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Environmental Protection Technology Series

Analysis of Pollution Control Costs

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EPA-670/2-74-009
February 1974

ANALYSIS OF POLLUTION CONTROL COSTS

By

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ARC Contract No. 72-87/RPC-713
Project 14010 HQC
Program Element 1BB040

Project Coordinator

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ABSTRACT

This report fulfills requirements for an effective, workable handbook on pollution control costs and factors effecting these costs for the Monongahela River Basin. The information in the report is based on the latest technological developments and cost analyses of recent reclamation projects. Although the report was developed for the Monongahela River Basin study, the cost estimates and supporting data should prove useful for all of Appalachia and other areas with similar topography, mine drainage pollution problems and mining history.

Specific areas covered by the report are surface mines, refuse piles, mine sealing, mine drainage treatment, air pollution control, solid waste handling and disposal, abandoned automobiles, and erosion and sedimentation control.

This report was submitted in partial fulfillment of Project Number 14010 HQC under Appalachian Regional Commission Contract Number 72-87/RPC-713 by Michael Baker, Jr., Inc., Beaver, Pennsylvania 15009, under the cooperative sponsorship of the Appalachian Regional Commission and the U.S. Environmental Protection Agency. Work was completed as of February 1973.

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EXECUTIVE SUMMARY

At the Monongahela Enforcement Conference convened in Pittsburgh, Pennsylvania in August, 1971, the Appalachian Regional Commission was charged with the task of developing a comprehensive environmental improvement program for the Monongahela River Basin. As part of this responsibility, the Commission must determine as accurately as possible the costs of various remedial programs which it recommends. An effective, workable handbook on pollution control costs and factors effecting these costs based on the latest technological developments and cost analyses of recent reclamation projects is needed to perform this function.

This study performed by Michael Baker, Jr., Inc. under ARC Contract No. 72-87/RPC-713 titled "Analysis of Pollution Control Costs" provides the data which will enable the Appalachian Regional Commission to estimate costs of pollution abatement in the Monongahela River Basin. Although this publication was developed for the Monongahela River Basin study, the cost estimates and supporting data should prove useful for all of Appalachia and other areas with similar topography, mine drainage pollution problems and mining history. The unit price cost estimates are based on the best available information and are suitable for budget estimates and preliminary planning, but they do not replace the detailed cost estimate required in producing contract plans and specifications.

The subject matter is separated into two parts. Part A, Abatement of Coal Mine Drainage Pollution and Mining Related Problems, contains: 1. Strip Mine and Refuse Bank Backfilling and Grading, 2. Revegetation of Lands Disturbed by Coal Mining, 3. Mine Sealing, 4. Stream Diversion, 5. Treatment of Mine Drainage, 6. Other Mine Drainage Abatement Procedures, 7. Refuse Bank and Mine Fires and 8. Mine Subsidence Control. Part B, Abatement of Pollution from Sources Other Than Coal Mining, contains: 1. Cost Estimates for Air Pollution Control Equipment, 2. Solid Waste Handling and Disposal Costs, 3. Abandoned Automobile Removal Costs, 4. Erosion and Sedimentation Control Costs and 5. Industrial Wastes "Orphan" and Other Environmental Problems in the Public Sector. An "Addendum" reports on recent publications noted after completion of the main body of the report. The report contains about 275 references to important publications on pollution abatement and nearly 200 tables and text figures.

Unit Costs for Mine Drainage Abatement

Significant unit costs for mine drainage abatement recommended for use in remedial program planning for the Monongahela River Basin are:

Surface Mine and Refuse Bank Reclamation

1.	Strip Mine Backfilling and Grading	$1,250/Acre
2.	Refuse Bank Contouring and Grading	$1,000/Acre
3.	Soil Cover for Graded Refuse Bank	$2,500/Acre
4.	Refuse Bank Removal and Burial	$ 1.00/C.Y.
5.	Soil Cover at Burial Site	$ 0.50/Yd.^{2}
6.	Clearing and Grubbing	$ 300/Acre
7.	Revegetation	$350 to $ 400/Acre

Mine Sealing

1.	Hydraulic Seals for Accessible Mines	
	a) Halliburton Type Seals (Chemical grout and aggregates including remedial grouting, but no grout curtain)	$10,000/Each
	b) Reinforced Concrete Seal including 100 L.F. of grout curtain	$15,000 to $20,000/Each
2.	Hydraulic Seals for Inaccessible Mines	
	a) Grouted Double Bulkhead Seal including 100 L.F. of grout curtain	$21,000/Each
	b) Grouted Single Bulkhead Seal including 100 L.F. of grout curtain	$ 5,000/Each
3.	Limestone Barrier Mine Seal (Permeable Plug)	$ 7,500/Each
4.	Air Seal (Masonry)	$ 5,000/Each
5.	Dry Seal (Clay)	$ 1,500/Each
6.	Dry Seal (Masonry)	$ 3,500/Each
7.	Grout Curtain	$40 to $ 80/L.F.

Stream Diversion $ 20/L.F.

Treatment of Mine Drainage

The design of mine drainage treatment plants is in its infancy. The capital and operating costs of existing treatment plants may not be an indication of future treatment costs because most of the actual cost data developed to date is based on lime neutralization. A great deal of effort has been expended in the last few years by government agencies and industry in developing processes for treatment of mine drainage other than lime neutralization which has several disadvantages including the production of large volumes of sludge and the addition of hardness to the effluent. The mine drainage treatment processes which show promise are: 1) limestone neutralization, 2) combination lime-limestone neutralization, 3) ion exchange, 4) biochemical oxidation followed by limestone neutralization, and 5) reverse osmosis. Several treatment plants are now in operation using the first four processes. A reduction in capital and operating costs should occur as progress is made in design and methods of operation.

It is difficult to recommend capital and operating cost formulas for use in developing overall cost estimates for mine drainage treatment in the Monongahela River Basin. It is necessary to not only predict inflationary trends, but also the effect a technological development or breakthrough would have on costs. Based on the mine drainage treatment data in this report, Gibbs & Hill, Inc. proposed using the following capital cost formula and operating cost in their study for the Appalachian Regional Commission:

Installed Capital Cost $\$ = 350,000\ Q^{0.72}$

Where Q is flow expressed in MGD

Operating Cost 20¢/1,000 gallons treated

The capital cost is developed from U. S. Bureau of Mines cost curves for limestone treatment plants, whereas, operating cost is based on using hydrated lime as a neutralizing agent.

Unit Costs for Mining Related Problems

Extinguishment of Coal Refuse Bank Fires

The following formula based on project costs tabulated in this report, where refuse was sluiced into a lagoon using a water cannon, is being used by Gibbs & Hill, Inc. in their study for the Appalachian Regional Commission:

$\$ = 1.1\ V^{0.7}$ Where V is volume in million cu. yds.

Mine Subsidence Control

Fly Ash Injection Methods	$75,000/Acre
Grouted Aggregate Pier Method	$85,000/Acre

The report contains the results of an extensive study of pollution control project cost data. A thorough search was made of the literature, and it is believed most of the significant recent publications were reviewed. Significant pollution control cost figures in older publications were updated using the Engineering News-Record Cost Index. Comparisons were made of the estimated costs of construction with actual "as built" project costs and factors causing errors have been identified. Meetings were held with many individuals in government and industry and their cooperation in supplying unpublished information used in this study is gratefully acknowledged.

INTRODUCTION

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INTRODUCTION

Purpose and Scope of Report

In 1971, the Environmental Protection Agency reconvened in Pittsburgh, Pennsylvania an interstate water pollution control conference on the Monongahela River Basin[1,2]. The purpose of the conference was to adopt new standards at both the state and federal levels to curb mine drainage pollution, to recommend a mine drainage abatement program and to discuss the results of studies on mine drainage pollution within the basin completed since the first conference was held in 1963[3,4,5].

The conferees, consisting of representatives from the states of West Virginia, Pennsylvania and Maryland, the Ohio River Valley Water Sanitation Commission (ORSANCO) and the Federal Government, recognizing that abandoned mine drainage pollution in the Monongahela River Basin is primarily a regional problem, requested the Appalachian Regional Commission to direct and coordinate with the Environmental Protection Agency and other appropriate agencies the abatement program recommended by the state and interstate conferees[6].

The Appalachian Regional Commission is charged with the task of developing a comprehensive environmental improvement program for the Monongahela River Basin. As part of this responsibility, the Commission must determine as accurately as possible the costs of various remedial programs which it recommends. An effective, workable handbook on pollution control costs and factors effecting these costs is needed to perform this function. The Appalachian Regional Commission engaged Michael Baker, Jr., Inc. to perform the pollution control cost study under ARC Contract No. 72-87/RPC-713 titled "Analysis of Pollution Control Costs."

This report provides data which will enable the Appalachian Regional Commission to estimate costs of abating mine drainage and other environmental problems in the Monongahela River Basin. In order to produce an effective, workable handbook, it is necessary to accumulate and analyze available project cost data on pollution control on a region-wide basis and translate it into a form from which projections for costs of future work can be estimated. For this assignment, Michael Baker, Jr., Inc. was required to perform the following tasks:

1. Collect, become familiar with, analyze and evaluate currently available literature on costs of mine drainage pollution abatement. Existing publications[7,8] on mine drainage pollution control costs were developed using data prior to 1966, but more effective work has been accomplished in this field since 1966 than in all the previous years.

2. At meetings with State, Federal and private individuals or through other analysis gather relevant data and then analyze recent (since 1966) mining area restoration projects in Appalachia to determine the costs of reclamation.

3. Compare the estimated costs of construction with actual "as built" project costs to furnish initial insight into the problem of accurately projecting construction costs.

4. Identify factors causing errors in cost estimates.

5. Using appropriate factors, update pollution control cost figures in the literature prior to 1970 where updating would be reliable and of current usefulness.

6. Prepare a handbook setting forth unit costs for abatement of coal mine drainage pollution and mining related problems. The handbook should include figures for the latest technological developments or processes including those utilized immediately prior to the reporting.

7. Prepare analyses of presently available abatement techniques and determine average unit costs for abatement of pollution from sources other than coal mining. This part of the project merely asked for the best estimates of costs from the best data presently available for the following environmental deterrent categories: a) air pollution, b) solid wastes, c) abandoned automobiles, d) erosion and sedimentation, and e) industrial wastes "orphan" and other environmental problems in the public sector.

Although this publication is concerned mainly with an analysis of pollution control costs applicable for use in developing a comprehensive environmental improvement program for the Monongahela River Basin, the cost estimates and supporting data should prove useful for all of Appalachia and other areas with similar topography, mine drainage pollution problems and mining history. Emphasis was placed on reclamation project cost data from areas within or adjacent to the Monongahela River Basin. But since Pennsylvania, followed by West Virginia, are the leaders in mine drainage pollution abatement, the project cost data from these states would include most of the significant data on mine drainage abatement in the United States. Maryland, Ohio, Kentucky and Tennessee have recently passed stringent mining regulations and have active mine drainage abatement programs, but there is only a limited amount of information available from these states at present.

The unit price cost estimates in this publication are based on the best available information and are suitable for budget estimates and preliminary planning, but are not intended to replace the need for a detailed cost estimate required in producing contract plans and specifications.

Format of Report

The report has been divided into two main categories, "Abatement of Coal Mine Drainage Pollution and Mining Related Problems" and "Abatement of Pollution From Sources Other Than Coal Mining." Each category contains sections dealing with individual environmental problems within that category. For convenience and easy reference, there is a general "Table of Contents" at the beginning of the report and each section has a detailed "Table of Contents" which lists tables and figures found in the section. An "Addendum" was necessary to report on recent publications noted after completion of the appropriate section.

Monongahela River Basin Pollution Studies

The Monongahela River Basin overlies one of the most valuable and extensively developed deposits of bituminous coal in the world. Coal mining, coking and iron and steel manufacturing have made this district world famous[9]. The basin lies entirely in the Appalachian Plateau Province and is characterized by rugged topography with narrow stream valleys. The drainage basin comprises a total of 7,340 square miles of which 57 percent is in West Virginia, 38 percent in Pennsylvania and 5 percent in Maryland. Stream flow in the basin is regulated to some extent by a network of multiple purpose dams and reservoirs in the headwaters. The lower Monongahela River passes through one of the most densely developed industrial areas in the nation.

The mine drainage inventory completed by the Environmental Protection Agency[1,2] documented the belief that the Monongahela River Basin is more intensely polluted by mine drainage than any other major drainage basin in the United States. The total net acid load from all coal mining sites was over one million pounds per day and the iron load more than 300,000 pounds per day. This data did not reflect the additional pollution of other chemicals or sediment which are found in mine drainage as a result of industrial and urban development, timbering, farming and other activities within the basin. Less than 18 percent depletion of the original bituminous coal resources has resulted in this vast mine drainage pollution problem.

If we assume that drainage from combination underground-surface mines originates primarily from underground sites, the inactive underground mines would be responsible for about 55 percent of the net acid load and 54 percent of the iron. Active mining sites (8 percent of the total inventoried) contributed 35 percent of the total net acid load and 40 percent of the iron. Approximately 20 percent of the total sources inventoried contribute 85 percent of the net acid load.

The Environmental Protection Agency[1,2] estimated the total cost for "at source" abatement of mine drainage and water treatment range from $218 million to $656 million for a 20 year period. Garvey[10] believes the high figure is much too low and should be in the neighborhood of two billion dollars.

The damaging environmental effects of mine drainage pollution in the Monongahela River Basin has been a topic of discussion for over 60 years[11, 12]. Since at least the 1920's, mining activity along the Monongahela River has been causing increasing problems for public water works located on the river[13]. The first comprehensive approach to mine drainage control in the drainage basin was initiated in the 1930's by Federal and State governments through relief administration programs such as Works Progress Administration, Federal Emergency Relief Administration and Civil Works Administration[7]. Much of this work consisted of the construction of air seals at abandoned mines. In 1938, Hodge[14] concluded from his studies that air sealing of abandoned mines, diversion of water from mines, and the construction of large flood control dams were the best methods for assuring the maintenance of satisfactory stream conditions for public water supplies, industrial uses and recreational activities. The U. S. Public Health Service[15] came to a similar conclusion in 1942. Their study indicated there was a significant reduction in acid mine drainage as a result of the air sealing program, but chemical neutralization of mine drainage was not economically feasible. Madison[16] in a paper presented before the American Chemical Society in 1950, stressed the significant amounts of organic pollution carried by the Monongahela River and indicated that as effective mine drainage controls are developed, the need for sewage treatment plants will increase.

In the 1960's as a result of pollution studies by the U. S. Public Health Service[3] and others, the Federal Government became increasingly aware that a serious interstate pollution problem was occurring in the Monongahela River Basin. The Secretary of Health, Education and Welfare called an Interstate Water Pollution Control Conference which was held in Pittsburgh, Pennsylvania in December, 1963. The conferees established a Technical Committee to explore the means of abating pollution caused by coal mine drainage. The Committee established a project called the Monongahela River Mine Drainage Remedial Project and set up headquarters in Wheeling, West Virginia in 1964. The Project was charged with making a study to determine sources, types and amounts of pollution from coal mines, and the means and costs for abating such pollution. The actual work of locating, sampling and describing the sources of mine drainage began in 1965 and continued through 1968. Interim reports were published by the Federal Water Pollution Control Administration[17] and Pash[18, 19] between 1968 and 1970. During this period, Ward and Wilmoth[20] of the U. S. Geological Survey made a study of the effects of mine drainage on the groundwater hydrology of the Monongahela River Basin. The final report of the Monongahela River Mine Drainage Remedial Project was made public by the Environmental Protection Agency[1, 2] at the second conference held in Pittsburgh, Pennsylvania in August, 1971. The Advisory Work Group of the Project was responsible for the first handbook on mine drainage pollution control costs[7].

The activities of the Ohio River Valley Water Sanitation Commission[4] since its beginning in 1948 in reducing pollution, especially mine drainage, in the Monongahela River Basin should not be overlooked. This organization was responsible for early interstate cooperation and studies on the fundamental principles of acid mine drainage formation and methods of control[21]. Based on ORSANCO studies, Clark[22] in 1964, analyzed the water quality trends in the Monongahela River Basin during the past 50 years.

The extent of pollution in the Monongahela River Basin is discussed in several studies on mine drainage pollution in Appalachia. Biesecker and George[23] of the U. S. Geological Survey made the first major regional stream quality reconnaissance of Appalachian in 1965 and reported that the severity of mine drainage pollution was substantially greater in the more heavily mined northern third of the Appalachian region which includes the Monongahela River Basin. The Federal Water Pollution Control Administration[24, 27] in their 1967 report, revised 1969, came to a similar conclusion. The Appalachian Regional Commission under the Appalachian Regional Development Act published a series of reports in 1969 on acid mine drainage in Appalachia[8, 25-30].

The Mine Drainage Abstracts prepared by Bituminous Coal Research, Inc.[31] and their Coal Mine Drainage Library has facilitated the study of mine drainage pollution and methods of control in the Monongahela River Basin. The library, established in 1961, is sponsored by the Coal Industry Advisory Committee to ORSANCO. The preparation of the mine drainage abstracts is supported by the Pennsylvania Department of Environmental Resources. References in the text of the report include the code designation used by Bituminous Coal Research, Inc. in their bibliography, ex. (BCR 71-39).

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PART A

ABATEMENT OF COAL MINE DRAINAGE POLLUTION AND MINING RELATED PROBLEMS

STRIP MINE AND REFUSE BANK BACKFILLING AND GRADING

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STRIP MINE AND REFUSE BANK BACKFILLING AND GRADING

Introduction

Since the primary purpose of this section is a cost analysis of strip mine and refuse bank backfilling and grading, a discussion of the extent of coal mining and its impact on the Monongahela River Basin is omitted. The extent of acid mine drainage pollution in the Monongahela River Basin caused by strip mining and refuse banks is discussed in recent publications by the Environmental Protection Agency(1, 2), U. S. Army Corps of Engineers(3)* and Lyon(4).

According to the U. S. Army Corps of Engineers Report(3)*, 1969, the objectives of basic strip mine and refuse bank reclamation are 1) water quality through proper drainage, 2) the covering of toxic materials, and 3) the revegetation of affected areas. This definition does not imply restoration to approximate original contour and is primarily concerned with the control of acid mine drainage and siltation of receiving streams. Udall(5), U.S. Department of Interior(6) and Sullivan(7) suggest the inclusion of restoration of reclaimed lands and water courses to productive uses compatible with adjacent areas and restoration of pre-mining aesthetic values as additional objectives for sound reclamation programs.

Prevention of acid mine drainage by burial of acid producing materials and backfilling is based on the principle that in the absence of oxygen, the oxidation of pyritic material is significantly reduced or prevented (Singer and Stumm(8), NUS Corporation(9), Smith and Shumate(10), Truax-Traer Coal Company(11), Wilson, et al.(12)). Grube, et al.(13) and Caruccio and Parizek(14) conclude that reduced acid mine drainage formation can be obtained by segregating acid producing materials from spoil overburden and burying these materials with clay or other impervious materials at the base of a backfill. Proper backfilling and grading of spoil material not only decreases the volume of water flow through acid producing areas, but also reduces contact time as implied by Hill(15).

The two major types of strip mine backfilling procedures in current use in the Monongahela River Basin and surrounding areas are contour and terrace methods. Several modifications of these two methods are employed to meet the requirements of particular geographic and topographic conditions and type of mining operation. A description of other backfilling methods is presented in Krause(16).

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*This report was prepared by the U. S. Army Corps of Engineers for the Appalachian Regional Commission. The majority of the report consists of material previously published by FWPCA and the U. S. Bureau of Mines in 1967-68. The FWPCA publication was revised for this report.

Contour backfilling consists of moving spoil material back into the pits and grading to approximately the original contour with an absence of possible water collection depressions (Figure 1). This type of backfill is generally restricted to slopes of 10° to 15° or less because of problems resulting in increased erosion and subsequent siltation of receiving waters as pointed out by Cyrus Wm. Rice and Company[17]. Contour backfilling has been recommended on the majority of Pennsylvania reclamation projects but is of limited use on most reclamation projects in West Virginia because of slope limitations in the West Virginia part of the Monongahela River Basin.

Terrace backfills involve the grading of spoil to form a "modified bench" gently sloping either toward or from the highwall area. Sufficient grading is required to insure adequate burial of acid producing substances and usually includes outslope and highwall slope limitations. Highly fractured highwalls should be "topped" to avoid possible safety and drainage interference problems (Hill[18]). Particular attention should be given to proper backfilling techniques on the "outslope" areas to reduce the possibility of landslides.

There are several variations of terrace backfills of which pasture backfill (Figure 2), reverse terrace backfill (Figure 3) and swallow-tail backfill (Figure 4) are the most common. These variations are primarily designed to divert or reduce the volume of surface and ground water flow through potential acid producing areas in the backfilled spoil (Bullard[19]).

The backfilling and grading of deep mine refuse piles usually requires some type of physical sealing to reduce the volume of acid mine drainage. The most commonly used sealants are soil and clay, but bituminous products and possibly plastics could be used if economically feasible. Adequate precautions should be taken to avoid possible degradation of borrow areas.

Grading of refuse is performed in such a manner as to limit erosion and the formation of water collection depressions (Figure 5). Compaction of refuse may be necessary to reduce percolation of water through the acid producing materials. In some areas, slope characteristics will necessitate removal of refuse as the only feasible method of reclamation. Removal of refuse banks is probably most feasible when performed in conjunction with adjacent strip mine reclamation projects. The refuse can be placed in the bottom of strip pits prior to backfilling.

Cost Analysis

The cost data presentation is limited to an analysis of the costs for recent abandoned strip mine and refuse bank reclamation projects in the Monongahela River Basin and surrounding areas. Although this limitation significantly reduces the amount of available data that can be used, it does minimize the errors that can be introduced by variables in geographic location, the differences in topography, on site physical

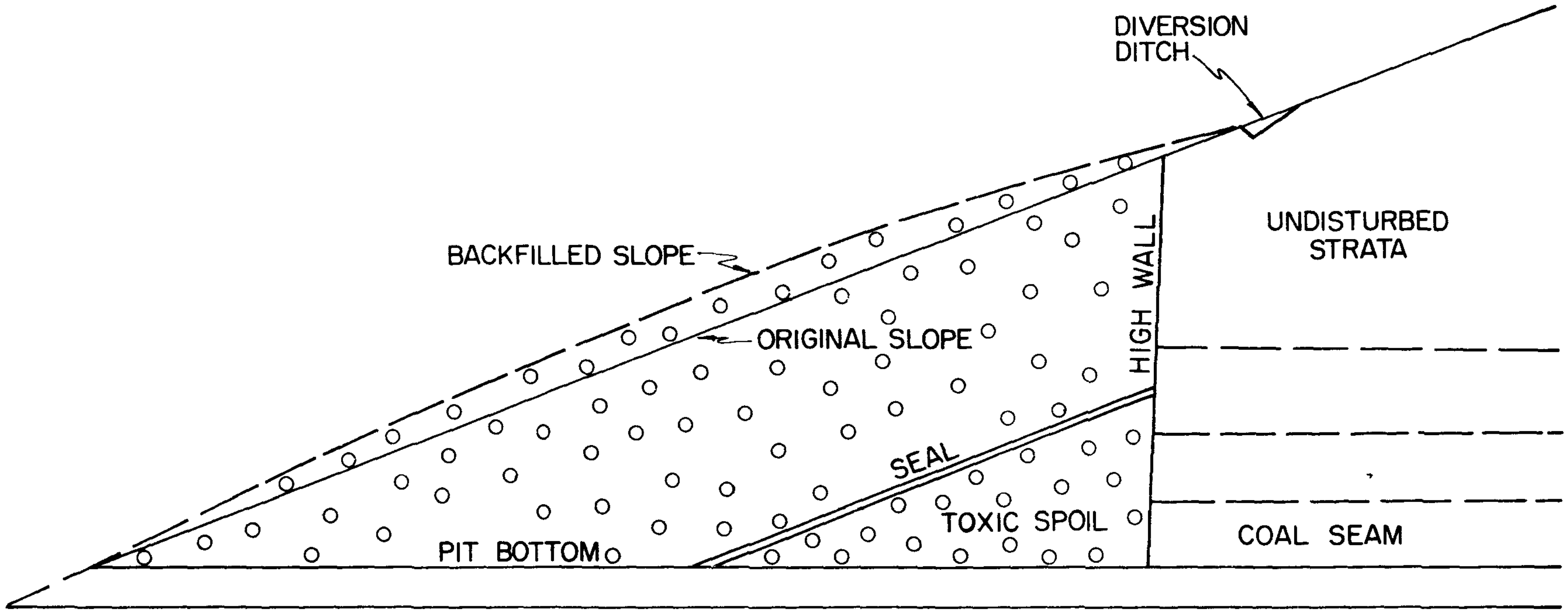

FIGURE I

CONTOUR BACKFILL

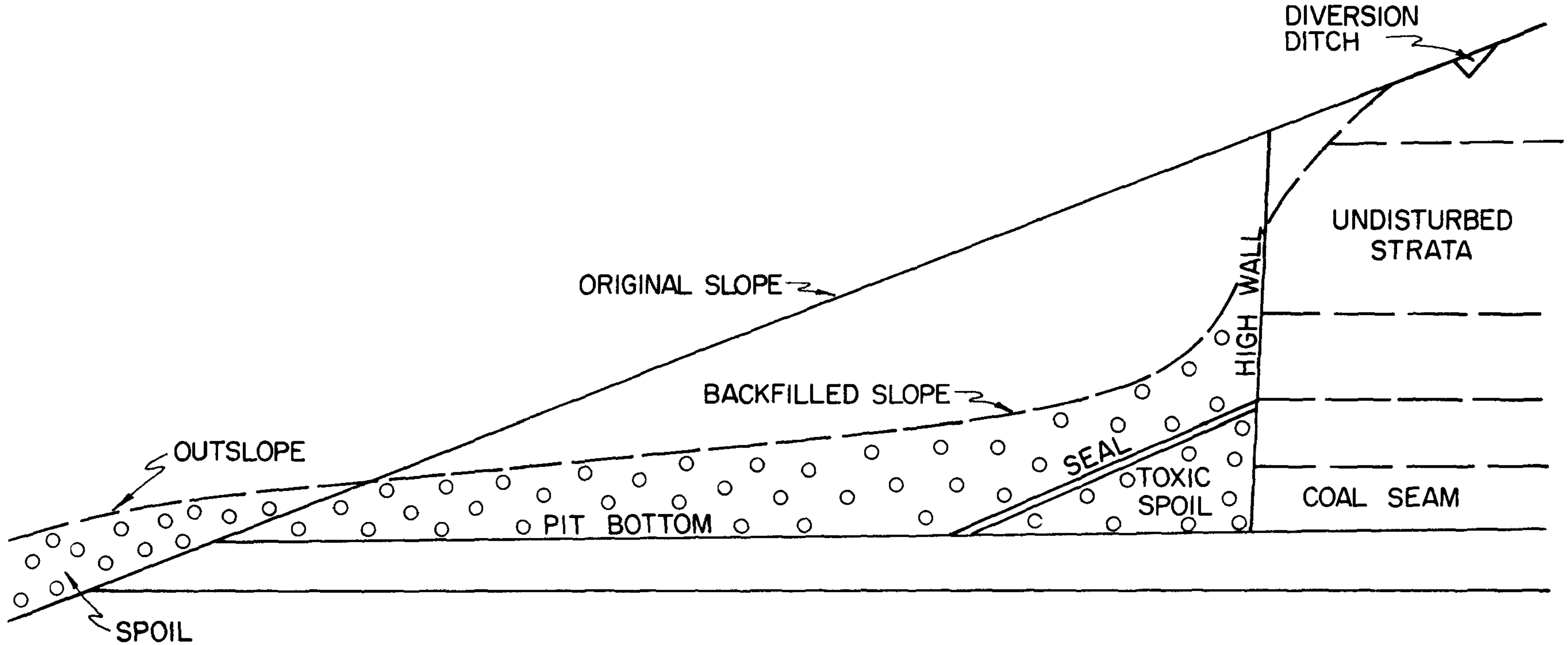

FIGURE 2

PASTURE BACKFILL

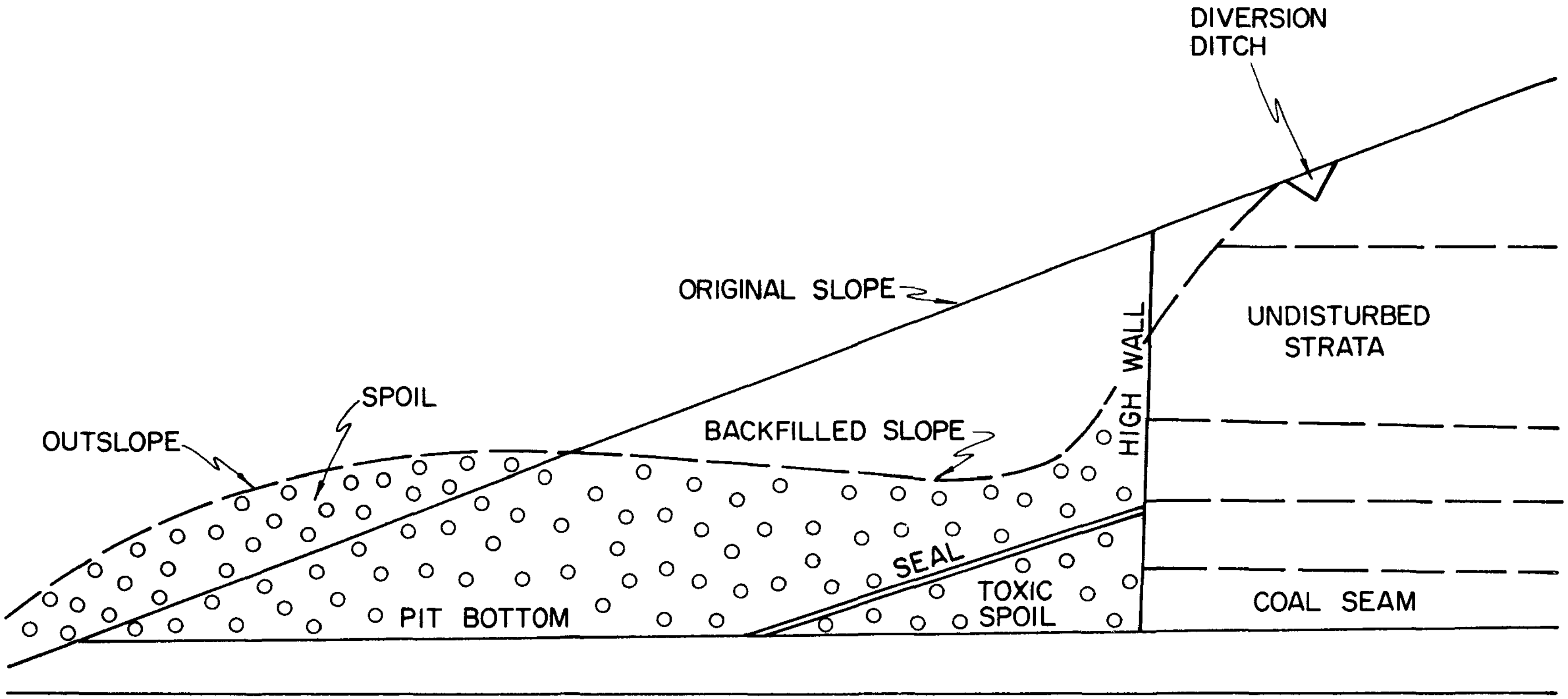

FIGURE 3

REVERSE TERRACE BACKFILL

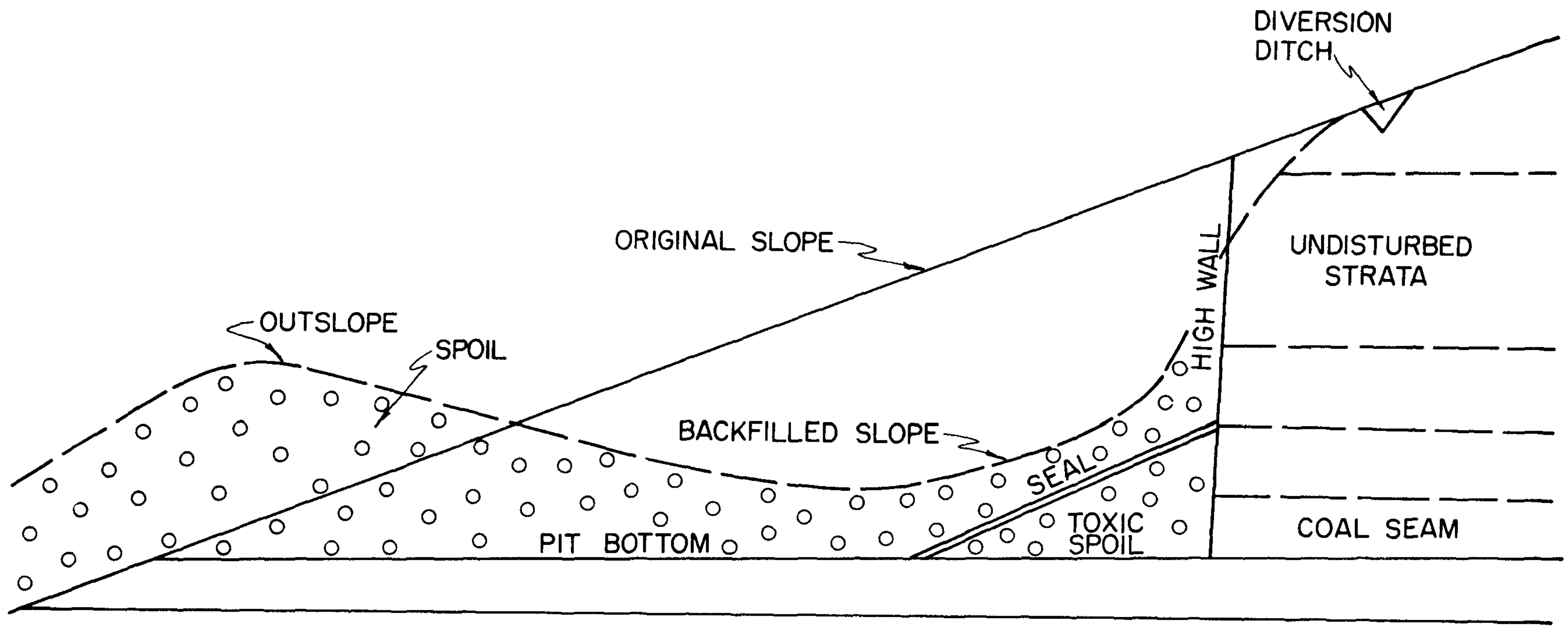

FIGURE 4

SWALLOW-TAIL BACKFILL

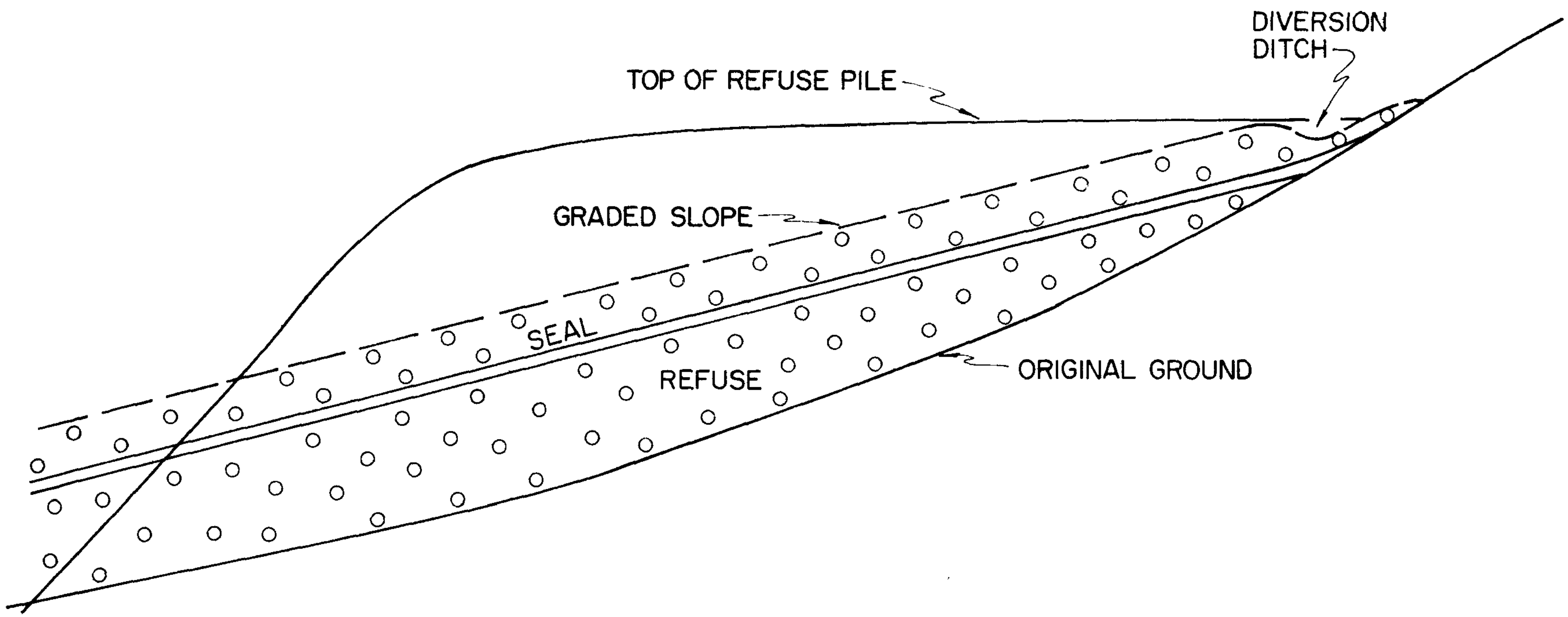

FIGURE 5

REFUSE PILE — GRADING AND CONTOURING

and chemical characteristics, methods of mining, and the inequalities in bond forfeiture reclamation projects from one area to another. To better facilitate cost estimation, cost analyses have been divided into several major categories. Since some projects, depending on physical and chemical conditions present, will not require all aspects of the reclamation program, it will be possible to delete those parts not applicable. Administrative, engineering and post-reclamation evaluation costs as well as cost of mine seals, water diversion, spoil neutralization and revegetation have been omitted from this section. It will, therefore, be necessary to review other sections of the report to arrive at the total strip mine or refuse pile reclamation cost estimate.

