| 5 | 4000 | 4000 | 8000 | | 50000 |

*Includes application cost

All lakes were originally acid and void of any fish populations. The post treatment animal communities consisted primarily of chironomid and ceratopogonid larvae and a few aquatic beetle species. Cattails (*Typha latifolia*) were present in each of the lakes prior to treatment. The only other aquatic vascular plant present before treatment was narrow-leafed cattail (*T. angustifolia*) in lake 2.

After treatment, the aquatic biological communities drastically changed. This change in the aquatic ecosystem was a response to a more favorable pH range. After [illegible]tment and subsequent neutralization the lakes supported diverse aquatic commun[illegible] consisting of both vertebrates and invertebrates. The diversity of aquatic [illegible]oinvertebrates now included a wide assortment of species representing 9 orders as opposed to 4 before treatment (Table 4). The invertebrates, with the exception of *Physa* spp. at lake 2, were not introduced in any of the lakes and represented pioneering species. Fish (largemouth bass (*Micropterus salmoides*), bluegill (*Lepomis macrochirus*), and channel catfish (*Ictalurus punctatus*) were stocked in each of the lakes the spring following treatment. Once stocked, fish have maintained successful populations since establishment. Growth rates have been excellent. Stocked as fry, largemouth bass have attained a length of 25.4-28 cm. (10-11 in.) in 12 months and bluegills reached 15.2-20 cm. (6-8 in.) in 16 months. Channel catfish had grown to 20-30.5 cm. (8-12 in.) in 10 months after fall stocking of fingerlings. In addition to stocked vertebrates (fish) natural invasion of frogs, toads, turtles and snakes has taken place (Table 4). Bird and mammal species (muskrat (Ondatra zibethicus), mink (Mustela vison), raccoon (Procyon lotor), waterfowl, wilson's snipe (Capella gallinago) and others) common to wetland habitats have appeared or increased in numbers since lake renovation. Furthermore there are upland game species such as bobwhite quail (Colinus virginianus) and cottontail rabbit (Sylvilagus floridanus) that are encouraged by the edge effect created by the marsh habitat intermeshing with reclaimed spoil. These ecotones tend to increase the carrying capacity of the spoil.

A major change observed in the vascular aquatic flora was an almost immediate appearance of narrow-leaf pondweed (Potamogeton foliosus) after the pH approached or exceeded 6. This pondweed appeared in all the lakes during the first growing season after the water pH had stablized in the 6 range. This plant has formed e[illegible]tensive beds in lake water 0.5 to 2 meters in depth. Potamogeton diversifolius Naiad (Najas minor), and Chara sp. have appeared in some of the lakes and will probably spread to the others.

## Discussion

The experience with these five lakes has demonstrated in Kentucky and perhaps where similar conditions exist that acid lakes can be successfully and economically renovated (Table 4). One has to realize that lakes serve as large collection basins for their watershed. In addition, the quality of water in the lake is simply a reflection of the physical, chemical and biological processes within the watershed. AMD formation does not take place in the lake but rather in the spoil piles (Brant and Shumate 1971, and Parsons 1964). Assuming the above, no defensible argument can be forwarded for the wholesale elimination of acid lakes. If the lake is eliminated, the problem is exacerbated by the system producing more silt, greater peak flows of floods, higher metal concentration in water, loss of carrying capacity of wildlife and the ecosystem being simplified by the loss of the aquatic community. The following is a listing of potential advantages of renovated spoil lakes:

1) Minimize any offsite damage.
2) Provide for future water supply.
3) Increase in carrying capacity for wildlife.
4) Reduce local flooding.
5) Provide for recreation area (fishing and hunting).
6) Improve the aesthetic appeal of the area.
7) Increase the interspersion of habitats.
8) Improving the water quality from the area.

Lakes also act as large buffering basins which can offset uncontrolled acid mine drainage (Cole, 1960). Several investigators have noted that acid lakes formed during surface mining tend with age to approach a mormal pH range in excess of 6 (Campbell et al 1965, Riley 1965, and 1974). By correcting various deficiencies in the watershed of an acid lake this aging process can be accelerated by: 1) diminishing or eliminating acid loading, and 2) increasing potential alkalinity.

Limestone was chosen for the neutralizing agent because: 1) it is a relatively inexpensive material, 2) it is natural material in watersheds forming a bic[illegible]bonate buffer system, and 3) unreacted material will be present for an extended period to contribute alkalinity to the bicarbonate buffer system.

The oxidation of sulfur bearing materials is a moderately rapid process, whereas dissolution of limestone by $CO_2$ and water to form $H_2CO_3$ is a slow process (Stumn and Morgan 1970). The whole process is analygous to the acid water that is sometimes present in the exposed pit of a new final impoundment. As the water level increases acid bearing materials are flooded, thus excluding oxygen and diminishing acid production. Bicarbonate production on the other hand is now exceeding acid input. It is simply a matter of time and natural neutralization until the lake reaches a natural state.

1) Acid Production $>$ Alkalinity Inflows = Acid Lake

2) Acid Production $<$ Alkalinity Inflows = Natural Lake

An important point in this discussion is to realize that acid lakes are not causing or producing AMD. The lakes are only serving as holding basins for their watersheds.

The biological community of an acid lake is a meager, simplified community (Humphrey 1970 and Stockinger and Hays 1960) and as such supports a short food chain and simplified food web (Fig. 5). The food web depicted in Figure 5 illustrates the complexity and varied interconnection between different groups of organisms in the renovated lake. This species variety gives stability to the ecotem. The type of aquatic community that develops once an acid lake has been ovated is prehaps the best barometer of the health of that ecosystem.

These case studies have shown that if the various deficiencies in each watershed of an acid lake are corrected a natural body of water will be the product. By working with the various ecological processes already in progress in the watershed, the system will respond rather quickly. However if the watershed is denuded and extensively regraded, any initial progress made in weathering is lost.

Two goals which are foremost in Peabody's Reclamation Program are:

1) Eliminate any offsite damage.
2) Return the reclaimed land to a stable ecological unit in the shortest time-frame possible.

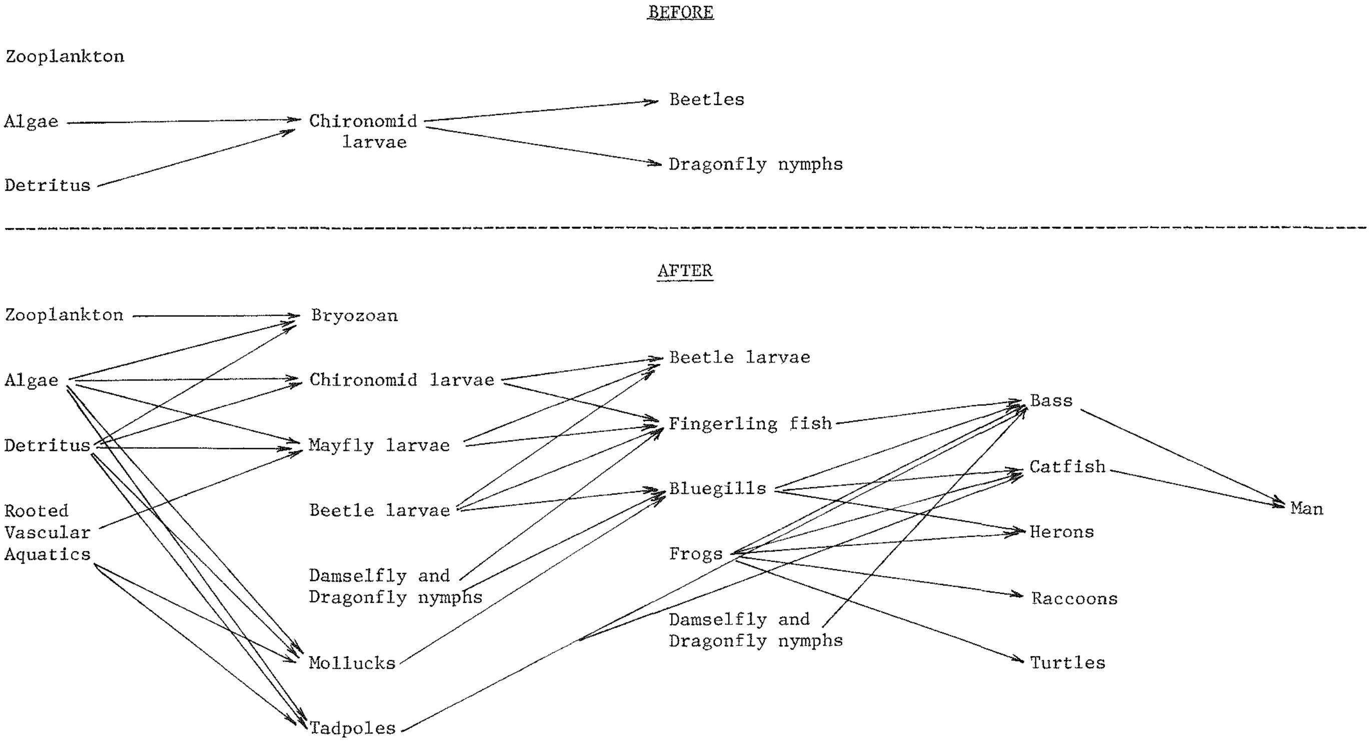
It is believed that renovating acid lakes serves to achieve these goals in addition to being economically feasible and ecologically sound.

Table 4. Major components of the macroinvertebrate and vertebrate fauna with the five study lakes, Muhlenberg County, Kentucky 1972-1977.

| | LAKE | | | | |
|---|---|---|---|---|---|
| TAXON | 1 | 2 | 3 | 4 | 5 |
| INVERTEBRATES | | | | | |
| Bryozoa | | | | | |
| Plumatella | AX | | | | |
| Insecta | | | | | |
| Ephemeroptera (Mayflies) | | | | | |
| Caenis | AX | AX | AX | AX | AX |
| Hexagenia | | AX | AX | AX | [illegible] |
| Coleoptera (Beetles) | | | | | |
| Gyrinus | BAX | BAX | BAX | BAX | BAX |
| Berosus | BAX | BAX | BAX | | BAX |
| Laccophilus | BAX | BAX | BAX | BAX | AX |
| Megaloptera (Alderfly) | | | | | |
| Sialis | BAX | BAX | BAX | BAX | |
| Hemiptera (True Bugs) | | | | | |
| Gerris marginatus | BAX | BAX | BAX | BAX | BAX |
| Odonata (Dragonflies) | | | | | |
| Anax | BAX | BAX | BAX | BAX | AX |
| Aeschna | BAX | BAX | | | |
| Zygoptera | AX | AX | AX | AX | AX |
| Diptera (Flies) | | | | | |
| Chironomus | BAX | BAX | BAX | BAX | BAX |
| Ceratopogonidae | BAX | BAX | BAX | BAX | BAX |
| Mollusca | | | | | |
| Physa | AX | AX | | | AX |
| VERTEBRATES | | | | | |
| Fishes | | | | | |
| Micropterus salmoides (Largemouth Bass) | AX | AX | AX | AX | AX |
| Lepomis macrochirus (Bluegill) | AX | AX | AX | AX | AX |
| Ictalurus punctatus (Channel Catfish) | AX | AX | AX | AX | AX |
| Esox masquinongy (Muskellunge) | | | | | AX |
| Esox lucius (Northern Pike) | | | | | AX |
| Stizostedion vitreum (Walleyed Pike) | | | | | AX |
| Pimephales vigilax (Fathead Minnow) | | | | | AX |
| Amphibians - Reptiles | | | | | |
| Bufo woodhousei (Fowler's Toad) | AX | AX | AX | AX | AX |
| Acris crepitans (Cricket Frog) | AX | BAX | AX | BAX | [illegible] |
| Rana clamitans (Green Frog) | AX | AX | AX | AX | [illegible] |
| R. pipens (Leopard Frog) | | AX | AX | AX | [illegible] |
| R. catesbeiana (Bullfrog) | AX | AX | AX | AX | AX |
| Natrix sipedon (Water Snake) | | | | | AX |
| Pseudemys scripta (Red-eared Turtle) | AX | AX | | | AX |

X = present
BX = present before renovation
AX = present after renovation
BAX = present before and after renovation

Figure 5. Generali[illegible]odweb of the lakes before and after renovation.



## LITERATURE CITED

Brant, R. R. and K. S. Shumate. 1971. At-source abatement - practical consideration: In acid mine drainage formation and abatement by Ohio State University research foundation. U.S. Evironmental Protection Agency,. Water Poll. Control Res. Ser., 14010 FPR: 57-73.

Campbell, R. S., Lind, O. T., Harp, G. L., Geiling, W. T., and Letter J. E. , Jr. 1965. Water pollution studies in acid strip-mine lakes: Changes in water quality and community structure associated with aging. Symp. Acid Mine Drainage Res. Reprints, Pittsburgh, Pa. 188-198.

Cole, V. W. 1960. Impounding and liming acid mine drainage. Ind. Wastes 5(1)10-11.

Humphrey, S. A. 1970. A qualitative survey of the marco-invertebrates from thr[illegible] acid-polluted strip-mined lakes. Unpub. M. S. Research Report. So. Ill. Univ., Carbondale, Ill. 36pp.

Parsons, J. D. 1964. Comparative limnology of strip-mine lakes. Verh. Internal. Verein. Limnol. XV (293-298).

Riley, C. V. 1974. Ecology -- Ally of mined land restoration. Second Symp. on Mined-Land Reclamation. 54-69.

________. 1965. Limnology of acid mine water impoundments. Symp. of Acid Mine Drainage Res., Pittsburgh, Pa. 175-187.

Stockinger, N. F. and H. A. Hays. 1960. Plankton, benthos, and fish in three strip-mined lakes with varying pH values. Trans. Kan. Acad. Sci. 63: 1-11.

Stumn, W. and J. J. Morgan. 1970. Aquatic chemistry. Wilkey Interscience, New York, N.Y. 583pp.

Figure 1. Renovated lake No. 1, Muhlenberg County, Kentucky 1977.

Figure 2. Renovated lake No. 2, Muhlenberg County, Kentucky 1977.

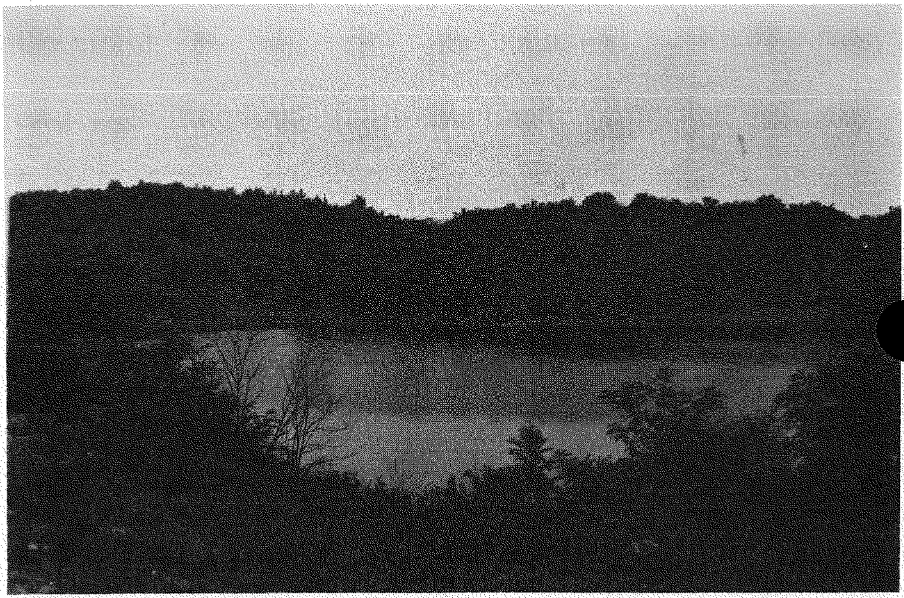


Figure 3. Renovated lake No. 3, Muhlenberg County, Kentucky 1977.

Figure 4. Renovated lake No. 4, Muhlenberg County, Kentucky 1977.

# GROUNDWATER RE-ESTABLISHMENT IN CAST OVERBURDEN

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## Introduction

In the past there has been considerable study of surface water associated with mining activity. Particular emphasis has been placed upon water quality, but only [illegible]ted attention given to water quantity changes dues to mining. Effects of mining [illegible] groundwater have been practically ignored. However, this situation is rapidly changing.

Federal surface mining legislation recently enacted will serve as a tremendous stimulus to detailed hydrologic studies of mine areas. Studies must address the quantity and quality of both surface water and groundwater before, during, and after mining. Such terms as groundwater, aquifers, alluvial valley floors, recharge capacity, hydrologic balance, hydrologic regime, acid-forming materials, toxic-forming materials, and leachate will become frequently used by more and more people in the mining industry as well as state and federal regulatory agencies.

## Purpose and Scope

This paper is presented to give a better understanding of the groundwater regime in surface-mined areas in the humid midwestern climate. The coal-producing region under consideration is that part of the Eastern Interior Coal Province (Illinois Basin) situated in Illinois, Indiana, and Western Kentucky. The paper is based in part upon limited hydrology studies at AMAX Coal Company mines in Indiana and Kentucky. Much of the information has been obtained from existing publications. While the mines studied are believed to be fairly representative of midwestern operations, the reader is cautioned that sufficient data do not yet exist to define the hydrologic regime at any given mine without conducting site-specific studies.

## Factors Defining Groundwater Re-Establishment

Groundwater re-establishment in cast overburden can be defined by several interrelated factors. These include:

Climate
Overburden characteristics
Aquifer coefficients
Topography
Recharge and discharge
Water quality
Water use

Each of these factors will be discussed separately for conditions existing be[illegible], during, and after mining.

## Climate

The climate of the region is essentially continental in character with rather wide extremes in precipitation and temperature. Mean annual precipitation ranges from 34 to 48 inches while mean annual temperatures vary from 52 to 59 degrees Fahrenheit. Mean maximum July temperatures are 88 to 92° F. Mean minimum January temperatures vary from 17 to 28° F. The average date of the last frost in spring ranges from about April 1 to April 22. The average date of the first frost in fall varies from about October 15 to November 4. Average annual snowfall varies from 6 to 22 inches. Wind velocity averages 7 to 12 miles per hour. Wind direction is predominately from the southwest quadrant. Thunderstorms with high intensity rainfall are common during spring and summer months. Rainfall during these storms in a 24-hour period sometimes exceeds 2 to 3 inches and occasionally reaches 5 or 6 inches.

Although there are microclimate changes associated with mining the overall climate is not affected. However, the climate plays an obvious role in post-mining reclamation, and in the re-establishment of surface water and groundwater.

## Overburden Characteristics

Several disciplines are involved in the study of overburden. Important ov[illegible]burden characteristics include the type, thickness, extent, and stratigraphic r[illegible]lationships of individual formations (soils and geology), chemical composition (geochemistry), and physical properties (soil and rock mechanics). With the exception of geologic studies little has been done to define overburden characteristics on a mine-specific basis until the last few years.

Soils may range from thin, relatively infertile soils in some of the hilly areas to thick, highly productive soils in the more level areas in the northern portions of the region. Unconsolidated deposits (including glacial till, weathered rock material below soil horizons, alluvium, and colluvium) range in thickness from zero in some of the unglaciated, hilly areas in the south to over 100 feet in parts of the northern glaciated areas. Bedrock is Pennsylvanian in age and consists predominately of shale, sandy shale and sandstone with minor amounts of coal and limestone. Within the region many different coal seams are mined. These seams and the overburden vary considerably in chemical composition. In some places there are considerable pyritic materials (potential acid-producing) in the overburden and little material capable of effectively neutralizing acids generated. However, this situation is not typical. In most cases the overburden has a neutralization potential exceeding the acid-producing potential.

The process of mining results in the cast overburden having quite different physical properties from the pre-mining overburden. The rock is changed from a layered sequence of distinct rock types in a generally well-consolidated state to a heterogeneous mixture of pieces of rock of quite variable size. Originally unconsolidated materials are often mixed with the broken rock material. Recently, however, due to state and federal legislation, there have been great efforts made to replace original unconsolidated materials, including topsoil, at the top of the cast overburden. The overall volume of cast overburden is about 20 per cent greater than that of unmined overburden.

## Aquifer Coefficients

Some published groundwater hydrology studies are available which help define characteristics of hydraulic conductivity (permeability) and storage coefficient for aquifers and other geologic strata. In most of the region the principal aquifers in areas likely to be mined are sandstone formations. In some cases shale, coal, limestone, or a combination of formations is used. Unconsolidated sand a[illegible] gravel aquifers are used to some extent, particularly in parts of the north hal[illegible] the region where thick glacial deposits occur. Water wells completed in overbu[illegible] materials may range in yield from practically 0 to as much as 50 gallons per minute (gpm), although wells producing over 25 gpm are not common. Median well yields are less than 10 gpm.

Aquifer permeabilities are low, usually within the range of 1 to 25 gallons per day per square foot (gpd/ft$^2$). Aquifer thicknesses vary considerably over short distances and transmissivities (permeability times saturated thickness) commonly range from about 20 to 500 gallons per day per foot (gpd/ft). Storage coeffficients usually reflect artesian conditions and may vary from .01 to .0001. Geologic formation overlying aquifers usually are very low in permeability. Values of .01 to .0001 gpd/ft are typical for these aquitards.

The process of surface mining involves the physical disruption of any aquifers in the overburden at the active pit. Concurrent with the aquifer disruption is the drainage of the fragmented materials. Water draining from these materials is pumped from the active pit in order to keep it relatively free of water. This must be done so that the uncovered coal may be extracted. The overburden materials fragmented by blasting are cast by shovel or dragline onto the area where the coal has been removed in a previous cut. These operations are illustrated by Figure 1, a cross section of what may be regarded as a "typical" active area-surface mine in the Midwest. Figure 2 shows how the same area may look following mining.

The cast overburden becomes an aquifer during the active mining process. It begins to fill with water moving laterally from previously mined areas and from vertical recharge of local precipitation. It has been the observation of many in the industry that more water enters the active pit from the cast overburden side than from the highwall (unmined) side. This would indicate the cast overburden aquifer has a greater transmissivity and/or greater recharge than do aquifers in the unmined overburden.

In Figure 1 a buckwall is shown at the base of each ridge of cast overburden. Such a buckwall is sometimes intentionally created by the dragline operator to improve stability of the cast overburden. The buckwall is composed of bedrock and is generally used when considerable soft overburden (such as lacustrine or alluvial deposits) overlies the bedrock. Because of the very coarse nature of the buckwall and its low position it may constitute a zone of extremely high permeability. Also, even when buckwalls are not constructed, there is a natural tendency of some of the coarser rock fraction of the cast overburden to roll down and accumulate at the base of the cast overburden. Van Voast (1976) has observed this condition in southeastern Montana. He has further determined by test well observations that this more permeable zone will eventually contain water under artesian conditions, being confined by the overlying finer-grained materials. At Colstrip, Montana, the mean permeability of the coal aquifer (9 tests) was about 8 gpd/ft$^2$. The mean permeability of the cast overburden (as determined from 11 tests) was about 18 gpd/ft$^2$.

On September 15, 1976, the author conducted a controlled constant-rate pumping test on well GIB#2 in the cast overburden at the Gibraltar Mine near Central City in Muhlenberg County, Kentucky. The well location is shown in Figure 3. The Kentucky No. 11 and 12 coal seams had been mined and the area reclaimed between 1959 and 1965. The hydrologic regime appears to have reached equilibrium before 1972. Equilibrium is indicated by the fact that the last-cut lakes and incline lakes exhibit water levels and water level fluctuations very similar to those of the cast overburden aquifer. The overburden originally consisted primarily of shale and sandstone, although a few feet of Providence Limestone separated the No. 11 and 12 coal seams.

Analysis of the data collected during the September 15 test yielded an aquifer transmissivity of 1494 gpd/ft when the Jacob modified non-leaky artesian formula [illegible] applied as shown in Figure 4. Application of the Theis formula gave an aquifer transmissivity of 1563 gpd/ft. Dividing this by a saturated thickness of 31 feet gave a permeability of 50 gpd/ft$^2$. The well produced 15 gallons per minute for three hours with 12.64 feet of drawdown. This yield probably exceeds that of most water wells in the Lisman Formation in Muhlenberg County. De Vaul and Maxwell (1962) indicate that wells in the shale and sandy shale yield practically no water but that wells penetrating sandstone, particularly the Anvil Rock Sandstone, yield enough water for a modern domestic supply.

Figure 5 shows the recovery curve for a test well in the Lisman Formation. Well 4832 is 78 feet deep and is open to the Anvil Rock Sandstone and underlying

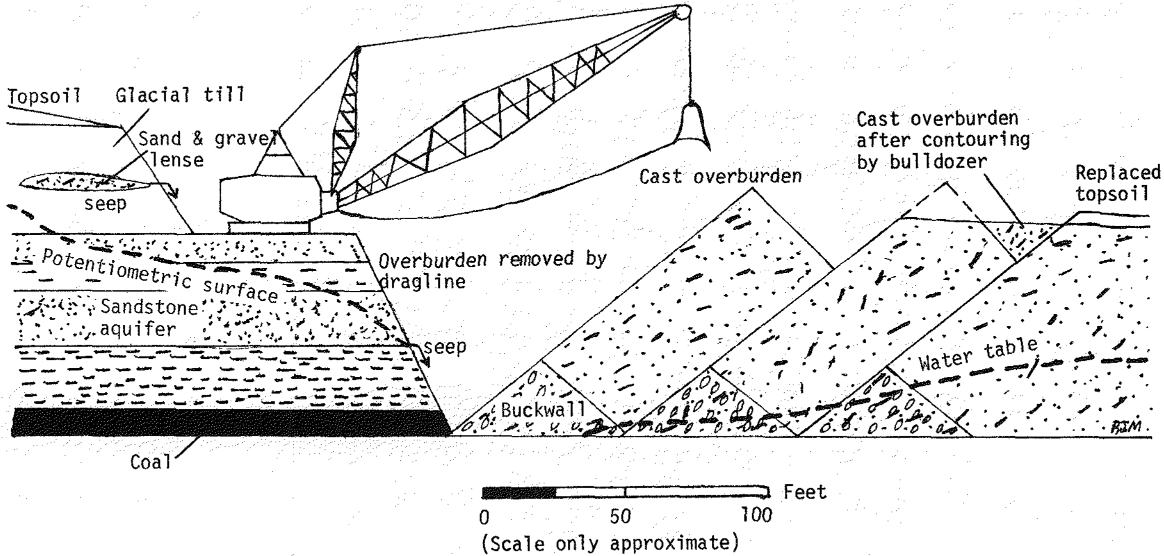

Figure 1. Cross section of active area-surface mine in the Midwest.

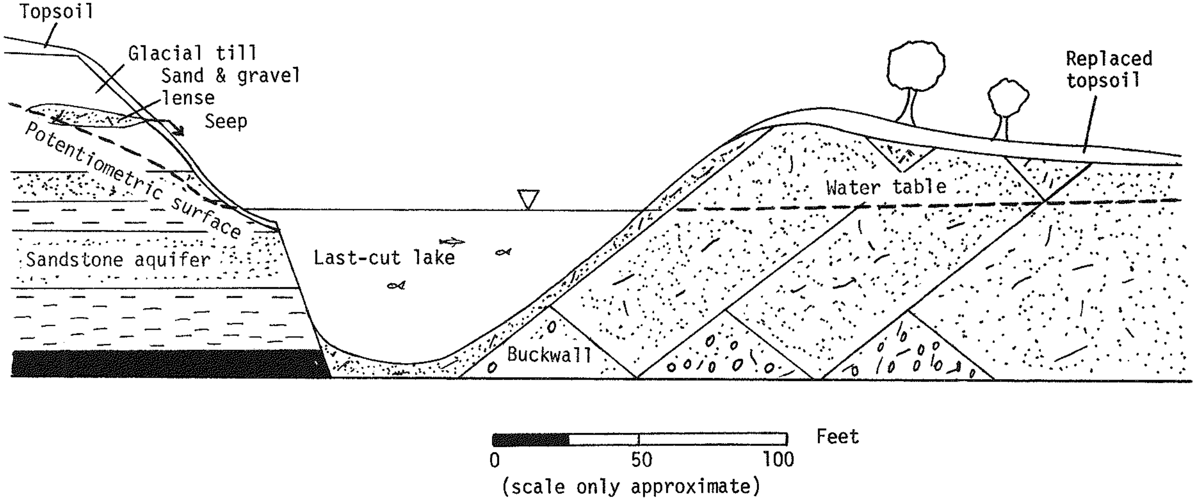

Figure 2. Cross section of reclaimed area-surface mine in the Midwest.

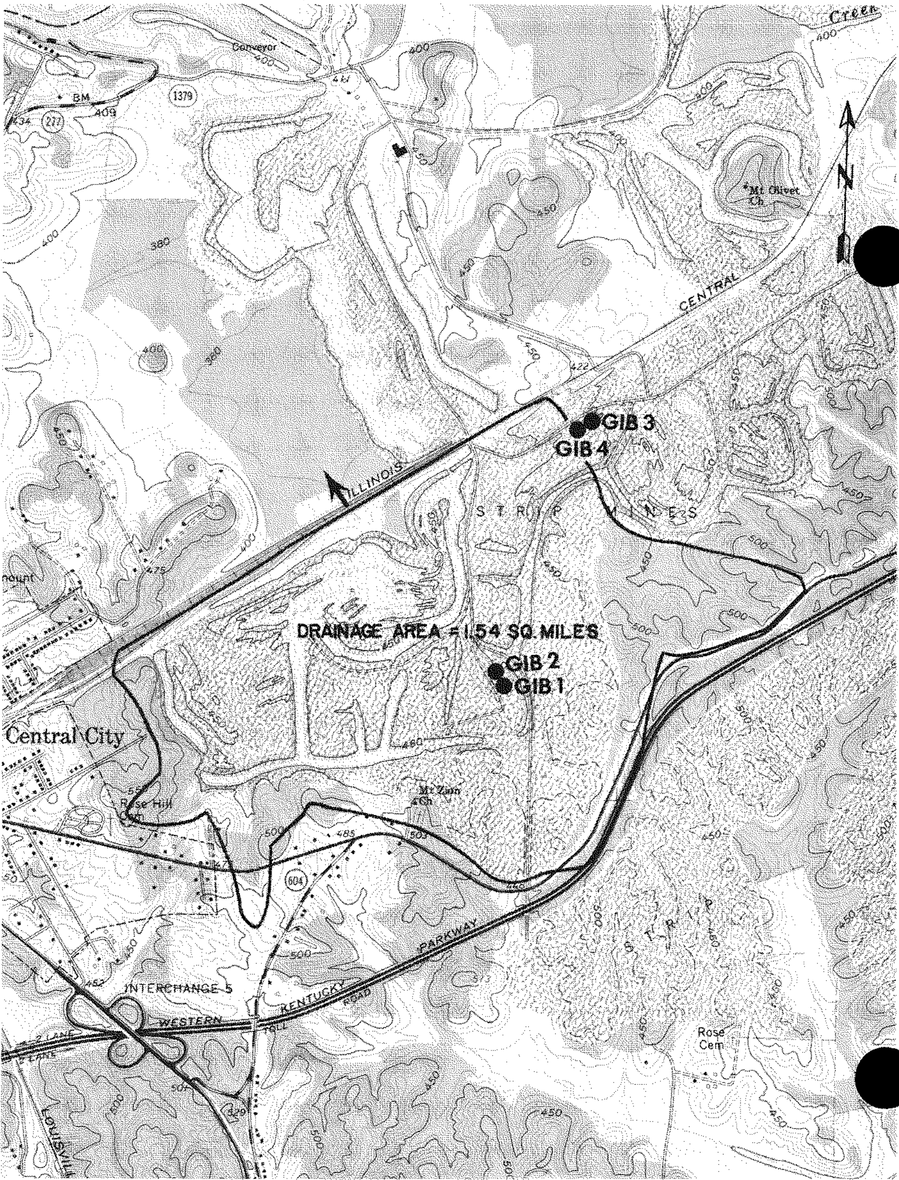

Figure 3. Map showing location of wells in cast overburden (Lisman Formation) near Central City, Kentucky.

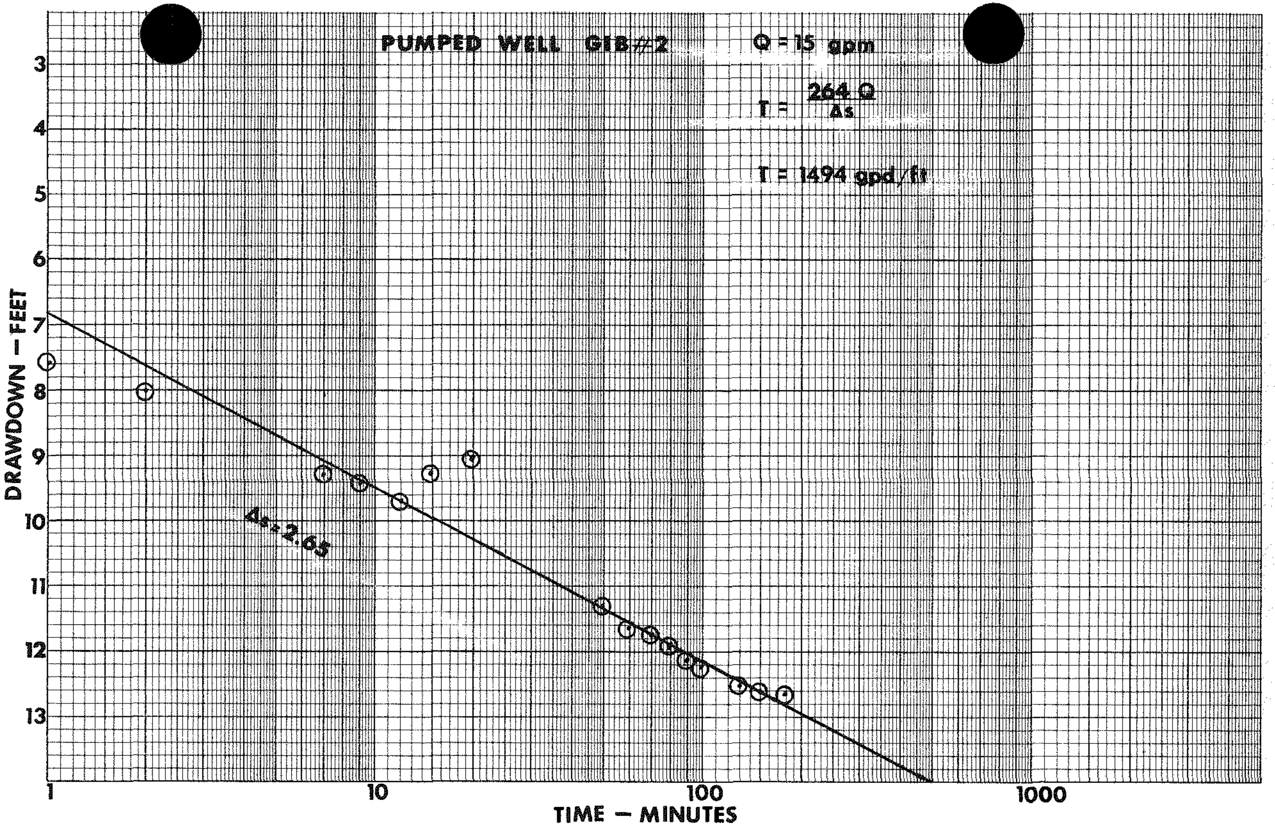

Figure 4. Drawdown curve for well in cast overburden (Lisman Formation).

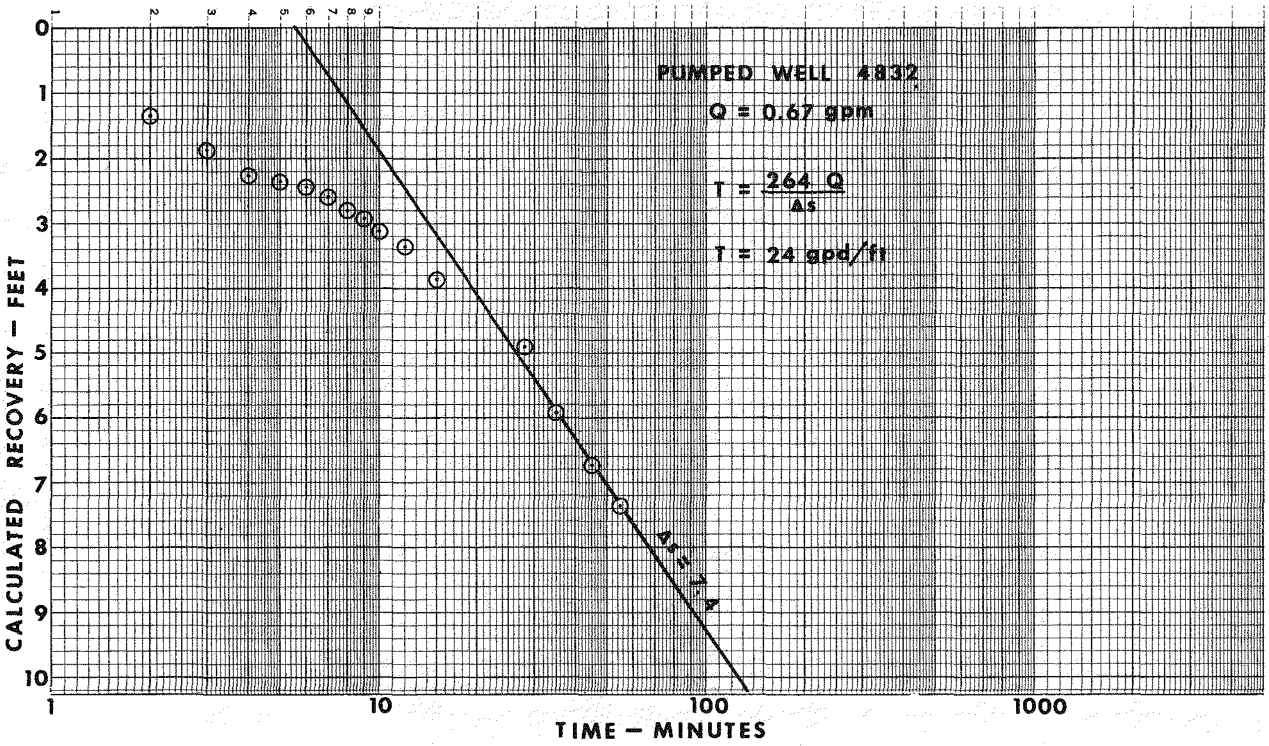

Figure 5. Recovery curve for well in Lisman formation.

formations down to the Providence Limestone between the Kentucky No. 11 and No. 12 coal seams. Analysis of the data gives an aquifer transmissivity of only 24 gpd/ft, less than two percent of that obtained from the cast overburden in well GIB#2. This difference may not be typical, but it does serve as an example of quite different aquifer properties.

## Topography

The topography of the region varies from level to very hilly. Generally speaking, groundwater recharge occurs in the higher areas and discharge occurs in the low areas. This is also shown by the fact that water levels or potentiometric surfaces for shallower aquifers usually present a subdued surface that tends to reflect the land surface, i.e., water level elevations are higher beneath hilltops t[illegible]n the valleys, although the depth to water may be substantially greater be[illegible] hilltops.

In the more hilly areas, such as much of the heavily dissected (by streams) Western Kentucky Coal Field, shallow aquifers are quite limited by the topography. Shallow, gently dipping bedrock aquifers are often limited to long, relatively narrow ridges. On either side of the ridges streams have completely eroded these aquifers. Before and after mining these areas may not have any significant aquifers since the unmined valleys serve to naturally depress water levels. This is illustrated in Figure 6.

The effects of area-surface mining on the topography are well known. In the past typical changes were the creation of numerous steep, parallel ridges of loosely compacted cast overburden and depressions in the form of inclines and final-cut pits. These depressions then filled with water after mining had ceased. Today, state and federal reclamation laws require extensive grading. As a result the cast overburden is more compacted and slopes on the reclaimed overburden are more gentle, but are also much longer. There has been a definite discouragement of closed depressions that allow water to accumulate and percolate into the cast overburden. Inclines are being filled and the areas reclaimed. Last-cut areas are often filled with cast overburden and material from the highwall side and graded so that no depression exists for water to accumulate. The net result of these mining and reclamation practices is to cause more surface water runoff from reclaimed areas following precipitation events than would have occurred under some old practices. This water then is not available for groundwater recharge or as impoundment water. This greater volume of storm-runoff water further serves to increase erosion over what could have occurred had more depressions (including those between ridges of cast overburden) been created by some of the old reclamation techniques. This is not to say the old ways are always best, but in some circumstances they are.

As Riley (1976) noted, there has emerged and prevailed a philosophy that only natural systems are correct and suitable and should remain inviolate. Or, if disturbed, the ecosystem must be returned to its original condition. The requirements of grading to approximate original contour is a reflection of this philosophy. The benefits of such grading are several, and will not be discussed here. However, it must be noted that a cost in the form of decreased water-management potential should be considered in any future reclamation schemes. In many areas, particularly in rolling to hilly areas with poor soils, the creation of a topography suitable for d[illegible]pment of lakes and land surfaces that will become highly productive for fish, w[illegible]owl, upland game, and other forms of wildlife should be given due consideration. Benefits of increased water resources available for industrial, municipal, domestic, and livestock supply as well as recreation and irrigation are too important to overlook.

## Recharge and Discharge

Recharge to shallow aquifers in the region is essentially derived from local precipitation which percolates downward through the soil and other overburden materials. This recharge varies considerably over the region and is dependent upon

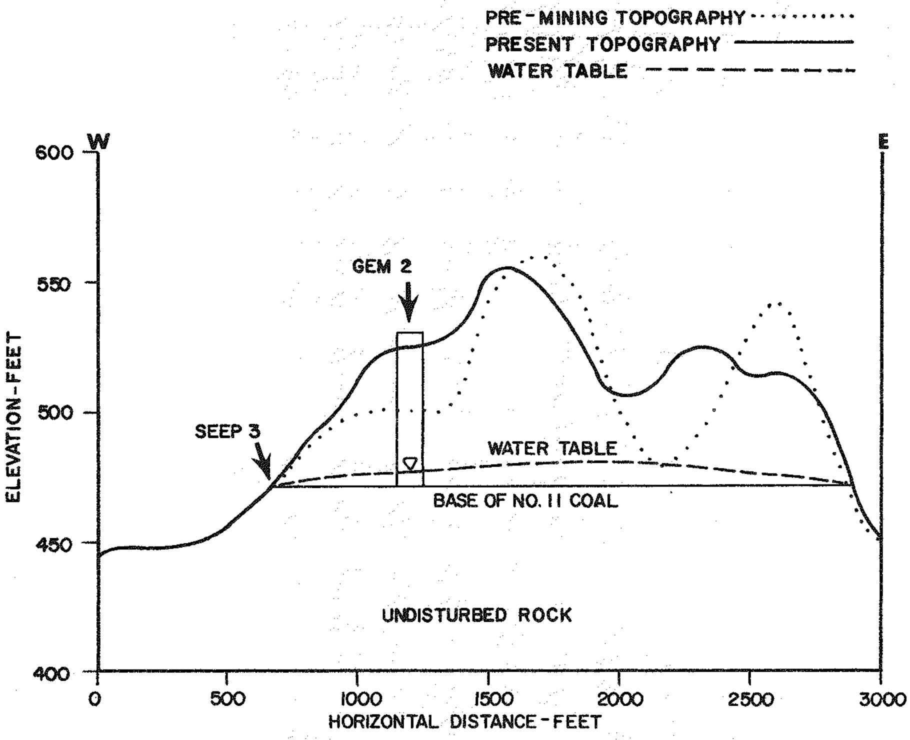

Figure 6. Cross section of a reclaimed surface mine in which a narrow ridge was mined through near Central City, Kentucky.

the general factors of climate, topography, soils, vegetation and geology. There are many more specific variables that could be described within each general factor; however, such a treatment is beyond the scope of this paper.

In areas where little consumptive use of groundwater takes place the amount of groundwater recharge can be fairly easily estimated for certain drainage basins by hydrograph separation techniques or base flow measurements of streams draining the area. For some of the streams draining areas where surface mining occurs in Illinois, Walton (1965) has shown groundwater runoff may vary from about .07 to .25 cubic feet per second per square mile (cfs/sq mi). This amount to 0.95 to 3.39 inches per year. Walton has shown that groundwater runoff (and therefore, recharge) is significantly greater in similar basins when the bedrock is permeable than in those basins where bedrock is relatively impermeable. He further states that "groundwater runoff increases appreciably as the amount of surface sand and gravel increases; in fact, surface sand and gravel deposits control groundwater runoff to a great extent". This conclusion then leads to the next logical conclusion regarding area-surface mining. Since the process of surface mining results in the transformation of consolidated, relatively impermeable bedrock into broken, unconsolidated, very permeable cast overburden it would be reasonable to conclude that considerably greater groundwater recharge and runoff will occur in those areas extensively mined.

Harza Engineering Company (1975) conducted a study of the effects of area surface mining in the Busseron Creek watershed in Indiana. Figure 7 is a set of flow duration curves for gauged streams West Fork Busseron Creek (1 percent mined), Buttermilk Creek (30 percent mined), and Mud Creek (48 percent mined). At the 40 percent flow duration (which gives a reasonable value for groundwater runoff) discharges are 0.2, 0.43, and 0.73 cfs/sq mi, respectively. Expressed in inches per year this is 2.71, 5.84, and 9.91 inches, respectively. Mining half of the watershed has apparently increased groundwater recharge and runoff by nearly 4 times.

## Water Quality

Groundwater obtained from shallow aquifers in the region is typically a calcium-magnesium-bicarbonate type. It is hard and commonly has an iron content exceeding the 0.3 mg/l recommended standard of the U.S. Public Health Service. Hardness commonly ranges from 150 to 400 mg/l in the glaciated areas and from 50 to 250 mg/l in the unglaciated, hilly areas. In localized areas sulfates may be quite high, but usually are less than 100 mg/l. Deeper aquifers often show a decrease in hardness, a condition generally attributable to progressive sodium depletion of ion-exchange minerals in the clays and shales of the Pennsylvania rocks. Deep aquifers may contain a sodium-bicarbonate or sodium-chloride type water.

As illustrated by the limited quality data in Table 1, surface mining will cause some changes in the quality of shallow groundwater. Most obvious in the example area near Central City, Kentucky is an increase in the dissolved solids of groundwater in the Lisman Formation. Total dissolved solids increased from about 325 mg/l before mining to about 2600 mg/l in the cast overburden aquifer composed of Lisman Formation rocks. The principal constituents in this increase are calcium, magnesium, sulfate, and bicarbonate. Small increases are noted in iron and manganese in some wells.

The example in Table 1 is only that — an example showing groundwater quality changes associated with area-surface mining at the location shown in Figure 3. It may or may not be typical of much of the mined areas in the region. The factors of climate, overburden geochemistry, topography, mining and reclamation practices, and time are extremely important in determining the resultant groundwater quality. While the climate is quite similar throughout the region, the other factors vary considerably from mine to mine and within relatively short distances. More site-specific studies are needed in order to better describe quality changes and to predict likely water quality before mining takes place. However, it can be stated as a general rule that the groundwater in cast overburden will have higher dissolved

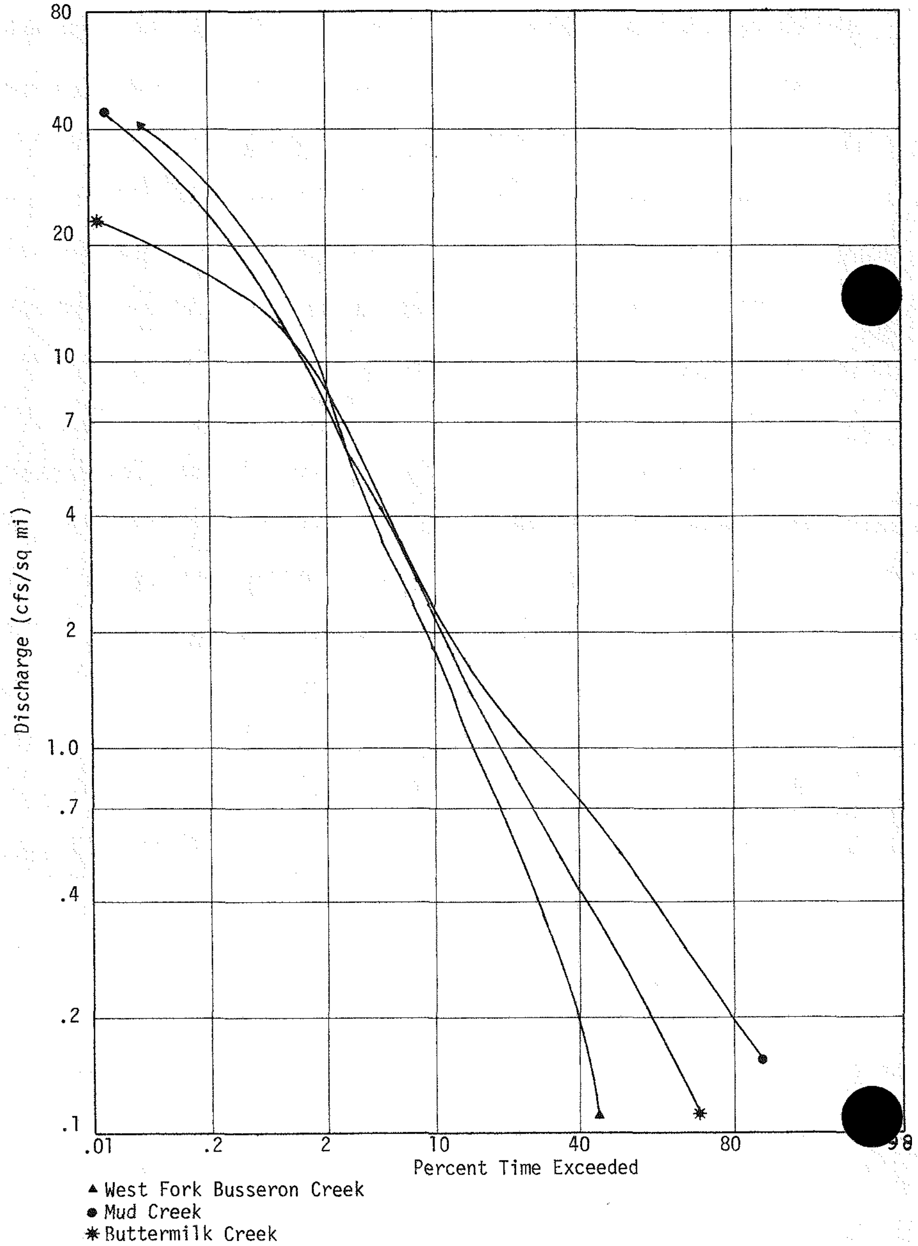

Figure 7. Flow duration curves for streams in West Fork Busseron Creek Watershed, Indiana.

Table 1. Water quality data for selected wells near Central City, Kentucky.

|  | Unmined Area |  |  | Mined Area |  |  |  |
|---|---|---|---|---|---|---|---|
| Well | 4913(A) | Williams | Kessinger | Gib#1 | Gib#2 | Gib#3 | Gib#4 |
| Aquifer | Recent Alluvium | Carbondale Fm. | Lisman Fm. | Cast Overburden (Lisman Fm.) |  |  |  |
| ph (units) | 8.28 | 7.39 | 7.30 | 6.90 | 6.70 | 7.08 | 7.79 |
| Alkalinity (as $CaCO_3$) | 261.60 | 69.60 | 20.60 | 507.60 | 515.00 | 177.00 | 186.00 |
| Acidity-T (as $CaCO_3$) | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Iron-Total | 5.16 | 2.26 | 0.19 | 1.00 | 1.62 | 0.27 | 0.83 |
| Manganese | 1.14 | 0.14 | 0.05 | 3.11 | 3.26 | 0.2 | 0.1 |
| Dissolved Solids | 632.70 | 326.00 | 323.50 | 3609.40 | 2639.40 | 1952.00 | 2369.60 |
| Conductivity (μmhos/cm) | 605.00 | 210.00 | 330.00 | 2400.00 | 2800.00 | 2900.00 | 1550.00 |
| Sulfates | 90.00 | 86.00 | 99.00 | 720.00 | 992.5 | 862.50 | 430.00 |
| Hardness | 326.00 | 62.00 | 132.00 | 1498.00 | 692.00 | 421.00 | 804.00 |
| Chloride | 40.70 | 88.60 | 50.80 | 34.00 | 20.20 | 9.60 | 8.00 |
| Calcium | -- | 38.08 | 49.84 | 348.70 | 104.40 | 61.50 | 93.50 |
| Magnesium | -- | 7.77 | 82.16 | 165.00 | 191.40 | 168.70 | 129.30 |
| Sodium | 71.10 | 5.60 | 29.70 | 76.00 | -- | -- | 34.70 |

All values mg/l except where specified.

solids and that much of the increase consists of sulfates. This is not to say that the water will become unfit for use, but that it will differ from water in unmined areas.

## Water Use

Before an area is surface-mined groundwater use is generally limited to domestic supplies obtained from individual private wells in predominately rural settings. A few separate livestock wells exist. In a few instances a public supply well may occur within or near the proposed mining area. In most of those cases the well is considerably deeper than the lowest coal seam to be mined. Well yields are limited and therefore the use and potential use is also. It could be noted that exceptions occur in such areas at the main valleys of the Wabash River, White River, Ohio River, Mississippi River, and some of the major tributarie[illegible] However, because the coal seams have been eroded, are too deep, or are cover[illegible] soft overburden which causes severe water and/or slope-stability problems, these areas will not likely be mined. So, the prolific sand and gravel aquifers in these glacial outwash and alluvial valleys will be little disturbed.

To the author's knowledge there have not been any water supply wells installed which tap the cast overburden aquifer. However, this is not to say that groundwater in the cast overburden is not used. Groundwater is continually discharging into pit lakes or streams draining the mined areas. As such it becomes surface water which is put to many valuable uses. These uses include industrial, municipal, livestock, fish and wildlife, and recreational.

Many active mines use water from pit lakes in coal preparation plants. These plants may continually pump several thousand gallons per minute and require a few hundred gallons per minute make up water. Many of the larger mines also use water from pit lakes for watering haul roads in order to control dust. This often amounts to a few hundred gallons per minute, or several hundred thousand gallons each day. Since many of these lakes are sustained by groundwater from cast overburden, it could be reasoned that groundwater usage is quite significant.

Some municipal supplies use pit lakes, even though some drainage also may come from unmined areas. An example is the town of Lynnville, Indiana. Other examples may also exist. This is an area needing better documentation. Certainly many municipal and industrial supplies farther downstream use groundwater draining from cast overburden, even though it is usually mixed with considerable water from unmined areas.

Thousands of head of livestock (principally cattle) make use of water in pit lakes and streams draining cast overburden in many reclaimed areas. Many of these lakes and streams constitute prime habitat for game fish and waterfowl. Hundreds of species of upland game animals and other wildlife use these waters. Many lakes are heavily fished by sportsmen who often drive long distances just to fish in these pits. Local citizens find many of these lakes quite suitable for swimming.

While some of the above uses may be difficult to quantify, they are nevertheless very important. There is a definite need to assign monetary value to these benefits, to consider them in evaluating future environmental impacts. Ther[illegible] exists the potential for much more usage of water resulting from mining oper[illegible]s. There has been adequate criticism of the detrimental effects of mining. It is time to give proper consideration to existing and potential uses of water associated with mining.

## Summary

The climate plays a major role in post-mining reclamation, and in the reestablishment of surface water and groundwater.

Overburden characteristics may vary considerably from one area to another, and must be studied carefully before mining. In most cases the overburden has a neutralization potential exceeding the acid-producing potential. The overburden is changed from a sedimentary layered sequence of distinct rock types in a generally well-consolidated state to a heterogeneous mixture of pieces of rock of quite variable size. The overall volume of the cast overburden is about 20 per cent greater than that of unmined overburden, and the cast overburden is now being capped with top soil.

In most of the Illinois Basin area the principal aquifers likely to be mined are sandstone formations having relatively low transmissivities. Studies to date indicate cast overburden aquifers have greater transmissivities, greater recharge and greater discharge than do aquifers in the unmined overburden.

Generally speaking, groundwater recharge occurs in topographic highs and discharge occurs in topographic lows. In the past the surface-mined area has been left with numerous steep, parallel ridges of loosely compacted overburden and depressions in the form of inclines and final-cut pits that filled with water after mining. Today federal law requires that the cast overburden is more compacted, slopes on the overburden are more gentle and longer, and that there are no closed depressions left that would allow water to accumulate and percolate into the cast overburden.

The net result of these mining and reclamation practices is to cause more surface-water runoff and erosion from reclaimed areas following precipitation. In many areas, particularly in rolling to hilly terrain with poor soils, the creation of a topography suitable for development of lakes and land surface that will become highly productive for fish, waterfowl, upland game and other forms of wildlife should be given greater consideration.

Recharge to shallow aquifers in the region is essentially derived from local precipitation which percolates downward through the soil and other overburden materials. The process of surface mining results in the transformation of consolidated, relatively impermeable bedrock into broken, unconsolidated, very permeable cast overburden. Greater groundwater recharge and runoff will occur in those areas extensively mined.

It can be stated as a general rule that the groundwater in cast overburden will have higher dissolved solids and that much of the increase will consist of sulfates. This is not to say that the water will become unfit for use, but that it will differ from water in unmined areas.

Before an area is surface mined, groundwater use is generally limited to domestic supplies obtained from individual private wells in predominately rural areas. During and after mining groundwater is continually discharging into pit lakes or streams draining the mined area. As such it becomes surface water which is put to many valuable uses, including industrial, municipal, livestock, fish, wildlife and recreational. There exists the potential for much greater usage of water resulting from mining operations.

## Selected References

Agnew, A. F., 1966, A quarter to zero -- surface mining and water supplies: Mining Congress Journal, v. 52, no. 10, p. 29, 32-34, 38-40.

Agnew, A. F. and Corbett, D. M., 1969, Hydrology and chemistry of coal - mine drainage in Indiana: American Chemical Society, Division of Fuel Chemistry, v. 13, no. 2, presented at Minneapolis, Minnesota, April 13-18, 1969.

Agnew, A. F., and Corbett, D. M., 1969, Hydrology of a watershed containing S.C.S. reservoirs and coal surface-mining activity, southwestern Indiana: presented before Disturbed Sites Symposium, International Institute of Ecology and Revegetation, August, 1969, Pennsylvania State University, University Par Pennsylvania.

Burner, C. C., 1973, Fishery management in strip mine lakes: Research and Applied Technology Symposium on Mined-land Reclamation, National Coal Association, Pittsburg, Pennsylvania, p. 304-318.

Cable, L. W., Watkins, F.A., Jr., and Robinson, T. M., 1971, Hydrogeology of the principal aquifers in Vigo and Clay Counties, Indiana: State of Indiana, Department of Natural Resources, Division of Water Bulletin No. 34, 34 p.

Corbett, D. M., 1965, Water supplied by coal surface mines, Pike County, Indiana: Indiana University Water Resources Research Center, Report of Investigations No. 1, 67 p.

Corbett, D. M., 1966, Surface mining for coal -- effect on storm runoff: Indiana University Water Resources Research Center, First Interim Report, 19 p.

Corbett, D. M., 1968, Ground-water hydrology pertaining to surface mining for coal -- Southwestern Indiana, reprints of papers presented before Second Symposium on Coal Mine-Drainage Research: Mellon Institute, May 14-15, 1968, Pittsburgh, Pennsylvania.

Corbett, D. M., and Agnew, A. F., 1968, Coal mining effect on Busseron Creek Watershed, Sullivan County, Indiana. Indiana University Water Resources Research Center, Report of Investigations No. 2, 185 p.

Devaul, R. W., and Maxwell, B. W., 1962, Availability of ground water in McLean an Muhlenberg Counties, Kentucky: U.S. Geological Survey Hydrologic Investigations Atlas HA-29.

Environmental Protection Agency, 1973, Water quality criteria 1972 - a report of the Committee on Water Quality Criteria, Environmental Studies Board, National Academy of Sciences, 594 p.

Federal Water Pollution Control Administration, 1968, Water quality criteria - report of the National Technical Advisory Committee to the Secretary of the Interior, 234 p.

Ferris, J. G., Knowles, D. B., Brown, R. H., and Stallman, R. W., 1962, Theo of aquifer tests: U.S. Geological Survey Water-Supply Paper 1536-E, 174 p.

Grubb, H. F., and Ryder, P. D., 1972, Effects of coal mining on the water resources of the Tradewater River Basin, Kentucky: U.S. Geological Survey Water-Supply Paper 1940, 83 p.

Harza Engineering Company, 1975, Hydrologic effects of strip mining - Busseron watershed, Indiana: Soil Conservation Service, USDA, AG 18-00160, 21 p.

Hem, J. D., 1970, Study and interpretation of the chemical characteristics of natural water: U.S. Geological Survey Water-Supply Paper 1473, 363 p.

Indiana State Board of Health, 1968, Data on Indiana public water supplies, revised 1968. Bulletin S.E. 10, 83 p.

Maxwell, B. W., and Devaul, R. W., 1962, Hydrologic investigation of Butler and Ohio Counties, Kentucky: U.S. Geological Survey Hydrologic Investigations Atlas HA-26.

Minear, R. A., and Tschantz, B. A., 1975, Impact of coal surface mining on water quality of mountain drainage basin streams: Water Pollution Control Federation, 48th Annual Conference.

Mull, D. S., Cushman, R. V., and Lambert, T. Wm., 1971, Public and industrial water supplies of Kentucky, 1968-1969: Kentucky Geological Survey, Information Circular 20, 107 p.

National Academy of Sciences, 1974, Nutrients and toxic substances in water for livestock and poultry, 93 p.

Plass, W. T., 1976, Changes in water chemistry resulting from surface-mining of coal on four West Virginia watersheds: West Virginia Surface Mining and Reclamation Association. Green Lands, Winter, 1976, p. 22-27.

Riley, C. V., 1976, Surface mined land reclamation research and legislation - a paradox: Fourth Symposium on Surface Mining and Reclamation, National Coal Association, Louisville, Kentucky, p. 106-115.

South Dakota School of Mines and Technology, 1976, Potential of coal strip-mine spoils as aquifers in the Powder River Basin: The Old West Regional Commission, 107 p.

Truax, C. N., Jr., 1965, Water storage potential of surface mined coal lands: Mining Congress Journal, November, 1965, p. 40, 41, 45, 46.

U. S. Geological Survey, 1977, Water resources data for Kentucky - water year 1976: U.S. Geological Survey Water-Data Report KY-76-1, 477 p.

Van Voast, W. A., Hedges, R. B., and McDermott, J. J., 1976, Hydrologic aspects of strip mining in the subbituminous coal fields of Montana: Fourth Symposium on Surface Mining and Reclamation, National Coal Association, Louisville, Kentucky, p. 160-172.

Van Voast, W. A., 1974, Hydrologic effects of strip coal mining in southeastern Montana -- emphasis: one year of mining near Decker: Montana Bureau Mines and Geology Bulletin 93, 24 p.

Van Voast, W. A., and Hedges, R. B., 1975, Hydrogeologic aspects of existing and proposed strip coal mines near Decker, southeastern Montana: Montana Bureau Mines and Geology Bulletin 97, 31 p.

Walton, W. C. 1962, Selected analytical methods for well and aquifer evaluation: Illinois Water Survey Bulletin 49, 81 p.

Walton, W. C., 1965, Ground-water recharge and runoff in Illinois: Illinois Water Survey Report of Investigation 48, 55 p.

Woodruff, J. G., 1930, Map of the areal and structural geology of Muhlenberg County, Kentucky: Kentucky Geological Survey ser. 6.

# INVESTIGATION OF ION EXCHANGE TREATMENT OF ACID MINE DRAINAGE

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## INTRODUCTION

Coal is returning to prominence as the nation's primary energy resource. [illegible]pansion of mining operations and increases in production are stressed almost daily by energy officials in response to the current energy crisis. As mining operations expand, the quantities of pyritic materials in the strata surrounding the coal seams that are exposed to natural oxidation forces are similarly increased; this increased exposure creates additional concern over the problem of acid mine drainage production.

The Environmental Protection Agency (EPA), in cooperation with industry and the scientific community, began several years ago to investigate acid mine drainage treatment processes that were capable of producing potable effluents. Reverse osmosis and ion exchange were foremost among these more-sophisticated processes.

This paper will briefly discuss several ion exchange treatment schemes conceived for the production of a potable water from acid mine drainage and will present specific data from research on one of these processes recently studied by EPA at the Crown Mine Drainage Control Field Site near Morgantown, West Virginia.

## WHAT IS ION EXCHANGE?

Ion exchange is defined as a "reversible exchange of ions between a solid and a liquid in which there is no substantial change in the structure of the solid. In this definition, the solid is the ion-exchange material (resin)."(1)

## CURRENT APPLICATIONS OF ION EXCHANGE TO ACID MINE DRAINAGE SUL-BISUL PROCESS(2,3)

The Commonwealth of Pennsylvania has notably been the pioneer in the development and implementation of acid mine drainage treatment technology. Pennsylvania has constructed two full-scale ion exchange plants on acid mine drainage (AMD). A third plant is in the planning stage. The first of these plants was built in 1969 for the Smith Township community and was designed for the production of 500,000 gpd of potable water. The plant went on-line in 1971. Although the water problem [illegible] the Smith Township was degraded by mining, the water to be treated turned out to be more brackish than acidic. The major problems were high sulfate and manganese levels.

The Sul-biSul process was chosen for this application. A continuous countercurrent regeneration system (the Higgins System) was utilized to provide a continuous supply of water to the Township. The Higgins System is a doughnut-shaped column in which the resin is hydraulically moved from one section to another for backwash, regeneration, rinsing, and service. Some quantity of resin is always in service to provide a constant supply of product.

In the Sul-biSul process, the sulfate form of a strong-base anion exchanger is used. The acidic condition of AMD converts the sulfate on the resin to the monovalent bisulfate ion, which frees one resin exchange site that may then be occupied by another anion (sulfate or bisulfate):

$$Ra^{\cdot}SO_4 + H_2SO_4 \rightleftarrows R^{\cdot}(HSO_4)_2$$

Regeneration of this resin requires a shift of equilibrium to convert the bisulfate back to the sulfate form. This is accomplished by an alkaline rinse [illegible]ng:

$$R^{\cdot}(HSO_4)_2 \rightarrow R^{\cdot}SO_4 + H_2SO_4$$

At Smith Township, a strong-acid cation exchanger is coupled to the Sul-biSul anion exchanger (Figure 1). Sulfuric acid is used to regenerate the cation column. The effluent from the cation process (primarily sulfuric acid) is treated by the Sul-biSul anion column to remove free mineral acidity. Lime-neutralized water is used to regenerate the anion column. The end product is chlorinated and meets potable standards.

The plant, however, did not meet design capacity specifications and is currently not operating because of pending litigation.

## MODIFIED DESAL PROCESS(2,3,4)

The Hawk Run facility was the second ion exchange plant to be constructed in Pennsylvania for drinking water use. A moderately severe acid mine drainage stream is treated at the Hawk Run plant. This plant was designed at 500,000 gpd and utilizes the modified Desal process.

The modified Desal process incorporates a weak-base anion exchange resin that operates in the bicarbonate form. To achieve the bicarbonate form, the weak-base resin is first regenerated with ammonium hydroxide to the free-base ($OH^-$) form; then, in a second step, the resin is charged with a carbon dioxide solution to convert the resin to the bicarbonate ($HCO_3^-$) form. This bicarbonate form of the resin is capable of converting metal sulfates to their respective carbonate salts. For example, ferrous sulfate ($FeSO_4$) in the AMD reacts with the anion resin (Ra) as follows:

$$2\ Ra^{\cdot}HCO_3 + FeSO_4 \rightarrow (Ra)_2{}^{\cdot}SO_4 + Fe(HCO_3)_2$$

The sorbed sulfate ion occupies two exchange sites on the resin. Acidity in the [illegible]s removed as follows:

$$2\ Ra^{\cdot}HCO_3 + H_2SO_4 \rightarrow Ra_2{}^{\cdot}SO_4 + 2H_2CO_3$$

The soluble constituents in the effluent from this stage of treatment will be the bicarbonate salts of calcium, magnesium, ferrous iron, manganese, and sodium. With the removal of acidity and increase in pH, aluminum and ferric iron will precipitate. Subsequent aeration and lime treatment are required for the removal of the remaining cations (except for sodium) as follows:

$$2\ Fe(HCO_3)_2 + \tfrac{1}{2}O_2 + H_2O \rightarrow \underline{2Fe(OH)_3} + 4CO_2$$

$$Ca(HCO_3)_2 + Ca(OH)_2 \rightarrow \underline{2CaCO_3} + 2H_2O$$
$$Mg(HCO_3)_2 + 2Ca(OH)_2 \rightarrow \underline{2CaCO_3} + \underline{Mg(OH)_2} + 2H_2O$$
$$Mn(HCO_3)_2 + \tfrac{1}{2}O_2 + 2Ca(OH)_2 \rightarrow \underline{2CaCO_3} + \underline{MnO_2} + 3H_2O$$

To accomplish the removal of these metals, it is necessary to increase the pH to approximately 10. It is therefore necessary to post-treat with an acid to reduce the pH to acceptable potable levels and to apply chlorination for bacteria control.

Several optimizing modifications have been made on the Hawk Run plant to increase its efficiency. Such modifications as pre-carbonating the AMD have contributed to a significant increase in capacity (from 500,000 to 800,000 gpd) [illegible] schematic of the process is shown in Figure 2. The waste regenerant is composed of an ammonium sulfate solution. This is lime treated to form calcium sulfate, which is removed by filtration. The filter effluent is sent to a distillation process where 92 to 95 percent of the ammonia is recovered for reuse as the first-stage regenerant.

The Hawk Run facility was originally constructed to augment a degrading water supply; lately, however, water quality has improved to the point that the plant is not currently needed. The facility has been placed in the standby mode for future use as required. While it was operating, it performed extremely well.

## STRONG ACID - WEAK BASE TWO-RESIN PROCESS

In 1972, the U.S. Environmental Protection Agency contracted with Culligan International Company(3) to conduct bench-scale feasibility studies on various schemes of ion exchange treatment of acid mine drainage. Two processes were chosen from the studies as having the greatest potential for use in AMD treatment; i.e., the two-resin process and the Modified DeSal process. Since Pennsylvania was already investigating the Modified DeSal process, EPA chose to conduct pilot-plant studies on the two-resin process and performed these studies in-house at the EPA Crown Field Site.

### Ion Exchange Process at Crown

The ion exchange process investigated at Crown involves the use of a 2-resin system; the first resin being an $H^+$-form, strong-acid cation exchanger and the second resin being a weak-base anion exchanger in the free-base ($OH^-$) form.

In the cation column, $H^+$ ions are exchanged for the metal ions (iron, aluminum, magnesium, calcium, manganese, sodium, etc.) in the AMD. Since the only anion in Crown AMD is sulfate, the cation effluent becomes predominately $H_2SO_4$ with r[illegible]l concentrations of metals.

The basic reversible reaction involved in the strong-acid cation process is illustrated in the following example using manganese; $R_c$ represents the cation resin and sulfuric acid is the regenerant:

$$MnSO_4 + 2H^+R_c \underset{\leftarrow\text{Regeneration}}{\overset{\text{Exhaustion}\rightarrow}{\rightleftarrows}} Mn\cdot 2R_c + H_2SO_4$$

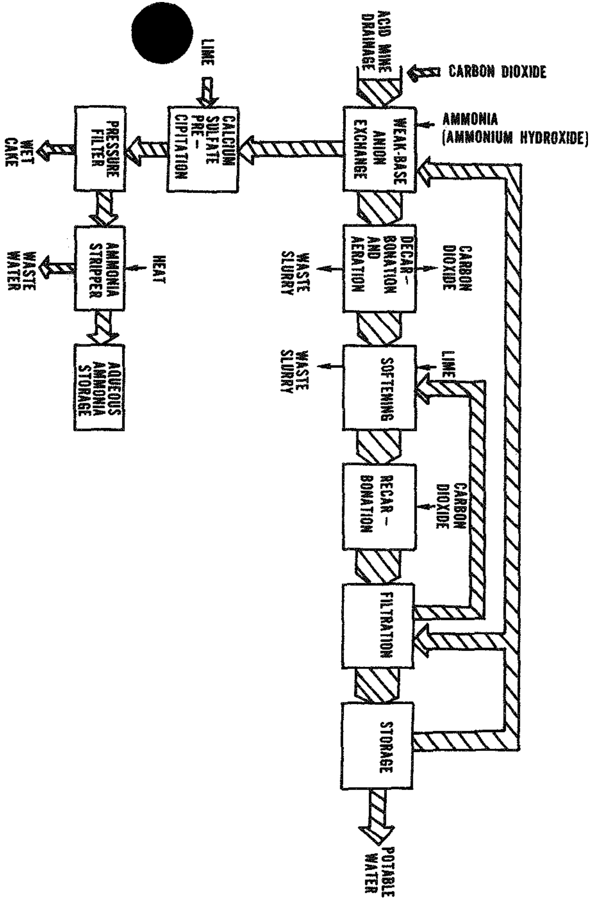

FIGURE 2. ACID MINE DRAINAGE TREATMENT PLANT
PHILIPSBURG, PENNSYLVANIA
USING THE MODIFIED DESAL PROCESS

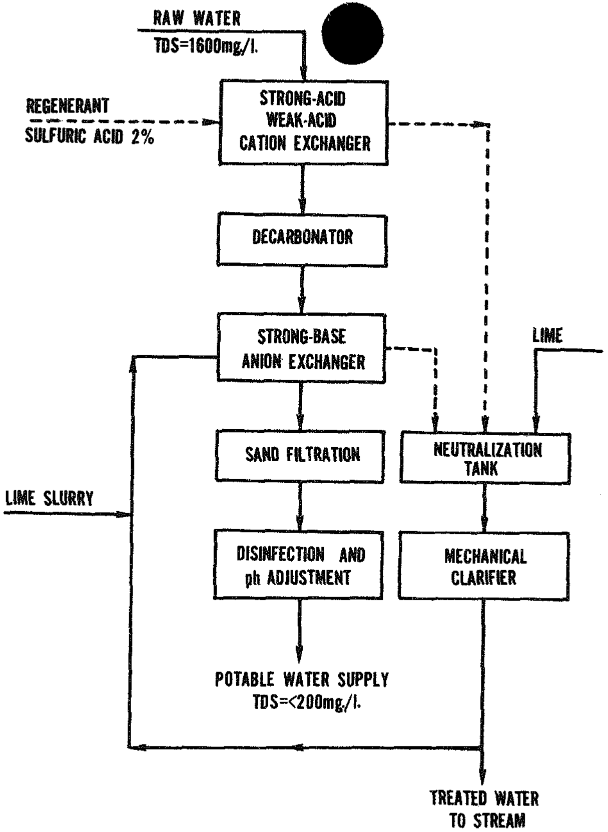

FIGURE 1. SUL-BISUL CONTINUOUS ION EXCHANGE FLOWSHEET FOR THE POTABLE WATER TREATMENT SYSTEM AT SMITH TOWNSHIP, PENNSYLVANIA

The concentration of residual metals is largely governed by the amount (dosage) of regenerant used initially to charge the cation resin with hydrogen ions. Thus, by regulating regenerant dosage, it is possible to establish the degree of residual metal concentration remaining in the cation effluent. Removal of residual metals and regenerant dosage are not linearly related, however, and the utilization efficiency of the regenerant drops drastically as the dosage is increased and process costs skyrocket accordingly. The choice of cation regenerant dosage then becomes largely an economic one and the intent is to operate the column at the largest residual metal level consistent with the objectives of product end-use and thereby minimize both regenerant requirements and cost.

The effluent from the cation column (predominately sulfuric acid) then enters the weak-base anion exchanger where the acid is totally absorbed by the resin. A weak-base anion exchanger can only absorb acid; it cannot split neutral salts. Some carryover therefore exists of metal salts that were not removed by the cation exchanger and pass unaffected through the anion column. Because of the alkaline nature of the anion exchanger, some precipitation of iron and aluminum residuals can be expected. The effect of this accumulation on anion resin efficiency and capacity must be investigated during this study. The basic weak-base anion exchange reactions are illustrated using sodium hydroxide as the regenerant; $R_a$ designates the anion resin, and $H_2SO_4$ is the cation effluent:

Exhaustion: $R_a + H_2SO_4 \rightarrow R_a{\cdot}H_2SO_4$

Regeneration: $R_a{\cdot}H_2SO_4 + 2NaOH \rightarrow R_a + Na_2SO_4 + 2H_2O$

Iron precipitation:(1) $Fe_2(SO_4)_3 + 3R_a + 6H_2O \rightarrow 2Fe(OH)_3\downarrow + 3R_a{\cdot}H_2SO_4$

As the anion effluent contains residual levels of ferrous iron and manganese, it must be further treated to meet potability requirements. This is accomplished by lime neutralization to pH 9 or 10, followed by filtration, and then followed by pH readjustment back to neutral levels. A small portion of the cation effluent is added to the filtered effluent to reduce the pH to acceptable values.

Either hydrochloric acid or sulfuric acid may be used for regenerating the cation column. Sulfuric is generally preferred because it is considerably cheaper. A potential problem of gypsum (calcium sulfate) precipitation is present with the use of sulfuric acid as the regenerant; no precipitation problems are anticipated with hydrochloric acid. The waste stream during regeneration with sulfuric acid will consist of excess sulfuric acid plus iron, aluminum, sodium, manganese, calcium, and magnesium sulfates.

The anion exchanger is regenerated with sodium hydroxide (caustic). The anion regenerant waste stream consists mainly of sodium sulfate.

<u>The Basic Ion Exchange Unit</u>--

The operating specifications for the basic ion exchange unit designed for Crown are given in Table 1. The system included individually adjustable timers and adjustable flow controls for each operating cycle. Both the cation and anion

Table 1. GENERAL SPECIFICATIONS FOR EPA ION EXCHANGE TREATMENT UNIT (TWO-RESIN SYSTEM)

| | Cation exchanger | Anion exchanger |
|---|---|---|
| T[illegible] | Strong acid | Weak base |
| Resin | Duolite C-20 | Dowex WGR |
| Volume of resin, cu m | 0.93 | 0.54 |
| Approximate tank size, cm | 91 x 213 | 76 x 213 |
| Approximate tank area, sq m | 0.65 | 0.45 |
| Service flow rate, liters/min | 40 | 40 |
| Service flow rate, liters/min/cu m | 43 | 74 |
| Service flow direction | Downflow | Downflow |
| Backwash flow rate, liters/min | 115 | 100 |
| Backwash flow rate, liters/min/sq m | 180 | 190 |
| Backwash flow direction | Upflow | Upflow |
| Bed expansion during backwash, percent | 50 | 75 |
| Regenerant flow rate, liters/min | 100 | 40 |
| Regenerant flow rate, liters/min/sq m | 150 | 90 |
| Regenerant flow rate, liters/min/cu m | 110 | 74 |
| Regenerant flow direction | Downflow | Downflow |
| First rinse flow rate, liters/min | 100 | 40 |
| First rinse flow rate, liters/min/cu m | 110 | 90 |
| First rinse flow direction | Downflow | Downflow |
| Second rinse flow rate, liters/min | 115 | 100 |
| Second rinse flow rate, liters/min/cu m | 120 | 190 |
| Second rinse flow direction | Downflow | Downflow |
| Regenerant | Sulfuric acid | Sodium hydroxide |
| Regenerant concentration, percent by weight | 2 | 3 to 5 |

column operated in the downflow mode (Figure 3). The regeneration sequence could be initiated either manually or automatically (by sensing changes in conductivity).

## STUDY RESULTS

The AMD quality (Table 2) at Crown was significantly worse than that of Hawk Run. The high sodium levels at Crown proved to be important in this investigation. These studies on the process basically characterized system performance under different conditions of cation regenerant dosage. Typical pollutant concentration trends during each cycle of the treatment process are shown in Figures 4 and 5 for the cation and anion columns respectively.

Typical operational data from the treatment process for three sets of cati[illegible] dosage conditions (48, 96, and 144 grams of 100-percent sulfuric acid per liter of resin) are given in Tables 3, 4, and 5.

The regeneration system on the ion exchange unit was interlocked so that both the cation and anion columns were sequentially regenerated. This was necessary to insure that both units did not attempt simultaneous regeneration because the cation unit needed to be on-stream to provide water for the anion regeneration process. This interlocking, however, worked to a disadvantage in evaluating and optimizing anion column performance. Since the anion column was totally dependent upon the cation column, it was essential that the cation exhaust first and thus initiate regeneration. The anion column was, therefore, necessarily overdosed to assure a greater capacity than the cation column. Because of this, it must be emphasized that the anion capacities and efficiencies in Tables 3, 4, and 5 were not optimized and the apparent changes largely reflect the differences in cation capacities.

Chemical data from the studies are given in Table 6. As the cation dosage increased, the concentrations of each of the pollutants in the cation effluent tended to decrease. Very little removal of sodium was achieved, however. Passage through the anion column effectively removed all acidity and imparted alkalinity. Precipitation of iron within the anion column was particularly apparent from the data. An increase in sodium imparted by the anion column was also noted.

## LONG-TERM SYSTEM OPERATION

From run 515 thru 773, the system was operated at minimal cation dosage (48 gram/liter), 32-gram/liter anion dosage, and 60-liter/min service flow rate. The intent of the 258 regenerations was to expose the anion column to maximal influent iron concentrations to observe long-term performance trends.

The results of the study are presented graphically in Figure 6 and in Tab[illegible] and 7.

No apparent reduction in anion column performance was noted over the duration of the tests (Table 7 compared with Table 5). This result was somewhat unexpected because of the observed iron precipitation in the column. It was felt that the use of low pH cation effluent for backwashing and rinsing the anion column tended to continually remove the iron hydroxide that had precipitated during the previous service cycle.

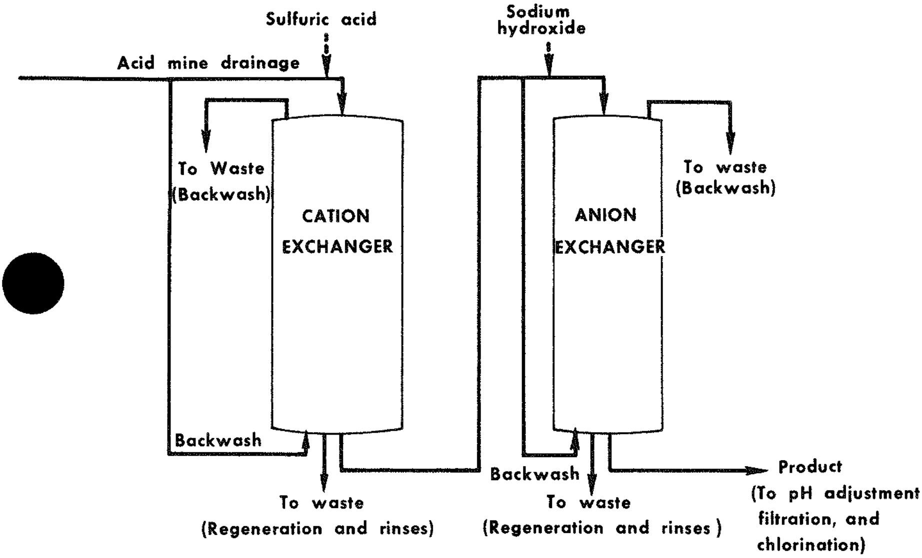

Figure 3. Schematic flow diagram of EPA 2-resin ion exchange unit.

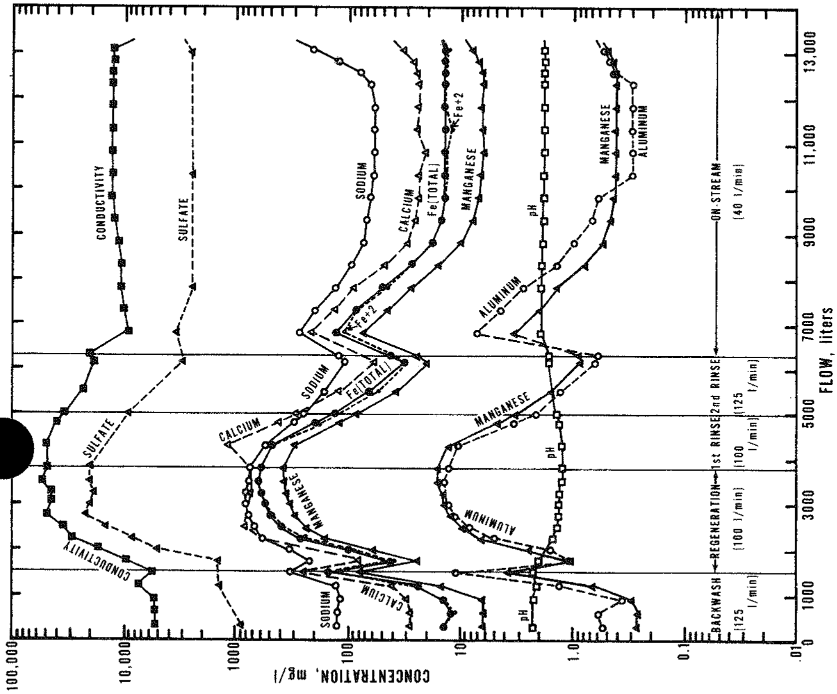

Figure 4. Trends of pollutant concentration throughout a typical cation service cycle at 48 grams/liter (3 lb/cu ft) sulfuric acid regenerant dosage.

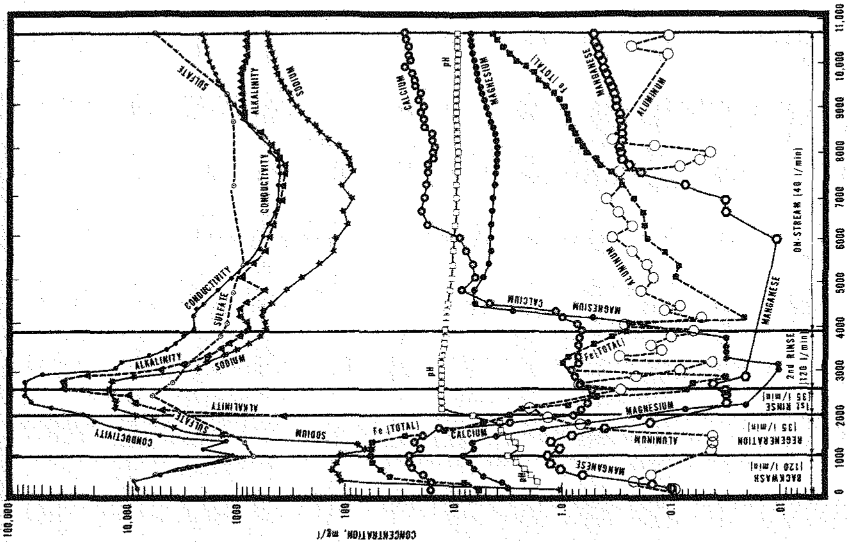

Figure 5. Trends of pollutant concentration throug[illegible] anion service cycle at 63 grams/liter (4 lb/cu ft) sodium hydroxide regeneran[illegible]

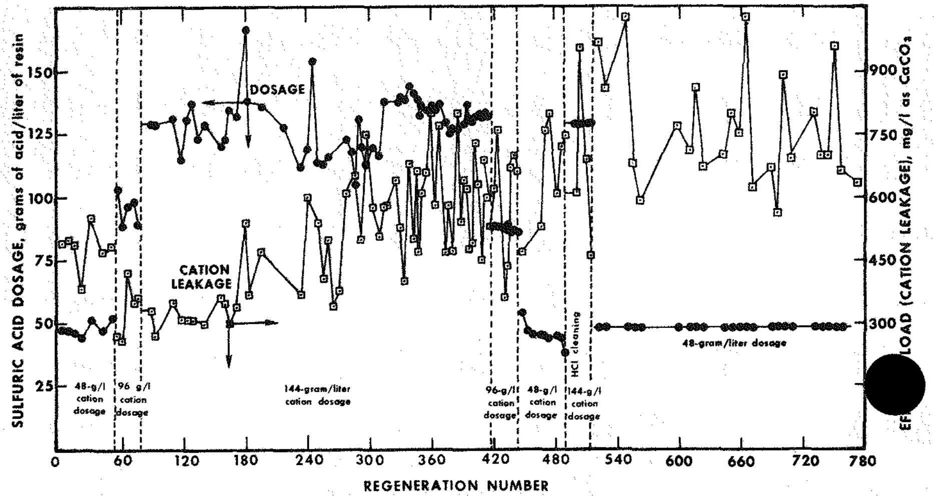

**Figure 6. Relationship between cation dosage and leakage during the EPA studies.**

Table 2. CROWN WATER QUALITY DATA, 8/76 THRU 3/77

| Parameter | Unit | Mean | Maximum | Minimum | Standard deviation |
|---|---|---|---|---|---|
| pH | pH | 5.1 | 6.1 | 3.5 | 0.6 |
| Specific conductance | µmhos/cm | 2790 | 4000 | 2350 | 540 |
| Acidity as $CaCO_3$ | mg/l | 420 | 610 | 260 | 90 |
| Calcium | mg/l | 340 | 400 | 310 | 20 |
| Magnesium | mg/l | 110 | 130 | 96 | 7.2 |
| Total iron | mg/l | 210 | 270 | 140 | 32 |
| Ferrous iron | mg/l | 200 | 270 | 120 | 33 |
| Sodium | mg/l | 360 | 470 | 290 | 40 |
| Aluminum | mg/l | 7.6 | 18 | 0.5 | 3.9 |
| Manganese | mg/l | 5.1 | 6.6 | 3.6 | 0.7 |
| Sulfate | mg/l | 2500 | 3040 | 2100 | 200 |
| Alkalinity | mg/l | 20 | 100 | 0 | 25 |
| Total dissolved solids | mg/l | 3540 | 4260 | 3040 | 270 |
| Temperature | °C | 17 | 25 | 14 | 1.7 |
| Exchangeable cations as $CaCO_3$ | mg/l | 2510 | 3060 | 2180 | 180 |

Table 3. ION EXCHANGE SYSTEM PERFORMANCE AT 48-GRAMS/LITER SULFURIC ACID DOSAGE

| | Cation | Anion |
|---|---|---|
| Regenerant | $H_2SO_4$ | NaOH |
| Bulk regenerant cost, cents/kg | 7.72 | 11.0 |
| Bulk solution concentration, weight percent | 93 | 20 |
| Desired regenerant concentration, weight percent | 2.0 | 3.0 |
| Desired dosage, grams of regenerant/liter of resin | 48 | 40 |
| Desired dosage, pounds of regenerant/cu ft of resin | 3 | 2.5 |
| | | |
| Influent load, milligrams/liter as $CaCO_3$ | 2710 | 1770 |
| Effluent load (leakage), milligrams/liter as $CaCO_3$ | 780 | 0 |
| Effective removal, milligrams/liter as $CaCO_3$ | 1930 | 1770 |
| Average actual dosage, grams of regenerant/liter of resin | 45 | 44 |
| Average actual regenerant concentration, percent by weight | 1.95 | 3.71 |
| Exchanger capacity, grams/liter of resin as $CaCO_3$ | 27.7 | 19.0 |
| Exchanger capacity, kilograins/cu ft of resin as $CaCO_3$ | 12.1 | 8.3 |
| Regenerant utilization efficiency, percent | 60 | 34 |
| Regenerant cost, cents/cu m | 39 | 98 |
| Regenerant cost, cents/1000 gal | 150 | 370 |
| Total volume to waste, liters/regeneration | 6400 | 3280 |

Table 4. ION EXCHANGE SYSTEM PERFORMANCE AT 96-GRAMS/LITER SULFURIC ACID DOSAGE

| | Cation | Anion |
|---|---|---|
| Regenerant | $H_2SO_4$ | NaOH |
| Bulk regenerant cost, cents/kg | 7.72 | 11.0 |
| Bulk solution concentration, weight percent | 93 | 20 |
| Desired regenerant concentration, weight percent | 2.0 | 5.0 |
| Desired dosage, grams of regenerant/liter of resin | 96 | 40 |
| Desired dosage, pounds of regenerant/cu ft of resin | 6 | 2.5 |
| | | |
| Influent load, milligrams/liter as $CaCO_3$ | 2410 | 1730 |
| Effluent load (leakage), milligrams/liter as $CaCO_3$ | 650 | 0 |
| Effective removal, milligrams/liter as $CaCO_3$ | 1730 | 1730 |
| Average actual dosage, grams of regenerant/liter of resin | 88 | 46 |
| Average actual regenerant concentration, percent by weight | 1.92 | 4.77 |
| Exchanger capacity, grams/liter of resin as $CaCO_3$ | 29.2 | 26.5 |
| Exchanger capacity, kilograins/cu ft of resin as $CaCO_3$ | 12.7 | 11.6 |
| Regenerant utilization efficiency, percent | 33 | 46 |
| Regenerant cost, cents/cu m | 59 | 67 |
| Regenerant cost, cents/1000 gal | 230 | 250 |
| Total volume to waste, liters/regeneration | 8720 | 2890 |

Table 5. ION EXCHANGE SYSTEM PERFORMANCE AT 144-GRAMS/LITER SULFURIC ACID DOSAGE

| | Cation | A[illegible] |
|---|---|---|
| Regenerant | $H_2SO_4$ | NaOH |
| Bulk regenerant cost, cents/kg | 7.72 | 11.0 |
| Bulk solution concentration, weight percent | 93 | 20 |
| Desired regenerant concentration, weight percent | 2.0 | 5.0 |
| Desired dosage, grams of regenerant/liter of resin | 144 | 40 |
| Desired dosage, pounds of regenerant/cu ft of resin | 9 | 2.5 |
| | | |
| Influent load, milligrams/liter as $CaCO_3$ | 2480 | 1800 |
| Effluent load (leakage), milligrams/liter as $CaCO_3$ | 520 | 0 |
| Effective removal, milligrams/liter as $CaCO_3$ | 1960 | 1800 |
| Average actual dosage, grams of regenerant/liter of resin | 129 | 46 |
| Average actual regenerant concentration, percent by weight | 1.95 | 4.94 |
| Exchanger capacity, grams/liter of resin as $CaCO_3$ | 29.4 | 29.1 |
| Exchanger capacity, kilograins/cu ft of resin as $CaCO_3$ | 12.8 | 12.7 |
| Regenerant utilization efficiency, percent | 22 | 51 |
| Regenerant cost, cents/cu m | 91 | 63 |
| Regenerant cost, cents/1000 gal | 350 | 240 |
| Total volume to waste, liters/regeneration | 10270 | 281[illegible] |

Table 6. SUMMARY OF ION EXCHANGE SYSTEM CHEMICAL ANALYSES

| Sample | Cond | Acid Alk* | pH | Ca | Mg | Total iron | $Fe^{2+}$ | Na | Al | Mn | $SO_4$ | TDS | Exch cations |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| OPERATION AT 48-G/L (3-LB/CU FT) DOSAGE OF SULFURIC ACID | | | | | | | | | | | | | |
| Raw feed | 2870 | 410 | 4.9 | 400 | 110 | 210 | 190 | 360 | 9.3 | 5.0 | 2600 | 3690 | 2670 |
| Cation eff. | 8890 | 1780 | 1.54 | 42 | 12 | 23 | 22 | 260 | 0.6 | 0.6 | 2460 | 2790 | 760 |
| Anion eff. | 1230 | 280* | 9.4 | 38 | 12 | 3.1 | 0.3 | 320 | 0.1 | 0.4 | 610 | 980 | 860 |
| OPERATION AT 96-G/L (6-LB/CU FT) DOSAGE OF SULFURIC ACID | | | | | | | | | | | | | |
| Raw feed | 2870 | 410 | 5.1 | 330 | 110 | 200 | 190 | 340 | 8.7 | 5.0 | 2430 | 3410 | 2410 |
| Cation eff. | 8910 | 1730 | 1.55 | 29 | 6.0 | 14 | 13 | 240 | 0.6 | 0.3 | 2380 | 2670 | 650 |
| Anion eff. | 1370 | 340* | 9.3 | 21 | 5.3 | 2.4 | 0 | 380 | 0.3 | 0.2 | 570 | 970 | 890 |
| OPERATION AT 144-G/L (9-LB/CU FT) DOSAGE OF SULFURIC ACID | | | | | | | | | | | | | |
| Raw feed | 2790 | 430 | 5.0 | 340 | 110 | 210 | 200 | 350 | 7.8 | 5.2 | 2470 | 3500 | 2480 |
| Cation eff. | 9700 | 2000 | 1.58 | 24 | 5.6 | 16 | 13 | 190 | 0.7 | 0.8 | 2280 | 2550 | 520 |
| Anion eff. | 1430 | 290* | 9.5 | 19 | 4.5 | 1.4 | 0 | 400 | 0.5 | 0.2 | 730 | 1150 | 950 |
| LONG-TERM OPERATION AT 48-G/L (3-LB/CU FT) DOSAGE OF SULFURIC ACID | | | | | | | | | | | | | |
| Raw feed | 2770 | 500 | 4.5 | 350 | 100 | 180 | 170 | 330 | 8.5 | 5.3 | 2440 | 3420 | 2410 |
| Cation eff. | 8220 | 1930 | 1.61 | 45 | 13 | 22 | 19 | 250 | 0.74 | 0.62 | 2370 | 2700 | 760 |
| Anion eff. | 1310 | 290* | 9.3 | 38 | 13 | 6.7 | 1.1 | 330 | 0.21 | 0.44 | 660 | 1050 | 900 |

NOTE: All units are mg/l except for conductivity (micromhos/cm) and pH. Acidity, alkalinity, and exchangeable cations are expressed as $CaCO_3$.

Table 7. LONG-TERM ION EXCHANGE PERFORMANCE AT 48-GRAM/LITER SULFURIC ACID DOSAGE

|  | Cation | Anion |
|---|---|---|
| Regenerant | $H_2SO_4$ | Na[illegible] |
| Bulk regenerant cost, cents/kg | 7.72 | 11.0 |
| Bulk solution concentration, weight percent | 93 | 20 |
| Desired regenerant concentration, weight percent | 2.0 | 3.0 |
| Desired dosage, grams of regenerant/liter of resin | 48 | 32 |
| Desired dosage, pounds of regenerant/cu ft of resin | 3 | 2 |
| Influent load, milligrams/liter as $CaCO_3$ | 2400 | 1930 |
| Effluent load (leakage), milligrams/liter as $CaCO_3$ | 770 | 0 |
| Effective removal, milligrams/liter as $CaCO_3$ | 1630 | 1930 |
| Average actual dosage, grams of regenerant/liter of resin | 48 | 32 |
| Average actual regenerant concentration, percent by weight | 2.11 | 2.85 |
| Exchanger capacity, grams/liter of resin as $CaCO_3$ | 22.6 | 19.9 |
| Exchanger capacity, kilograins/cu ft of resin as $CaCO_3$ | 9.9 | 8.7 |
| Regenerant utilization efficiency, percent | 46 | 50 |
| Regenerant cost, cents/cu m | 43 | 70 |
| Regenerant cost, cents/1000 gal | 155 | 263 |
| Total volume to waste, liters/regeneration | 6640 | 3110 |

An unexpected deterioration was observed, however, in the performance of the cation column. This can be seen by comparing Table 7 with Table 5 where the operating characteristics of the cation column were similar. The average cation exchanger capacity dropped from 27.7 to 22.6 gram/liter (as $CaCO_3$) and utilization efficiency of the sulfuric acid regenerant lowered from 60 to 30 percent; however, effluent quality was comparable to the earlier study results.

The process, as is, will not produce a potable-quality effluent from the Crown AMD because of the unusual characteristic of the high sodium level in the influent AMD. The sodium concentration and its equivalent quantity of sulfate exceed the [illegible] mg/l total dissolved solids standard for potability. If the sodium were not present in the AMD, the effluent could be post-treated and filtered for residual iron and manganese removal and chlorinated to meet potability requirements.

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## REFERENCES

1. The Dow Chemical Company, Dowex: Ion Exchange, The Dow Chemical Company, Midland, Michigan, 1964.

[illegible] Skelly and Loy, Processes, Procedures, and Methods to Control Pollution From Mining Activities, EPA-430/9-73-011, The U.S. Environmental Protection Agency, Washington, D.C., October 1973.

3. Holmes, Jim and Ed Kreusch, Acid Mine Drainage Treatment by Ion Exchange, U.S. Environmental Protection Agency Report EPA-R2-72-056, Washington, D.C., November 1972.

4. Colma, Carol and John J. Demchalk, The Use of Amberlite Ion Exchange Resins in Treating Acid Mine Waters at Phillipsburg, Pennsylvania, The F. S. Gallagher Co., Princeton, N.J.

# CHEMICAL LIMNOLOGY OF AN ACID MINE DRAINAGE SLUDGE SETTLING IMPOUNDMENT

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## ABSTRACT

A stripmine lake in southeastern Illinois was intensely studied from February to August 1972 to (1) characterize chemical and physical stratification; (2) determine the "stability" of stratification and (3) assess the relationship between impoundment stratification and the primary influent source - neutralized acid mine drainage from the Will Scarlet water treatment plant (USEPA - Peabody Coal Company Project No. 14010 DAX).

The sludge settling impoundment was characterized as a unique example of an artificially induced crenogenic meromictic (partly-mixing) impoundment. Dichotomized pH stratification and the subsequent accumulation of iron (ferrous) bicarbonates in the lower strata indicated that the origin and maintenance of impoundment meromixis was directly related to the deposition of iron hydroxides from the neutralization process as per the impoundment's intended use.

Stability of impoundment stratification was compared to other types of meromictic lakes and found to be low in value. Moreover, observation of the study lake during treatment plant down-time further indicated a tendency toward holomixis (whole-mixing) with the appearance of iron solutes in upper lake strata.

## INTRODUCTION

### Background

The surface mining of coal has been carried on extensively in the United States. One result of area surface mining methods, usually practiced in flat to rolling terrain as found in the Midwest, is the creation of large numbers of small lakes and ponds in the form of "final cuts." These bodies of water can vary in surface area from a few hundred square meters to several hectares with the depth dictated by the depth of coal mined in that particular area.

With the advent of strict reclamation and water pollution control laws, current surface mining practices are a tremendous asset by increasing the water resource base within an area of operation. The development of previous surface mined areas for hunting, fishing, camping and other forms of outdoor recreation are common in many areas of the Midwest. However, the utilization of "final cuts" in association with an industrial process as acid mine neutralization is not common in the literature. Further, the characterization of a final cut, utilized as a sludge settling impoundment, for a full-scale acid mine drainage neutralization plant has not been accomplished in previous studies.

Physical and chemical conditions that can occur in stripmine lakes are reasonably well known, at least in broad outline. Several studies have contributed to knowledge of the conditions that exist in numerous geographical areas. Nevertheless, a strikingly different impoundment has resulted with the utilization of a strip pit lake as a sludge settling impoundment for a full-scale industrial process, and will be dealt with in this paper.

It is the intent of this study to: (1) characterize the sludge settling impoundment as to its physical and chemical stratification; (2) determine "stability" and functional reliability of the impoundment for its intended industrial process; and (3) assess and determine origin and nature of impoundment stratification.

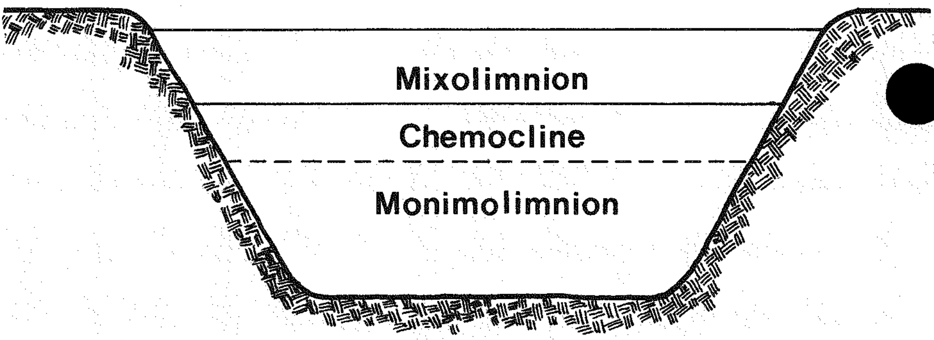
Many lakes naturally stratify thermally in the summer, as warm [illegible]er is less dense than cold water. When the temperature of the [illegible]per water is higher (above 4C), then the deep water (which has to [illegible] denser or at least as dense as the upper water) may be denser due to increased concentrations of dissolved(or suspended) matter. Such lakes in which a stratification is brought primarily by differences in the concentration of dissolved (or suspended) matter are characterized as "meromictic" (part-mixing), thus the phenomenon of meromixis.

Reports as to the phenomenon of meromixis are well represented in the literature. Findenegg (1935) introduced the term meromictic, which describes a lake in which some water remains partly or wholly unmixed with the main water mass during spring and fall circulation ("turnover") periods. This type of lake is in contrast to the more common type in which the whole of the water body is mixed at such circulation periods and is termed holomictic ("whole-mixing"). Findenegg designated the perenially stagnant deep layer of a meromictic lake the monimolimnion, and Hutchinson (1937) introduced the term mixolimnion for the remaining part of a lake in which free circulation periodically can occur. The boundary between the mixolimnion and the monimolimnion is known as the chemocline. (Refer to Fig. I).

The accumulation of dissolved (or suspended) matter can occur in the lower strata of lake in several ways. Hutchinson (1937) listed the following types of meromixis and their causes: (1) ectogenic meromixis, due to some external catastrophe bringing either salt water into a freshwater lake or freshwater into a saline lake, so establishing a deeper, dense saline layer covered by a less dense, less saline superficial layer; (2) biogenic meromixis, due to the accumulation in the monimolimnion of salts liberated from the sediments, primarily as the results of chemical changes of biochemical origin; (3) crenogenic meromixis, due to saline springs delivering dense water into the depths of a lake. This water will displace the freshwater of the mixolimnion, forcing it out the effluent.

Concerning the last type of meromixis, Hutchinson (1957) noted that the definition of crenogenic meromixis may have to be widened [illegible] include cases where solid salts in the bottom deposits are going [illegible] solution, or where saline rivers or dense industrial wastes en[illegible] the lake at the surface and flow into the monimolimnion as density currents. This latter example of dense industrial waste rendering a lake meromictic is that encountered in the study impoundment.

During the course a limnological investigation of several surface mine impoundments in southeastern Illinois in February, 1971, vertical thermal characterization was performed on the study impoundment. Unlike other impoundments in the area, Pit #10 exhibited a very unusual temperature regime, i.e., an inverse clinograde temperature



MEROMICTIC LAKE STRATIFICATION

Figure 1

gradient. That is, an upper strata of water had achieved winter stagnation with a homogeneous temperature of 4°C. However, a lower stratum of the lake exhibited higher temperatures. Further laboratory investigations of physical and chemical parameters showed a remarkable increase in pH, alkalinity, total iron and acidity with increasing depth. A precursory review of the literature with special reference to Kjensmo's work on iron meromixis (1962, 1967, 1968) led to the hypothesis that the Pit #10 impoundment was an example of artificially-induced crenogenic meromixis.

## Description of Study Area

The study lake was formed from 1965 to 1968 during surface mining operations of the Peabody Coal Corporation's Will Scarlet Mine, and located in Williamson and Saline counties, Illinois. (88° 42' W. Long.; 37° 39' N. Lat.). (Refer to Fig. 2). The "final cut" impoundment serves as a settling basin for chemically treated effluents from an acid mine drainage neutralization plant, under joint sponsorship of the Peabody Coal Corporation and the Federal Water Quality Administration. Acid mine drainage, which is accumulated from approximately 2,000 acres of previously surface-mined land, was channeled to the plant site via a system of pumps and canals into a central holding channel prior to treatment.

pH, acidity and iron concentrations of impounded water (Table 1) in each of the major pits which served as feed water for the treatment plant varied with the amount of rainfall in the drainage basins. Table 2 gives a range for numerous water quality parameters of the plant influent. Koehrsen and Grandt (1970) noted extremely high acidities from the surface of respective pits.

TABLE 1 - WATER QUALITY OF IMPOUNDED ACID MINE DRAINAGE (Koehrsen and Grandt, 1970)

| Mine Pit No. | pH Range | Total Acidity (mg/l as $CaCO_3$) | Total Iron (mg/l as Fe) | Estimated Volume (gals) |
|---|---|---|---|---|
| 1 | 2.5 - 2.7 | 1,380 - 8,490 | 1 - 75 | $6.4 \times 10^7$ |
| 2 | 2.7 | 2,330 - 2,760 | 1 | $1.04 \times 10^8$ |
| 3 | 2.4 - 2.6 | 12,389 - 13,360 | 315 -1,200 | $1.08 \times 10^8$ |
| 4 | 2.5 - 2.6 | 11,950 - 14,740 | 1,000-2,400 | $3.06 \times 10^8$ |
| 9 | 2.7 | 1,470 - 1,620 | 130 - 150 | $5.89 \times 10^8$ |
| 10 | 2.9 - 3.0 | 620 - 660 | 8 - 35 | $1.76 \times 10^8$ |

Samples collected at depths of 15 to 30 feet in several impoundments yielded acidity values several times as great as at the surface, in one instance running as high as 32,000 ppm acidity as $CaCO_3$.

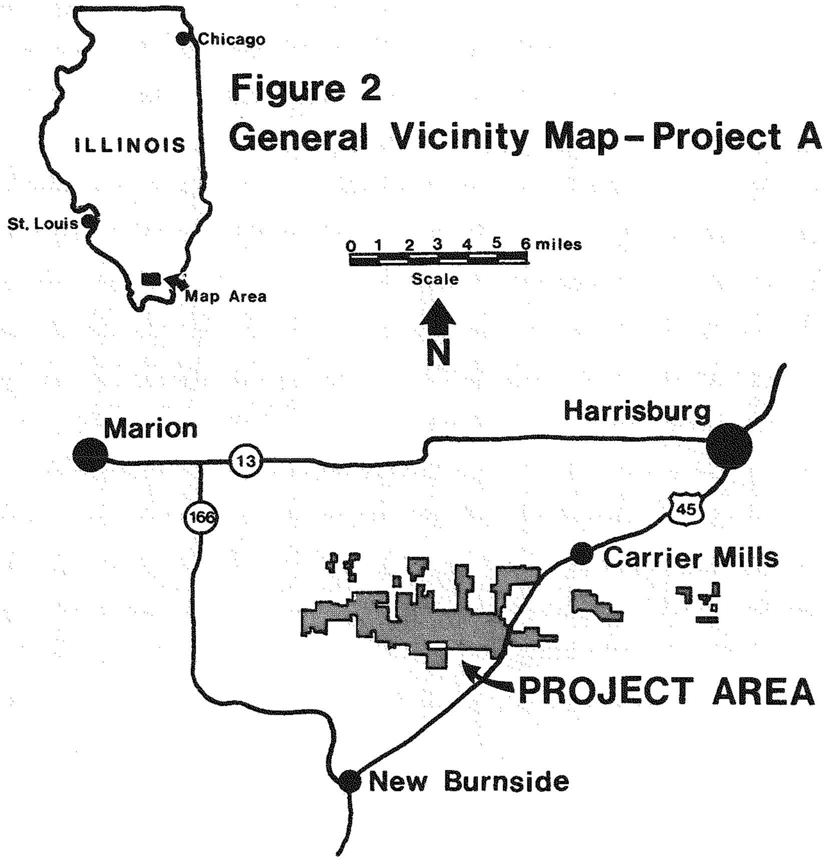


Figure 2
General Vicinity Map-Project Area

TABLE 2 - RANGE OF WATER QUALITY OF PLANT INFLUENT

| PARAMETER | RANGE |
|---|---|
| pH | 2.4 - 3.1 |
| Acidity[1], b.p. to pH 8.3 | 1700 - 9200 |
| Acidity,[1] cold with $H_2O_2$ to pH 7.3 | 1500 - 8500 |
| Alkalinity[1], to pH 4.5 | 0 - 93 |
| Specific Conductivity[2] | 2800 - 7900 |
| Iron, total, ppm | 145 - 1070 |
| Iron, ferrous, ppm | 0 - 65 |
| Iron, ferric, ppm | 145 - 1070 |
| Sulfate, ppm | 2200 - 6600 |

Note: [1] ppm as $CaCO_3$

[2] μmhos/cm at 25C

Plant operation during the research period was on an experimental basis. The basis chemical process utilized during the research period was chemical neutralization with hydrated lime, Ca $(OH)_2$ and consisted of the addition of a pre-determined quantity of chemical to a known volume of acid mine drainage:

(1) $FeSO_4 + H_2SO_4 \quad 2Ca(OH)_2 = 2CaSO_4 \quad Fe(OH)_2 + 2H_2O$

This process was followed by aeration thus: (2) $4Fe\ OH + 4OH + 6H_2O + O_2 = 4Fe(OH)_3 + 4H_2O$

The treated effluents were then discharged into the settling impoundment, Pit #10, as a dense reddish-brown discharge. Table 3 indicates the probable nature of lime-treated effluents for the Will Scarlet Treatment Plant during the research period.

A bathymetric map (Figure 3) as well as morphometric data for the study impoundment (Table 4) were determined using a sonic depth sounder and methods described in Welch(1948). Only an approximation of these parameters was attempted, as a more detailed study would be desireable but quite difficult, due to the irregular shoreline and [illegible]om contours.

## METHODS AND METERIALS

The research project was begun on 17 April 1972 and continued for a period of 12 weeks to 4 July 1972. Weekly sampling of water was conducted at approximately the same time of day (1200 hours) and involved methods of physical and chemical analysis. Two 24-hour series were conducted during the month of June, 1972. Temperature, oxygen and light were taken every four hours, beginning at 1200 hours and concluding at 0800 hours on the following day. Each diurnal

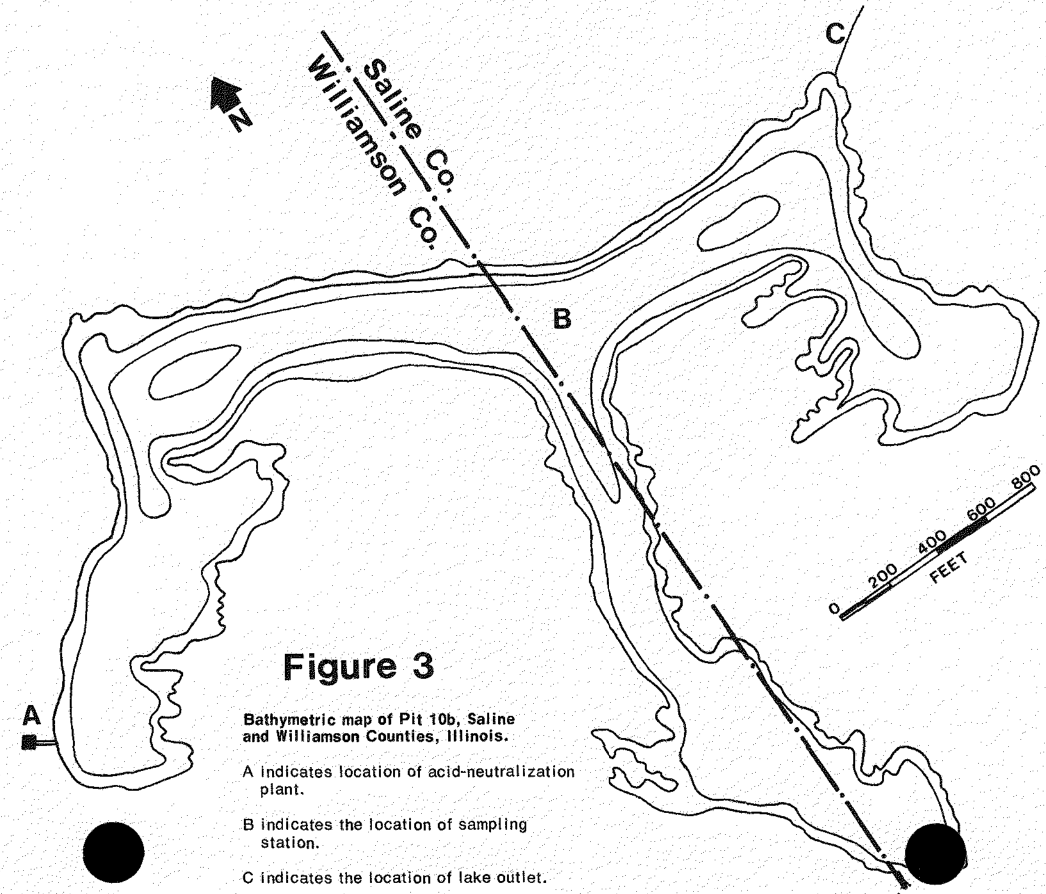


**Figure 3**

**Bathymetric map of Pit 10b, Saline and Williamson Counties, Illinois.**

A indicates location of acid-neutralization plant.

B indicates the location of sampling station.

C indicates the location of lake outlet.