It is recommended that a uniform method of reporting data be developed and adopted by state and federal agencies involved in reclamation programs. This not only would make future reclamation cost estimates more meaningful, but would also increase the efficiency of data retrieval and enhance the possibility of computerization of data. The variables that should be considered in reporting strip mine and refuse bank reclamation project data are presented in Tables 1 and 2. These variables should also be considered in the planning stage in order to obtain a more meaningful estimate of reclamation costs.

Access Roads - Very little information exists on access road construction costs for strip mine and refuse bank reclamation. In most instances, this cost has been included in the backfilling and grading costs. From the limited information available, it appears the construction costs for access roads including clearing and grubbing, ranges from $2.50 to $3.00 a lineal foot. An increase in the cost of construction can be expected if culverts or other drainage structures are needed.

Clearing and Grubbing - The costs of clearing and grubbing range from $33.54 to $700.00 per acre with a mean of $218.77 per acre. Forty three recent reclamation projects were reviewed and only seven included sufficient data to permit an estimation of clearing and grubbing costs. A summary of this data is presented in Table 3. The costs reported by McNay[20] for clearing and grubbing at Moraine State Park, Pennsylvania are based on work time and the average operating cost of a D-7 Dozer and do not represent actual recorded values.

The higher costs per acre for clearing and grubbing can be attributed to density of growth and a requirement on some projects to cut pulpwood for the landowner (Scott, et al.[21]); slope of terrain and weather conditions (McNay[20]); the amount of partially buried timber encountered (Griffith, et al.[22]); and the amount of scrap and solid waste present (Jones[23]). The overall reclamation cost may be reduced if brush and trees are chipped and used as mulch instead of burying and burning.

TABLE 1

STRIP MINE RECLAMATION PROJECTS
VARIABLES AFFECTING BACKFILLING AND GRADING COSTS

1. Geographic location

2. Topographic setting (Original, pre-reclamation and final ground slopes)

3. Type of strip mine

   a) Area b) Contour c) Area-contour d) Other

4. Coal seams mined and thickness

5. Inclination of coal seams in back of highwall

   a) Dip b) Rise C) Horizontal

6. Condition of coal seams in back of highwall

   a) Not mined b) Auger mined c) Drift mined (Entries opened or caved)
   d) Mine workings exposed by stripping operation

7. The probable hydraulic head that could develop if coal in back of highwall was mined

8. Strip mine area information

   A. Length, width and area (acres) covered by spoil before reclamation
   B. Highwall height (maximum and average height)
   C. Highwall length
   D. Number of cuts
   E. Total area affected during reclamation in acres (including area above highwall and outside outslopes)
   F. Volume of spoil to be moved (cubic yards)
   G. Average haul distance for backfilling and grading
   H. Texture of spoil
   I. Amount of large rock and material requiring special handling (mining timbers, machinery and debris, junked cars, and other solid waste)
   J. Amount and reactivity of pyritic material (mineralogy and mode of occurrence, e.g., finely dispersed; single crystals or crystal aggregates; coatings on joint surfaces; in form of lenses, layers or nodules; "sulfur balls"; pyritic shales; etc.)
   K. Clearing and grubbing requirements

9. Type of backfill
   a) Contour b) Pasture-reverse slope c) Swallowtail
   d) Head of hollow e) Submergence f) Other

10. Physical sealants for covering toxic material
    a) None b) Clay c) Bituminous material c) Plastic material
    e) Other

11. Compaction desired
    a) None b) Only toxic materials c) All spoil material with exception of upper layer (1 to 3 feet)

TABLE 1 (continued)

12. Accessibility factors

    A. Right-of-way problems
    B. Ingress and egress construction (include clearing and grubbing for access and post-construction revegetation)
    C. Other factors affecting access

13. Surface and subsurface ownership of strip mined area. Also ownership of properties for ingress and egress.
    a) Public b) Private c) In process of being acquired or lien placed on property d) Abandoned e) Temporary easement f) Other

14. Time of year reclamation performed

15. Weather conditions during reclamation period(s)

16. General contractor and subcontractors

17. Types of construction equipment used and equipment records if available

18. Source of project funding

19. Productive use to be made of reclaimed land

20. General observations and recommendations

    A. Difficulties in writing an effective bid proposal
    B. Contractual problems during construction
    C. Unanticipated problems requiring change orders
    D. Recommendations and possible solutions that could in future projects avoid the difficulties encountered in A, B and C

21. Evaluation of the overall success or failure of the project (one, two and five years later)

    A. Percent of pollution reduction (acid mine drainage and siltation)
    B. Cost per pound of acid reduction
    C. Effectiveness of soil treatment if any
    D. Growth and survival of vegetation
    E. Aesthetic evaluation

TABLE 2

COAL REFUSE BANK RECLAMATION PROJECTS
VARIABLES AFFECTING GRADING AND REMOVAL COSTS

1. Geographic location

2. Topographic setting (Original, pre-reclamation and final ground slopes)

3. Coal refuse bank area information

   A. Length, width and area (acres) before reclamation
   B. Height of refuse bank (maximum and average height)
   C. Total area to be affected during reclamation in acres (including areas outside perimeter of refuse bank and burial sites)
   D. Volume of refuse to be graded or removed (cubic yards)
   E. Average haul distance for grading
   F. Average haul distance to burial site(s)
   G. Texture of refuse
   H. Amount of large rock and material requiring special handling (mining timbers, machinery and debris, junked cars, and other solid waste) See Item 8.C
   I. Amount and reactivity of pyritic material (mineralogy and mode of occurrence, e.g., finely dispersed; single crystals of crystal aggregates; coatings on joint surfaces; in form of lenses, layers or nodules; "sulfur balls"; pyritic shales; etc.)
   J. Clearing and grubbing requirements

4. Method of refuse bank construction

   a) Tippler form   b) Layer piling   c) Layer piling with clay   d) Other

5. Coal seam that was deep mined and its characteristics

6. Type of roof and bottom rock in the deep mine

7. History of refuse bank

   A. Years during which refuse bank was being constructed and last year of placement of refuse on bank (Mining methods have changed over the years and the composition of banks are variable depending on mining method, coal seam mined, type of roof and bottom rock, and age of bank)
   B. Has refuse bank ever been on fire or is part of refuse bank burning now?
   C. Has refuse bank been cleaned for waste coal?

8. If refuse bank is burning

   A. Volume of burning refuse (cubic yards)
   B. Special procedures or methods of handling burning refuse
   C. Number and size of large lumps of fused ash requiring special handling

9. Reclaimable resources that can offset cost of reclamation

   a) Coal   b) Red dog   c) Other

10. Type of reclamation

   a) Grading   b) Grading and sealing   c) Other

TABLE 2 (continued)

11. Physical sealants for covering toxic material

    a) None b) Clay c) Bituminous material d) Plastic material e) Other

12. If clay is used as a sealant

    A. Size of borrow area and volume of material needed for sealing (cubic yards)
    B. Location, accessibility, and distance from borrow area to refuse bank
    C. Clearing and grubbing requirements at borrow area
    D. Revegetation requirements at borrow area

13. Compaction desired

    a) None b) All of refuse material with exception of upper layer (1 to 3 feet) c) All of the refuse material and all but upper layer of clay covering (1 to 3 feet d) Other

14. Accessibility factors

    A. Right-of-way problems
    B. Ingress and egress construction (include clearing and grubbing for access and post-construction revegetation)
    C. Other factors affecting access

15. Ownership of refuse bank and surface area. Also ownership of properties for ingress, egress and borrow areas.

    a) Public b) Private c) In process of being acquired or lien placed on property d) Abandoned e) Temporary easement f) Other

16. Time of year reclamation performed

17. Weather conditions during reclamation period(s)

18. General contractor and subcontractors

19. Types of construction equipment used and equipment records if available

20. Source of project funding

21. Productive use to be made of reclaimed land

22. General observations and recommendations

    A. Difficulties in writing an effective bid proposal
    B. Contractual problems during construction
    C. Unanticipated problems requiring change orders
    D. Recommendations and possible solutions that could in future projects avoid the difficulties encountered in A, B and C.

23. Evaluation of the overall success or failure of the project (one, two and five years later)

    A. Percent of pollution reduction (acid mine drainage and siltation)
    B. Cost per pound of acid reduction
    C. Effectiveness of soil treatment if any
    D. Growth and survival of vegetation
    E. Aesthetic evaluation

TABLE 3

CLEARING AND GRUBBING COST ANALYSIS

Project Location	Project Number	Year Completed	Total Cost	Acreage	Cost/Acre
Moraine State Park (N.C. Area) Butler County, Pennsylvania	ASMR 1	1968	$ 1,921.85	57.3	$ 33.54[1]
Moraine State Park (N.W. Area) Butler County, Pennsylvania	ASMR 1	1968	19,402.24	424.0	45.76[1]
Rausch Creek Schuylkill County, Pennsylvania	SL 112-4	1971	8,550.00	19.0	450.00
North Strabane Township Washington County, Pennsylvania	SL 102-4	1971	3,000.00	16.0	187.50
Two Lick Creek Indiana County, Pennsylvania	SL 109-1B	1970	8,400.00	14.0	600.00
Two Lick Creek Indiana County, Pennsylvania	SL 109-1C	1971	3,850.00	5.5	700.00
Roaring Creek-Grassy Run Watershed Randolph County, Pennsylvania	SDP 1	1968	214,509.00[2]	651	329.51[2]
Summary			$259,633.09	1186.8	$218.77

(1) McNay, 1970[20]

(2) Scott, Hill and Wilmoth, 1970[21]

Strip Mine Backfilling and Grading - The strip mine backfilling and grading costs used in preparing the cost analysis are presented in Table 4. For all methods of backfilling and grading, the costs per acre range from \$211.57 to \$2,007.00 and the mean cost is \$859.78 per acre.

The cost of contour-type backfilling and grading ranged from \$472.00 to \$1,520.00 per acre and the mean is \$922.66. Table 4 indicates that terrace-type reclamation methods, which include the pasture reverse slope and swallowtail methods, are about 43 percent lower in cost per acre compared to the contour-type. The average cost for terrace-type backfilling and grading is \$525.98 per acre and costs range from \$211.57 to \$918.00 per acre. Combination contour-terrace reclamation methods ranged from \$472.00 to \$2,007.00 per acre and the mean is \$1,263.84.

A review of the projects show there is no relationship between the number of acres reclaimed and the backfilling and grading costs per acre for any of the reclamation methods. A definite relationship does exist for the contour-type reclamation method between the volume of spoil per unit area and the cost per unit volume of backfilling and grading (Figure 6).

The mathematical expression for this relationship is

$$y = 760.2\, x^{-1.82760}$$

or

$$\log y = -1.82760 \log x + 2.88094$$

where y is the cost per unit volume (cents/cubic yard) and x is the total volume of spoil to be moved per unit area (cubic yards/acre).

Because of the lack of data on volume for the majority of terrace-type reclamation projects that were reviewed, the relationship between cost per unit volume and total volume of spoil per unit area to be moved can only be inferred. If it is assumed that differences in cost per cubic yard are proportioned to differences in cost per acre when comparing costs of contour and terrace-type reclamation methods, it would be possible to use the same relationship developed for the contour reclamation method by reducing total cost by an appropriate cost differential factor. Using the cost per unit area data presented in Table 4, it appears the cost of the terrace-type reclamation method is about 57 percent of the contour-type. This value compares favorably with figures presented by Cyrus Wm. Rice and Company[17] in their 1969 report to the Appalachian Regional Commission in which cost estimates for terrace reclamation methods were 53 percent of the contour-type.

Using the 57 percent differential as a reducing factor, the following inferred mathematical expression for terrace-type backfilling and grading costs is possible.

FIGURE 6

STRIP MINE BACKFILLING AND GRADING COST ANALYSIS

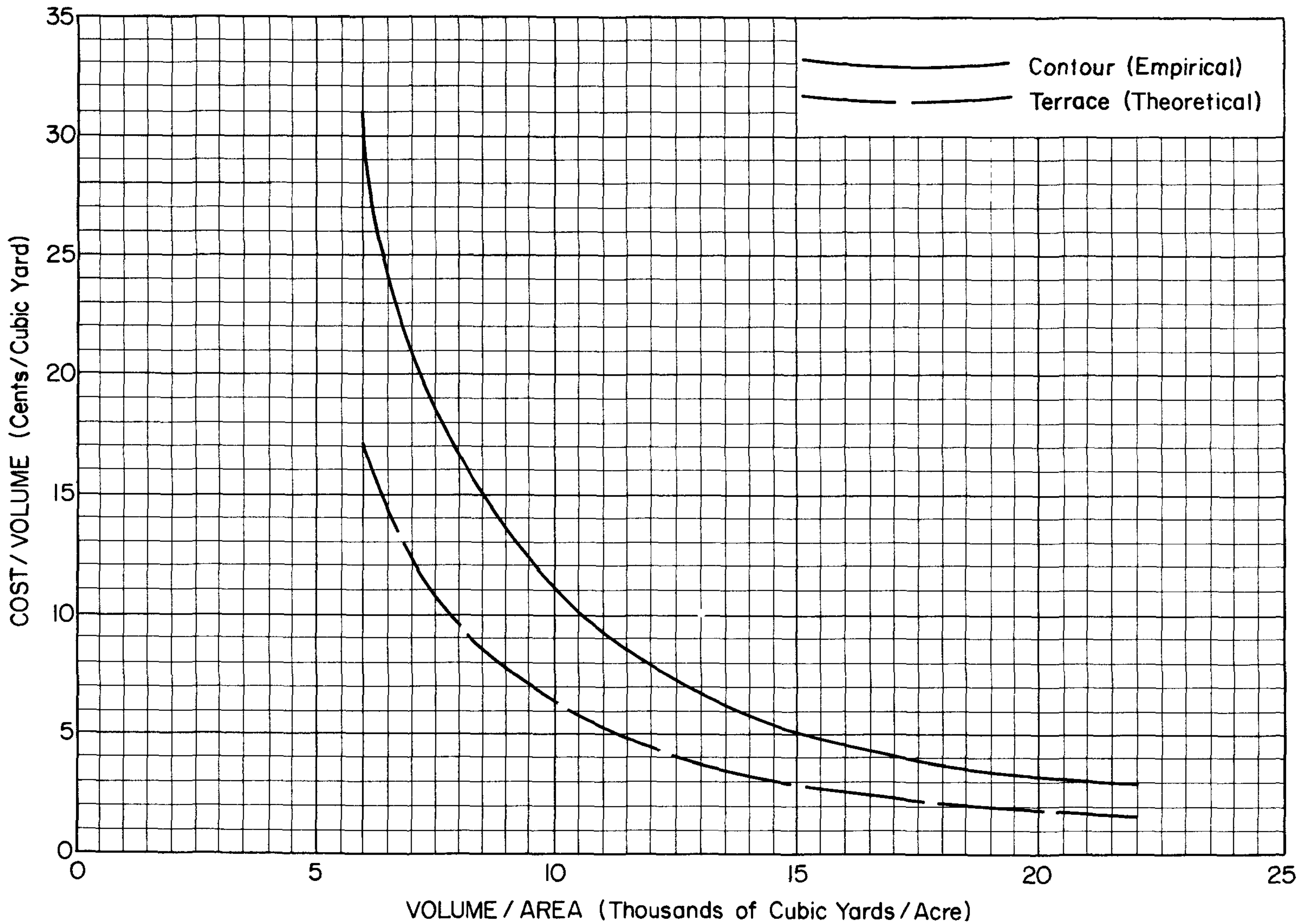

TABLE 4

STRIP-MINE BACKFILLING AND GRADING COST ANALYSIS

Project Location	Project No.	Year Comp.	Backfill Area (Acres) Approximate Original Contour	Backfill Area (Acres) Terrace	Volume (C.Y.)	Volume/Area (C.Y./A.)	Total Cost	Cost per Acre	Cost per Cubic Yard
Butler Co., Pa.	ASMR 1	1967	177.5	---	1,383,500	7,794.4	$219,118.00	$1,234.46	$0.158
Allegheny Co., Pa.	ASMR 4	1969	24.6	---	296,300	12,044.7	13,234.80	538.00	0.045
Butler Co., Pa.	SL 105-1 N.W.	1967	26.2	19.6	295,100	6,443.2	91,920.60	2,007.00	0.312
Butler Co., Pa.	SL 105-1 S.W.	1969	21.7	38.4	484,100	8,054.9	90,150.00	1,500.00	0.186
Butler Co., Pa.	SL 105-1 E	1969	4.8	99.8	732,000	6,998.1	104,600.00	1,000.00	0.143
Butler Co., Pa.	SL 105-1A	1969	---	8.7	61,000	7,011.5	7,992.00	918.62	0.131
Butler Co., Pa.	SL 105-1B	1970	15.6	2.4	NA	NA	27,000.00	1,500.00	NA
Blair Co., Pa.	SL 153	1970	112.0	---	733,000	6,544.6	170,240.00	1,520.00	0.232
Fayette Co., Pa.	SL 141-1	1970	56.3	---	518,000	9,200.7	56,300.00	1,000.00	0.109
Butler Co., Pa.	SL 110-2A	IP	78.2	---	1,742,000	22,276.2	54,740.00	700.00	0.0314
Tucker Co., W. Va.	4609 & 4136	1971	---	120.0	NA	NA	72,000.00	600.00[1]	NA
Taylor Co., W. Va.	TA-9-71	1971	---	14.5[1]	NA	NA	8,207.00	566.00[1]	NA
Grant Co., W. Va.	S 5714		---	218.3[1]	NA	NA	139,999.75	641.23[1]	NA
Grant Co., W. Va.	1,2,3,4-GR-69 1,2,3-GR-70	1970	---	43.0[1]	NA	NA	11,879.61	276.27[1]	NA

TABLE 4 (continued)

STRIP-MINE BACKFILLING AND GRADING COST ANALYSIS

Project Location	Project No.	Year Comp.	Backfill Area: Approximate Original Contour	Backfill Area: (Acres) Terrace	Volume (C.Y.)	Volume/Area (C.Y./Ac.)	Total Cost	Cost per Acre	Cost per Cubic Yard
Kanawha Co., W.Va.	K-1,2,3,4-71	1971	---	36.0[1]	NA	NA	$ 8,111.88	$ 225.33[1]	NA
Boone Co., W.Va.	4443 4572	IP	---	8.0[1]	NA	NA	3,500.00	437.50[1]	NA
Kanawha Co., W.Va.	K-10,11,12-71	1971	---	8.0[1]	NA	NA	1,888.00	236.00[1]	NA
Logan Co., W.Va.	SRP-1,2,3	1971	---	60.5[1]	NA	NA	12,799.99	211.57[1]	NA
Randolph Co., W.Va.	SDP 1	1968	---	112.5[2]	NA	NA	64,726.00	575.34	NA
Randolph Co., W.Va.	SDP 1	1968	221.3[2]	---	NA	NA	104,453.60	472.00	NA
Randolph Co., W.Va.	SDP 1	1968	---	187.3[2]	NA	NA	211,836.30	1,131.00[2]	NA

NA - Not Available
IP - In Progress

(1) Compiled by Grim, Elmore C., Surface Mining Specialist. EPA, National Environmental Research Center, Cincinnati, Ohio, 1972[24]
(2) Scott, Hill, and Wilmoth, 1970[21]

SUMMARY

Type of Backfill	Total Area (Ac.)	Total Cost	Cost per Acre: Range	Cost per Acre: Mean
Contour	669.9	$618,086.40	$472.00 - $1,520.00	$ 922.66
Terrace	629.5	$331,104.23	$211.57 - $ 918.00	$ 525.98
Contour-Terrace	415.8	$525,506.90	$472.00 - $2,007.00	$1,263.84

$$y = 433.3\, x^{-1.82760}$$

or

$$\log y = -1.82760 \log x + 2.63679$$

Again, y is the cost per unit volume (cents/cubic yard) and x is the total volume of spoil to be moved per unit area (cubic yards/acre). Because of the limited data used in formulating this expression, it should only be used for a rough approximation of terrace-type backfilling and grading costs.

The amount of spoil that has to be moved during reclamation is the principal factor in the differences in backfilling and grading costs per unit area. In the cost analysis made by Cyrus Wm. Rice and Co.[17], it was estimated that the contour reclamation method required movement of 75 percent of the total spoil present while the terrace-type method required movement of only 25 to 40 percent of the total spoil. Other factors responsible for greater costs for the contour method are the increased amount of buried timbers encountered (Griffith, et al.[22]) and a longer average haul distance (Oldham[25]).

Increased overall backfilling and grading costs as compared to pre-reclamation estimates can be attributed to several factors. McNay[20] reports that costs were greater because of frozen ground conditions, the number of sandstone slabs larger than one cubic yard, and the spoil texture. Scott, et al.[21] lists separation of toxic materials, adverse weather conditions, and highwall "topping" as the factors which increased backfilling and grading costs.

A possible cost offset which may be employed during certain strip mine reclamation operations, where the highwall area has been mined, is recovery of coal. Proponents of this method of cost offset usually concur that it is generally restricted to areas of shallow mine cover where there has been limited underground mining because of the expense of separating coal from collapsed mine workings. However, it is the contention of some individuals that even though this procedure may be inefficient from the standpoint of coal recovered vs. cost of recovery, it may be economical when considering savings on mine seals and mine drainage treatment costs. An individual site would have to be studied before a conclusion could be made as to whether this method would result in an overall cost reduction.

Refuse Bank Contouring and Grading - The majority of refuse bank reclamation projects have been performed in conjuction with strip mine and subsidence area backfilling operations. Because of the ambiguity and incompleteness of records for many of the refuse bank reclamation projects, only those projects permitting a somewhat reliable cost analysis of contouring and grading costs are summarized in Table 5. It must be emphasized that these costs only reflect the cost of contouring and grading of refuse and do not include the cost of access road construction, clearing and grubbing, sealants, water diversion and revegetation.

TABLE 5

REFUSE PILE CONTOURING AND GRADING COST ANALYSIS

Project Location	Project Number	Year Completed	Area (A)	Volume (CY)	Total Cost (Dollars)	Cost/Area (Dollars/A)	Cost/Volume (Dollars/CY)
Washington Co., Pa.	SL 102-4	1971	30.0[1]	NA[2]	3,000.00[1]	100.00	NA[2]
Indiana Co., Pa.	SL 109-1B	1970	26.0[1]	NA[2]	40,800.00[1]	1,569.23	NA[2]
Indiana Co., Pa.	SL 109-1C	1971	10.0[1]	40,000	30,000.00[1]	3,000.00	0.750
Indiana Co., Pa.	SL 109-2	1970	3.5[1]	1,500[1]	500.00[1]	142.84	0.333
Centre Co., Pa.	SL 111-1	1971	5.5[1]	4,000[1]	4,000.00[1]	727.27	1.000
Westmoreland Co., Pa.	SL 122-1	1971	7.0[1]	NA[2]	4,400.00[1]	628.57	NA[2]
Summary			82.0		82,700.00	1,008.54	0.758

(1) Compiled by Molinski, 1972[26]
(2) NA - Information Not Available

Based on Table 5, the cost of contouring and grading ranged from \$100.00 to \$3,000.00 per acre and the mean is \$1,008.54. The cubic yard cost ranges from \$0.333 to \$1.00 and the average cost is \$0.758 cubic yard. Only one of the projects reviewed, SL 109-1C in Indiana County, Pennsylvania, involved the removal and deposition of refuse. During one phase of the project, 47,500 cubic yards were removed at any average cost of \$0.944 cubic yard. This cost per cubic yard is approximately three times the average cost reported by Danielson and White[27] for refuse disposal at two active coal mines in Kentucky and Alabama. The difference in cost probably can be attributed to haul distances, use of on-site equipment and the advantage of removal at an active site.

Future reclamation projects involving removal of refuse could be combined with refuse utilization where economically feasible. Refuse material has been crushed for secondary coal recovery, for base materials for roadways and parking areas, and for production of anti-skid material and cement (Greenlee and Spicer[28]). Production of brick (Environmental Science and Technology[29]), carbonate bonding of refuse for roadway use and as a sealant, and sulfur recovery (Black, Sivalls and Bryson, Inc.[30, 31]) have been demonstrated and may possibly be economical uses for coal mine refuse.

Strip Mine and Refuse Bank Sealants - The cost of borrow and spreading of sealants over toxic material during strip mine and refuse bank reclamation ranged from \$0.26 to \$2.00 per cubic yard and the mean was \$0.406 based on the data presented in Table 6. All but one of the projects reviewed employed soil as a sealant. The soil material was used to cover the toxic material to reduce infiltration of water and to promote revegetation. The soil was approved run of the bank material and can be loosely classified as "topsoil." The high cost of \$2.00 per cubic yard on Project SL 111-1 can be attributed to an unbalanced bid and it should be noted only a total of 5,000 cubic yards was needed for the project. The only project that employed a sealant classified as clay had a cost of \$1.75 per cubic yard. There does not appear to be a relationship between cost of sealant and borrow area distance for the projects reviewed, but haul distances were less than one mile.

Little data exists for sealants other than "clay" and soil. The MSA Research Corp.[32] in 1971 conducted studies on several possible sealants for sealing toxic material in strip mines and refuse banks. The sealants included polyethylene sheeting, urethane foam, linseed oil, polyvinyl chloride cacooning and fly ash. Only polyethylene sheeting and urethane foam were effective in reducing water percolation. The cost of polyethylene sheeting was estimated at \$4,356.00 per acre and urethane foam at \$10,018.00 per acre. The life expectancy of the sheeting is three to five years according to Kamal[33]. The costs do not include contouring and grading. It is highly improbable that these sealants can be economically applied in reclamation projects at the present time.

Summary - The cost estimates were made using data from recent abandoned strip mine and refuse bank reclamation projects in the Monongahela River Basin and surrounding area. Table 7 is a summary of the cost estimates.

TABLE 6

STRIP MINE AND REFUSE BANK SEALANT COST ANALYSIS

Project Location	Project Number	Year Completed	Clay (CY)	Soil (CY)	Total Cost (Dollars)	Unit Cost (Dollars/CY)	Borrow Area Distance
Fayette Co., Pa.	SL 301	1970	1,000		1,750	1.750	NA
Centre Co., Pa.	SL 111-1	1970		5,000	1,000	2.000	0.5
Westmoreland Co., Pa.	SL 122-1	1970		10,400	4,160	0.400	0.2
Indiana Co., Pa.	SL 109-1B	1970		154,000	40,040	0.260	0.5
Indiana Co., Pa.	SL 109-1C	1971		38,000	36,300	0.955	0.5 - 0.75
Washington Co., Pa.	SL 102-4	1971		96,800	32,912	0.340	0.5
Indiana Co., Pa.	SL 109-2	1970		18,200	16,400	0.901	NA
Cost for Clay			1,000		1,750	1.75	
Mean Cost for Soil				322,400	130,812	0.406	

Compiled by Molinski, 1972[26]

NA - Not Available

TABLE 7

SUMMARY OF COST ESTIMATES
STRIP MINE AND REFUSE BANK RECLAMATION

		Cost (Dollars/Unit)	
	Unit	Range	Mean
1. Access Roads	L.F.	2.50-3.00	(1)
2. Clearing and Grubbing	Acre	33.54-700.00	218.77
3. Strip Mine Backfilling and Grading			
a) Contour Reclamation Method	Acre	472.00-1520.00	922.66
	CY	$y = 760.2x^{-1.82760}$	(2)
b) Terrace-Type Reclamation Method	Acre	211.57-918.00	525.99
	CY	$y = 433.3x^{-1.82760}$	(2)
4. Refuse Bank Contouring and Grading	Acre	100.00-3000.00	1,008.54
	CY	0.333-1.00	0.758
5. Refuse Bank Excavation and Removal	CY	0.944	(1)
6. Sealants			
a) Soil	CY	0.26-2.00	0.406
b) Clay	CY	1.75	(1)

(1) Limited data available.

(2) Where y is cost per unit volume (cents/cubic yard) and x is volume per unit area (cubic yards/acre). See Figure 6.

Based on analysis of strip mine backfilling and grading costs for projects in both Pennsylvania and West Virginia, it appears updated (1972) costs would be about:

Contour type	$1,000/acre
Terrace type	600/acre

An analysis using only Pennsylvania projects, which included contour and combination contour-terrace methods, indicates the average cost per acre is a little over $1,200. The strip mine backfilling and grading costs were much lower for West Virginia projects, but no information was available for any of the West Virginia projects on volume of material moved per acre and cost/cubic yard.

Since Federal and State reclamation requirements are becoming more stringent, and since West Virginia reclamation requirements prior to passage of new surface mining reclamation regulations in 1971 were not as strict as Pennsylvania's, a cost of $1,250/acre is estimated for strip mine backfilling and grading in the Monongahela River Basin.

This cost estimate of $1,250/acre is for backfilling and grading old abandoned operations in which the spoil material is mixed. Although it is difficult to separate actual stripping costs from reclamation costs for active operations meeting State and proposed Federal reclamation regulations, it is the opinion of individuals in the coal mining industry that complete reclamation including revegetation cost can be accomplished for $200 to $300/acre above actual stripping cost, if the work is performed at the time of stripping. Accomplishing this work at such a low cost requires pre-planning and proper development of the strip mine operation. The acidic materials must be separated and buried during stripping, the backfilling performed as stripping progresses and the top soil stockpiled for later covering of the completed operation, all this work being performed with on-site equipment used in the stripping operation.

This estimated cost for active operations conducted in accordance with the above methods and procedures does not imply that bond forfeiture requirements are adequate or inadequate. A poorly planned stripping operation in which the operator goes bankrupt or forfeits his bond can conceivably cost as much to reclaim as an old abandoned strip mine.

There is very little reliable information available on the cost of refuse bank contouring and grading. Therefore, based on limited information and discussions with individuals familiar with this work, a cost of $1,000/acre is estimated. This cost estimate would not include a soil cover. Covering the graded refuse with soil should cost about $2,500/acre ($0.50/cubic yard).

Refuse bank removal and burial is another item on which there is very little reliable information, probably because much of this work to date has been performed in conjunction with strip mine reclamation and costs are not separated. Major factors effecting a cost estimate for this work are haul distance, volume of material to be moved, volume of large rock and material requiring special handling, and compaction requirements at burial site (see Table 2 for other factors).

For general planning purposes in the Monongahela River Basin, a cost estimate of $1.00/cubic yard should be used for refuse bank removal and burial. Where specific site information is available, cost estimates should be based on recognized construction estimating practices, taking into consideration haul distances, hourly wage and equipment rates, site accessibility and other known factors that would affect removal and burial costs. Soil covering at the burial site should be estimated at $0.50/cubic yard, i.e., $0.50/square yard of cover.

An average cost of $300/acre for clearing and grubbing is satisfactory for estimates in the Monongahela River Basin, but all sites will not require this item. Most of the refuse banks, culm ponds and some highly acidic strip mines should be more or less barren.

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REVEGETATION OF LANDS DISTURBED BY COAL MINING

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Introduction

To insure the success of strip mine and refuse bank reclamation projects adequate vegetation cover must be established (U.S. Department of Agriculture[1]). Revegetation of areas disturbed by coal mining prior to 1940 consisted almost entirely of tree planting (U.S. Department of Interior[2]). However, it has been demonstrated from past reclamation experience that an easily established ground cover (grasses and legumes) is needed for erosion control and initial surface stabilization (Struthers and Vimmerstedt[3]). The most logical approach to revegetation appears to be the methods outlined by Hill[4] in which a ground cover is rapidly established followed by overplanting with trees.

Low pH is the most common factor responsible for the failure of revegetation on strip mines and refuse banks (Czapowskyj and McQuilkin[5]; Mellinger[6] and Smith, et al.[7]). The Truax-Traer Coal Company[8] and Tyner and Smith[9] found that repeated applications of lime were necessary to enable the establishment of a ground cover. Capp and Adams[10] report similar results with the application of fly ash to increase buffering capacity of spoils. However, Magnuson and Kimball[11] conclude that application of lime on spoils having an initial pH above 4.5 is not likely to increase survival rate. Other factors responsible for revegetation failures are salt toxicities (Berg[12]; Berg and Vogel[13]; Beyer and Hutnik[14] and Coleman, et al.[15]), nutrient deficiencies (Cummins, et al.[16]; Hart and Byrnes[17] and Struthers[18], soil temperatures and moisture content (Maguire[19] and Marx and Bryan[20]). A detailed description of adverse factors affecting the revegetation of strip mines and refuse banks is presented in a publication by Nicholas and Hutnik[21].

Since soil characteristics can vary considerably from one reclamation site to the next (Sullivan[22]), it is unlikely that uniform planting recommendations can be developed. However, soil mapping of spoils to obtain representative samples as suggested by Limstrom and Merz[23], Paton, et al.[24] and Grube, et al.[25] can supply the information needed to develop planting recommendations at specific sites. Krause[26] recommends greenhouse tests of various spoils to get more specific information on the capability of the materials to produce and sustain vegetation. Grube, et al.[25] concurs and recommends independent soil analysis prior to soil treatment, fertilizing and seeding.