## TABLE 3 - WATER QUALITY OF LIME-TREATED PLANT EFFLUENT TO PIT #10

| PARAMETER | LIME RESEARCH STAGE NO. 2 |
|---|---|
| pH | 7.1 |
| Acidity[1] | 8 |
| Alkalinity[1] | 10 |
| Specific Conductance[2] | 5200 |
| Sulfate, ppm | 3500 |
| Copper, ppm | 0.03 |
| Chromium, ppm | 0.07 |
| Lead, ppm | 0.03 |
| Manganese, ppm | 1.94 |
| Zinc, ppm | 0.03 |
| Alumnium, ppm | 1.80 |
| Nickel, ppm | 0.59 |
| Magnesium, ppm | 135 |
| Calcium, ppm | 900 |

Note: [1] ppm as $CaCO_3$ [2] μmhos/cm at 25C

## TABLE 4 - MORPHOMETRIC DATA FOR PIT #10, 4 JULY 1972 (SYMBOLS FROM HUTCHINSON, 1957)

| | |
|---|---|
| Surface altitude above sea level | 120m |
| Surface area (A) | .23 $km^2$ |
| Maximum depth ($^{z}$m) | 27m |
| Mean depth ($\bar{z}$) | 16.3m |
| Volume (V) | 376 X $10^4 m^3$ |
| Length of shoreline (L) | 16.2 km |
| Length of lake (l) | 835 m |
| Maximum breadth of lake ($^{b}$m) | 536 m |
| Relative depth ($^{z}$r) | 4.59% |
| Mean breadth of lake ($\bar{b}$) | 14.2 m |
| Shoreline development ($^{D}$L) | 19.1 |
| Volume development ($^{D}$V) | 1.8 |
| Depth of center of gravity ($^{z}$g) | 6.0 m |
| Volume of mixolimnion | 300.8 X $10^4 m^3$ |
| Volume of monimolimnion | 75.2 X $10^4 m^3$ |
| [illegible]te of inflow | unknown |
| [illegible]te of Outflow | 1.9 X $10^5 m^3$ per day |
| Theoretical replenishment time of mixolimnion | 15.7 days |
| Theoretical replenishment time of lake | 18.7 days |

series was followed on the second day by a weekly analysis of physical and chemical parameters of the water column. All samples were taken at the sampling station shown in Figure 3.

TEMPERATURE and LIGHT were measured at one-meter intervals from surface to the bottom using a Whitney Underwater Thermistor and Light Meter. DISSOLVED OXYGEN was measured at one-meter intervals from the surface to a depth of 14 m with a Yellow Springs instrument Model 54 oxygen meter. Measurements of oxygen with the Winkler technique, modified with azide and potassium flouride (National Eutrophication Research, 1969) were not successful, apparently due to iron interference.

Water samples were collected with a Kemmerer-type water [illegible]ler at two-meter intervals from the surface to the bottom. Sampl[illegible] were stored in two B.O.D. bottles (60-ml and 300-ml capacity) and placed in a styrofoam cooler with the ice to maintain temperature at approximately 4C. The following physical and chemical determinations were made 15 - 25 minutes after collection:

pH was measured with a Beckman Electromate pH meter (Model 1009) with a combination electrode on 25-ml samples from the 60-ml B.O.D. bottle. The instrument was standardized with a buffer solution of pH 4.01 prior to analysis.

ACIDITY was determined electrometrically on a 25-ml sample using the Peroxide Oxidation and Boailing Method (A.S.T.M. Manual, 1970, pp. 161 - 162). The sample was titrated with 0.02 N HCl to a pH of 4.0 or less; then 5 drops of reagent grade $H_2O_2$was added, and the sample was boiled for approximately 2 - 3 minutes and allowed to cool. The sample was then titrated with 0.02 N NaOH to a pH of 8.2.

TOTAL ALKALINITY determinations (Standard Methods, 13th ed., pp. 52 - 56) were made by the electrometric titration of a 25-ml sample with 0.02 N HCl to a pH 4.5; and pH 4.2.

CONDUCTIVITY was measured with a Barnstead Conductivity Bridge. Freshly-opened sample temperature (at 20 - 25C) was determined with a mercury thermometer and recorded. The meter probe was then added to the sample bottle and the resistivity was determined in ohms cm at sample temperature. Calculation of conductance was then determined according to Standard Methods, 13th ed., pp. 323 - 327.

SULFATE ion concentrations were measured turbimetrically with a Hach Kit (Model DR-A). Because of the high sulfate concentrations in the study lake, it was necessary to dilute samples 1- 50.

TOTAL IRON concentrations were measured with the Hach Kit utilizing the FerroVer method. It was again necessary to dilute some samples considerably.

## RESULTS

### Temperature

The upper mixolimnetic waters warmed gradually throughout the research period. By 15 May 1972, a sharp metalimnion had formed at 4 to 8 m depth. Extreme seiche activity occurred at these depths as shown by temperature variations in excess of 5C units at a fixed depth. By the end of the research period, the metalimnion (1C/m drop in temperature) was located from 4 to 10 m and was lower at the end of the sampling period than it had been at the beginning (Fig. 4).

The chemocline (Fig. 1) appeared to stabilize at about 12 m after the third week of sampling. Below this depth, temperature increased with increasing depth, characteristic of a meromictic lake. The relationship of temperature to dissolved solids is illustrated in Fig.4 in contrasting winter and summer stratification.

Diurnal variation in temperature indicated that there was more variation in the mixolimnion than in the isolated monimolimnion with the chemocline corresponding to the stratum with the temperature minimum. During the first diurnal series 12-13 June 1972, the temperature varied at 0 m from 23.9C at 1200 hours to 25.1C at 2400 hours. The temperature variation in the monimolimnion at 16 m depth for the same time interval was 11.9C to 12.7C, a gain of 0.8C units. In general, the mixolimnion showed a temperature increase throughout the daylight hours as did the monimolimnion. However, the gain (or loss) of heat was much greater in the upper stratum.

Diurnal temperature change as well as seasonal effects throughout the research period revealed the thermal stratification of Pit #10 (Fig. 5). This was the generalized thermal stratification that existed throughout the research period.

Dissolved Oxygen

Dissolved oxygen concentrations were observed throughout the research period to a depth of 14 m. It was assumed that there was negligible amounts of the dissolved gas below this depth. Jackson and Dence (1958) reported 0.5 ppm oxygen in the monimolimnion of Fayetteville Green Lake, but Brunskill and Ludlam (1969) found none, using a Winkler method.

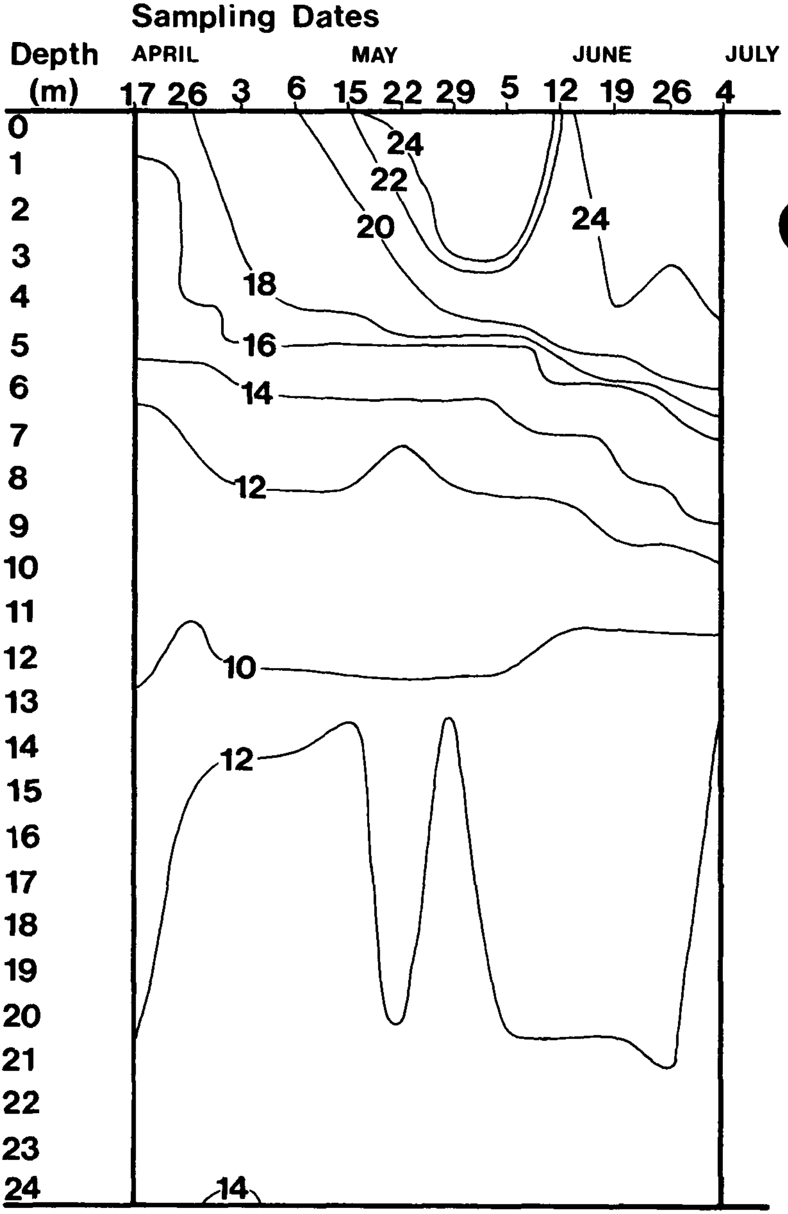
Dissolved oxygen concentrations varied considerably through the week of 22 May 1972 with a strict stratification forming between 8 and 9 m from 29 May to the end of the research period. Supersaturation in excess of 120% was positively correlated to meteorological data, that is, sunny and fair weather, while the abundance of phytoplankton did not show any relationship. The depletion of dissolved oxygen at this depth corresponded to the lower stratum of the metalimnion which extended from 5 to 9 m depth.

The lake exhibited supersaturation to near saturation in the mixolimnion throughout the majority of the research period. Sampling dates 29 May to 26 June, 1972 illustrated supersaturation to a depth of 6 m. Variation in dissolved oxygen concentrations over the two diel series followed a general pattern. During the daylight readings of 1200 and 1600 hours, supersaturation of the mixolimnion to a depth of 6 to 7 m was most pronounced, as photosynthesis exceeded respiration. With the setting sun, respiring plankton dissipated this excess [illegible] that by 2000 hours, less than 100% saturation values were observed. [illegible] 2400 hours to 0400 hours, further depletion of the gas was the rule. By 0800 hours, two hours after sunrise, the photosynthesis again exceeded respiration and the concentration of dissolved oxygen approached saturation values in the mixolimnion.

Light

The decrease in light (or transparency) was approximately exponontial throughout the water column with the k %(1% of surface illumination) lying well below the metalimnion of the mixolimnion. No layers of great turbidity were detected. Thus, the majority or all of

# Figure 4



Depth-time diagram of Temperature (C),
17 April – 4 July 1972.

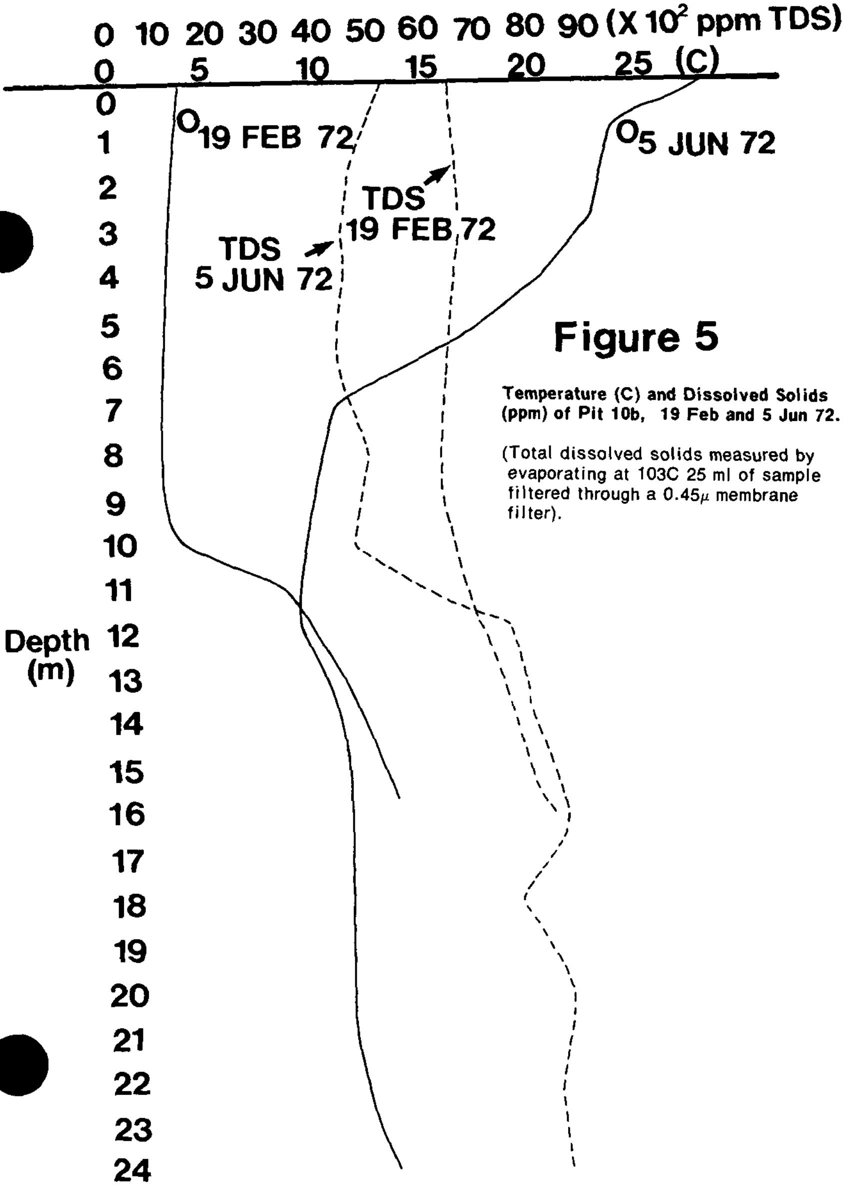


Figure 5

**Temperature (C) and Dissolved Solids (ppm) of Pit 10b, 19 Feb and 5 Jun 72.**

(Total dissolved solids measured by evaporating at 103C 25 ml of sample filtered through a 0.45μ membrane filter).

the mixolimnion was included within the photic zone which varied from a depth of 6 m on May 15 to 13.6 m on 27 June, 1972.

TABLE 5 - DEPTHS AT WHICH 1% AND 10% OF SURFACE ILLUMINATION OCCURRED

Sampling Dates

| $k_i$ | Apr 26 | May 3 | May 8 | May 15 | May 29 |
|---|---|---|---|---|---|
| 1% | 10.2m | 9.0m | 8.1m | 6.0m | 9.8m |
| 10% | 5.2 | 3.8 | 4.1 | 3.0 | 4.9 |

Sampling Dates

| $k_i$ | Jun 5 | Jun 13 | Jun 19 | Jun 26 |
|---|---|---|---|---|
| 1% | 10.1m | 12.6m | 9.8m | 13.6m |
| 10% | 6.8 | 8.8 | 6.2 | 6.9 |

## Hydrogen Ion Concentration

Pit #10 exhibited a strong dichotomized pH stratification throughout the research period. The minimal pH stratum was initially located at 10m depth but shifted upward to the 8m stratum from 29 May to the end of the research period. This change was due mainly to the falling surface water level throughout the month of June.

The upper pH stratum(0 to 6 m depth) exhibited a rather narrow pH range, 4.0 to 5.4, while the lower pH stratum ranged from 4.4 to 6.4 at depths from 10 to 24 m. The acidic stratum, which was located at 8 to 9 m throughout the research period, had a range of 2.1 to 3.9. The most extreme example of dichotomized pH stratification is illustrated in Fig. 6. This was, in general, the pattern of pH stratification that existed throughout the research period.

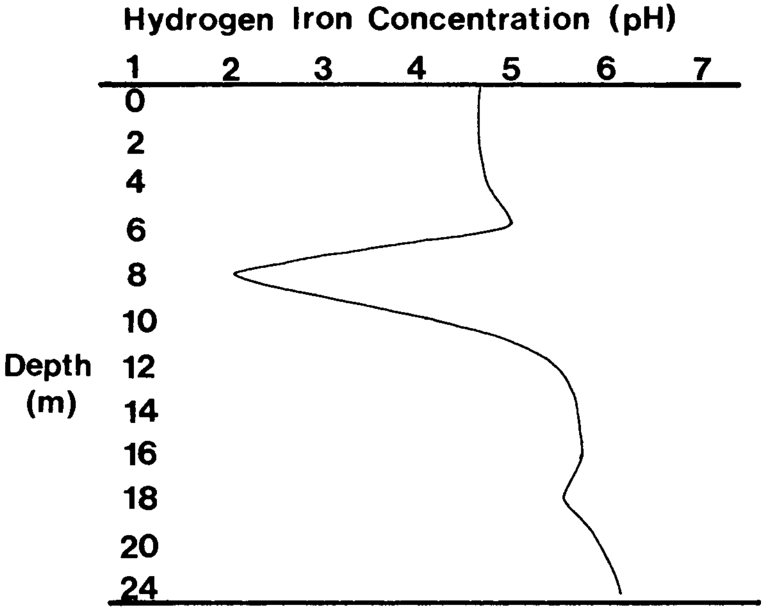
## Total Alkalinity

Pit #10 is a lake of low alkalinity. The mixolimnion exhibited little to no buffering capacity, while alkalinity in the monimolimnion increased with increasing depth from 0 to 134 ppm as $CaCO_3$ (Fig. 7). There was a slight dichotomy of alkalinity on 3 May at 14 m; however, such fluctuations are considered to be evidence of internal seiche activity and eddy diffusion between the mixolimnion and the monimolimnion.

## Acidity

"The acidity of a water is the capacity of that water to donate protons. This includes the un-ionized portions of weakly ionizing acids such as carbonic acid and tannic acid, as well as hydrolyzing salts like ferrous sulfate and/or aluminum sulfate. This determination provides an estimate of the lime application which may be required to make such water supplies for general use." (Standard Methods,

**Figure 6**



Depth-pH diagram, 13 June 1972.

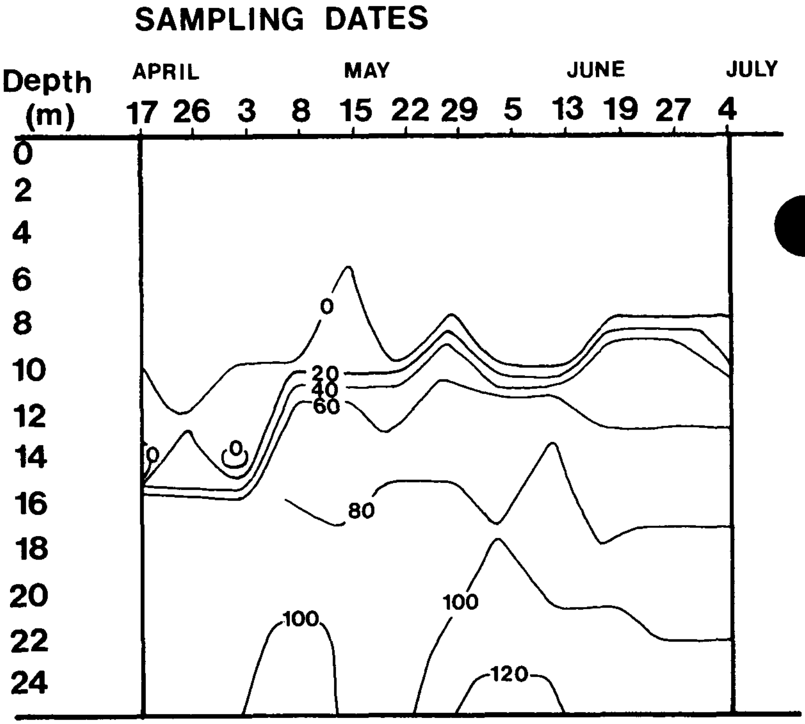
13th ed.).

Acidity in the mixolimnion was considerably less than that of the monimolimnion. In general, there was an increase in titrable acidity with increasing depth; however, erratic readings were observed again at 10 to 12 m depth due to seiche activity. The range of acidity was considerable throughout the water column, 40 to 2360 ppm as $CaCO_3$. However, evidence of acidity stratification was suggested throughout the research period, with considerable variation.

Conductivity

Concentrations of ionically active materials are effectively monitored by measuring specific conductance (Brunskill, *et al.*, 1969; K[illegible]smo, 1968). Specific conductance varied throughout the water [illegible]n, though this variation was over a narrow range for any particu[illegible]r sampling date. The high value recorded at 8 m depth on 13 June corresponds with the lowest pH recorded at the same depth and date and was probably due to internal seiche activity and increased mixing, following a windy day. There was a general trend toward decreasing specific conductance in the lake throughout the research period. By the end of the research period, the entire water column had become rather homogeneous with respect to the total ionically active constituents. However, the technique for measuring conductivity could blur or lessen differences from one sample and one depth to another, due to sample carry-over.

## Figure 7



Depth-time diagram of total alkalinity (ppm), 17 April – 4 July 1972.

Analysis for calcium in the surface waters of the lake indicated that this ion occurs in concentrations in excess of 1,000 ppm(Hearn, personal communication). The source of this ion was the acid-neutralization process (equation 1, p.4). The presence of hydrated, supersaturated $CaSO_4$solution in the surface waters was exemplified by the occurrence of gypsum crystals ($CaSO_4 . 2H_2O$) on all equipment during regular sampling.

Sulfate

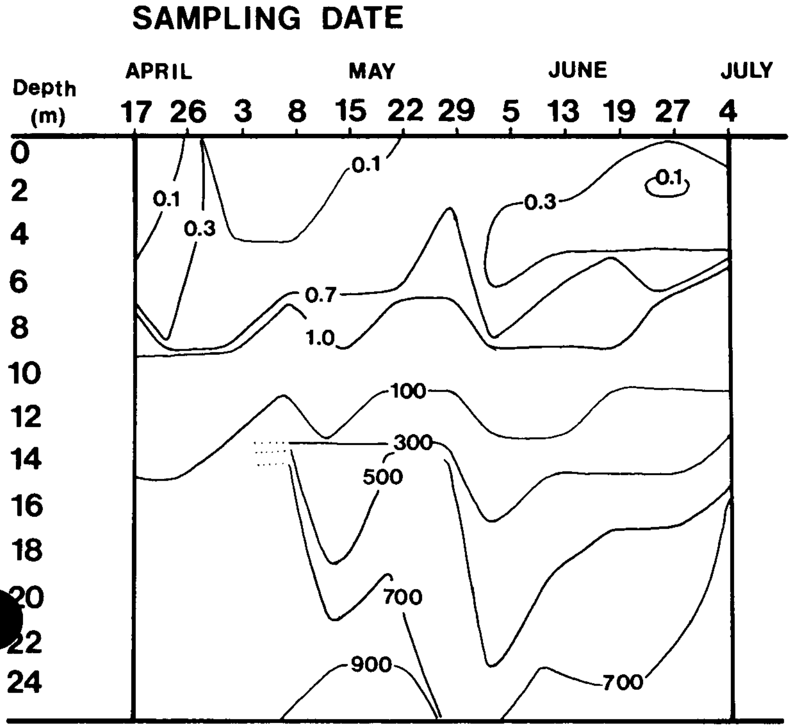
The concentration of sulfate ions was extremely high throughout the water column. The concentrations ranged from 2800 to 9500 ppm, with a general tendency toward increasing concentration with increasing depth. The mixolimnetic sulfate concentrations were approximately one-half that of the monimolimnion on any particular sampling date, with considerable variation within each stratum.

Total Iron

Fig. 8 clearly indicates that there was a steep gradient in the concentration of total iron (ferric and ferrous) with increasing depth. Total iron concentrations to a depth of 8 to 9 m were negligible (<1.0 ppm as Fe) when compared to iron concentrations in the monimolimnion. Exposure of monimolimnetic water to the atmosphere brought an immediate oxidation and precipitation of ferrous iron as ferric hydroxide. Kjensmo (1968) noted that the majority of iron present in the lower stratum of iron-meromictic European lakes was in the ferrous state. This was the condition in Pit #10, as well.

A tremendous range in total iron concentration was exhibited throughout the water column (Fig. 7). On 22 May at 0 m total iron concentration was 0.75 ppm, while at 24 m depth on the same day, the concentration increased to 910 ppm. This was a greater than 1,000-fold increase from surface to bottom. The range for this parameter for the entire study period was 0.09 ppm at 4 m on 17 April to 910ppm at 24 m on 15 May 1972.

**Figure 8**



Depth-time diagram of total iron concentrations of Pit 10b, 17 April – 4 July 1972.

## DISCUSSION

Initial investigations of the phenomenon of meromixis originated in Europe. As recently as 1950, Newcombe and Slater reported only four dichothermic (=meromictic) lakes in North America, while Frey (1963) noted that the number of meromictic lakes had increased to more than fourteen. Thus, analysis of the physical and chemical parameters of meromixis is available on a small number of meromictic lakes.

To a large extent, meromixis is brought about by the extent of inflow-outflow, geographic location, size, shape and history of the lake basin (Hutchinson, 1957). Ordinarily, the presence of warmer waters in the lower strata of a lake is a physically unstable con[illegible]tion (Vallentyne, 1957). However, the marked stratification of s[illegible] content that exists between the mixolimnion and the more dense mon[illegible]olimnion appears to be a very stable condition in some instances (Frey, 1955). The introduction of density currents into the lower strata of a lake may prevent mixing (Frey, 1955). Langsee was rendered meromictic by the accumulation of silt in the lower strata, while Pit #10 was probably initially rendered meromictic by ferric hydroxide density currents from the acid-neutralization process. This phenomenon of crenogenic meromixis was further maintained by an interrelationship of several factors.

The density difference that exists between the strata of a meromictic lake must be considered in not only a quantitative but a qualitative sense. Kjensmo (1962, 1967) observed that the accumulation of iron in soft water lakes of northern Europe was the primary factor in initiating meromixis. This accumulation of iron in the lower stratum was the major factor that accounted for the meromictic stratification of Pit #10.

A catchment area (as the monimolimnion) yielding a rich supply of iron in the lake was present in Pit #10. A number of other factors, however, must be considered in establishing the origin and maintenance of meromixis: (1) The chemistry of iron; (2) sulfate ion;(3) dissolved oxygen and (4) the effects of lake morphometry.

The majority of iron supplied to the lake originated from the acid-neutralization plant process as a dark, reddish-brown precipitate, ferric hydroxide, which is insoluble in water (0.7 X $10^{-36}$M at 25C) from the plant which had a pH 7.0. As the precipitate entered the lake, it began to settle out of the upper strata and into the lake depths. As the anaerobic stratum was approached, the ferric compound was reduced to ferrous bicarbonate in the presence of free carbon dioxide and dissolved in the monimolimnion. Yoshimura (1932) and Juday, et al. (1935) noted that the generation of ferrous carbonates(and bicarbonates) can, therefore, occur only in the anaerobic state; it is not strange that lakes without dissolved oxygen in their hypolimnion show enormous increases of ferrous ions, with a consequent di[illegible]otomous stratification of pH as a result of iron and free $CO_2$reac[illegible]

The further dissociation of ferrous compounds and their accumulation in the monimolimnion is exemplified by the increase in titrable acidity. This parameter, which is the capacity to donate protons, increased with increasing depth with an appreciable increase at the chemocline. The partial exchange of mixo- and monimolimnetic water at the chemocline had a profound effect upon the chemistry of iron and the production of the pH minimum. Ferrous sulfate salts from the monimolimnion were oxidized in the presence of dissolved oxygen, water and mineral acid to produce ferric sulfate, which, in turn, was hydrolized to produce ferric hydroxide and sulfuric acid, the mineral acid. The ferric hydroxide did not form a precipitate because it is soluble in acid (Cooper, 1937); thus, it was available in ionic form for further reactions. The latter product, sulfuric acid, was responsible for the pH minimum at 8 m depth. A second source which probably initiated the pH minimum and contributed to the acid stratum was the hydrolysis of free $CO_2$ to form carbonic acid.

Large concentrations of sulfate ions throughout the water column had their origin from two sources: (1) The treatment plant effluent (as $CaSO_4$) and (2) the watershed, as sulfuric acid drainage from the shoreline. Mortimer (1942) observed that dissolved oxygen was a primary factor in determining the concentration of sulfate in anaerobic [illegible]s. In lakes in which marked oxygen deficits develop during summer [illegible]gnation, $H_2S$ will generally appear in the bottom water. However, if the alkalinity is too great, the reduction of sulfate to sulfide in the presence of ferrous ions as ferric sulfide will not occur (Hutchinson, 1957, p. 769). Thus, with the apparent suppression of sulfide production, the elimination of ferrous ions as ferrous sulfide did not take place in Pit #10 and the accumulation of ferrous ions was enhanced. Analytical determination of sulfide concentrations was not performed in this study; however, gross observation of bottom sediment samples indicated no traces of the black precipitate, ferrous sulfide. No $H_2S$ smell was noted.

In direct association with the above parameters was the oxygen profile of the lake. With the resistance to mixing imposed by the dissolved salt content of the lower stratum, the mixolimnion effective sealed off the monimolimnion from surface turbulence. High transparency of the upper strata allowed for photosynthesis to occur well into the metalimnion and hypolimnion of the mixolimnion. Thus, the production of oxygen by phytoplankton and its consequent accrual was favored by the depth of the euphotic zone in Pit #10 (Eberly, 1963).

The morphometry of the lake basin also has a profound effect upon meromixis. The wind-protected situation of some alpine lakes is an ideal situation. Vegetation and surrounding hills reduce the effects of the wind in initiating turbulence and eddy diffusion, and the exchange of mixo- and monimolimnetic waters (Findenegg, 1965). The slight protection afforded to Pit #10 by the unvegetated strip pit spoil hills had apparently reduced the effects of the wind. However, as the conductivity data indicate, increased mixing was occurring by the end of the research period.

This then leads one to calculate the stability of meromictic stratification of Pit #10. Hutchinson (1957, p. 512) defines the stability of crenogenic meromixis as the amount of work needed to keep the chemocline at a constant level. Thus, when this parameter was calculated (according to Hutchinson, 1937), the value was found to be rather low in comparison to the other meromictic lakes in North Ameri[illegible] (Table 6).

Nonetheless, the continuous input of iron-rich effluent from the acid-neutralization plant in the form of ferric hydroxide density currents will maintain this meromictic condition while insuring the condition while insuring the continuing functional reliability of this "final cut" reservoir as an integral part of the treatment system.

## CONCLUSIONS

1. The acid mine drainage sludge settling impoundment, Pit #10, was an example of an artificially-induced crenogenic meromictic strip pit

TABLE 6 - STABILITY OF PIT #10 AND OTHER SELECTED MEROMICTIC LAKES (BRUNSKILL, ET AL., 1969)

| Lake | S (g-cm cm$^{-2}$ |
|---|---|
| 1. Clark Reservation Green Lake | 27 |
| 2. Devil's Bathrub | 5.6 |
| 3. Fayetteville Green Lake | 1700 |
| 4. Fayetteville Round Lake | 1650 |
| 5. Pit #10 (5 June 1972) | 3.37 |

lake in association with the acid mine drainage neutralization processes of the Will Scarlet Mine Treatment Plant.

2. The origin and maintenance of impoundment meromixis were from the precipitation of iron as iron hydroxides (primarily ferric hydroxide) during neutralization processes.

3. Though the "stability" of the impoundment is low in comparison to other meromictic systems, the functional reliability continues to perform adequately.

## REFERENCES

Annual book ASTM Standards, Part 23. 1970. Peroxide oxidation and boiling method. ASTM, Washington, D.C. 1052 p.

Brunskill, G. and S. Ludlam. 1969. Fayetteville Green Lake, New York I. Physical and chemical limnology. Limnol Oceanog., 14: 81-829.

__________________, S. Ludlam and W. Diment. 1969. A comparative study of meromixis. Verh. Internat. Verein. Limnol., 17: 137-139.

Cooper, L. H. N. 1937. Some conditions governing the solubility of iron. Proc. Roy. Soc., Ser. B, 124: 299-307.

Eberly, W. 1963 Oxygen production in some Northern Indiana lakes. Proc. 17th Ind. Waste Conf., Purdue Univ., 47: 733-747.

Findenegg, I. 1935/ Limnologische Untersuchungen im Kartner Seen Gebiete. Ein Beitrag zur Kenntnis des Stoffhaushaltes in Alpenseen. Int. Rev. Hydrobiol., 32: 369-423.

______________. 1965. Factors controlling primary productivi[illegible] especially with regard to water replenishment, stratificati[illegible] and mixing. Mem. Inst. Ital. Idrobiol., Suppl. 18: 105-119.

Frey, D. G. 1955 Langsee: A history of meromixis. Mem. lnst. Ital. Idrobiol., Suppl. 8: 141-161.

___________. 1963. Limnology of North America. Univ. Wisconsin Press, Madison. 734 p.

F.W.P.C.A. 1969. Analytical techniques for National Eutrophication Program. Pacific Northwest Lab., Corvallis, Wash., pp. 14-23.

Holland, C., J. Carsaro and D. Ladlish. 1968. Factors in the design of an acid drainage treatment plant. 2d Sym. Coal Mine Drainage, Mellon Inst., Pitts., Pa. pp. 274-279.

Hutchinson, G. E. 1937. A contribution to limnology of arid regions. Trans. Conn. Acad. Arts Sci., 33: 47-132.

________________. 1957. A treatise on limnology. v.I. Geography, physics and chemistry. Wiley, New York. 1015 p.

Jackson, D. and W. Dence. 1958. Primary productivity in a dichothermic lake. Am. Midland Naturalist, 59: 511-517.

[illegible]y, C., E. Birge and V. Meloche. 1935. The carbon dioxide and hydrogen ion content of the lake waters of northeastern Wisconsin. Trans. Wisconsin Acad. Sci., 29: 1-82.

Koehrsen, L. G. and A. F. Grandt. 1970 Mine Drainage Control: Design for Reclamation and Neutralization. Prac. 25th Annual Purdue Industrial Waste Conference, 11 pp.

Kjensmo, J. 1962. Some extreme features of the iron metabolism in lakes. Schweiz. Z. Hydrol., 24: 244-252.

___________________. 1967. The development and some main features of "iron-meromictic" soft water lakes. Arch. Hydrobiol. Suppl. 32: 137-312.

___________________. 1968. Iron as the primary factor rendering lakes meromictic, and related problems. Mitt. Internat. Verein. Limnol., 14: 83-93.

Mortimer, C. 1942. The exchange of dissolved substances between mud and water in lakes. J. Ecol., 30: 147-201.

Newcombe, C. and J. Slater. 1950. Environmental factors of Sodon Lake - a dichothermic lake in southeastern Michigan. Ecol. Monographs, 20: 307 - 227.

Standard Methods for the Examination of Water and Wastewater, 13th edition. 1971. A.P.H.A., Washington, D.C. 874 p.

Vallentyne, J. 1957. Principles of modern limnology. Am. Sci., 45: 218-244.

Welch, P. 1948. Limnological Methods. Blakiston Co., Philadelphia. 381 p.

Yoshimura, S. 1932. On the dichotomous stratification of hydrogen ion concentrations of some Japanese lakes. Japanese Journ. Geol. Geog., 9: 155-185 .

# EFFECT OF STRIP MINE RECLAMATION

on

An Underlying Mine Pool Outflow
in the Southern Anthracite Coalfield
Pennsylvania

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## Introduction

The Commonwealth of Pennsylvania's abandoned mine acid drainage abatement program is in its ninth year. During this period a considerable number of projects, consisting either of contour or terrace grading, were completed. The purpose of most of these projects was to decrease time and area contact between acid-forming material and the unpolluted surface runoff (1)(2). In some cases strip mine reclamation incorporated the sealing of deep mine workings, intercepted by the stripping operations, to prevent an easy access of surface flows into the deep mines.

Generally, the benefit-cost economics do not justify an abatement project which would incorporate strip mine reclamation over an entire deep mine pool area. A suitable condition, when such a project was found to be economically feasible, presented itself in the Swatara Creek Watershed. Furthermore, this mine pool is drained by just one outflow, which simplified the problem of post-construction monitoring.

Upon completion of the project, and following two years of monitoring, it was *found that the volume decrease from the drainage outflow closely coincided with the* Department estimates; however, total acid and iron load abatement exceeded the original estimates considerably.

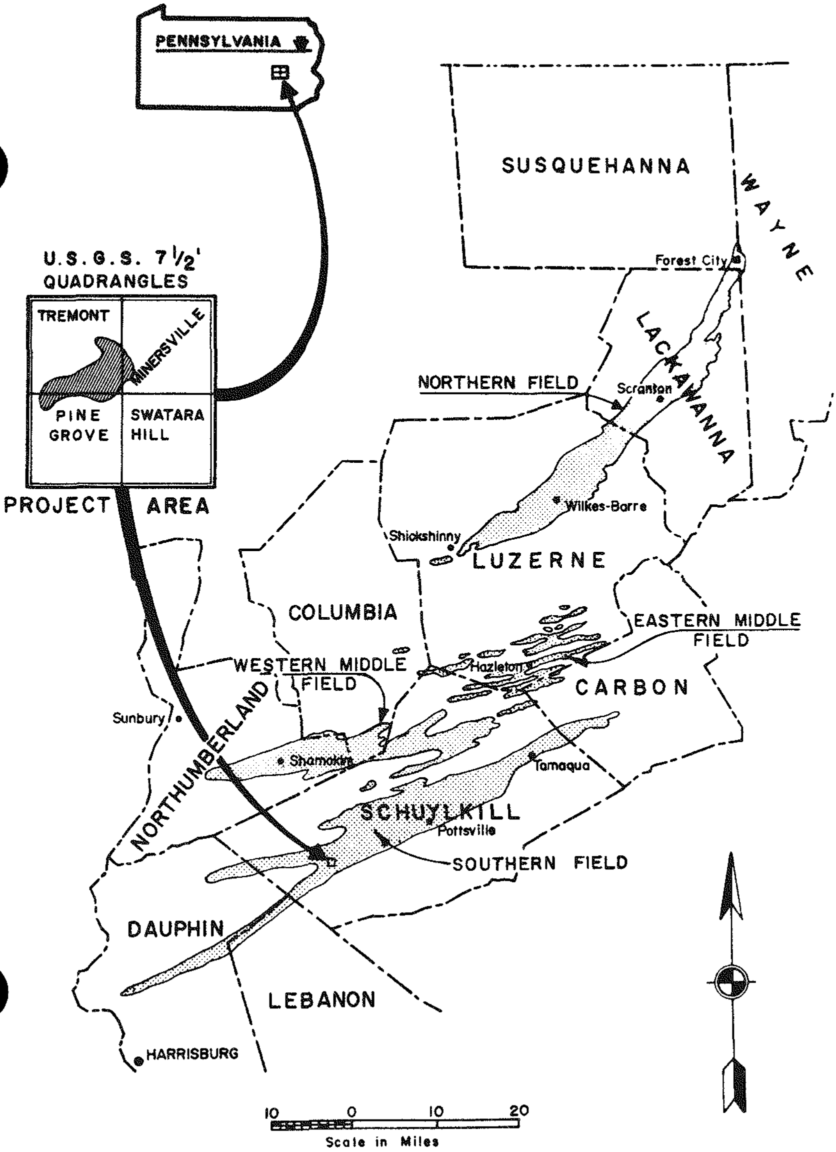
## Location

The project area is situated within the central section of the Southern Anthracite Coalfield, Schuylkill County, Pennsylvania, on the north slope of Broad Mountain, just north of the Borough of Tremont (Fig. 1).

## Mine Pool and Mining Conditions (3)

The mine pool, known locally as the Middle Creek Mine Pool, acts as a collection reservoir for underground drainage, groundwater percolation and any surfac[illegible] flows intercepted by abandoned strip mines. It is formed by a number of inte[illegible]nected deep mines which were driven into the coal veins of the rising limb of [illegible] Donaldson Syncline. The axis of the syncline follows the Good Spring Creek Valley and is buried under some 100+ feet of unconsolidated deposits (Figs. 2 & 3).

The Middle Creek Pool *trends E.N.E. to W.S.W. and is approximately four miles* long. Its width ranges from 400± to 2,000± feet. It is estimated to hold some 93 million cubic feet (2,140± acre feet) of mine water.



ANTHRACITE FIELDS OF NORTHEASTERN PENNSYLVANIA

FIG. 1 LOCATION MAP

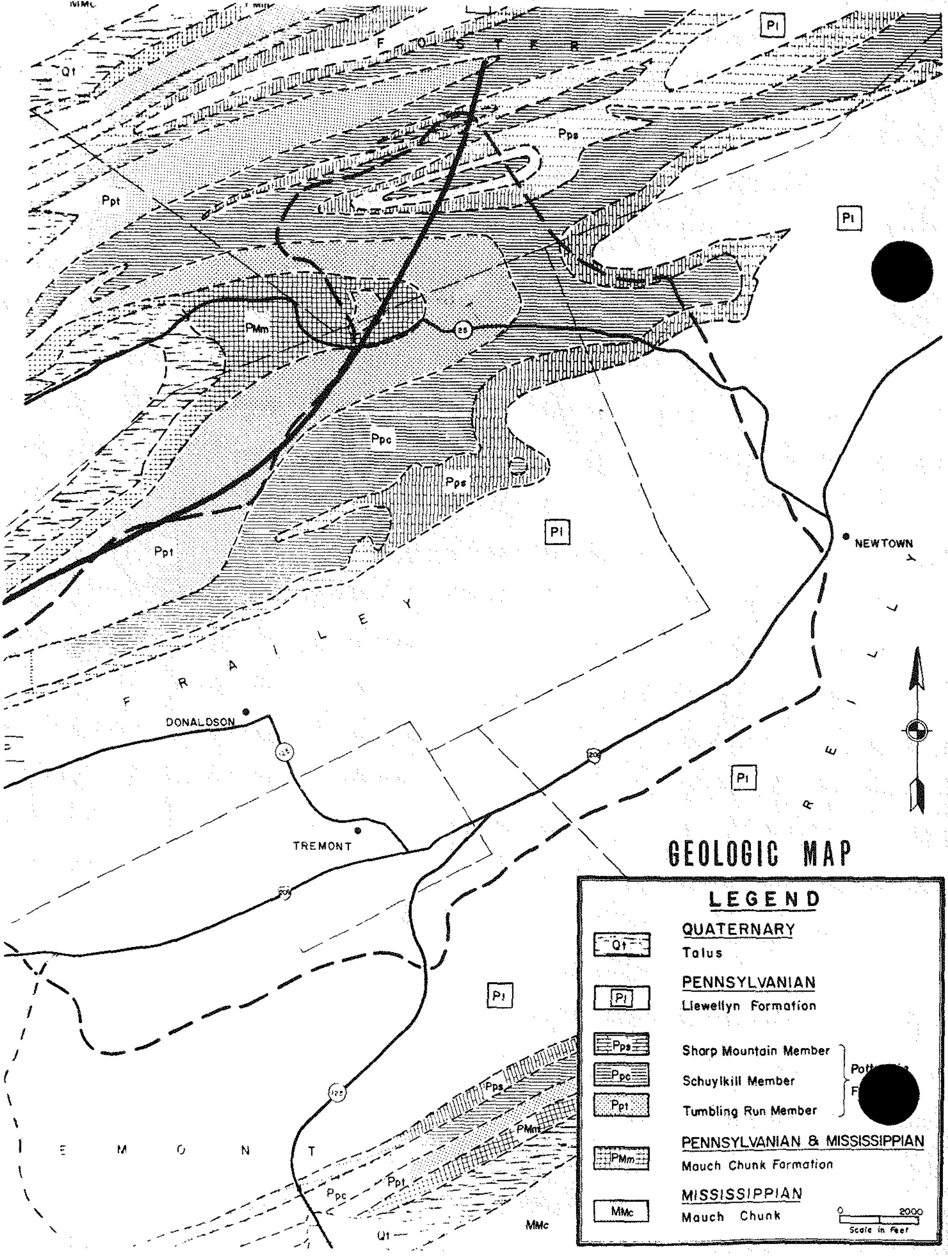
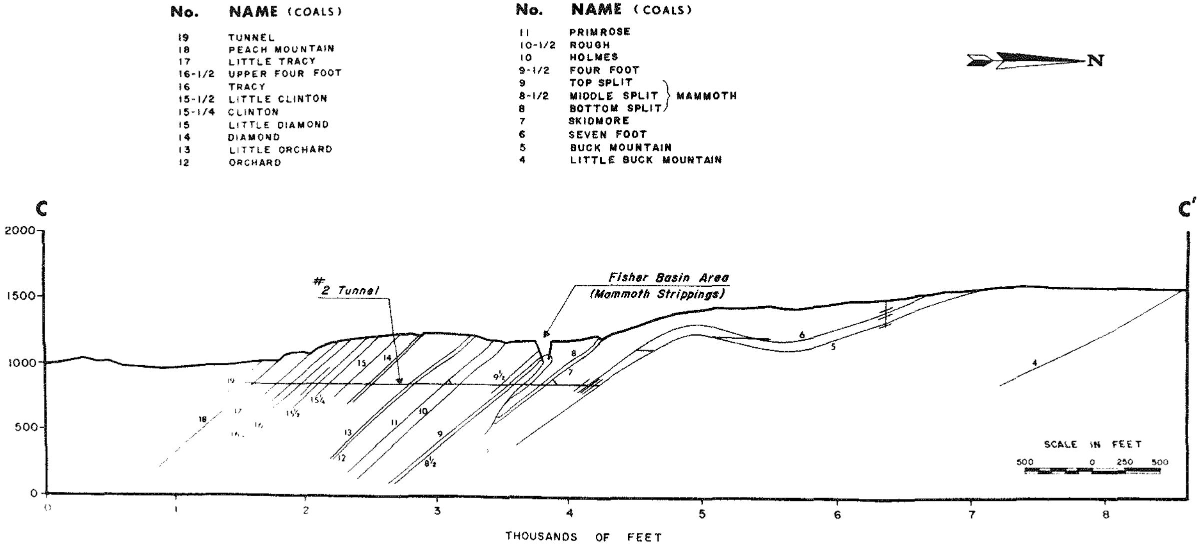


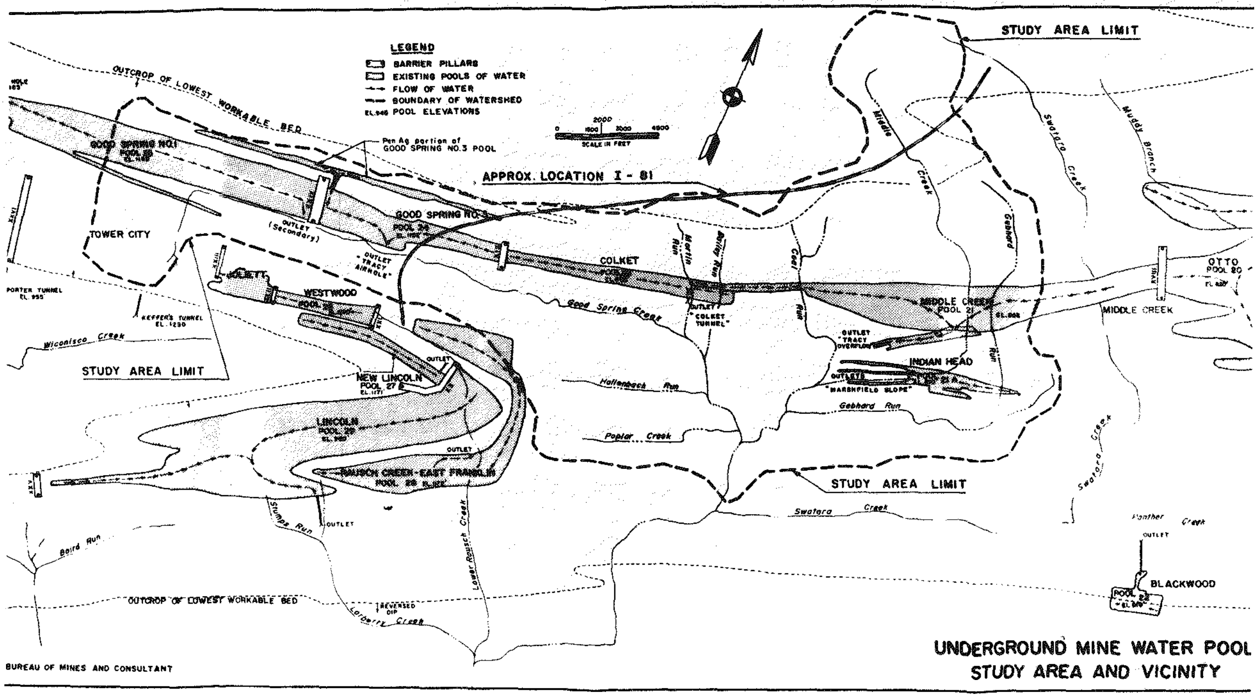
FIG. 2 GEOLOGIC MAP
(from U.S.G.S.)



| No. | NAME (COALS) |
|---|---|
| 19 | TUNNEL |
| 18 | PEACH MOUNTAIN |
| 17 | LITTLE TRACY |
| 16-1/2 | UPPER FOUR FOOT |
| 16 | TRACY |
| 15-1/2 | LITTLE CLINTON |
| 15-1/4 | CLINTON |
| 15 | LITTLE DIAMOND |
| 14 | DIAMOND |
| 13 | LITTLE ORCHARD |
| 12 | ORCHARD |

| No. | NAME (COALS) | |
|---|---|---|
| 11 | PRIMROSE | |
| 10-1/2 | ROUGH | |
| 10 | HOLMES | |
| 9-1/2 | FOUR FOOT | |
| 9 | TOP SPLIT | MAMMOTH |
| 8-1/2 | MIDDLE SPLIT | |
| 8 | BOTTOM SPLIT | |
| 7 | SKIDMORE | |
| 6 | SEVEN FOOT | |
| 5 | BUCK MOUNTAIN | |
| 4 | LITTLE BUCK MOUNTAIN | |

FIG. 3 CROSS SECTION
NEAR NO. 2 TUNNEL INDIAN HEAD COLLIERY
FROM PA. GEOLOGICAL SURVEY



BUREAU OF MINES AND CONSULTANT

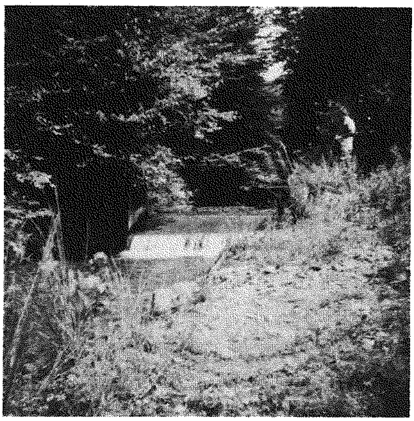
FIG. 4 MIDDLE CREEK MINE POOL LOCATION MAP

To the east, the Middle Creek Mine Pool is contained by a barrier pillar which separates it from the Otto Mine Pool. To the west it borders the Colket Mine Pool. There is no known barrier separating the Middle Creek and the Colket pools, but the Middle Creek Mine Pool occupies the workings in the lower coal seams. The two mine pools overlap for a distance of approximately 2,000 feet (Fig. 4).

It is understood that for a period of time the two pools were connected by a rock tunnel; however, an extensive roof fall effectively separated them at a later date. Inasmuch as the present elevations of the Middle Creek Pool and the Colket pool are 885 and 945, respectively, there seems to be little doubt that the two pools are independent.

The Middle Creek pool is drained by the Tracy Overflow. The overflow is a [illegible]ade trench into the Tracy coal vein which was used in the latter stages of [illegible]ve deep mining to lower the Middle Creek mine water pool. The overflow, which is at elevation 885, was reportedly excavated in 1952.

Tracy Overflow



Tracy Overflow Weir

Prior to the excavation of this trench, when mining was in progress, the water was pumped to the surface at the Middle Creek Shaft, ground elevation 980, and maintained at the 798 level. Since pumping ceased, the mine pool level has risen to elevation 885 and is presently controlled by the Tracy Overflow.

It is estimated that the ground surface recharge area of the mine pool is about 1030 acres, 522 of which were strip mined and left unrestored.

Six streams cross the Middle Creek mine pool area, five of which were inter[illegible]ed by the strip mines. These streams, from West to East, are: Martins Run, Bailey Run, Coal Run, Middle Creek, and Gebhard Run. The easternmost stream, Swatara Creek, was losing its flow into a series of cave-ins caused by undermining. The percentage of flow loss depended upon the flow volume; during low flow Swatara Creek lost all of its flow into the deep mines while during high flow some found its way downstream.

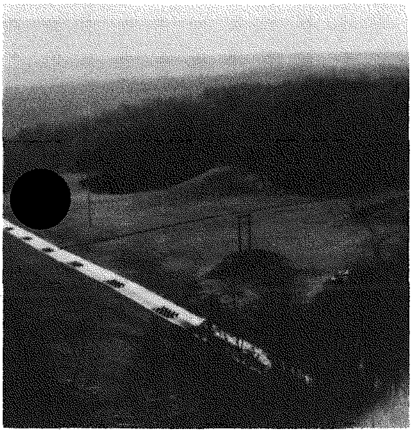
Abandoned strip mine above Middle Creek Pool. Prior to Restoration.

Abandoned strip mine above Middle Creek Pool. Prior to Restoration. Note indications of seasonal drainage.

Restored strip mine. Note flat grading.

Reclaimed strip mines above Middle Creek Mine Pool. Note steeper grade and surface drainage collection channel.

Reclaimed strip mine above Middle Creek Mine Pool. Note drainage collection system and rip-rap protection.



Restored strip mines and creek channel. Note energy dissipators.

## Reclamation Project

The reclamation project consisted of the following:

a. Terrace type backfill of 400 acres of strip mines, using available strip mine waste.

b. Excavation of 15,050 L.F. of diversion ditches above the highwall to direct surface runoff away from the restored acreage into connector channels and thence to the receiving stream.

c. Construction of 16,650 L.F. of stream channels on Martins Run, Gebhard Run and Swatara Creek. Bailey and Coal Runs were flumed across the mined out area prior to the study and construction of this project.

Following the start of construction, right-of-entry difficulties arose with a central property within the reclamation project. Consequently, 122 out of 522 acres of strip mined land as well as the Middle Creek channel could not be restored. The Tracy Overflow is actually located along the southern boundary and is equidistant from the eastern and western boundaries of the above property.

Total cost of construction was $2,313,000. Mean acid abatement in 1976 was 3430 lbs/day, mean iron and sulphate abatement were 443 lbs/day and 13,260 lbs/day respectively. Cost of abatement of one pound of acid per day was $675. The Pennsylvania Department of Environmental Resources bases its benefit-cost ratio primarily upon pounds of acid/day abated, but the number of miles of stream improved, or cleaned, is also taken into consideration.

## Pre-Construction and Post-Construction Monitoring

The acid mine drainage survey was performed by Berger Associates, Inc., under contract to the Department of Environmental Resources. The monitoring of the Tracy Overflow by the consultant's personnel began on October 5, 1969 and terminated on December 23, 1970. Fifty-nine flow measurements and water sample analyses were obtained during this period.

The construction contract for the project was awarded in July, 1973. However, due to the damage by Tropical Storm Eloise, in 1975, the project, minus the central section, was not completed until the fall of 1976.

The Department staff began the post-construction monitoring in December, 1975, some nine months ahead of project completion. During 1976, flow measurements and water samples were obtained once every two months. By the end of the year it became apparent that the estimated abatement did not correspond with the actual data obtained through the year. It was, therefore, decided to carry out the monitoring on a monthly basis. The preconstruction and post-construction flow measurement and water sampling were performed at a 10' wide rectangular weir; however, due to siltation the post-construction flow measurements now are performed with a flow meter.

Tables I and II show the discharge rates and water quality parameters at [illegible] Tracy Overflow, based on mean and median values prior to and following the pro[illegible] construction.

## Discussion

Based on mean flow and water quality figures, reclamation of the entire strip mined area (522 acres) and restoration of the remaining four stream channels, it was estimated that a 43% flow volume reduction could be achieved (3). There was no evident reason to presume that the quality of the Tracy Discharge would be improved inasmuch as only two abatement parameters, the discharge rate and the pollution load, are directly related. That is, percentage abatement of the discharge rate from Tracy Overflow would more or less correspond to that of pollution load; this relation is demonstrated by Morth, Smith & Shumate (4) Figs. 22 & 29.

Various factors such as air accessibility, humidity, temperature, physical properties of the sulphides present in the rock formations, percolation rate through sulphide bearing formations are known to affect the quality of acid mine drainage. Undoubtedly, the changes in some of the above parameters, after construction, must have affected the quality of the Tracy Overflow.

The Department is well aware of the shortcomings of the available data. A number of chemical parameters, which are of significance in evaluating the causes of the chemical changes were not obtained during the study. Furthermore, no monitoring was performed during the years 1971 to 1975 and it is possible that the [illegible]ges took place during this period.

Nevertheless, the following causes that might have resulted in the post-construction chemical improvement of acid mine drainage can be eliminated.

1. Five deep mines, located uphill in adjacent mine pools, were operating during the 1970 survey period and had to resort to pumping. The pumped water was discharged into the strip mines, from where it entered the mine pool. The chemical quality of this pumped water was considerably better than that of the Tracy Overflow. Consequently, the premise that the quality of acid mine drainage had improved due to post-construction diversion of mine pumpage away from the mine pool can be discounted.

2. Total precipitation in 1976 was approximately 7" greater than in 1970. On this basis, the decrease in the Tracy Overflow discharge in 1976 cannot be attributed to a drier season.

TABLE I (3)

(Prior to Construction)

| Description | Min. | Max. | Mean | Median |
|---|---|---|---|---|
| pH | 2.7 | 3.9 | 3.4 | 3.4 |
| Acidity (ppm) | 32 | 250 | 142 | 140 |
| Alkalinity (ppm) | 0 | 0 | 0 | 0 |
| Iron (total) (ppm) | .5 | 57.5 | 19.9 | 22.0 |
| Sulphates (ppm) | 170 | 1300 | 554 | 530 |
| Flow (GPM) | 866 | 6029 | 2471 | 1800 |

TABLE II *

(Post-Construction)

| Description | Min. | Max. | Mean | Median |
|---|---|---|---|---|
| pH | 4.0 | 4.4 | 4.2 | 4.3 |
| Acidity (ppm) | 16.0 | 58.0 | 38.0 | 36.0 |
| Alkalinity (ppm) | 0 | 8 | 2 | 0 |
| Iron (total) (ppm) | .45 | 5.7 | 2.3 | .8 |
| Iron #2 | .35 | 5.2 | 2.0 | .65 |
| Sulphates (ppm) | 120 | 235 | 154 | 140 |
| Flow (GPM) | 591 | 3114 | 1715 | 1440 |

* Results of chemical tests and of flow measurements can be obtained from the Pennsylvania Department of Environmental Resources.

## TABLE III

(Abatement Results)

| Description | Prior to Constr. | | Post Constr. | | Change | | % Change | |
|---|---|---|---|---|---|---|---|---|
| | Mean | Median | Mean | Median | Mean | Median | Mean | Median |
| pH | 3.4 | 3.4 | 4.2 | 4.3 | +0.8 | +0.9 | +23.5 | +26.5 |
| Acidity (ppm) | 142 | 140 | 38.0 | 36.0 | -104 | -104 | -73.2 | -74.3 |
| Alkalinity (ppm) | 0 | 0 | 2 | 0 | +2 | 0 | - | - |
| Iron (total) (ppm) | 19.9 | 22.0 | 2.3 | .8 | -17.6 | -21.2 | -88 | -96 |
| Iron (+2) (ppm) | | | 2.0 | .65 | - | - | | |
| Sulphates (ppm) | 554 | 530 | 154 | 140 | -400 | -390 | -72.2 | -73.6 |
| Flow (GPM) | 2471 | 1800 | 1715 | 1440 | -756 | -360 | -30.6 | -20.0 |

3. Mean acid load reduction in the watershed, from 1970 to 1976, was 22%± as against 80%± at Tracy Overflow. Therefore, general improvement in the watershed was much less than that of the Middle Creek Mine Pool.

It is reasonable to assume that the changes in the chemical quality of the outflow, such as a drop in acidity by 74%±, sulphates by 73%±, iron by 88% mean and 96% median, and discharge rate 30.6% mean and 20% median, can be attributed to the reclamation project (see Figs. 5 & 6). No such changes were observed in the neighboring Colket Mine Pool.

We believe that the following factors had an influence on the chemical improvement of Tracy Outflow.

1. Four hundred acres of strip mines out of a total of 522 acres were [illegible]imed. These strip mines were backfilled with locally available loose strip mine and deep mine refuse material that was scattered around and within the strip pits. The refuse material was prone to leaching, the leachate then entering the mine pool either directly through intercepted deep mine workings or by percolation through roof formations which resulted in further leaching (5).

2. Sidehill runoff between the eastern and western boundaries of the mine pool, a distance of 4± miles, was intercepted by strip mines. Part of the runoff inflow followed mine drifts, intercepted by strip mines, on its way toward the mine pool. These drifts had a direct air access resulting in sustained active breathing by the four-mile-long deep mining complex. The free accessibility of air, its free inflow and outflow, were reduced to 1± mile following strip mine reclamation. Consequently, there was a shortening of the length of the flow path and a reduction of air inflow and outflow (4).

3. Ground limestone was applied to the reclaimed strip mines at the rate of 4 tons per acre. Solution of the limestone may result in formation of calcium sulphate and coat some of the exposed sulphides resulting in a decrease of chemical activity. Inasmuch as the ratio of acidity to sulphates remained practically constant, prior to and after construction (.25±), there was no slow down in the rate of the chemical reaction. This leads us to believe that the extent of available reactive area has decreased (6). The presence of calcium sulphate (selenite) in sulphide bearing rocks below limestone beds has been observed by members of our staff in the Bituminous Coalfield.

4. Limited fluctuation in mine pool elevation.

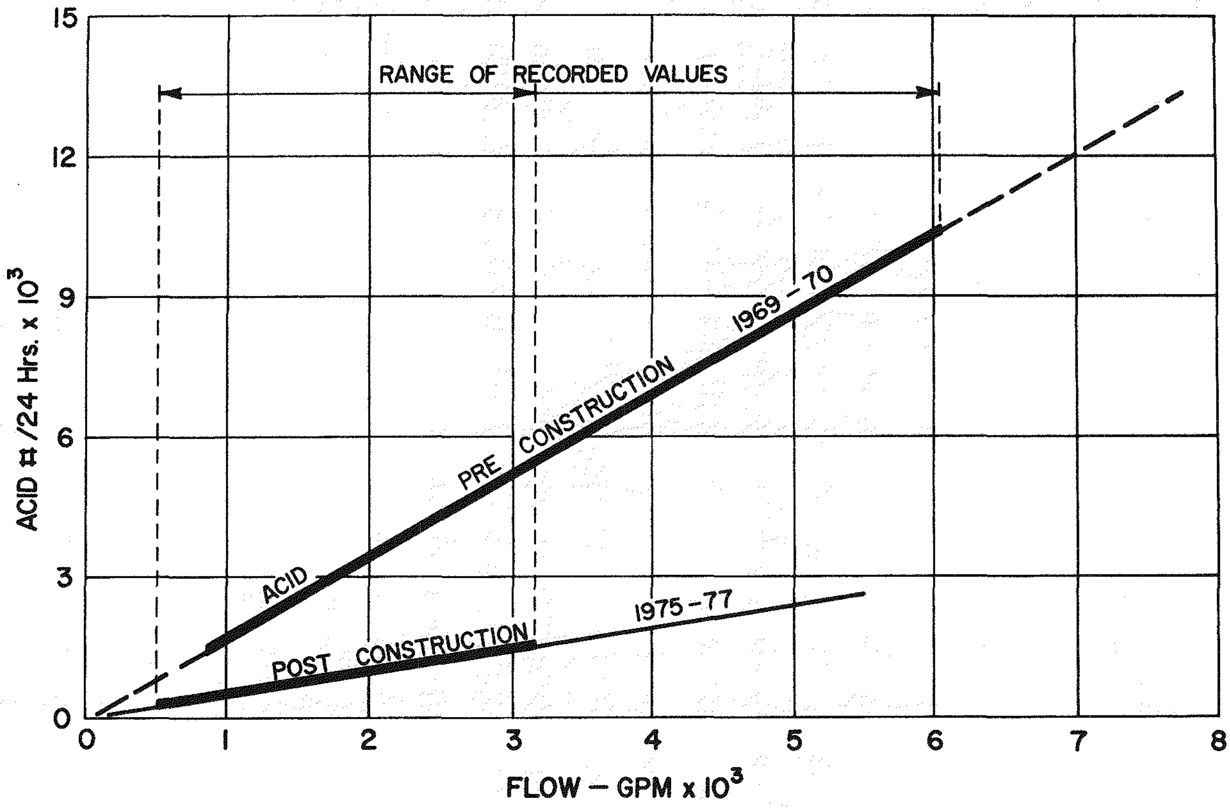
## Summary

The Middle Creek Acid Mine Drainage Abatement Project presented an opportunity to evaluate the results of strip mine reclamation and surface flow diversion over an area covering an entire mine pool. Furthermore, the mine pool is controlled by a single outflow.

While the watershed study was in progress, the justification of such a project was not anticipated and thus only routine chemical testing of acid mine drainage was performed.

The four year gap in monitoring of the Tracy Overflow is probably of no great importance, as the quality of the mine pool water has not been affected by mining conditions or mining operations.

The general improvement of quality in the mine pool water is primarily attributed to the reclamation project. Reduction of free air access, the total length of inflow paths, mine pool level fluctuation, and acid formation in spoil material are believed to be the major factors. Acidity and iron content curves presented in Fig. 6 show a more pronounced scatter in 1970 than in 1976-77.



**ACID/FLOW RELATIONSHIP**
**SAMPLING STATION C-34**
**TRACY OV[illegible]LOW**

FIG. 5 ACID LOAD ABATEMENT
AFTER CONSTRUCTION

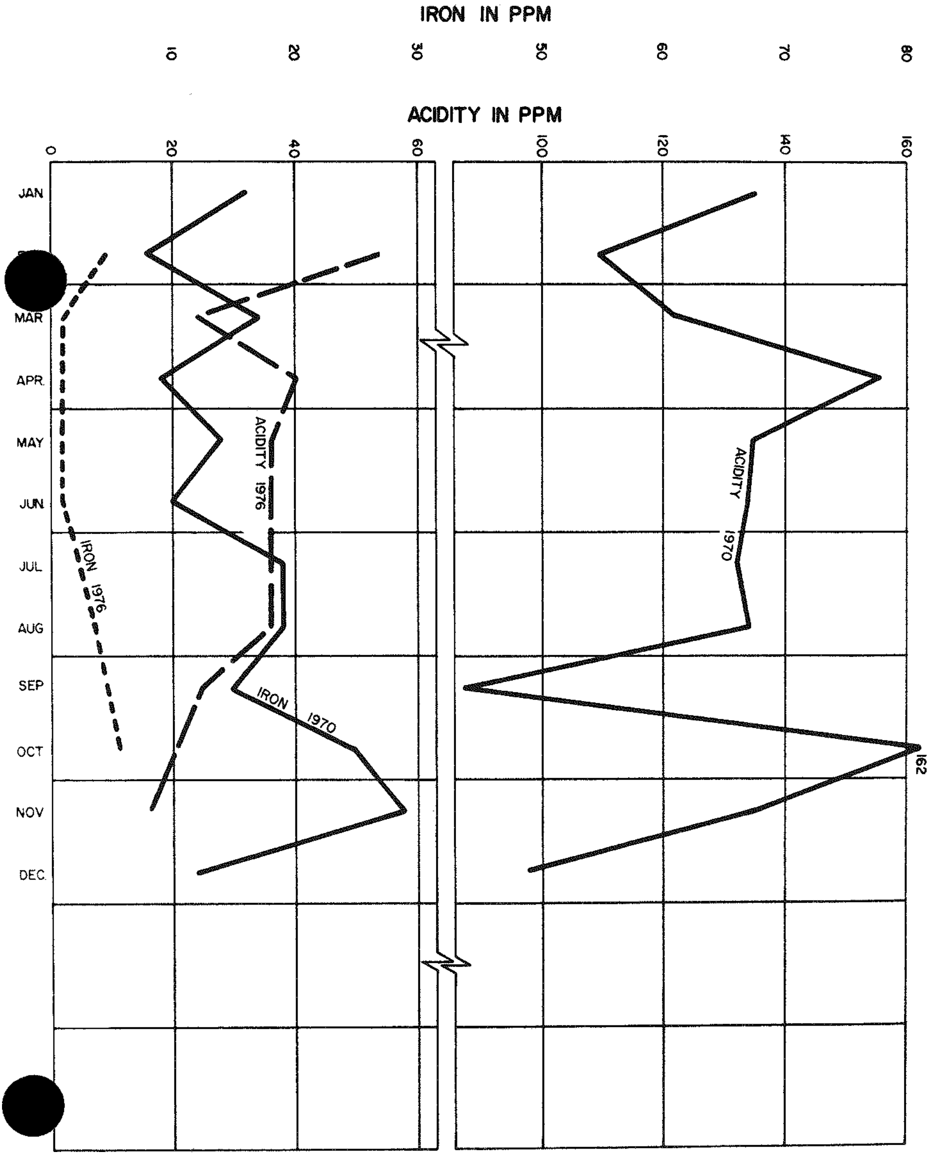


FIG. 6 PRE AND POST-CONSTRUCTION
ACIDITY AND IRON CONTENT CURVES

Monitoring of the chemical parameters and discharge rate measurements is to be continued. The possibility of calcium sulphate coating of the strip mine backfill within the reclaimed strip mines will require testing and evaluation.

It is anticipated that the remaining 122 acres of the unrestored strip mines will be reclaimed eventually, and the channel of Middle Creek will be restored. At the present time, Middle Creek flow represents 2/5 of the volume of the Tracy discharge. Examination of the chemical parameters of the mine inflow and outflow will be expanded for future evaluation.

As of to date considerable proportional reduction in acid, iron and sulphate loads has been achieved. Following a five year post-construction monitoring program, abatement results and their causes should be re-evaluated.

## REFERENCES

1. Caruccio, F. T., and Parizek, R. R. "An Evaluation of Factors Affecting Acid Mine Drainage Production in Western Pennsylvania". Proc. Second Symposium on Coal Mine Drainage Research, Pittsburgh, Pennsylvania (1968).

2. Ohio State University Research Foundation, "Sulphide to Sulphate Reaction Mechanism", Water Pollution Control Research Series 14010, FPS-02/70, F. W. Q. A., Department of Interior (1970).

3. Berger Associates, Inc., "Swatara Creek Mine Drainage Pollution Abatement Project, SL 126-2, Operation Scarlift". Survey report prepared for the Pennsylvania Department of Environmental Resources (1972).

4. Morth, A. H., Smith, E. E., and Shumate, K. S., "Pyritic Systems: A Mathematical Model". E. P. A. - R2-72-002, Environmental Protection Technology Series (November, 1972).

5. Corbett, D. M., "Ground Water Hydrology Pertaining to Surface Mining for Coal - Southeastern Indiana". Proc. Second Symposium on Coal Mine Drainage Research, Pittsburgh, Pennsylvania (1968).

6. Selmeczi, J. G., and Miller, J. P., "Gypsum Sealing in AMD Treatment Plants - An Absolute Index of Scaling Potential". Proc. Fifth Symposium on Coal Mine Drainage Research, Louisville, Kentucky (1974).

# PROGRESS IN METHODOLOGY OF THE LIGNITE MINE WATERS PURIFICATION

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## Introduction

Poland is a country with peculiar climatic conditions, effected by both oceanic [illegible] continental climates. Water resources are small. Among the 28 European countries Poland belongs to the group with the poorest water resources. The present basic water requirement amounts to about 13 billion of m$^3$/annually, of which industry uses 58%, agriculture 27%, and communal economy about 15%. By the year 1980 the annual use will increase to 19 billion m$^3$ and by 1990 to 29 billion m$^3$. According to the calculations of experts this usage will amount to almost 100% of annual drainage of rivers in Poland. Simultaneously about 40% of this outflow will constitute domestic and industrial use. These figures are averages and do not take into consideration variables such as the period of year nor the different areas of the country. The future water needs of the country will be difficult to meet, and will require repeated use of the same water from rivers flowing from source to mouth. Because of the need for reuse, the employment of processes to treat municipal and industrial wastes in order to assure adequate water quality is essential.

Lignite is mined in Poland at the present time in open pits at a depth of 150 m. In the future the depth will reach 400 m. The quantity of waters removed from any particular open pit mine depends on the sizes of the mine and the hydrogeological and atmospheric conditions. Average volume range from 20-120 m$^3$/min.

The quantity of polluted water that is removed from open pits or from underground draining galleries within the pits constitutes 40-100% of total quantity of waters removed. The remaining high quality water is removed by means of draining wells surrounding the mine. The latter waters are pumped directly to surface streams without purification and are directly utilized as a source of drinking or industrial water.

Total quantity of waters drained today from the lignite mines amounts to between 300-320 million m$^3$/year (this figure includes waters from the Belchatow mine that is being constructed). Of this quantity of waters approximately 102 million m$^3$ requires purification each year. As a "rule-of-thumb" lignite deposits produce an average of 5 m$^3$ of water per ton of excavated coal.

The waters discharged from lignite open pit mines represents a significant percentage of the overall quantity of Poland's water resources and are suitable as water sources for domestic and industrial use. Since the lignite mines occur in regions of industrialization with a significant population density, the need for a high level of purification of mine waters is important from the viewpoint of [illegible] resources management and environmental protection.

On the legal side the problems of industrial and domestic waste quality, which can be discharged to water courses were regulated by decrees of 1975. According to these laws rivers and reservoirs are divided into three classes of purity dependent on the assignment of the water. The quality of discharged polluted waters or sewage to surface waters must not deteriorate the waters composition below the level specified for a given class of purity. Table 1 presents information on various purity levels.

Table 1

Classes of Purity for Polish Water Courses and Reservoirs

| Kind of Pollutions | Concentration Unit | Class of Purity I | II | III |
|---|---|---|---|---|
| BOD$_5$ | mg/l | 4 | 8 | 12 |
| Permanganate, C.O.D. | mg/l. | 10 | 20 | 30 |
| Chlorides (Cl) | mg/l | 250 | 300 | 400 |
| Sulphates (SO$_4$) | mg$_4$/l | 150 | 200 | 250 |
| Total Hardness | mval/l | 7 | 11 | 14 |
| Soluble Substances | mg/l | 500 | 1000 | 1200 |
| Total Suspended Solids | mg/l | 20 | 30 | 50 |
| pH | -- | 6.5-8.0 | 6.5-9.0 | 6.0-9.0 |
| Total Iron (Fe) | mg/l | 1.0 | 1.5 | 2.0 |
| Manganese (Mn) | mg/l | 0.1 | 0.3 | 0.8 |
| Temperature | °C | 22 | 26 | 26 |

## Characterization of Waters Drained from Lignite Mines

Chemical composition of the water drained from lignite mines is similar to the ground water in the area of the coal deposit. Water quality as a rule does not exceed permitted indices of pollutions for Class I or II. Some typical data on mine water quality is presented in Table 2.

Table 2

Typical Mine Water Quality, Polish Lignite Mines

| Kind of Pollutions | Unit | Turow Mine I | Turow Mine II | Adamow Mine | Konin Mine Open Pit Patnow | Open Pit Kazimierz | Open Pit Jozwin |
|---|---|---|---|---|---|---|---|
| B.O.D. | mg/l | 0.8-4.2 | 1.2-2.0 | 1-40 | - | - | - |
| C.O.D. | mg/l | 3-36/30 | 22-600/60 | 64-390 | 8-52 | 10-55 | - |
| Chlorides (Cl) | mg/l | 27-42 | 16-52 | 20-100 | 13 | 14 | 13 |
| Sulphate (SO$_4$) | mg/l | 270-480 | 104-350 | 50-150 | 40 | 10 | 18 |
| Soluble Substances | mg/l | 650-1050 | 560-1000 | 600 | 270-500 | 500 | 600 |
| Total Suspended Solids | mg/l | 1000 | 20-7500 | 60-2800 | 44-400 | 73-370 | 350 |
| pH | - | 7.5-8.1 | 7.5-8.1 | 7.0-8.1 | 7.0-8.0 | 7.6-8.3 | 7.0-8.0 |
| Total Iron (Fe) | mg/l | 0.02-2.0 | 0.07-3.0 | 0.0-5.0 | 2.0 | 1.0 | 0.7 |
| Colour (Pt) | mg/l | 10-30 | 30-90 | 15-20 | 3-50 | 10-45 | 30 |
| Turbidity (SiO$_2$) | mg/l | 10-1000 | to opaque | 10-opaque | 5-500 | 30-50 | 10 opaque |

As noted in the data presented in Table 2, the major pollutant is the high concentration of suspended solids, and the related turbidity. Sometimes the oxygen demand is also high.

The suspended solids consist of mineral and organic fractions. The mineral portion is composed of sand, clay and dust grains washed from the bottom, slopes and overburden within the mine. The organic fraction is composed of various size coal particles from the bottom and working coal levels of the mine and at times from active underground draining galleries.

Studies have shown the electric potential of colloidal particles to be 20 μV for suspensions coming from open pit mines Adamow and Konin and approaching 70 μV for suspensions from the open pit mine Turow.

## Purification of Mine Waters

Purification of mine waters in Poland is limited to reducing the excessive concentration of suspended solids to a level stipulated by regulations. The first phase of reduction takes place in the reservoirs or surge tanks of the pumping stations. Here some suspended solids settle out. Further reduction takes place in reservoirs (natural ponds) or artificial sedimentation basins constructed outside the mine pit or at the bottom of the excavation. In Table 3 specific physical characteristics and performance data of the four largest sedimentation basins constructed at lignite mines is presented.

## Research on New Methods of Mine Water Purification

In 1971 research commenced on the purification of lignite mine waters. The [illegible]ctive of this work was to improve the performance of existing sedimentation [illegible]sins. The research was an analysis of the hydraulics of sedimentation basins and the process of the suspended matter reduction and its dependents on retention time and the distance of travel. The results showed that the retention time in sedimentation basins could be reduced from three days to 16-20 hours and equal performance obtained. In order to reduce the retention time the sedimentation within the basin must be correct in relationship to the flow and the construction of the inlet and outlet must be proper.

The investigations had shown, that by means of the sedimentation processes, mine waters with small or average content of suspended solids could be reduced to 30 mg/l by sedimentation basins. These results could only be achieved with favorable atmospheric conditions, i.e., low wind velocities. However, waters with a high content of fine sized suspended solids (the Turow mine) and other waters in inclement weather conditions could not be purified in sedimentation basins to the required level.

Other methods to remove suspended solids from mine waters were investigated. The following methods appeared to have merit:

1. gamma radiation
2. flocculation
3. filtration through sand beds
4. coagulation
5. filtration through plants, i.e., so called grass filters

Studies on the first three processes were conducted in cooperation with the U. S. Environmental Protection Agency. Investigations of the purification of mine waters by means of grass filters are planned to start in 1977.

## Application of Gamma Radiation for the Purification of Mine Waters

Studies were conducted on waters from three lignite open pit mines. The tests [illegible] performed in a radiation chamber enabling the irradiation of water samples with [illegible]sure doses of 200 and 800 k Rad/hour. The source of radiation was cobalt (Co-60), of a quantum gamma energy of 1.33 and 1.17 MeV. Total activity of installed radioactive sources amounted to about 12,300 Ci. The tested samples had volumes of 300 and 1000 ml. To obtain absorption of the applied doses, the required times of irradiation were:

## Table 3

### Physical Characteristics and Performance Data of Major Sedimentation Ponds

| Name of Sedimentation Basin and Year of Construction | Name of Mines | Average Inflow (cubic meters per inch) | Sedimentation Basin Area (hectares) | Present Capacity of Sedimentation Basin (thousand cu.m) |
|---|---|---|---|---|
| Struga Biskupia 1960 | Patnów (Konin) | 20 | 10 | 123 + 126 |
| Rów Główny 1967 | Patnów Jóźwin | 98 | 21.1 | 210 |
| Teleszyna 1968 | Adamów | 17 | 7.8 | 170 |
| Sedimentation basin by the shaft | Kazimierz (Konin) | 20 | 6.0 | 87 |

| | Average Depth (meters) | Theoretical Retention Time (day) | Suspended Solids Concentration on Inlet (mg/l) | Concentration of Suspended Solids on Outlet (mg/l) | Average Percent in Reduction % |
|---|---|---|---|---|---|
| Struga Biskupia 1960 | 2.50 | 4.3 | 60-120 | 20 | 67-84 |
| Rów Główny 1967 | 1.00* | 1.5 | 100-200 | 30-60 | 65-70 |
| Teleszyna 1968 | 2.20 | 7** | 180-250 | 10-20 | 90-95 |
| Sedimentation basin by the shaft | 1.45 | 1.3 | 350 | 33 | 92 |

* - Provisional depth, target depth will be about 2.20 m

** - In relation to expected inflow of about day and a half

| Absorption Dose (K Rad) | Low Radiation Rate (Time-Min) | High Radiation Rate (Time-Min) |
|---|---|---|
| 100 | 30 | 7.5 |
| 500 | 150 | 37.5 |
| 1000 | 300 | 75 |
| 1500 | 450 | 112.5 |
| 2000 | - | 150.0 |

The effectiveness of the radiations on purification was measured by changes [illegible] light transparency, oxygen consumption, iron content and the zeta potential [illegible] the suspended solids particle. The physico-chemical composition of the waters [illegible] similar to that presented in Table 2. Typical results of the test series are presented in Figures 1 and 2.

The results showed that Co-60 gamma radiation accelerated the sedimentation of suspended solids in the tested mine waters. The effect is observed starting with the absorbtion dose of 500 k Rad.

Changes in sedimentation speed were observed when the water was treated prior to radiation. In some cases improvement in radiation sedimentation was noted. This occurred in tests where small changes in pH were made. A change in settling rate, independent of radiation, was observed when just pH changes were made.

The increase in sedimentation rate is dependent to a greater or lesser degree on the absorbed radiation dose. This relationship, as a rule, is directly proportional. The greatest changes in the settling velocity, under the influence of radiation, were those with a large natural oxygen demand.

Tests, in which pH value was measured before and after radiation, showed that radiation caused a decrease in pH in the tested waters. The change in pH is subject to the absorbed dose. The pH decrease is fastest within the 500-1000 k Rad range. For equal absorbed radiation doses, equal pH value reductions are obtained, independent of whether the sample was irradiated at 200 or 800 k Rad.

Irradiation had a small effect on the zeta potential of particles of colloidal suspended matter. The observed changes are difficult to define, and depend probably both on the radiation dosing rate, and on the dosing velocity, as well as the chemical composition of the mine waters. In no cases were there observed definable changes in the zeta potential, that could explain increase in the settling velocity of colloidal suspended matter. As opposed to zeta potential, oxygen demand of the tested waters undergoes a singificant reduction after radioactive treatment, and the effect was intensified by an increase in absorbed dose. It is evident that in waters with a large natural oxygen demand, radiation will increase the removal of suspended matter.

## Employment of Flocculants in Purification of Mine Waters

### Laboratory Tests

Investigations of the flocculation process were performed on samples of one $dm^3$ volume on a six-place jar test unit coagulator. Fast mixing was at a velocity of 80 rev/min and lasted for two minutes followed by a slow mixing at a velocity of 20 rev/min for twenty minutes. All types of flocculants, anionic, and cationic, were tested.

Polyelectrolytes were dosed as water solutions with concentrations of 0.05-0.5%, while the remaining chemicals were dosed as 1-5% water solutions.

After flocculation and sedimentation for 20-30 minutes, the following measurements were made: colour, turbidity, alkalinity, pH and oxygen demand. In some cases the analyses were augmented with hardness, and iron measurement. In addition the electrokinetic potential of both the colloidal particles of raw water, and the coagulated particles were determined.

In research work of coagulation with the best flocculants, the influence of pH and temperature on the process was determined. The doses of polyelectrolytes were varied within limits of 0.1-5.0 $g/m^3$. The effect of pH was determined by adjusting the pH between 5 and 11 with 0.1 n of soda lye, or 0.1 n of hydrochloric acid. The temperature of the tests was controlled with a temperature controlled immersion bath. The temperature was varied within limits of 273 to 296 K for water from the Turow mine, from 275 to 296 K for water from Konin-Patnow, and from 276 to 296 K for water from Adamow.

Investigated in the laboratory tests were 18 flocculants of American and Polish production as shown in Table 4.

Table 4

Specification of Flocculants Used in Laboratory Tests

| Name of Flocculant | Type | Manufacturer |
|---|---|---|
| Calgon M-502 | cationic | Calgon Corporation USA |
| Calgon M-503 | cationic | " |
| Calgon M-550 | non-ionic | " |
| Calgon M-570 | anionic | " |
| Calgon M-580 | anionic | " |
| Calgon M-590 | anionic | " |
| Calgon WL-2640 | cationic | " |
| Calgon WL-2570 L | cationic | " |
| Polyhall 295 | anionic | Stein-Hall |
| Polyhall 297 | anionic | " |
| Polyhall 650 | anionic | " |
| Polyhall 540 | anionic | " |
| Polyox | non-ionic | Union Carbide Corporation USA |
| Rokrysol WF 1 | non-ionic | Nadodrzańskie Z-dy Przemyslu Organicznego "ROKITA" - Poland |
| Rokrysol WF-2 | anionic | " |
| Rokrysol WF-3 | cationic | " |
| Rokrysol WF-5 | cationic | " |
| Gigtar | anionic | Tarnowskie Zaklady Przemyslu Azotowego Tarńow - Polska |

The laboratory tests showed that the most suitable flocculants for the purification of mine waters were cationic polymers with high molecular weights. The most effective of those investigated were Calgon 502 and Calgon 503 and of polish production Rokrysol WF-5.

The required doses of these flocculants were 0.1-5.0 mg/l and were dependent on the origin and quality of the mine water. Doses within the limits of 0.5-3.0 mg/l were sufficient in purification of waters with low and average pollution level from the mines of Konin and Adamow. For waters from Turow the required dose sometimes exceeded 5.0 mg/l. With the above doses of Calgon 502 the level of turbidity reduction in Adamow mine waters was 80-97%, oxygen consumption 16-80%. For waters from the Konin mine the reduction was 80-98% and 30-60% respectively. In waters from the Turow mine the results varied within wide ranges, turbidity within 20-99%, oxygen consumption

30-80% and in some case no reduction in turbidity or oxygen consumption was attained. With the application of the polish flocculant, Rokrysol WF-5, the effects were on the average 30% worse.

The investigations did not indicate any visible influence of temperature changes within the 275-296 K limits on the effects of purification with the employment of cationic flocculant.

Raising the water pH to 9-10 improved the performance of the flocculant. The tests showed that in the majority of cases some unknown change in the zeta potential was causing both destabilization in the colloidal system, and the process of flocs formation. In some cases an increase in zeta potential after addition of polyelectrolytes, in relation to value in raw water was observed. Despite this increase the process of floc formation was occurring. One may conclude that in these cases zeta potential was not decisive in the colloid stability. The investigations showed that in the flocculation processes, the temperature of water does not effect the changes in the zeta potential.

## Field Tests

Field tests constituted the second phase of research work on flocculants. For this an experimental sedimentation basin near the Adamow mine was constructed.

The objective of this part of the investigations was primarily to verify the results obtained in the laboratory. The tests comprised mainly of:

-investigations of flow hydraulics in the sedimentation basin
-technological tests of flocculation processes

The experimental sedimentation basin was constructed in the neighborhood of a large sedimentation basin purifying the waters drained from the Adamow mine. Waters for the experimental sedimentation basin were taken from a ditch draining the Adamow mine waters. The dimensions and the shape of the sedimentation basin are shown in Figure 3. Flocculant solutions were dosed by means of a piston pump to an inlet well, to which mine water flowed. After gravitational mixing the water with the added flocculants, the treated water flowed by an open ditch to the sedimentation basin. The ditch was fitted with partitions causing local dammings of the waters to improve mixing. After reaching the pond the water flowed into an ante-chamber, where existing natural conditions prompted slow mixing. The water then flowed through an overflow structure into the sedimentation chamber proper.

The sedimentation basin was equipped in a manner that enabled regulation of the flow over a wide range. Continuous measurement of the volume was made. Samples of waters at determined time intervals were taken with automatic equipment. In addition wind velocities were measured. The bottom and the walls of the sedimentation basin were lined with a layer of plastic, preventing the infiltration of water into the soil.

Total capacity of the sedimentation basin, after its filling to a depth of 1.20 m was 670 $m^3$, and to depth of 2.20 m - 1536 $m^3$.

Two flocculants, Calgon 502 and Rokrysol WF-5, which had the best results in the laboratory phase were used in the field tests. Flocculants were dosed as 0.1-0.5% solutions. The doses were varied from 0.5 to 2.0 mg/l. The effects of the flocculant was judged mainly through measurement of turbidity of the water at the inlet and outlet of the sedimentation basin. Water samples were being collected sporadically for more detailed analysis.

On the whole the field tests confirmed results which were obtained in the laboratory investigations. Mine waters after passing through experimental basin without the addition of flocculation aids, were reduced in turbidity on an average from 40-50 NTU down to 20-30 NTU, or a corresponding decrease in suspended solids from 80-220 mg/l to 30-40 mg/l. The use of flocculation aids caused the turbidity to be reduced to 10-12 NTU, which corresponds to the value of suspended solids of 8-12 mg/l. Optimal dose of Calgon 502 flocculant was 0.75-1.0 mg/l.

## Laboratory Tests of the Flocculation Process Parameters

### Influence of Concentration of Dosed Solutions on the Effects of Purification

Tests were performed on the Adamow mine waters with an average turbidity of 40-50 NTU, and on waters from the Turow mine with a turbidity of 350-400 NTU. For these tests the flocculant Calgon M-502 in 7 dilutions from 0.025 to 2.0% and doses from 1 to 20 ppm values was used.

The tests were made using the following procedures:

| | | | |
|---|---|---|---|
| -fast mixing | 80 rev/min | - | 8 mins. |
| -slow mixing | 20 rev/min | - | 20 mins. |
| sedimentation | | - | 20 mins. |

Results of tests showed that the concentration of the applied flocculant did not effect the performance of the flocculant.

### Influence of Fast Mixing Time on the Effects of Flocculation

In the first series of laboratory tests uniform times of mixing were employed, e.g. two minutes of fast mixing, twenty minutes of slow mixing and twenty minutes of sedimentation. Selection of cationic flocculant, as the most suitable ones, caused an additional analysis be made of effectiveness of the mixing time, chiefly fast mixing.

These tests were made with Adamow mine waters with a turbidity of 40 NTU. Calgon M-502 in concentration of 0.1% and in doses of 0.1, 0.3, 0.5, and 1.0 ppm were used. The time of fast mixing (80 rev/min) was varied from 1-30 minutes. Results of tests are presented on Figure 4.

As seen, the length of fast mixing had a significant influence on the effects of turbidity removal. It was determined that the best time of fast mixing, independently of the flocculant dose, was 8-20 minutes. Longer periods did not improve the performance signifcantly.

## Conclusions

1. In the majority of cases the only pollutant of waters discharged from lignite open pit mines in Poland is the excessive quantity of suspended solids and the resulting high turbidity and colour.

2. The current technology in Poland to purify mine waters is based on utilization of the sedimentation process. Large sedimentation basins are used with retention periods of 1-5 days. In favorable weather conditions a reduction suspended solids of 60-95% occurs, leaving an effluent concentration of 20- mg/l. In inclement weather and with those waters with high contents of colloidal particles, the basins do not produce satisfactory results.

3. Laboratory investigations of the employment of radiation processes in purification of mine waters gave positive results enabling a three-fold acceleration in the settling velocity of suspensions, after employment of adequate doses of radiation.

4. Laboratory and field tests have shown that the application of flocculants increased the settling velocity of the suspended solids in mine waters and

produced an effluent with less than 20 mg/l. The most suitable flocculants were the cationic polymers with high molecular weight.

5. Tests on water purification optimization with flocculants indicated that the length of time rapid mixing occurred played a significant role in performance and usage of chemical reagents. The best results were obtained with a mixing period of 8 to 10 minutes.

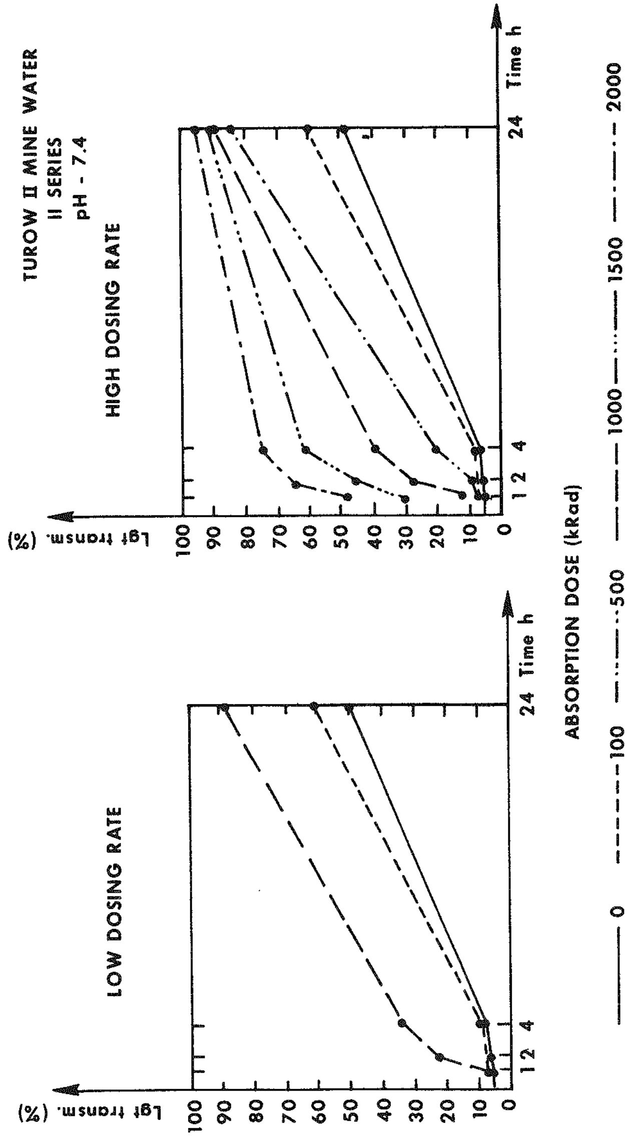
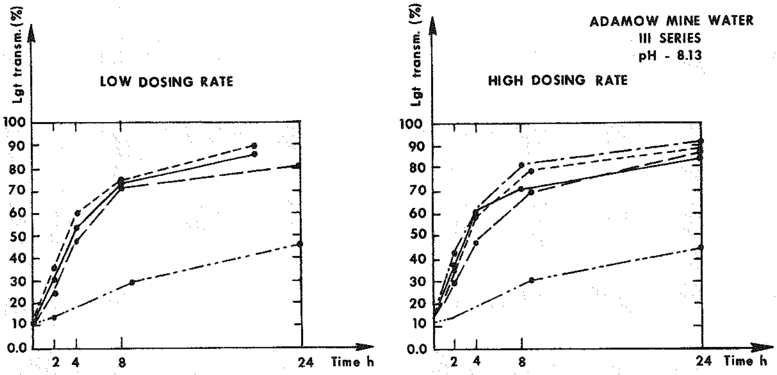
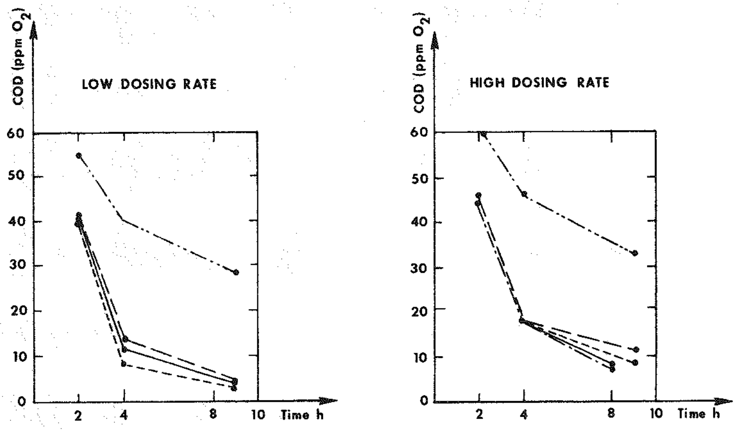


FIGURE 1. EFFECT OF RADIATION TIME ON LIGHT TRANSMISSION



RADIATION APPLICATION EFFECT



CHANGE OF COD

FIGURE 2. EFFECT OF RADIATION TIME ON LIGHT TRANSMISSION AND COD

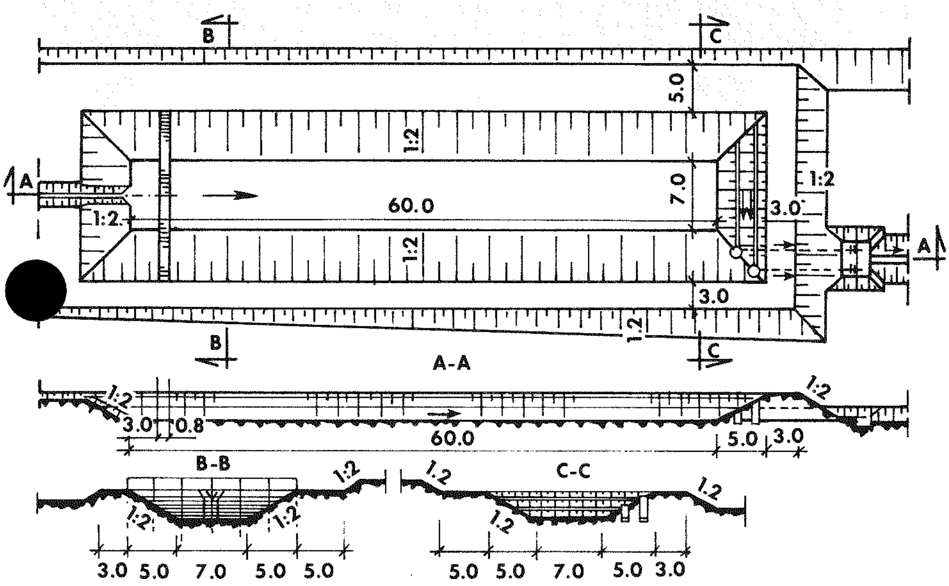


FIGURE 3. DESIGN OF EXPERIMENTAL SEDIMENTATION POND

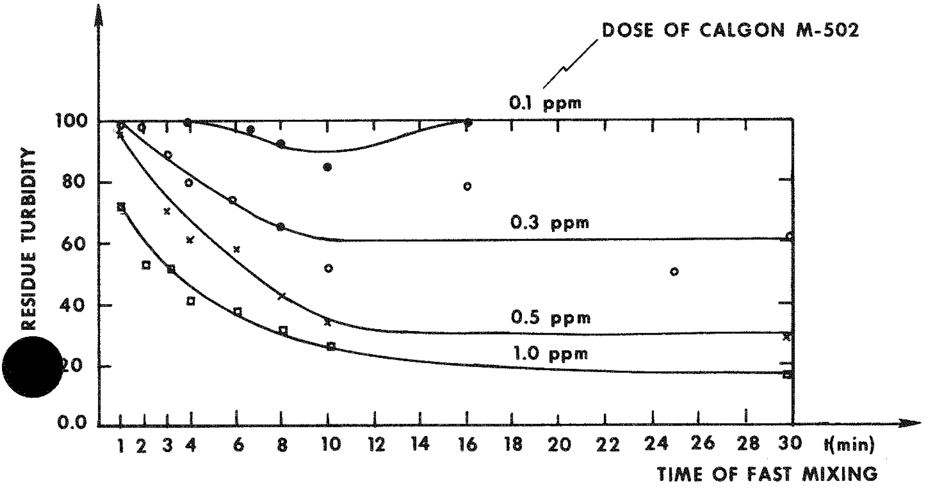


FIGURE 4. EFFECT OF TIME LENGTH OF FAST MIXING ON THE TURBIDITY REMOVAL

# A Mathematical Model for Determining the Optimal Locations of Coal Mine Drainage Neutralization Plants

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## THE COAL MINE DRAINAGE PROBLEM

Within the Appalachian Region of the United States there are 5,700 miles streams rendered continuously acidic due to coal mine drainage (CMD). An additional 4,800 miles of streams are intermittently degraded by drainage discharges. Although an Appalachian regional problem, coal mine drainage pollution occurs to some extent in all coal mine regions east of the Mississippi River. Many streams of this area are severely degraded. Federal and state regulations (Federal Register, April 1977) require effluent quality control for active mining operations. Accordingly, outfalls from abandoned mining operations represent the predominating pollution source, some of which can be controlled only by chemical treatment. Besides reducing the recreational potential of a particular stream as a fishery, CMD also interferes with municipal and industrial water supplies, reduces the capacity of the stream to assimilate organic wastes, poses a corrosive threat to bridges and other public works, and is aesthetically displeasing.

The formation of coal mine drainage is a complex process affected by geological, physical, hydrological, chemical, and bacteriological factors. Lachman and Lovell (1973) and Lorenz and Stefan (1969) have discussed each of these factors separately and qualitatively described their effects on the production of acid. Although the exact formation mechanism is not fully established, it is known that CMD results from the oxidation of insoluble pyrite ($FeS_2$) and the solubilization of other mineral components. Pyrite is present in the unmined coal and in the strata associated with coal.

When pyrite is exposed to air and water, soluble ferrous sulfate and sulfuric acid are produced:

$$2FeS_2 + 7O_2 + 2H_2O \rightarrow 2FeSO_4 + 2H_2SO_4$$

Subsequent oxidation of the ferrous sulfate produces a ferric sulfate as follows:

$$4FeSO_4 + O_2 + 2H_2SO_4 \rightarrow 2Fe_2(SO_4)_3 + 2H_2O$$

The reaction can proceed to form insoluble ferric hydroxide or basic ferric sulfate:

$$Fe_2(SO_4)_3 + 6H_2O \rightarrow 2Fe(OH)_3 + 3H_2SO_4$$

$$Fe_2(SO_4)_3 + 2H_2O \rightarrow 2Fe(OH)SO_4 + H_2SO_4$$

The basic ferric sulfate and ferric hydroxide will precipitate and the mixture of the two forms the brownish-yellow precipitate known as "yellowboy" which commonly coats the bottoms of CMD streams. As protons are being formed by the above equations, the pH of the water is lowered. At these lower pH's, other metallic ions in the mine strata (e.g., aluminum and manganese) become soluble and also enter the mineralized waters.

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## CONTROL MEASURES

Several measures have been developed to control coal mine drainage. The Appalachian Regional Commission (1969) has identified 24 possible CMD control measures, 12 of which have had sufficient use to allow for an assessment of their costs. The complexity of these techniques ranges from surface land reclamation, which reduces the amount of pyritic material exposed to air, to sophisticated treatment alternatives such as electrodialysis and reverse osmosis. All of the known corrective techniques, whether tested or untested, fall into four categories:

1.) at source controls
2.) permanent containment of the CMD
3.) dispersion or dilution of the CMD
4.) treatment of the drainage, preferrably near its origin location

Preventative measures, though preferrable, often are impractical and inadequate, necessitating treatment of these waters. Though long term with continuing costs, neutralization treatment is the most reliable, economically feasible alternative as evidenced by its widespread application. Baker, Inc. (1974) listed 14 reagents that could be used to neutralize CMD. All of the reagents are alkalis which when mixed with CMD, react to reduce the hydrogen ion concentration, and precipitate the contaminating heavy metals.

Most of the neutralization processes to date have used calcined lime (CaO), hydrated lime ($Ca(OH)_2$), or limestone ($CaCO_3$). Lovell (1973) stated that limestone is the least expensive reagent to purchase, but has a slow response time. The choice of an alkaline reagent is dependent upon the following factors:

1.) cost of the reagent
2.) availability of the reagent
3.) chemical nature of the CMD
4.) reaction time of the reagent
5.) characteristics of the resulting sludge

Treatment by neutralization with alkaline reagents will be the principle control measure considered in this study.

## THE MODEL

### Purpose

To evaluate coal mine drainage control policies, an efficient method for the preliminary screening of alternative policies can be helpful. A mathematical programming formulation can identify those policies worthy of further plan-by-plan analysis using more detailed, more accurate, and generally more expensive simulation models. The prescriptive mathematical programming model is presented as a front-end approach, not a substitute, for more exact methods of analysis.

The planning program of improving the water quality of a basin polluted by coal mine drainage is multi-faceted. Broadly put, the planning objective is the [illegible]mination of the set of control measures that will improve drainage quality [illegible] different sources so that prescribed water quality goals for the basin can [illegible] met at a minimum cost.

Six major aspects must be evaluated before a prescriptive model can be developed to assist attainment of the objectives for a particular watershed:

1.) What types of control measures are to be considered?
2.) Where are the possible locations of these control measures?
3.) What chemical parameters are to be modeled?
4.) In what terms will the water quality goals be specified?
5.) For what areas in the watershed are the water quality goals to be met?
6.) What is the hydrological-water quality nature of the basin?

The following sections will discuss each of these aspects in light of the model being presented.

## Selection of Control Measures

It will be assumed that only chemical treatment plants are possible control measures. Although this assumption is made in order to keep the model relatively simple and relevant, all feasible preventive measures to reduce acid loading should be accomplished prior to treatment. Martin and Hill (1968) presented calculations which indicate that the application of conventional at-source controls to coal mine drainage throughout the United States would not result in significant reductions of this pollution in the future. Basing their calculations on an assumed five percent increase per year in CMD production, and an average at-so[illegible] effectiveness of seventy percent, they concluded that by the year 1990, the to[illegible] acid load to streams in the United States would approach the original high leve[illegible] of the 1960's. They conclude only the application of more effective control measures, as chemical treatment, could favorably alter the future CMD pollution.

## Potential Locations of the Control Measures

The model will assume that the planning agency responsible for implementing a CMD abatement plan has predetermined that there are N possible sites in the watershed at which chemical treatment plants could be constructed. This assumption precludes the model from being a site-selection optimization model. A site-selection model would entail the use of a benefit-cost analysis requiring the assessment of the overall benefits derived by minimizing the pollution versus the cost of water treatment. The potential response of alternative control measures could be tested by this model by assuming some percentage acid loading reduction at any given monitoring location. Separate evaluations could provide a basis for the proposed level of reduction. By limiting the number of potential plant sites, the model being developed becomes cost-effective, i.e., the model will determine the minimum cost of meeting water quality goals through the construction of p plants at N possible sites in a watershed ($p \leq N$).

## *Chemical Parameters to be Modeled*

The chemical parameter that will be used in a model as a measure of the water quality is the net acidity. Net acidity is defined to be the difference between the acidity of a water, determined by titrating a sample with a standard base to a pH = 8.3, and the alkalinity of a water, determined by titrating a sample with a standard acid to a pH = 4.5.

The net acidity has characteristics that make it particularly attractive for modeling purposes. Rozelle (1968a) has shown that this parameter can be regarded as conservative as it is transported through a stream. For example, in the system shown in Figure 1, the net acidity concentration at point c can be calculated by

$$C_c = (C_a Q_a + C_b Q_b)/Q_c \tag{1}$$

where:

$C_i$ = the net acidity concentration at point i = a,b,c ($m/l^3$)

$Q_i$ = the flow at i = a,b,c ($l^3/t$)

Equation (1) is a statement of the conservation of mass for net acidity and could be rewritten as

$$NA_c = NA_a + NA_b \tag{2}$$

where:

$$NA_i = kC_iQ_i = \text{the net acidity at point } i = a,b,c \ (m/t)$$

(k is a unit conversion factor)

Figure 2 illustrates the predictive capability of equation (1) for stream data collected in northeastern Pennsylvania.

For the situation in which there are s tributary inputs above point c, equation (2) could be expanded to the form

$$NA_c = \sum_{i=1}^{s} NA_i + NA_j^u \qquad (3)$$

[illegible]re $NA_j^u$ is the net acidity loading entering the main stream above point c via direct surface runoff, ground water inflow, or direct precipitation.

Selection of Chemical Parameters to be Used as Water Quality Goals

In order to improve the water quality at a monitoring point in a CMD basin, a planner must specify a water quality goal to be met, and then determine the pollutant reduction necessary to meet this goal. For the model being developed, the goal will be expressed in terms of pH. U.S. EPA Final Effluent Guidelines requires an effluent pH be maintained in the range of 6.0 to 9.0.

It is possible to develop a pH-net acidity relationship for a given watershed, although geological differences between watersheds make it difficult to establish a general pH-net acidity relationship applicable to all areas. Figure 3 illustrates the pH-net acidity curve developed for the Bennett Branch of Sinnemahoning Creek in northcentral Pennsylvania. The general slope of the curve and the increasing variation of the data about the fitted line for decreasing pH's is likely to be representative of all CMD basins. The latent acidity in CMD as controlled by the water's buffering equilibria is principally responsible for the variation of pH about the fitted line.

Selection of Areas for Which Water Quality Goals are to be Met

The selection of the areas in a watershed for which quality control points are established will be dictated by the problem framework. If the modeler must be concerned with industrial water users, then the control points should be located near potential or existing industrial sites. If it is desired to achieve a water quality of the main stream in the watershed capable of supporting game fish then the quality control points could be equally spaced along the main stream at a prescribed interval or they could be located downstream from each polluted tributary entering the main stream.

Hydrological and Water Quality Considerations

Within a CMD basin, streamflows and pollutant loads vary spatially and temporally. The proper development of a CMD prescriptive model must account [illegible] these variations. Consequently, both hydrological and water quality predic[illegible] equations will allow the model user to estimate the flow magnitudes at any point within a watershed corresponding to a specified design flow, e.g., the ten year recurrence interval low flow. The flow-water quality predictive equations then permit the estimation of the pollutant load carried at any point in the basin during the design flow. The base data used in the development of this model and the cited example were made available by Mr. Marvin White, Berger Associates, Inc., from a study of the Bennett Branch funded by the Commonwealth of Pennsylvania.

## Model Formulation

The basin system will be conceptualized as shown in Figure 4. Potential treatment plant sites exist on a number of acid tributaries, which will be denoted by $i \leftarrow \{1, 2, \ldots N\}$. Locations in the watershed where quality standards will be specified will be denoted by $j \leftarrow \{1, 2, \ldots M\}$.

Based on the concept that the net acidity is a conservative parameter, the following situation holds true for a stated flow condition in a watershed. Given a stream that is fed by s tributaries, the net acidity at any point j in the stream is defined by:

$$NA_j^e = \sum_{i=1}^{s} t_{ij} NA_i + NA_j^u \qquad (4)$$

where:

$NA_j^e$ is the existing net acidity at point j (m/t)

$t_{ij}$ is the transfer coefficient between point j and tributary i (m/m)

The transfer coefficient relates the change in mass of net acidity at point j caused by a unit input of net acidity from tributary i. Since the net acidity is being regarded as a conservative parameter, the value that the transfer coefficient can assume is one or zero, depending on whether tributary i is above or below point j.

$NA_i$ is the net acidity contained in tributary i (m/t), and $NA_j^u$ is the net acidity contained in direct surface runoff, ground water inflow, precipitation on the main stream, and in unmonitored tributaries located above point j (m/t).

Equation (4) is the transfer equation for the system and states that an amount of net acidity, $NA_j^e$, occurring at point j must be coming from either controllable sources, $\sum_{i=1}^{s} t_{ij} NA_i$, or uncontrollable sources, $NA_j^u$. Since the net acidity is conservative, this allows for an easy inventorying of pollution in the basin.

The purpose of the monitoring points established in the watershed is to evaluate the water quality. The water quality at a monitoring point, when expressed as pH, will vary according to the acid loading of the stream at that point. The total acid load flowing past a monitoring point is related to the pH through the expression:

$$NA_j^e = kQ_j f^{-1}(pH_j^e) \qquad (5)$$

where, for the monitoring point j,

$NA_j^e$ is the net acidity (m/t),

$f^{-1}(pH_j^e)$ is the net acidity concentration corresponding to the existing pH$(m/l^3)$

$Q_j$ is the flow $(l^3/t)$, and

k is a unit conversion factor.

For a polluted stream segment, the value of $pH_j^e$ will be below a desired level, say $pH_j^g$. In order to improve the water quality to the point at which $pH_j^g$ is attained, an amount of acid must be removed from the controllable sources upstream of point j. For a stated goal, the allowable quantity of acid that can flow past the control point j is:

$$NA_j^g \leq kQ_j f^{-1}(pH_j^g) \tag{6}$$

where:

$NA_j^g$ is the net acidity flowing past the monitoring point when the pH goal is attained (m/t).
k and $Q_j$ are defined as previously, and
$f^{-1}(pH_j^g)$ is the net acieity concentration corresponding to the pH goal.

Equation (6) represents one set of constraints in the model. It states that for each monitoring point j, an amount of net acidity no greater than $NA_j^g$ can be [illegible]ing past the point if the pH goals are to be met.

The minimum total amount of acid that must be controlled in order to meet the pH target at point j is obtained by subtracting equation (6) from equation (5). Letting $w_j^{min}$ equal this amount of acid, then:

$$w_j^{min} = kQ_j[(f^{-1}(pH_j^e) - f^{-1}(pH_j^g)] \tag{7}$$

The problem now becomes how to optimally control the amount of acid $w_j^{min}$ from the upstream sources. The modeler wants to determine the combination and size of treatment plants that will control the required amount of acid at the minimum cost. For a basin with s polluted tributaries, we can write:

$$w_j^{min} = \sum_{i=1}^{s} t_{ij} w_i \tag{8}$$

where $w_i$ becomes the decision variable for the model. $w_i$ represents the amount of acid to be controlled in the i th tributary in order to meet the water quality goals at a minimum cost.

A second set of constraints in the model is obtained by observing that, since $NA_i$ is the total amount of net acidity in tributary k, $w_i$ cannot be greater than $NA_i$. By defining $NA_i^a$ to be the total amount of net acidity entering the main stream from tributary i after a treatment plant has been built on it to control $w_i$, then this set of constraints can be written as:

$$NA_i^a = NA_i - w_i \geq 0 \tag{9}$$

A third set of constraints acting on the system is obtained by applying the transfer equation (equation (4)) to the situation in which some treatment plants have been constructed in the basin. These constraints can be written as:

$$NA_j^g = \sum_{i=1}^{s} t_{ij} NA_i^a + NA_j^u \tag{10}$$

[illegible] expression states that in order to meet the specified water quality goals at the j control points, the amount of allowable net acidity must be coming from either the residual net acidity entering from the s tributaries, $\sum_{i=1}^{s} t_{ij} NA_i^a$, or from uncontrollable sources, $NA_j^u$.

An important observation can be made on the model by considering the following: for a given control point j, we can define $w_t$ to be the total amount of net acidity that is contained within the polluted tributaries on which treatment plants can be constructed. Then

$$w_t = \sum_{i=1}^{s} t_{ij} NA_i \tag{11}$$

Having previously defined $w_j^{min}$ as:

$$w_j^{min} = \sum_{i=1}^{s} t_{ij} w_i ,$$

we note that if $w_j^{min}$ is greater than $w_t$, the solution to the problem is infeasible, since even if all of the controllable net acidity is removed from the upstream sources, there still will be an amount left of $(w_j^{min} - w_t)$ which [illegible] make it impossible to meet the water quality goals. This tells us that the uncontrollable sources, $NA_j^u$, are acidic in their overall nature.

For the cases in which $w_j^{min}$ is less than $w_t$, the modeler must determine how much net acidity should be controlled in each tributary. The cost of removal of net acidity from each tributary will vary, being dependent on the size of the plant built and on the concentration of net acidity in the tributary. In order to optimize the plant locations and sizes, the modeler must develop cost functions relating the cost of treatment to the decision variable $w_i$. The form of the cost functions developed will be dependent on the data used in their derivation.

The coal mine drainage optimization model can now be written out in the general programming format. The objective function is:

$$\text{Minimize } Z = \sum_{i=1}^{s} C_i(w_i)$$

where Z expresses a treatment cost value and the constraints are defined by: 1.) equation (6) which states that in order to meet the pH goal at point j, $pH_j^g$, it is necessary to reduce the net acidity loading flowing past point j to at least $NA_j^g$. 2.) Equation (10) which defines the amount of net acidity flowing past point j when the pH at that point equals $pH_j^g$ must be coming from the residual net acidity remaining in tributaries on which treatment plants have been built, $\sum_{i=1}^{s} t_{ij} NA_i^a$, and the uncontrollable net acidity above point j, $NA_j^u$. 3.) Equation (9) stating that the amount of net acidity treated, $w_i$, cannot be greater than the amount present, $NA_i$.

If the cost functions are derived so as to give the costs in terms of dollars/year, then the model described above will minimize the annual cost of treatment subject to environmental quality constraints. For the situation in which there are r control points established for an optimization run and s tributaries which have sites for possible treatment plants, there will be 2r + s linear constraints in the model and s cost functions contributing to the obje[illegible] function.

## An Example

The model described has been applied to the Bennett Branch of Sinnemahoning Creek, located in northcentral Pennsylvania. A stream map of the watershed is presented in Figure 5. The Bennett Branch flows northeast from its headwaters near Mountain Run to its confluence with the Driftwood Branch of Sinnemahoning Creek, draining an area of 367 square miles. The upper reaches of the stream are unpolluted and support a trout population. Near the town of Penfield, acidic tributaries begin to enter the Bennett Branch resulting in poor water quality for the remaining 34 miles of stream until its confluence with the Driftwood Branch. At its mouth, the Bennett Branch has a pH of 3.5 (mathematic mean from a set of observations), with acid, iron, and sulfate concentrations of 58, 0.35, and 145 mg/l, respectively (Skelly and Loy, 1973).