Cost Analysis

To facilitate future cost estimates for revegetation, it is recommended that a standard format be developed for reporting costs. A listing of the variables that can affect revegetation costs in strip mine and refuse bank reclamation is presented in Table 1. In Table 1, soil treatment, seeding and mulching

TABLE 1

VARIABLES AFFECTING REVEGETATION COSTS* LANDS DISTURBED BY COAL MINING

1. Soils Analysis (Based on soil mapping to obtain representative samples)

   A. pH Soil
   B. pH Buffer**
   C. Soil Nutrient Level (P, K, Ca and Mg)
   D. Moisture Content
   E. Drainage Characteristics of Soil
   F. Organic Content
   G. Toxic Salts
   H. Other Factors

2. Greenhouse Analysis (Using proposed soil treatment, seeding mixtures and mulching)

3. Recommended Soil Treatment (Methods, applications, rates, year and months)

   A. Lime or Ground Limestone (tons/acre)
   B. Fertilizer (lbs. of N-P_2O_5-K_2O/acre)

4. Recommended Vegetation (Planting methods, species or varieties, rates, year and months)

   A. Ground Cover
      1. Grasses (lbs./acre)
      2. Legumes (lbs./acre)
   B. Trees and Shrubs, seedling or saplings (number/acre)
   C. Special Wildlife or Ornamental Plantings (description and number/acre)

5. Recommended Mulching (None, one or more of the following)

   A. Hay or Straw (tons/acre)
   B. Wood Cellulose Fiber (lbs./acre)
   C. Hardwood Bark (cubic yards/acre)
   D. Chipped Brush and Trees from Clearing and Grubbing (cubic yards/acre)
   E. Other Mulch

6. Vegetation Survival Analysis (1, 2, 3 years or a longer period following initial planting)

   A. Percent of Ground Cover (including survival of individual varieties of grasses and legumes)

TABLE 1 (Continued)

B. Percent of Trees and/or Shrubs (including survival of individual species or varieties)
C. Size of Surviving Trees and/or Shrubs (below average, average, above average for age of each species or variety)
D. Reasons for Poor Survival of Specific Grasses, Legumes, Trees and Shrubs (non-adaptive to soil conditions, climatic factors, competition from other species or other factors)

7. Volunteer Vegetation (1, 2, 3 years or a longer period following initial planting)

   A. Grasses (species or varieties and percent of ground cover)
   B. Weeds, Wildflowers and Other Plants (species and percent of ground cover)
   C. Trees and Shrubs (species, size and percent of cover)

8. Subsequent Recommended Soil Treatment

   A. Same Information as Item 3

9. Subsequent Recommended Vegetation

   A. Same Information as Item 4

10. Soils Analysis (1, 2, 3 years or a longer period following initial planting)

   A. Same Information as Item 1
   B. Weathering Characteristics of Soil

*These variables are in addition to those factors listed in Tables 1 and 2 of the section titled "Strip Mine and Refuse Bank Backfilling and Grading".

**Used to determine lime requirement and to calculate the milli-equivalents of hydrogen ions per 100 gm soil (me H^+ per 100 gm soil). The second value is used in calculation of the cation exchange capacity (CEC).

are treated as separate operations, but in actual practice one, two or all three of the operations may be combined into one operation, as in the example of hydroseeding. Also even when these operations are combined or performed separately, the total requirements for soil treatment, seeding and mulching may not be applied at the same time. As an example, seed and one half of the fertilizer requirement may be hydroseeded in one application in the spring and the remainder of the fertilizer applied in the fall.

In preparing this section, only information from recent strip mine and refuse bank reclamation projects in the Monongahela River Basin and surrounding area was used. Table 2 presents a tabulation of revegetation costs for these projects. Revegetation costs ranged from $90 to $500 per acre and the mean cost was $278.56. A wide variety of soil treatment and planting methods is represented on this table and variable degrees of revegetation success is reported. Generally, figures are presented as lump sums or cost per acre. Where possible, the application rates of limestone and fertilizer are included. Because of the limited sample size and a lack of information on initial soils analysis, no conclusions can be made on cost of planting various species or varieties of grass, legumes, trees and shrubs or possible relationships between area, spoil pH and revegetation costs.

A further difficulty in evaluating revegetation costs even when only recent projects are used in the analysis, is that knowledge concerning revegetation of lands disturbed by coal mining has increased so rapidly in the last year or two that it is doubtful the same vegetation procedures would be used on many of these projects today.

Based on a review of selected revegetation projects, either planned in the near future or completed, it is estimated that revegetation costs per acre should be between $350 and $400 depending upon soil treatment requirements, the type of revegetation and the use of mulch.

Use of Soil Tests and Factors Affecting Reclamation Decisions

Figure 1 shows an agricultural soil test report for a strip mine area in Elk County, Pennsylvania made by Pennsylvania State University for Michael Baker, Jr., Inc.[29]. The area strip mined is approximately 15 acres. Three samples were submitted for soils analysis and each sample was a composite of at least 15 samples collected throughout a portion of the strip mine and quartered down to about a 1/2 pint size. The test results of the samples are comparable and Figure 1 is representative of soil conditions.

The area was more or less graded after strip mining, but there are no trees and it is barren except for occasional poverty grass, ferns and an annual sage. Intermittent acid seepage occurs at several places and during rainfall ponding occurs in some areas. Only minor grading is required in areas gullied by erosion and to improve drainage. The strip mine is surrounded by densely wooded land. The objective of reclamation, in this case,

FIGURE 1

DATE	LAB NO.	SERIAL NO.	COUNTY	ACRES	FIELD	SOIL
08/25/70	4533	72874	ELK		7CC	

• SOIL TEST REPORT FOR:

MICHAEL BAKER JR INC
P O BOX 111
ROCHESTER PA 15074

THE PENNSYLVANIA STATE UNIVERSITY
SOIL & FORAGE TESTING LABORATORY
COLLEGE OF AGRICULTURE
UNIVERSITY PARK, PENNSYLVANIA 16802

• LABORATORY RESULTS:

pH SOIL	pH BUFFER	P (lbs/A)	K (meq per 100 gm.)	Mg (meq per 100 gm.)	Ca (meq per 100 gm.)	CEC	K % Saturation	Mg % Saturation	Ca % Saturation
3.9	5.4	4	0.10	0.5	0.7	17.4	0.5	3.4	4.3

OTHER:

• SOIL NUTRIENT LEVELS:

	LOW	MEDIUM	HIGH	EXCESSIVE
PHOSPHORUS (P)				
POTASSIUM (K)	XXXX			
CALCIUM (Ca)				
MAGNESIUM (Mg)	XXXXXXXXX			

• LIMESTONE AND FERTILIZER RECOMMENDATIONS FOR A SEEDING OF LEGUME OR LEGUME-GRASS MIXTURE.
CALCULATED NUTRIENT REQUIREMENT IS 20-211-420 PER ACRE.
***FERTILIZER-WORK IN DEEPLY 180 LBS OF PHOSPHATE PLUS 360 LBS OF POTASH PER ACRE.
***FERTILIZER - DRILL 20-40-40 PER ACRE. BAND PLACE IF POSSIBLE.

***LIMESTONE-APPLY 14000 POUNDS OF STANDARD GROUND LIMESTONE OR EQUIVALENT PER ACRE.

APPLY 240 LBS OF MAGNESIUM PER ACRE. IF RECOMMENDED AMOUNT WAS APPLIED WITHIN THE LAST 12 MONTHS, NO ADDITIONAL MAGNESIUM IS NEEDED NOW. SEE LEAFLET ST-2.

FOR OTHER CROPS, SEE LEAFLET ST-2, FERTILIZER TABLE, COLUMN 1

FERTILIZER APPLIED ____________ TOTAL COST/ACRE ____________

TABLE 2

COST ANALYSIS FOR REVEGETATION
LANDS DISTURBED BY COAL MINING

Project Location	Project Number	Year Completed	Area (Acres)	Type of Vegetation	Limestone /Acre (Tons)	Fertilizer /Acre (Pounds)	Total Cost	Cost/ Acre
Butler Co., Pa.	SL 105-1 N.W.	1967	45.8	G, T	2.5	300[1]	$ 17,701.70	$386.50
Butler Co., Pa.	SL 105-1 S.W.	1969	60.1	G, T	2.5	300[1]	30,050.00	500.00
Butler Co., Pa.	SL 105-1 S.E.	1969	104.1	G, T	2.5	300[1]	52,300.00	500.00
Butler Co., Pa.	SL 105-1A	1969	8.7	NA	NA	NA	783.00	90.00
Butler Co., Pa.	SL 105-1B	1970	18.0	G, T	NA	NA	9,000.00	500.00
Blair Co., Pa.	SL 153	1970	112.0	G, T	4.0	500[2]	27,664.00	247.00
Fayette Co., Pa.	SL 141-1	1970	56.3	G	4.0	500[2]	21,957.00	390.00
Washington Co., Pa.	SL 102-4	1971	46.0	G	NA	NA	5,880.00	127.83
Indiana Co., Pa.	SL 109-1B	1970	40.0	G	2.0	1,000[3]	10,000.00	250.00
Indiana Co., Pa.	SL 109-1C	1971	15.0	G	NA	NA	5,625.00	375.00
Indiana Co., Pa.	SL 109-2	1970	4.0	G	NA	NA	1,400.00	350.00
Centre Co., Pa.	SL 111-1	1971	6.0	G	NA	NA	5,400.00	900.00
Westmoreland Co., Pa.	SL 122-1	1971	7.2	G	NA	NA	3,420.00	475.00

TABLE 2 (continued)

COST ANALYSIS FOR REVEGETATION
LANDS DISTURBED BY COAL MINING

Project Location	Project Number	Year Completed	Area (Acres)	Type of Vegetation	Limestone /Acre (Tons)	Fertilizer /Acre (Pounds)	Total Cost	Cost/ Acre
Randolph Co., W. Va.	DP 1	1968	709.0	G, T	2-4 T[4]	1,000[5]	$175,727.00	$248.00[6]
Tucker Co., W. Va.	4609-4136	1971	120.0	G, T	NA	NA	10,800.00	90.00[7]
Kanawha Co., W. Va.	K-1, 2, 3, 4, -71	1971	36.0	G, T	NA	NA	10,356.00	287.00[7]
Kanawha Co., W. Va.	K-10, 11, 12-71	1971	8.0	T	NA	NA	864.00	108.00[7]
			1396.2				$379,927.70	$278.56

G Grass or Grass Legumes
T Trees
NA Not available at present time - Information Limited

(1) 10-10-10 Fertilizer
(2) 5-10-10 Fertilizer
(3) 10-20-20 Fertilizer

(4) Limestone was not applied in areas where trees only were planted.
(5) 10-10-10 Fertilizer (Not applied in areas where only trees were planted.)
(6) Scott, et al., 1970[27]
(7) Compiled by Grim, 1972[28]

is to improve soil conditions so that a volunteer tree cover can be established. This can best be accomplished by improving soil pH and establishing a ground cover of grass and legume (creeping red fescue and birdsfoot trefoil).

The lime recommendation of 7 tons per acre shown on the Soil Test Report will adjust the soil pH to 7.0 In strip mine reclamation, a soil pH adjustment of 6.0 to 6.5 should be sufficient, depending on the intended use of the land. Therefore, in this example, an application of 6 tons of ground limestone per acre was recommended. It was further recommended that one half of the ground limestone requirement be spread and incorporated into the soil to a minimum depth of 4 inches in the fall preceding spring planting so the limestone would have time to react with the acid soil. One cause of seeding failure is soil acidity, and failure may occur even though sufficient ground limestone is applied at seeding time because the limestone does not have enough time to react with the acid soil before germination.

Of significance in Figure 1 is the magnesium requirement of 240 lbs. per acre. In some areas soils are highly deficient in magnesium and this requirement is often overlooked when it can be met with little or no additional cost during revegetation. If the local limestone source produces a high calcium limestone, the magnesium requirement can be met by blending one ton of imported high magnesium limestone per acre with local limestone. This is probably the cheapest way but other magnesium materials such as Magox, GranuMag and Alcan Magnesia can be used to satisfy this requirement.

The calculated nutrient requirement shown on Figure 1 is the amount of nitrogen, phosphate and potash (N-P_2O_5-K_2O) calculated by a standard formula needed to support the yield goal of a crop, taking into consideration the nutrients available in the soil and the requirements to maintain nutrient level in the soil (Hinish, et al.[30]). Since this calculated nutrient requirement is for top agricultural production, the fertilizer amount can be reduced by 1/4 to 1/3 for reclamation of lands disturbed by coal mining unless the intended use is agricultural or grazing.

In most revegetation projects to date, fertilizers of the home garden variety such as 10-10-10 and 5-10-10 have been used. These N-P_2O_5-K_2O standard ratios* of 1-1-1 and 1-2-2 do not appear to be indicative of nutrient levels of "soil" found at many strip mine and refuse bank areas based on soil test reports. A 1-4-4 standard ratio appears to be more applicable. In Figure 1, the calculated nutrient requirement of 20-211-420 can be satisfied by using a 6-24-24 custom mix, therefore, 50-200-200 lbs. N-P_2O_5-K_2O was recommended. Although the potash requirement is twice that of phosphate, the latter is more significant since there is no crop yield and removal index

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*At the request of the fertilizer industry, many states have agreed to restrict fertilizer recommendations to a minimum of ratios. The calculated nutrient requirement is adjusted to the "best fit" of one of twelve standard fertilizer ratios.

values for potash do not have to be considered. This is not the only recommendation that would satisfy nutrient requirements. As an example a 5-10-10 or a 10-10-10 fertilizer could have been used along with 20 or 46% super phosphate. In addition to satisfying nutrient requirements, recommendations should be based on cost and availability of fertilizer mixtures.

Bulk deliveries in tank trucks of blended fertilizer mixtures should be considered because equivalent nutrient values can be obtained with a reduction in trucking and material costs.

Green Thumb Program

Substantial savings in revegetation and in clearing and grubbing costs may result if advantage is taken of the Green Thumb program(31). Green Thumb is an Operation Mainstream program sponsored by the National Farmers Union and funded by the U. S. Department of Labor. The program provides community improvement jobs for men 55 and older with farm or rural backgrounds.

Crews of Green Thumbers are assigned to projects at the request of local nonprofit organizations, both public and private. Local sponsors supply materials, equipment and supervision in return for the manpower needed for a particular project. There is no red tape, no bookkeeping and no cash contributions. The crews remain on the Green Thumb payroll and all agreements are informal.

The program was started in 1966 and many crews are working in Appalachia. They have worked at developing state parks, highway beautification and development of roadside parks.

In the Monongahela river Basin, the program is presently operating in Pennsylvania. For information contact:

Pennsylvania Farmers Union Green Thumb
240 N. 3rd Street, Room 1106
Payne-Shoemaker Building
Harrisburg, Pennsylvania 17100

Requests for expanding Green Thumb into states where there is now no program should be addressed to:

U. S. Department of Labor
Manpower Administration
Division of Work Experience
1741 Rhode Island Avenue, N. W.
Washington, D. C. 20210

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MINE SEALING

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MINE SEALING

INTRODUCTION

Mine sealing has been defined as the closure of mine entries, drifts, slopes, shafts, subsidence holes, fractures and other openings into underground mines with clay, earth, rock, timber, concrete blocks, brick, steel, concrete, fly ash, grout and other suitable materials (Foreman[1]).

Mine seals can be classified into three general types based on function and method of construction which to a certain extent is the result of geohydrological conditions. The three types and their functions are:

1. Dry Seal - The function of a dry seal is to prevent air and water from entering the mine. This type of seal is constructed at openings which do not have a discharge or the discharge is so slight there is little danger of a hydraulic head developing.

2. Air Seal - An air seal is designed to exclude air from entering a mine but it permits the normal water flow from the mine to be discharged. The air seal is designed with a water trap and the principle is similar to the way water traps in sinks and drains function.

3. Hydraulic Seal - A hydraulic seal is constructed at a mine with a discharge to prevent water flow from the mine. A hydraulic head is created which floods the mine and air is excluded by inundation.

Although acid mine drainage discharges from deep mines has been a significant pollution problem for over a century, any mine sealing work prior to the 1930's generally was performed as a safety precaution and not to reduce acid discharges. The concept of sealing coal mines as a means of reducing acidity was the subject of discussion in several technical papers in the 1920's and early 1930's. The U.S. Bureau of Mines performed much of the early research and an experimental mine sealing program was started in 1932 in which three mines were sealed with a water trap designed to exclude air from entering the mine but permitting the normal flow of water at the discharge (Air Seals). An analysis of water samples collected from the mines over a period of a year indicated a decrease in acidity of the discharges.

A large mine sealing program was started in Pennsylvania and West Virginia in 1933 as a result of these studies. The mine sealing work was performed under the Works Progress Administration and the Civil Works Administration. The effectiveness of the programs in reducing acid discharges has been questioned by some, but Maize[2] indicates acid discharges were reduced in some Pennsylvania streams to the extent that fish life appeared and the water could be used for industrial and domestic purposes. The U.S. Public Health Service[3] estimated a 28 percent reduction in acid loading in the Ohio River as as result of the abandoned mine sealing programs. However, the work performed in many areas was not adequate to exclude air from the underground workings and some mine seals failed after several years. In other areas, the acid water found new discharge openings.

Pennsylvania in 1935 passed The Bituminous Mining Law, Act No. 55, which provided for sealing of abandoned mines by the Pennsylvania Department of Mines. Section 1 of the Act stated "That it shall be the duty of each and every owner, operator, or lessee of any abandoned bituminous coal mine or abandoned working, which is discharging polluted water which flows into any of the streams or rivers of this Commonwealth, or which is in danger of being set afire, to shoot down, or cause to be shot down, or otherwise seal, or cause to be sealed, the entries and air shafts of such abandoned coal mine or working for the purpose of cutting off the supply of air from the abandoned mine or working." Mine sealing was continued under this Act by the Pennsylvania Department of Mines until 1947 when a law was passed by the State Legislature establishing a Mine Sealing Bureau within the Department of Mines. Over 2.5 million dollars was appropriated for mine sealing under this program between 1947 and 1949.

The first mine sealing performed by the new Bureau was in the watershed of the Casselman River, a tributary of the Youghiogheny River. According to Maize(2) this stream was highly polluted with acid mine drainage, but five years later the Casselman River was alkaline and supported fish. Maize also states that water analyses of the Youghiogheny River in 1937 at a point just before it enters the Monongahela River showed the stream was carrying 870 tons of acid per day. In 1950 a water sample taken at the same place indicated the acid load to be 185 tons per day. As a result of this reduction in acid, the City of McKeesport again began taking its domestic water supply from the Youghiogheny River(2). The mine sealing work under the program consisted of dry and air seals, filling of cracks, subsidence areas, slopes and shafts, and also a limited amount of drainage diversion.

The very encouraging results obtained with dry and air seals in the Casselman River watershed and other areas in Pennsylvania as reported by Maize(2) contrasts sharply with the negative results reported by others, such as the recent Elkins, West Virginia demonstration project(4) and the study by Braley(5) reported in 1962. Braley indicated air sealing did not substantially reduce the oxygen content of the mine atmosphere and implied that mine sealing of abandoned drift mines above drainage is ineffective in reducing the quantity of acid discharged. No study has been made to determine why air sealing methods appear to be effective in some areas and not in others. A study of this type may be rewarding because air seals are less expensive to construct than hydraulic seals. It may be difficult to interpret results of a study of this type because active mining operations continue to the present in many of the watersheds where air seals were constructed and it appears the amount of acid discharged has increased yearly because of this later mining. The Casselman River watershed is an example of an area where the effects of an active air and dry mine sealing program was negated by later mining operations.

Mine sealing research continued in the 1950's and 1960's with studies being made by Bituminous Coal Research, Inc., Mellon Institute, U.S. Bureau of Mines and several universities and State agencies. The Ohio River Valley Sanitation Commission (ORSANCO) adopted Resolution No. 5-60 in 1960, amended 1963, which in part stated "Upon discontinuance of operations of any mine all practicable mine-closing measures consistent with safety requirements, shall be employed to minimize the formation and discharge of acid mine-drainage". The coal industry in the Ohio River watershed is required to carry out provisions of ORSANCO Resolution 5-60. An explanation of the measures approved in the Resolution was published in 1964(6) and it was recommended where practical hydraulic mine seals should be constructed because mine sealing is not effective in preventing acid mine drainage unless the coal seam and other acid producing strata and materials are submerged.

Until recently most seals constructed at mine portals were air seals. New developments in mine sealing techniques including methods of hydraulic sealing are a result of increased interest in the field of environmental control. From 1966 through 1969, the Halliburton Company(7) had a contract with the Federal Water Pollution Control Administration, now Environmental Protection Agency, to develop and field test new concepts for watertight or hydraulic seals. Moebs and Krickovic(8) reported in 1970 on a U.S. Bureau of Mines air sealing project of an above drainage coal mine. A comparison of the chemical analyses of the mine effluent during the two year, seven month period before sealing and during the two year, eight month period after sealing showed that the acid load had been reduced.

Since 1969 most of the seals constructed at deep mine portals in Pennsylvania have been hydraulic mine seals. Grouted double bulkhead seals were developed in Pennsylvania for the Moraine State Park and Slippery Rock Creek projects and a grouted single bulkhead seal was designed for the Thomas Mills mine area. This extensive hydraulic mine sealing effort is part of "Operation Scarlift," Pennsylvania's 500 million dollar bond issue for a Land and Water Conservation and Reclamation Fund.

HYDRAULIC MINE SEALS

The objective of hydraulic or watertight mine seals is to exclude air from the mine by flooding mine workings. Watertight bulkheads in mine openings must be capable of withstanding the maximum anticipated hydrostatic head. Installation of hydraulic mine seals includes sealing of all drifts, slopes, shafts, subsidence areas and adjacent strata that can affect the integrity of the watertight seal.

Properly designed and constructed hydraulic mine seals will reduce the rate at which oxygen is supplied for pyrite oxidation in the mines. Theoretically, by flooding the mine with water, atmospheric oxygen will not be available for acid producing chemical reactions. Oxygen, however, can be supplied at a reduced rate through the following mechanisms:

1. Water percolating downward through the overlying strata contains dissolved oxygen, usually 10 to 14 mg/l.

2. Groundwater containing dissolved oxygen may move through the mine environment.

3. Oxygen in void spaces above the water table may dissolve and diffuse downward to react with pyrite in the mine environment.

Any or all of these mechanisms can operate to yield acid mine waters within sealed mines or in unsealed abandoned mines advanced down dip which are now flooded. However, since less oxygen is available for chemical reactions, less acid should be produced in a given time. In some cases sufficient carbonate minerals may be present in the mine environment to neutralize the smaller amount of acid produced or alkaline groundwater flow through the mine environment may result in neutralization of acid.

Hydraulic mine sealing construction methods are divided into two general classifications:

1. Accessible Hydraulic Mine Sealing - The mine openings are open from the portal to the construction area or can be opened with minor effort. The seals are constructed from within the mines. This type of sealing has the advantage of visual inspection during construction and should afford a greater degree of success.

2. Inaccessible Hydraulic Mine Sealing - The mine openings are caved at the portal and cannot be reopened for mine sealing unless there is a large expenditure for preparation and safety. In this case, mine sealing must be accomplished from above ground by drilling holes for placement of bulkhead materials and for grouting techniques. Since there is no opportunity for visual inspection other than a borehole camera, exploratory and observation borings may be required.

A substantial number of abandoned mines within the Monongahela River Basin can be classified as inaccessible. Abandoned mines can be expected to have fracturing of adjacent strata due to the lack of mine support and relief stresses. The strata adjacent to the mine usually has to be grouted to insure a watertight seal.

Within the last few years, several methods of constructing hydraulic seals have been tested and other designs are proposed for future projects. With the exception of the grouted double bulkhead seal, which has been used extensively in Pennsylvania on the Moraine State Park and Slippery Rock Creek projects, most hydraulic seal methods have only been tested experimentally on demonstration projects.

The following hydraulic mine sealing methods are discussed:

Inaccessible Hydraulic Mine Sealing Methods

1. Grouted double bulkhead seal.

2. Grouted single bulkhead seal.

Accessible Hydraulic Mine Sealing Methods

1. Quick setting double bulkhead seal.

2. Quick setting single bulkhead seal.

3. Expendible grout retainer seal.

4. Grouted (horizontally) aggregate seal.

5. Reinforced concrete seal.

Grouted Double Bulkhead Seal

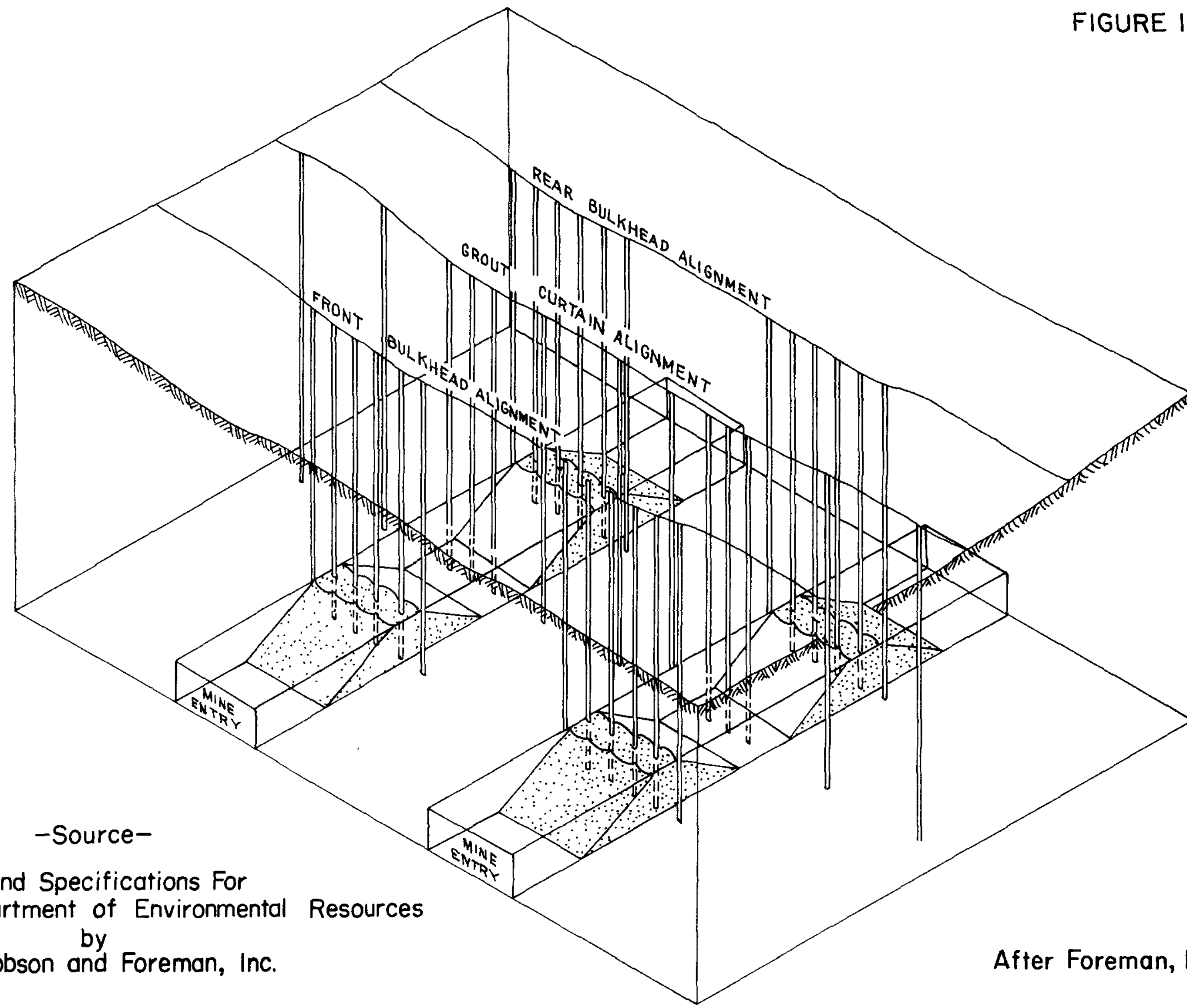
The grouted double bulkhead method of sealing inaccessible mines was developed for use at Moraine State Park, Butler County, Pennsylvania. This project was one of the first to be constructed under "Operation Scarlift," Pennsylvania's 500 million dollar bond issue for a Land and Water Conservation and Reclamation Fund.

A total of 69 hydraulic seals were installed in drift mines which were advanced up dip. It is the most extensive use of this type of seal to date. The design of the double bulkhead hydraulic seal is shown on Figures 1 and 2.

The engineering survey of the Moraine State Park Watershed Area recommended hydraulic sealing of 60 mines at an estimated cost of $15,000 per seal (Gwin Engineers, Inc.[9]). A contract was awarded in 1969 for sealing 53 of these mines. While work was in progress, the Pennsylvania Department of Mines and Mineral Industries, now Department of Environmental Resources, recommended the sealing of an additional 20 mines. It was later discovered, through exploratory drilling, that some of the depressions were natural and not caved mine headings, therefore, only 69 mine seals were constructed. Curtain grouting of adjacent strata was extended a minimum of 50 feet on both sides of a mine entry.

Table 1 is a cost tabulation showing estimated contract quantities for various items of construction, unit bid prices, actual quantities required, and actual cost. The unit cost for Item 1, Mine Sealing, includes all the work needed for construction of grouted double bulkhead seals, such as placing front and rear coarse aggregate bulkheads, grouting of bulkheads, pumping of water from cavity between bulkheads and grouting of center plug.

FIGURE 1



–Source–

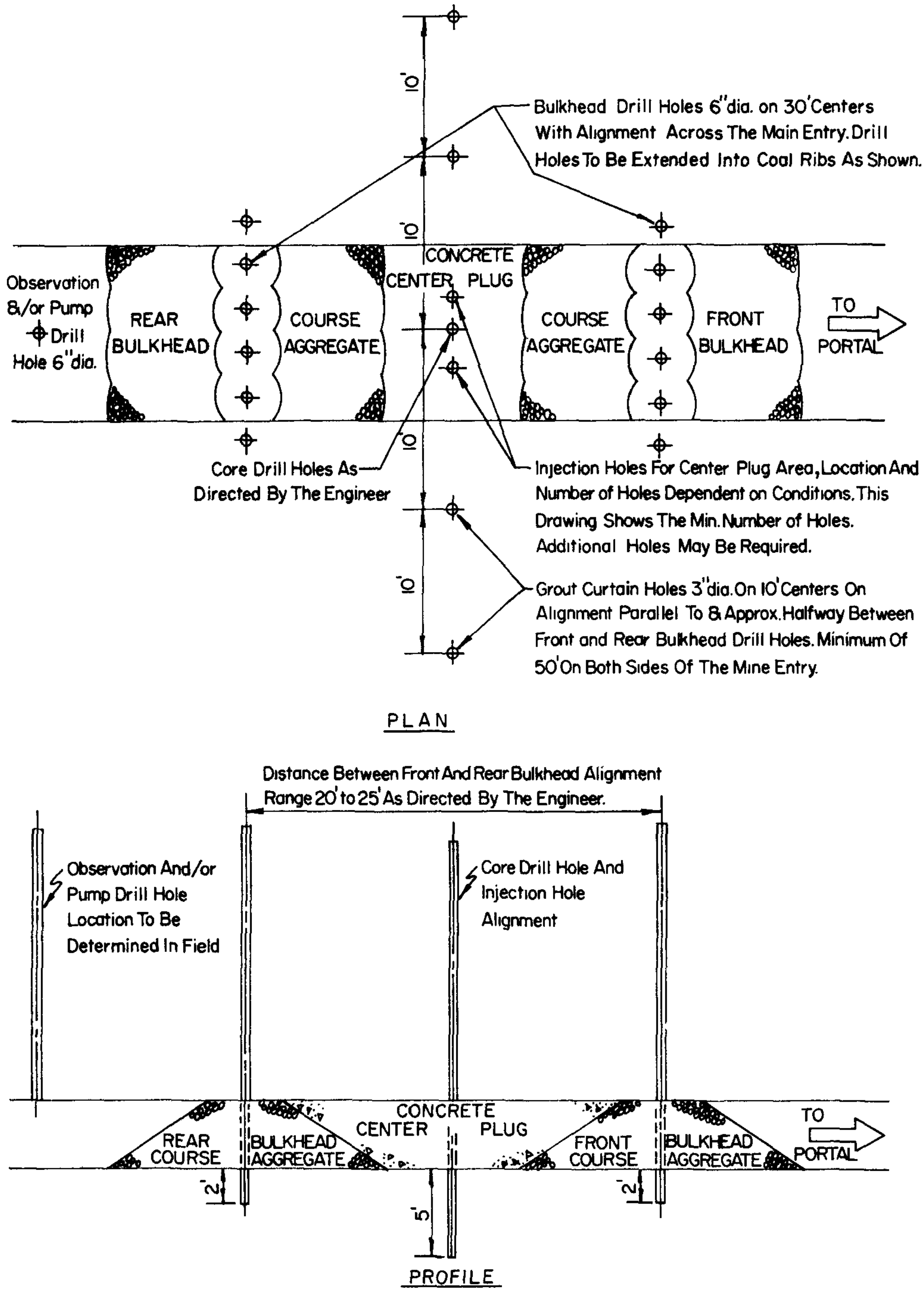
Plans and Specifications For
Pennsylvania Department of Environmental Resources
by
Gwin, Dobson and Foreman, Inc.

After Foreman, 1970[10]

ISOMETRIC DRAWING OF GROUTED DOUBLE BULKHEAD SEALS

No Scale

FIGURE 2



CONSTRUCTION DRAWING OF GROUTED DOUBLE BULKHEAD SEAL

After Foreman, 1970[10]

TABLE 1

COST TABULATION - DEEP MINE SEALS

Moraine State Park, Butler County, Pennsylvania
Operation Scarlift Project SL-105-3

Item No.	Description	Original Estimated Contract Quantities	Estimated Contract Quantities For 20 Additional Seals	Unit	Unit Price	Actual Quantities Required	Actual Cost	% Cost Over or Under Estimate
1.	Mine Sealing (Double Bulk-head Hydraulic Seal)	53	20	Seal	$ 7,000.00	69	$ 483,000.00	-5.5%
2.	Observation Drill Holes							
	a) Drilling 6" Holes	4,000	800	L.F.	5.00	2,211.6	11,058.00	-53.9%
	b) Casing Left in Place	600	600	L.F.	3.00	1,407.0	4,221.00	+ 17.3%
3.	Curtain Grouting							
	a) Drilling 3" Min. Holes	60,000	10,600	L.F.	3.25	100,335.0	326,088.75	+ 42.4%
	b) Cement for Grouting	30,000	9,500	Sacks	5.00	67,820.0	339,100.00	+ 72.0%
	c) Fly-ash for Grouting	1,000	440	Tons	35.00	4,383.91	153,436.85	+ 204.4%
	d) Sand for Grouting	1,000	10	Tons	40.00	28	1,120.00	- 97.2%
	e) Admixture for Grouting	500	80	Sacks	10.00	---	---	---
	f) Pressure Testing	1,000	40	Hours	20.00	---	---	---
4.	Air Shaft Sealing							
	a) Concrete for Filling	100	---	C.Y.	35.00	86	3,010.00	-14.0%
	b) Impervious Material	100	---	C.Y.	10.00	58.8	588.00	-41.2%
5.	Mobilization and Demobilization	L.S.	---	Job	30,000.00	100%	30,000.00	0.0%
							$1,351,622.60	

Original Base Bid (January 31, 1969)	$ 867,300.00
Estimated Cost for 20 Additonal Seals	245,150.00
Total Estimated Cost for 73 Seals	$1,112,450.00
Average Estimated Cost per Seal	$ 15,239.04*

Total Actual Cost	$1,351,622.60
Average Actual Cost per Seal	$ 19,588.73*
% Over Estimated Cost per Seal	28.5%

* Includes cost of curtain grouting and air shaft sealing.

NOTE: A change order for $240,000.00 was necessary to cover additional costs mainly for curtain grouting.

An analysis of the cost tabulation in Table 1 shows that based on estimated quantities and unit bid prices the average estimated cost per seal is $15,239.04 for 73 seals. Using the original base bid for 53 seals, the average estimated cost per seal is $16,364.15. The actual cost per seal for the 69 completed seals was $19,588.73. The cost per seal includes curtain grouting and air shaft sealing. Air shaft sealing was a minor item, but curtain grouting was a major factor in increasing the cost per mine seal and the actual quantities shown on Table 1 greatly exceed the original estimates.

The costs of individual seals ranged from $8,300 to $58,000. The estimating of quantities of materials for inaccessible mine sealing is difficult, particularly the quantities needed for curtain grouting. In most cases, the existing subsurface conditions cannot be determined with any degree of certainty for quantity estimates unless there is an extensive and costly subsurface investigation. The cost of this investigation would only add to the overall cost of reclamation. A limited subsurface investigation is necessary, though, to obtain information on the probable hydrostatic head and the general character of the rock to be grouted. Grouting estimates should be on the conservative side.

Curtain grouting, Item 3 in Table 1, represented 60.6 percent of the total cost of the Moraine State Park Project and it is estimated the cost per lineal foot of grout curtain was $80.00.

Curtain Grouting Costs - Item 3

	Estimated Contract Cost	Actual Costs
Item 3	$517,750.00	$819,745.60
% Total Cost	46.5	60.6
Cost L.F./Drilled	7.33	8.17
Cost L.F./Curtain	51.76	80.00 (Estimate)

The grouted double bulkhead mine sealing program at Moraine State Park was successful in reducing acid discharges. The reduction in pounds of acid was estimated to be 76 percent in December, 1969 and continued observation according to Foreman[11] indicates the reduction in pounds of acid is 68 percent as of January, 1972.