The majority of the acid tributaries enter the Bennett Branch along its upper reaches. Coal mining has been extensive in the upper part of the watershed and has taken the form of both deep mining and strip mining. However, the majority of the acid entering the Bennett Branch emanates from deep mines (Skelly and Loy, 1973).

The basis for the example is the attainment of a net acidity concentration of z[illegible] at the monitoring point below Dixon Run (monitoring point 7 on the stream [illegible]for a design flow equal to twice the average mean annual flow in the basin. T[illegible]cost data utilized was presented by Young, et al. (1973), and is shown in Figures 6 and 7. The costs apply to neutralization using hydrated lime. The cost functions derived from the data are of the general form:

$$c_i^T = k_i w_i + l_i w_i^{-0.12} I(w_i) + m_i w_i^{0.88} (1 - I(w_i)) \tag{12}$$

where:

$c_i^T$ = Total annual cost of treatment for a plant located on tributary i ($/year),

$k_i$, $l_i$, $m_i$ = cost coefficients,

$$I(w_i) = \begin{cases} 1 \text{ if } w_i \geq w_{mi} \\ 0 \text{ if } w_i \leq w_{mi} \end{cases}$$

and

$w_{mi}$ is the net acidity load carried in tributary i when the flow is equal to the average mean annual flow.

Table 1 lists the values of the cost coefficients for the acidic tributaries upstream of monitoring point 7. The objective function is thus represented by

$$\min Z = \sum_{i=1}^{9} C_i^T$$

The constraint set represented by equation (6) is simply

$$NA_7^g \leq 0$$

The constraint set represented by equation (9) can be written:

$NA_1^a = 11{,}381 - w_1$,

$NA_2^a = 4{,}932 - w_2$,

[illegible]$A_3^a = 2{,}389 - w_3$,

$NA_4^a = 9{,}545 - w_4$,

$NA_5^a = 19{,}790 - w_5$,

$NA_6^a = 297 - w_6$,

$NA_7^a = 2{,}665 - w_7$,

$NA_8^a = 2{,}037 - w_8$,

$NA_9^a = 21{,}834 - w_9$.

The constraint imposed by equation (10) is:

$$NA_7^g = NA_1^a + NA_2^a + NA_3^a + NA_4^a + NA_5^a + NA_6^a + NA_7^a + NA_8^a + NA_9^a - 26,315.$$

The solution to the example problem is presented in Table 2. The solution was obtained by using separable programming techniques to handle the non-linearity of the objective function. A discussion of separable programming can be found in Plane and Kockenberger (1972) or Loucks and McBean (1974).

## SUMMARY

The paper has presented a prescriptive, non-linear mathematical model capable of assisting water quality planners in their efforts to control coal mine drai[illegible] pollution. The prescriptive model developed is an efficient tool that can be [illegible] for the preliminary screening of many coal mine drainage control strategies. This preliminary screening is often needed in large comprehensive river basin planning projects prior to a more detailed data collection and simulation analysis.

## LITERATURE CITED

Appalachian Regional Commission, Acid Mine Drainage in Appalachia: A Report to the President of the United States, 1969.

Baker Engineers, Inc., Michael, Analysis of Pollution Control Costs, A Report to the Appalachian Regional Commission, ARC Contract No. 72-87/RPC-713, 1973.

Federal Register, Final Effluent Guidelines for Coal Mining Point Source Category, Volume 42, No. 80, Pages 21380-21390, April 26, 1977.

Lachman, R. I. and Lovell, H. L., An Investigation of the Natural Beneficiation of Coal Mine Drainage, Report Number SR-76, Coal Research Board of Pennsylvania, 1970.

Lorenz, W. and Stefan, T., "The Formation of Acid Mine Drainage," The Incidence and Formation of Mine Drainage Pollution in Appalachia: Appendix C to: Acid Mine Drainage in Appalachia: A Report to the Appalachian Regional Commission, 1969.

Loucks, D. P. and McBean, E. A., Planning and Analysis of Metropolitan Water Resources Systems, Cornell University Water Resources and Marine Sciences Center, Ithaca, New York, June 1974.

Lovell, H. L., An Appraisal of Neutralization Processes to Treat Coal Mine Drainage, No. EPA-670/2-3-093, Environmental Protection Agency, Office of Research and Development, 1973.

Martin, E. J. and Hill, R. D., "Mine Drainage Research Program of the Federal Water Pollution Control Administration," Second Symposium on Coal Mine Drainage Research, Pittsburgh, Pennsylvania, 1968.

Miknis, J. J., "A Mathematical Model for Determining the Optimal Locations of Mine Drainage Treatment Facilities," M.S. Thesis, The Pennsylvania State University, 1977.

Plane, D. R. and Kockenberger, G. A., Operations Research for Managerial Decisions, Irwin Publishers, Homewood, Ill., 1972

Rozelle, R. B., Proposed Mathematical Model for the Interaction of Acid and Alkaline Waters in the Susquehanna River Basin, A Report to the U.S. Public Health Service, 1968a.

Rozelle, R. B., Kimball, G. D., Simpson, D. G., Maier, H. N. and Potera, G. T., Studies on the Kinetics of Iron II Oxidation in Mine Drainage, A Report submitted to the Federal Water Pollution Control Administration, 1968b.

Skelley and Loy Engineers, Coal Mine Drainage in the Susquehanna River Basin, A Report to the Susquehanna River Basin Commission, 1973.

Young, G. K., Taylor, R. S., and Selekof, J. S., Simulation and Optimization of Acid Mine Drainage Abatement Alternatives, A Report prepared for the U.S. Army Corp of Engineers, Baltimore, Maryland, 1973.

## Table 1

### Cost Data for Example Problem

| Source i= | Name | $k_i$ | $l_i$ | $m_i$ | $w_{mi}$ |
|---|---|---|---|---|---|
| | | Cost Coefficients | | | |
| 1 | Moose Run | 8.52 | 744,000 | 106 | 7,540 |
| 2 | Mill Run | 10.76 | 522,000 | 138 | 3,943 |
| 3 | Tyler #14 | 4.18 | 46,400 | 24 | 2,062 |
| 4 | Tyler Reservoir Run | 10.1 | 693,000 | 130 | 5,485 |
| 5 | Tyler Run | 5.04 | 532,000 | 39 | 14,053 |
| 6 | Unnamed | 9.40 | 22,800 | 117 | 204 |
| 7 | Cherry Run | 21.53 | 528,000 | 304 | 1,776 |
| 8 | Kersey Run | 106.14 | 1,440,000 | 1,273 | 1,159 |
| 9 | Dixon Run | 5.52 | 786,000 | 51 | 15,682 |

Cost Functions $C_i^T = k_i w_i + l_i w_i^{-0.12} I_i(w_i) + m_i w_i^{0.88}[1 - I_i(w_i)]$

$$\text{where } I_i(w_i) = \begin{matrix} 1 \text{ if } w_i \geq w_{mi} \\ 0 \text{ if } w_i \leq w_{mi} \end{matrix}$$

## Table 2

### Solution of Example Problem

| Source i | Name | Acid Load Reduced $w_i$ (lbs/day) | Plant Capacity (mgd) |
|---|---|---|---|
| 1 | Moose Run | 4,542 | 6.1 |
| 2 | Mill Run | 0 | 0 |
| 3 | Tyler #14 | 2,389 | .28 |
| 4 | Tyler Reservoir Run | 0 | 0 |
| 5 | Tyler Run | 19,790 | 7.1 |
| 6 | Unnamed | 0 | 0 |
| 7 | Cherry Run | 0 | 0 |
| 8 | Kersey Run | 0 | 0 |
| 9 | Dixon Run | 21,834 | 10.8 |

Minimum cost Z = \$858,335/yr

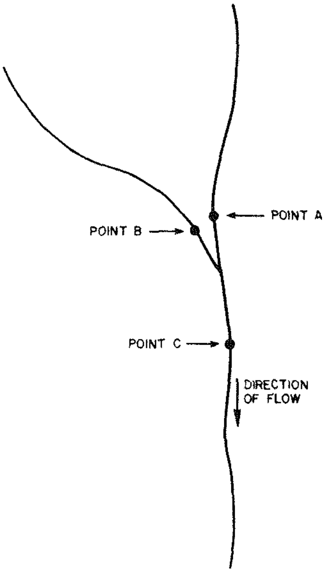

FIGURE I DIAGRAM DEPICTING COMPLETE MIXING OF TWO STREAMS

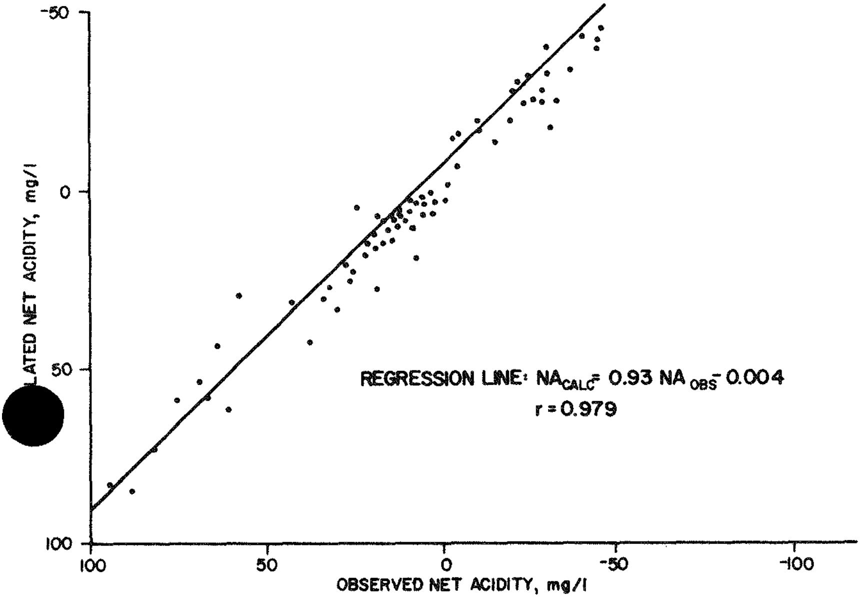

FIGURE 2 CALCULATED NET ACIDITY VERSUS OBSERVED NET ACIDITY FOR NEWPORT CREEK (AFTER ROZELLE, 1968b)

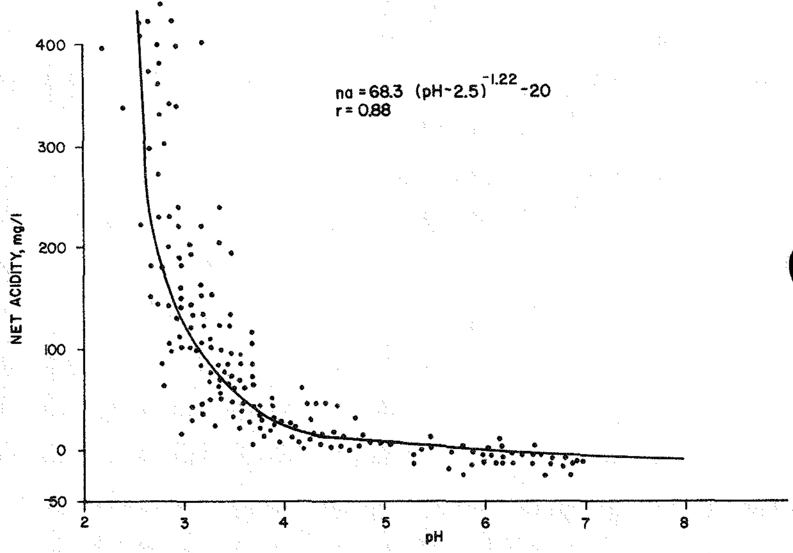

FIGURE 3 pH-NET ACIDITY RELATIONSHIP FOR BENNETT BRANCH (MIKNIS, 1977)

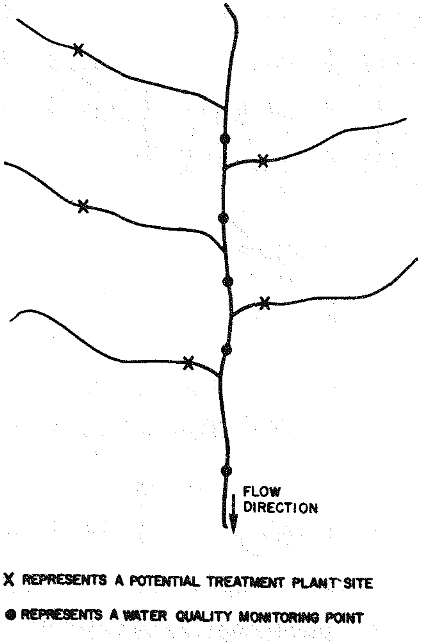

FIGURE 4 REPRESENTATION OF CMD MODELING SITUATION

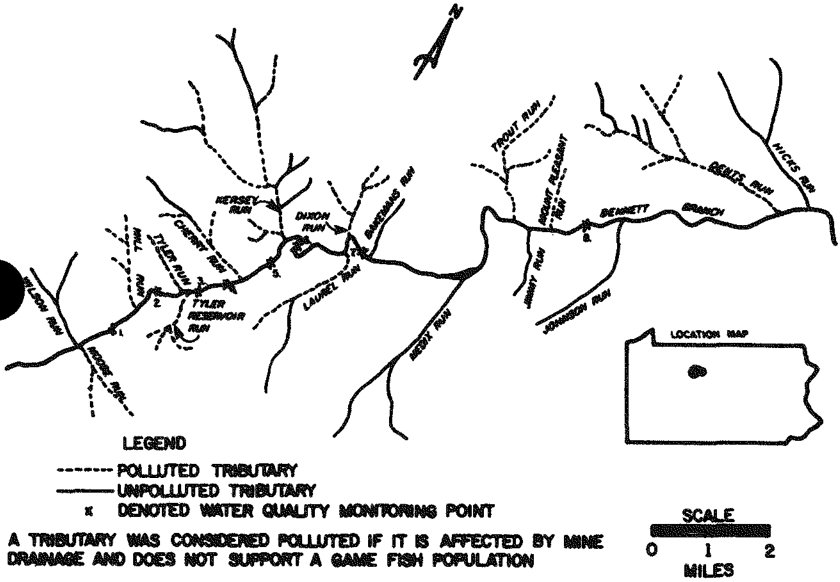

FIGURE 5 STREAM MAP OF THE BENNET BRANCH WATERSHED

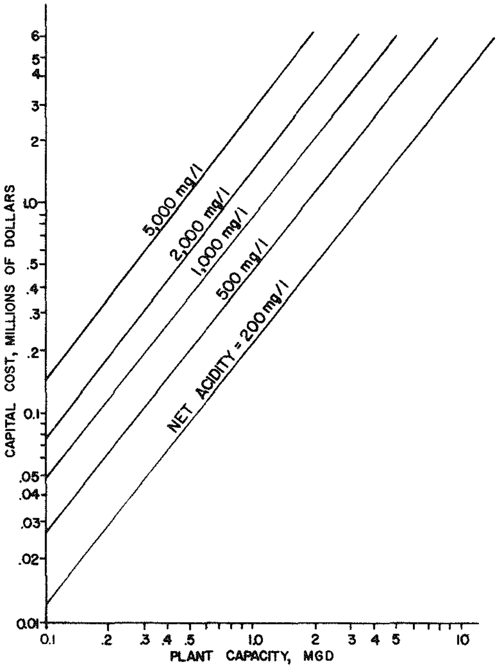

FIGURE 6 CAPITAL COST CURVES FOR LIME NEUTRALIZATION (YOUNG et al. 1973)

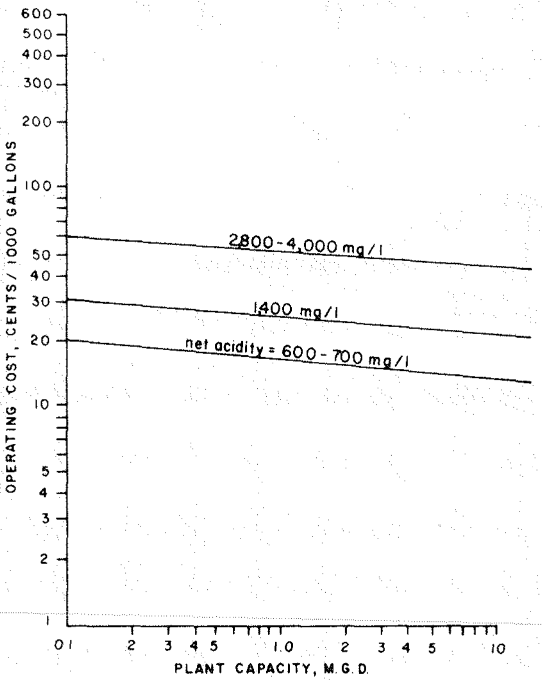

FIGURE 7 OPERATING COST CURVES FOR LIME NEUTRALIZATION (YOUNG et al., 1973)

# IMPACT OF GOB AND POWER - PLANT ASH DISPOSAL ON GROUND WATER QUALITY AND ITS CONTROL

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The planned fast development of coal mining and coal-fired power plants in [illegible] United States of America and in other countries will produce respectively [illegible]ater amounts of refuse and fly ashes. At the same time, the wider use of sur[illegible]ce mining methods will create numerous old abandoned open-pits which can be utilized for gob and ash disposals. However, this seemingly rational solution conceals a very serious danger in that there is a possibility of ground water pollution with substances leached from the disposed waste material. These substances filtrating to the aquifers may migrate long distances, polluting large volumes of water within aquifers, which are used for drinking and for commercial purposes.

As a result, more stringent environmental requirements for ground water protection can be expected.

In 1973, the confluence of these two problems stimulated a joint project between POLTEGOR (Poland) and the U. S. Environmental Protection Agency with the following objectives:

-the determination of the influence of gob and fly ash disposal on ground water quality
-propositions to ameliorate the influence of the storage on groundwater and reclamation
-providing investigation and monitoring systems recommendations

To meet these program goals two test disposal sites were constructed and systematically observed. The first site had a capacity of 1500 $m^3$ of gob and ash and eleven monitoring wells within and around the disposal area were installed (Figure 1). The second disposal area was much larger. Gob from underground mines was placed in the pit at a rate of 20-30,000 $m^3$/month up to 500,000 $m^3$ (Figures 2 and 3). Fourteen monitoring wells were installed around it. The samples of ground water were taken every three weeks, and the results of their analysis were compared with the results of the analyses of the pure ground water within the aquifer and also with the waste leachates obtained in laboratory leaching tests.

The model tests were also conducted to evaluate pollutant migration under various hydrogeological conditions. These investigations demonstrated the existence of an unquestionable influence by the gob storage on the deterioration of ground water quality.

[illegible] Gob and fly ash thickness of 2.5 m the first clear signs of pollutants [illegible]eared after seven months (Figure 6). For a gob storage of 20 m the pollutants appeared at a distance of 60 m after approximately 15 months. In the case of gob stored above the ground water table a clear relationship was observed during the first period between the pollutant concentration and the intensity of precipitation. In a later period this relationship is unclear because of a reciprocal imposition of particular waves of pollutants upon themselves. The main bulk of the pollutants is transported downstream from the main ground water stream at approximately the velocity of the ground water movement (Figures 4 and 5).

However, particular ions show enormous differences as to their susceptibility to leaching from the stored bulk material, their different velocity of movement within the aquifer, and their different trends of dispersal migration. The last phenomenon appears as a very uneven concentration increase of various ions outside the main direction of the ground water flow. As an example, this is most evident by a comparison of the migration of ions of sodium and potassium.

The storage of gob and fly ash, 2.5 m thick, within the main flow of ground water, effected the ground water and drinking water quality as follows:

-an increase in the weight by volume of ground water by 0.2%
-an increase in the conductivity of water about seven times(as a rule of thumb) the multiplication of the conductivity value by 0.6 produces the sum of TDS in mg/l
-an increase in TDS of approximately ten times, with a clear dependence on the precipitation quantity, particularly during certain periods
-an increase in the content of the Cl ion - up to forty times
-an increase in the content of the $SO_4$ ion - up to ten times
-an increase in the content of the Na ion - up to one hundred times
-an increase in the content of the K ion - up to twenty times
-an increase in the content of the Ca ion - up to six times
-an increase in the content of the Mg ion - up to two times
-an increase in the content of the $NH_4$ ion - up to four times
-an increase in the content of the $PO_4$ ion - up to eight times
-an increase in the content of the CN ion - up to ten times
-an increase in the content of the phenols - up to two times
-an increase in the content of the Cd - up to three times
-an increase in the content of the Sr ion - up to five times
-an increase in the content of the Cu ion - up to six times
-an increase in the content of the Mo ion - up to fifteen times
-an increase in the content of the B ion - up to twenty-five times

It appears however that the presence of the waste material did not cause an increase in ion content of Fe, Ma, Al, Cr in the ground water or effect any clear changes in the pH.

Because of ambiguous results there is difficulty in explaining to what extent, if any, the disposal storage area effected an increase in ground water content of Zn, Pb, and Hg. The exclusion of such an influence cannot be made, but such an influence can only be expressed in two to three times increased values.

Considering the above data it can be said that within approximately three years about 11,000 Kg of TDS were leached from the gob and ash disposal (1600 $m^3$ capacity to ground water). Of this total, 7,500 Kg were sulfates, 1,500 Kg chlorides, and about 2,000 Kg other elements.

Although generally qualitatively and quantitatively similar, particular ions differ somewhat--pollution was acquired from the disposal of exclusively coal mine refuse (gob). The presence of molybdenum, strontium and cyanides were not observed among the polluting components, but there was an increase in the concentration of aluminum, chromium and iron.

Model tests conducted in parallel with the field tests indicated:

i. that for a 2% weight by volume difference of leachates from the storage and to the pure ground water, gravitation mixing did not cause in depth vertical migration of pollution underneath the disposal area;

ii. that the relationship of the shape of the polluted stream to the dose of pollutants is relatively small with respect to the calculation of unit area, that is the pollutants exhibit a tendency to migrate near to the surface of the ground water table;

iii. that the trends discussed above are most distinct, the smaller the permeability of the storage in relation to the aquifer, when the gob is immersed.

Presented here in digest form are the results of research work which afford a formulation of certain conclusions and recommendations for the planning and storage operations of gob and fly ash from coal-fired power plants.

## 1. Waste classification and testing

a. The investigations clearly suggest the necessity of an effective division of the waste material coming from the coal mines and coal fired power plants into subgroups. These subgroups should be based upon mechanical and chemical characteristics of leaching toxic compounds from the waste in a water environment.

b. Coal mine refuse should be divided into dry and wet waste.

i. The dry waste material comes from the mining operations and is associated with the ripping of the floor or roof, the construction of stone drifts etc., and sometimes from dry separation (mechanical). These wastes are characterized by identical mineral and chemical composition, similar to the sterile rocks accompanying the coal seams, and are usually quite coarsely grained (gross from 10 to 200 mm). The pollutants leached from it, from the qualitative aspect, are entirely dependent upon the chemical composition of the rock formations. The quantity of these pollutants which may pass into solution is relatively small, because of the small surface area contact with the leaching water (the effect of large granulation of this refuse) and the great velocity of water through this type of gob; when it is located above the ground water table.

ii. Wet waste material usually comes from water washers, using either the heavier media or flotation process.

-the wastes from the water washers are characterized by a granulation from a silty fraction up to an 80 mm fraction, and their chemical composition is a function of both the rock and the coal. Moreover, the influence on their chemical character is dependent upon the composition of the wash water (for example where highly mineralized drainage water is used). The wide range of the granulation provides conditions for both the movement of the water through the stored material, and a large contact surface with water for the leaching of greater quantities of components than with dry refuse. Moreover, independent of pollutants of a chemical type, pollutants from the washed out material may also be convected in a shape of finest grained silty fractions (suspension).

-Waste materials coming from washers using heavy media are characterized by a coarser grained material than waste from washers whose size usually fall between 20-250 mm. The chemical composition of both types is similar to the composition of the coal seam and associated rocks. The chemical composition of the heavy media used also has a substantial influence; particularly during the course of washing. The components of the washing medium settle on the surface of the granules and in the first stages of cleaning are washed out with the waste. The chemical character of this fluid should be a subject of interest from the environmental point of view. The coarse granulation of such refuse does not provide conditions for the leaching of large quantities of components from them because of the relatively small contact surface of the refuse grains with the filtrating water and the considerable velocity of the rain water filtration (especially in dry disposals).

- The flotation waste material is characterized by a very fine granulation in fractions from silty to 2 mm diameter. Their chemical composition is a function of the coal character, accompanying rock formations, and also of the chemical substances used as flotation fluids. The fine granulation of these wastes provides conditions for leaching from them large quantities of components particularly in wet sites saturated with water. In the case of dry sites a fine granulation of this refuse limits the possibility of the filtration of the rain water through the stored material and may increase the evaporation. The composition of the fluid used in the flotation process may also be a substantial influence on the chemical character of the leachates. Some of the fluid's components may settle on the surface of the grains. The type of fluids in flotation should therefore also be controlled in this aspect of refuse storage.

c. Waste materials from power plants fired with coal should be divided into fly ashes and slags.

   i. The ashes are characterized by a very fine granulation composition with a chemical composition subject to the quality of coal burnt in the power plants. The quantity of pollutants which can be leached from ashes and passed into ground water is theoretically very great because conditions for leaching are provided by very fine graining giving a large contact area with water. In reality this quantity is much smaller due to the lesser permeability of ashes, especially when disposals are situated above the ground water table. As previously mentioned the character of these pollutants depend on the chemical character of the burnt coal.

   ii. The slags are characterized by a similar chemical composition to the ashes, but of a much coarser graining. The quantity of pollutants which can be leached from slags and passed into the ground water, although theoretically smaller than in the case of ashes (smaller contact area of particular granules with the leaching water) because of their good permeability, can in practice be about the same. This is applicable to deposits situated above the ground water table and to deposits situated below as well. The character of the pollutants depends on [illegible] type of burnt coal.

d. The threat to ground water as posed by the particular types of waste assuming their comparative chemical compositions under various conditions of storage from the most harmful is as follows:

| | In Conditions of Precipitational Leaching | | In Conditions of Full Water Saturation |
|---|---|---|---|
| 1. | Wastes from water washer | 1. | Wastes from water washer |
| 2. | Wastes from heavy washer | 2. | Ash |
| 3. | Slags | 3. | Flotation wastes |
| 4. | Wastes of dry separation | 4. | Wastes from heavy washer |
| 5. | Fly ash | 5. | Wastes from dry separation |
| 6. | Flotation wastes | 6. | Slags |

e. Laboratory tests of wastes with respect to their storage should be carried out considering the conditions of storage and the available time.

f. In connection with the statement in part d, it would serve no purpose to perform a full chemical analyses of wastes as this can lead to erroneous conclusions because only a portion of their components can pass into free solution, and only this portion is affecting the quality of ground waters.

g. When there is enough time and available funds for the performance of the tests, the most adequate method is the lysimetric tests carried out in columns of 1 m diameter and 3-4 m high. Such tests require six months to one year. The proportions of water and wastes should be considered. Full saturation should be used when the material is intended for storage below the ground water. When the storage will be subjected only to the filtration of precipitational water, the performance of the test can be made by a periodic sprinkling at the expected intensity of rain. In the first case ground water from the aquifer within which the storage is planned should be used. In the second case a lysimeter may be installed outdoors, or if in a laboratory distilled water can be used. Such a procedural method is recommended because of the various dissolving properties of different types of water.

h. To obtain faster results an intense leaching of the wastes can be employed in columns of 10 cm diameters and 1 m height and provided with a filtrating layer at the bottom. One can then obtain in two weeks approximate results of maximium quantities of particular components which can pass from a given waste material to ground water under optimal conditions. In the interpretation of these results caution is recommended as time is not represented in the case of difficult soluble compounds. The time factor in the case of ashes can be shortened by increasing the saturation with water to the proportion of 1:1. The results however, will remain approximate.

i. It is recommended that the tests described in part g be performed prior to storage. The tests described in part h should be performed during storage to check on the variability of the material being stored.

j. The physicochemical analyses of the leachate should take into account all possibilities to formulate physicochemical parameters, as one cannot judge beforehand which of these components might prove to be harmful.

k. The analyses mentioned in part i should be performed to the greatest possible degree of accuracy, as a potential threat may be posed not only by the content of a given toxic component in ground waters, but also often by the secondary, increased concentration in organisms of plants or animals using these waters. This secondary concentration may be more harmful.

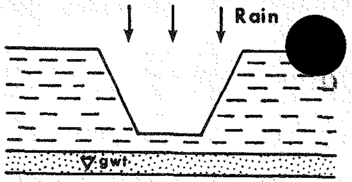
## 2. Disposals classification

The classification and evaluation of the old open pits' suitability for the storage of waste materials with the objective of protecting ground waters should be made with respect to various criteria. To this end the following proposals are presented:

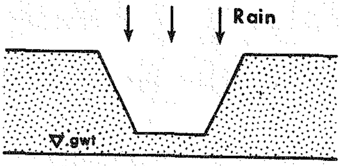
a. The hydrogeological criterion is based on the reciprocal partial relations of the disposal site and the aquifer that will constitute a potential threat. An introductory classification is as follows:

i. "Dry" disposals type (situated above the ground water table)

a) localized within reach of an impermeable layer

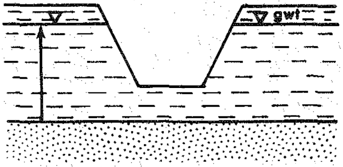


b) localized within reach of a permeable layer

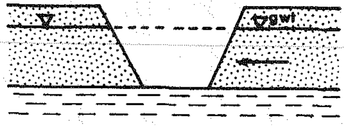


ii. "Wet" disposals (situated below the ground water table)

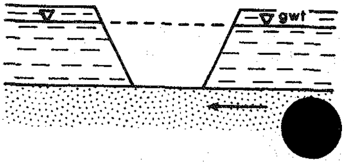
a) localized within reach of an impermeable layer underlined with an aquiferous layer with hydrostatic thrust of the ground water table



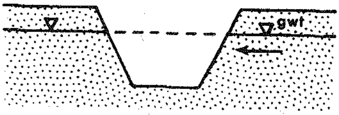
b) localized within reach of a permeable layer underlined with an impermeable layer



c) localized within reach of an impermeable layer directly underlined with a permeable layer with hydrostatic thrust of the ground water table.



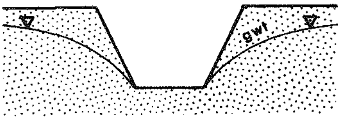
d) localized within the reach of a permeable layer



The disposals mentioned in part ii b, c, and d could be:

1) filled with water the waste material stored in the water) or

2) retained in a dry state by dewatering the disposal area (ditches, pumping stations) - the waste material stored in a dry open pit and then saturated with water.



In the first example, the pollutants pass into water much faster, and in the second example, at a much slower rate although the sum of the leached out compound over an optionally long period would be similar.

b. Hydrogeological criterion based on the ratio of the disposal permeability to the surrounding aquifer.

A - disposal with the permeability coefficient lower than the surrounding aquifer. (As a rule, disposals of ashes and flotation waste should be included.)

B - disposals with a higher permeability than the surrounding aquifer (included here will be mainly disposals of dry quarry refuse).

C - disposals of similar permeability to the surrounding aquifer.

c. The criteria for a protected object distinguished here are disposals planned under conditions when:

A - the entire aquifer must be protected

B - a determined part of the aquifer must be protected or the consumption water intakes determined

d. The criteria for the interdependent position of the disposal and the protected object. The following contingencies are to be discerned:

A - A protected object is situated in a zone directly threatened by waters entering into direct contact with the disposal (downstream of ground waters)

B - A protected object is situated in a zone of direct influence, where pollutants may appear either as very diluted or as a result of dispersion

C - A protected object is situated within the reach of this same aquifer outside the hydrodynamic or dispersional influence zone of the disposal (upstream of the ground water flow).

e. The degrees of ground water protection distinguished here are:

| | |
|---|---|
| 1st degree: | total protection where the ground waters remain under total protection and their quality cannot be subject to any change |
| 2nd degree: | partial protection - when the objective is the preventing of the exceeding of certain permissible values, or the protection of water against an increase in content of only determined components (i.e., Cl, or heavy metals) |
| 3rd degree: | when a given aquifer is not subject to special protection |

3. Disposals planning and designing

a. Planning the storage of coal mining refuse and coal fired power plants' ashes in an old open pit should be preceded by:

i. an exact knowledge of the character of the gob and ashes (with respect to their eventual influence on ground waters based on tests described in part 1) and of the quantity provided for storage at a given time.

ii. an accurate assessment of the hydrogeological conditions of the open pit to be used for storage.

iii. determinations as to what parts and to what extent the ground waters should be subject to protection.

b. The survey of hydrogeological conditions should include:

-spatial parameters (thickness, spreading and hydraulic relations with other aquifers entering into contact with the disposal)
-parameters of permeability (especially coefficients of permeability and specific yield)
-a representation of the hydrodynamic network of the ground waters' hydrostatic heads
-an exact knowledge of the original ground waters' chemical character
-lithology of aquifer

c. Dimensional parameters of the aquifer should be surveyed by means of:

-drilling wells (existing from the period of the exploitation deposit, or wells specially designed for this purpose)
-geophysical investigations (where possible)
-an analysis of general geological information

d. Parameters of permeability should be determined by the performance of standard field tests (e.g., tested pumping, or water forcing - especially in the zone of aeration) or laboratory tests (bleeding in filtration columns, granulometric analyses).

e. Reproduction of the hydrodynamic net should be based on surveys of the ground water table through bore holes, or where possible, by means of remote sensing geophysical methods. The termistor or tracer methods is not recommended for large objects and nonpoint pollutions, as they are less adequate than the use of the above methods in analyzing wells. The following model verification of the hydrodynamic network is recommended for there are considerably greater possibilities for a more precise adaptation to real conditions. This can be obtained by means of digital of physical modeling methods (e.g., EHDA). The representation of the hydrodynamic net of the disposal region is the most important element for determining its eventual influence and should be made with the greatest possible accuracy.

f. The chemistry of the waters of a considered aquifer should be determined by the analysis of ground water sampled several times from the places specified in the above mentioned investigation, at 2-3 month intervals. This is necessary due to frequent changes (e.g., seasonal or caused by other factors) in the ground water quality, especially in urbanized areas. This phenomenon was observed during the present research.

g. Knowledge of the lithology of the aquifer formations is necessary for the evaluation of the phenomena of absorption and ion exchange, that can take place between the pollutants and the rock (soil) skeleton.

h. The assignment of sections of the aquifer and the extent to which such sections are to be protected. Not only actual conditions should be taken into account, but also future plans for their utilization, because the influence of the disposal may persist even for scores of years.

i. By obtaining data from the above procedures, it is possible to prepare a forecast of the influence of the wastes storage in an old open pit upon the whole or selected sections of the aquifer being considered. Such a prognosis may be of a qualitative or quantitative character both with respect to time and the degree of deterioration of the water quality. The prognosis may be prepared either by the application of computer methods, physical analogy, or a descriptive computation method. One should realize that there are no all-purpose programs which would afford a formulation of all phenomena in a three dimensional system with respect to time considerations for the differing behavior or various ions, and for phenomena occurring in the unsaturated zone. One can, however, make approximate forecasts which will enable the undertaking of proper decisions. It is also possible to obtain more accurate results when the prognosis concerns only one component, e.g., chlorides or molybdenum, and not all of the polluting components.

j. After the prognosis, recommendations pertaining to the method of storage and eventual prevention should follow.

k. For particular types of disposals (see part b) and for various kinds of stored wastes (see part a) one does see solutions: storage methods whereby the influence of ground waters either can be eliminated, limited, or where adequate means of protection can be introduced. Therefore:

   i) In open pits of the I-a type, the discussed wastes can be stored without any greater limitations,

   ii) In open pits of the I-b type, coarse wastes cannot be stored without risk (such as slags, gob washed by heavy fluid or from water washers, or dry rock when this contains soluble or polluting components). However, ashes can be stored, as well as flotation silts with a surface morphology of such surface reclamation as to maximally increase the superficial runoff of rain water and evapotranspiration and to decrease to a minimum the leaching of precipitational waters.

For coarsely grained wastes, one has to cover their surface with an impermeable material (e.g., clayey layer), making the infiltration of precipitation into the disposal interior impossible. Mixed waste material should have the coarsely grained waste put on the bottom and a weakly permeable material on top, thereby conforming to the recommendations as proposed for the weakly permeable wastes.

The above preventive methods may be satisfactory only when the storage is formed as a single horizon and where the immediate shaping of the surface and reclamation of its final profile is possible. It is estimated, that the above operational method should diminish the quantity of leaching pollutants to the ground waters by approximately 80%. When the open pit must be successively filled with waste to several levels, this method is not possible and a temporary surface sealing with plastic sheeting should be used, or a total sealing of the bowl of the open pit. Decisions should also depend on the required degree of ground water protection and on the spatial relation of the disposal--the protected object.

iii) In the open pit of the II-a type waster material may be stored without any greater limitations.

iv) In open pits of the II-b type the storage of any kind of waste material will lead to a deterioration in quality of the ground waters. This deterioration will decrease when smaller amounts of water flow through the disposal, therefore the smaller the ratio of the disposal permeability to the permeability of the aquifer surrounding the disposal, the lesser the deterioration. In this type of disposal, the pollutants will flow through the entire width of the aquifer. Therefore, in such disposals, the waste can be stored only when the required degree of protection will be of the second or third rank, and when the prognosis shows that the permitted values for a given point are not being exceeded, when the first degree of the waters' protection is required, or when a threat occurs that the permitted pollutant level will be exceeded. It is then necessary to employ preventive means, which can be:

-vertical sealing method, by a digging or an injecting method, complete to the depth of the impermeable layer,
-protection of the slopes with impermeable plastic sheeting or sprinkling with substances which when coagulated will set an impermeable layer (this bonding is possible only when the disposal bowl is not filled with water in the course of storage).
-barrier of wells pumping water back to within the reach of the disposal. The selection of the method should be based on economic criteria.

v) In open pits of the II-c type all types of mentioned waste can be stored when the required level of water protection is of the second or third degree. This is due to the balanced hydrostatic head (i.e., it is not a factor as a pure and polluted water density difference) and there will be no large scale of vertical migration of pollutants. Such a migration will occur only on a rather small scale with only a dispersional effect and these pollutants within the aquifer will disperse only in the uppermost part of the aquifer. If total disposal insulation from ground water is considered, the most appropriate solution would be a clay sealing of the disposal bottom, by spreading corresponding quantities of clay on the water surface, which when sinking will form an impermeable layer resistant to the direct impact of the material being stored. When the insulation treatment is to be made of a dry disposal, an impermeable sheeting or sprinkling with a sealing substance can be used. This substance can be used. This treatment, however, would be very difficult, because the removal of draining arrangements could cause the pressure of the floor water to rise and damage the insulating layer.

vi) In open pits of the II-d type the storage of waste will always lead to the pollution of ground waters. In the case of first degree protection of the ground water, the disposal must always be insulated irrespective of the type of waste being stored. Such insulation may be static in character as to the shape of the sealing on the floor, impermeable sheeting on the slopes, and substances sprinkled which set the surface layer. The insulation may be of a dynamic character as in a barrier of wells barring the contact of polluted water with pure water. If during the sealing application, the open pit should get filled with water, there would then be no possibility of using sheeting or sprinkling--only clay sealing can be employed. With a second degree ground water protection requirement and when the available waste material is of varying permeability, the material should be stored selectively--the material of weak permeability (e.g., ash or flotation silt) should be placed close to the slopes and the floor of the disposal and the coarsely grained material in the disposal interior. The permeability of the disposal will then be limited by the permeability of its outer layer, and this in effect will permit a much smaller quantity of pure water to come into contact with the disposal. Moreover, in this situation, the pollutants as a result of ground water flow (round), will concentrate only in the uppermost section of the aquifer, and in a narrow belt of the horizontal dispersion.

1. Considering the planned disposal with respect to its position to the protected part of the aquifer, this can be said:

-when the protected part is situated upstream to the ground water flow then a few dozen m. as a protection zone will suffice, because the dispersion influence will not exceed this limit
-when the protected part is situated in the disposal's zone of indirect influence, the disposal can then be planned without protection (if there is a second degree protection requirement). But this is not allowed when there is first degree protection requirement.
-when the protected part is located in the zone of direct influence of disposal, i.e., downstream, disposal planning cannot then be entertained without providing protections, unless an appropriate prognosis indicates that this is permissible.

## 4. <u>Designing the monitoring wells and the control performances</u>

a. Monitoring of the waste material disposals' influence on the ground water quality can only be performed through the sampling and analysis of water from monitoring wells, through shallow probes, and where possible, from natural springs. So far there are no remote sensing methods which would enable measurement of the ground water quality without direct access to them.

b. Depending on local geological conditions and on inspection requirements, the monitoring wells can be one, two, or three-horizontal for separate aquifers. When more than one pipe is installed in a drilled well, then it becomes absolutely necessary that total insulation be provided against particular aquifers.

c. When it is necessary to determine the content (e.g., in the case of an aquifer of great thickness) of pollutants in vertical zones, a single monitoring well will suffice for zonal sampling.

d. When a disposal site is executed wholly insulated from the aquifer, the monitoring system should then have as its objective the monitoring of the sites tightness. The wells location, varying according to site, should be about 20 m upstream, 30 m in the intermediate zone, and 60 m. downstream from the ground water. The spacing between the wells should be a short distance downstream from the ground water, greater in the intermediate zone and still greater upstream. The respective numerical values can be for example 1:3:5. The localization of particular wells should be based on the analysis of the affected sealing and on the hydrodynamic water heads' distribution.

e. For the disposalssites which can be expected to influence the quality of the ground water, the inspection wells should be localized by taking into account two basic hydrogeological criteria:

-the hydrodynamic water heads' network

-the spatial structure of the aquifer and its transmissivity, and the reciprocal spatial relationship of the site and the protected zone. When the entire aquifer is to be monitored then individual wells ought to be located upstream from the ground water, and in the indirect zone, whereas, downstream from the ground water, consecutive wells should be placed linearly at gradually increasing distances, e.g.:

| | |
|---|---|
| 1st well | 100m |
| 2nd well | 300m |
| 3rd well | 700m |
| 4th well | 1500m |

The wells in this direction should be located along the lines of a stream with the greatest hydraulic head, or if an area is encompassed by extremal streams of the ground water that could come into contact with the disposal site the wells should be placed in cross sections. When the objective of the monitoring is only for a specific zone of the aquifer, then the monitoring wells can only be located along one or two lines between the disposal site and the protected zone. Distance between the wells can be similar to the example given above.

f. The monitoring wells should be drilled using a dry method or a [illegible] washing method. Drilling by the application of other fluid wash[illegible] should not be done because such drilling may lead to a colmatation of the zone near the well thereby providing erroneous results. This is due to the possibility that the ground water may flow around the zone of the well, which would hinder the exchange of water between the well and the surrounding aquifer. A filter diameter from 4 to 6 inches is recommended.

g. During the drilling, a lithological log of all drilled layers, the well leveling, and the leveling of the stabilized ground water table should be accurately determined. Future investigations should be performed to determine the permeability and specific yields of all tested aquifer layers.

h. After removal of a quantity of water from the well of approximately one to two-fold volume, water sampling from the monitoring wells should be done. A greater removal of water from the well can change the natural course of the flow. By not removing the water, the sampled water will have been in contact too long either with the air or the wells' casing.

i. For the investigation of the unsaturated zone and compacted rock material characterized by very fine minute pores, rock material samples taken from centrifuging may be used to obtain water microsamples.

j. Taking water samples, transportation samples, preservation fixing, should conform to the rules and standards of performance analysis.

k. Water sampling related to the measurement of the water table position should be carried out at a frequency of at least:

Once a month for disposals of the I type

Every three months for disposals of the II type

l. For disposals of I type full analyses of the waters should be made every three months (about 40 designations) and the remaining analyses shortened (about 15-18 designations specified on the basis of filtrate analysis acquired under laboratory conditions), or according to standards, if they exist.

m. Particularly in developed regions, quite significant fluctuations in water quality are frequently encountered because of various activities (e.g., fertilization, dust emission). It is therefore essential to have initial data which can be:

-the analytical results of a minimum of a one year cycle of the entire ground water aquifer, prior to storage
-in considering a part of the aquifer, the results of analyses from such a sector, that does not undergo influence from the disposal

n. The test results should be periodically (a minimum of once a year) tabulated and discussed with the goal of drawing conclusions and to propose appropriate recommendations.

## 5. Further Research

a. The recommendations regarding further studies should be divided into these groups:

-investigations with the objective of clarifying certain phenomena, so far insufficiently investigated
-investigations concerning the implementation of better methods of prognosis elaboration
-investigations, of the real influence of the wastes on the ground waters' pollution, on a greater number of disposalssites in order to acquire empirical and statistical material

b. Studies to clarify phenomena insufficiently known should include:

-investigations of the water balance of disposal sites (surface runoff, evapotranspiration, and underground runoff) for different types of waste materials stored on the surface and under various climatic

conditions, in order to determine the quantity of precipitation water leaching the disposal
-investigations of the flow of pollutants through the zone of aeration (unsaturated area)
-investigations of the process of sorption and ion exchange
-investigations of vertical dispersion in porous mediums

c. Investigations for the improvement of forecast methods should comprise

-elaboration of methods to obtain ground water table samples without the necessity of drilling observation wells,
-the preparation of mathematical methods of modeling all phenomena affecting pollutant migration through porous and fissured media
-the preparation of programs to facilitate the modification and checking of the above methods, taking into account the differences in the phenomenon course for various ions.

d. Investigations of the real course of the phenomena should be based on ten assigned disposal sites of coal mining refuse and coal fired plants which are situated in various hydrogeological and climatic conditions and included into systematic, long term observations. The observations should begin before storage, and last for at least five years.

Qualitative and quantitative forecasts of the influence of these disposals on the ground water quality should be prepared beforehand. These prognoses should be currently compared with actual results and correspondingly verified. Investigations mentioned in parts. 2 and 3 should also be performed on these disposals. The performance method of the investigations on all ten disposals should be coordinated by one person and the results periodically compared.

e. It seems, that with technical and financial means and an adequate staff, this problem can be fully solved within six to seven years.

## Acknowledgment

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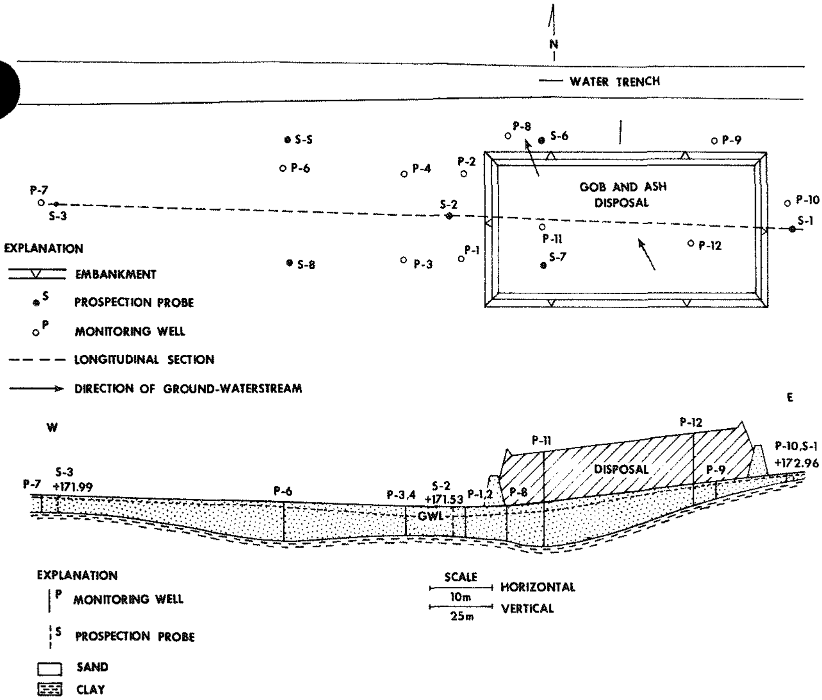

FIGURE 1. THE SITUATION MAP AND LONGITUDINAL SECTION OF TEST DISPOSAL NO. 1

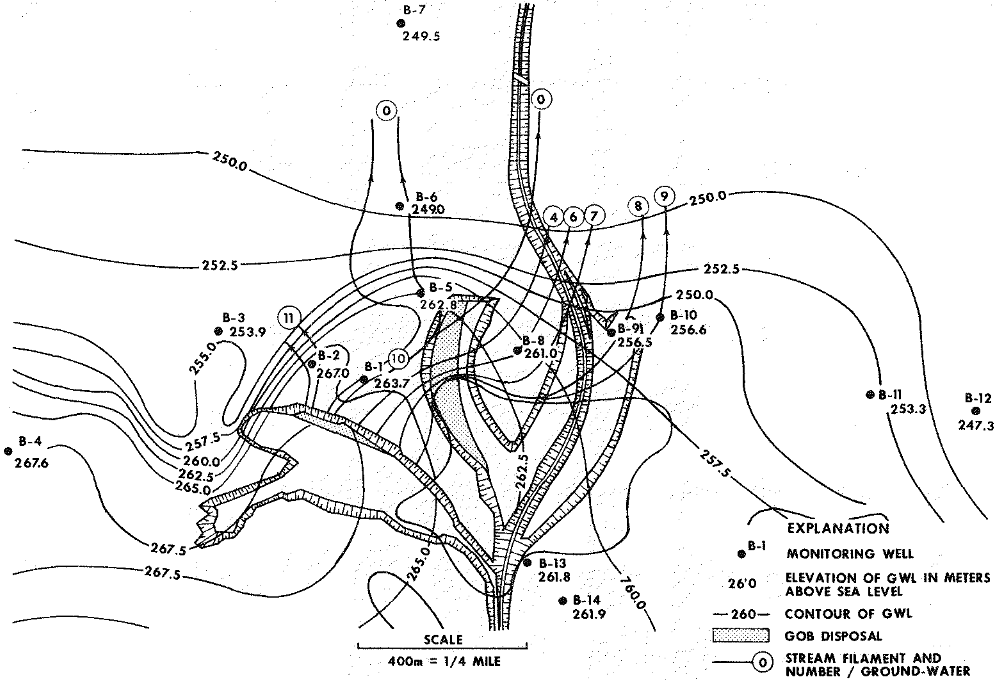

FIGURE 2. DISPOSAL NO.2 THE CONTOUR MAP OF GROUND WATER TABLE

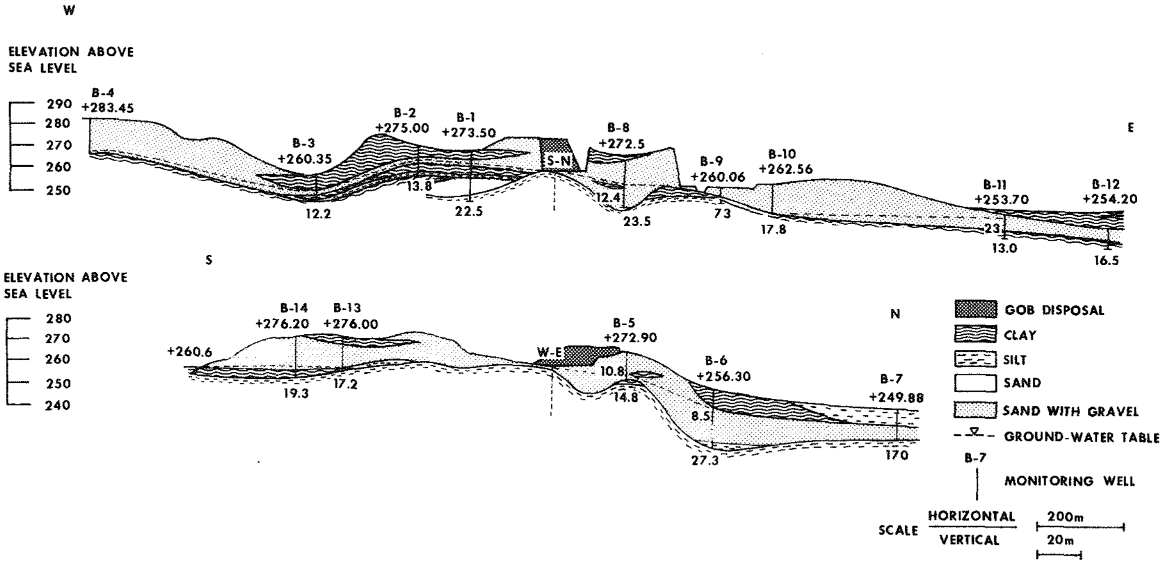

FIGURE 3. DISPOSAL NO. 2 HYDROGEOLOGICAL SECTIONS

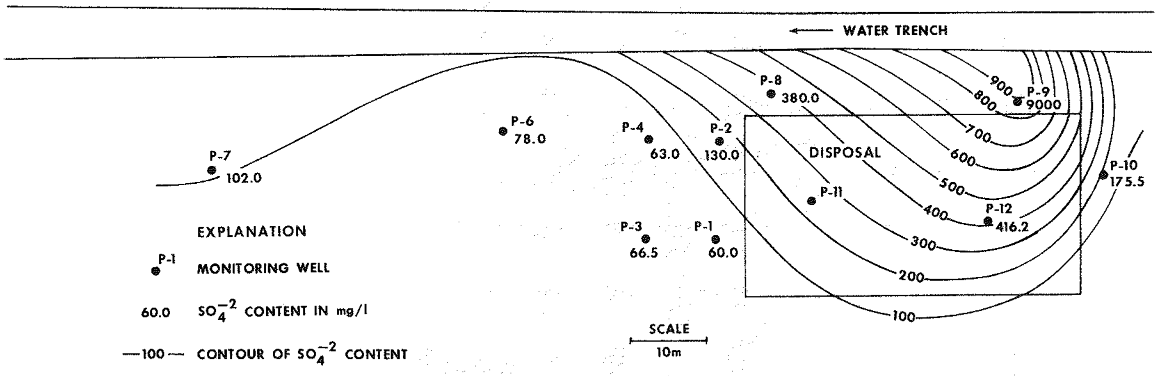

FIGURE 4. DISPOSAL NO. 1 THE CONTOUR MAP OF $SO_4^{-2}$ ion CONTENT AUG. 13. 1976/20 MONTHS AFTER STORAGE/

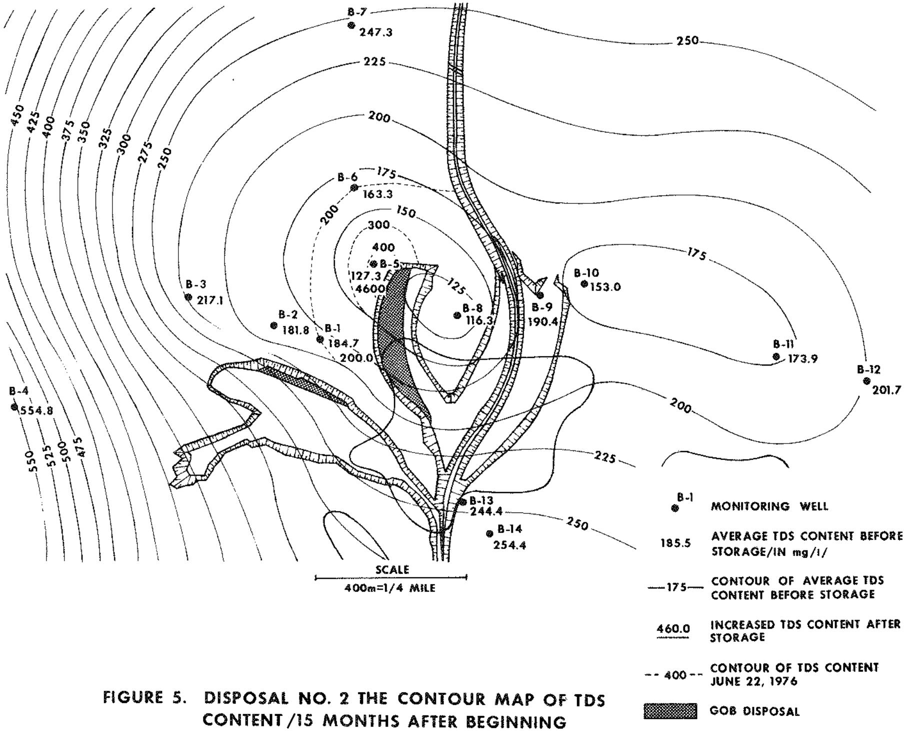

FIGURE 5. DISPOSAL NO. 2 THE CONTOUR MAP OF TDS CONTENT/15 MONTHS AFTER BEGINNING OF STORAGE

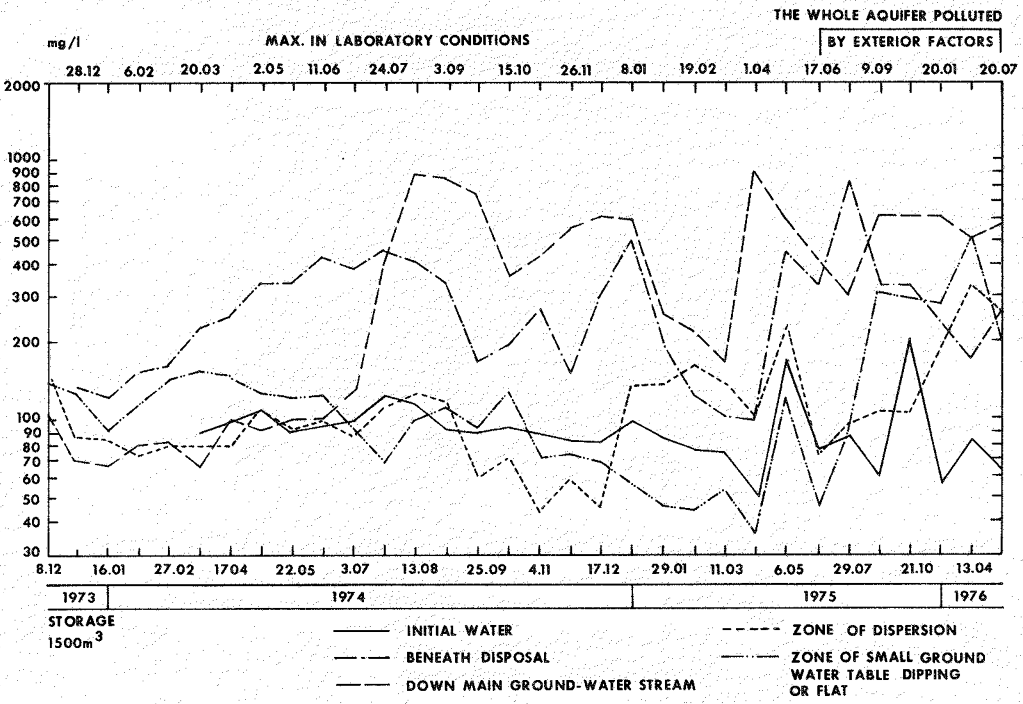

FIGURE 6. DISPOSAL NO. 1 DIAGRAM OF $SO_4^{-2}$ CONTENT

# WATER POLLUTION FROM DRAINAGE AND RUNOFF OF WASTEWATER FROM COAL STORAGE AREAS

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## Introduction

A study of the water pollution potential of coal stockpiles main[illegible]ned outdoors at production and user sites was conducted under EPA [illegible]ntract No. 68-02-1874 (1). These storage piles are sources of polluted effluents due to the drainage, and runoff of wastewater which occurs during and after precipitation. The runoff flows from the drainage area into the nearest waterway. This study quantified the effluent levels from these sources by examining coals (both freshly mined and aged) from six coal regions of the U.S. Data were obtained by placing these coals beneath a rainfall simulator and collecting grab samples of the drainage. These samples were analyzed for organic and inorganic substances and for water quality indicators.

A representative stockpile was defined to characterize the drainage and runoff effluent levels from all sources. Hydrologic relationships were used to estimate the runoff concentrations. These runoff concentration levels were then compared with water quality criteria to estimate the potential environmental impact.

The final report on this project also discussed available control technologies for each pollutant studied, and their efficiencies are discussed, along with future control techniques applicable to storage areas. The growth of coal stocks and methods of stockpiling coal were also included in the report.

## Coal Stockpiles As Sources

There are about 950 coal stockpiles containing 124 x $10^6$ metric tons of coal at user facilities throughout the U.S. Three-fourths of the coal produced is consumed at electric utilities.

These stocks are maintained outdoors where they are exposed to a variety of atmospheric conditions. Rainfall leaches pollutants from the stockpile and drains into waterways. Aquatic lifeforms in these waterways are thus exposed to these pollutants. It is well known that drainage in coal mining operations produces high sulfate concentrations and low pH values in nearby streams. The potential for this same problem exists at coal stockpiles since pyrites, the prime factor in acid mine drainage, exist within the coal pile.

In addition, coal contains inorganic substances in the "ash" (extraneous mineral matter) and in the coal structure which may enter the drainage. Since coal, however, is primarily organic, drainage releases organic contaminants also.

## Water Pollution Levels

Coal is a complex aggregate capable of discharging a vast range of compounds. This study was limited to: (a) compounds listed on the EPA Toxic Substances List (2); (b) pollutants with effluent limitations for coal storage areas; and, (c) other water quality criteria used to indicate the presence of classes of compounds. Due to the diversity of stockpile sources and coal compositions, a representative source was defined to characterize the water pollutant levels from all coal storage areas.

The content of the representative coal was determined from coal-production weighted arithmetic mean parameters. An analysis of the range of inorganic element contents within coals indicated that one coal sample could not be used to represent the source. Therefore one sample of coal from each of the six coal regions of Table 1 was obtained. These coals were collected fresh at the mine, ready for storage. They had been exposed to the atmosphere for at least 30 days. The sampling of drainage waters took place another 45+ days after this. Therefore, the coal represented 75+ days of storage, which is within 12% of the average stockpiling duration for utili[illegible].

Two samples were also collected of aged coal, that is; coal that had been in storage for an indeterminate (>5 years) length of time, to observe the effect of this factor on effluent levels. However, an in-depth study was not performed on quantifying the effect of each specific variable, rather representative (average) conditions were created.

The apparatus shown in Figure 1 was used to create simulated rainfall of representative intensity and duration. This unit consisted of an array of enclosed plastic modules with numerous surgical tubings protruding at the bottom. Water was fed under differing pressures to these modules so that droplets were emitted through the surgical tubing.

The eight coal samples were placed under this apparatus. Drainage seeped through the coal, out the bottom of the pans, and into collection bottles. A background sample of the rainfall water used was also collected. All these samples were then returned to the laboratory for analysis. Three simulation runs were completed over a period of 30 days. The time between runs was varied to observe this effect. The average effluent concentration per coal region is presented in Table 2. The average effluent factors per coal region are listed in Table 3. These data represent the effluent levels for coals mined from each region.

Concentration levels for coals from the representative source were computed as coal-production-per-region weighted averages. Table 4 presents the representative levels at the source. However, the pollutant concentration levels of concern are those that enter the nearest waterway. These runoff levels result from the dilution of pile drainage by runoff waters in the entire coal storage area. They are computed for the representative source to quantify the environmental impact, as a ratio of concentration level and water quality criteria.

The representative storage pile maintains 95,000 metric tons of coal stockpiled to a height of 5.8 meters (1). The area around the pile is a small drainage basin with direct and base runoff flow to [illegible] waterway located 86 meters downstream from the pile. This study is concerned with direct runoff from the pile and surrounding area which occurs promptly after precipitation. The representative rainfall rate is 0.7 cm/hr over a stockpile area of 18,792 square meters. This rainfall occurs 139 days/year, every 2.6 days, and lasts for approximately 1 hour. However only 15% of this rainfall volume on the pile appears as direct runoff at the waterway. This is based on the coefficients of runoff used in the rational method of hydrology (4). Volumetric flow from the pile was computed as 21 cubic meters per hour.

Runoff from the entire coal storage area was obtained from a survey of coal storage sites. The average runoff was 610 cubic meters per hour (5).

The concentration levels of Table 4 are diluted by the drainage area volumetric flow to obtain the effluent concentrations of Table 5. Thorough mixing of runoff waters with pile drainage is assumed. The coal aggregate retards the runoff flow for a time period sufficient to enable mixing of upstream runoff. These runoff levels are compared with published and computed water quality criteria for each pollutant. The ratios of these two levels are presented in Table 6.

Downstream $BOD_5$ levels at which the critical oxygen deficit is [illegible]eved is computed from the Streeter-Phelps equation (6) as $<0.52$ g/m$^3$ [illegible] to a discharge of $\leq 3.56$ g/m$^3$. However, it is believed that the wastewater may have been toxic to the $BOD_5$ test seed, due to the high COD and TOC levels obtained.

A comparison of effluent concentration levels from the representative source with the effluent limitations for the coal mining and steam electric power generating point sources is presented in Table 7. All computed runoff concentration levels are within the limitations for the representative source.

The effect of coal age and rainfall frequency were observed during the simulation runs using two aged coals. In general, the trend showed that increasing rainfall frequency and coal age increased the concentration levels of pollutants.

## Control Technology

While control of effluents from coal stockpiles is not widely practiced, the best practicable control technology currently available for complying with effluent limitations at steam electric power generating sources is collection, neutralization, and sedimentation. These treatments are best for pH and TSS control. Process design considerations include construction of drainage ditches, installation of surface covering with drainage to a sump, storage in bins and hoppers with runoff into trenches, and establishment of vegetative surroundings to retard runoff, erosion, and sedimentation.

Future control of the other effluents included in this study are numerous and limited by their economic feasibility. The biological and physical/chemical treatments applicable to each pollutant in this study are presented in Tables 8 and 9 respectively. Efficiencies for these treatments are discussed in the final report (1).

Other control considerations can reduce the oxidation of pyrites in the coal. These include the use of sealed bins or bunkers, sealing of pile surface with tar or asphalt, storage in concrete pits, and storage in compacted layers. Removal of pyrite can be accomplished [illegible]ugh flotation during coal preparation. In addition, better [illegible]aning of the coal in general will reduce the ash content and the presence of inorganics.

## Growth of Coal Stocks

Stockpile growth follows consumption trends closely. Consumption is expected to grow 7% per year over the next ten years while coal stocks increase 3.8% per year. Effluent levels will increase correspondingly.

Storage piles will continue to be located outdoors to facilitate the loading and handling, inhibit spontaneous combustion, and for its economic practicality. Bin storage and handling may become more popular as greater physical and environmental control of the pile is required.

## Conclusion

Predicted water pollutants from the representative coals stockpile create runoff concentrations that enter the nearest waterway in levels from one to seven orders of magnitude less than water quality criteria. However pollution from these sources is a site-specific problem. Large, aged coal stockpiles located in areas of frequent rainfall will generate much higher effluent concentrations. In addition, the time of year is important. Coal pile runoff in th[illegible] summer, when waterways have low flow rates and high temperatures [illegible]e more damaging than in the wintertime. Therefore, specific sites are better studied using the effluent factors per coal region (coal type). The runoff quantities for that site (and time of year) can then be estimated using local meteorological data and estimated runoff coefficients. Site-specific runoff concentrations can then be computed and compared with hazardous levels and effluent limitations. The need for control technology can then be established.

## References

1. Wachter, R. A. and T. R. Blackwood. Source Assessment: Water Pollutants from Coal Storage Areas - State of the Art. Contract 68-02-1874, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina (Final document submitted to the EPA by Monsanto Research Corporation, June 1977). 112 pp.

2. Sampling and Analysis Procedures for Survey of Industrial Effluents for Priority Pollutants. U.S. Environmental Protection Agency, Cincinnati, Ohio, March 1977. 180 pp.

3. Mayer, E.M., H.J. Hall, and G.M. Varza, Jr.; Potential Pollutants in Fossil Fuels. EPA-R2-73-24g, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina, June 1973. 151 pp.

4. Handbook of Water Resources and Pollution Control. H. W. Gehm and J. I. Bregman, eds. Van Nostrand Publishing Company, New York, New York, 1976. pp. 444-447.

5. Development Document for Proposed Effluent Limitation Guidelines and New Source Performance Standards for the Steam Electric Power Generating Point Source Category. EPA 440/1-73/029, U.S. Environmental Protection Agency, Washington, D.C., March 1974. pp. 128-130.

6. Metcalf and Eddy, Inc., Wastewater Engineering: Collection, T[illegible]tment, and Disposal. McGraw-Hill Book Company, New York, New [illegible] 1972. 782 pp.

Table 1. COAL REGIONS OF THE UNITED STATES (3)

| Region | States included |
|---|---|
| Appalachian | Pennsylvania, Ohio, West Virginia, Maryland, Virginia, Eastern Kentucky, Tennessee, Alabama, Georgia |
| Interior-Eastern | Illinois, Indiana, Western Kentucky, Michigan |
| Interior-Western | Iowa, Missouri, Nebrasks, Kansas, Oklahoma, Arkansas, Texas |
| Western | Wyoming, Idaho, Utah, Colorado, New Mexico, Arizona, Washington |
| Southwestern | Utah, Colorado, Arizona, New Mexico |
| Great Northern Plains | Montana, North Dakota, South Dakota |

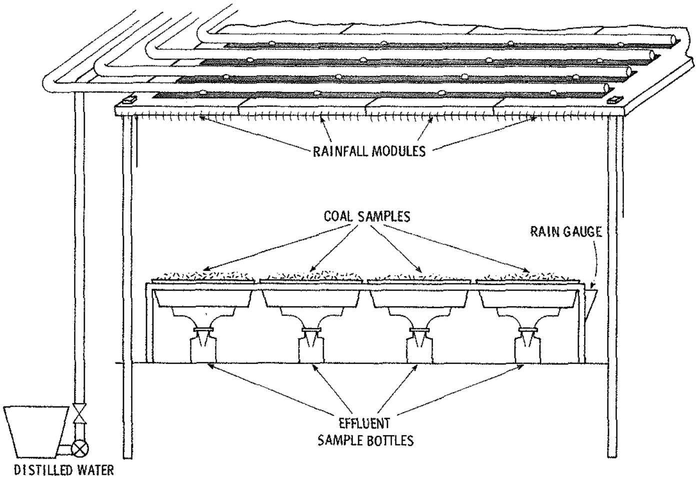

Figure 1. Rainfall simulation apparatus.

Table 2. AVERAGE EFFLUENT DRAINAGE CONCENTRATIONS PER COAL REGION

| Effluent parameter | Effluent concentration, g/m3<br>Appalachian | Great Northern Plains | Interior Eastern | Interior Western | Western | Southwestern |
|---|---|---|---|---|---|---|
| Total suspended solids | 1,521 | 1,282 | 1,264 | 1,853 | 2,486 | 1,538 |
| Total dissolved solids | 259 | 430 | 1,136 | 5,539 | 1,900 | 356 |
| Sulfate | 66 | 1,598 | 648 | 4,860 | 240 | 190 |
| Iron | 3.1 | 1.5 | 9.1 | 1,131 | 8.2 | 5.5 |
| Manganese | 0.03 | 0.14 | 0.44 | 17.9 | 0.4 | 0.04 |
| Free silica | 12.3 | NDL[a] | 0.8 | 86.3 | NDL | NDL |
| Cyanide | <0.001 | NDL | 0.002 | NDL | NDL | NDL |
| $BOD_5$ | <5.0 | <7.5 | NDL | <1.2 | <2.5 | <7.5 |
| COD | 1,407 | 1,324 | 1,556 | 1,053 | 1,826 | 769 |
| Nitrate | 0.12 | 0.14 | 0.33 | 0.09 | 1.8 | 0.16 |
| Total phosphate | NDL | NDL | NDL | NDL | NDL | NDL |
| Antimony | 2.1 | NDL | 7.5 | 10.3 | 14.0 | 6.5 |
| Arsenic | 23 | 1.8 | 4.1 | 10.1 | 5.6 | 4.1 |
| Beryllium | NDL | NDL | NDL | NDL | NDL | NDL |
| Cadmium | NDL | NDL | NDL | 0.05 | 0.005 | NDL |
| Chromium | NDL | NDL | NDL | 0.03 | 0.04 | NDL |
| Copper | 0.02 | NDL | NDL | 2.2 | NDL | 0.02 |
| Lead | 0.05 | 0.05 | 0.06 | 0.33 | 0.07 | 0.05 |
| Nickel | 0.06 | 0.02 | 0.09 | 10.2 | 0.05 | 0.03 |
| Selenium | 23.8 | NDL | 12.5 | 25.2 | 15.0 | 21.5 |
| Silver | NDL | NDL | NDL | NDL | NDL | NDL |
| Zinc | 0.008 | 0.17 | 0.14 | 25.0 | 0.15 | 0.04 |
| Mercury | <0.001 | 0.003 | NDL | 0.004 | 0.005 | 0.002 |
| Thallium | NDL | NDL | NDL | NDL | NDL | NDL |
| pH[b] | 6.28[b] | 6.93[b] | 7.62[b] | 2.81[b] | 7.24[b] | 6.60[b] |
| Chloride | 0.33 | NDL | NDL | 2.3 | NDL | NDL |
| Total organic carbon | 251.7 | 373.2 | 380.1 | 90.5 | 318.4 | 158.7 |

[a] No detectable level.

[b] Negative logarithm of hydrogen ion concentration.

Table 3. AVERAGE EFFLUENT FACTORS PER COAL REGION

| Effluent parameter | Effluent factors, mg/kg-hr ($10^{-3}$ lb/ton-hr)<br>Appalachian | | Interior Eastern | | Interior Western | | Great Northern Plains | | Southwestern | | Western | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | mg/kg-hr | $10^{-3}$ lb/ton-hr | mg/kg-hr | $10^{-3}$ lb/ton-hr | mg/kg-hr | $10^{-3}$ lb/ton-hr | mg/kg-hr | $10^{-3}$ lb/ton-hr | mg/kg-hr | $10^{-3}$ lb/ton-hr | mg/kg-hr | $10^{-3}$ lb/ton-hr |
| Total suspended solids | 23 | 46 | 19 | 38 | 28 | 56 | 19 | 38 | 23 | 46 | 37 | 74 |
| Total dissolved solids | 4 | 8 | 17 | 34 | 83 | 166 | 6 | 12 | 5 | 10 | 28 | 56 |
| Sulfate | 1 | 2 | 10 | 20 | 73 | 446 | 24 | 48 | 3 | 6 | 4 | 8 |
| Iron | 0.04 | 0.08 | 0.1 | 0.2 | 17 | 34 | 0.03 | 0.06 | 0.09 | 0.18 | 0.1 | 0.2 |
| Manganese | 0.0004 | 0.0008 | 0.006 | 0.012 | 0.3 | 0.6 | 0.002 | 0.004 | 0.0006 | 0.0012 | 0.006 | 0.012 |
| Free silica | 0.2 | 0.4 | 0.01 | 0.02 | 1.4 | 2.8 | NDL[a] | | NDL | | NDL | |
| Cyanide | <0.00001 | <0.00002 | 0.00003 | 0.00006 | NDL | | NDL | | NDL | | NDL | |
| $BOD_5$ | <0.08 | <0.16 | NDL | | <0.02 | <0.04 | 0.1 | 0.2 | 0.1 | 0.2 | <0.03 | <0.06 |
| COD | 21 | 42 | 23 | 46 | 16 | 32 | 20 | 40 | 12 | 24 | 27 | 54 |
| Nitrate | 0.002 | 0.004 | 0.004 | 0.008 | 0.001 | 0.002 | 0.002 | 0.004 | 0.003 | 0.006 | 0.03 | 0.06 |
| Total phosphate | NDL | | NDL | | NDL | | NDL | | NDL | | NDL | |
| Antimony | 0.03 | 0.06 | 0.1 | 0.2 | 0.2 | 0.4 | NDL | | 0.09 | 0.18 | 0.2 | 0.4 |
| Arsenic | 0.3 | 0.6 | 0.06 | 0.12 | 0.2 | 0.4 | 0.03 | 0.06 | 0.06 | 0.12 | 0.09 | 0.18 |
| Beryllium | NDL | | NDL | | NDL | | NDL | | NDL | | NDL | |
| Cadmium | NDL | | NDL | | 0.0008 | 0.0016 | NDL | | NDL | | 0.00007 | 0.00014 |
| Chromium | NDL | | NDL | | 0.0004 | 0.0008 | NDL | | NDL | | 0.0006 | [illegible] |
| Copper | 0.0003 | 0.0006 | NDL | | 0.03 | 0.06 | NDL | | 0.0003 | 0.0006 | NDL | |
| Lead | 0.0008 | 0.0016 | 0.0009 | 0.0018 | 0.004 | 0.008 | 0.0008 | 0.0016 | 0.0008 | 0.0016 | 0.001 | [illegible] |
| Nickel | 0.0009 | 0.0018 | 0.001 | 0.002 | 0.2 | 0.4 | 0.0003 | 0.0006 | 0.0004 | 0.0008 | 0.0008 | 0.0016 |
| Selenium | 0.4 | 0.8 | 0.2 | 0.4 | 0.4 | 0.8 | NDL | | 0.3 | 0.6 | 0.2 | 0.4 |
| Silver | NDL | | NDL | | NDL | | NDL | | NDL | | NDL | |
| Zinc | 0.0001 | 0.0002 | 0.002 | 0.004 | 0.4 | 0.8 | 0.003 | 0.006 | 0.006 | 0.0012 | 0.003 | 0.006 |
| Mercury | 0.00002 | 0.00004 | NDL | | 0.00006 | 0.00012 | 0.00004 | 0.00008 | 0.00003 | 0.00006 | 0.00008 | 0.00016 |
| Thallium | NDL | | NDL | | NDL | | NDL | | NDL | | NDL | |
| Chloride | 0.004 | 0.008 | NDL | | 0.03 | 0.06 | NDL | | NDL | | NDL | |
| Total organic carbon | 4 | 8 | 6 | 12 | 1 | 2 | 6 | 12 | 2 | 4 | 5 | 10 |
| pH (log $1/H^+$) | 6.3 | | 7.6 | | 2.8 | | 6.9 | | 6.6 | | 7.2 | |

[a] No detectable level.

NOTE: Blanks indicate no data applicable.

Table 4. COAL PRODUCTION-WEIGHTED EFFLUENT CONCENTRATIONS

| Effluent parameter | Concentration, g/m$^3$ |
|---|---|
| Total suspended solids | 1,551 |
| Total dissolved solids | 754 |
| Sulfate | 401 |
| Iron | 39 |
| Manganese | 0.69 |
| Free silica | 10.1 |
| Cyanide | <0.001 |
| BOD$_5$ | <3.8 |
| COD | 1,436 |
| Nitrate | 0.31 |
| Total phosphate | NDL[a] |
| Antimony | 4.6 |
| Arsenic | 15.7 |
| Beryllium | NDL |
| Cadmium | 0.002 |
| Chromium | 0.004 |
| Copper | 0.08 |
| Lead | 0.06 |
| Nickel | 3.1 |
| Selenium | 19.9 |
| Silver | NDL |
| Zinc | 0.80 |
| Mercury | <0.001 |
| Thallium | NDL |
| pH | 6.58[b] |
| Chloride | 0.27 |
| Total organic carbon | 280.1 |

[a] No detectable level.

[b] Negative logarithm of hydrogen ion concentration.

Table 5. CALCULATED RUNOFF CONCENTRATIONS FROM THE REPRESENTATIVE SOURCE

| Effluent parameter | Concentration entering waterways, g/m$^3$ |
|---|---|
| Total suspended solids | 0.16 |
| Total dissolved solids | 0.08 |
| Sulfate | 0.04 |
| Iron | 0.007 |
| Manganese | $7 \times 10^{-5}$ |
| Free silica | 0.001 |
| Cyanide | $<1 \times 10^{-7}$ |
| Nitrate | $3 \times 10^{-5}$ |
| Total phosphate | NDL[a] |
| Antimony | $4 \times 10^{-4}$ |
| Arsenic | 0.001 |
| Beryllium | NDL |
| Cadmium | $2 \times 10^{-7}$ |
| Chromium | $4 \times 10^{-7}$ |
| Copper | $7 \times 10^{-6}$ |
| Lead | $6 \times 10^{-6}$ |
| Nickel | $4 \times 10^{-5}$ |
| Selenium | 0.002 |
| Silver | NDL |
| Zinc | $7 \times 10^{-5}$ |
| Mercury | $1 \times 10^{-7}$ |
| Thallium | NDL |
| Chloride | $2 \times 10^{-5}$ |
| Total organic carbon | 0.003 |
| 2-Chloronaphthalene | 0.02[b] |
| Acenaphthene | 0.02[b] |
| Fluorene | 0.02[b] |
| Fluoranthene | 0.02[b] |
| Benzidine | 0.02[b] |
| Di-iso-octylphthalate | –[c] |
| Benzo(ghi)perylene | 0.07[b] |

[a] No detectable level.

[b] $10^{-6}$ g/m$^3$ = ng/ℓ = ppt.

[c] Assumed to be within the background water.

Table 6. HAZARDOUS AND RUNOFF CONCENTRATION LEVELS FOR POLLUTANTS FROM COAL STORAGE AREAS

| Effluent | Runoff concentration ($C_R$), g/m³ | Hazardous concentration ($C_H$), g/m³ | $C_R/C_H$ ratio |
|---|---|---|---|
| Antimony | 0.0004 | 0.225 (41, 44) | 0.0018 |
| Arsenic | 0.001[a] | 0.05 (45) | 0.02 |
| Asbestos | 0.001 | 0.63 (41, 44) | 0.0016 |
| Beryllium | NDL[b] | 0.011 (45) | –[c] |
| Cadmium | $2 \times 10^{-7}$ | 0.01 (45) | 0.00002 |
| Chromium | $4 \times 10^{-7}$ | 0.05 (45) | 0.000008 |
| Copper | $<7 \times 10^{-6}$ | 1.0 (45) 0.000007 | 0.000007 |
| Cyanides | $7 \times 10^{-7}$ | 0.005 (45) | 0.00014 |
| Lead | $6 \times 10^{-6}$ | 0.05 (45) | 0.00012 |
| Mercury | $1 \times 10^{-7}$ | 0.002 (45) | 0.00005 |
| Nickel | $4 \times 10^{-5}$ | 0.0013 (45) | 0.031 |
| Selenium | 0.002 | 0.01 (45) 0.2 | 0.2 |
| Silver | NDL[b] | 0.05 (45) | –[c] |
| Thallium | NDL[b] | 0.008 (42, 44) | –[c] |
| Zinc | $7 \times 10^{-5}$ | 5.0 (45) | 0.000014 |
| Total phosphate | NDL[d] | $1 \times 10^{-7}$[e] | –[f] |
| Sulfate | 0.04 | 250 (45) | $2 \times 10^{-4}$ |
| Nitrate | $3 \times 10^{-5}$ | 10 (45) | $3 \times 10^{-6}$ |
| TDS | 0.08 | 250 (45) | $3.2 \times 10^{-4}$ |
| Acenaphthene | 0.02[g] | 1,350 | $1.5 \times 10^{-11}$ |
| Benzidene | 0.02[g] | 0.695 | $2.9 \times 10^{-8}$ |
| Benzo(phi)perylene | 0.07[g] | 0.054 | $1.3 \times 10^{-6}$ |
| 2-Chloronaphthalene | 0.02[g] | 4.68 | $4.3 \times 10^{-9}$ |
| Fluoranthene | 0.02[g] | 4.5 | $4.4 \times 10^{-9}$ |
| Fluorene | 0.02[g] | 33.8 | $5.9 \times 10^{-10}$ |

[a] Free silica concentration.

[b] No detectable level.

[c] Not calculated.

[d] No detectable level.

[e] Phosphorus standard.

[f] Not calculated.

[g] $10^{-6}$ g/m³.

Table 7. COMPARISON OF RUNOFF CONCENTRATION LEVELS WITH EFFLUENT LIMITATIONS (g/m³)

| | Coal mining point sources | | | | | | Steam electric power generating | |
|---|---|---|---|---|---|---|---|---|
| | Based on BPCTCA | | Proposed, based on BATEA | | Proposed, new sources | | Based on BPCTCA, BATEA, and for new sources | |
| Effluent parameter | Maximum for 1 day | Average of 30 days | Maximum for 1 day | Average of 30 days | Maximum for 1 day | Average of 30 days | | Runoff concentration |
| Total iron | 7.0 | 3.5 | 3.5 | 3 | 3.5 | 3.0 | –[a] | 0.007 |
| Total manganese | 4.0 | 2.0 | 4.0 | 2 | 4 | 2 | –[a] | 0.00007 |
| TSS | 70 | 35 | 40 | 20 | 70 | 35 | ≤50 | 0.16 |
| pH | Within 6 to 9 range | Within 6 to 9 range | Within 6 to 9 range | Within 6 to 9 range | Within 6 to 9 range | Within 6 to 9 range | Within 6 to 9 range | 6.9 |

[a] No limitation promulgated at present.

Table 8. BIOLOGICAL WATER TREATMENTS APPLICABLE TO COAL STOCKPILE WATER POLLUTANTS

| Treatment technique | BOD | COD | TOC | TSS | Nitrate |
|---|---|---|---|---|---|
| Aerobic | | | | | |
| Activated sludge | x | x | x | x | |
| Trickling filters | x | x | x | x | |
| Aerated lagoons | x | x | x | x | |
| Aerated ponds | x | x | x | x | |
| Activated sludge modifications | x | x | x | x | |
| Anaerobic | | | | | |
| Sludge digestion | x | x | | x | x |
| Contact process | x | x | | x | x |
| Aerobic filter | x | x | | x | x |
| Anaerobic ponds | x | x | | x | x |
| Anaerobic-aerobic ponds | x | x | x | x | x |

Table 9. PHYSICAL/CHEMICAL TREATMENTS APPLICABLE TO COAL STOCKPILE WATER POLLUTANTS

| Treatment techniques | BOD | COD | TOC | TSS | TDS | Phosphate | Sulfate | Acidity | Nitrate | Lead | Nickel | Chromium | Arsenic | Zinc | Mercury | Cadmium | Iron | Calcium | Manganese | General heavy metals | Copper | Chlorides | Cyanide |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Coagulation, flocculation, precipitation | | | | x | x | x | | | | x | x | x | | x | x | x | x | x | x | x | x | | |
| Carbon adsorption | x | x | x | x | | x | | | | x | | | | | | | | | | | | | |
| Filtration | x | x | | x | x | x | | | | | | | | | | | | | | | | | |
| Sedimentation | x | x | | x | | x | | | | | | | | | | | | | | x | | | |
| Chemical oxidation reduction | | | | | | | x | | | | | | | | | | x | | x | | | | |
| Chlorination | x | x | | | | | x | | | | | | | | | | x | | x | | | x | x |
| Ozonation | x | x | | | | | | | | | | | | | | | x | | x | | | | x |
| Reverse osmosis | x | x | | | x | x | x | | x | x | x | x | x | x | | x | x | x | x | x | x | x | |
| Ion exchange | x | x | | | x | x | x | | x | x | x | x | x | x | x | x | x | | x | x | x | | |
| Electrodialysis | | | | | x | x | x | | | x | x | x | x | x | x | x | x | x | x | x | x | x | |
| Dissolved air, flotation and foam separation | x | x | | x | | | | | | | x | x | | | | | | | | | | | |
| Neutralization | | | | | | | | x | | | | | | | | | | | | | | | |
| Magnetic separation | x | x | | x | | x | | | | | | | | | | | | | | x | | | |
| Wet air combustion | x | x | x | | | | | | | | | | | | | | | | | | | | |
| Evaporation | | | | | x | | | | | | x | x | | | | | | | | | x | | |
| Freezing | | | | | x | | | | | | | | | | | | | | | | | | |

# MEASUREMENT AND MODELING OF STORM WATER RUNOFF FROM COAL STORAGE PILES AND THE IMPACT ON RECEIVING WATERS

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## 1.0 Introduction

As most industries and many municipalities are meeting the point source standards of the interim goal of 1977, the effect of non-point source pollution on water quality is gaining more attention. The National Commission on Water Quality reported that "non-point pollutant sources are significant to the Commission's study because they may in some instances overwhelm and negate the reductions achieved through point source effluent limitations"[1]. Based on these findings, the Commission recommended to Congress that "control or treatment measures shall be applied to agricultural and non-point discharges when these measures are cost-effective and will significantly help in achieving water quality standards"[2].

In January, 1976, TRC - THE RESEARCH CORPORATION of New England was retained by the Industrial Environmental Research Laboratory of the U.S. Environmental Protection Agency to evaluate waterborne fugitive emissions (non-point sources) in relationship to industrial activities. The objectives of the program included:

- An evaluation of industrial sources which might contribute to non-point source pollution.
- An assessment of present day sampling techniques for non-point sources.
- A review of existing mathematical models for predicting non-point source pollution.
- An evaluation (including a field program) of storm water runoff from the coal-fired utility and iron and steel industries.
- The adaptation of a mathematical model for predicting storm water pollution from an industrial site.

This paper presents the highlights of the coal-fired utility storm water measurement program. The major emphasis of this paper is on runoff from coal storage piles. Included is a description of the mathematical model used for predicting runoff from coal-fired utilities and its application to the sites measured.

## 2.0 Measurement Program

Why should the runoff from the coal-fired utility industry be measured?

Electrical energy is generated from fossil and nuclear fuels at approximately 1,000 sites in the United States. At these sites, coal provides approximately 54% of the total heat input for electrical generation. In 1974, this amounted to a coal usage rate of 328 million metric tons per year. Increasing demands for energy self-sufficiency are likely to push coal usage up to 454 million metric tons per year by 1990. Subsequently, in 1990 a typical 100-day supply of coal storage will increase from the current 100 million tons to 138 million tons. Land use for coal storage at electric facilities will increase to 81 million square meters from an approximate 1974 total of 58 million square meters. Storm water runoff from coal storage piles can also be expected to increase substantially as coal usage is expanded.

The effect of storm water runoff on receiving waters will become more pronounced as water quality improves through regulation of point sources. These projections are the basis for selecting the coal-fired utility industry for a sampling program.

## 2.1 Objective of Measurement Program

The field study was designed to determine:

1. Background conditions in the receiving water prior to a storm event.
2. Volume of and pollutant concentrations in storm water runoff as a function of time for the storm event.
3. Post-storm effect of the runoff on the receiving water.

Table 1 lists the parameters measured in the program. These parameters were chosen on the basis of three considerations. Sulfate, iron, aluminum, manganese and acidity are characteristically present in coal pile leachate. Total suspended solids (TSS) and total dissolved solids (TDS) are commonly washed off coal piles during storm events, and dissolved oxygen (DO), pH and alkalinity are indicative of the general water quality of the receiving water. Any noticeable changes in their respective values traceable to the coal pile could have water quality related impacts.

TABLE 1

PARAMETERS MEASURED IN UTILITY PROGRAM

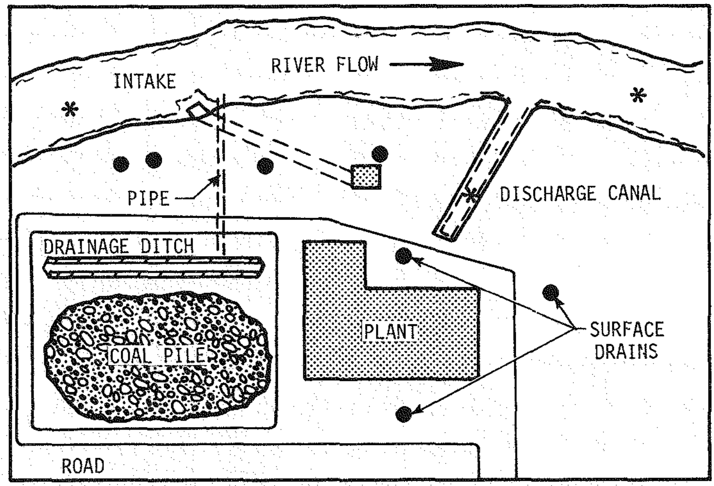
pH
Dissolved Oxygen
Total Suspended Solids
Total Dissolved Solids
Acidity/Alkalinity
Sulfate
Iron
Aluminum
Manganese

## 2.2 Site Descriptions

Two coal-fired steam electric generating facilities in Pennsylvania were chosen for the field study to identify and quantify runoff characteristics. These utilities were selected because they were located on rivers which had good water quality. Specific characteristics of each site are shown in Table 2.

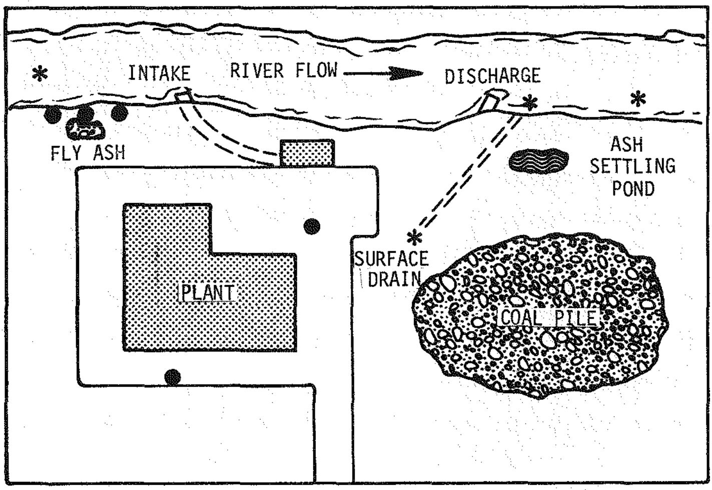
The Warren Station of the Pennsylvania Electric Company in Warren, Pennsylvania is a small generating plant (84 Mw) and is used primarily as a peaking facility. It is located on the Allegheny River below the Kinzua Dam. Bituminous coal is delivered by truck to the station on a daily schedule from mines in Clarion County, Pennsylvania.

Figure 1 shows the site layout for the Warren Station. Coal pile runoff is channeled to a drain pipe by a drainage ditch that parallels unused railroad tracks next to an access road for the coal trucks. (The road and tracks lie



SITE #1
✱● SAMPLING LOCATIONS

FIGURE 1: SITE LAYOUT WITH SAMPLING LOCATIONS - WARREN STATION OF PENNSYLVANIA ELECTRIC CO., WARREN, PA.



SITE #2
✱● SAMPLING LOCATIONS

FIGURE 2: SITE LAYOUT WITH SAMPLING LOCATIONS - PORTLAND STATION OF METROPOLITAN EDISON CO., PORTLAND, PA.

between the drainage ditch and river on Figure 1.) The drain pipe continually drains small quantities of leachate during dry periods and substantial quantities of runoff during rainfall events. All runoff from the coal pile must pass through the drain pipe for discharge to the river. The paved access road is used by coal trucks to enter and leave the coal unloading area. The road is covered with coal dust and earthen materials, although the pavement is still visible through the accumulation. The material is washed off during rainfall events. The water drains across the road through a rockstrewn area of rubble approximately 12 meters wide to the river bank. There are several distinctly visible areas where this road dirt and coal dust are carried to the river.

The Portland Station of Metropolitan Edison Company is located in Portland, nnsylvania on the Delaware River. This 410 Mw facility is used as a baseload tion. Bituminous coal is delivered by railroad car from Pennsylvania and West rginia mines.

Figure 2 shows the site layout for the Portland Station. A substantial portion of the storm water runoff from the coal pile is intercepted by the ash settling pond and never flows directly into the river. One sector of the coal pile runoff does go to a surface drain and is discharged with parking lot and road runoff into the river.

## 2.3 Warren Sampling Program

The test plan was implemented at Warren without major difficulties. River samples were collected with an ISCO Model 16800L Sequential Sampler. It was programmed to collect 200 ml grab samples every minute to provide a two liter composite every ten minutes during the first 90 minutes of a rainfall period. From the 90th minute to the storm's end, the sampler was programmed to collect a two liter sample every half hour. During dry periods, the sampler collected an hourly composite of two liters.

The upstream site was established approximately 152 meters upstream of the cooling water intake, 7.6 meters from the river's edge. This location was well upstream of the runoff area from the access road. An air-filled buoy was used to suspend the pH/DO and temperature sensors and the sample line at about half-depth, 1.2 meters above the bottom. Dissolved oxygen (DO) and pH were measured with a Model ODEC Aqua Monitor.

The downstream site was secured approximately 152 meters downstream from the cooling water discharge-river interface, 46 meters from the river's edge. An inflatable raft was used to suspend the sensor probe and sample line at two meters, approximately mid-depth. The ISCO Sequential Sampler was also mounted on the raft. A recording rain gauge was installed at this site to record the rainfall rate during storm events.

The runoff drainage areas were well-delineated by the appearance of vegetation between the road and the river. It was difficult to set the sampling plugs vertically into the rocky, rubblestrewn surface, so they were installed in the ground at a slight horizontal angle with the screened opening facing uphill. proximately 50 plugs were distributed in the three main drainage areas and were t covered with tape until a rainfall event started. A compositing bucket was aced under the coal pile drain pipe and an ISCO Sequential Sampler was used to collect runoff samples from this bucket. In operation, the sampler intake was continually plugged with push-along solids, and the sampler was replaced by manual sampling.

## 2.4 Portland Sampling Program

The program test plan remained basically unchanged for the Portland survey, but modifications in implementing it were necessary to reflect the differences between the two sites.

## TABLE 2

## CHARACTERISTICS OF THE TWO SAMPLING SITES USED IN THE SURVEY

| Utility | Pa. Electric Co. | Metropolitan Edison |
|---|---|---|
| Plant | Warren Station | Portland Station |
| Location | Warren, Pa. | Portland, Pa. |
| Capacity<br>Mw output, net | 84 | 410 |
| Coal | | |
| Usage (metric tons/yr) | 315,000<br>est. 1974 | 840,000<br>est. 1974 |
| Source | Clarion Co., Pa. | PA & W. VA |
| Storage, metric tons | 27,200 | 172,000 |
| Sulfur % | 1.84 | 1.47 |
| Iron % | 0.35 | 0.38 |
| Manganese % | 0.003 | 0.004 |
| Aluminum % | 0.56 | 0.37 |

At Portland a small area of land north of the plant is used for fly ash storage during winter months. Runoff from this area drains under the plant fence and into the river. The upstream station was placed just upstream from this location approximately nine meters from the shore. An air-inflatable raft was anchored at the upstream site to hold the sensors and sample lines at mid-depth, approximately three meters below the surface.

The lower river station was established approximately 30 meters downstream from the cooling water discharge tunnel, approximately 230 meters from the upstream site. An identical instrumentation and sampling arrangement as at the upstream site was used.

The coal pile runoff drained to both the ash pond and the storm sewer. A [illegible]tion of the runoff to the storm drain was intercepted for sampling. Initially, [illegible] ISCO Sequential Sampler was installed in the storm drain, but large coal particles continually plugged the sample intake line and pump. To solve this problem, sampling plugs were placed in an array around the storm sewer inlet. Approximately 25 sampling plugs were also deployed in the drainage basin of the fly ash storage area. As with the sequential samplers, samples were collected every ten minutes for the first 90 minutes, and every half hour for the duration of the storm event.

Runoff flow measurements were unsuccessful due to effluent turbidity which masked the dyes and the complexity of storm drains which delayed and trapped velocity markers. A second storm could not be sampled at this site due to a prolonged dry spell, followed by the beginning of cold weather and freezing conditions.

## 2.5 Results of Field Surveys

Despite the less than desirable amount of storm activity at Warren and Portland, enough data were collected to show some interesting effects. A summary of the storm activity appears in Table 3. From the analyses of the coal pile runoff and receiving waters during dry and wet weather, some general characterizations can be made.

The laboratory analyses of the field data during dry and wet periods at all sampling stations show a broad range of values. These ranges of values were substantial enough to mask any apparent relationships between sites and sampling locations. Several statistical summaries have been prepared for selected pollutants during dry and wet periods at the two sampling locations in the receiving body.

### 2.5.1 Warren Results

Table 4 shows the range of pollutant concentrations at the various sampling locations at the Warren Station. The only significant observation is that the pollutants in the coal pile discharge pipe are more concentrated during dry weather (leachate) than wet (runoff), as would be expected.

The downstream pH values do appear lower under both wet and dry sampling [illegible]nditions. More data are necessary to establish a cause and effect relationship [illegible]tween runoff and pH behavior in the river.

Table 5 presents the mean concentrations with 95% confidence limits for selected pollutants in the Allegheny River. These data show the extreme variability in the measurements made upstream and downstream.

Table 6 shows the results of 't' and 'F' tests performed for the comparisons of data from the upstream and downstream sites during dry and wet periods. There is no statistical difference between mean pollutant concentrations at the upstream and downstream sites during dry weather. The sample variances for TSS and

## TABLE 3

## SUMMARY OF STORM ACTIVITY

| Location | Date | Storm Activity | Rainfall Intensity (Time) | Rainfall Intensity (in/hr) | Total Rainfall (in) | Comments |
|---|---|---|---|---|---|---|
| Warren Generating Station | 8-26-76 | Shower | 1435-1455 | 0.33 | 0.11 | Last Prior Storm Occurred on 8-15-76 |
| Warren Generating Station | 9-17-76 | Steady Drizzle, Intermittent Showers-Heavy at Short Intervals | 0800<br>0930<br>1050<br>1130<br>1230<br>1510 | 0.00<br>0.04<br>0.05<br>0.11<br>0.07<br>0.03 | 0.33 | |
| Portland Generating Station | 10-20-76 | Steady Drizzle, Intermittent Showers-Heavy at Short Intervals | 0800<br>0810<br>0910<br>1010<br>1110<br>1140<br>1155<br>to<br>2130 | 0.00<br>0.06<br>0.10<br>0.05<br>0.09<br>0.16<br>0.16<br><br>0.12* | 1.55 | Last Prior Storm Occurred on 10-13-76 |

*Average Intensity Based on Measured Value for Cumulative Rainfall in that Time Period.

## TABLE 4

## RANGE OF POLLUTANT CONCENTRATION AT THE SAMPLING LOCATIONS AT WARREN STATION OF PENNSYLVANIA ELECTRIC CO., WARREN, PA. AUGUST - SEPTEMBER, 1976

| Pollutant | RANGE OF POLLUTANT CONCENTRATIONS, mg/l | | | | | |
|---|---|---|---|---|---|---|
| | Upstream | | Downstream | | Coal Pile Discharge Pipe | |
| | Dry | Wet | Dry | Wet | Dry | Wet |
| Total Suspended Solids | 1 - 21 | 2 - 5 | 1 - 11 | 2 - 12 | 12 - 19000 | 1700 - 13000 |
| Total Dissolved Solids | 100 - 170 | 60 - 130 | 80 - 180 | - | 2300 - 21700 | 2300 - 115000 |
| Iron | .14 - .40 | .09 - .17 | .06 - .34 | .09 - 1.03 | 160 - 23500 | 700 - 1400 |
| Aluminum | N.D.[1] | N.D.[1] | N.D.[1] | N.D.[1] - 26.6 | 20 - 1800 | 70 - 100 |
| Manganese | .013 - .090 | .025 - .040 | N.D.[2]- .040 | .030 - .060 | 2 - 100 | 9 - 15 |
| Sulfate | 11 - 20 | 12 - 17 | 11 - 22 | 12 - 24 | 90 - 57000 | 1600 - 2700 |
| Total Alkalinity @ $CaCO_3$ | 38 - 48 | 38 - 42 | 36 - 45 | 40 - 41 | - | - |
| Total Acidity @ $CaCO_3$ | - | - | - | - | 200 - 38000 | 1900 - 2900 |
| pH | 6.77 - 7.80 | 6.60 - 6.76 | 6.77 - 7.60 | 6.36 - 6.87 | 1.48 - 3.37 | 2.35 - 3.36 |

[1] None detected, <0.2 mg/l

[2] None detected, <0.012 mg/l

## TABLE 5

## MEAN POLLUTANT CONCENTRATIONS WITH 95% CONFIDENCE LIMITS IN THE ALLEGHENY RIVER AT WARREN STATION OF PENNSYLVANIA ELECTRIC CO., WARREN, PA. AUGUST - SEPTEMBER, 1976

| | POLLUTANT CONCENTRATION, mg/l | | | |
|---|---|---|---|---|
| | Upstream | | Downstream | |
| Pollutant | Dry | Wet | Dry | Wet |
| TSS | 8.11 ± 2.26 | 7.25 ± 3.18 | 4.13 ± 2.04 | 5.50 ± 2.71 |
| $SO_4$ | 13.89 ± 0.84 | 15.09 ± 0.94 | 13.83 ± 1.45 | 16.65 ± 2.25 |
| Fe | 0.23 ± 0.02 | 0.12 ± 0.03 | 0.21 ± 0.09 | 0.39 ± 0.27 |
| Mn | 0.028 ± 0.005 | 0.032 ± 0.003 | 0.023 ± 0.005 | 0.043 ± 0.012 |
| Alk | 41.65 ± 0.85 | 40.33 ± 0.94 | 39.33 ± 0.89 | 40.30 ± 0.34 |

95% confidence limits = $\bar{x} \pm t_{\nu,.025} \sqrt{\frac{s^2}{n}}$

# TABLE 6

## COMPARISONS OF MEAN VALUES & VARIANCES WITHIN 95% CONFIDENCE LIMITS AT UPSTREAM & DOWNSTREAM SITES DURING DRY & WET SAMPLING PERIODS
## WARREN, PENNSYLVANIA
## AUGUST - SEPTEMBER, 1976

| Pollutant | Degrees of Freedom | t Test | Difference Between Means | Is Difference Between Means Significant? | Critical 'f' for 95% Confidence | 'F' Ratio | Is Difference Between Variances Significant? | |
|---|---|---|---|---|---|---|---|---|
| **UPSTREAM DRY - DOWNSTREAM DRY** | | | | | | | | |
| TSS | 50 | 7.47 | 3.98 | No | 2.69 | 3.38 | Yes | Upstream > Downstream |
| $SO_4$ | 44 | 3.06 | 0.06 | No | 2.53 | 0.55 | No | |
| Fe | 52 | 0.138 | 0.02 | No | 2.416 | 0.12 | Yes | Upstream < Downstream |
| Mn | 51 | 0.015 | 0.005 | No | 2.422 | 2.00 | No | |
| Alk | 65 | 2.59 | 2.32 | No | 2.173 | 1.72 | No | |
| **UPSTREAM WET - DOWNSTREAM WET** | | | | | | | | |
| TSS | 16 | 8.45 | 1.75 | No | 4.82 | 1.88 | No | |
| $SO_4$ | 19 | 4.57 | 1.56 | No | 3.96 | 0.196 | Yes | Upstream < Downstream |
| Fe | 17 | 0.495 | 0.27 | No | 4.36 | 0.011 | Yes | Upstream < Downstream |
| Mn | 18 | 0.019 | 0.011 | No | 4.72 | 0.10 | Yes | Upstream < Downstream |
| Alk | 17 | 1.86 | 0.03 | No | 4.10 | 6.52 | Yes | Upstream > Downstream |
| **UPSTREAM WET - UPSTREAM DRY** | | | | | | | | |
| TSS | 45 | 9.26 | 0.86 | No | 2.50 | 0.43 | No | |
| $SO_4$ | 37 | 2.91 | 1.20 | No | 2.57 | 0.41 | No | |
| Fe | 43 | 0.086 | 0.11 | Yes | 2.52 | 0.33 | No | |
| Mn | 44 | 0.017 | 0.004 | No | 2.42 | 0.10 | Yes | Wet < Dry |
| Alk | 50 | 3.81 | 1.32 | No | 2.44 | 0.20 | Yes | Wet < Dry |
| **DOWNSTREAM WET - DOWNSTREAM DRY** | | | | | | | | |
| TSS | 21 | 6.71 | 1.37 | No | 3.38 | 0.77 | No | |
| $SO_4$ | 26 | 4.96 | 2.82 | No | 2.98 | 1.16 | No | |
| Fe | 26 | 0.42 | 0.18 | No | 3.01 | 3.62 | Yes | Wet > Dry |
| Mn | 25 | 0.0202 | 0.0200 | Marginal | 3.10 | 2.00 | No | |
| Alk | 32 | 2.80 | 0.97 | No | 2.73 | 0.05 | Yes | Wet < Dry |

Fe during the dry period at both sites were statistically different.

Table 7 shows the characteristics of the coal pile leachate during the dry weather sampling. The site layout with the drainage ditch and pipe facilitated the collection of leachate samples. These data show that the leachate is concentrated and extremely acidic. The leachate flow rate was very low and no effect on the river was detected. The total suspended and dissolved solids concentrations seem to be dependent upon the length of time since the previous rain. As this time increases, the concentrations decrease. The color of the leachate remained amber during the dry period.

Table 8 presents the characteristics of the coal pile runoff during the second storm event. At the start of the storm, the "first flush" effect with its higher pollutant concentrations can be seen. These values generally decli through the rainfall period. Some perturbations do appear since the rain did not fall at a constant rate throughout the day. All measured pollutant values are lower during rain than during dry periods. When a comparison of the data in Tables 7 and 8 is made, it appears that water stored in the coal pile solubilizes various impurities in the coal and leaks out very slowly. Rainfall washes out the stored water within the pile, thus greatly diluting the impurities.

A comparison of the coal pile runoff with the dry weather leachate, indicated that the rate of mass loadings of all pollutants on the river, except suspended solids, is greater during the dry period. A closer examination of this behavior is warranted.

The coal pile runoff responded very quickly to rainfall intensity. The ground around the coal pile had a very low porosity, practically zero. Within minutes after the rain stopped, the coal pile discharge returned to its prior appearance and flow rate.

The 't' and 'F' tests presented in Table 6 show no statistically significant effect of runoff on the river. However, in the case of sulfate, iron, manganese and alkalinity, the sample variances were significantly different. In the cases where differences were noted, except for total alkalinity, the upstream sample variance was lower than downstream. This difference is partly related to the sampling locations. Although both locations were as representative of the river's cross-section as could be determined, it is likely that the downstream site contained a greater number of anomalies. The river was very wide at this point with a greater probability for peculiarities in flow patterns due to the delta formation, rapids, and the large island just upstream of the site.

In a comparison of each river site during the wet and dry periods, the data show only two statistically significant differences. At the upstream site, the data indicate a difference in the mean concentration of iron. The dry period had much higher concentrations than the wet period. There was a marginal difference in manganese concentrations during wet and dry periods at the downstream site. A comparison of these 'wet' versus 'dry' variances with upstream versus downstream variances, indicates that they are partly the result of differences in the characteristics of each site as well as differences created by the rainfall events.

### 2.5.2 Portland Results

Table 9 shows the range of values for each pollutant at the Portland Station sampling sites. These ranges are similar to those measured at the Warren Station sites. They commonly vary by up to an order of magnitude.

The pH values during the short sampling period at Portland appear to cover a higher range downstream from the plant, contrary to pH values observed at Warren.

Table 10 shows the 95% confidence limits for the upstream and downstream sites during dry and wet periods. As was true with the Warren sampling data, most of the Portland data at each river sampling site seems to be similar during both

## TABLE 7

## CHARACTERISTICS OF COAL PILE LEACHATE-DRY WEATHER AT WARREN STATION OF PENNSYLVANIA ELECTRIC CO., WARREN, PA. AUGUST - SEPTEMBER, 1976

| Date | Hours Since Last Rain | Pollutant Concentration, mg/l | | | | | | | | Discharge Flow Rate lpm (gpm) |
|---|---|---|---|---|---|---|---|---|---|---|
| | | TSS | TDS | $SO_4$ | Fe | Al | Mn | Acidity | pH | |
| 8/25/76 | 250 | 200 | 40,000 | 57,000 | 23,500 | 1,800 | 100 | 18,000 | 2.4 | 1.5 (.39) |
| 8/27/76 | 17 | 18,700 | 82,600 | 45,000 | 14,000 | 1,400 | 70 | 27,000 | 2.1 | 1.5 (.39) |
| 9/16/76 | 505 | 12 | 21,700 | 25,000 | 9,700 | 1,100 | 70 | 37,600 | 1.5 | 1.4 (.39) |

## TABLE 8

## CHARACTERISTICS OF COAL PILE RUNOFF DURING SECOND STORM EVENT AT WARREN STATION OF PENNSYLVANIA ELECTRIC CO., WARREN, PA.

17 SEPTEMBER 1976

| | POLLUTANT (mg/l) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | COAL PILE RUNOFF | | | | | | | DISCHARGE FLOW RATE lpm (gpm) |
| TIME | TSS | TDS | $SO_4$ | FE | AL | MN | ACIDITY | |
| 1000 - 1015 - Rain Start | 9800 | 4600 | 2300 | 900 | 100 | 40 | 3200 | 22 (5.8) |
| 1015 - 1030 | 4200 | 3300 | 2300 | - | - | - | 2600 | |
| 1030 - 1045 | 6400 | 2400 | 1600 | 700 | 90 | 10 | 3100 | |
| 1045 - 1100 | 11400 | 2400 | 1800 | 1400 | 70 | 10 | 2000 | |
| 1100 - 1115 | 5000 | 2500 | 2100 | 700 | 80 | 10 | 2200 | 20 (5.3) |
| 1115 - 1130 | 1700 | 3700 | 2100 | 500 | - | - | 2900 | |
| 1130 - 1200 | 1400 | 3800 | 2700 | - | - | - | - | 20 (5.3) |
| 1200 - 1230 | 1600 | 3100 | 1700 | 300 | - | - | - | |
| 1230 - 1300 | 1700 | 3000 | 1000 | 200 | - | - | - | |
| 1300 - 1330 | 1700 | - | - | - | - | - | | |
| 1330 - 1500 - Rain End | 23000 | 500 | 200 | - | - | 2 | 500 | 17 (4.5) |

## TABLE 9

## RANGE OF POLLUTANT CONCENTRATION AT THE SAMPLING LOCATIONS AT PORTLAND STATION OF METROPOLITAN EDISON CO., PORTLAND, PA.

## OCTOBER, 1976

| Pollutant | RANGE OF POLLUTANT CONCENTRATION, mg/l | | | | | |
|---|---|---|---|---|---|---|
| | Upstream | | Downstream | | Coal Pile Runoff | |
| | Dry | Wet | Dry | Wet | Dry | Wet |
| Total Suspended Solids | 3 - 33 | 10 - 20 | 2 - 43 | 4 - 11 | - | 220 - 3800 |
| Total Dissolved Solids | 43 - 72 | 62 - 89 | 38 - 71 | 46 - 67 | - | 600 - 7500 |
| Iron | .18 - 2.0 | .18 - .45 | .18 - 1.4 | .18 - .63 | - | 18 - 400 |
| Aluminum | N.D.[1] - .63 | N.D.[1] | N.D.[1] - 1.25 | N.D.[1] | - | 2.75 - 88 |
| Manganese | .03 - .14 | N.D.[2] - .03 | .01 - .18 | N.D. - .03 | - | 3.75 |
| Sulfate | 10 - 18 | 9 - 22 | 5 - 12 | 5 - 11 | - | 380 - 6000 |
| Total Alkalinity @ $CaCO_3$ | 12 - 25 | 16 - 19 | 12 - 21 | 16 - 20 | - | - |
| Total Acidity @ $CaCO_3$ | - | - | - | - | - | 300 - 4600 |
| pH | 6.2 - 6.8 | 6.5 - 6.8 | 6.3 - 7.2 | 6.6 - 7.2 | - | 2.35 - 3.10 |

[1] None detected, <0.2 mg/l

[2] None detected, <0.012 mg/l

## TABLE 10

## MEAN CONCENTRATIONS WITH 95% CONFIDENCE LIMITS FOR SELECTED POLLUTANTS AT THE PORTLAND STATION OF METROPOLITAN EDISON CO., PORTLAND, PA. OCTOBER, 1976

| | POLLUTANT CONCENTRATION, mg/l | | | |
|---|---|---|---|---|
| | Upstream | | Downstream | |
| Pollutant | Dry | Wet | Dry | Wet |
| TSS | 12.72 ± 4.86 | 13.54 ± 5.91 | 11.66 ± 6.96 | 7.39 ± 2.20 |
| $SO_4$ | 12.86 ± 1.31 | 14.25 ± 6.12 | 10.10 ± 1.10 | 8.15 ± 1.31 |
| Fe | 0.56 ± 0.22 | 0.30 ± 0.10 | 0.56 ± 0.18 | 0.43 ± 0.21 |
| Mn | 0.051 ± 0.016 | 0.020 ± 0.010 | 0.055 ± 0.020 | 0.016 ± 0.006 |
| Alk | 16.07 ± 1.82 | 17.60 ± 1.42 | 15.59 ± 1.26 | 16.38 ± 0.43 |

the 'dry' and 'wet' sampling periods. A comparison of Portland data with Warren data indicates that the Delaware River at Portland has higher suspended solids, iron and manganese, but lower alkalinity and similar sulfate concentrations.

Student's 't' and 'F' distribution tests of significance were performed to establish any apparent relationships between sites and sampling locations (see Table 11). As expected, the 't' and 'F' tests on the dry weather data show no significant differences between means or variances at upstream and downstream sites. The sample variances at Portland were noticeably greater than at Warren, due possibly to the smaller sample size at Portland. The intrinsic characteristics of each river's behavior, as well as the sampling techniques used, are also undefined contributors to the sample variance.