The second most extensive hydraulic mine sealing project to date has been sealing of abandoned drift mines in the Argentine and Whiskerville areas in Slippery Rock Creek drainage basin[11]. The project is currently nearing completion and it is one of Pennsylvania's many "Operation Scarlift" projects. The cost tabulation for this project is presented in Table 2.

TABLE 2

COST TABULATION - DEEP MINE SEALS

Slippery Rock Creek Mine Drainage Project, Butler County, Pennsylvania
Argentine and Wiskerville Areas
Operation Scarlift Project SL-110-BD

Item No.	Description	Estimated Contract Quantities	Unit	Unit Price	Estimated Contract Cost	Quantities As of May 1, 1972	Actual Costs As of May 1, 1972
1.	Mine Sealing (Double Bulk-head Hydraulic Seal)	34	Seal	$ 6,000.00	$204,000.00	24.	$144,000.00
2.	Observation Drill Holes						
	a) Drilling 6" Holes	2,000	L.F.	2.10	4,200.00	221.	464.10
	b) Casing Left in Place	400	L.F.	3.00	1,200.00	223.	669.00
3.	Curtain Grouting						
	a) Drilling 3" Min. Holes	40,000	L.F.	2.10	84,000.00	13,211.	27,743.10
	b) Cement for Grouting	20,000	Sacks	5.40	108.000.00	25,886.4	139,786.56
	c) Fly-ash for Grouting	1,200	Tons	30.00	36,000.00	2,930.55	87,916.50
	d) Sand for Grouting	50	Tons	10.00	500.00	---	---
	e) Admixture for Grouting	300	Sacks	5.00	1,500.00	292.	1,460.00
	f) Pressure Testing	100	Hours	20.00	2,000.00	---	---
4.	Mobilization and Demobilization	L.S.	Job	28,000.00	28,000.00	---	(Assume) 28,000.00
					$469,400.00		$430,039.26

Estimated Contract Cost for 34 Seals	$469,400.00	Estimated Final Cost for 24 Seals	$440,000.00
Average Estimated Cost per Seal	$ 13,805.88	Estimated Average Actual Cost per Seal	$ 18,330.00
		% Over Estimated Bid Cost per Seal = 32.8%	

* Includes costs of curtain grouting.

NOTE: Project is near 100% completion.

The design of the double bulkhead hydraulic seals is the same as those constructed at Moraine State Park except that grouting of aggregate bulkheads before placement of the center plug was deleted from the contract. This change order was the result of a law suit brought by Layne-New York Company, Inc., for alleged damages arising out of patent infringement. Layne-New York Company, Inc.(12) is claiming sole ownership in United States Patent No. 3,469,405 of the concept covering design and placement by grouting methods of double bulkhead seals. The Commonwealth of Pennsylvania is challenging this claim. Although, it is believed the law suit had no affect on the bid prices for this project, it is difficult to determine what affect it will have on future bids for this type seal.

The physiography and geology in the Argentine and Whiskerville area and in the Moraine State Park area are similar. Bidding was based on an estimated 34 mine seals. Only 29 mine headings were believed to require sealing, but an additional five were estimated in case others were found during construction. Actually, only 24 seals were constructed because five of the locations were proved by exploratory drilling to be natural depressions and not caved headings. Even though less seals are being constructed, actual project cost will approach estimated total cost because curtain grouting quantities are higher than estimated.

Final cost figures are not available, but it is estimated the average cost per seal, including curtain grouting, will be $18,330.00, or 32.8% over the contract estimated cost. The cost per individual seal will be dependent upon the extent of required curtain grouting. It is estimated the minimum cost per seal will be approximately $7,500 and the maximum cost $40,000.

Grouted Single Bulkhead Seals and Curtain Grouting

Mine sealing and curtain grouting work is currently being performed in the Thomas Mills Mine Area, Somerset County, Pennsylvania (Operation Scarlift Project, No. SL 151-1). This project is under the supervision of the Pennsylvania Department of Environmental Resources and a plan of part of the mine area is shown in Figure 3.

The work in progress involves placement of a continuous grout curtain, 2,200 feet in length, with construction of single grouted aggregate bulkhead barriers or seals whenever mine rooms or passage ways are encountered.

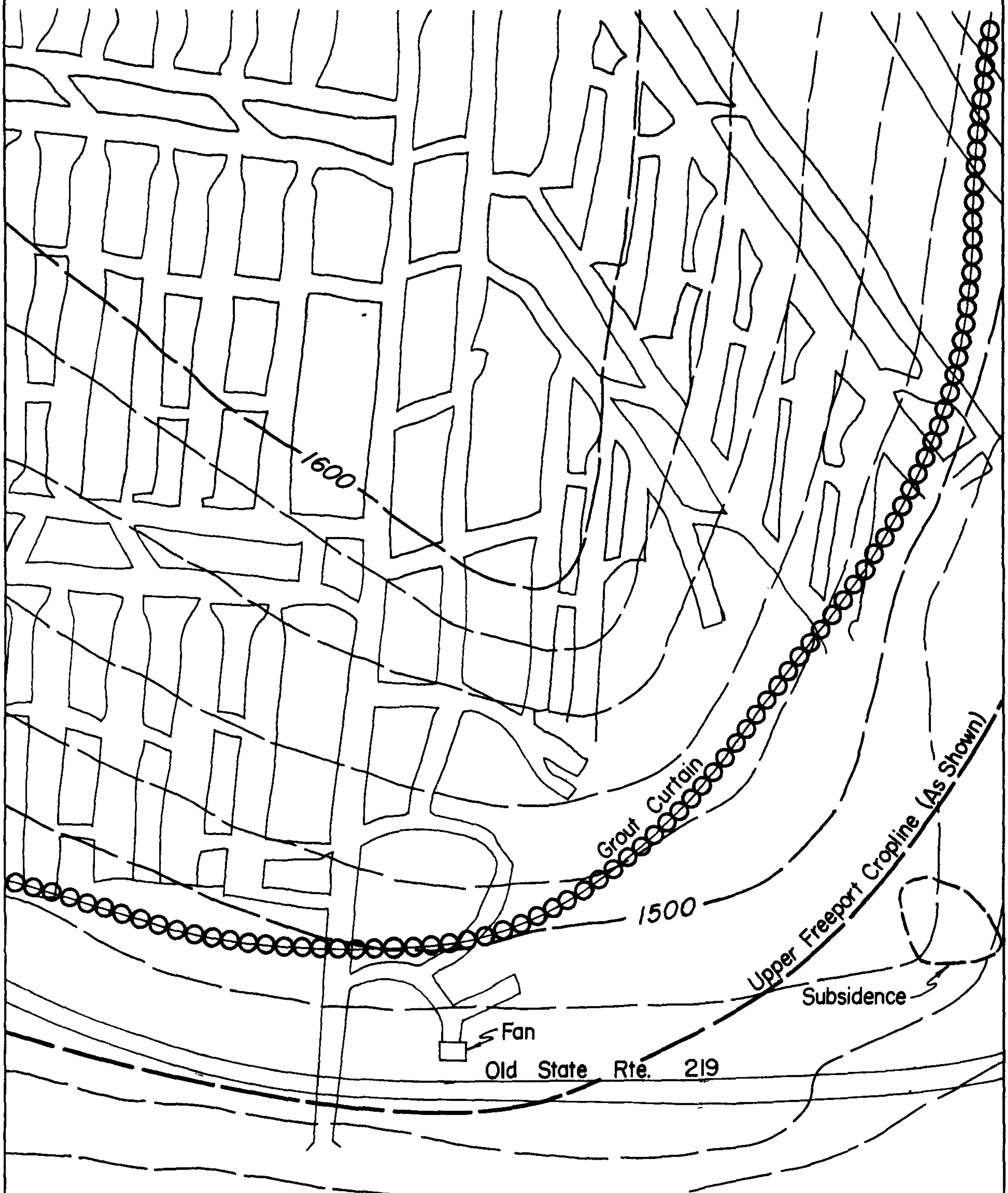
The design of this type seal is shown on Figure 4. The barriers are being constructed by injecting Pennsylvania Department of Transportation Specification 2B coarse aggregate into bore holes spaced on two foot centers. The aggregate is spread by mechanical methods such as tamping, vibrating a and/or flushing until a cone of material is built up to the headwall of the mine. The barriers are then pressure grouted, through metal pipes extending into the aggregate, using a cement fly ash slurry or a cement fly ash slurry with bentonite or AM 9 admixture to form the hydraulic seal.

FIGURE 3

PLAN VIEW

PORTION OF THOMAS MILLS MINE AREA

Somerset County, Pennsylvania



Source: Pennsylvania Department of Environmental Resources[13]

Scale: 1" = 100'

FIGURE 4

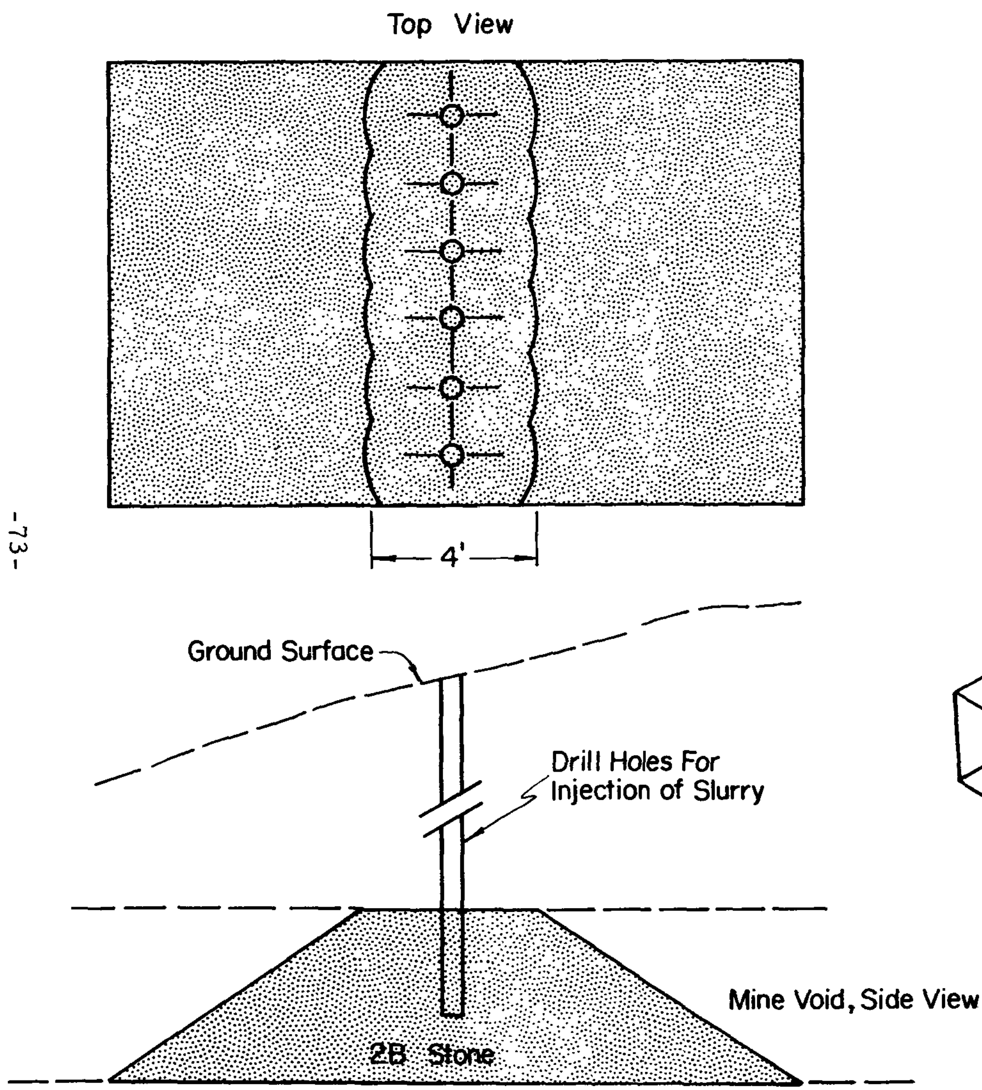
DESIGN OF SINGLE BULKHEAD MINE SEAL

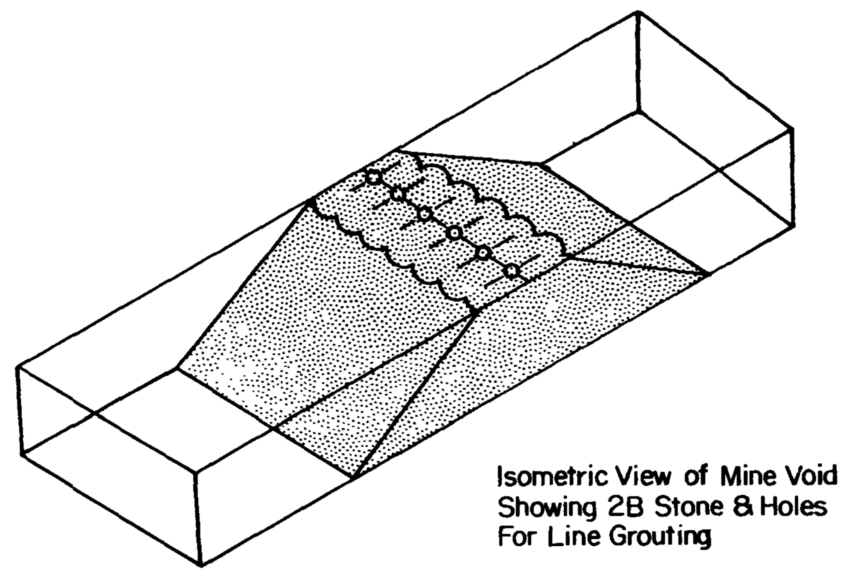
THOMAS MILLS MINE AREA

Somerset County, Pennsylvania

Operation Scarlift Project SL 151-1

After: Pennsylvania Department of Environmental Resources[13]





The cost tabulation of unit prices is presented in Table 3 and it is anticipated the contract price will be exceeded, perhaps greatly, because more mine voids are being encountered than originally expected. The voids will require additional grouted aggregate mine seals. The nonavailability of sufficiently detailed mine maps is considered the main factor in underestimating material quantities. Also of significance, is the fact that unit prices for cement, fly ash and bentonite admixture are substantially above engineering estimates. The unit price for these items includes material cost, transportation, storage, and labor associated with the mixing and grouting operations. The unit cost of $9.00/ton for fly ash appears reasonable considering prices for other similar projects and indicates an underestimate by the engineer. The unit price for concrete at $10.00/sack and bentonite at $1.00/lb. appears very high.

By applying contract unit prices to a mine void five (5) feet in height, twelve (12) feet in width, and at a depth of 50 feet, the approximate cost for construction of a grouted seal would be $2,100 as follows:

Item	Quantity	Unit Price	Cost
Drill holes (8)	424 L.F.	$ 2.10	$ 890.40
Cement for grouting	35 Sacks	10.00	350.00
Fly ash for grouting	3.9 Tons	9.00	351.00
Bentonite for grouting	200 lbs.	1.00	200.00
#2B Stone	30 Tons	9.75	292.50
		Total	$2,083.90
		Call	$2,100.00

If the strata is curtain grouted for 50 feet on both sides of the seal, the approximate cost would be $2,000 as follows:

Item	Quantity	Unit Price	Cost
Drill holes (10)	530 L.F.	$ 2.10	$1,113.00
Curtain grouting materials	(assume same quantities as above, except 2B Stone)		901.00
		Total	$2,014.00

Increasing the above costs by 10% to cover mobilization and demobilization, the total cost, including curtain grouting, should be about $4,500.

TABLE 3

COST TABULATION - PRESSURE CURTAIN GROUTING

Thomas Mills Area, Somerset County, Pennsylvania
Operation Scarlift Project SL-151-1

Item No.	Description	Approximate Quantities	Engineer's Estimate Unit Price	Engineer's Estimate Total	Successful Bidder - M. F. Fetterolf Coal Co. Unit Price	Successful Bidder - M. F. Fetterolf Coal Co. Total	% of Bid Over or Under Engineer's Estimate
1	Drilling 3" Minimum Holes	22,000 L.F.	$ 3.00	$ 66,000.00	$ 2.10	$46,200.00	-30.0%
2	Cement for Grouting	1,500 Sacks	5.50	8,250.00	10.00	15,000.00	+81.8%
3	Fly-ash	900 Tons	6.00	5,400.00	9.00	8,100.00	+50.0%
4	Bentonite Admixture for Grouting in 100 Lb. Bags	2,000 Lbs.	.15	300.00	1.00	2,000.00	+567. %
5	AM-9 Admixture for Grouting	300 Lbs.	5.00	1,500.00	4.00	1,200.00	-20.0%
6	# 2B Stone	500 Tons	12.00	6,000.00	9.75	4,875.00	-18.8%
7	Dismantle Old Fan House, Fill 3 Openings with Noncombustible Material	L.S. Job	L.S.	4,000.00	L.S.	1,000.00	-75.0%
8	Mobilization and Demobilization, Roads Including Grading, Reclamation and Seeding Estimated 4 Acres	L.S. Job	10,000.00	10,000.00	L.S.	6,025.00	-39.6%
				$101,450.00		$84,400.00*	

Estimated Cost for 2,200 L.F. Pressure Grout Curtain
(Using Engineer's Estimate)
$101,450.00 minus Item 7 and 1/2 (Item 8) = $92,450.00
Estimated Cost per L.F. = $ 42.02

Estimated Cost for 2,200 L.F. Pressure Grout Curtain
(Using Bid Price)
$84,400.00 minus Item 7 and 1/2 (Item 8) = $80,387.50
Bid Cost per L.F. * = $ 36.54

NOTE: Project is presently under construction. Many more mine voids are being encountered than originally anticipated requiring additional grouted barriers. It is expected that the contract price will be exceeded, perhaps greatly.

Review of Unit Bid Prices for Three Hydraulic Mine Sealing Projects

Tables 4, 5 and 6 show the unit prices bid by contractors on the following projects:

1. Moraine State Park, Butler County, Pennsylvania
   Operation Scarlift Project SL 105-3

2. Slippery Rock Creek, Argentine and Whiskerville Areas, Butler County, Pennsylvania
   Operation Scarlift Project SL 110-1BD

3. Thomas Mills Area, Somerset County, Pennsylvania
   Operation Scarlift Project SL 151-1

The range in unit bid prices, particularly grouting materials, indicates this could be a major factor in cost overruns. For example: fly ash - $9.00 to $96.00/ton; bentonite - $0.10 to $1.50/lb.; No. 2 Stone - $6.00 to $24.00/ton; sand - $5.80 to $50.00/ton and cement - $3.00 to $10.00/sack. When larger quantities of material are used than anticipated in design, and the unit bid price for the item is high, large cost overruns are bound to occur. It is suggested that in preparing bid proposals, maximum quantities be estimated. This would, to a certain extent, prevent contractors from capitalizing on the fact that quantities are underestimated.

Contractors are in business to make money, and a contractor in order to survive must take advantage of every opportunity to make a legitimate profit, even a very large one, if he is to offset projects which showed a loss or only a marginal profit. An experienced contractor many times can tell when quantities are underestimated and he will balance his unit price bids to make the most profit and at the same time attempt to come up with an overall low bid for the project. State and federal agencies on occasion are guilty of the practice of underestimating the cost of a project, either because of false optimism and the desire to get a project started, or because of an intentional underestimate in order to get a project approved within a limited budget, knowing full well that additional funds will be appropriated at a later date to complete the project.

TABLE 4

UNIT BID PRICES

Deep Mine Seals - Moraine State Park
Butler County, Pennsylvania
Operation Scarlift Project SL-105-3

Item No.	Description	Approx. Quantity	Unit	UNIT PRICES: Unit Prices Successful Bidder B.H. Mott & Sons, Inc.	UNIT PRICES: Range of Unit Bid Prices (Four Bidders)
1.	Mine Sealing (Double Bulk-head Hydraulic Seal	53	Seal	$ 7,000.00	$ 7,000.00 - $11,462.72
2.	Observation Drill Holes				
	a) Drilling 6" Holes	4,000	L.F.	5.00	2.25 - 5.00
	b) Casing Left in Place	600	L.F.	3.00	2.92 - 3.00
3.	Curtain Grouting				
	a) Drilling 3" Min. Holes	60,000	L.F.	3.25	1.90 - 3.25
	b) Cement for Grouting	30,000	Sacks	5.00	3.00 - 5.80
	c) Fly-ash for Grouting	1,000	Tons	35.00	13.13 - 52.00
	d) Sand for Grouting	1,000	Tons	40.00	5.80 - 40.00
	e) Admixture for Grouting	500	Sacks	0.00	0.00 - 2.65
	f) Pressure Testing	1,000	Hours	20.00	20.00 - 27.00
4.	Air Shaft Sealing				
	a) Concrete for Filling	100	C.Y.	35.00	20.00 - 40.00
	b) Impervious Material	100	C.Y.	10.00	1.84 - 45.00
5.	Mobilization and Demobilization	L.S.	Job	30,000.00	30,000.00 - 92,540.00

Total Amount of Lowest Base Bid $867,300.00

Range of Base Bids (4 Bidders) $867,300.00 to $998,840.00

NOTE: Bids opened November 6, 1968. Contract awarded to B. H. Mott & Sons, Inc. - January, 1969

TABLE 5

UNIT BID PRICES

Deep Mine Seals - Slippery Rock Creek
Argentine and Whiskerville Areas, Butler County, Pennsylvania
Operation Scarlift Project SL-110-1BD

Item No.	Description	Approx. Quantity	Unit	UNIT PRICES: Unit Prices Successful Bidder Allied Asphalt Co., Inc.	UNIT PRICES: Range of Unit Bid Prices (Five Bidders)
1.	Mine Sealing (Double Bulkhead Hydraulic Seal)	34	Seal	$ 6,000.00	$5,000.00 - $8,000.00
2.	Observation Drill Holes				
	a) Drilling 6" Holes	2,000	L.F.	2.10	2.10 - 4.75
	b) Casing Left in Place	400	L.F.	3.00	2.50 - 4.00
3.	Curtain Grouting				
	a) Drilling 3" Min. Holes	40,000	L.F.	2.10	1.90 - 3.50
	b) Cement for Grouting	20,000	Sacks	5.40	4.00 - 5.40
	c) Fly-ash for Grouting	1,200	Tons	30.00	30.00 - 40.00
	d) Sand for Grouting	50	Tons	10.00	30.00 - 50.00
	e) Admixture for Grouting	300	Sacks	5.00	0.00 - 50.00
	f) Pressure Testing	100	Hours	20.00	10.00 - 40.00
4.	Mobilization and Demobilization	L.S.	Job	28,000.00	1,000.00 - 28,000.00

Total Amount of Lowest Bid $469,400.00

Range of Bids (5 Bidders) $469,400.00 to $527,040.00

NOTE: Bids opened April 30, 1970. Contract awarded to Allied Asphalt Co., Inc. - June 3, 1970

TABLE 6

UNIT BID PRICES

Pressure Curtain Grouting and Reclamation
Thomas Mills Area, Somerset County, Pennsylvania
Operation Scarlift Project SL-151-1

Item No.	Description	Approx. Quantity	Unit	Engineer's Estimate	UNIT PRICES: Unit Prices Successful Bidder M. F. Fetterolf Coal Co.	UNIT PRICES: Range of Unit Bid Prices (Seven Bidders)
1.	Drilling 3" Minimum Holes	22,000	L. F.	$ 3.00	$ 2.10	$ 2.10 - $ 3.60
2.	Cement for Grouting	1,500	Sacks	5.50	10.00	3.05 - 10.00
3.	Fly-ash	900	Tons	6.00	9.00	9.00 - 96.00
4.	Bentonite Admixture for Grouting in 100 lb. Bags	2,000	Lbs.	0.15	1.00	0.10 - 1.50
5.	AM-9 Admixture for Grouting	300	Lbs.	5.00	4.00	0.35 - 10.00
6.	# 2B Stone	500	Tons	12.00	9.75	6.00 - 24.00
7.	Dismantle Old Fan House, Fill 3 Openings with Non-combustible Material	L.S.	Job	4,000.00	1,000.00	1,000.00 - 5,000.00
8.	Mobilization and Demobilization, Roads Including Grading, Reclamation and Seeding Estimated 4 Acres	L.S.	Job	10,000.00	6,025.00	6,025.00 - 41,675.00

Total Amount of Engineer's Estimate	$101,450.00
Total Amount of Lowest Base Bid	$ 84,400.00
Total Amount of Second Lowest Base Bid	$ 95,900.00
Range of Bids (7 Bidders)	$ 84,400.00 to $177,490.00

NOTE: Bids opened November 11, 1971.

Hydraulic Sealing of Accessible Mine Headings

The work performed in hydraulic sealing of accessible mine headings is limited. The Halliburton Company[7] under contract to the Environmental Protection Agency has developed several methods and techniques for hydraulic sealing of accessible mines. The demonstration projects were performed at mine openings in Harrison County, West Virginia from 1967 to 1969. The following is a description of some of the hydraulic seals constructed under this program.

Quick Setting Double Bulkhead Seal
Mine No. 62-008, Opening No. 5

As a result of a series of laboratory and field tests on the applicability of quick setting slurries, this site was chosen for construction of a quick setting double bulkhead seal. A drawing of a section through the seal is presented in Figure 5.

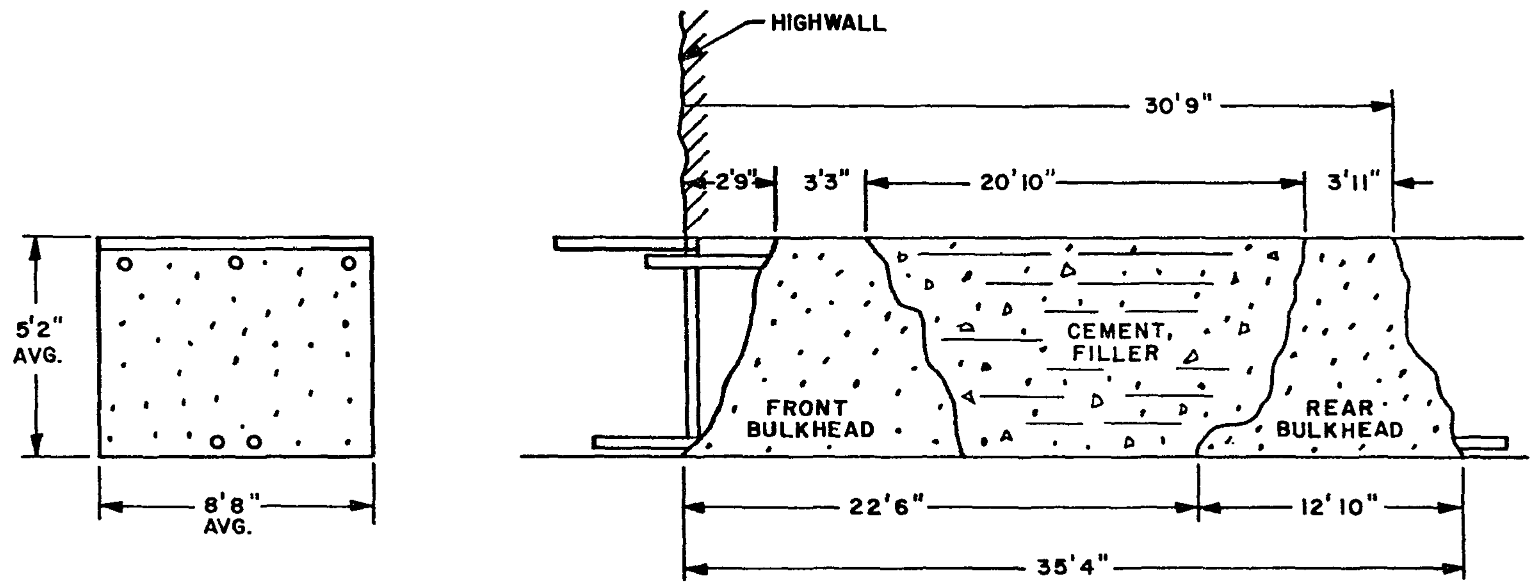
The slurry used for construction of the bulkhead was a blend of two separate slurries which were mixed immediately before being pumped into the mine. The blended slurry consisted of equal parts of the following:

Slurry No. 1		Slurry No. 2	
Water	870 gallons	Water	1,050 gallons
Cement	180 sacks	Bentonite	700 pounds
		Sodium Silicate	350 gallons

The void between the bulkheads was filled by pumping Halliburton LIGHT Cement, through a grout pipe. This grouting material is a blend of 65% portland cement, 35% fly ash and 6% bentonite with 9.9 gallons of water per bulk cubic foot of dry material, or 61 parts cement, 26 parts fly ash, 5.2 parts bentonite and 82.5 parts water by weight.

The mine sealing is considered to be completely successful as all flow from the mine at this heading was stopped. The construction cost of the seal was $9,449.00 based on the following breakdown of costs:

Item	Cost
Site Preparation	$ 894.00
Grouting Materials	3,872.00
Equipment and Operators	4,683.00
Total	$9,449.00



SECTION - MINE SEAL - OPENING NO. 5 - MINE NO. 62-008

FIGURE 5

From: Halliburton Co.[7]

Quick Setting Double Bulkhead Seal
Mine RT 5-2, Seal No. 1

The construction details of this mine sealing project are shown in Figures 6 and 7. A quick setting slurry was used for construction of the bulkheads as in Mine No. 62-008. After construction of the rear bulkhead, a center plug was constructed by pneumatic placement of limestone aggregate. This aggregate was grouted with a cement-fly ash-bentonite mixture (Halliburton LIGHT Cement) after placement of the front bulkhead. Grouting of the mixture was continuous until a fill-up was obtained to within a few inches of the roof. At that time, leaks appeared around the top corners of the front bulkhead, so the slurry was altered by adding shredded cellophane, sawdust and shredded cane fiber. This material successfully closed the leaks.

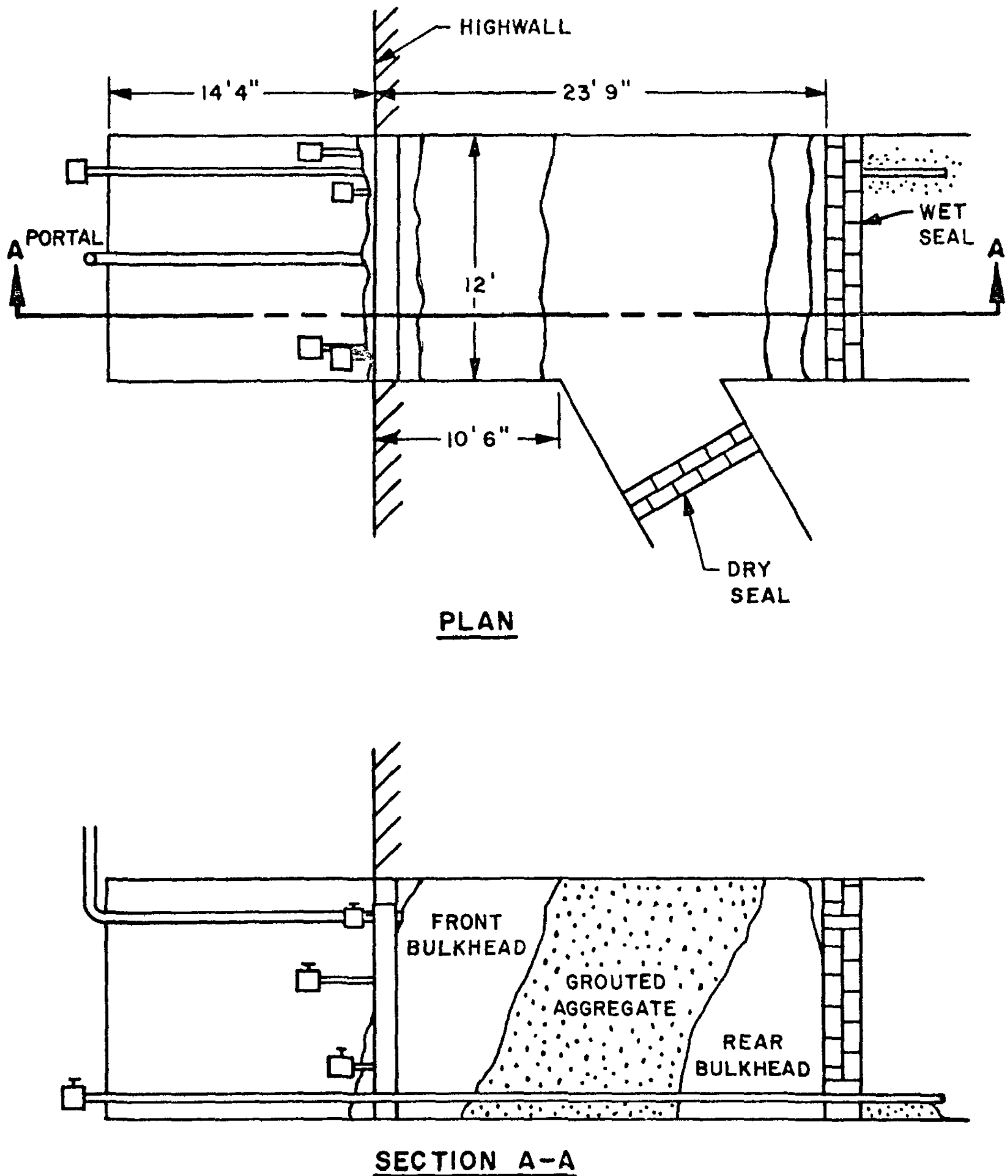
The total construction cost for the seal, including the site preparation cost of $1,079.00, was $9,463.00 for materials and equipment.

The purpose of the project was to develop methods of remote grouting application for use in mine drifts having high water discharge rates. The water flow from the mine opening prior to construction of the seal was in excess of 50 gallons per minute. The seal appears to be effective in preventing water flow from the opening, but when the head of water impounded behind the seal increased, the pressure caused a substantial leakage from an unknown adjacent opening. Remedial work on the second opening, Seal No. 2, was accomplished by constructing a bulkhead of graded aggregate and agricultural lime; this work is discussed under "Limestone Barrier Mine Sealing."

Quick Setting Single Bulkhead Seal
Mine No. 62-008, Opening No. 4

The single bulkhead seal was constructed using the same slurry mixture as used in constructing the double bulkhead seal at Opening No. 5 of the same mine. Figure 8 is a drawing of a section through the bulkhead. The mine sealing appears to be successful since only a slight seepage occurred with a hydraulic head of 54.4 inches. The total construction cost was $3,564.00 as follows:

Item	Cost
Site Preparation	$ 647.00
Grouting Materials	1,165.00
Equipment and Operators	1,752.00
Total	$3,564.00

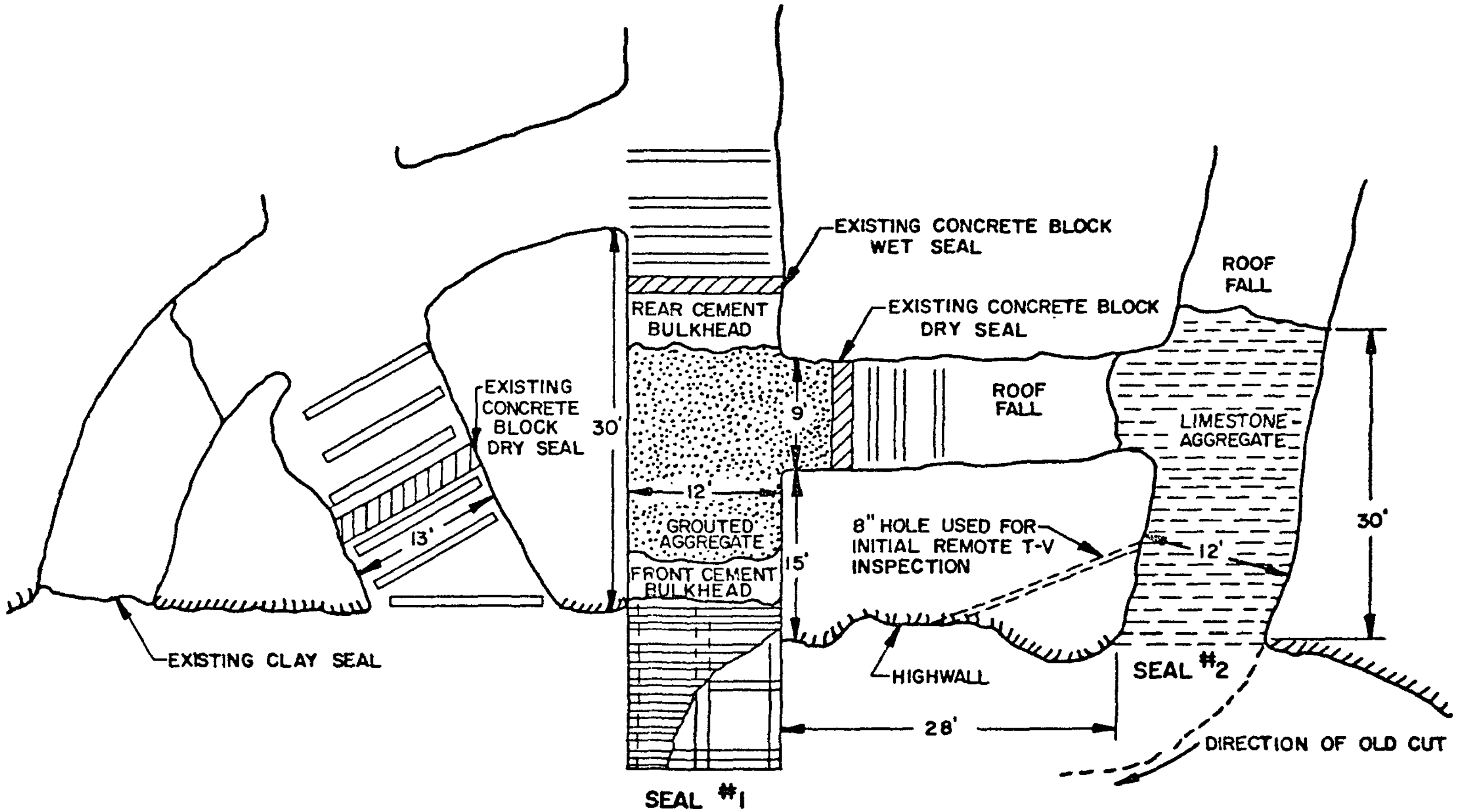


CONSTRUCTION DETAIL

SEAL NO. 1 - MINE NO. RT5-2

FIGURE 6

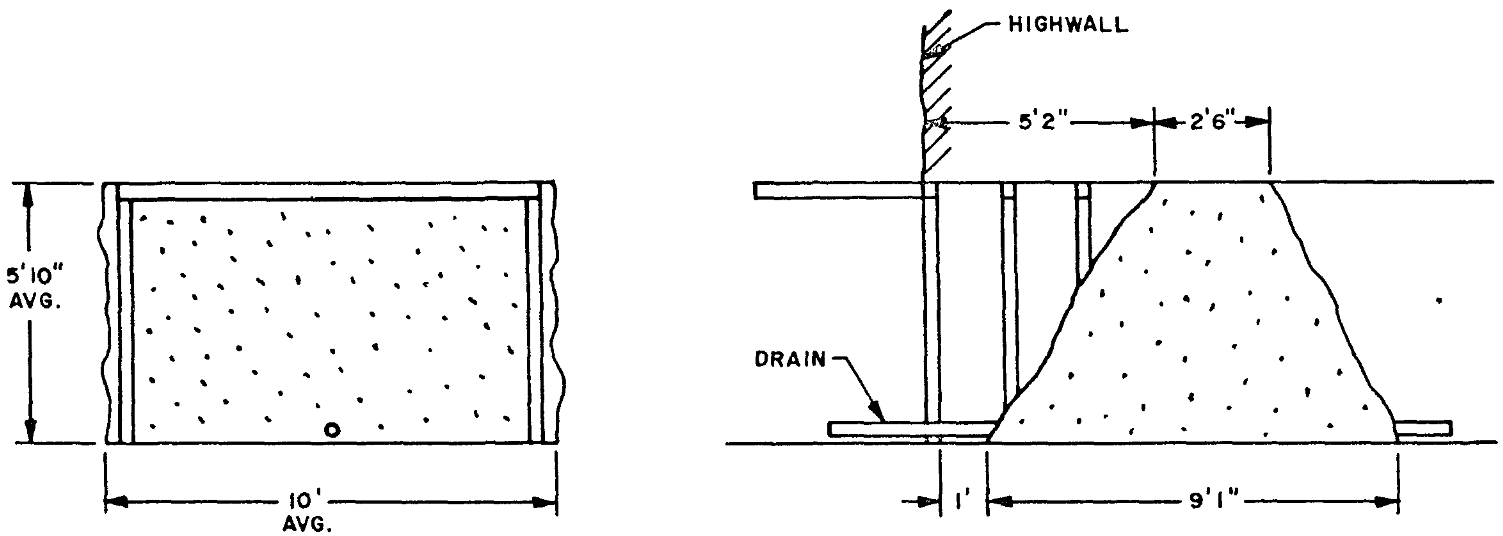
From Halliburton Co. (7)



PLAN VIEW OF REMEDIAL CONSTRUCTION - MINE NO. RT5-2

FIGURE 7

From: Halliburton Co.(7)



SECTION - QUICK SETTING BULKHEAD - OPENING NO. 4 - MINE NO. 62-008

FIGURE 8

From: Halliburton Co.[7]

Expendable Grout Retainer Seal
Mine No. 14-042A

An abandoned mine near Clarksburg, West Virginia was selected for application of a mine seal because of its remote location, small but easily accessible area and highly acid discharge. The seal was constructed by placing successive layers of expandable nylon and cotton cloth grout retainers and filling them with a cement grout slurry to conform to the shape of the opening. Figure 9 is a drawing of the seal showing the installation and mine configuration.

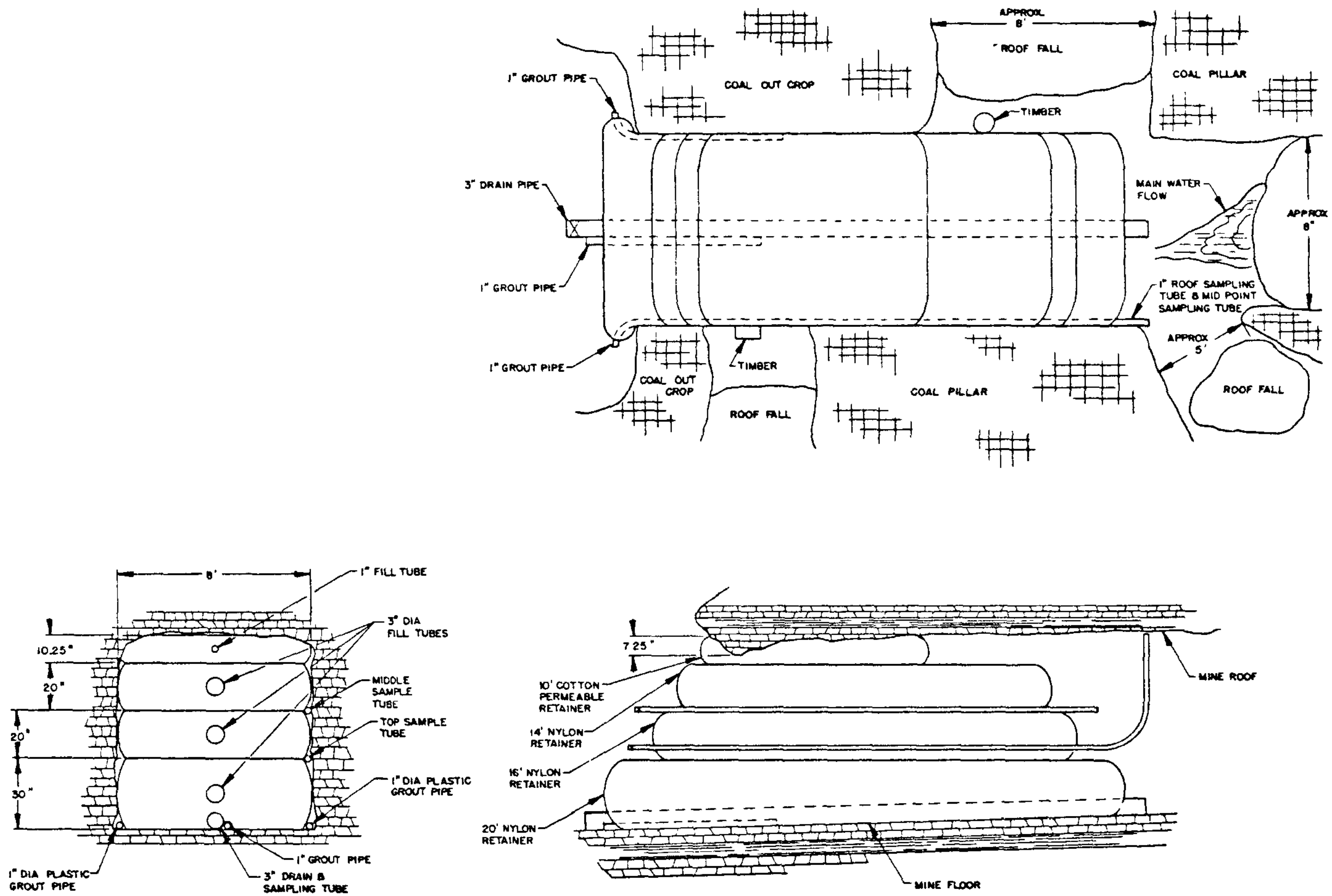
After the mine seal was installed, a reduction of 92 percent in the discharge was observed, but cumulative leakage from small leaks in the coal surfaces around the seal amounted to about 1.5 gallons per minute. Grouting around the grout retainers with Halliburton PWG grout fluid, an acrylamide monomeric solution, reduced the leakage to 0.33 gallons per minute. Grouting was discontinued because it appeared the remaining leakage was coming from coal fractures several feet from the seal.

An attempt was made to further reduce the leakage by injecting a gelling agent into the mine behind the seal. The gelling material would flow into leakage points from inside the mine. The gelling material consisted of bentonite, shredded cane fiber (Fibertex) and fresh water. At the start of this remedial work the flow rate from the mine was 0.40 gallons per minute. A total of 41,200 gallons of gelled fluid was pumped into the mine over a four day period utilizing 30,000 pounds of Wyoming bentonite and 295 pounds of Fibertex. Figure 10 is a schematic drawing of the mine to show the condition following remedial work.

The flow rate at completion was 0.55 gallons per minute, an increase of 0.15 gallons over the initial rate. The leakage has continued to average 0.5 gallons per minute since treatment, therefore, the treatment did not accomplish desired results.

Construction costs were not available for the grout retainer seal and Halliburton PWG grout fluid treatment(14). The following construction costs were incurred for remedial work using the gelling material for treatment:

Item	Cost
Access Rights	$ 300.00
Materials and Equipment	2,771.00
Site Restoration	279.00
Total	$3,350.00



MINE SEAL INSTALLATION

MINE NO. 14-042A

HARRISON COUNTY, WEST VIRGINIA

FIGURE 9

From: Halliburton Co.[7]

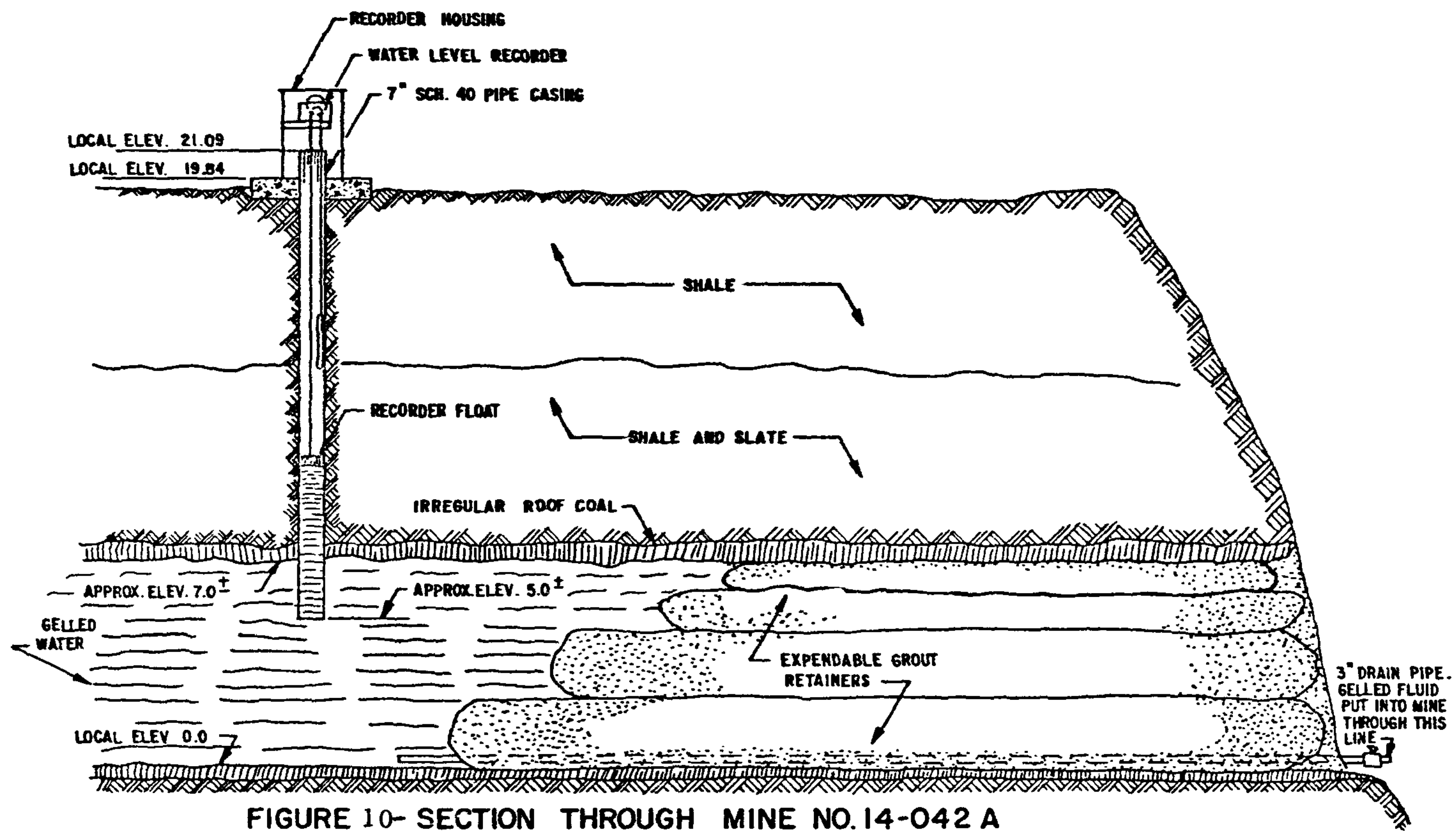


FIGURE 10- SECTION THROUGH MINE NO. 14-042 A

From: Halliburton Co.(7)

Grouted Limestone Aggregate Seal
<u>Mine No. 40-016, 2 Openings</u>

This small abandoned mine south of Clarksburg, West Virginia had a moderately acid discharge and the flow from the mine ranged from 7 to 150 gallons per minute. Two drifts were sealed by pneumatically placing limestone aggregate in the openings and then grouting the aggregate with a cement grout. A cross-section of the installation showing construction details is presented in Figure 11. Sealing reduced the flow by 85 percent, but leakage occurred through and around the seal.

Remedial grouting was performed using other grout slurries in an attempt to reduce the flow further. Essentially there was little reduction in flow as a result of the remedial work. The grout slurries used in the remedial grouting were:

1. A grout slurry consisting of preblended 50% portland cement and 50% fly ash by volume, with 18% salt and 0.4% Halad-9. Halad-9 is a Halliburton additive to prevent water being lost into permeable formations due to applied pressure. This grout slurry was chosen because of low water loss and good expansive characteristics. The grout slurry was mixed at a weight of 14.5 pounds per gallon using impounded mine water.

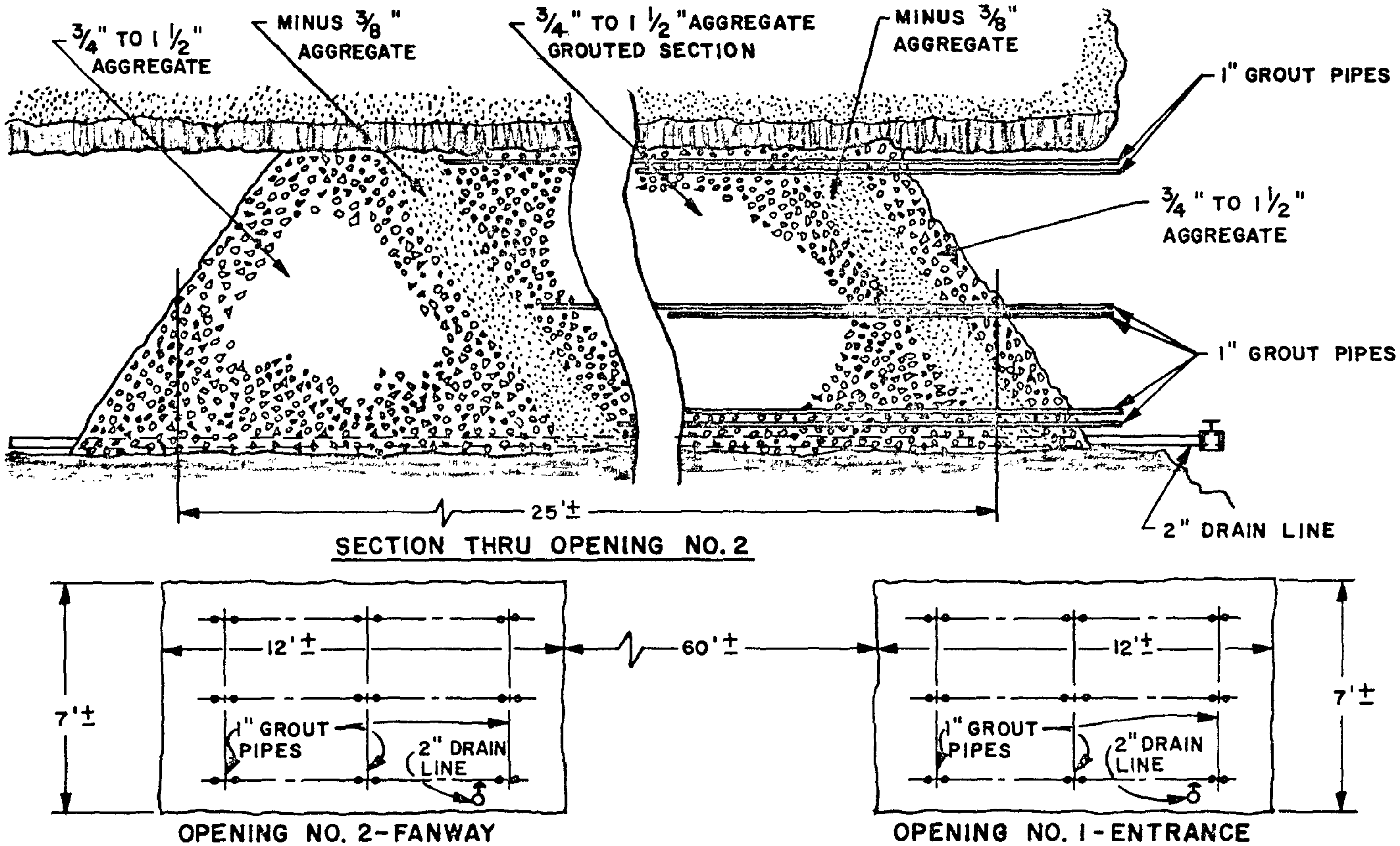
2. Halliburton's DOC slurry which consists of cement particles surrounded by a hydrocarbon base fluid incorporating a surface-active agent, or kerosene, cement and a dispersant type surfactant. These materials are mixed to form a slurry that remains inactive unless contacted by water. The slurry will absorb water like a sponge to cause a hard dense set.

3. The cement-fly ash mixture used in No. 1 with the addition of Flocele, a shredded cellophane, as a plugging material.

The cost figures for construction of the two limestone aggregate seals and later remedial grouting are presented in Table 7. The total cost was estimated to be $17,696.00 for two seals or $8,848.00 per seal.

<u>Reinforced Concrete Hydraulic Seal</u>

Figures 12 and 13 show a proposed design for a reinforced concrete hydraulic seal. The seal was designed by the Ebensburg Office of the Pennsylvania Department of Environmental Resources[16] and is to be constructed at the Essen No. 2 Mine, Chartiers Creek Watershed, Allegheny County, Pennsylvania, as part of Operation Scarlift Project SL 102-6. Construction of this type of seal requires excavation of a hitch within the mine heading to firmly anchor the seal. In addition to the hitch, mine timbering and the construction of form walls are necessary. Pressure curtain grouting will be extended a minimum of 50 feet on both sides of the mine entry. The grout curtain holes drilled from the surface will be on ten (10) foot centers on alignment with the seal.



AGGREGATE PLUG DETAIL - MINE 40-016

FIGURE 11

From: Halliburton Co.(7)

TABLE 7

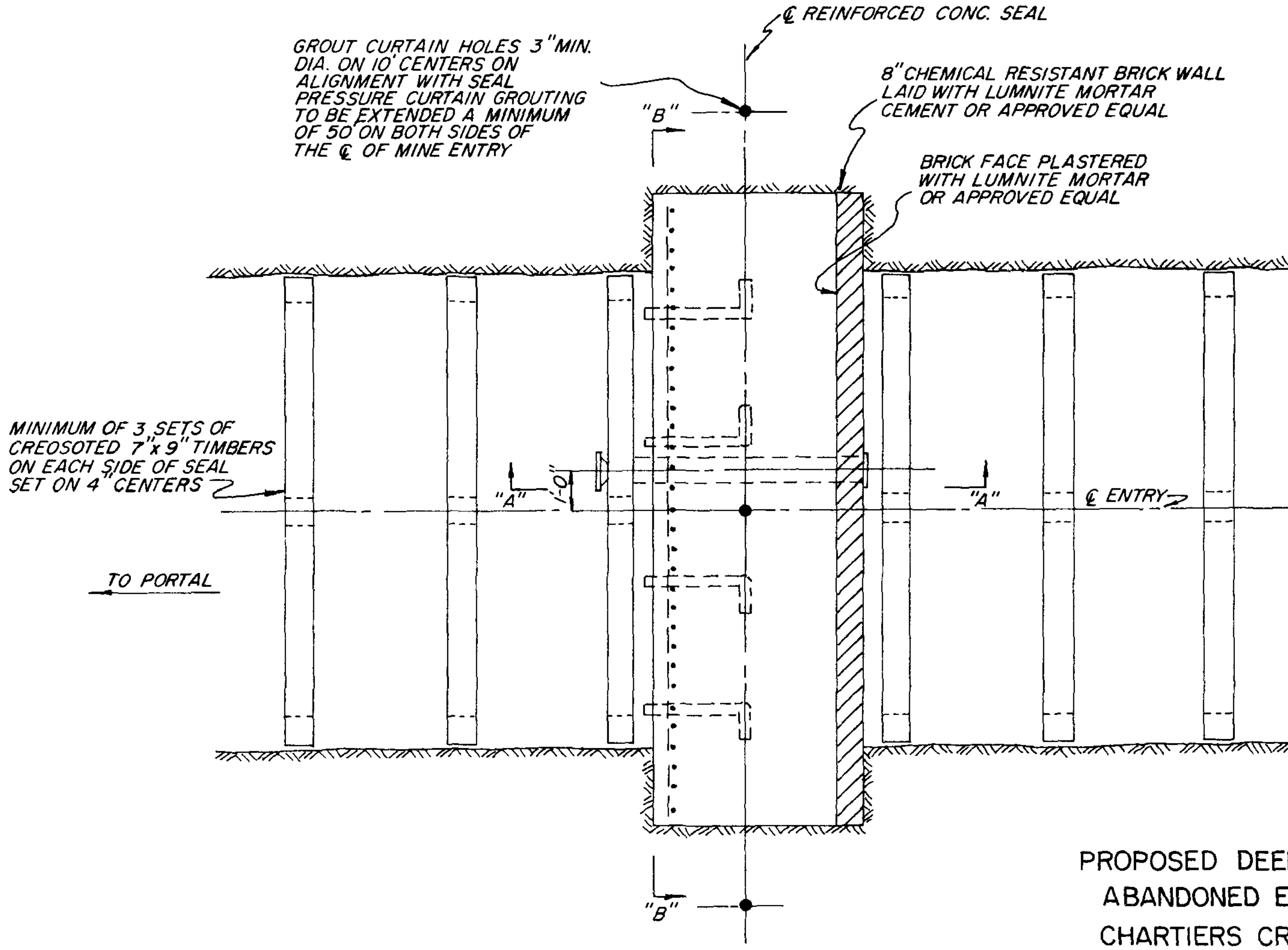
COST DATA

Grouted Limestone Aggregate Seals
Mine No. 40-016, Two Openings
Harrison County, West Virginia

Cleaning	Equip. Rental	--	$ 267.00
	Labor @ $5.00/Hr.	24 Hours	120.00
	Total		$ 387.00
Aggregate Placement	Equip. Rental	---	$ 3,060.00
	Material @ $3.30/Ton	300 Tons	990.00
	Labor @ $5.00/Hr.	128 Hours	640.00
	Total		$ 4,690.00
Aggregate Grouting	Equip. Rental	---	$ 1,322.00
	Material	---	3,260.00
	Labor @ $5.00/Hr.	144 Hours	720.00
	Total		$ 5,302.00
Additional Remedial Grouting Work	Equip., Materials and Labor	---	*$ 6,007.00
	Site Preparation and Restoration	---	1,310.00
	Total		$ 7,317.00
Total Cost for 2 Openings			$17,696.00
Cost per Opening			$ 8,848.00

*Drilling and preparation of grout holes accounted for $1,468.00 of this cost.

Source: Halliburton Co.[7] and Wenzel[15]

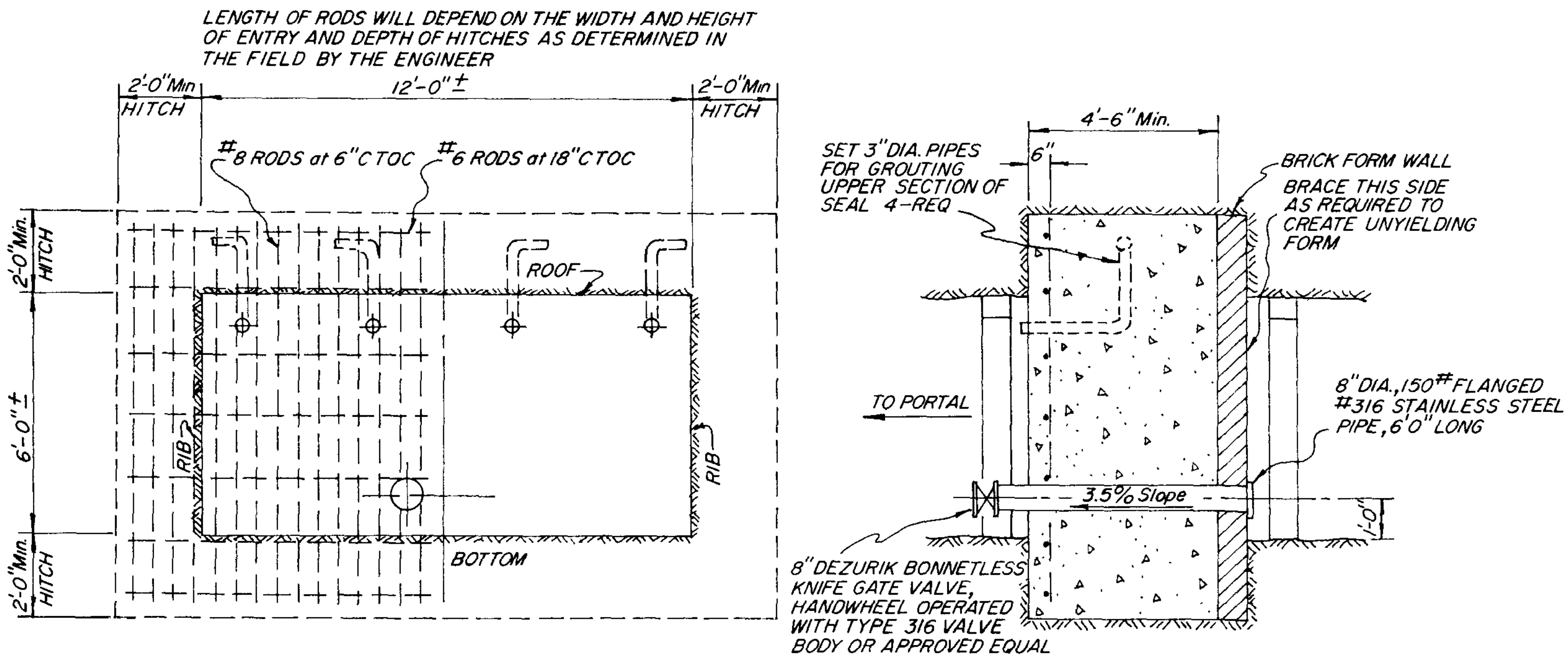


PLAN VIEW

FIGURE 12

PROPOSED DEEP MINE SEAL FOR
ABANDONED ESSEN NO. 2 MINE
CHARTIERS CREEK WATERSHED
ALLEGHENY COUNTY, PENNSYLVANIA
OPERATION SCARLIFT PROJECT NO. SL 102-6

Source:
Penna. Dept. of Environmental Resources[16]



SECTION "B-B"

SECTION "A-A"

PROPOSED DEEP MINE SEAL FOR
ABANDONED ESSEN NO. 2 MINE
CHARTIERS CREEK WATERSHED
ALLEGHENY COUNTY, PENNSYLVANIA
OPERATION SCARLIFT PROJECT NO. SL 102-6

Source:
Penna. Dept. of Environmental Resources[16]

FIGURE 13

The project has not gone out for bids as yet and engineers estimates were not available. However, the total cost, including construction of a minimum of 100 feet of grout curtain, should be between $15,000 to $20,000.

Summary of Costs for Sealing Accessible Mine Openings

The following list summarizes available recent information on actual and anticipated costs for sealing accessible mine openings including remedial grouting costs.

Type of Hydraulic Seal	Location	Total Cost
Quick Setting Double Bulkhead Seal - Mine 62-008	Harrison County, West Virginia	$ 9,449.00
Quick Setting Double Bulkhead Seal - Mine RT5-2	Harrison County, West Virginia	$ 9,463.00
Quick Setting Single Bulkhead Seal - Mine 62-008	Harrison County, West Virginia	$ 3,564.00
Expendible Grout Retainer Seal - Mine 14-042A	Harrison County, West Virginia	$18,000.00 (Estimated)
Grouted Aggregate Seals (Two Seals) Mine 40-016	Harrison County, West Virginia	$ 8,848.00/ seal
Reinforced Concrete Seal Essen No. 2 Mine	Allegheny County, Pennsylvania	$15,000.00 to $20,000.00

The cost of sealing accessible mine openings varies greatly and depends on site conditions and type of seal proposed. The work performed by Halliburton Company was experimental and in most cases was not effective in completely sealing a mine. It appears successful mine sealing requires curtain grouting because the rock above and to either side of the mine opening is usually fractured allowing flow from the sealed mine.

Using one of the Halliburton methods of seal construction, drift mines probably can be sealed at an average cost of $10,000 including remedial grouting, if a small flow from the mine can be tolerated. How long these seals will be effective is not known and it is possible substantial flows may occur from openings in a few years.

A more permanent, water tight seal such as the one proposed by the Pennsylvania Department of Environmental Resources for Essen Mine No. 2 could cost as much as the average grouted double bulkhead seal installed at inaccessible mine entries in Moraine State Park and Slippery Rock Creek.

Estimated Cost for Grouted Double Bulkhead Seal

The following is a tabulation of average unit and quantity costs for construction of grouted double bulkhead seals at abandoned mines based on costs for the 93 seals installed at Moraine State Park and Slippery Rock Creek.

	Item	Unit	Unit Price	Quantity	Cost
1.	Mine Sealing	Seal	$8,000.00	1	$ 8,000.00
2.	Observation Drill Holes				
	a) Drilling 6" Holes	L.F.	4.00	80	320.00
	b) Casing Left in Place	L.F.	3.20	40	128.00
3.	Curtain Grouting				
	a) Drilling 3" Min. Holes	L.F.	2.50	1,700	4,250.00
	b) Cement for Grouting	Sacks	5.70	900	5,130.00
	c) Fly ash for Grouting	Tons	15.00	75	1,500.00
	d) Sand for Grouting	Tons	20.00	1	20.00
	e) Admixture for Grouting	Sacks	4.00	3	12.00
	f) Pressure Testing	Hours	20.00	8	160.00
4.	Mobilization & Demobilization	L.S.	1,000.00	1	1,000.00
	Total Cost per Seal				$20,520.00

Based on this tabulation, an estimated cost of $21,000 per seal should be used when applied to the Monongahela River Basin to allow for increased construction costs.

Factors Affecting Cost of Hydraulic Mine Seals

Important factors that can affect the cost of hydraulic mine sealing projects are:

1. Condition of portal
2. Degree of fracturing in rock adjacent to portal
3. Thickness of overburden above mine roof
4. Width of barrier between outcrop and mine workings
5. General character of rock along outcrop
6. The maximum hydraulic head that can develop after mine sealing
7. The availability of accurate mine maps
8. Accessibility of project area and haul distances

9. Site preparation

10. Type of seal to be constructed

11. Availability and costs of materials, equipment and labor

LIMESTONE BARRIER MINE SEALING (PERMEABLE PLUG)

The principle involved in design of a permeable plug of graded limestone aggregate is in-place treatment of acid mine drainage as it passes through the plug. The aggregate must be so graded that acid mine water flowing through the plug has sufficient retention time to be partially or completely neutralized. As acid water reacts with the limestone, iron hydroxide and possibly calcium sulfate are precipitated and eventually the aggregate void spaces are filled. The final result is a solid plug which seals the mine.

It is difficult to classify a permeable plug seal because of its assumed changing characteristics. If the plug performs according to design assumptions, there is an initial reduction in volume of discharge and an improvement in quality of the mine water which is discharged. At this stage it cannot be compared with an air seal because air can enter the mine through aggregate void spaces, and in addition, mine water is being treated. As precipitates form, there should be further reductions in mine water discharges. Theoretically, the end result is a hydraulic seal.

Research and development for design of a permeable plug was performed by the Halliburton Company[7] under contract to the Environmental Protection Agency. Extensive laboratory tests and research followed by field tests indicated this type of seal showed promise. Two drift mines in Harrison County, West Virginia were sealed with permeable plugs as part of this study.

Mine No. 62-008, Opening No. 3

This mine near Clarksburg, West Virginia had a flow of about 3 gallons per minute, a pH of 3 and on acidity of 300 mg/l. Placement of AASHO No. 8 aggregate was performed pneumatically. The completed seal filled the mine entry for a length of 36 feet at the base and 25 feet at roof contact. The drift measured 52 inches by 12 feet. A total of 67 tons of limestone aggregate was emplaced. The construction cost was $3,048.00 as follows:

Item	Cost
Site Preparation	$ 756.00
Materials	237.00
Equipment and Operators	2,055.00
Total	$3,048.00

Monitoring of the water flowing through the limestone plug showed a reduction in acidity to 112 mg/l and an increase in pH (6.3 to 6.9), but there was no reduction in flow from the mine.