When compared with the Warren data, the coal pile runoff has substantially lower concentrations of pollutants (see Table 12). In part, this is the result of the different sampling procedures required at each site as determined by the site layout. At Warren, the entire runoff from the coal pile was intercepted by a drainage ditch. At Portland, only a small portion of the total runoff was captured from a coal pile that was much farther from the sampling location. Collection of samples had to be made near the surface drain since the terrain near the pile was uncertain and the survey objective was to examine only the portion draining to the river. It is also possible that the distance between the coal pile and the surface drain allowed the soil to filter pollutants out of the runoff.

Compared with Warren, the response of runoff flow at Portland was much slower (i.e., there was a greater time lag) with respect to the rainfall intensity. The runoff did have sufficient force to transport quite large (1-5 mm) particles. Plug sampling replaced automatic sampling after the sequential samplers became inoperative from being jammed with these particles. The plug collectors, even with screen covers, did collect some of the push-along particles that the sequential sampler did not. This could explain the change of pollutant concentrations at 1000 hours. There is also the possibility that rainfall intensities, with their effect of washing out more of the soluble material, could have caused this increase. Acidity, sulfate, and metals concentrations were lower. The flow from the coal pile could not be quantified with any success. If the study had continued for another rain event, semi-permanent weirs would have been installed to eliminate this problem.

As indicated in Table 11, the runoff from the coal pile did not have any measurable effect on the river. Statistically, there was no measured difference at either site during the wet and dry sampling periods. These observations must be mitigated by the small sample size as well as statistically significant differences in the sample variances.

The sample variances at Portland, except for dry weather comparisons, are statistically different for each of the compared sample sets. There is no apparent consistency to these differences with respect to pollutant, site, or sampling condition. It can be concluded that a rain event does introduce an additional degree of variability to the data. The Portland 'dry' data shows no difference in variance between samples taken at the two sampling sites. This contrasts with the Warren 'dry' data which did have some differences. The sampling location is another factor affecting the Warren data but not the Portland data, where the river flow pattern was less complex. The sample variances are similar at Warren and Portland for each pollutant with few exceptions, despite the slight differences in sample size. Total suspended solids and iron seem to have the greatest degree of variation at both sites under the different sampling conditions.

The Warren and Portland station data do not show any coal pile runoff impact on the river. It appears sample sizes may be too small (due to lack of rain) to indicate a definitive effect of the runoff at either Warren or Portland. The data certainly can be improved with a larger data base (more rain events) and some improvement in sample variances. This program points out the inherent

## TABLE 11

## COMPARISONS OF MEAN VALUES & VARIANCES WITHIN 95% CONFIDENCE LIMITS AT UPSTREAM & DOWNSTREAM SITES DURING DRY & WET SAMPLING PERIODS - PORTLAND STATION

| Pollutant | Degrees of Freedom | t Test | Difference Between Means | Is Difference Between Means Significant? | Critical 'f' for 95% Confidence | 'F' Ratio | Is Difference Between Variances Significant? | |
|---|---|---|---|---|---|---|---|---|
| UPSTREAM DRY - DOWNSTREAM DRY | | | | | | | | |
| TSS | 27 | 17.48 | 1.06 | No | 2.96 | 0.378 | No | |
| $SO_4$ | 35 | 3.32 | 2.76 | No | 2.62 | 1.18 | No | |
| Fe | 37 | 0.55 | 0 | No | 2.53 | 1.21 | No | |
| Mn | 36 | 0.05 | 0.004 | No | 2.55 | 0.50 | No | |
| Alk | 29 | 4.20 | 0.48 | No | 2.86 | 1.65 | No | |
| UPSTREAM WET - DOWNSTREAM WET | | | | | | | | |
| TSS | 11 | 9.82 | 6.15 | No | 5.52 | 3.26 | No | |
| $SO_4$ | 16 | 7.34 | 6.10 | No | 4.12 | 5.16 | Yes | Upstream > Downstream |
| Fe | 16 | 0.631 | 0.13 | No | 4.04 | 0.091 | Yes | Upstream < Downstream |
| Mn | 16 | 0.044 | 0.004 | No | 4.04 | 1.00 | No | |
| Alk | 11 | 2.22 | 1.22 | No | 5.52 | 4.81 | No | |
| UPSTREAM WET - UPSTREAM DRY | | | | | | | | |
| TSS | 16 | 17.40 | 0.82 | No | 4.12 | 0.350 | No | |
| $SO_4$ | 20 | 7.02 | 1.39 | No | 3.73 | 3.76 | Marginal | Dry < Wet |
| Fe | 22 | 0.791 | 0.26 | No | 3.44 | 0.052 | Yes | Dry > Wet |
| Mn | 21 | 0.058 | 0.031 | No | 3.50 | 0.100 | Yes | Dry < Wet |
| Alk | 17 | 6.52 | 1.53 | No | 4.00 | 0.131 | No | |
| DOWNSTREAM WET - DOWNSTREAM DRY | | | | | | | | |
| TSS | 22 | 20.29 | 4.27 | No | 3.29 | 0.041 | Yes | Dry > Wet |
| $SO_4$ | 31 | 3.38 | 1.95 | No | 2.72 | 0.861 | No | |
| Fe | 31 | 0.568 | 0.13 | No | 2.73 | 0.688 | No | |
| Mn | 31 | 0.055 | 0.039 | No | 2.73 | 0.05 | Yes | Dry > Wet |
| Alk | [illegible] | 3.79 | 0.79 | No | 3.22 | 0.045 | Yes | Dry > Wet |

# TABLE 12

## CHARACTERISTICS OF COAL PILE RUNOFF DURING THE RAINFALL EVENT AT PORTLAND STATION OF METROPOLITAN EDISON CO., PORTLAND, PA. 20 OCTOBER 1976

| TIME | POLLUTANT (mg/l) | | | | | | |
|---|---|---|---|---|---|---|---|
| | COAL PILE RUNOFF | | | | | | |
| | TSS | TDS | $SO_4$ | FE | AL | MN | ACIDITY |
| 0700 - 0730 | 240 | - | - | 20 | 8 | 0.4 | 290 |
| 0730 - 0800 | 300 | - | - | 40 | 19 | 0.8 | 300 |
| 0800 - 0830 | 350 | 500 | 500 | - | - | - | - |
| 0830 - 0900 | - | 600 | 500 | 60 | 15 | 0.6 | 370 |
| 0900 - 1000 | 230 | 600 | 400 | 80 | 15 | 0.5 | 300 |
| 1000 - 1100 | 280 | 3400 | 2000 | 400 | 50 | 1.8 | 2400 |
| 1100 - 1200 | - | - | - | - | - | - | - |
| 1200 - 1300 | - | - | - | - | - | - | - |
| 1300 - 1400 | 1700 | 4200 | - | 300 | 30 | 1.6 | - |
| 1400 - 1500 | 2200 | 7500 | 6000 | - | - | - | 4600 |
| 1500 - 1700 | 2200 | 4800 | - | 200 | 50 | 2.5 | - |
| 1700 - 1830 | 3800 | 4300 | 2600 | 400 | 90 | 2.5 | 2600 |

problem of sampling runoff; i.e., the need of representative storm events. A field program of this nature can be costly if it does not rain. Even if it rains, a sampled event must be related to other cases of rainfall duration and intensity and to antecedent dry days before the storm. It is these problems which make the use of a mathematical model to predict runoff and its impact on receiving waters so valuable. Therefore, before regulations can be generated for industrial storm water runoff, more problem definition (sampling and modeling) must be performed.

## 3.0 Mathematical Modeling

Recognizing that it is extremely costly to conduct extensive field measurement programs on a site-by-site basis, the USEPA asked TRC to develop and apply a mathematical model capable of simulating both the quantity and quality of industrial non-point source pollution and its impact on receiving waters. The T[illegible] developed model was applied at two coal-fired utility stations and evaluated in conjunction with field measurements made at these stations.

A description of the TRC model development program, including model selection, application, and evaluation, is presented herein.

## 3.1 Model Selection

Prior to the work described in this paper, little had been done to develop a mathematical model to quantify and qualify industrial non-point source pollution and its impact on receiving waters for specific industries, with the exception of agriculture and mining. The objective of this program was to develop such a mathematical model capable of quantifying and qualifying non-point source industrial loadings associated with storm water runoff - the predominant mechanism for non-point source pollution - and the impact of such runoff on receiving waters. To increase model utilization, the model was to be inherently flexible so that it could be applied to various types of industry with only minor modifications.

To effectively satisfy the above objective, existing mathematical models were reviewed and the model best able to meet the study objective was chosen for development and adaptation.

Of the ten models reviewed, the simplest, most flexible model requiring the least amount of modification with the capability to quantify and qualify storm water runoff from industry and to determine the impact of such runoff on receiving waters was the Short Storm Water Management Model[5] and Receiv II[6] (SSWMM-RECEIV II).

The Short Storm Water Management Model (SSWMM) and Receiv II (RECEIV II) are both modified versions of the EPA-SWMM model[7]. SSWMM, developed by the University City Science Center in 1976, is a simplified version of the runoff portion of the EPA-SWMM model, and RECEIV II, developed by the Raytheon Company for the EPA in 1974, is a modified version of the receiving water portion of the EPA-SWMM model. When combined, SSWMM and RECEIV II are capable of dynamically simulating both the quantity and quality of storm water runoff and the impact of such runoff on the quantity and quality of receiving waters, including rivers, lakes, and estuaries. The user can define, with certain restrictions, the quality parameters which h[illegible] chooses to simulate. Pollutant transport can be modeled by both overland flow and sewer routing. Dry weather flows can also be simulated. The model is primarily designed to simulate individual storm events but can be used to model multiple storm periods.

## 3.2 Model Development

Model development is described in terms of the model development tasks, a description of SSWMM-RECEIV II as developed by TRC, and model utilization.

### 3.2.1 Model Development Tasks

To meet the program objectives, it was necessary to both modify and interface SSWMM and RECEIV II. Specifically, TRC:

- Modified the storm water runoff quality relationship in SSWMM to make the model more suitable for industrial application.
- Modified RECEIV II to increase the model's sensitivity in the receiving water to a specific plant's point and non-point discharges.
- Created a program to combine SSWMM and RECEIV II.

### 3.2.2 Description of SSWMM-RECEIV II

#### 3.2.2.1 General Description

The SSWMM-RECEIV II model as developed by TRC[8] consists of four programs:

SSWMM (Short Storm Water Management Model Program)
LNKPRG (Link Program)
SETUP/QUANTITY (RECEIV II Quantity Program)
QUALITY (RECEIV II Quality Program)

SSWMM simulates both the quantity and quality of storm water runoff. LNKPRG interfaces SSWMM and RECEIV II (SETUP/QUANTITY and QUALITY). RECEIV II SETUP/QUANTITY simulates hydraulics in the receiving water and the impact of the storm water runoff on these hydraulics. RECEIV II QUALITY simulates water quality in the receiving water and the impact of the storm water runoff on the quality of the receiving water. A flowchart for SSWMM-RECEIV II is presented in Figure 3.

SSWMM-RECEIV II is written in Fortran IV and was developed for installation on a Univac 90/30 digital computer with a basic compiler (equivalent to an IBM 370 Level G Compiler). The program requires 100K bytes of core storage.

#### 3.2.2.2 Input Information Requirements

Model input information requirements are fairly extensive and best described in terms of the individual program requirements for SSWMM, LNKPRG, SETUP/QUANTITY and QUALITY.

SSWMM Input

SSWMM input includes information such as physical descriptions of user-selected simulation elements, storm activity, and pollutant generation and washoff data.

As initial steps in preparing input information, the user must divide the land area to be modeled into discrete spatial elements representative of drainage patterns and land use characteristics, and must choose the temporal framework for model computation. The discrete elements can be either subcatchments (drainage areas within a watershed with overland flow) or gutters (drainage ditches, pipes, manholes, and inlets; i.e., points of runoff entry to receiving waters). Information necessary to establish this spatial framework is normally available from plant engineering drawings. The temporal framework (computational timestep length) for SSWMM should be chosen to reflect storm activity and the user's needs.

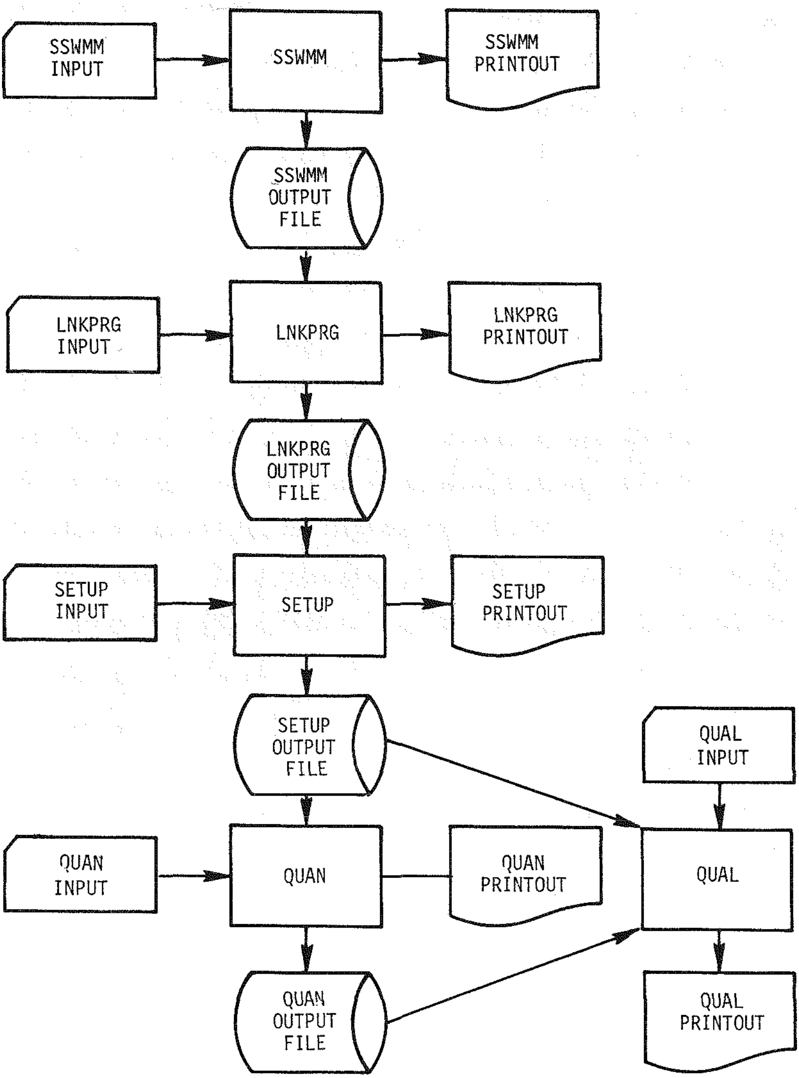


FIGURE 3
SSWMM-RECEIV II FLOWCHART

Information necessary relative to storm activity includes rainfall intensity, storm duration, and the number of days between storms. This data may be obtained from a local National Weather Service meteorological station or from rainfall data gathered by plant personnel. If neither source is available, a rain gauge must be installed to measure rainfall intensity at the plant.

Information model requirements for pollutant generation and washoff data are critical. The amount of pollutant washed from the land surface during a storm is, in part, related to the initial (pre-storm) mass of pollutant on the land surface. The initial pollutant mass load is equal to the dust and dirt accumulation rate multiplied by the area of the watershed with that dust and dirt accumulation rate, the number of dry days between storms, and the amount of a rticular pollutant in the dust and dirt. The dust and dirt accumulation rate d the amount of a particular pollutant in the dust and dirt can be determined y field measurement and laboratory analysis, or from information available in the literature. For most industrial sites, very little pollutant generation data is available in the literature, and it is necessary to conduct a field measurement and laboratory analysis program. The area of the watershed with the dust and dirt accumulation rate and the number of dry days between storms are determined from the physical descriptions of the simulation elements and from storm activity records.

### LNKPRG Input

LNKPRG input includes the information output file from SSWMM and an input card deck. The card input consists of user-determined program interface instructions to link SSWMM and RECEIV II (SETUP/QUANTITY, QUALITY) and non-storm inputs to or withdrawals from the receiving water (background receiving water flows and pollutant mass loads, industrial process and cooling water flows and pollutant mass loads, etc.). Information on non-storm inputs can be gathered from plant personnel and from government groups such as the United States Geological Survey (USGS), National Oceanic and Atmospheric Administration (NOAA), and the U.S. Army Corps of Engineers.

### SETUP/QUANTITY Input

Input requirements for the SETUP/QUANTITY portion of RECEIV II include the information output file from LNKPRG and two input card decks. The input card decks include geographical, hydraulic, and meteorological data describing the receiving water.

As with SSWMM, in SETUP/QUANTITY the user must first divide the receiving water to be modeled into discrete elements representative of the waterway's hydrology and characteristic uses (industrial withdrawals and discharges, etc.), and choose, with certain restrictions, the temporal framework for model computation. The discrete elements include nodes or junctions (sections of the receiving water with uniform hydraulic and water quality properties) and channels linking the nodes. Information necessary to establish this spatial framework is normally available from National Ocean Survey bathymetric charts, USGS 7.5' topographic maps, and U.S. Army Corps of Engineers flood studies. More specific spatial formation might be available from plant personnel if they had conducted any udies on the receiving water adjacent to the plant. The temporal framework computational timestep length) for SETUP/QUANTITY should be chosen to reflect the user's needs, but must meet certain restrictive requirements determined by the choice of the spatial framework.

In addition to this geographical and hydrological information, meteorological information, including rates of rainfall and evaporation which influence the volume and flow of water in the receiving water, can be input to SETUP/QUANTITY. If required, this information is normally available through the National Weather Service.

QUALITY Input

The QUALITY information requirements include the information output file from SETUP/QUANTITY and a card deck input. The card deck input includes information describing the initial pollutant concentrations in the receiving water and pollutant reaction kinetics (reaction rates, water temperatures, and temperature compensation coefficients). Values for initial pollutant concentrations in the receiving water can be determined from the USGS or NOAA, but more specific information might be available from plant personnel. Information on pollutant reaction kinetics is often available in the literature. If this information is not adequate, a field measurement program may be conducted to determine reaction kinetics; however, this is often costly.

### 3.2.2.3 Output Information

Model results are printed for each of the programs (SSWMM, LNKPRG, SETUP/QUANTITY, QUALITY) in the SSWMM-RECEIV II model.

Results from SSWMM include:

- o Initial pollutant loads (mg) on each subcatchment prior to the storm.
- o Storm water flow (cfs) and associated pollutant mass loads (lbs./min.) for each timestep.
- o Total amount of rainfall (cu. ft.), total infiltration (cu. ft.), total runoff (cu. ft.), total surface storage (cu. ft.), and the percentage error computed for unaccounted water.
- o Total pollutant mass (lbs.) washed from the land surface during the storm.

LNKPRG results include the storm water flows and pollutant mass loads from SSWMM converted to a format acceptable to RECEIV II (SETUP/QUANTITY, QUALITY).

Results from SETUP/QUANTITY include:

- o Hydraulic head (m) or water level in the receiving water at each node for each timestep.
- o Water flow ($m^3$/sec) and velocity (m/sec) in the receiving water in each channel for each timestep.

Results from QUALITY include:

- o Pollutant concentrations (mg/l) in the receiving water at each node for each timestep.
- o Daily maximum, minimum, and average pollutant concentrations (mg/l) in the receiving water at each node.

### 3.2.3 Model Utilization

SSWMM-RECEIV II can be used to effectively simulate industrial non-point source pollution associated with storm water runoff from material storage piles and from areas of dust and dirt accumulation without performing a detailed field measurement program. The model can also be used to simulate the subsequent impact of this runoff on receiving waters (rivers, lakes, or estuaries). Pollutants that can be modeled are user-selected and include items such as solids, nutrients, and metals.

Typical model applications for new or existing plants might include:

- Defining industrial storm water runoff flow and pollutant concentrations.
- Defining the impact (flow and pollutant concentration changes in the receiving water) resulting from the storm water runoff.
- Defining design criteria for storm water treatment.
- Evaluating storm water treatment alternatives.

In addition to the industrial uses cited above, SSWMM-RECEIV II can be used with minor modification to simulate non-point source pollution associated with storm water runoff for urban and rural environments. This information can be used in river basin planning for 208 planning activities.

As with any mathematical model, care must be taken to apply SSWMM-RECEIV II correctly. The user must understand and work within the model limitations. At this time SSWMM-RECEIV II:

- Cannot simulate storm water percolation through or the erosion of material storage piles such as coal piles, but can simulate storm water runoff from material storage piles.
- Has not been tested to simulate dynamic background source flows and loadings in the receiving water.
- Must be used within temporal and spatial limits defined in the model.

## 3.2 Model Application

To test the validity of SSWMM-RECEIV II, the model was used to simulate storm-induced, non-point source pollution and the impact of such pollution on receiving waters at the two coal-fired utility plants previously described. The results were compared to field measured data. The pollutants modeled included total suspended solids, total dissolved solids, sulfates, total iron, manganese, and aluminum.

Three storms were modeled, two at the Warren Generating Station and one at the Portland Generating Station. The storm of September 17, 1976, at the Warren Generating Station, was used for model calibration. This storm lasted approximately seven hours and was a steady drizzle with intermittent, short but heavy, showers. The maximum rainfall intensity was 0.11 inches/hour, and the total rainfall was 0.33 inches. The storm of August 26, 1976, was used for model verification at Warren. This storm was a short (20-minute) shower with a maximum rainfall intensity of 0.33 inches/hour, and a total rainfall of 0.11 inches. The storm used for the model run at Portland occurred on October 20, 1976. The storm lasted approximately 14 hours and was a steady drizzle with intermittent, short but heavy, showers. The maximum rainfall intensity was 0.16 inches/hour, and the total rainfall was 1.55 inches.

The model results were compared to field measurements to test the validity of the model where comparable information was available and at time intervals where maximum runoff flows and pollutant loadings occurred in the model. A comparative factor of 4 was considered to be adequate for model development purposes. The results described below primarily describe the runoff from the coal piles and its impact on the receiving waters.

For the storm of September 17, the initial model run at the Warren Generating Station, the modeled storm water runoff flow was 0.4 of the measured flow, and the modeled storm water runoff pollutant concentrations were within a factor of 4; (i.e., the model concentration divided by the measured concentration varied between .25 and 4.0) for total suspended solids, total iron, manganese, and aluminum, but were greater than a factor of 4 for sulfates and total dissolved solids. Modeled and measured pollutant concentrations in the Allegheny River compared within a factor of 3.

In the calibration model run at the Warren Generating Station for the storm of September 17, the impervious area water retention storage depth was reduced from .062 inches to .001 inches to increase the modeled percentage of the total rainfall that was runoff. This change was made since the area was almost completely impervious. The percentage of runoff, therefore, should be approximat[illegible] equal to 100%. In the initial model run, it was only 86%. In the calibration model run, the percentage runoff was 99%. The impervious area water retention storage was maintained at .001 inches for the remaining model runs.

In the calibrated model run at Warren for the storm of September 17, the modeled storm water runoff flow and pollutant concentrations and the modeled river pollutant concentrations compared to the field measurements with approximately the same degree of accuracy as did the initial model run for the storm of September 17.

For the storm of August 26, the verification model run at the Warren Generating Station, the modeled storm water pollutant concentrations also compared to the field measurements with approximately the same degree of accuracy as did the calibration model run for the storm of September 17. Modeled and measured pollutant concentrations in the Allegheny River compared within a factor of 4.

For the storm of October 20, the model run at the Portland Generating Station, modeled storm water pollutant concentrations were different from field measurements by greater than a factor of 4. Modeled and measured pollutant concentrations in the Delaware River compared within a factor of 5.

The model was not calibrated at Portland because storm water flow field measurements were not available due to measurement difficulties, and it is first necessary to calibrate flow in the model before any other model adjustments are warranted.

## 3.3 Evaluation of Model Development Program

The work completed in this study indicates that SSWMM-RECEIV II is capable of predicting the quantity and quality of storm water runoff and its impact on receiving waters for specific industries, but model limitations do exist.

SSWMM-RECEIV II is a versatile storm water and receiving water model suited for industrial application. It is inherently flexible so that it is applicable to many industries with only minor data input modifications.

The specific utility industry application described in this study has demo[illegible]strated that, where adequate field data were available, SSWMM-RECEIV II results compared favorably to field measurements. At the Warren Generating Station, calibrated model results for storm water runoff flow and pollutant concentrations compared within a factor of 4 and river pollutant concentrations compared within a factor of 3 to field measurements. The model-field measurement comparative factor of 4 was maintained for a second storm at Warren, indicating that the calibrated model could predict the effects of different storm conditions with the same degree of accuracy established in model calibration. In essence, the model was verified, increasing model credibility.

Some difficulties were encountered in this model study. Modeled storm water runoff concentrations of total dissolved solids and sulfates at the Warren Generating Station were different from the field-measured values by greater than a factor of 4. In addition, due to measurement difficulties, adequate field data were not available to ascertain the comparative validity of the model at the Portland Generating Station for either storm water runoff or the receiving water.

Inherent model limitations include the lack of capability to simulate storm erosion of infinite sources; i.e., material storage piles such as coal piles, and to simulate stormwater percolation through material storage piles.

Although difficulties were encountered, and additional work is needed to increase model credibility and usefulness, SSWMM-RECEIV II has been demonstrated to [illegible] a valid storm water runoff and receiving water model suited to industrial [illegible]ication.

## 4.0 Conclusions and Recommendations

The following conclusions resulted from the field survey and mathematical model development in this program:

1. The pollutant concentrations in the river at both sites were highly variable, often by an order of magnitude. These variations were independent of river flow and weather conditions.

2. The mass loadings of pollutants in the Delaware River increased substantially during and after the sampled storm event. This was due primarily to an increased flow attributable to upstream conditions and storm intensity. The mass loading of pollutants in the Allegheny River remained essentially unchanged for both sampled storm events since river flow was controlled by a dam approximately six miles upstream and neither storm event was substantial. Therefore, the pollutant concentrations in each river at both upstream and downstream sampling stations were not necessarily higher during storm conditions.

3. The data from these two sites generally show no statistical difference in mean concentrations of upstream versus downstream pollutant levels in either dry or wet conditions.

4. The data show no statistical difference in sample variances which are not consistently predictable with respect to pollutant, site, and sampling period.

5. The main contributors to the change in $S^2$ of the calculated variance were site location and the storm event. The site location was the major contributor at Warren, while the rain event was the major contributor at Portland. The sample variances were generally consistent for each pollutant at the Warren and Portland sites. The only exceptions were total suspended solids and iron.

6. The storm data from Warren show a "first flush" effect from the initial runoff of the access road which contained fugitive fallout from the coal pile and coal trucks.

7. The pollutant concentrations of the leachates from the coal pile at Warren were orders of magnitude higher than the storm runoff pollutant concentrations. For a short duration, moderate intensity storm and a moderate duration low intensity storm (the two events sampled at Warren), the leachate drained for several days. Thus, for the two

storms sampled at Warren, the pollutant loads on the river from the utility were less during rain than during dry weather with the exception of total suspended solids.

8. The SSWMM-RECEIV II model is capable of predicting the quantity and quality of storm water runoff and its impact on receiving waters for specific industries with model limitations. These limitations include the lack of capability to simulate storm erosion of infinite sources, i.e., material storage piles, and to simulate stormwater percolation through material storage piles.

9. Application of the model to the utility industry has demonstrated that for the most part, where adequate field data were available, the model results compared favorably to field measurements.

10. At Warren, calibrated model results for storm water runoff flow and pollutant concentrations (total suspended solids, total iron, manganese, and aluminum) compared within a factor of four to field measurements, and river pollutant concentrations for all six pollutants compared within a factor of three. EPA has indicated that an agreement within a factor of four to five should be considered indicative of a good predictive method. A model-field measurement comparative factor of four was maintained for a second storm at Warren indicating that the calibrated model could predict the effects of different storm conditions with the same degree of accuracy established in model calibration.

11. Due to a lack of runoff flow data at the Portland site, it was not possible to ascertain the comparative validity of the model at more than one site.

## 4.2 Recommendations

Based on the conclusions of this program, the following recommendations are made for future work:

1. Develop the SSWMM-RECEIV II model capability to simulate the erosion of material storage piles, i.e., coal piles, and to simulate the percolation of storm water runoff through material storage piles.

2. Conduct additional field surveys to provide data to compare to model predictions, thus enhancing model credibility. Specifically, more field data are required on:

    a) Storm water runoff flow and pollutant concentrations from industrial sites.

    b) Dust and dirt accumulation rates and the amount of pollutants in the dust and dirt.

    c) Flow and pollutant concentrations after the storm for the leachate from material storage piles, i.e., coal piles.

    d) Receiving water pollutant concentrations. To acquire definitive representative receiving water pollutant concentrations (background and storm-induced), it will be necessary to increase the number of sampling stations in the receiving water upstream and downstream from the storm water discharges. At least two, and preferably three, such stations should be established at both the upstream and downstream sites. With a single upstream station, the risk is greater of measuring an anomoly in the river characteristics. The additional upstream stations would be located either in an "across the flow" pattern or longitudinally with flow depending on river mixing characteristics to insure that the sampling locations and data are representative of the river. The additional downstream stations would be located longitudinally in the river to allow for better definition of the impact of storm water runoff on the river (i.e., dilution and reaction of non-point pollutants in the river.

3. Once model credibility has been enhanced, apply the model to a site on an estuary or lake and compare the results with those of a field sampling program.

## REFERENCES

1. Staff Report, National Commission on Water Quality (Washington, D.C., April, 1976).

2. Report to the Congress, National Commission on Water Quality (Washington, D.C., April, 1976).

3. Development Document for Effluent Guidelines and New Source Performance Standards for the Steam Electric Power Generating Point Source Category (Washington, D.C.: U.S. Environmental Protection Agency, Effluent Guidelines Division, EPA-440/1-74-029-a, 1974).

4. 1975 Keystone Coal Industry Manual (New York, N.Y.: McGraw-Hill, Inc., 1975).

5. Short Storm Water Management Model Documentation Report, University City Science Center (Philadelphia, PA: unpublished, June, 1976).

6. New England River Basins Modeling Project Final Report, Volume III - Documentation Report, Part I - RECEIV II Water Quantity and Quality Model, Raytheon Company (Washington, D.C.: U. S. Environmental Protection Agency, EPA Contract No. 68-01-1890, December, 1974).

7. Huber, Wayne, Heaney, James, Medina, Maguil, Peltz, W., Sheikh, Hagar and Smith, George, University of Florida, "Storm Water Management Model, User's Manual, Version II", Environmental Protection Agency, Office of Research and Development, National Environmental Research Center, Cincinnati, Ohio, EPA-670/2-75-017, March, 1975.

8. Brookman, Gordon, Wade, Willard, and Binder, James, TRC - THE RESEARCH CORPORATION of New England, "Technical Report, Sampling and Modeling of Non-Point Sources at a Coal-Fired Utility" (Draft Report), Environmental Protection Agency, Industrial Environmental Research Laboratory, Research Triangle Park, North Carolina, EPA 68-02-2133, February, 1977.

# TREATMENT OF PRECIPITATION RUNOFF FROM COAL STORAGE PILES

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Precipitation runoff from coal storage piles can produce wastewater con[illegible]ning objectionable amounts of acidity, metals, and suspended particulate matter. [illegible] recognizing this potentially objectionable discharge, the U.S. Environmental Protection Agency has begun setting limits on the constituents in the discharges from coal storage piles.

As early as October 1974, U.S. EPA promulgated effluent guidelines for runoff from coal storage areas at steam electric power plants. These guidelines are intended to regulate the pH and total suspended solids in the discharge from these storage areas.

In April 1977, U.S. EPA promulgated best practicable control technology (BPCT) effluent guidelines for the coal mining industry. These guidelines also included limitations on discharges from coal storage areas. These limitations are listed in Table 1.

Table 1. EFFLUENT GUIDELINES (BPCT)

| | Steam Electric Power Plants | Coal Mining Industry |
|---|---|---|
| pH (s.u.) | 6.0 - 9.0 | 6.0 - 9.0 |
| Total Suspended Solids | 50 mg/l | 35/70 mg/l |
| Total Iron | ---------- | 3.5/7.0 mg/l |
| Manganese | ---------- | 2.0/4.0 mg/l |
| | | (30-day Average/Maximum) |

Quite often the facilities necessary to treat coal storage area runoff are already available at a power plant or coal mine. One of the most widely used methods for treatment of coal pile drainage at a power plant is the intermixing of coal pile runoff into the power plant fly ash settling ponds. The usually alka[illegible]e fly ash transport water neutralizes the predominately acidic coal pile runoff. [illegible]ever, where such ash facilities are not available, on-site wastewater treatment [illegible]y be required. Also, the 1983 Best Available Technology requirement for fly ash handling will essentially require dry disposal of fly ash from power plants, thereby eliminating the possibility of intermixing coal pile runoff with fly ash transport water.

A recent survey, conducted for the Electric Power Research Institute, found that very little research has been done on the hydraulic and chemical aspects of coal pile runoff, and that there is even less actual coal pile drainage treatment experience.

With the increasing dependence on coal as an energy source, the accompanying expansion of coal docks and terminals not located at a power plant or coal mine will require engineered treatment facilities for the associated runoff from their coal storage areas.

American Electric Power (AEP) has two such coal transfer facilities, one handling eastern Ohio coals, the other handling low sulfur, western coal. Both of these facilities have wastewater treatment plants in operation for the treatment of coal pile runoff.

The Belpre Coal Dock is a coal transfer facility in southeastern Ohio where local coal is brought in by truck and transferred onto barges on the Ohio River for shipment to AEP System plants. At times, up to 200,000 tons of coal covering approximately 7.5 acres have been stored at this facility. The majori of the coal stored here is of medium to high sulfur content (2-4% wt.). Typica the rainfall runoff from the coal storage area has a pH of less than 3.0, a total iron concentration between 20 and 3,000 ppm and acidity of over 2,000 ppm. The high variability of the runoff can be seen in Table 2.

In 1973, it was decided that this quality runoff would require treatment prior to discharge to the Ohio River, and a consultant, International Hydronics Corporation, Princeton, New Jersey, was asked to assist in the design and engineering of a system that would treat the intermittent flows and highly variable quality water resulting from the rainfall and snowmelt runoff from the coal pile.

Because the chemistry of the runoff water was similar to acid drainage from coal mines on which there has been extensive development of treatment technology, it was decided that the simplest, most effective treatment would be lime neutralization, aeration and settling of precipitated calcium sulfate and metallic oxides and hydroxides. Lime neutralization was chosen because it would be the most cost effective for this facility, however, sodium hydroxide or soda ash could also have been used.

Laboratory tests were conducted on samples of runoff to determine optimum neutralization and aeration. Figure 1 is from a preliminary titration of the runoff with 0.1N sodium hydroxide. This was later confirmed in the lab by lime slurry neutralization. Tests on recycling treated sludge also confirmed that high density sludge could be produced with this type of wastewater, thereby reducing the sludge volume.

Rainfall data from a nearby airport weather station were obtained (Table 3) and, assuming a coefficient of runoff* of 0.33, it was determined that a treatment rate of 45 gallons per minute (gpm) with a recycle of a portion of the treated wastewater and sludge would produce the desired effluent and sludge density from the runoff from the 7.5 acres of storage area.

Table 2. ANALYSES OF RUNOFF FROM BELPRE COAL STORAGE AREA

| Sample No. | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| pH (s.u.) | 3.0 | 2.9 | 2.1 | 2.2 | 3.2 |
| Iron (mg/l) | 32.0 | 26.0 | 2,702.1 | 810.0 | 85.0 |
| Acidity (mg/l) | 114.5 | 1328 | 7,700 | ----- | 1,358 |
| Sulfate (mg/l) | 516.5 | 447.6 | 10,107 | 4,500 | ----- |

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*Coefficient of runoff is the ratio of actual surface runoff water from a rainfall event to total recorded rainfall of that event.

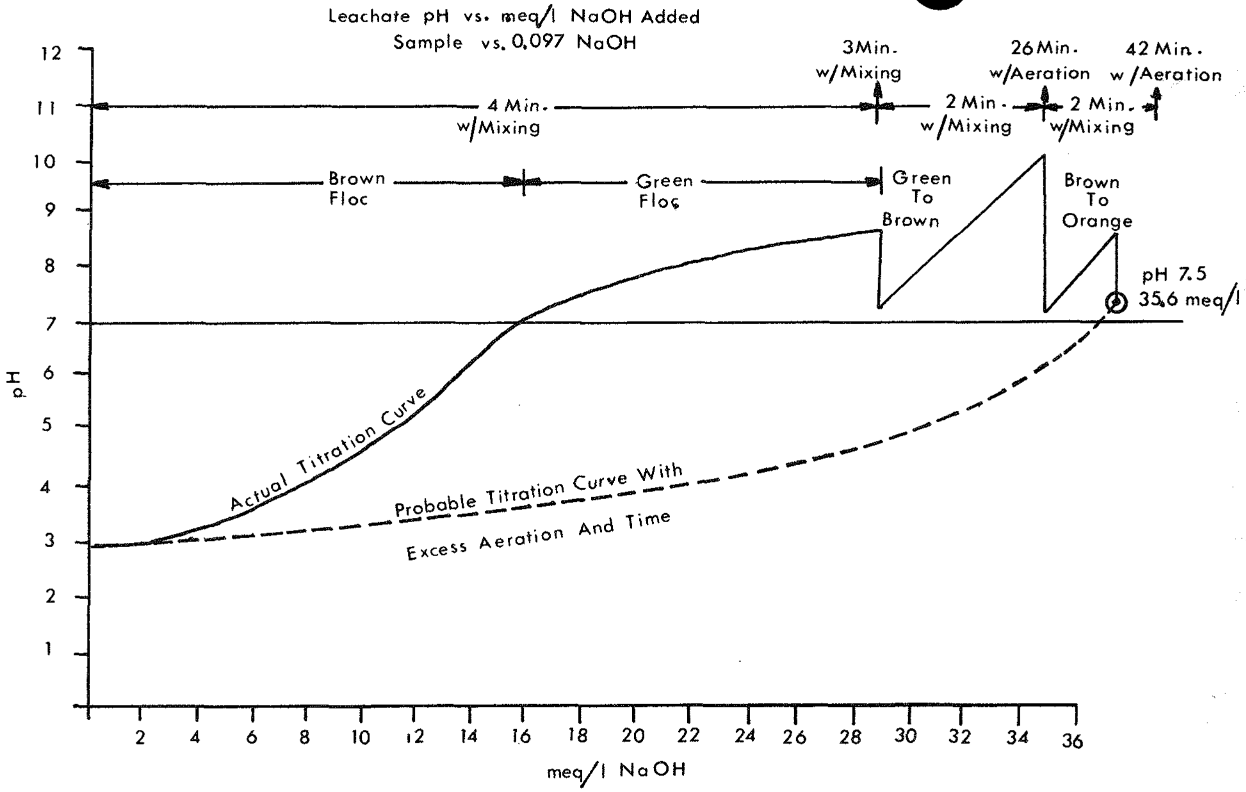

Figure 1. Preliminary Titration Curve

Table 3. RAINFALL DATA FOR PARKERSBURG, W.VA.

| Month | Average Rainfall (inches) | Max. Rainfall in 24 Hours (in.) |
|---|---|---|
| January | 3.34 | 2.97 |
| February | 2.83 | 2.89 |
| March | 2.52 | 3.46 |
| April | 2.15 | 3.40 |
| May | 3.70 | 3.00 |
| June | 4.27 | 3.58 |
| July | 4.11 | 4.81 |
| August | 3.78 | 3.60 |
| September | 2.71 | 3.00 |
| October | 2.05 | 3.40 |
| November | 2.36 | 3.22 |
| December | 2.84 | 2.69 |
| TOTAL | 38.77 | |
| Ten Year, 24-hour Rainfall . . . . . . . . . . . . . . . . . . . . . . . | | 3.8 INCHES |

The general layout and flow diagram of the system that was designed and installed is shown in Figures 2 and 3. Runoff from the coal storage area is diverted to the 207,000 gallon equalization basin. It is important that the runoff not be allowed to stand in contact with the coal and should be collected and treated as soon as possible. The water then flows into the concrete treatment sump where 2% lime slurry is added upon demand from a pH controller. The lime tank has been sized to provide lime slurry at maximum through-put for two days to allow for unattended operation over a weekend. After the plant was installed, it was decided to reduce the pH controller on-off settings from the original setting of pH7 and 8.5 to pH6.0 and 7.0 to prevent the over-liming that was occurring. The water in the sump is both mixed and aerated by a 2.0 H.P. blower rated at 54 cfm operating in conjunction with a Rollmix Air Diffuser. The treated water is pumped to a 79,000 gallon, two-compartment settling basin where the solids settle and the clarified water is decanted and discharged to the Ohio River. Both equalization basin and the settling basin are clay-lined to prevent seepage into the groundwater.

Due to the highly corrosive nature of the untreated water and the high concentration of scale forming constituents in the treated water, it was decided that all piping should be plastic. The use of pipe and pumps was minimized for ease of maintenance.

In order to create a denser sludge, a portion of the neutralized wastewater is diverted from the stream going to the settling basin and recycled back into the inlet of the treatment sump. Laboratory results indicate that this pro-

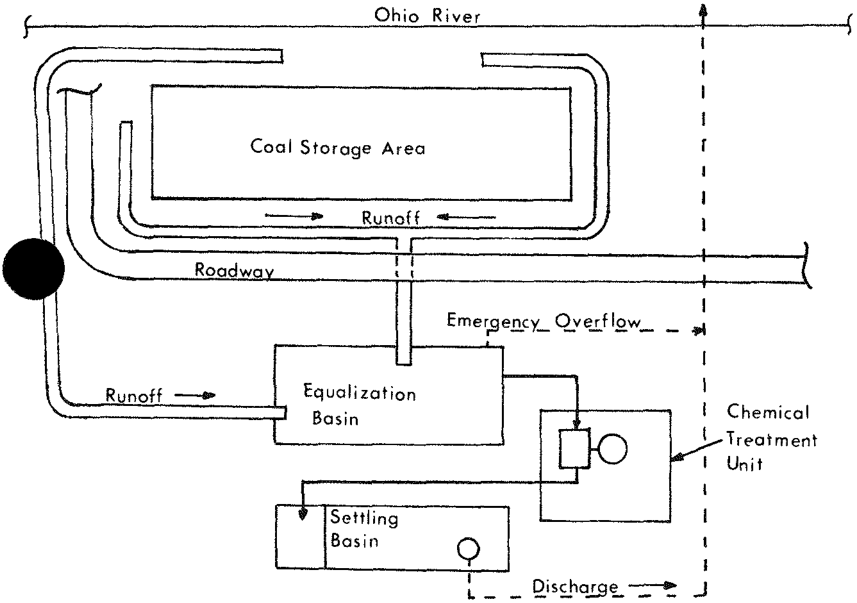

Figure 2. Belpre Coal Pile Runoff Treatment System

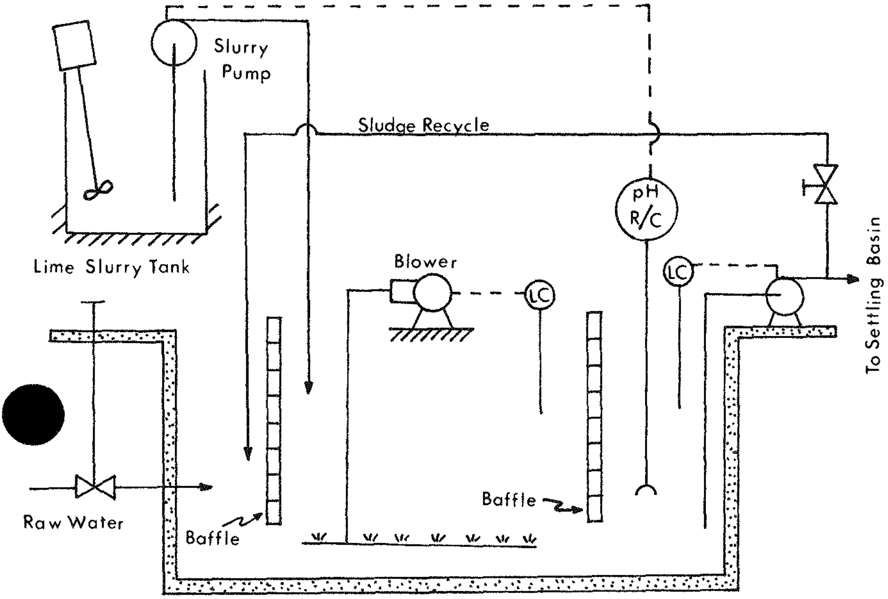

Figure 3. Belpre Chemical Treatment Unit

cedure is successful and that a sludge density of 30-40%* is obtainable. Normal sludge densities from this form of treatment without the recycle would range between 1-5%.

When the primary settling compartment of the settling basin fills with sludge, the treatment plant is shut down, the clarified water is decanted and drawn down, and the sludge is pumped onto the coal pile. From this point the coal and sludge can be loaded onto the barges to be taken to the power plants.

At the power plants the sludge is deposited with the coal on the plant coal pile. The sludge is then taken into the plant with the coal to be burned. Since the volume of sludge compared to the volume of coal is so minuscule, no air pollution problem is anticipated. If it should rain while the sludge is on the plant coal pile, the sludge and rainfall runoff water will be collected in the plant coal pile drainage system and pumped to an ash pond for treatment and final disposal.

As can be seen in Table 4, final effluent quality of the treated runoff at Belpre has a pH between 6.5 and 7.5, total iron concentration of less than 1 mg/l, alkalinity greater than acidity, and total suspended solids of less than 20 mg/l.

Table 4. FINAL SETTLING BASIN EFFLUENT ANALYSES - BELPRE

| Sample No. | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| pH (s.u.) | 7.1 | 6.9 | 7.0 | 6.7 |
| Total Iron (mg/l) | 0.25 | 0.10 | 0.15 | 0.10 |
| Acidity (mg/l) | 12 | 4 | 8 | 6 |
| Alkalinity (mg/l) | 86 | 88 | 34 | 36 |
| Total Suspended Solids (mg/l) | 6.8 | 5.6 | 1.2 | 16.0 |

The newest AEP facility for treatment of coal pile runoff is at the Cook Coal Terminal in Illinois.

To insure a reliable supply of low sulfur coal from western suppliers, AEP constructed the Cook Coal Terminal in southern Illinois to transfer western coal from railcars to Ohio River barges. Coal loaded onto the barges is moved upriver to the various system plants operating on the Ohio River.

In the earliest stages of design of this project, it was decided that a coal pile runoff collection and treatment system should be integrated into the layout of the coal transfer facility.

Before designing the runoff treatment system, several utilities in the western states using coal similar to those to be handled at the Cook Terminal w[illegible] contacted by AEP to try to determine design parameters for the coal pile runoff It was found that, due to the high evaporation rate and minimal rainfall of most western states, none of the utilities contacted had any data on rainfall runoff. However, a sample of snowmelt runoff from a stock pile of Wyoming coal was obtained from a northwestern utility. The results of this sample, shown in Table 5, indicated that total suspended solids was the only parameter that should be of concern.

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*Percent solids in sludge.

Table 5. SAMPLE OF SNOWMELT RUNOFF FROM A COAL IN THE NORTHWEST

| | |
|---|---|
| pH (s.u.) | 6.8 |
| Conductance | 374 µmho/cm |
| Iron | 0.79 mg/l |
| Aluminum | 0.40 mg/l |
| Manganese | 0.06 mg/l |
| Alkalinity (to pH 4.3) | 51.6 mg/l |
| Total Suspended Solids | 58 mg/l |

International Hydronics Corporation was retained to assist in the design and engineering of a treatment system. Based on the limited data available and the best engineering judgment and knowledge of sedimentation techniques, it was decided to install a system that would add a coagulant aid (alum) while monitoring the pH of the water. Provision for pH adjustment was also provided.

The treatment system consists of the primary settling and collection ponds, a chemical treatment unit and a two-compartment settling basin (Figures 4 and 5).

The entire affected coal storage area of approximately 100 acres was graded to direct rainwater runoff towards the two primary settling and collection ponds. These ponds were designed to collect the runoff equivalent of a 10-year, 24-hour storm with a 20% coefficient of runoff and pump it to the treatment facility (Table 6).

These ponds also collect miscellaneous sump discharges from the coal transfer and crushing buildings. These effluents contain various amounts of coal dust and coal fines from washing down floors and equipment in these buildings.

Runoff water from the primary ponds is pumped at a maximum rate of 1250 gpm to the chemical treatment unit. In the treatment unit the water flows through a Sutro weir box into a 3800 gallon agitated basin. A differential pressure sensor monitors the flow into the weir box and automatically feeds the required coagulant aid dosage. The agitator slowly mixes the runoff water and coagulant aid to develop the proper floc for rapid settling. The effluent then flows into the final settling basin, having a retention time of approximately 16 hours, where the solids settle and the supernatent treated water is discharged to the river. Although the native soil is a heavy clay, it was decided to use a hypalon liner in the final settling basin to insure prevention of seepage of treated water into the ground.

The treatment system was designed for minimum operator attention, in that water flow into the chemical treatment unit is controlled by level-acctuated pumps in the primary ponds, alum and caustic dosage are adjusted to fit the wastewater [illegible] automatically, the agitator starts and stops with flow into the weir box and [illegible] settling basin discharge pumps are controlled by the level in the settling basin.

Periodically, the accumulated sludge is pumped out of the settling basin and back on to the coal pile where it can be put onto the barges with the coal to be taken to the power plants for final disposal.

This system incorporates efficient removal of total suspended and collodial particles with a minimum of operator attention and is, so far as can be determined, one of the first such operating treatment systems for runoff from low sulfur coal.

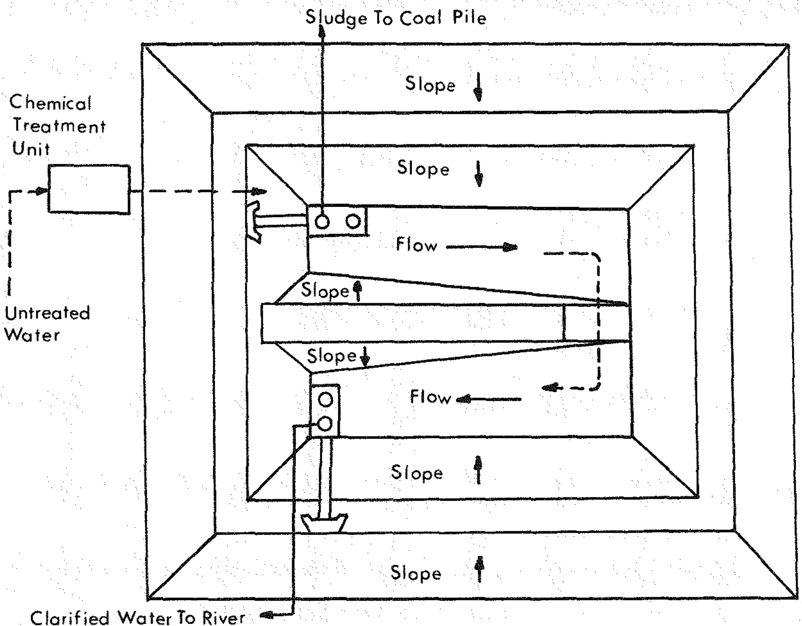

Figure 4. Chemical Treatment Unit And Settling Basin

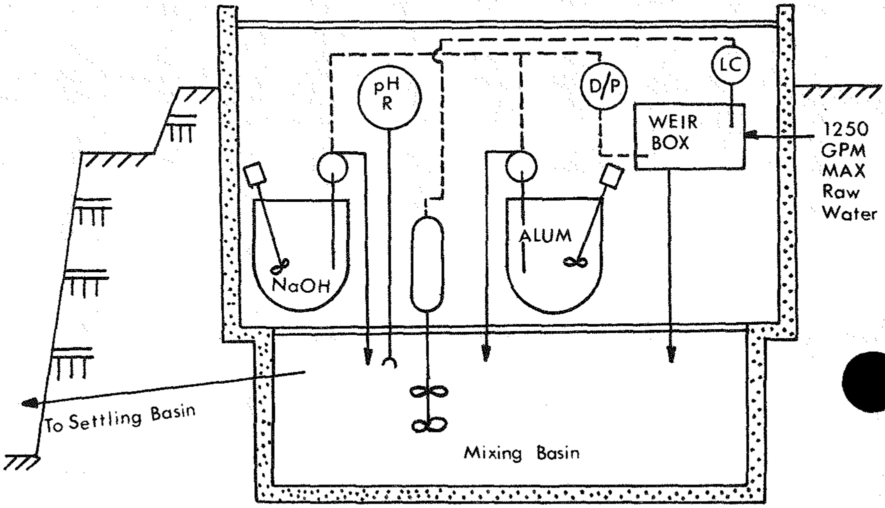

Figure 5. Chemical Treatment Unit

While the system has only been operating for a short while, results as shown in Table 7 are most encouraging.

Table 6. RAINFALL DATA FOR PADUCAH, KENTUCKY

| Month | Averaqe Rainfall (inches) |
|---|---|
| January | 5.0 |
| February | 3.90 |
| March | 5.28 |
| April | 4.38 |
| May | 4.02 |
| June | 3.70 |
| July | 3.03 |
| August | 3.30 |
| September | 3.36 |
| October | 2.75 |
| November | 3.72 |
| December | 3.55 |
| TOTAL | 45.99 |

Ten Year, 24-hour Rainfall . . . . 5.0 inches

Table 7. FINAL SETTLING BASIN EFFLUENT ANALYSES - COOK COAL TERMINAL

| Sample No. | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| pH (s.u.) | 7.9 | 7.7 | 7.9 | 7.7 |
| Total Suspended Solids | 5 | 6 | 2 | 12 |
| Total Iron (mg/l) | 0.3 | 0.6 | 0.0 | 0.5 |

# QUALITY AND TREATMENT OF COAL PILE RUNOFF

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## INTRODUCTION

Increases in energy use, coupled with delays and restrictions on constructi nuclear plants and decreases in supplies of fuel oil and natural gas, make incre in coal production and use inevitable. Coal, whether it is to be used directly steam generation, liquefaction, gasification, or other processes, must be stored in huge quantities. The volume to be stored, the methods of handling, and the explosive nature of coal dust all dictate outdoor storage, which presents numerous potential problems, such as blowing coal dust and an aesthetically displeasing appearance.

Another potential problem associated with open-air storage is rainfall runoff from the coal storage area. Long before major coal-fired steam-electric plants existed, the Welsh were familiar with the acidic character and distinctive orange color of coal mine drainage. For centuries naturalists have been aware of the orange-yellow stains that often accompany coal outcrops. When similar drainages emanated from coal storage facilities at power plants, they were largely ignored and passed off as a local and perhaps natural occurrence. However, as interest in the environment increased, industrial discharges came under closer scrutiny. As part of the overall study of potential discharges, a program was designed to provide an adequate characterization of drainage from coal storage piles.

The Tennessee Valley Authority (TVA) established programs at two coal-fired steam plants. Plant J has a rated capacity of 1700 MW with a 90-day coal supply amounting to about $9.6 \times 10^5$ $m^3$ ($1.26 \times 10^6$ $yd^3$) or $1.1 \times 10^9$ kg ($1.2 \times 10^6$ tons). Plant E has a rated capacity of 1400 MW, with a 90-day coal supply amounting to about $8.6 \times 10^6$ $m^3$ ($1.13 \times 10^6$ $yd^3$) or $9.88 \times 10^8$ kg ($1.08 \times 10^6$ tons).

Coal for plant J is mined in eastern Tennessee and Kentucky, transported by truck and rail to the plant site, and stored before any preparation. Coal for plant E is mined in western Kentucky, transported mainly by barge, and stored before any preparation. A typical analysis of coal from both plants is presented in Table 1.

Table 1. Coal analysis, dry basis

| Constituent | Plant J | Plant E |
|---|---|---|
| Total moisture, % | 3.8 | 4.2 |
| Volatile matter, % | 34.1 | 37.7 |
| Ash, % | 17.2 | 15.0 |
| Fixed carbon, % | 48.7 | 47.3 |
| Total sulfur, % | 2.1 | 3.9 |
| Energy, Btu/lb | 12,270 | 12,450 |
| Ash analysis | | |
| CaO, % of ash | 1.4 | 4.2 |
| MgO, % of ash | 1.1 | 1.1 |

## BACKGROUND

To ensure uninterrupted generation of electricity, an outdoor coal reserve is maintained at each power plant. This coal supply is available for use if normal deliveries are delinquent, temporarily discontinued, or inadequate to meet peak electricity demands. A 90-day coal supply is customarily maintained to provide a sufficient safety factor. Factors that preclude a large coal stockpile include the (1) cost of land required for storage, (2) workmen and equipment needed to maintain the coal storage area, (3) cost of the larger inventory, and (4) oxidation degradation that occurs when coal is stored for long periods of time. Although the physical volume of coal storage required varies with the plant consumption rate, coal piles are typically 8 to 12 m (25 to 40 ft) high and spread over an area of 10 to 40 ha (25 to 100 acres). Normally, 600 to 1800 m$^3$ (780 [illegible]340 yd$^3$) of coal storage is required for every megawatt of rated capacity.

Coal pile drainage results from percolation of rainfall through stored coal. The water quality of the drainage is affected by the leaching of oxidation products of metallic sulfides associated with the coal. The sulfide-bearing minerals that predominate in coal are pyrite and marcasite, both iron sulfide ores. Marcasite is unstable and degrades into pyrite. The oxidation of pyrite results in the production of ferrous iron and acidity (Federal Water Quality Administration 1970):

$$2FeS_2(s) + 7O_2 + 2H_2O \longrightarrow 2Fe^{+2} + 4H^+ + 4SO_4^{-2}. \qquad (1)$$

This ferrous iron then undergoes oxidation to the ferric state in a rate-limiting step:

$$4Fe^{+2} + O_2 + 4H^+ \longrightarrow 4Fe^{+3} + 2H^+ + 2OH^-. \qquad (2)$$

Ferric iron then hydrolyzes to form insoluble ferric hydroxide, thus producing more acidity,

$$Fe^{+3} + 3H_2O \longrightarrow Fe(OH)_3(s) + 3H^+ , \qquad (3)$$

or oxidizes pyrite directly, thus producing more ferrous iron and acidity.

$$FeS_2(s) + 14Fe^{+3} + 8H_2O \longrightarrow 15Fe^{+2} + 2SO_4^{-2} + 16H^+ . \qquad (4)$$

The stoichiometry of this reaction reveals that, for every mole of ferrous iron oxidized in equation (2), there is a net increase of two moles of hydrogen ion. This net increase in acidity provides hydrogen ions for further oxidation of ferrous iron and subsequent acid production.