Mine No. RT5-2, Opening No. 2

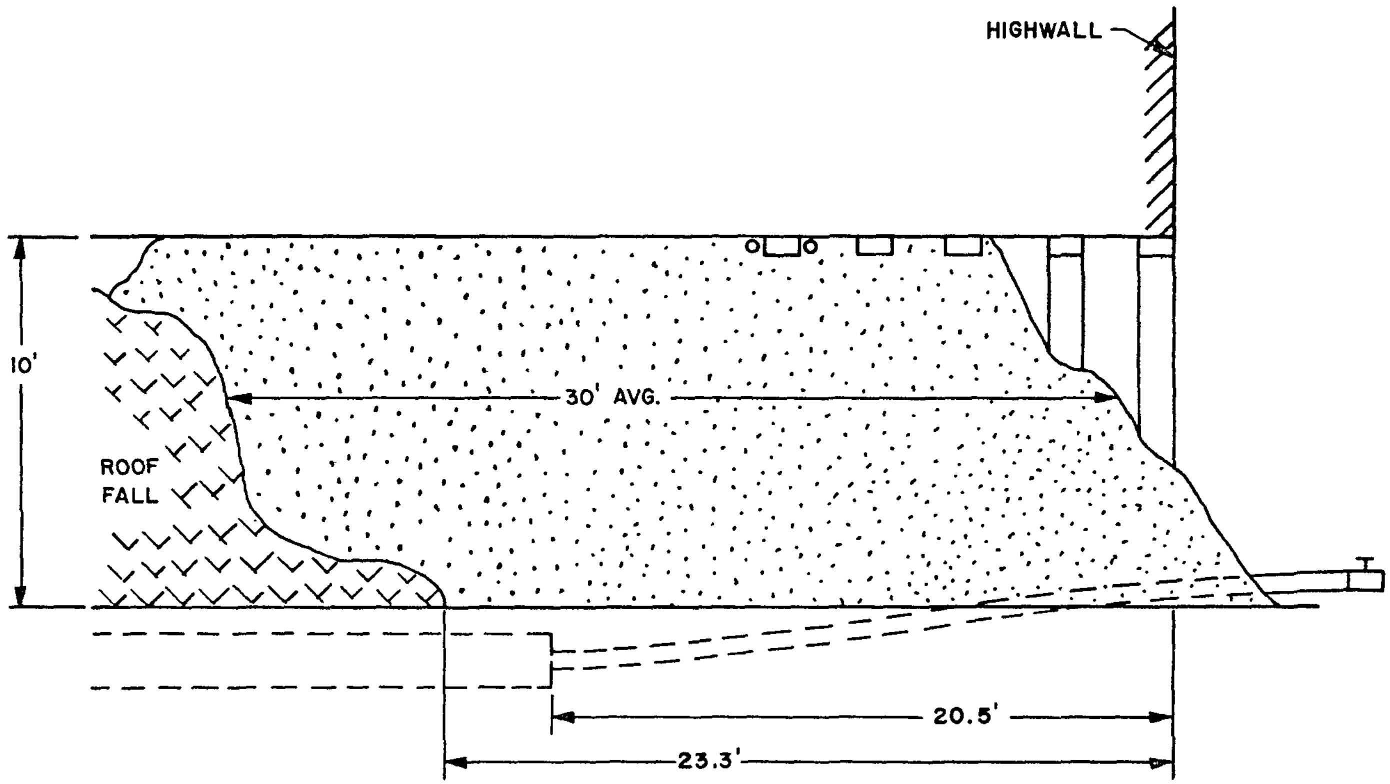
The second permeable plug was constructed at Opening No. 2 of Mine RT5-2. This opening was discovered after Opening No. 1 had been successfully sealed with a quick setting double bulkhead seal. The opening was filled with AASHO No. 8 crushed limestone blended with approximately 15% agricultural lime. The aggregate was pneumatically placed against a roof fall and 165 tons of material was emplaced. The pneumatic placement was hampered by the extreme amount of dust created when the limestone was blown into the mine drift. In order to combat this problem, the ratio of lime dust was later reduced to 10% and a pump was used to spray a jet of water. This helped to some degree, but the dust problem was still bad.

The upper portion of the limestone plug was grouted using approximately 100 cubic feet of Halliburton LIGHT Cement slurry. This was done to insure a seal along the roof section. Figure 14 presents a section view of the seal and Figure 7 is a plan view showing the relationship of Openings No. 1 and No. 2. A retaining wall was built in front of the opening with a 90 degree weir to measure flow rate. The graded aggregate seal was constructed at a cost of $8,463.00.

Item	Cost
Site Preparation	$3,447.00
Materials	1,696.00
Equipment and Operators	3,320.00
Total	$8,463.00

The cost was higher than the previous seal of this type because of excessive excavation required to prepare the opening, the extra materials required for grouting the upper section and a corresponding increase in the necessary equipment.

Monitoring of the completed installation showed the initial flow of 25 gallons per minute with a head of 3.3 feet of impounded water diminshed to a flow of 3.6 gallons per minute with a head of 5.44 feet in about 24 days. Analyses made of the mine water discharge before and after installation of the seal indicate a marked improvement in water quality.



SECTION VIEW OF SEAL - OPENING NO. 2

FIGURE 14

From: Halliburton Co.(7)

	Before Sealing	After Sealing
pH	2.9 to 3.2	5.6 to 6.3
Acidity	512 to 765 mg/l	0 to 102 mg/l
Iron	104 to 282 mg/l	36 to 57 mg/l
Sulfate	868 to 1,152 mg/l	780 to 940 mg/l

It is difficult to estimate an average unit cost for this type of seal because only two have been constructed as part of a demonstration project. A unit cost per mine seal of $7,500.00 is recommended for estimating purposes in the Monongahela River Basin.

DRY MINE SEALS

An effective mine sealing program requires the sealing of all openings and surface areas which permit passage of air and water into the mine. If a mine has an acid discharge at one or more openings, dry seals are used in conjunction with air, hydraulic or permeable plug seals to seal the openings which do not have a discharge. In the case of a hydraulic seal, the hydrostatic head that is developed should not cause significant hydrostatic pressure in the area of a dry seal.

Dry sealing can be defined as the complete closure of mine drifts, slopes, shafts, subsidence areas, fractures and other openings with impermeable material or structures at locations where there will be very little or no hydrostatic pressure. Dry mine seals can be of concrete block or masonry construction or openings can be filled with clay, concrete or other suitable materials. This type of sealing is generally confined to openings on the "high" side of the mine where the body of the mine workings lie to the dip.

The cost of a dry seal can vary greatly and the cost will depend on the opening to be sealed, its extent, condition and accessibility and the material used in construction. Drifts, shafts, subsidence areas and surface areas with fractures that allow passage of air and percolation of water into the mine may only require a fill or a covering of impervious material. Although the cost of this work could be measured on a cubic yard basis, the work is usually performed for a lump sum fee for the job, i.e., so many areas to be sealed. An example would be the dry mine sealing performed at Moraine State Park in conjunction with the hydraulic sealing program. This work involved the sealing of a total of 23 air shafts, drifts and other openings scattered throughout the area using available clay and other suitable materials. The lump sum fee was $28,000 or an average cost per seal of $1,217. This cost also included soil treatment and seeding of sealed areas.

Hill[4] reports that 450 subsidence holes were filled and 101 seals constructed as part of the Elkins Demonstration Project in West Virginia. A total of 41 openings were sealed with clay, but cost data was recorded for only two areas containing a total of 16 openings. The costs are based on the rental of equipment. The cost data for the 16 compacted clay seals as presented in Scott, et al.(17) is:

Work Area	No. of Seals	Cu. Yds. Compacted Backfill	Total Cost	Cost per Seal	Average Cu. Yd./ Seal	Cost/ Cu. Yd.
1-9	10	10,490	$ 9,500	$ 950	1,049	$0.91
10	6	11,670	$14,160	$2,360	1,945	$1.21
	16	22,160	$23,660	$1,479	1,381	$1.07

The cost per cubic yard of material for Work Area 10 was higher because the haulage distance from the borrow area was greater.

The cost of a masonry dry mine seal will depend on several factors, such as: 1) accessibility of the mine, 2) condition of the mine opening, 3) method of construction, 4) the volume of materials required including necessary timber, and 5) other items pertinent to seal construction. Recent costs are available for two projects where masonry dry seals were installed.

As part of the Elkins Demonstration Project(17), a total of 43 masonry dry seals were constructed. Seal construction consisted of a single solid wall of two courses of fly ash blocks and the seals were coated on both sides with urethane foam. Mine openings were timbered to keep the weight of the roof off the seals. The average cost per seal was $2,210 and costs per individual seal ranged from $1,358 to $6,376.

Seven masonry dry seals were installed at a mine site northeast of Pittsburgh in 1966 under the direction of the U.S. Bureau of Mines(8). The seals were erected on concrete footers and hitched 12" into ribs and roof. The seals were of double-wall, cored concrete block construction with 25 percent of the cement replaced by fly ash. A 2" space between the courses was filled with urethane foam. Urethane foam was also used to coat the inby and outby faces of the seals and to fill the hitch spaces. The average cost per seal was $5,089.

AIR MINE SEALS

Air mine sealing remains a controversial water pollution abatement measure. At some abandoned mine sites, air sealing has resulted in a significant reduction in acidity of the discharge, but at other mine sites there has been very little or no reduction in acidity in spite of an extensive air sealing program. It appears that the thickness and competence of the overburden above the mine are important factors in the success or failure of an air sealing project. As pointed out by Hill(4), air sealing was not successful at Elkins because a reduction in acidity cannot be expected in sealing a large complex mine with a tendency for subsidence. Moebs and Krickovic(8), on the other hand, were successful in reducing the acidity of a discharge from a mine that had a competent rock overburden and only one subsidence depression, whereas at Elkins, 450 subsidence holes had to be filled.

Conventional air sealing entails the closing of all openings to the mine with impermeable material or structures, except that an air trap is placed in one or more of the lower seals. Air sealing requires a comprehensive program of engineering which may be difficult and expensive under adverse conditions, with no guarantee of total success[8]. It is the opinion of Moebs and Krickovic[8] that abandoned mines above drainage which are discharging acid water should be evaluated as individual projects and if the geological conditions are favorable, they should be air sealed and have water diverted from them to the fullest extent practicable.

The method of construction of air seals at Elkins, West Virginia was essentially the same as for masonry dry seals, except that air seals had two or three walls. One of the walls was solid, except for two blocks being removed from the base. The outer wall was constructed to a higher elevation than the opening in the inner wall in order to form a water trap that would prevent air from entering the mine. A total of 12 air seals were installed and the average cost was $4,076 per seal. Costs per individual seal ranged from $3,128 to $5,032.

The U.S. Bureau of Mines project[8] sealed a small, abandoned, highly acid drainage drift about 40 miles northeast of Pittsburgh. The mine is representative of those which are responsible for about 35 percent of the stream pollution in the coal regions of Appalachia. The following topographic and geologic conditions made the mine favorable for air sealing:

1. The mine was overlain by competent siltstone and sandstone.

2. The overburden was 100 to 200 feet thick over more than 50 percent of the area above the mine.

3. Mine roof conditions were very good.

4. Most of the pyritic sulfur from which acid is formed occurs in the bottom portion of the coal bed and in the top layer of the underclay.

In addition to the installation of the seven masonry dry seals at this mine, one masonry air seal of similar construction was installed along with the two barriers to form the air traps. The entry width was 22 feet and the height was 5 feet. Figure 15 shows the general arrangement of an air seal. The cost of the air seal was $14,800.

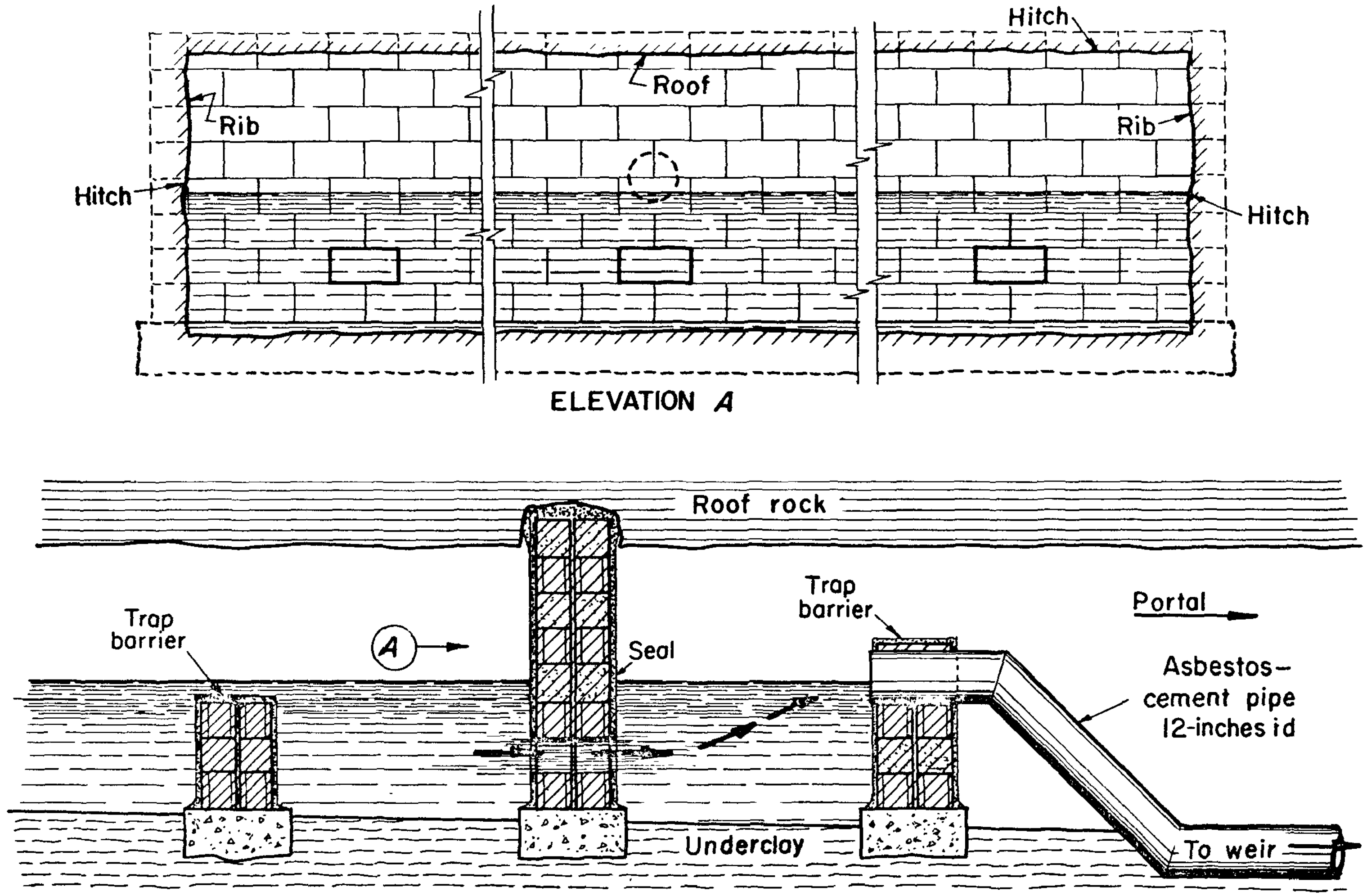


FIGURE 15
GENERAL ARRANGEMENT OF AN AIR SEAL

From: Moebs and Krickovic(8)

The total cost for sealing and related work and reclamation was $57,420 on this project and is itemized as follows:

Seals and related work:	
Timber, treated (24,390 bd ft)	$ 5,146
Urethane foam, 2,000-lb (755 sq ft)	3,510
Masonry blocks (2,002)	524
Pipe (167 ft)	528
Concrete (28 cu yd)	504
Miscellaneous	288
Total material	$10,500
Equipment, including operator	8,960
Labor (5,000 man-hours)	30,000
Total	$49,460
Sealing 2 strip pits (3 acres), 1 surface subsidence depression, and 1 caved entry	$ 7,000
Grading access roads and portal areas	960
Total	$57,420

Of the $49,460 for seals, 61 percent was spent for labor, 21 percent for materials, and 18 percent for equipment. Equipment costs were chiefly related to excavation and cleanup of the entries in which seals were constructed and to grading for drainage and stability around the portals. The significant quantities and costs of materials used were as follows:

Material	Unit	Quantity	Cost
Urethane foam per seal	lb.	222	$390
Timbering per sealed entry	bd. ft.	3,060	340
Masonry blocks per seal	each	222	58
Concrete footers per seal	cu. yd.	2.8	54

As a result of the mine sealing the acid load was reduced an average of 12 tons per year. The mean total acidity for a 2 year, 7 month period before sealing was 514 mg/l and for a 2 year, 8 month period after sealing it was 211 mg/l, an improvement in quality of 303 mg/l. The average monthly maximum total acidity after-sealing was 247 mg/l, which is well below the minimum of 331 mg/l before sealing. Figure 16 shows the average monthly total acidity and flow rate of the mine effluent before and after sealing.

A somewhat lower volume of effluent after mine sealing indicates the quantity of water directly entering the mine from the surface through entries was less.

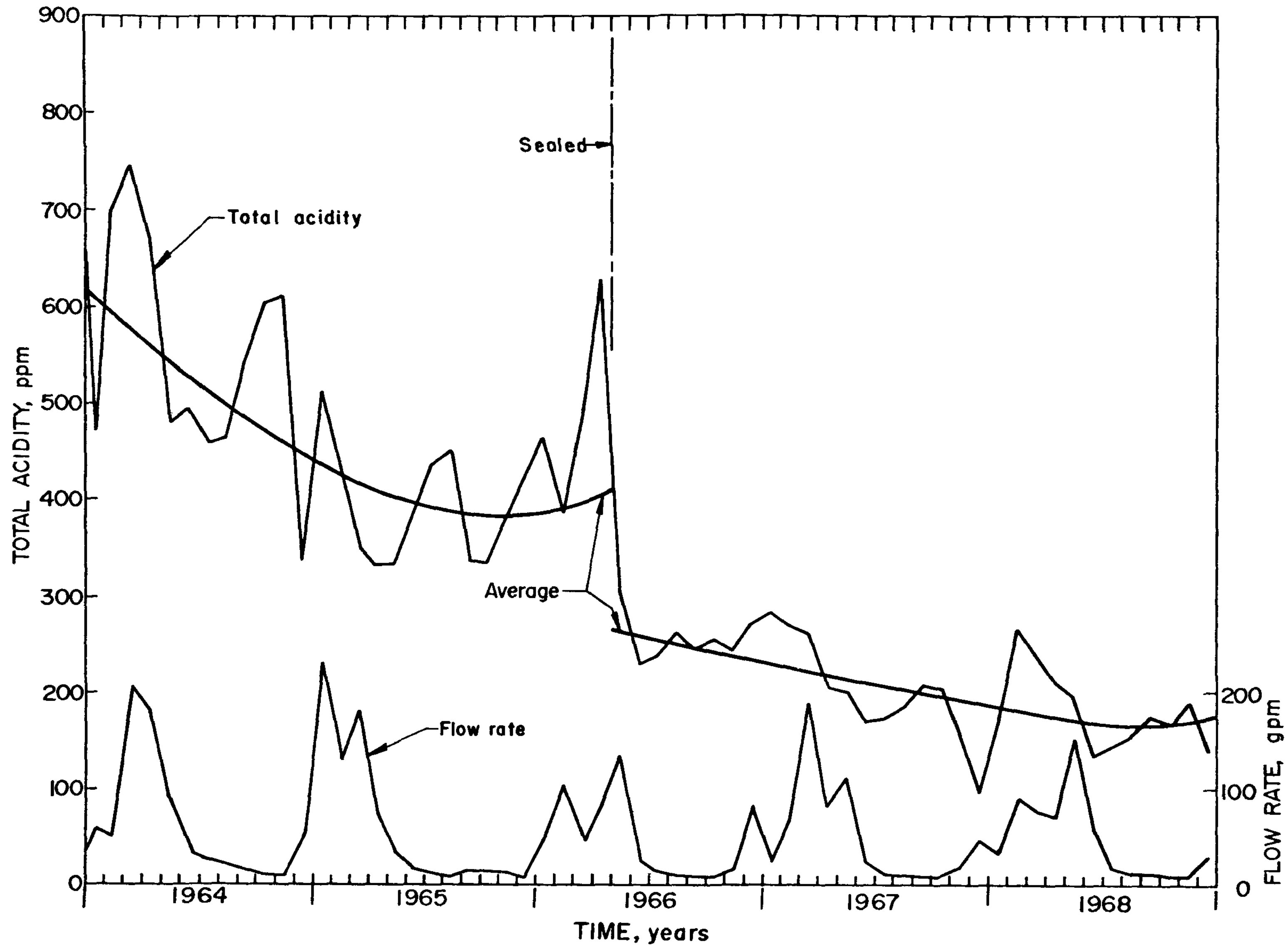


FIGURE 16 - Average Monthly Total Acidity and Flow Rate of the Mine Effluent.

From: Moebs and Krickovic[8]

There is no doubt air sealing was effective in reducing acidity and effluent volume, but it is interesting to conjecture what degree of abatement would have occurred, if after dry sealing the mine, a permeable plug of limestone aggregate was installed instead of an air seal. A demonstration project utilizing the permeable plug principle at a small abandoned mine with similar topography and geology may be rewarding.

SUMMARY OF COSTS FOR DRY AND AIR SEALS

The following tabulation summarizes available recent cost data for dry and air mine sealing:

Type of Seal	Project	No. of Seals	Aver. Cost per Seal	Range in Cost
Dry Seal (Clay)	Moraine S.P.	23	$ 1,217	---
	Elkins	16	1,479	---
Dry Seal (Masonry)	Elkins	43	$ 2,210	$1,358-$6,376
	Bur. Mines	17	5,089	
Air Seal (Masonry)	Elkins	12	$ 4,076	$3,128-$5,032
	Bur. Mines	1	* 14,800	

*The entry was 22 feet wide.

For general estimating purposes in the Monongahela River Basin it is suggested that the following average costs per seal be used:

Dry Seal (Clay)	$1,500
Dry Seal (Masonry)	$3,500
Air Seal (Masonry)	$5,000

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STREAM DIVERSION

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STREAM DIVERSION

Introduction

Water diversion is frequently utilized in active surface and deep mine operations to ease the physical and financial burden of pumping large quantities of water. In surface mining operations the most commonly used method is to construct a ditch on the uphill (highwall) side of the open cut. Other methods used in surface mining are 1) diversion of streams into new channels to prevent seepage into or flooding of the work area, and 2) construction of trenches or installation of pipes at the downhill side of the open cut to remove water as quickly as possible. Preventing the infiltration of surface waters into deep mine workings is much more complicated, but can be accomplished to a certain extent by diversion of stream channels or the lining of stream channels with impervious materials where they cross over deep mine workings.

When water comes in contact with oxidized sulfuritic materials, acid mine waters are produced. A considerable quantity of acid mine drainage can be prevented by diverting stream waters from sources of acid pollution. This is particularly true when the water course upstream of the pollution source is relatively unpolluted.

If the stream flow cannot be diverted into a new channel because of topographic limitations, it is usually feasible to reconstruct the channel so that the flow will be more efficient, thereby reducing contact time with the acid material. The channel can be lined with impervious material and in cases where there is seepage or flow into a deep mine it can be prevented by sealing the mine opening with clay or other suitable materials.

Cost of Stream Diversion

This section of the report is concerned with the cost of preventing acid mine drainage pollution by diverting stream flow away from surface and deep mines which are pollution sources. Only three stream diversion projects were found among the many projects performed by the Commonwealth of Pennsylvania under the Operation Scarlift Project program. The projects were in different areas of Pennsylvania, have significant lengths of channel construction and the volumes of excavation appear to be representative of what can be expected in this type of project. The cost per lineal foot of channel ranged from $12.00 to a high of $27.00 including all supplemental costs. Table 1 presents the pertinent data on these projects.

The cost experience in mine related stream diversion projects is limited, but there is, however, a large amount of applicable experience available in construction of channel changes for streams in connection with highway projects. This cost information is difficult to isolate because equipment needs are not separated in the mass contracts. It is estimated, however, that the costs should approximate the following:

Soil and shale excavation	- $0.80/C.Y.
Premium for rock excavation	- $0.50/C.Y.
Equipment costs	- $0.35/C.Y.

In addition to these costs, the channel slopes whould be seeded with a grass-legume mixture at an estimated cost of $450 per acre of slope area.

For the Monongahela River Basin a cost estimate of $20.00/L.F. will allow for increased construction costs, channel slope grading, soil treatment and seeding.

TABLE 1

STREAM DIVERSION COSTS FOR OPERATION SCARLIFT PROJECTS

Project No.	SL 102-1-1	SL 135-1	SL 143-1
Location	Chartiers Creek Allegheny County	Catawissa Creek Luzerne County	Alder Run Clearfield County
Length (L.F.)	4,200	1,720	4,000
Avg. Depth (Ft.)	5	10	5
Excavation Quantity (C.Y.)	11,000	17,300	107,000
Unit Price (C.Y.)	$1.50	$2.60	$0.61
Total Cost	$65,100	$30,500	$108,000
Cost per L.F.	$15.50	$12.00	$27.00

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TREATMENT OF MINE DRAINAGE

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TREATMENT OF MINE DRAINAGE

In the last few years, the technology of mine drainage treatment has been reviewed in a number of publications. An excellent review is "Mine Drainage Treatment, State of the Art and Research Needs" by Ronald D. Hill.[1] Most of the discussion in the first part of this section, particularly on mine drainage chemistry and the classification of mine drainage, was taken verbatim from Hill's publication.

CHEMISTRY AND CLASSIFICATION OF MINE DRAINAGE

The type of drainage produced by a particular mine is dependent upon the product mined and the nature of the surrounding geologic formation. In the case of coal mining, it is dependent upon the amount of sulfides present; the spatial distribution of these sulfides; the crystallinity of the pyrite; the size of the individual sulfide particles; the presence of bacteria associated with acid mine drainage; and the magnitude of the fluctuation of the water level within the mine, if the workings are below drainage. In addition, the presence or absence of calcium in the sulfide aggregates seems to have some effect upon the rate of sulfide oxidation and decomposition.

Wide variations exist in the chemical characteristics of mine drainage and some mine waters are decidedly acid whereas others are fairly alkaline. Generally, acid mine drainage can be said to have a low pH, net acidity (acidity greater than alkalinity), high iron (iron II and/or iron III), high sulfates and significant amounts of aluminum, manganese, calcium and magnesium. Alkaline mine drainage generally can be said to have a pH near or greater than neutrality, net alkalinity, high sulfate, significant calcium, magnesium and manganese, and low aluminum. Corbett and Growitz[2] reported that the zinc, cadmium, beryllium, copper, silver, nickel, cobalt, lead, chromium, vanadium, barium and strontium concentrations of coal mine drainage were less than 1 mg/l. Analyses of mine drainage samples collected in West Virginia and Pennsylvania by personnel from the Environmental Protection Agency revealed concentration of similar magnitude.

Although the exact mechanism is not fully understood, acid mine drainage results from the oxidation of pyrite (FeS_2) as illustrated in Equation (1):

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

Subsequent oxidation of ferrous sulfate produces a ferric sulfate:

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

The reaction may then proceed to form a ferric hydroxide or basic ferric sulfate:

$$Fe_2(SO_4)_3 + 6\ H_2O \longrightarrow 2\ Fe(OH)_3 \downarrow + 3\ H_2SO_4 \quad (3)$$

$$Fe_2(SO_4)_3 + 2\ H_2O \longrightarrow 2\ Fe(OH)(SO_4) + H_2SO_4 \quad (4)$$

Pyrite oxidation also occurs due to ferric iron as illustrated in equation (5):

$$14\ Fe^{+++} + FeS_2 + 8\ H_2O \longrightarrow 15\ Fe^{++} + 2\ SO_4^{=} + 16\ H^{+} \quad (5)$$

By either mechanism, an acid water is produced and the pH is lowered. At low pH's many metallic ions in the mine, for example aluminum and manganese, become more soluble and enter into the mine discharge.

Mine drainage is a complex solution varying in quality from seam to seam, mine to mine, and even within the same mine. The water quality from mines low in pyrite may be alkaline and closely resemble ground water. Often mines produce water high in ferrous iron and acidity, indicating that reactions (1) and/or (5) are occurring. The discharge may have high ferric iron and acidity concentration, indicating that reactions (2) and (3) are occurring. The discharge may also have been partially neutralized within the mines thus reducing the acidity level.

Although there is no "typical" mine drainage, waters discharging from mines can be divided into four general classes as shown in Table 1.

The wide variations in mine drainage characteristics indicate that a number of treatment methods may be applicable. The best method for any one site will depend on the quality of the mine discharge and the ultimate use of the water. Treatment to meet stream water standards will be different from that needed to meet domestic and industrial water use standards.

The following mine drainage treatment methods are discussed:

1. Neutralization

    a) Acid mine water with high ferric iron content

    b) Acid mine water with high ferrous iron content

    Methods of oxidizing ferrous ion to ferric ion will also be discussed.

2. Flash Distillation

3. Ion Exchange

4. Reverse Osmosis

5. Submerged Coal Refuse Combustion Process

TABLE 1
CLASSIFICATION OF MINE DRAINAGE

	Class I Acid Discharges	Class II Partially Oxidized and/or Neutralized	Class III Oxidized and Neutralized and/or Alkaline	Class IV Neutralized and Not Oxidized
pH	2 - 4.5	3.5 - 6.6	6.5 - 10.5	6.5 - 8.5
Acidity mg/l $CaCO_3$	1,000 - 15,000	0 - 1,000	0	0
Ferrous Iron mg/l	500 - 10,000	0 - 500	0	50 - 1,000
Ferric Iron mg/l	0	0 - 1,000	0	0
Aluminum mg/l	0 - 2,000	0 - 20	0	0
Sulfate mg/l	1,000 - 20,000	500 - 10,000	500 - 10,000	500 - 10,000

Source: In-house Studies, Environmental Protection Agency
After Hill[1], 1968

6. Freezing

7. Electrodialysis

8. Foam Separation

9. Neutradesulfating Process

NEUTRALIZATION

Principle of Neutralization - In the neutralization process an alkali is mixed with acid mine waters to neutralize the acid and to precipitate the contaminating metal salts, which can then be separated by sedimentation and/or filtration. The metal salts commonly found in acid mine drainage are separated because they are less soluble at neutral or higher pH's than at lower pH's.

Neutralizing Agents - The list of neutralizing agents suggested for acid mine drainage is presented in Table 2. While most neutralization work to date has utilized lime and limestone, other agents may be used successfully in some situations.

The choice of an alkaline agent should be based on the following considerations:

a) Cost of Agent - The cheapest agent capable of fulfilling the requirements should be used.

b) Availability of Agent - Availability is partially reflected in cost. The availability of certain alkaline materials, such as a by-product of another industry, may not be available over a long term.

c) Basicity Factor - The amount of alkali per unit weight of material varies among different alkaline agents. Basicity factor is defined as the grams of calcium carbonate equivalent per gram of alkaline agent. The basicity factor is a useful tool in comparing the cost of alkaline agents. The basicity factors for some commonly used alkaline agents are given in Table 2.

d) Reaction Time - The reaction rates of alkaline agents vary over a considerable range and are important factors in the size of mixing tanks, etc.

e) Sludge Characteristic - The settling rate and properties of the sludge are important factors in the design of settling tanks and lagoons, and in the disposal of the sludge.

TABLE 2

LIST OF NEUTRALIZING AGENTS
SUGGESTED FOR ACID MINE DRAINAGE TREATMENT

Neutralizing Agents		Basicity Factor*
Calcium Oxide (Quick Lime)	CaO	1.78
Calcium Hydroxide (Hydrated Lime)	$Ca(OH)_2$	1.35
Calcium Carbonate (Limestone)	$CaCO_3$	1.00
Calcium Magnesium Carbonate (Dolomite)	$(Ca\text{-}Mg)CO_3$	$1.09^{\pm}$
Magnesium Oxide	MgO	2.48
Magnesium Hydroxide	$Mg(OH)_2$	1.72
Sodium Hydroxide (Caustic Soda)	$NaOH$	1.25
Sodium Carbonate (Soda Ash)	Na_2CO_3	0.94
Sodium Sulfide	Na_2S	**
Potassium Hydroxide	KOH	0.89
Potassium Permanganate	$KMnO_4$	**
Ammonia	NH_3	2.94
Ammonium Hydroxide	NH_4OH	1.43
Trisodium Phosphate	Na_3PO_4	0.92

*Grams of Calcium Carbonate ($CaCO_3$) equivalent per gram of agent.

**Basicity factor will vary depending on cations present in the acid mine drainage.

Revised from Hill, 1968[1]

After treatment with calcium alkalis, the effluent has a higher hardness, may have a sulfate concentration up to 2,000 ppm, and may contain significant amounts of suspended solids depending on the solids separation technique. To the extent that acidity is removed and the soluble iron concentration reduced, neutralization with calcium based alkalis is successful.

The use of sodium based alkalis, such as soda ash and caustic soda, will effect a removal of acidity and iron. However, these alkalis are substantially more expensive to use. There is a major technical difference though, since sodium sulfate is a highly soluble salt, there is no reduction in sulfate content. The insoluble materials are iron and aluminum hydroxides and oxides and the volume of precipitates is less since sulfates are not removed from solution. The use of sodium based alkalis, however, does not add to effluent hardness as in the case of calcium based alkalis.

Many other alkaline materials could be used to neutralize acid mine drainage, but because of higher costs without commensurate advantages, these materials have not been used in other than laboratory experiments or small scale demonstration projects.

Coal mine drainage with a low pH, net acidity and dissolved iron can be neutralized with alkalis such as hydrated lime, limestone, caustic soda and soda ash. The neutralization process removes acidity and reduces the soluble iron concentration. The efficiency of the neutralization process depends on the alkali used, methods of application and the characteristics of the mine drainage.

The use of calcium alkalis, such as lime, hydrated lime and limestone will remove sulfate ions if the solubility product of calcium sulfate is exceeded. If neutralization is accompanied by aeration or other methods of oxidation, soluble iron salts will be removed as insoluble hydrated iron oxides. Thus, effluent solutions from such neutralization processes generally have no acidity or slight alkalinity, contain low concentrations of soluble iron, and have reduced sulfate concentrations if the original sulfate concentration exceeded about 2,000 ppm as calcium sulfate. Soluble aluminum salts are also removed from solution as precipitates of aluminum hydroxide.

Neutralization historically has been applied to Class I and II mine drainage (Table 1). Unslaked lime, hydrated lime and more recently limestone have been more widely used for neutralization, primarily because of lower costs.

Although neutralization and oxidation processes remove acidity and iron salts from acid mine drainage, significant technical problems exist in separating the precipitated solids. The sludge produced is characteristically difficult to filter and dewater. Sludge disposal is a serious consideration, since it is a pollutional waste. Disposal methods now in use include lagooning and disposal in abandoned dry mines. Accurate sludge handling and disposal costs have not been detailed well in the literature, although much information is available regarding the methods of sludge disposal and the factors involved in the consideration of each of these methods.

Chemistry of Lime Neutralization

Quick lime (CaO) and hydrated lime ($Ca(OH)_2$) have been used in the treatment of acid mine drainage. These limes may be either high-calcium or high-magnesium (dolomitic). The reactions of lime with acid mine drainage are illustrated in equations (6) through (10).

$$CaO + H_2O \rightarrow Ca(OH)_2 \quad (6)$$

$$Ca(OH)_2 + H_2SO_4 \rightarrow CaSO_4 + 2\ H_2O \quad (7)$$

$$3\ Ca(OH)_2 + Al_2(SO_4)_3 \rightarrow 3\ CaSO_4 + 2\ Al(OH)_3 \quad (8)$$

$$Ca(OH)_2 + FeSO_4 \rightarrow Fe(OH)_2 + CaSO_4 \quad (9)$$

$$3\ Ca(OH)_2 + Fe_2(SO_4)_3 \rightarrow 2\ Fe(OH)_3 + 3\ CaSO_4 \quad (10)$$

In addition to increasing the pH and decreasing the acidity, lime treatment will remove many of the metallic salts. Figures 1 and 2 show the solubility of aluminum, iron and manganese at various pH's. Aluminum and manganese will precipitate if the proper pH level is reached. Calcium sulfate will increase the hardness of the water until its maximum solubility is reached (approximately 2,000 mg/l), then it will precipitate. Ferrous hydroxide has a low solubility, which decreases as the pH increases. Ferric hydroxide is even less soluble and its solubility decreases at higher pH's. The oxidation of ferrous iron results in a decrease of the pH, which may result in an increase of the iron concentration because of the higher solubility of iron at lower pH's.

The addition of an alkaline agent will result in the conversion of ferrous sulfate to ferrous hydroxide and increase in pH. At the higher pH iron II will oxidize rapidly (Figure 3) to form insoluble ferric hydroxide. Holland, et el.[3], used lime in treating a mine discharge with high acidity and iron concentrations and found that a pH of 10.5 was needed to assure complete iron removal.

Chemistry of Limestone Neutralization

When iron sulfate salts are dissolved in a water medium the compounds undergo hydrolysis reactions to liberate the hydrogen ion. Hydrolysis is defined as a reaction of an ion with water to form an associated species plus H^+ or OH^-. The general equation for a cationic hydrolysis is:

FIGURE I

SOLUBILITY OF ALUMINUM, IRON AND MANGANESE IN ACID MINE DRAINAGE AT VARIOUS pH's

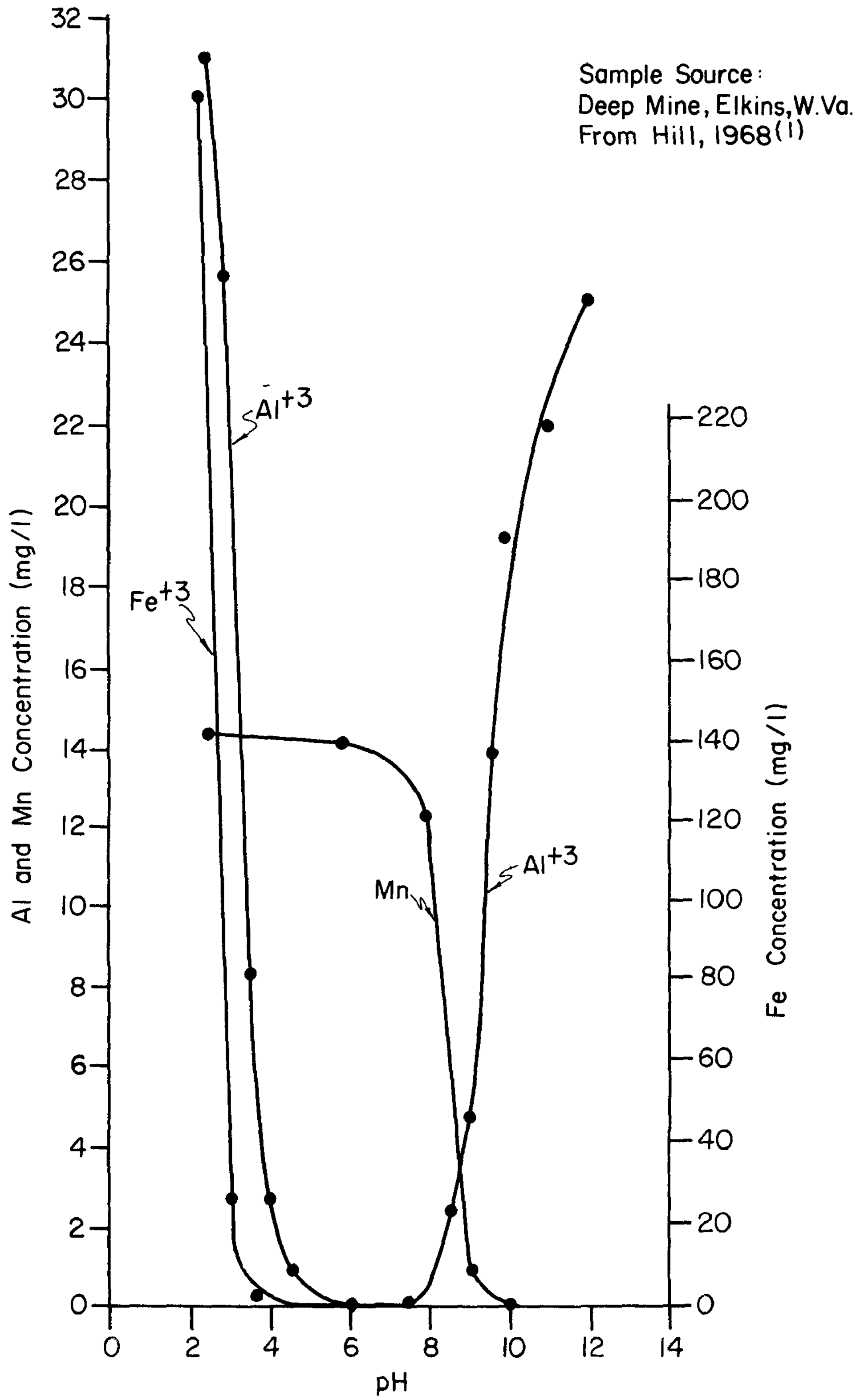
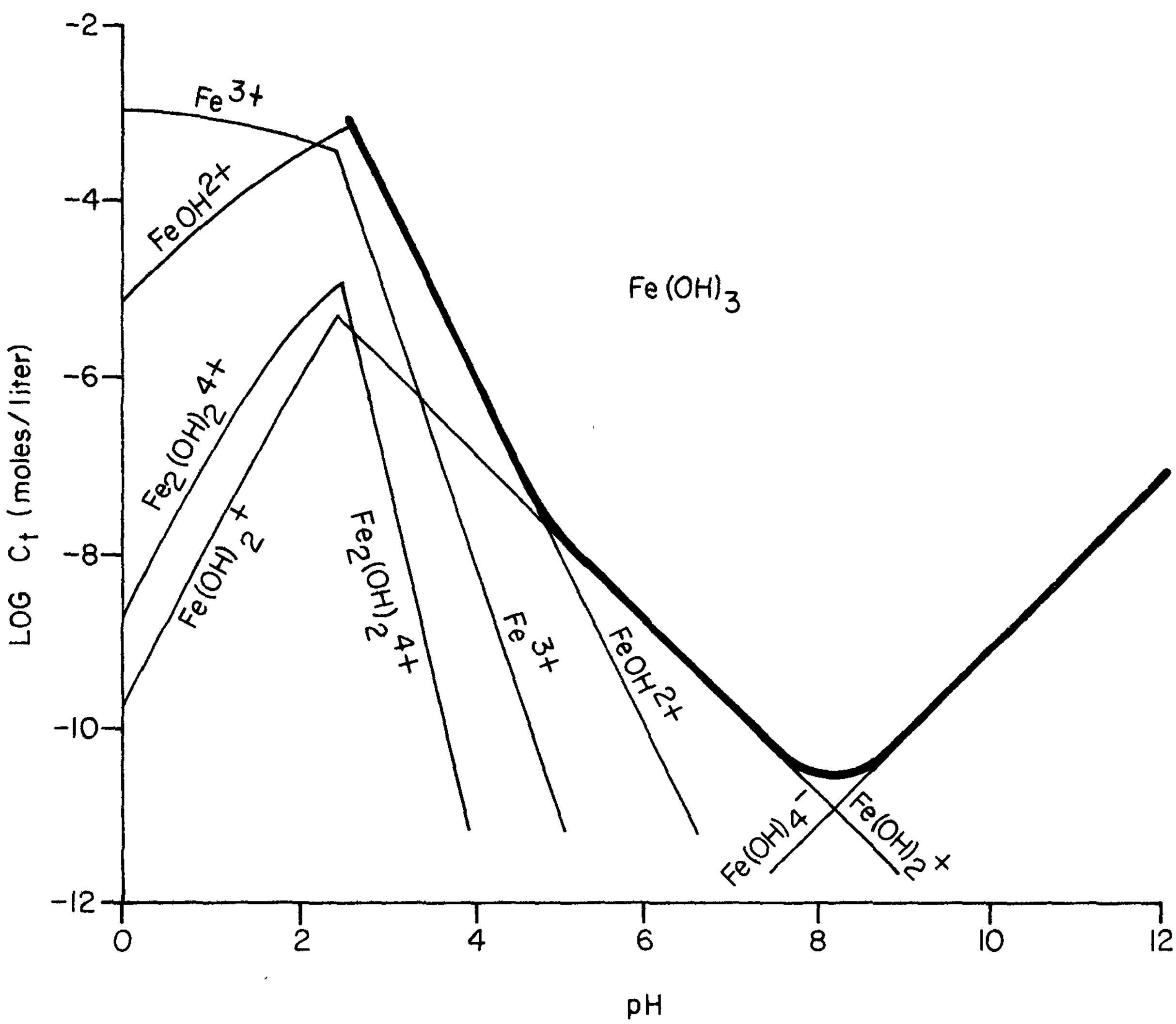


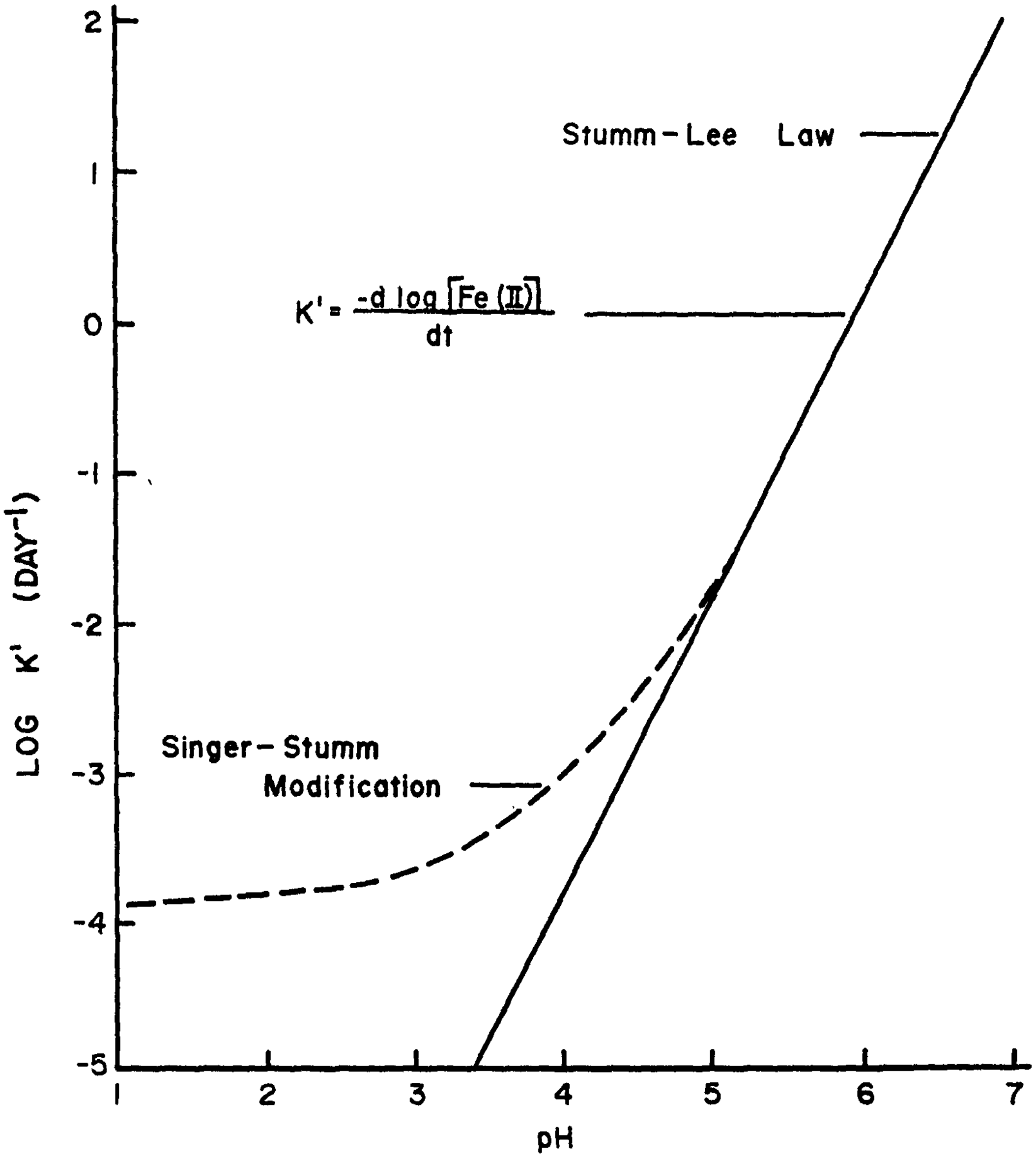
FIGURE 2

SOLUBILITY OF IRON



After O'Melia and Stumm, 1967[82]

FIGURE 3



IRON (II) OXIDATION RATE AT pH 2-7

After Singer and Stumm, 1968[83]
From Hill, 1968[1]

$$M^{+} + H_2O \rightleftharpoons MOH + H^{+} \qquad (11)$$

In the case of iron salts the reactions would be:

For ferrous iron

$$Fe^{+2} + H_2O \rightleftharpoons FeOH^{+} + H^{+} \text{ and} \qquad (12)$$

$$FeOH^{+} + H_2O \rightleftharpoons Fe(OH)_2 + H^{+} \qquad (13)$$

The net reaction would be

$$Fe^{+} + 2\ H_2O \rightleftharpoons Fe(OH)_2 + 2\ H^{+} \qquad (14)$$

For ferric iron

$$Fe^{+3} + H_2O \rightleftharpoons Fe(OH)^{+2} + H^{+} \qquad (15)$$

$$Fe(OH)^{+2} + H_2O \rightleftharpoons Fe(OH)_2{}^{+} + H^{+} \qquad (16)$$

$$Fe(OH)_2{}^{+} + H_2O \rightleftharpoons Fe(OH)_3 + H^{+} \qquad (17)$$

The net reaction being

$$Fe^{+3} + 3\ H_2O \rightleftharpoons Fe(OH)_3 + 3\ H^{+} \qquad (18)$$

These are equilibrium reactions and will go to completion (i.e. completely hydrolyzed) only if the hydrogen ion is pulled out of the equilibrium. This can be accomplished by neutralizing the hydrogen ion with a base.

Calcium carbonate in an acidic medium will undergo a reaction to form lime and carbon dioxide according to the equation:

$$CaCO_3 + H_2O \rightleftharpoons CaO + H_2CO_3$$

$$\text{where } H_2CO_3 \rightleftharpoons H_2O + CO_2 \qquad (19)$$

The lime will react with the hydrogen ion of the acid to neutralize it and form water plus the calcium salt of the acid.

$$CaO + 2\ H^{+} \longrightarrow Ca^{++} + H_2O \qquad (20)$$

For the case of ferric sulfate, the reactions would be

$$3\ CaO + 2\ H^{+} + SO_4^{=} \longrightarrow CaSO_4 + H_2O \qquad (21)$$

$$2\ Fe^{+++} + 3\ SO_4^{=} + 6\ H^{+} + 6\ OH^{-} \longrightarrow 2\ Fe(OH)_3 \downarrow + 6\ H^{+} + 3\ SO_4^{=} \qquad (22)$$

The reaction of calcium carbonate with acidic water to form calcium oxide, as an intermediate product, occurs at approximately pH 7 or lower. As the CaO reacts with free hydrogen ions (Equation 21), a resultant increase in hydroxal ions occurs.* This in turn results in attachment of a sufficient number of hydroxal ions (OH^- ions) to the ferric iron for precipitation of ferric hydroxide to occur, as indicated in Equation 22. In this reaction hydroxal ions are removed from solution by precipitation, and therefore, free hydrogen ions are released. These additional hydrogen ions are then neutralized according to Equation 21. The reaction of ferric iron in the above equations to form ferric hydroxide is essentially complete at pH 3.5.

In the case of mine waters high in ferrous iron, the addition of an alkali will precipitate all iron directly as ferrous hydroxide, $Fe(OH)_2$, only if a pH of 8.5 to 9.5 is reached. Since $CaCO_3$ is practically insoluble in neutral solutions, precipitation of ferrous iron by addition of limestone ($CaCO_3$) will not occur. If lime instead of $CaCO_3$ is used then the pH will rise to about 10 and all of the ferrous iron will precipitate.

It is obvious from the above chemistry, that ferrous iron must be oxidized to ferric iron with the formation of free acid before calcium carbonate can react to neutralize the mine water and precipitate all iron.

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*In all aqueous solutions any decrease in hydrogen ion concentration must result in an increase in the hydroxal ion concentration since the product of the two is a constant.

Neutralization of Mine Drainage with High Ferrous Iron Content

Extensive work has been accomplished in neutralization of acid mine drainage with high ferrous iron content. The following methods will be explored for their feasibility and cost:

1. BCR limestone treatment process.

2. U.S. Bureau of Mines limestone treatment process.

3. Combination limestone-lime treatment process.

4. Combination lime-limestone neutralization with rotary precoat filtration for sludge dewatering.

5. Electrochemical oxidation followed by limestone neutralization.

6. Ozone oxidation followed by limestone neutralization.

7. Biochemical oxidation followed by limestone neutralization.

BCR Limestone Treatment Process

As a result of extensive bench-scale tests, Bituminous Coal Research, Inc. [4,5], has developed a process whereby coal mine drainage containing ferrous iron can be treated with limestone. The process results in complete neutralization of acidity and removal of iron to acceptable limits.

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

A general concept of the limestone neutralization process is shown in Figure 4. The individual parts of the total system are: a) holding tank, b) pulverized limestone storage tank, c) limestone feeder, d) limestone reactor, e) aerator, f) settling tank, g) optional sludge recirculation, h) optional oxidation catalyst, and i) optional coagulant aid.

Advantages of Using Limestone

1. Lower costs per unit weight of chemical reagent necessary to neutralize the same quantity and quality of coal mine drainage.

2. Fewer safety problems in handling a less reactive reagent.

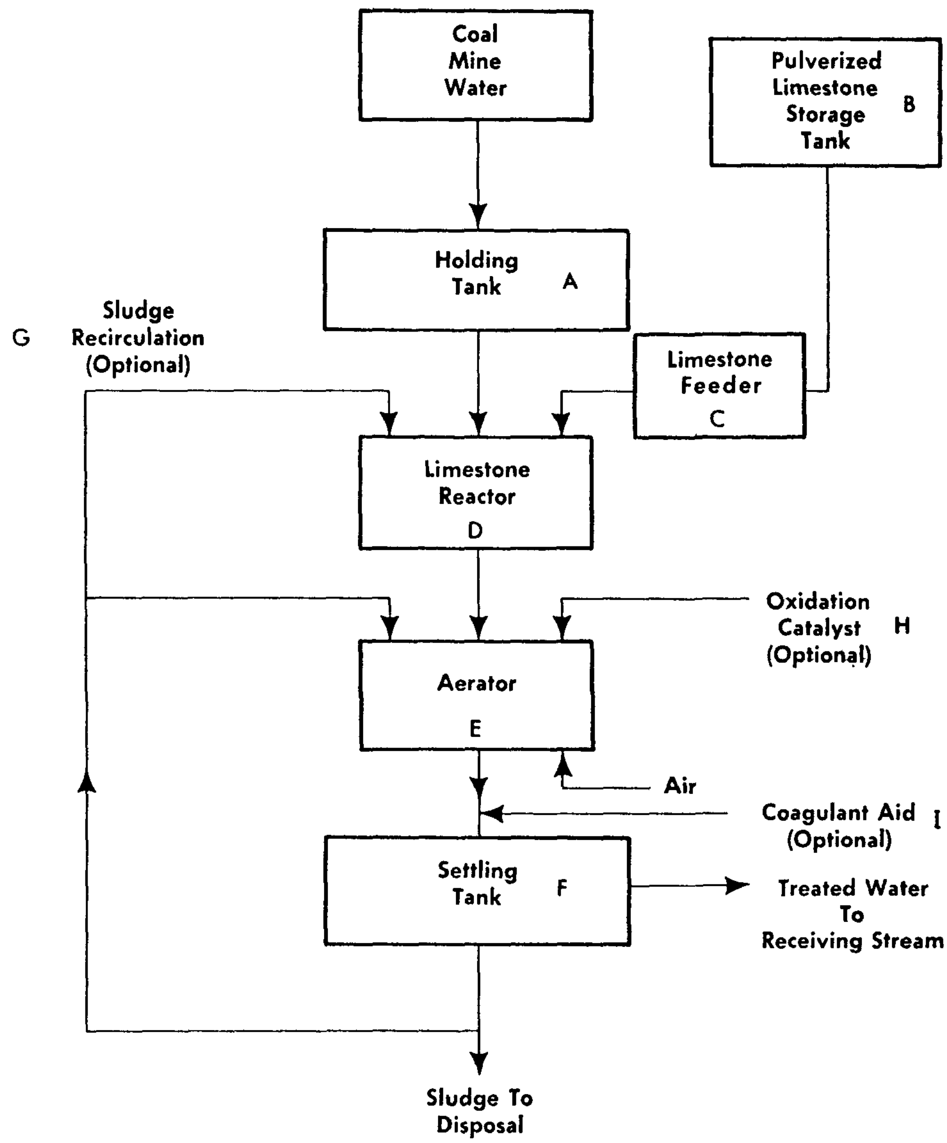
3. A less harmful effect on the body of water receiving the effluent in case of accidental overtreatment.

4. A reduction in sludge volume and an increase in sludge solids content. The volume of sludge from limestone treatment can be as little as one-fifth of that obtained in lime treatment, and the solids content can be almost 15 times greater. The reduction in sludge volume allows for the use of smaller settling basins, and this may be sufficient reason for selecting limestone treatment over lime in areas where space is at a premium.

Disadvantages of Using Limestone

1. The major disadvantage of the process is the slow rate of oxidation of ferrous iron at the relatively low pH attainable with limestone. Long detention time and, consequently, large tanks are required for mixing the mine water with limestone and for aerating until most of the ferrous iron has been oxidized. This results in higher costs, inefficient mixing, diffusion of oxygen, and sparging of carbon dioxide.

FIGURE 4



FLOW DIAGRAM OF
CONCEPTUAL LIMESTONE TREATMENT PROCESS

From Bituminous Coal Research, Inc., 1971[5]

2. The production of fine particles in the effluent which do not settle rapidly may require coagulant aids for their removal.

3. The availability of finely divided limestone of the desired quality.

To be used in the treatment process, the particle size of the limestone should be at least 74 microns (200 mesh) and preferably smaller. In addition, the limestone should approach pure calcium carbonate in composition with as low a content of magnesium as possible. Magnesites are the least effective neutralizing agents, followed closely by dolomitic limestones.

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

The laboratory studies demonstrated feasibility of the limestone treatment process using laboratory-scale pilot plant apparatus, delineated the individual operations and sequence of operations necessary for adequate treatment, and established basic information pertinent to engineering design of full-scale treatment plants. Based on the results of these studies, experimental results were related to engineering design of full-scale treatment plants. For these engineering evaluations, flows of 0.1, 1.0, and 7.0 million gallons per day (mgd) were chosen and data developed for construction and operation of plants to treat discharges having these flows. The EPA Class I mine drainage was chosen as the quality of mine water to be used in the evaluations, because that type of mine drainage would present the greatest problems in treatment.

The following three cases of the Class I mine drainage were used to develop the flow schematics, unit designs, and material balances:

<u>Case A:</u>	Acidity, mg/l (as $CaCO_3$)	1,000
	Ferrous iron, mg/l	500
	Ferric iron, mg/l	0
	Aluminum, mg/l	0
	Sulfate, mg/l	1,000
<u>Case B:</u>	Acidity, mg/l (as $CaCO_3$)	8,000
	Ferrous iron, mg/l	5,000
	Ferric iron, mg/l	0
	Aluminum, mg/l	500
	Sulfate, mg/l	10,000

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

In addition to the Class I mine drainage, a discharge from the South Greensburg, Pennsylvania area was used in the laboratory studies and for the engineering evaluation. The estimated flow of this discharge was 4.0 mgd and the water had the following average quality:

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

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

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

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

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

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

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

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

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

Facilities for a minimum of four (4) days storage of bulk pulverized limestone is provided at the plant site. It is assumed limestone will be delivered to the plant site by pneumatic unloading trucks. The limestone storage bins are equipped with level indicators, limestone feeders, and dust collectors.

The limestone feeders are installed in duplicate to reduce the possibility of plant shutdown due to mechanical equipment failure and to permit routine maintenance on the equipment. This equipment should be located near the reactor tank in order to reduce distance of conveying limestone.

A control building is required at the plant site to house the plant services, administration facilities, and chemical feed systems. The plant services and administration section of the control building should contain 1) an office for the plant operator; 2) a central control panel from which the treatment plant operations would be monitored; 3) laboratory facilities for water quality analysis and chemical dosage controls; 4) main motor control center, and 5) maintenance shop. The chemical feed equipment section of the control building contains the limestone and coagulant aid feed equipment.

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

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

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

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

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

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

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

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

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

7. The sludge solids content is five percent.

8. The sludge specific gravity is 1.05.

The cost parameters on which Bituminous Coal Research, Inc. based their costs of limestone treatment are given in Table 3. The costs are updated using Engineering News-Record (ENR) Construction Cost Index. It is assumed the cost index was 1575 when BCR made their cost estimates (June, 1971) and the updated costs are based on the estimated April, 1972 ENR cost index of 1700. The updated cost estimates are plotted in the form of cost curves (Figures 5 to 15).

Table 4 presents an estimate of capital cost for a limestone treatment plant to treat South Greensburg coal mine drainage at a 4.0 mgd flow rate. The total capital cost of the plant based on June, 1971 prices is estimated at $658,960. Using the April, 1972 ENR cost index, the total capital cost of the plant is $711,000.

Figures 6 through 9 give the estimated costs for various plant facilities based on plant capacity and chemical characteristics of the mine drainage to be treated. The cost of site clearing, final grading, access roads, engineering and contingencies should be added to arrive at the total plant costs which are indicated in Figure 5.

The operating costs for plants of various capacities and chemical characteristics of mine drainage to be treated are indicated on Figure 10. Figures 11 through 14 give cost estimates for various elements of plant operation and Figure 15 is an estimate of sludge accumulation for one year for various size plants with differing chemical characteristics of mine drainage. The costs of coagulant aids, if needed, and contingencies should be added to obtain the estimated total operation cost of the treatment plant.

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

1. The mixing requirements in the reactor tank

2. The cost of grinding coarse limestone versus the use of pulverized limestone

3. The use of mechanical aerators

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

5. The effect on treatment plant systems in treating coal mine drainage having sulfate concentrations of up to 20,000 mg/l with resultant precipitation of gypsum

6. The effect of coagulant aids on settling properties and on recycled sludge

7. The effect of more concentrated coal mine drainage on sludge volume.

TABLE 3
BASIS FOR ESTIMATED COSTS OF LIMESTONE TREATMENT
VARIOUS SIZE TREATMENT PLANTS

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

2. Labor

a. 0.1 MGD Treatment Plant:

1 Operator	$ 7,500.00
1 Part Time Laborer	3,000.00
	$10,500.00

b. 1.0 MGD Treatment Plant:

1 Operator	$ 8,000.00
1 Laborer	6,000.00
	$14,000.00

c. 7.0 MGD Treatment Plant:

1 Operator	$10,000.00
2 Laborers	15,000.00
	$25,000.00

d. 4.0 MGD Treatment Plant:

1 Operator	$10,000.00
1 Laborer	7,500.00
	$17,500.00

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

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

4. Coagulant Aid
$2.00 per pound

5. Power
a. 0.1 MGD Treatment Plant: $85.00 per horsepower per year
b. 1.0 MGD Treatment Plant: $80.00 per horsepower per year
c. 4.0 MGD Treatment Plant: $80.00 per horsepower per year
d. 7.0 MGD Treatment Plant: $75.00 per horsepower per year

6. Maintenance and Repairs
a. 0.1 MGD Treatment Plant: $ 3,000 per year
b. 1.0 MGD Treatment Plant: $ 5,000 per year
c. 4.0 MGD Treatment Plant: $ 8,000 per year
d. 7.0 MGD Treatment Plant: $10,000 per year

7. Contingencies
One percent of construction costs

8. Sludge Disposal Cost
$10.00 per 1,000 gallons

TABLE 4
ESTIMATE OF CAPITAL COST FOR LIMESTONE TREATMENT PLANT
SOUTH GREENSBURG COAL MINE DRAINAGE
4.0 MGD FLOW RATE

1.	Site Preparation	
	a. Clearing & Grubbing	$ 500.00
2.	Structures	
	a. Holding Lagoon	76,000.00
	b. Reactor Tank	43,200.00
	c. Aeration Tank	43,200.00
	d. Settling Basin	118,500.00
	e. Sludge Dewatering Basin	35,000.00
	f. Sludge Pump Well	12,000.00
3.	Control Building	48,000.00
4.	Mechanical Equipment	
	a. Mixers	25,500.00
	b. Aerators	31,000.00
	c. Sludge Recirculation Pumps	11,250.00
	d. Waste Sludge Pumps	1,950.00
	e. Settling Basin Sludge Pumps	11,250.00
5.	Chemical Feed Equipment	6,000.00
6.	Mechanical Piping	40,000.00
7.	Control Equipment	24,000.00
8.	Access Roadway	2,500.00
9.	Final Grading	6,000.00
10.	Electrical	30,000.00
11.	Contingencies	56,150.00
12.	Engineering	36,960.00
	TOTAL CAPITAL COSTS	$658,960.00

FIGURE 5

ESTIMATE OF CAPITAL COSTS Vs. PLANT CAPACITY
BCR LIMESTONE TREATMENT W/SLUDGE DEWATERING
EPA, WQO, CLASS I COAL MINE DRAINAGE (REF. 5)

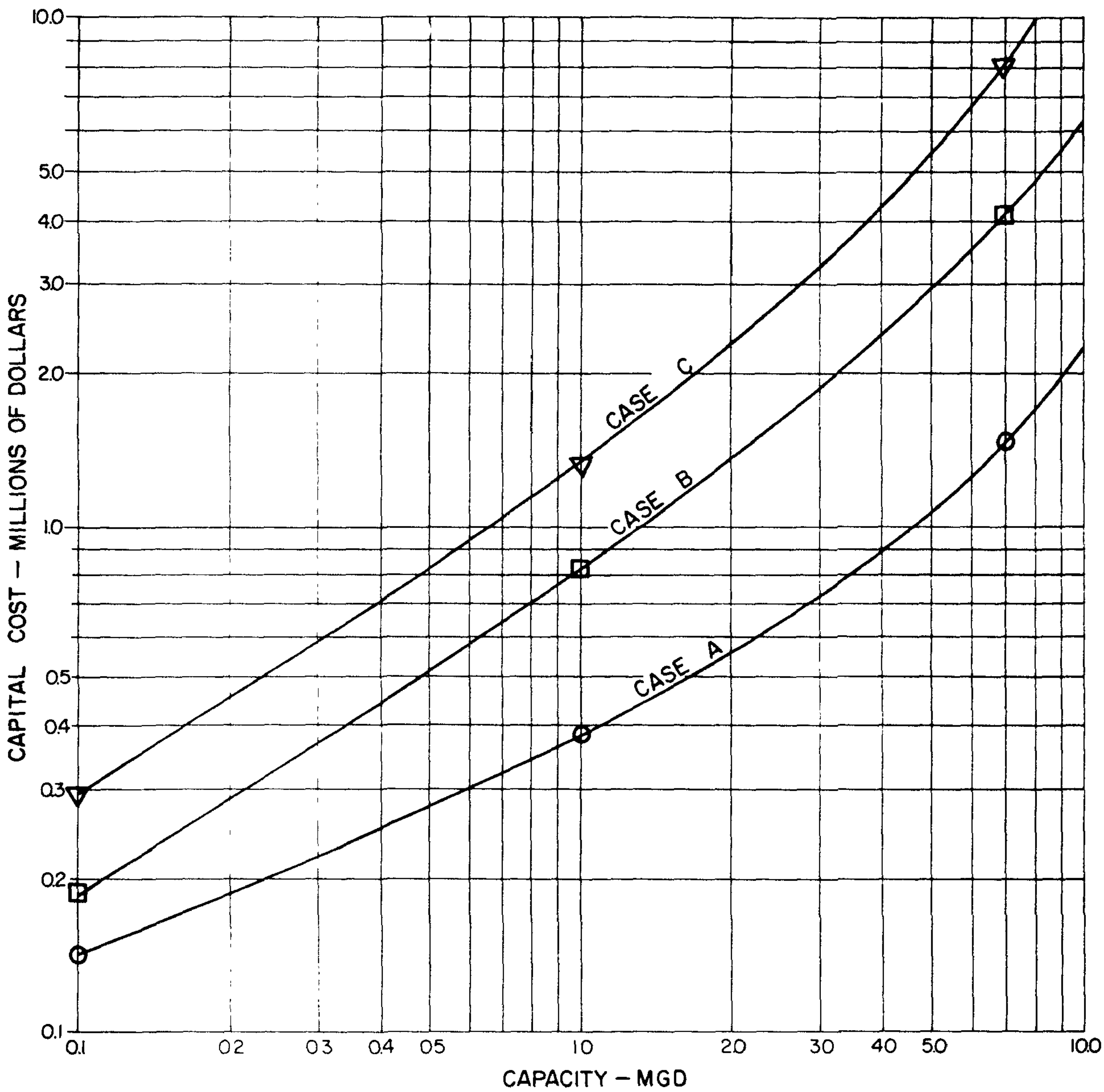


FIGURE 6

ESTIMATE OF CAPITAL COSTS Vs. PLANT CAPACITY
BCR LIMESTONE TREATMENT W/SLUDGE DEWATERING
EPA,WQO,CLASS I COAL MINE DRAINAGE (REF. 5)

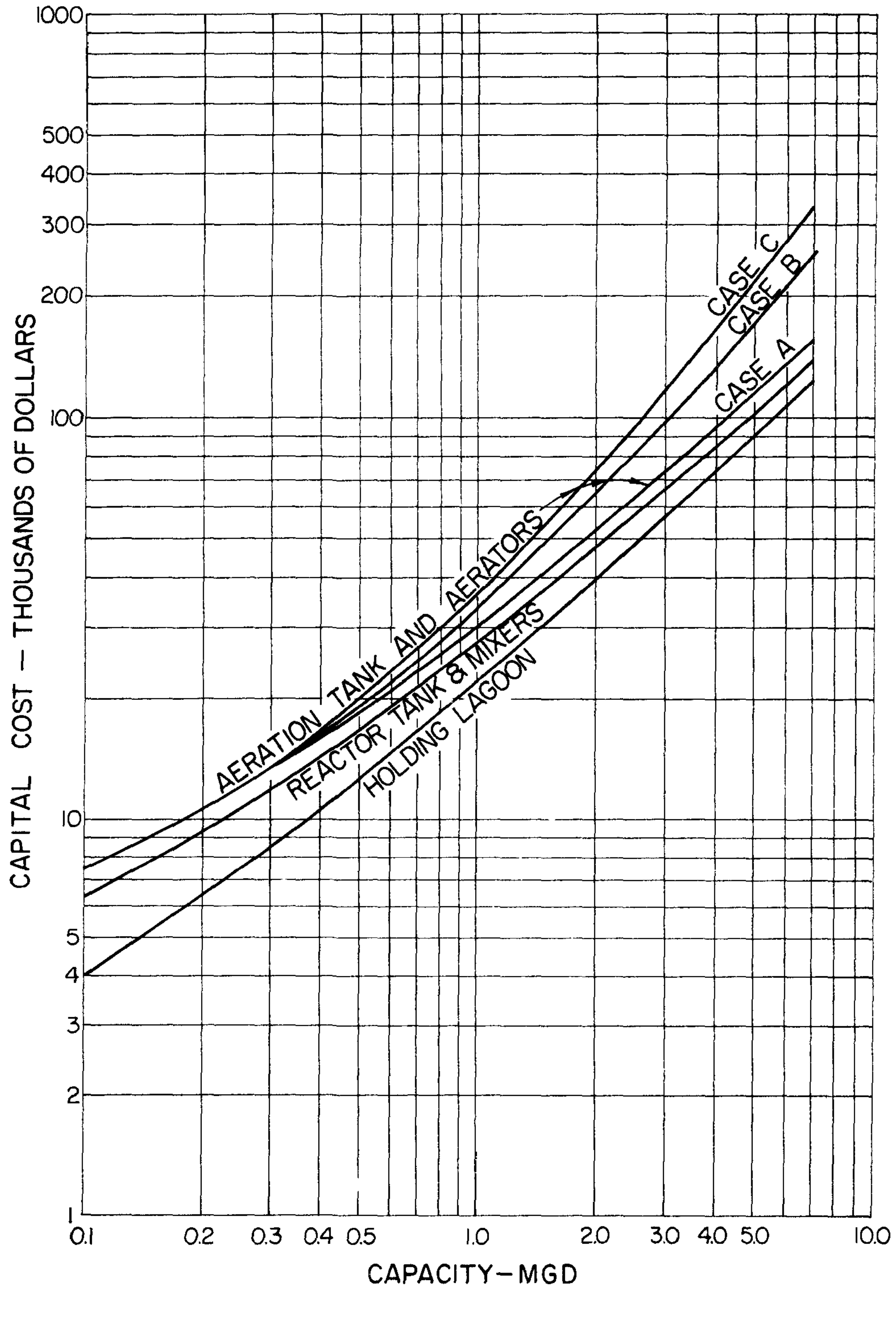


FIGURE 7

ESTIMATE OF CAPITAL COSTS Vs. PLANT CAPACITY
BCR LIMESTONE TREATMENT W/SLUDGE DEWATERING
EPA, WQO, CLASS I COAL MINE DRAINAGE (REF. 5)