As the pH decreases below 5, certain acidophilic, chemoautotrophic bacteria become active. These bacteria--<u>Thiobacillus ferrooxidans</u>, <u>Ferrobacillus ferrooxidans</u>, <u>Metallogenium</u>, and similar species--are active at pH 2.0 to 4.5 and use $CO_2$ as their carbon source (Silverman 1967). They are the main contributor to the oxidation of ferrous iron to the ferric state, the rate-limiting step in the oxidation sequence. Their presence indicates rapid pyrite oxidation and is usually accompanied by waters low in pH and high in iron, manganese, and total dissolved [illegible]ids.

Factors that possibly affect production of acidity in coal piles and the subsequent leaching of trace metals are (1) concentration and form of pyritic sulfur in the coal, (2) size of the coal pile, (3) method of coal preparation and cleaning before storage, (4) climate, including rainfall and temperature, (5) concentration of $CaCO_3$ and other neutralizing substances in the coal, (6) concentration and form of trace metals in the coal, and (7) the residence time in the coal pile.

## METHODOLOGY

### Plant J

In 1972 a system was installed to collect coal pile drainage and transfer it to an ash pond (Figure 1). Collection is accomplished by a series of maintained channels around the coal pile, which drain into a storage basin. A manually operated pump, an associated piping system, and a secondary maintained channel transfer the drainage from the storage basin to the ash pond. The storage basin is designed to contain the runoff from a moderately small storm at best. Because of this limited capacity, the pump is activated manually at the start of almost all rainfall events, and actual detention time in the basin proper is small.

A sampling system (Figure 2) was designed so that pressure in the line fro[illegible] the pump to the ash pond forces a sample into the collection barrels. The sample line is composed of tygon tubing with plastic fittings. The sample barrels are plastic garbage cans with an approximate volume of 150 l each. Flowrate of coal pile drainage from the storage basin to the ash pond is about 3400 l/min (900 gpm). This flowrate will be refined as more data becomes available. Flow through the sample line was adjusted to about 0.1 l/min (0.025 gpm). This arrangement supplies a sample that is a composite of the total volume pumped to the ash pond. Because of the acid nature of the waste and the desire to collect pH and acidity data, the sample was not preserved by acidification until the date of collection. The samples are manually stirred and then collected from a line draining both barrels. Chemical analyses were performed at the TVA Water Quality Laboratory with methods prescribed by the American Public Health Association (1971) and the Environmental Protection Agency (EPA 1974).

A rain gage was placed next to the coal pile so that a relationship between rainfall and runoff could be studied. This information will be used to design future storage basins and to estimate losses through evaporation and percolation. The amount of rainfall was compiled on a daily basis, tabulated, and compared with hours of pumping time. Pumping rate was determined by placing a temporary weir in the drainage channel downstream from the pump; this installation was subject to only minimal inflow from the immediate vicinity. In cases of intermittent rain on several consecutive days resulting in almost continuous operation of the pump, the determination of a single rainfall and its concurrent runoff was impossible. Instead, during consecutive days of rainfall, total rainfall and associated pumping over the entire period were considered as one event of rainfall and runoff.

### Plant E

Drainage from the coal pile at this installation is not collected systematically, although plans for total collection and transfer to the ash pond are being developed. The drainage now emanates in three distinct directions (Figure 3): Drainage A and B unite at some distance downstream and flow into a holding pond, where there is significant dilution of the coal drainage; drainage C quickly spreads out onto a mud flat. Because of the diverse nature of these discharges and the expense of installing and maintaining even temporary flow gages, drainage volume at plant E was not measured.

A modified automatic water sampler (ISCO model 780) was placed at one of the drainways, and a small sample pool was constructed (Figure 4). The water sampler was equipped with a stage activation device so that the sampler initiated sampling with the rise of the storm hydrograph. Samples were collected hourly and composited, thus representing a simple composite of each runoff event. Discrete samples were collected of a single storm event on February 24, 1977. Total rainfall for this event was 53 mm (2.10 in.). These samples were collected at 20-min intervals and analyzed for pH, acidity, dissolved solids, suspended solids, sulfate, iron, and manganese. Rainfall was measured on site so that runoff could be estimated. Loadings of pollutants can be projected by applying this estimate to composites of

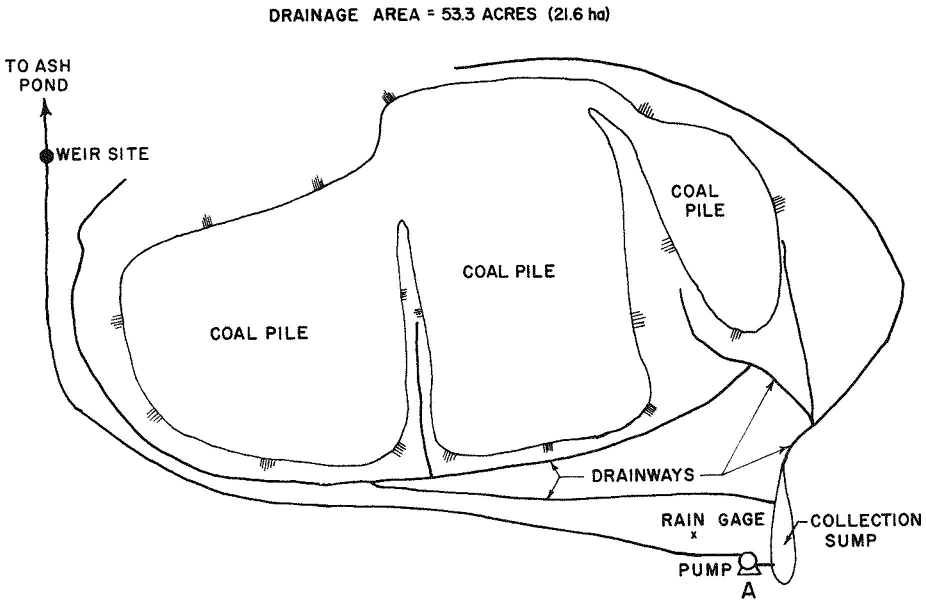

Figure 1. Coal pile and drainage collection system, plant J.

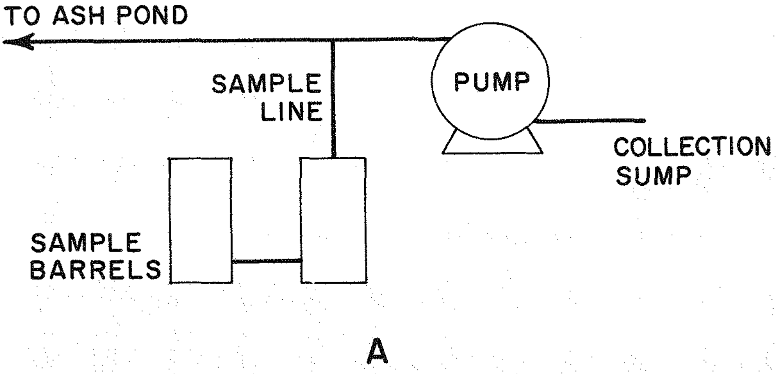

Figure 2. Sample collection system, plant J.

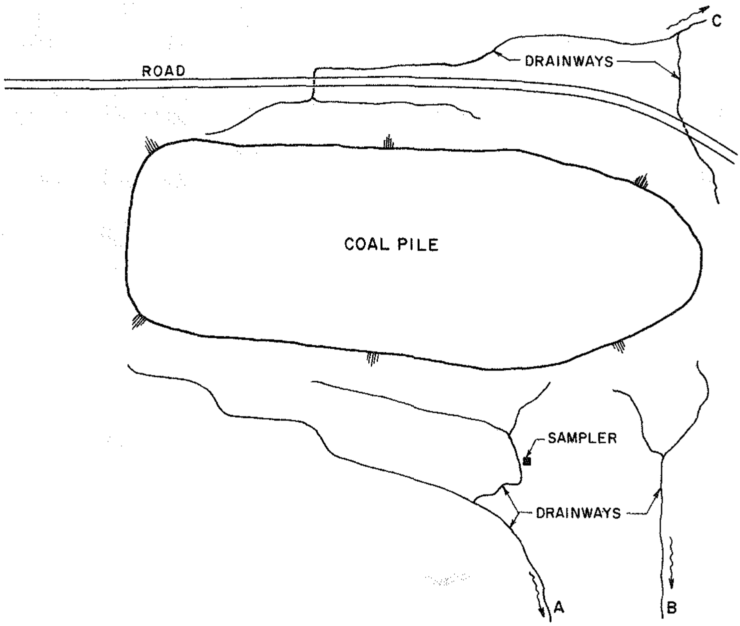

Figure 3. Coal pile and associated drainage system, plant E.

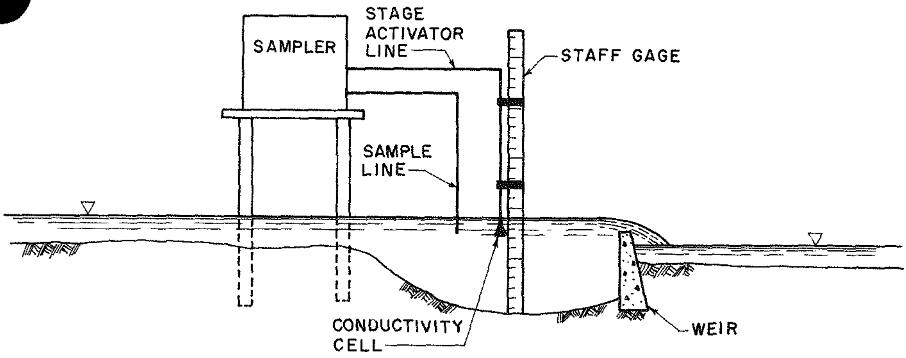

Figure 4. Sample collection system, plant E.

individual storm events. Application of this simple method of composite and average flow to calculate loadings of pollutants was demonstrated by Grizzard et al. (1976) to be adequate.

## HYDROLOGY

In most cases rainfall escapes as surface runoff, percolates into the soil to become groundwater, or is lost through evapotranspiration. However, in coal piles, even that fraction of the rainfall that percolates into the pile may be subject to some evaporation, and no transpiration can occur. Conventional estimates of evapotranspiration used in most hydrological models are, therefore, questionable. Because of these problems and the expense of installing large flumes for long-term measurement of flows, detailed hydrological models were not calibrated for use as a part of this study. Instead, a simple relationship between rainfall and runoff was developed for use at TVA facilities. Because rainfall, temperature, wind velocity, and humidity are similar throughout the Valley, such a rainfall-runoff relationship can be used to estimate detention basin design and to calculate acid loads to the ash pond.

A regression analysis of rainfall vs. runoff was performed for data collected over a seven-month period at plant J. Runoff was calculated by multiplying hours of pumping time by a known pumping rate. Rainfall was monitored continuously on site. A plot of the regression line and the 95 percent confidence intervals of the mean are presented in Figure 5. This relation [equation (5)] can be used to predict the runoff in inches per acre for a given storm event when total inches of rainfall are known:

$$\text{Runoff (in.)} = 0.855\ \text{rainfall (in.)} + 0.0082. \qquad (5)$$

Runoff can be converted to total runoff by applying a drainage area and obtaining the appropriate volumetric term. Losses due to evaporation and infiltration are about 14 percent. Losses decrease slightly at lower rainfalls because base flow is included in this relationship. Application of this relationship is, of course, limited to coal piles of similar size. Additional factors that could affect runoff include amount of snowfall and soil permeability.

## CHEMICAL AND PHYSICAL CHARACTERISTICS

### Acidity and pH

Both systems investigated exhibited highly acidic drainages. Acidity was determined as "cold" acidity to pH 7.0 and expressed as $CaCO_3$. Acidity was quite variable in both cases (Table 2), but pH was limited to a rather tight band (2.3 to 3.1). This illustrates that acidity is a measure of available protons, not hydrogen ions. Means (arithmetic) are similar: 21 of the 25 values fall between 2.6 and 3.0. Values of pH reported by Nichols (1974) exhibit a slightly broader range of 2.1 to 3.0. Anderson and Youngstrom (1976) report a pH of 2.2 to 5.8 for hourly pH measurements over a three-week period. Matsugu (1976) reports a pH of 2.4 to 3.0 for 67 grab samples of coal pile leachate. For these same samples, acidity varied from 10 to 120 milliequivalents/liter (meq/l). Thus, the pH of coal pile drainage, at least for eastern coal, is generally in the relatively narrow range of 2.2 to [illegible]

Another interesting observation involves comparison of pH values obtained at plant J with those obtained at plant E. Even though coal supplied to plant E was high in sulfur content (>3%) and coal supplied to plant J was moderate in sulfur content (1 to 3%), as classified by EPA (1976b), pH of the drainage was similar for both plants. Caruccio et al. (1976) showed that total sulfur concentration is not directly related to acid formation from pyritic material. A second explanation involves maintenance of an optimum pH range (2 to 4) of the autotrophic bacteria responsible for pyrite oxidation, as explained by Schnaitman et al. (1969).

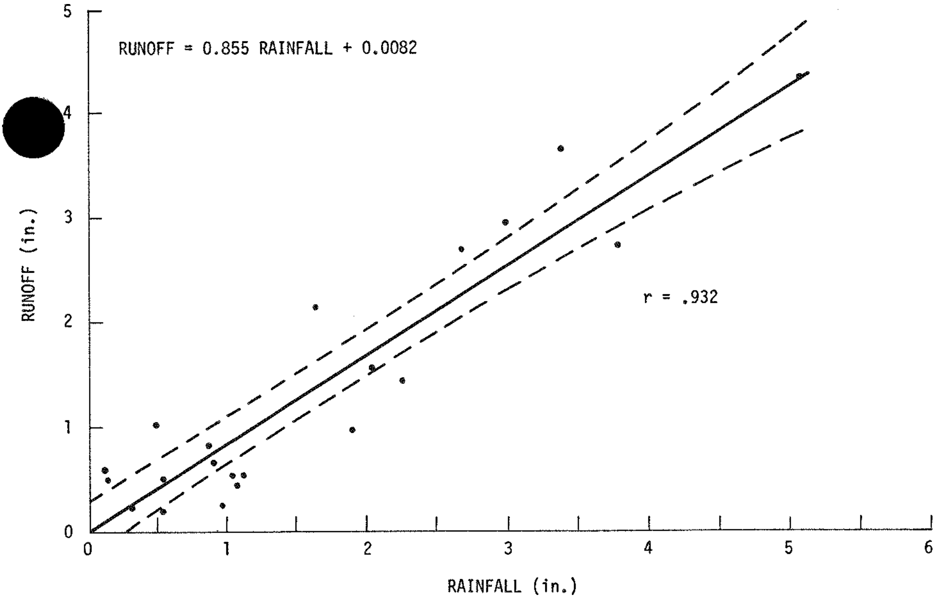

Figure 5. Regression of rainfall vs. runoff.

Table 2. Means and ranges of project data from plant J and plant E

| | pH | Acidity (mg/l $CaCO_3$) | Sulfate (mg/l) | Dissolved solids (mg/l) | Suspended solids (mg/l) | Iron (mg/l) | Manganese (mg/l) |
|---|---|---|---|---|---|---|---|
| | | | | Plant J | | | |
| Range | 2.3-3.1 | 300-7100 | 1800-9600 | 2500-16,000 | 8.0-2300 | 240-1800 | 8.9-45 |
| Mean | 2.79 | 3400 | 5160 | 7900 | 470 | 940 | 28.7 |
| N | 19 | 18 | 18 | 18 | 18 | 19 | 19 |
| | | | | Plant E | | | |
| Range | 2.5-3.1 | 860-2100 | 1900-4000 | 2900-5000 | 38-270 | 280-480 | 2.4-10.0 |
| Mean | 2.67 | 1360 | 2780 | 3600 | 190 | 380 | 4.13 |
| N | 6 | 6 | 6 | 6 | 6 | 6 | 6 |
| | | | | Plant E (discrete storm) | | | |
| Range | 2.5-2.7 | 300-1400 | 870-5500 | 1200-7500 | 69-2500 | 62-380 | 0.88-5.4 |
| Mean | 2.63 | 710 | 2300 | 2700 | 650 | 150 | 2.3 |
| N | 14 | 14 | 14 | 14 | 14 | 14 | 14 |

Acidity is higher at plant J than at plant E, even though pHs are similar. In essence, any substance capable of donating protons (most metals and many naturally occurring organic compounds) will be measured as acidity.

## Solids

Concentrations of total suspended solids are of primary interest in characterization of coal pile drainage. Elevated concentrations occur when rainfall and runoff suspend coal fines in the pile. This is generally not a problem during base-flow conditions, but occurs during runoff events at levels up to 2300 mg/l.

Concentrations of suspended solids at plant J ranged from 8 to 2300 mg/l, with a mean of 470 mg/l; however, these samples were collected after they had passed through a collection sump, where some settling occurred. At plant E, where direct runoff was collected as a single composite sample for each storm event, the mean and range of suspended solids concentrations were somewhat lower. However, when samples collected during a single storm event were examined, the range and mean were similar to those obtained at plant J, indicating that minimal settling occurred in the collection sump at that installation. Values for suspended solids much higher than this were reported by Matsugu (1976).

Concentrations of total dissolved solids were somewhat higher at plant J than plant E, even when the samples collected during a single storm event were considered. Inspection of the data reveals that most of the total dissolved solids are sulfate salts. Hence, higher concentrations of total dissolved solids are a consequenc[illegible] enhanced pyritic oxidation by equations (1) and (4). These data complement the acidity and pH data in suggesting that enhanced pyritic oxidation is occurring at plant J.

## Iron and Manganese

These metals are often discussed simultaneously because of their similar behavior in water. Both are increasingly soluble with decreasing pH, exist in both the reduced and oxidized state, and form coatings on particles that may limit solubilities of other metals (Jenne 1968). Typically, iron and manganese concentrations in pyritic systems are quite high. Iron minerals are the substrate necessary for acid production [equations (1) through (4)]. As such, lower concentrations would be expected only where pyritic oxidation is repressed or where pH is not depressed sufficiently to allow for iron solubility. Values for iron reported by Nichols (1974) ranged from 0.17 to 93,000 ppm, with a mean of 19,500 ppm. A somewhat narrower range of 10 to 5300 ppm and a lower mean of 1150 were reported by Anderson and Youngstrom (1976).

Iron concentrations at both plants are lower in range and mean than concentrations encountered by these other investigators. Iron concentrations at plant E ranged from 280 to 480 mg/l, with a mean of 380 mg/l. This is considerably higher than the iron concentrations in samples collected in a single storm, which ranged [illegible] 62 to 380 mg/l, with a mean of 150 mg/l. Concentrations of iron at plant J [illegible] higher, with a range of 240 to 1800 mg/l and a mean of 940 mg/l.

Manganese concentrations reported by Anderson and Youngstrom (1976) ranged from 4.5 to 72.0 mg/l, with a mean of 17.1 mg/l. Somewhat lower concentrations, ranging from 3.4 to 12 mg/l, with a mean of 6.9 mg/l, were reported by Matsugu (1976). Levels at plant J (Table 1) were comparable to those presented by Anderson and Youngstrom (1976); values for plant E were somewhat lower.

## Trace Elements

There is little information available on trace element concentrations in coal pile drainages. Trace elements of environmental concern in coal that have been identified by EPA (1976b) are presented in Table 3. These constituents, except for yttrium, were analyzed in drainages from both plants; several other elements, including aluminum and chromium, were also analyzed for several samples. Results of analyses for selected trace elements are presented in Table 4. Several other trace elements were also analyzed in drainages from both plants. Of these elements, lead, barium, and titanium were low or consistently below the limits of detection. Levels of antimony were above detection limits in several instances, but were not included because of a question of their significance to freshwater aquatic life. When an element was below detection limits, the detection limit was used for statistical purposes. Most means of trace element concentrations at plant J are three to eight times as high as those at plant E.

Table 3. Trace elements in coal[a]

| Element | Range (μg/g) | Element | Range (μg/g) |
|---|---|---|---|
| Beryllium | 0-31 | Selenium | 0.4-8 |
| Nickel | 0.4-104 | Yttrium | 0.1-59 |
| Copper | 2-185 | Cadmium | 0.1-65 |
| Zinc | 0-6000 | Mercury | 0.01-1.6 |
| Arsenic | 0.5-106 | Lead | 4-218 |

[a] Source: EPA 1976b.

Table 4. Means and ranges of trace metal data from plant J and plant E (in mg/l)[a]

| | Copper | Zinc | Cadmium | Aluminum | Nickel |
|---|---|---|---|---|---|
| | | | Plant J | | |
| Range | 0.43-1.4 | 2.3-16 | <0.001-<0.001 | 66.0-440 | 0.74-4.5 |
| Mean | 0.86 | 6.68 | <0.001 | 260 | 2.59 |
| $N_D$ | 0 | 0 | 19 | 0 | 0 |
| N | 19 | 19 | 19 | 19 | 19 |
| | | | Plant E | | |
| Range | 0.01-0.46 | 1.1-3.7 | <0.001-0.003 | 22.0-60.0 | 0.24-0.46 |
| Mean | 0.23 | 2.18 | 0.002 | 43.3 | 0.33 |
| $N_D$ | 0 | 0 | 2 | 0 | 0 |
| N | 6 | 6 | 6 | 6 | 6 |

| | Chromium | Mercury | Arsenic | Selenium | Beryllium |
|---|---|---|---|---|---|
| | | | Plant J | | |
| Range | <0.005-0.011 | <0.0002-0.0025 | 0.005-0.6 | <0.001-0.03 | 0.03-0.07 |
| Mean | 0.007 | 0.0004 | 0.17 | 0.006 | 0.044 |
| $N_D$ | 11 | 12 | 0 | 4 | 0 |
| N | 17 | 20 | 19 | 18 | 18 |
| | | | Plant E | | |
| Range | <0.005-0.011 | 0.003-0.007 | 0.006-0.046 | <0.001-0.001 | <0.01-0.03 |
| Mean | 0.007 | 0.004 | 0.02 | 0.001 | 0.014 |
| $N_D$ | 3 | 0 | 0 | 3 | 3 |
| N | 6 | 5 | 4 | 4 | 4 |

[a] $N_D$ = number of samples below detection limits.

Although concentrations of copper at plant J are higher than the criteria set by EPA (1976a), if discharged untreated, they are lower than those reported by Nichols (1974) or Anderson and Youngstrom (1976). Concentrations for plant E are lower still and do not appear to be significant from the standpoint of water quality.

Levels of zinc are also high with respect to ambient quality. The mean concentrations of 6.68 mg/l at plant J and 2.18 mg/l at plant E are similar to the means of 5.9 mg/l reported by Nichols (1976) and 3.67 mg/l reported by Anderson and Youngstrom (1976). The criteria established by EPA (1976a) for public water supply is 5 mg/l.

Cadmium concentrations are quite low in drainages from both plants. At plant J no samples exceeded detection limits; at plant E four of the six samples exhibited detectable concentration, but none were above water quality criteria (EPA 1976a).

Aluminum is included as a toxic substance by the National Academy of Science (NAS 1973) in their development of proposed water quality criteria, but eliminated by EPA (1976a) in their development of finalized criteria. Thus, the significance of aluminum as a toxic substance is questionable. Mean concentrations of 260 mg/l at plant J and 43 mg/l at plant E were found.

Concentrations of nickel are also above levels found in surface water (NAS 1973), but are significantly less than concentrations of aluminum.

Chromium concentrations are well below established criteria at both plants and pose no threat to the aquatic community or man.

Toxicity of beryllium, like that of several other metals, is inversely related to hardness of the solute. Coal pile drainage is quite hard (the mean calcium and magnesium concentrations for plant J were 300 and 230 mg/l, respectively). Levels [illegible] beryllium are well below established criteria for waters of this hardness (EPA [illegible]a).

Mercury concentrations were an order of magnitude higher at plant E than at plant J. Levels at both plants exceeded established water quality criteria (EPA 1976a).

Arsenic levels in drainage from plant J ranged from 0.005 to 0.6 mg/l, with a mean of 0.17 mg/l. These values generally exceeded established criteria, whereas those concentrations found at plant E generally did not.

Concentrations of selenium behaved similarly to those of arsenic in that levels at plant J generally exceeded criteria whereas levels at plant E did not. This is significant since selenium and arsenic exhibit antagonistic toxicities (Levander 1976).

### Mass Input vs. Output

Mass flows of several constituents were calculated at plant J for June 1976. The total flow for this month was 49 million liters (13 million gallons). Runoff from the coal pile during this period contained 4.5 x $10^4$ kg (50 tons) of iron, 1.5 x $10^4$ kg (17 tons) of aluminum, 1.6 x $10^4$ kg (1.8 tons) of manganese, 152 kg (335 lb) of nickel, 58 kg (127 lb) of copper, and large quantities of sulfate, dissolved and suspended solids, and hardness.

To assess the contribution of rainfall to the coal pile system, a rainfall sample was collected during a storm that occurred on June 29-30. This storm lasted 33 h, with a total precipitation of 3.43 cm (1.35 in.). Total precipitation for June was 20.3 cm (7.99 in.). Concentrations of several constituents were analyzed in the rainfall samples, and loadings were extrapolated for the month of June. Calculated values were iron, 6.1 kg (13.5 lb); aluminum, 8.8 kg (19.4 lb); manganese, 0.5 kg (1.0 lb); nickel, 2.2 kg (4.9 lb); and copper, 3.0 kg (6.7 lb). Thus, contaminants in rainfall appeared to be insignificant.

## LABORATORY STUDIES FOR TREATMENT OF COAL PILE DRAINAGE

The low pH of coal pile drainage increases the solubility of iron, manganese, [illegible] other trace metals, thus resulting in high concentrations of the metals. A [illegible]rtain degree of treatment may be required to prevent environmental impact to receiving streams. The current Federal guidelines on effluent limitations for the steam-electric power industry have promulgated regulations only for pH and suspended solids in runoff from material storage. However, iron concentrations in coal pile drainage are extremely high.

Coal pile drainage can be treated to remove metals by (1) lime or limestone neutralization (McDonald 1974) or sulfide precipitation followed by sedimentation (Ross 1973) or (2) by sedimentation and filtration followed by ion exchange or reverse osmosis (Rosehart 1973). These processes have been used to treat acid mine drainage, which is somewhat similar to coal pile runoff. However, all methods are costly, and some were found to be either impractical or unreliable. TVA has investigated an economic method of treating coal pile drainage in alkaline ash disposal ponds. The coal pile runoff can be collected in a storage basin and then routed through an ash pond before it is discharged into receiving streams. Reducing the concentration of iron in the coal pile drainage to 1.0 mg/l by treatment in the ash pond is desirable.

The fly ash has been used successfully as a treatment aid in sewage and industrial wastewaters. Reports indicate that fly ash can be used to remove heavy metals from aqueous solutions (Gangoli et al. 1975; Chu et al. 1977); phosphates (Gangoli and Thedos 1973; Tenney and Cole 1968; Tenney and Echelberger 1975); organics such as phenolic compounds (Lorenz 1954; Rieche and Strankmueller 1968); TNT (Bolin and Kustka 1958); alkyl benzene sulfonate (ABS) (Mancy et al. 1965); refractory orga[illegible] in secondary treated sewage effluents (Deb et al. 1967); and color in paper mill effluents (Rhoad 1969; Nasr et al. 1976). Fly ash consists primarily of metal oxides such as $SiO_2$, $Al_2O_3$, $Fe_2O_3$, CaO, and MgO and other oxides such as $SO_3$. Metal oxides in contact with water will produce an alkaline solution; conversely, sulfides will be oxidized in aerobic waters to sulfate and sulfuric acid, yielding an acidic solution. The final pH of the solution depends on the ratio of alkaline metal to sulfate concentration in the ash pond effluent (Chu et al. 1976). Metallic cations will precipitate as hydroxides at high pH. Also, metal ions may adsorb on fly ash because of the high content of silica and alumina in fly ash (Gangoli et al. 1975). Benchscale treatment tests were performed to examine the ability of fly ash slurry to remove iron from coal pile drainage. The characteristics of coal pile drainage used for these studies are shown in Table 5.

Table 5. Chemical composition of coal pile drainage used for treatment study

| Constituent | Concentration (mg/l) | |
|---|---|---|
| | Total | Dissolved |
| Acidity, as $CaCO_3$ | 9100 | |
| Total dissolved solids | | 19,000 |
| Total suspended solids | 6 | |
| Iron | 3000 | 3000 |
| Manganese | 46 | 44 |
| Zinc | 12 | 12 |
| Nickel | 4.4 | 4.4 |
| Copper | 1.6 | 1.3 |
| Arsenic | 0.28 | 0.28 |
| Selenium | <0.001 | <0.001 |
| Chromium | <0.005 | <0.005 |
| Mercury | <0.002 | <0.0002 |

## pH of Coal Pile Drainage and Ash Sluice Water Mixture

Aliquots (100-ml) of two types of fly ash slurry, neutral and alkaline, with pH ranges typical of ash concentrations for sluicing, were titrated with coal pile drainage. Figures 6 and 7 show the resulting titration curves. At TVA's 12 coal-fired power plants, the annual volumetric ratio of total flow of coal pile drainage to total flow of ash pond effluent averages 0.001 to 0.012. However, coal pile runoff occurs only intermittently whereas the flow of ash pond effluent is continuous. Thus, the instantaneous volumetric ratio of coal pile drainage to ash sluice water could be greater than 0.012 (1.2 ml coal pile drainage in Figures 6 and 7). This would cause a significant drop in pH in the neutral ash solutions at

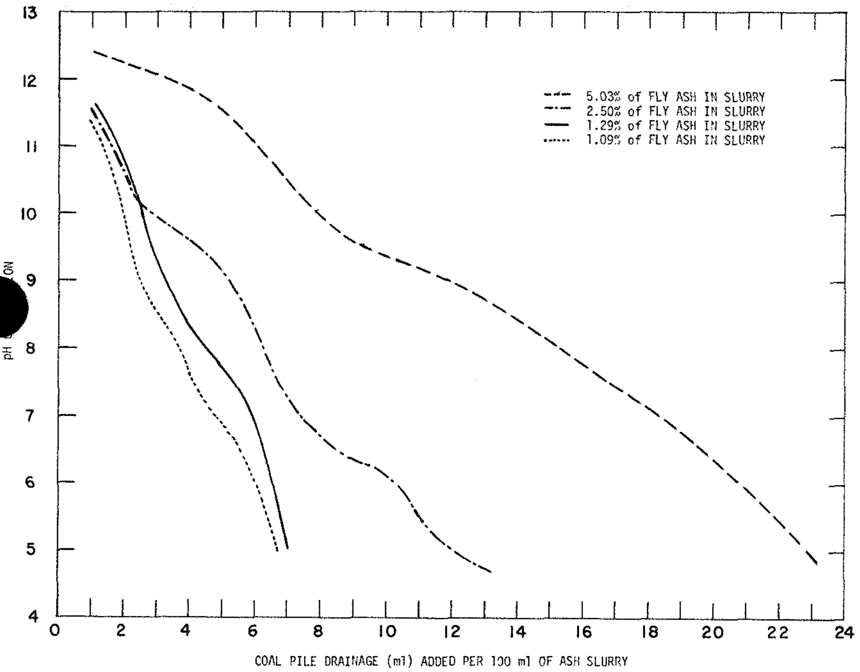

Figure 6. Titration curves for alkaline fly ash slurry with coal pile drainage.

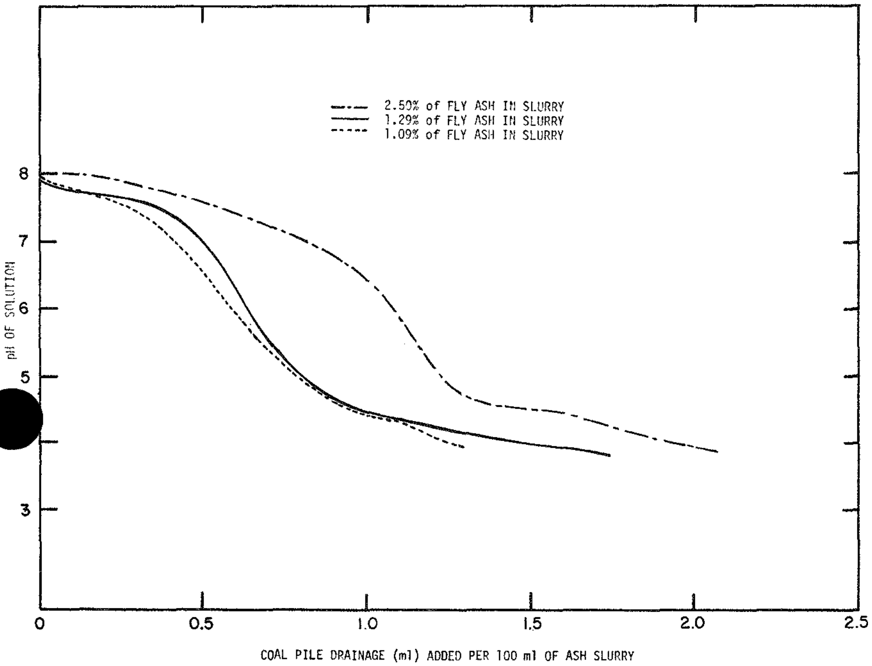

Figure 7. Titration curves for neutral fly ash slurry with coal pile drainage.

*the high ratios, as shown in Figure 6. The pH values of the mixture of coal pile* drainage and ash sluice water also depend on the ash concentration in the slurry.

## Removal of Metal Ions by Precipitation

### Effect of the volumetric ratio of coal pile drainage to ash sluice water

In these tests equal amounts of alkaline fly ash from plant E were vigorously mixed with deionized water for 2 h. The ash concentration, 20 g/l, was a typical ratio of ash to water for sluicing. After mixing, one set of these ash solutions was filtered through 0.45-μ filters to remove the ash; the second set remained unfiltered. Various amounts of coal pile drainage were added to each duplicate filtered and unfiltered solution. These solutions were mixed at 100 rpm for 3 m[illegible] and at 30 rpm for 30 min. The floc in the solutions was then allowed to settle, and the supernatants were filtered and analyzed.

Figure 8 shows the residual iron concentrations in the supernatant vs. the pH of the mixtures. Filtering the ash before the addition of coal pile drainage had no effect on the pH of the solution (11.9). However, the filtered solutions experienced a larger change in pH with addition of the coal pile drainage than did the unfiltered solutions (Figure 8). These differences were caused by the reaction of acid radicals from the coal pile drainage with alkaline metal oxides remaining *on the fly ash. The iron concentration in the coal pile drainage was 3000 mg/l* (Table 5). Therefore, the initial iron concentrations, with dilution ratios of 0.005:1 to 0.07:1, ranged from 15 to 196 mg/l. The additional iron removed by adsorption on fly ash (i.e., the differences of iron concentrations remaining in the solutions between filtered and unfiltered beakers, but having an equal amount of coal pile drainage added) was not detectable. These results indicate that the removal of iron resulting from combining the coal pile drainage with alkaline ash solutions is caused by precipitation.

As shown in Figure 8, the supernatant iron concentrations drop sharply at a pH of about 6, which indicates that, by comparison with the solubilities of ferric iron in water (Stumm 1964), much of the iron dissolved in the coal pile drainage was in the form of ferrous iron. A pH of 6.3 or more is required to remove iron to the level of 1 mg/l. However, if the "equivalent" concentration is requested *(i.e., the remaining iron concentration should be multiplied by a dilution factor* to exclude the effect by dilution with ash sluice water), a pH of 7 or more would be necessary.

### Effect of ash character and ash concentration

As described previously, iron is removed by precipitation at an alkaline pH level. The character and concentration of ash during sluicing will significantly affect the change in pH caused by adding coal pile drainage to ash sluice water. As shown in Figure 6, the neutral fly ash would not be sufficient to treat the coal pile drainage because of the low alkalinity. Therefore, to remove iron, only alkaline fly ash is favorable for neutralization of the high acidity in coal pile drainage at high-volume ratios. The factors that govern the formation of alkali[illegible] fly ash at coal-fired power plants were discussed by Chu et al. (1976). Figure [illegible] shows the supernatant iron concentrations vs. the pH of the solutions that were affected by the different ash concentrations used for sluicing: 6, 12, 20, and 36 g/l. The ratio of coal pile drainage to ash sluice was 0.015. The experimental procedures were the same as described earlier.

Before the coal pile drainage was added, the pH was the same for ash-filtered and ash-unfiltered solutions having the same initial ash concentration. For solutions having ash concentrations of 6, 12, 20, and 36 gl, the pH values were 11.5, 11.7, 11.9, and 11.95, respectively. After equal volumes of coal pile drainage were

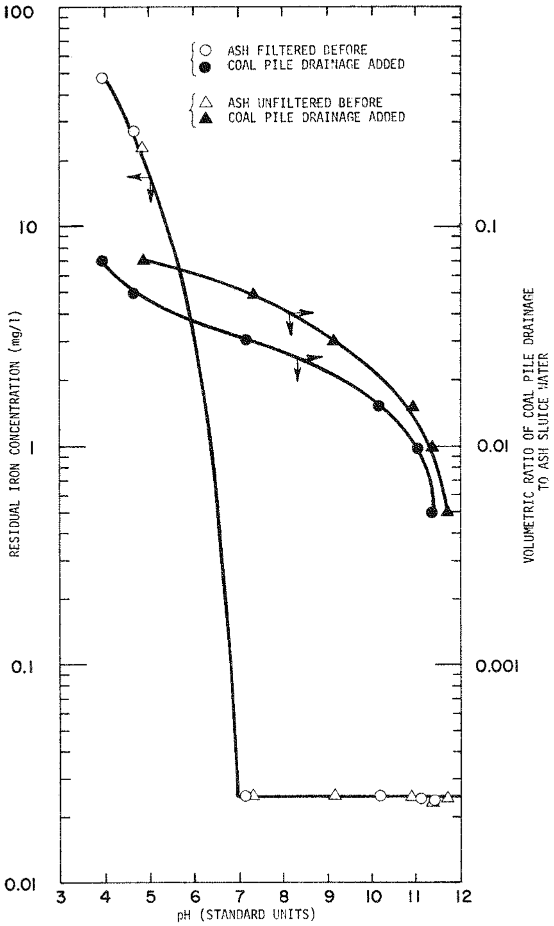

Figure 8. Residual iron concentration and volumetric ratio of coal pile drainage to ash sluice water vs. pH. (The minimum detectable concentration of iron was 0.05 mg/1; therefore, 0.025 mg/1 was used as the average of 0.05 mg/1 and zero.

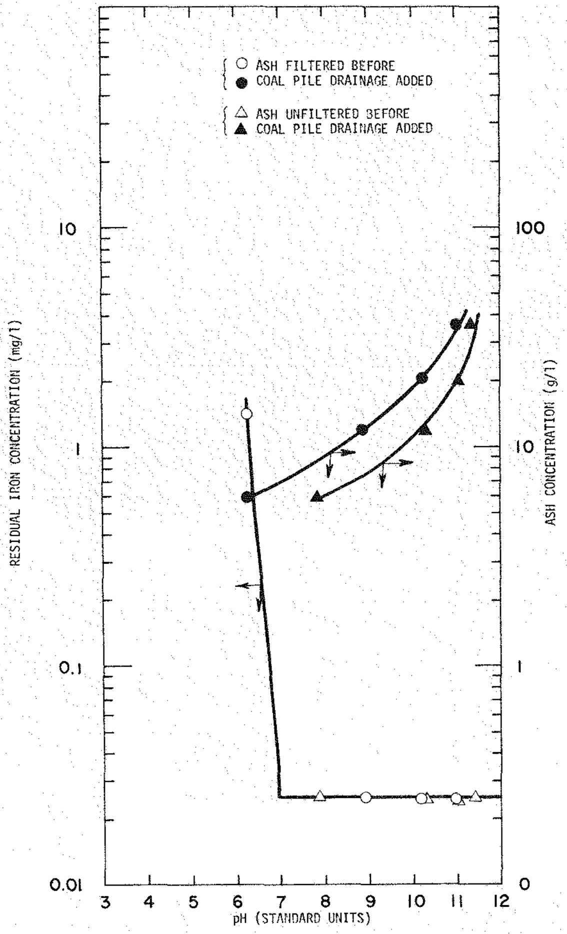

Figure 9. Residual iron concentration and ash concentration vs. pH. (The minimum detectable concentration of iron was 0.05 mg/l; therefore, 0.25 mg/l was used as the average of 0.05 mg/l and zero.)

added, the pH values decreased; this decrease was proportional to the decrease in fly ash concentration. As discussed earlier, the pH values were higher for unfiltered ash solutions than for filtered solutions, and the relationship between residual iron concentration and pH in Figure 9 follows the same curve as shown in Figure 8.

## Effect of retention time

In several tests it was observed that the pH of the mixture of coal pile drainage and ash sluice water changed with retention time. Therefore, tests were conducted to evaluate the effect of retention time, including cumulative mixing to [illegible]ulate ash pond systems.

In these tests alkaline fly ash from TVA's plant L was vigorously mixed for 2 h with river water in four tanks holding identical ash concentrations of 25 g/l. Coal pile drainage was added to the fly ash solutions at volumetric ratios of 0.035:1, 0.06:1, 0.08:1, and 0.105:1 to give pH values of 9.5, 7.6, 6.36, and 4.35, respectively. Then, the solution in each tank was mixed at 100 rpm for 3 min and at 10 rpm for six days. During the slow mixing, almost all the ash settled to the bottom of the tanks. Grab samples were taken at varying time intervals. Figure 10 shows that the pH values of the solutions change with retention time because the alkaline metal oxides dissolve continuously from the ash and the $CO_2$ from the air goes into the solution. About 28 h was required to change the initially acidic solution (pH 4.35) to pH 7, the pH required to reduce the iron concentration to below 0.05 mg/l. This change in pH may not occur if the fly ash does not contain sufficient alkalinity.

As part of this study, samples were also analyzed for iron. Results, shown in Figure 11, indicate a similar relationship between residual iron concentration and pH.

## Solids settling

In addition to fly ash, solids can be produced by iron precipitation as ferrous and ferric hydroxides. The fly ashes are spherical particles, whereas iron hydroxides are flocculent materials. Bench-scale settling tests were conducted to investigate the settling characteristics of (1) iron hydroxides and (2) iron hydroxides mixed with fly ashes. In these tests, alkaline fly ash from plant L was mixed with river water in two beakers, with an ash concentration of 25 mg/l for each. After being mixed, the solution in one beaker was filtered to remove all the fly ash. Coal pile drainage was added to both beakers at a volumetric ratio of 0.08:1 to give a pH value of 7. After the jar test procedures, both solutions were transferred into two cylinders for settling tests. The resulting settling curves, shown in Figure 12, indicate a good settling character for the iron hydroxide floc and the sludge of iron hydroxides plus fly ash. The initial settling velocity for iron hydroxide floc is calculated as 3 cm/min, and the settling velocity for iron hydroxide floc combined with fly ash is calculated as 8.6 cm/min. The area required for thickening per unit flow rate of wastewater is 0.56 $cm^2 \cdot cm^{-3} \cdot min^{-1}$ for iron hydrox[illegible]s flow and 0.42 $cm^2 \cdot cm^{-3} \cdot min^{-1}$ for iron hydroxide floc plus fly ash.

## Field evaluation

To verify these experimental results, data collected from field tests at plant J were evaluated. This plant uses pulverized coal from eastern Kentucky and eastern Tennessee, and the fly ashes produced have a neutral character. As mentioned, all the coal pile drainage at plant J is collected in a storage basin and then pumped into the ash pond. Further modifications are being made, including additional diversion dikes and similar runoff control structures, to increase the efficiency of runoff collection and transfer to the ash pond. The pH of this ash pond has

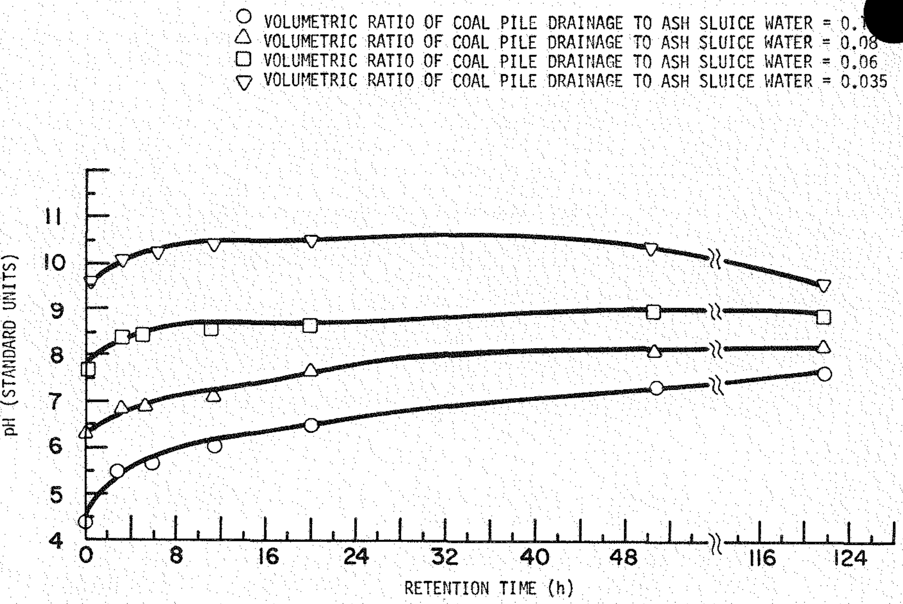

Figure 10. pH vs. retention time.

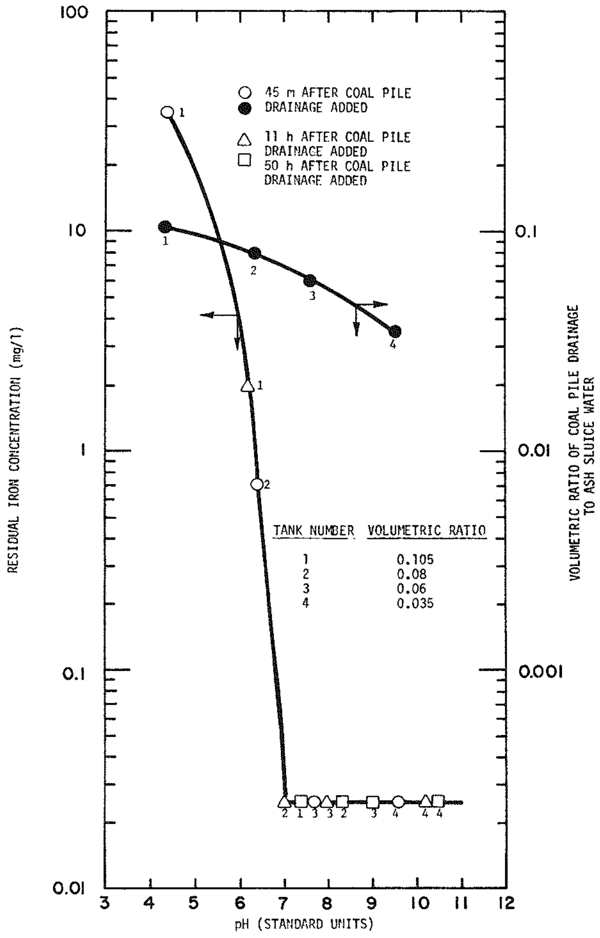

Figure 11. Residual iron concentration and initial volumetric ratios of coal pile drainage to ash sluice water vs. pH.

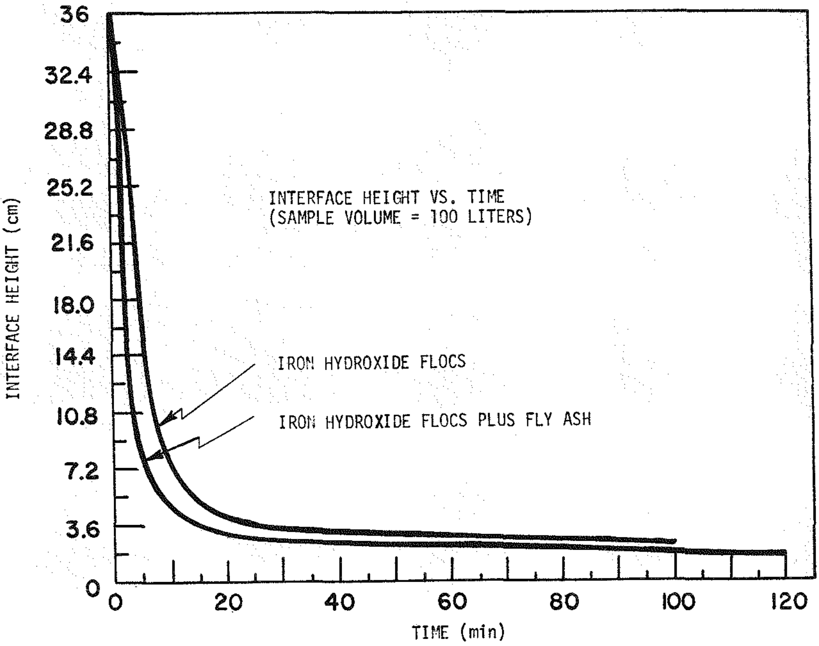

Figure 12. Settling curve of coal pile drainage--fly ash mixture.

varied seasonally, possibly as a result of (1) the low buffer capacity of water used for sluicing or (2) the discharge of coal pile drainage into the ash pond. Based on the quarterly data of ash pond effluent collected in three years, Figure 13 indicates that the iron from the coal pile drainage and ash materials is mostly removed in the complex ash pond system at the high pH level. It has been verified that the iron concentration in the solutions of coal pile drainage and ash sluice water mixture will be less that 1 mg/l if the pH is about 6.3 or more.

## BACTERIAL INHIBITION

Sediment samples were taken from the bottoms of channels draining the coal le. These samples consisted of mud, coal fines, pyrite chips, and an amorphous llow precipitate. In many places, green precipitates covered the small pebbles. hese sediment samples were examined for iron-oxidizing bacteria. The genus *Thiobacillus* was identified in all samples. The amorphous precipitate appeared to be elemental sulfur, an amorphous pyrite, or ferric chloride. This precipitate appeared on the surface of gullies eroded into the sides of the coal pile. The precipitate appeared only on the gully bottom and was not visible after removing about one centimeter of the fines forming the gully bottom. If this actually was elemental sulfur, its source can be attributed to the bacterial oxidation of pyrite, where it has been identified as an intermediate in the oxidation of sulfide to sulfate. Identification of iron oxidizers indicates the possibility of inhibiting the responsible organism to control drainage. Investigators working on control of acid mine drainage, a waste also mediated by *Thiobacillus*, have reported dramatic decreases in acid production rates when bacterial inhibitors were employed (Shearer et al. 1968). One proven inhibitor is ferrous iron in high concentrations. The rate of acid production could be reduced by applying an inhibitor and sprinkling for dust control. This method of control could be particularly appropriate for areas in which dry ash disposal is used.

## CONCLUSIONS

Coal pile drainage is a highly acidic waste stream containing high concentrations of a wide variety of inorganic constituents. Further, the acidity of this waste stream may not be governed by sulfur content of the coal. However, transfer of this drainage to an ash pond, where neutralization and precipitation occur, appears to provide adequate treatment.

## ACKNOWLEDGMENTS

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## REFERENCES

American Public Health Association, American Water Works Association and Water Pollution Control Federation. 1971. *Standard Methods for the Examination of Water and Wastewater*. 13th ed. Washington, D.C.

Anderson, W. C., and M. P. Youngstrom. 1976. Coal pile leachate quantity and quality characteristics. In *Proceedings of the Sixth Symposium on Coal Mine Drainage Research, NCA/BCR Coal Conference and Expo III*.

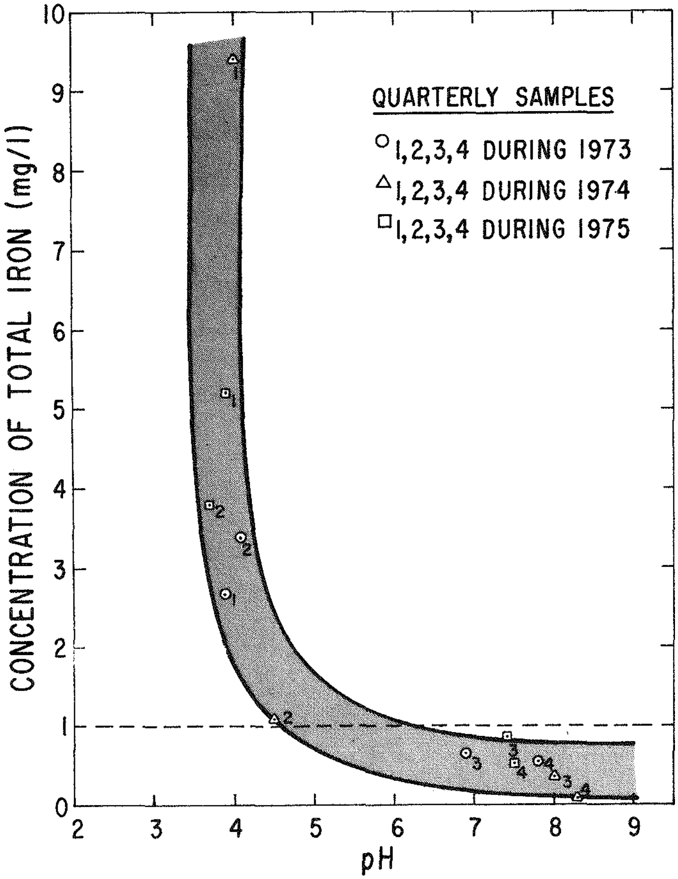

Figure 13. pH vs. total iron concentrations in an ash pond effluent. (Pond also receives coal pile drainage.)

## $254_a$ - Mine Drainage

## $274_a$ - Coal Preparation

Bolin, V., and M. Kustka. 1958. Science Papers, Institute of Chemical Technology, vol. 2, p. 247. Faculty of Technology of Fuel and Water, Prague.

Caruccio, F. T., G. Geidel, and J. M. Sewell. 1976. The character of drainage as a function of the occurrence of framboidal pyrite and groundwater quality in Eastern Kentucky. In Proceedings of the Sixth Symposium on Coal Mine Drainage Research, NCA/BCR Coal Conference and Expo III.

Chu, T.-Y. J., R. J. Ruane, and G. R. Steiner. 1976. Characteristics of wastewater discharges from coal-fired power plants. In Proceedings of the 31st Annual Purdue Industrial Waste Conference.

Chu, T.-Y. J., G. R. Steiner, and C. L. McEntyre. 1977. Removal of complex copper-ammonia ions from aqueous wastes with fly ash. In Proceedings of the 32nd Annual Purdue Industrial Waste Conference.

Deb, P. K., A. J. Rubin, A. W. Launder, and K. M. Mancy. 1967. Removal of COD from wastewater by fly ash. In Proceedings of the 21st Annual Purdue Industrial Waste Conference.

Environmental Protection Agency. 1974. Manual of Methods for Chemical Analysis of Water and Wastes. EPA-625/6-74-003. Washington, D.C.

Environmental Protection Agency. 1976a. Quality Criteria for Water. EPA-440/9-76-023. Washington, D.C.

Environmental Protection Agency. 1976b. EPA Program Conference Report. Fuel Cleaning Program: Coal. EPA-600/7-76-024. Washington, D.C.

Federal Water Quality Administration. 1970. Oxygenation of Ferrous Iron. U.S. Government Printing Office, Washington, D.C.

Gangoli, N., and G. Thedos. 1973. J. Water Pollut. Control Fed. 45(5): 842.

Gangoli, N., D. C. Markey, and G. Thedos. 1975. Removal of heavy metal ions from aqueous solutions with fly ash. In Proceedings of the 2nd National Conference on Complete Water Reuse.

Grizzard, T. J., C. W. Randall, and R. C. Hoen. 1976. Data collection for water quality modeling in the Occoquan Watershed of Virginia. In Proceedings of the Conference on Environmental Modeling and Simulation. EPA-600/9-76-016.

Jenne, E. A. 1968. Controls on Mn, Fe, Co, Ni, Cu, and Zn concentrations in soils and water: The significant role of hydrous Fe and Mn oxides. In Trace Inorganics in Water, American Chemical Society, Washington, D.C.

Levander, O. A. 1976. "Metabolic Interrelationships Between Arsenic and Selenium." Presented at the NIEHS International Conference on Environmental Arsenic, Fort Lauderdale, Fla. Oct. 5-8, 1976.

Lorenz, K. 1954. Gesundh. Ing. 75: 189.

Mancy, K. H., W. E. Gates, J. D. Gye, and P. K. Deb. 1965. Adsorption kinetics of ABS on fly ash. In Proceedings of the 19th Annual Purdue Industrial Waste Conference.

Matsugu, R. S. 1976. Ontario Hydro Research Division Report.

McDonald, D. G., H. Yocum, and A. F. Grandt. Studies of lime-limestone neutralization of acid mine drainage. In Proceedings of the Fifth Symposium on Coal Mine Drainage Research, NCA/BCR Coal Conference and Expo. I.

Nasr, M. S., R. G. Gillies, N. N. Bakshi, and D. G. McDonald. 1975. Color removal of pulp mill effluents with fly ash. In Proceedings of the 2nd National Conference on Complete Water Reuse.

National Academy of Science. 1973. Water Quality Criteria 1972. U. S. Government Printing Office, Washington, D.C.

Nichols, C. R. 1974. Development Document for Effluent Limitations Guidelines and New Source Performance Standards for the Steam Electric Power Generating Point Source Category. U.S. Environmental Protection Agency, Washington, D.C.

Rhoad, F. H. 1969. Pulp Pap. 32(9): 62.

Rieche, A., and J. Strankmueller. 1968. Wasserwirtsch. Wassertech. 8: 64.

Rosehart, R. G. 1973. Mine water purification by reverse osmosis. Chem. J. Chem. Eng. 51(6).

Ross, L. W. 1973. Removal of Heavy Metals from Mine Drainage by Precipitation. EPA-670/2-73-080.

Schnaitman, C. A., M. S. Korczyski, and D. G. Lundgren. 1969. Kinetic studies of iron oxidation by whole cells of Ferrobacillus ferrooxidans. J. Bacteriol. 99.

Shearer, R. E., W. A. Everson, and J. W. Mausteller. 1968. Reduction of acid production in coal mines with use of viable antibacterial agents. In Proceeding of the 2nd Symposium on Coal Mine Drainage Research, Mellon Institute.

Silverman, M. P. 1967. Mechanism of bacterial pyrite oxidation. J. Bacteriol. 94:4.

Stumm, W. 1964. Chemistry of natural waters in relation to water quality. In Symposium on Environmental Measurements. U.S. Public Health Service Publ. 99-WP-15, p. 299.

Tenney, M. W., and T. G. Cole. 1968. J. Water Pollut. Control Fed. 40(8): R281.

Tenney, M. W., and W. F. Echelberger. 1970. Fly ash utilization in the treatment of polluted waters. In Proceedings of the 2nd Ash Utilization Symposium. U.S. Bureau of Mines Inf. Circ. 8488.

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