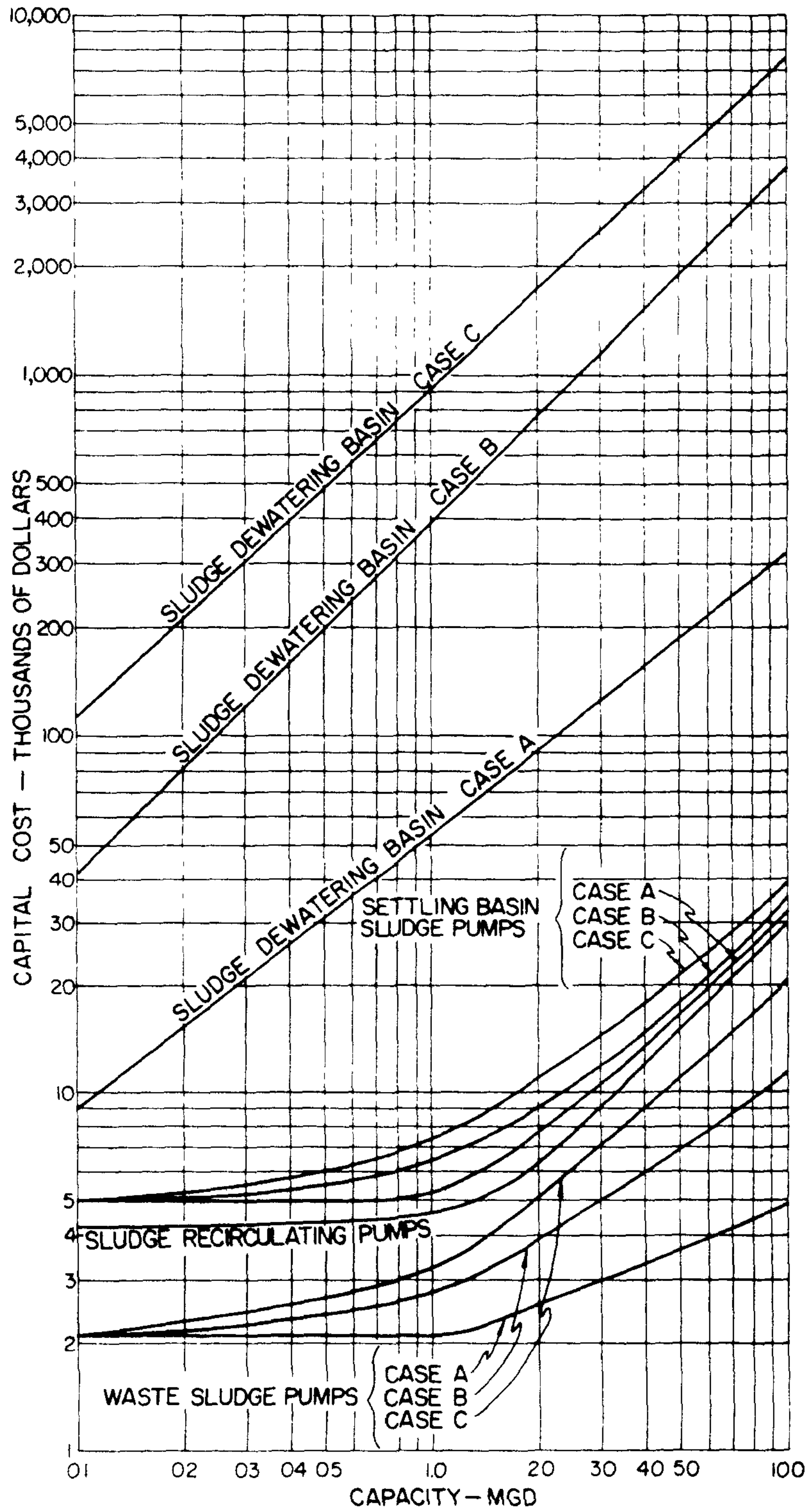


FIGURE 8

ESTIMATE OF CAPITAL COSTS Vs. PLANT CAPACITY
BCR LIMESTONE TREATMENT W/SLUDGE DEWATERING
EPA, WQO, CLASS I COAL MINE DRAINAGE (REF. 5)

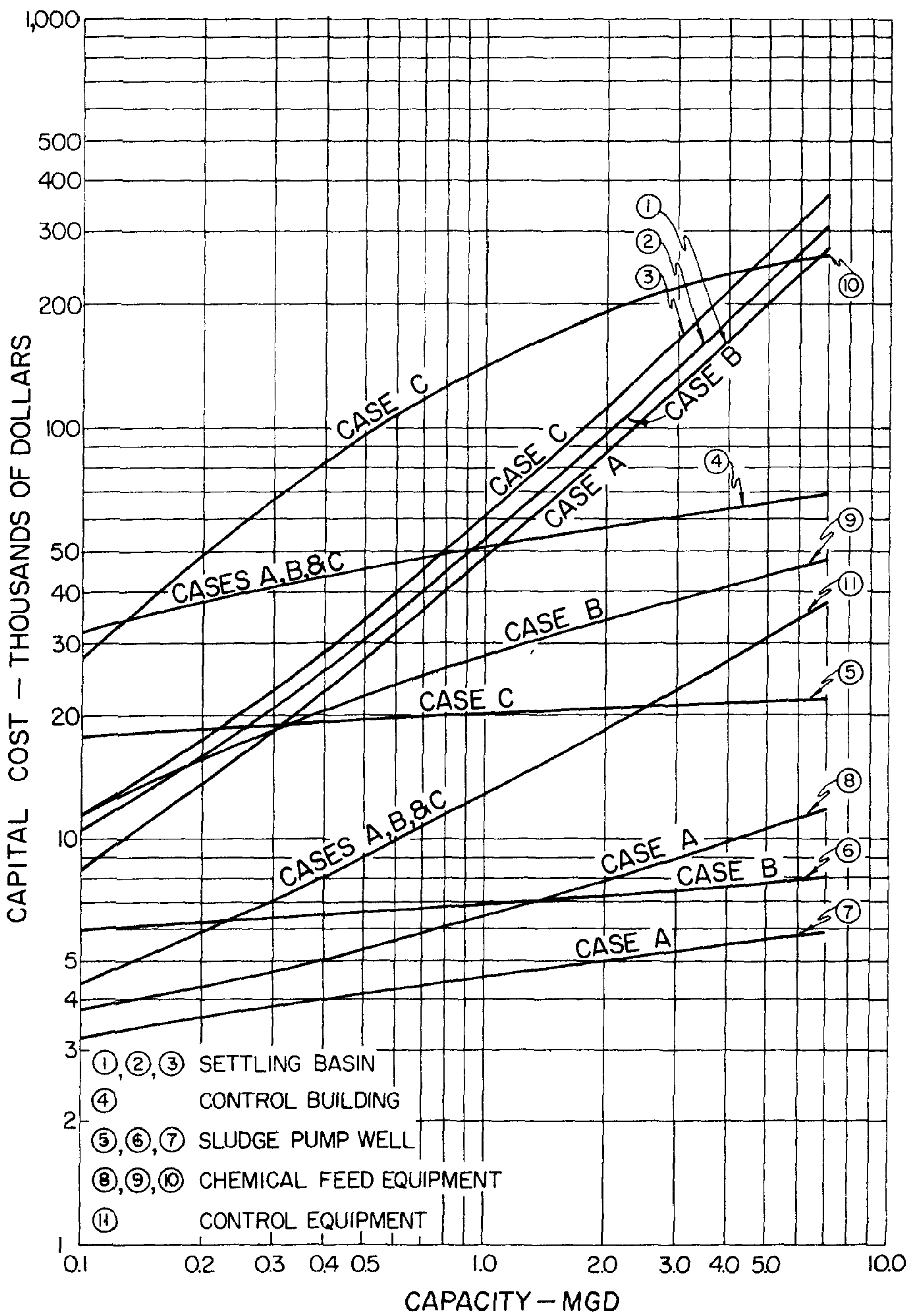


FIGURE 9

ESTIMATE OF CAPITAL COSTS Vs. PLANT CAPACITY
BCR LIMESTONE TREATMENT W/SLUDGE DEWATERING
EPA, WQO, CLASS I COAL MINE DRAINAGE (REF. 5)

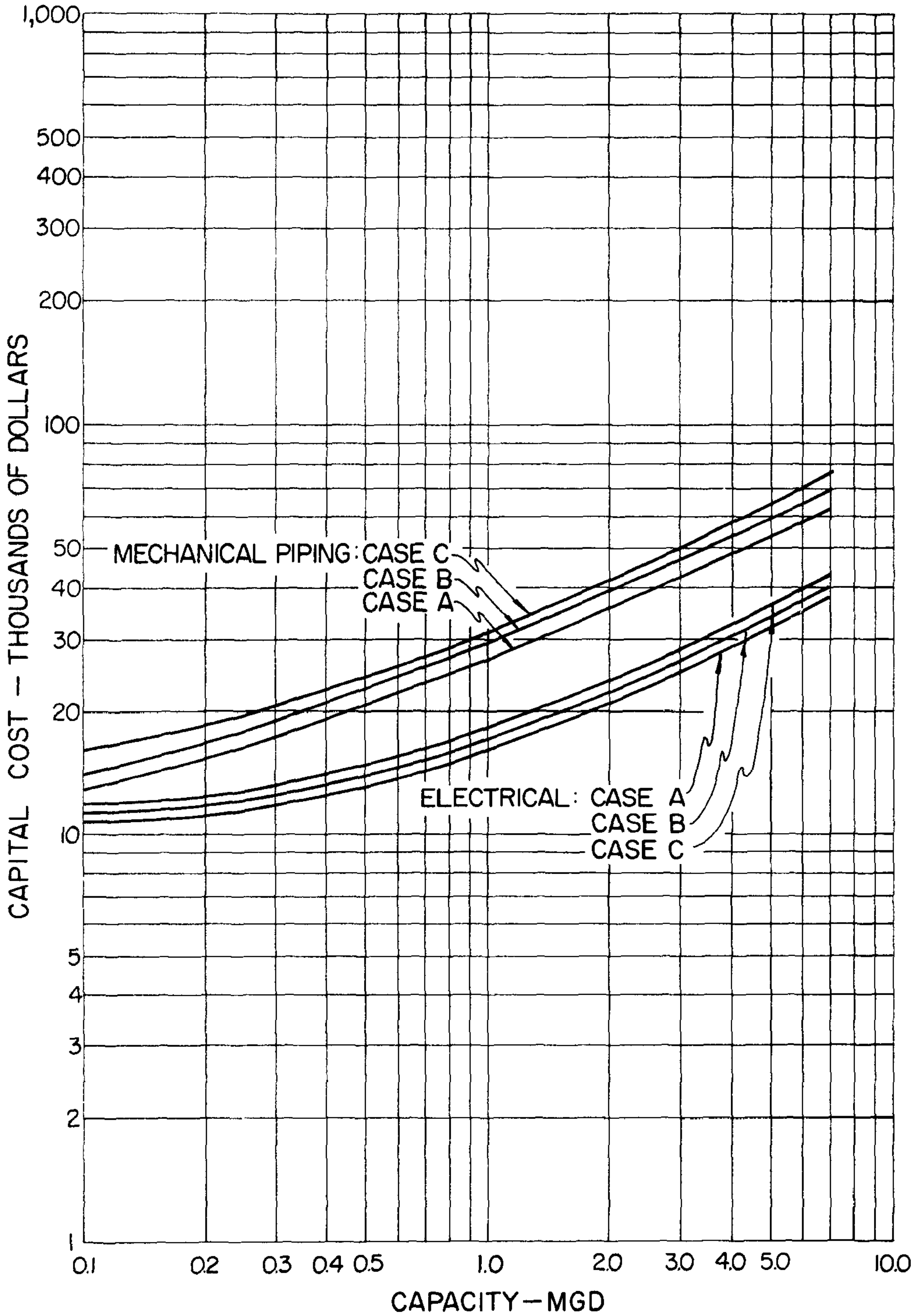
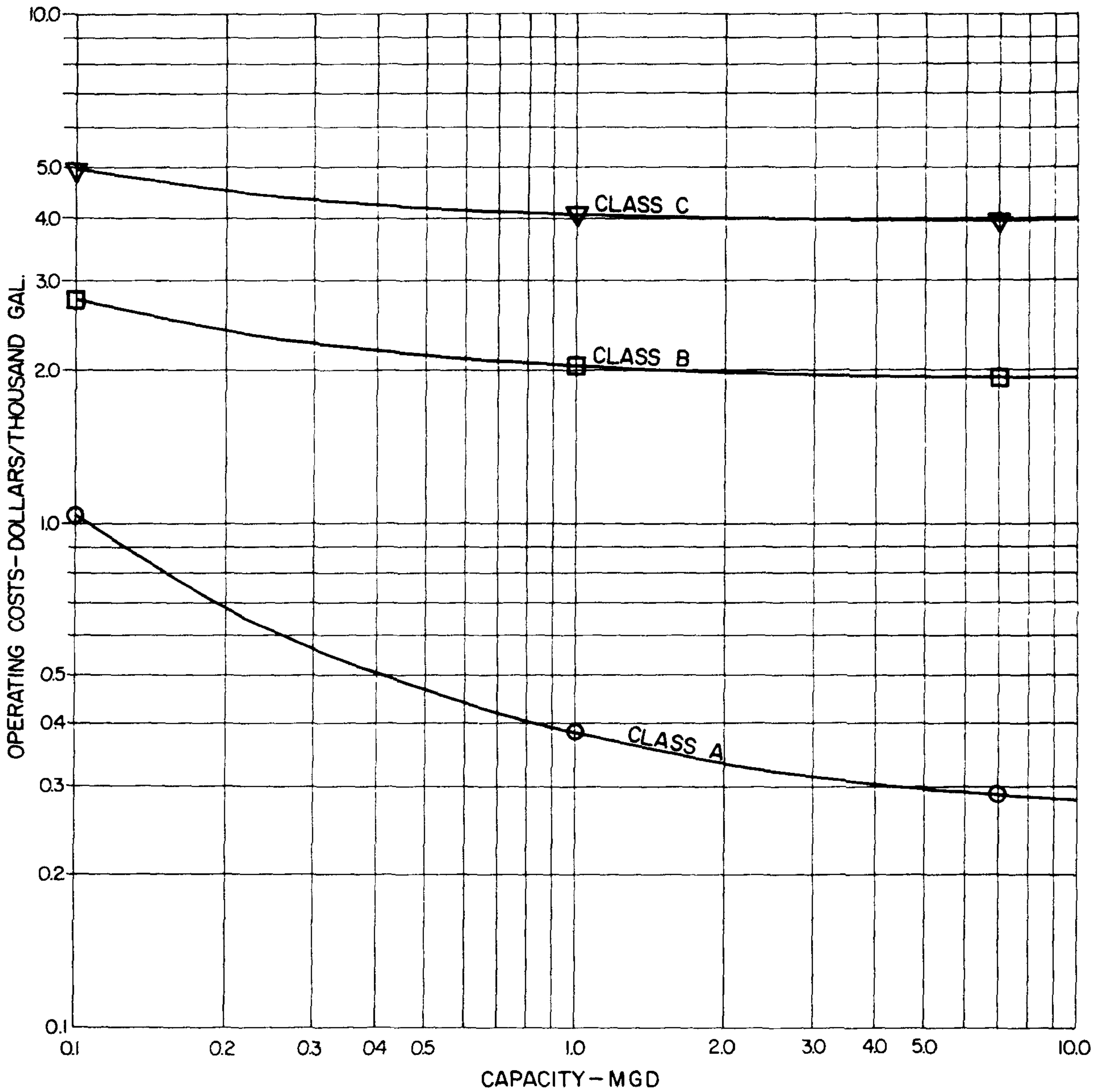


FIGURE 10

ESTIMATE OF OPERATING COSTS Vs. PLANT CAPACITY
BCR LIMESTONE TREATMENT W/SLUDGE DEWATERING
EPA, WQO, CLASS I COAL MINE DRAINAGE (REF. 5)



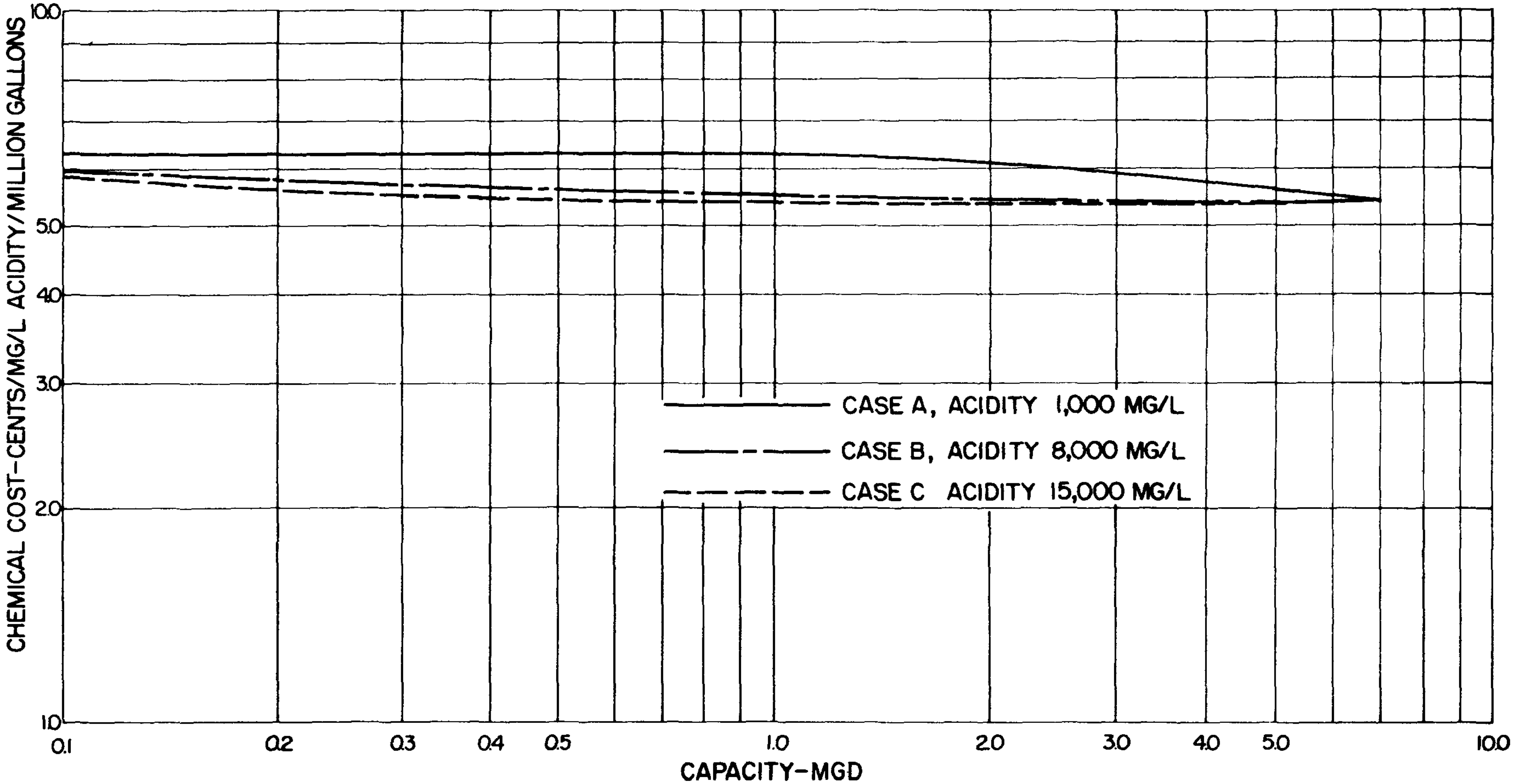


FIGURE 11

ESTIMATED CHEMICAL COSTS (CENTS/MG/L ACIDITY/10^6 GALLONS)
BCR LIMESTONE TREATMENT OF EPA,WQO CLASS I COAL MINE DRAINAGE (REF. 5)

FIGURE 12

ESTIMATED COSTS (CENTS/THOUSAND GALLONS)
BCR LIMESTONE TREATMENT W/SLUDGE DEWATERING
EPA,WQO,CLASS I COAL MINE DRAINAGE (REF. 5)

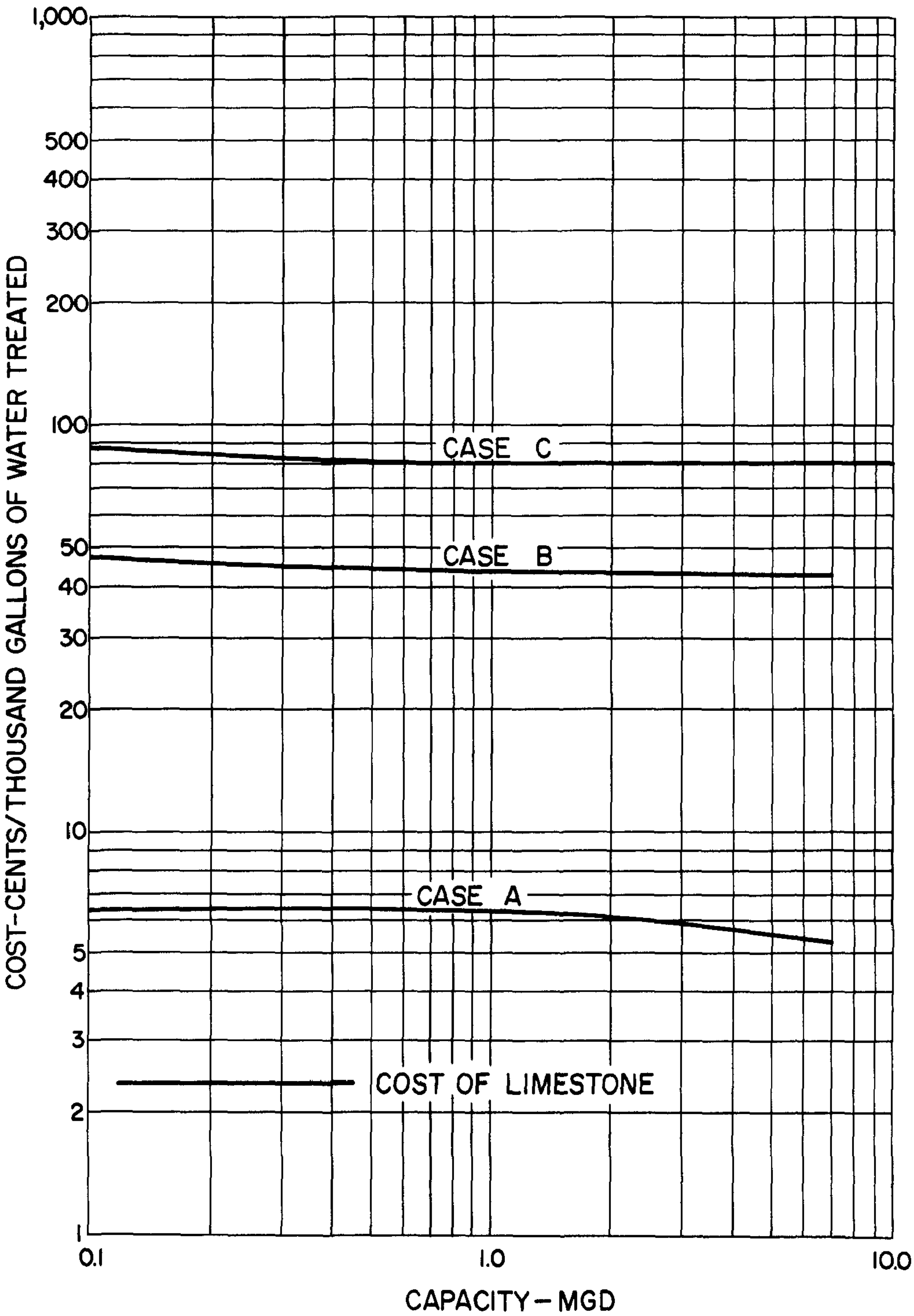


FIGURE 13

ESTIMATED COSTS (CENTS/THOUSAND GALLONS)
BCR LIMESTONE TREATMENT OF
EPA, WQO, CLASS I COAL MINE DRAINAGE (REF. 5)

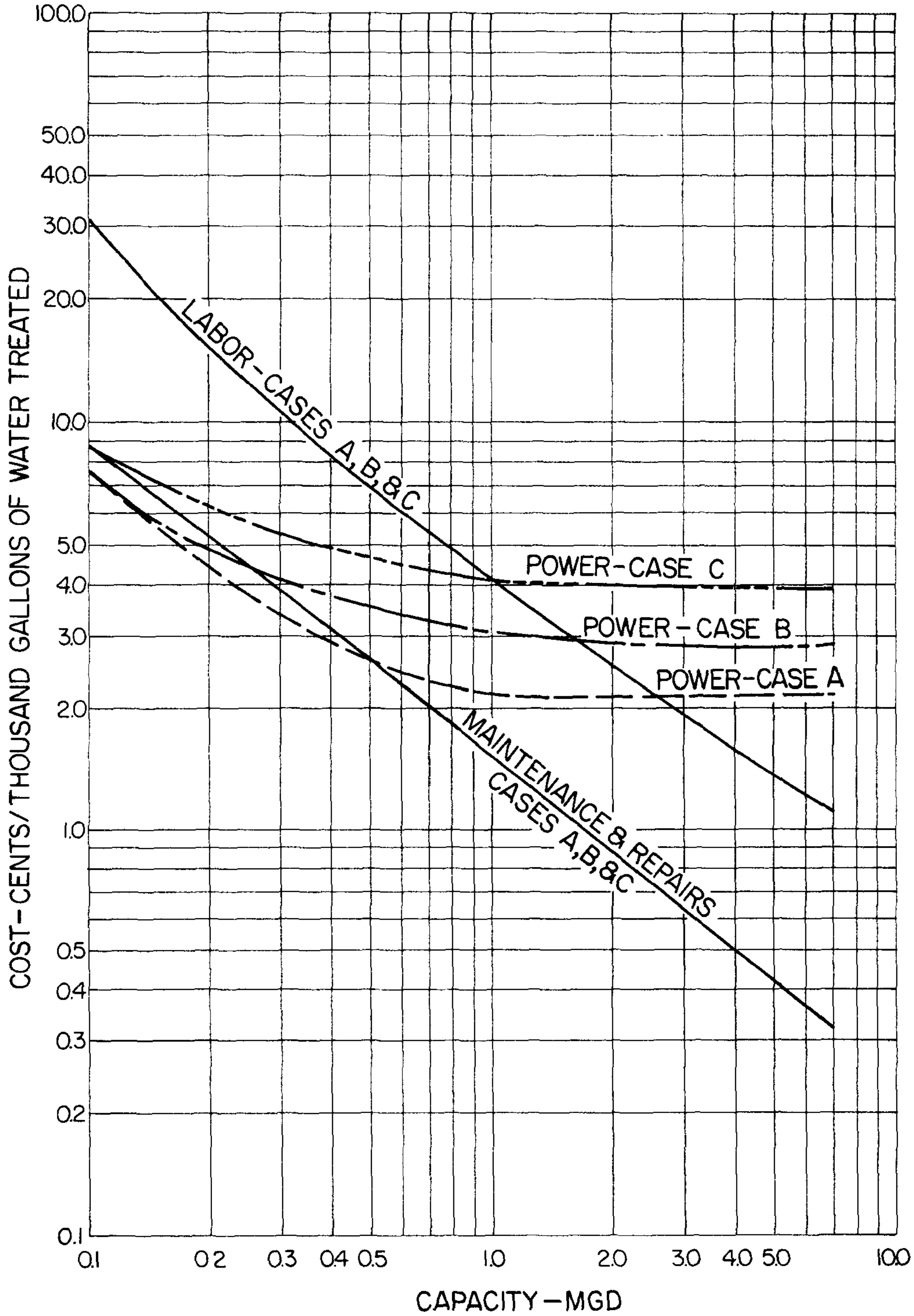


FIGURE 14

ESTIMATED COSTS (CENTS/THOUSAND GALLONS)
BCR LIMESTONE TREATMENT OF
EPA, WQO, CLASS I COAL MINE DRAINAGE (REF. 5)

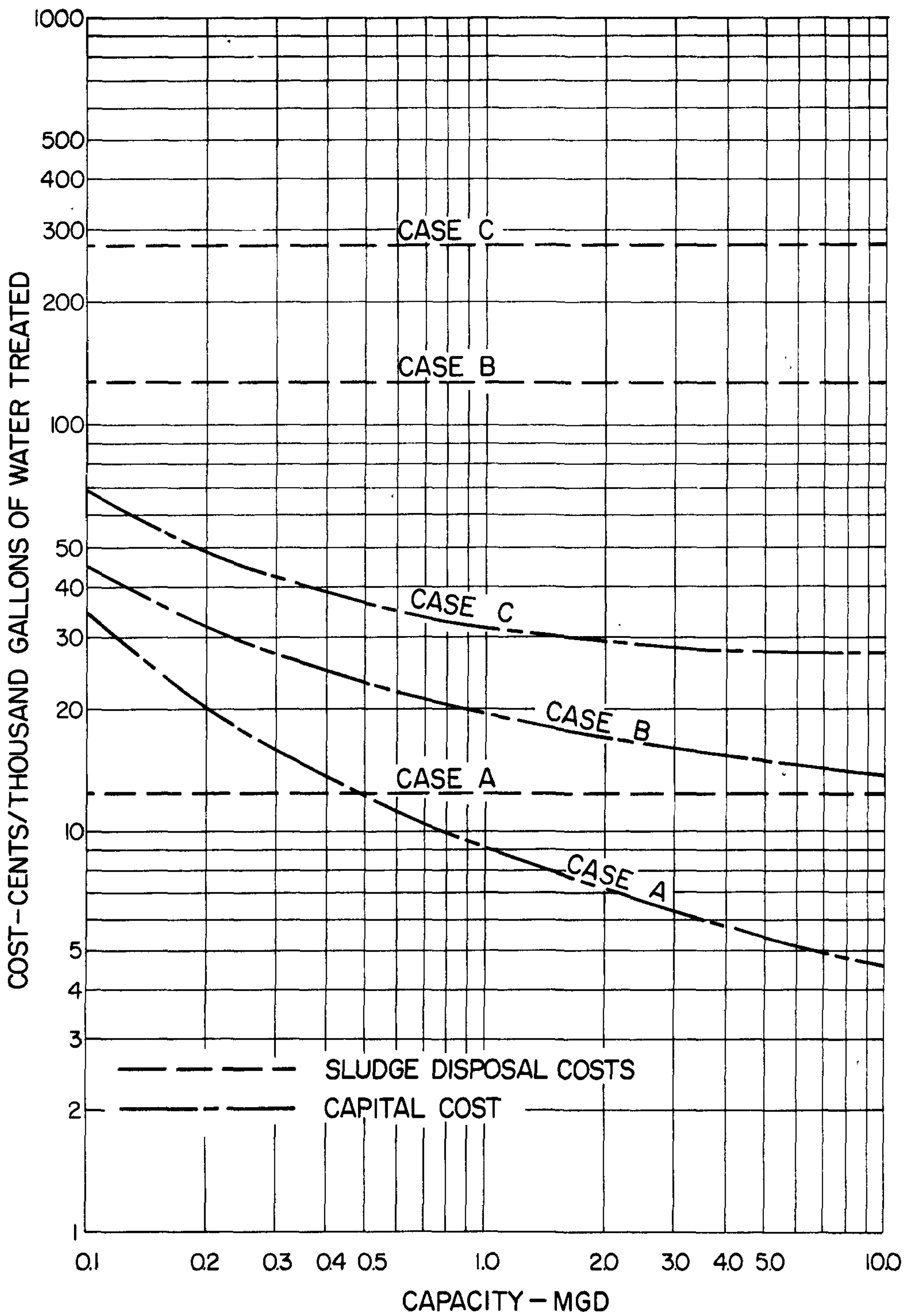
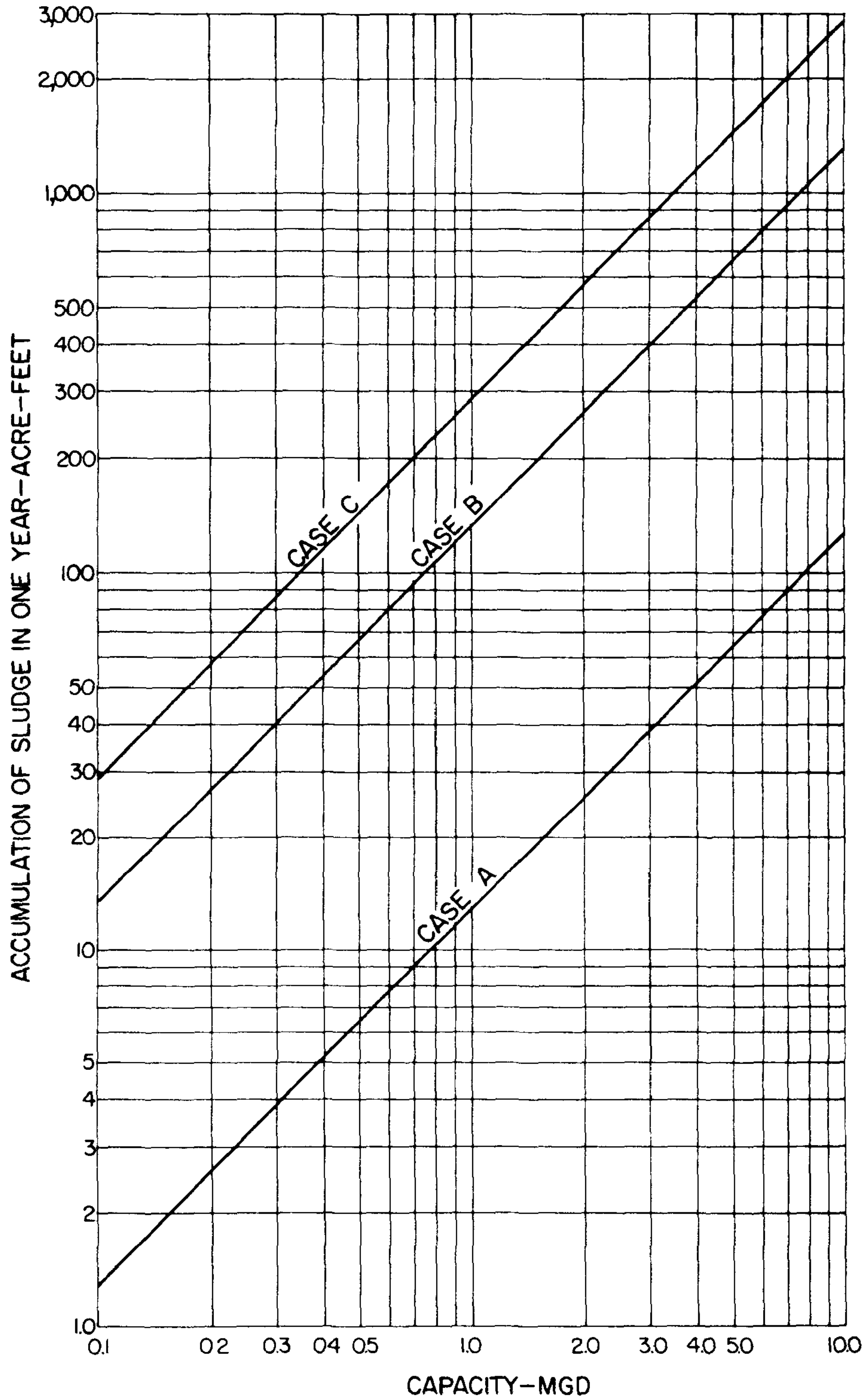


FIGURE 15

ESTIMATED SLUDGE ACCUMULATION IN ONE YEAR FROM BCR LIMESTONE TREATMENT OF EPA,WQO, CLASS I COAL MINE DRAINAGE (REF. 5)



U. S. Bureau of Mines Limestone Treatment Process

The U. S. Bureau of Mines initiated an effort in 1966 to develop a low-cost practical neutralization process for treatment of acid mine water. The emphasis was on using limestone as the neutralizing agent because of its low cost and availability. As a result of their effort [6,7,8,9,10], a limestone neutralization process was developed to treat mine water of any quality and preliminary plant design and total cost estimates were developed.

The general process for treatment of acid mine water effluent consists of limestone neutralization, aeration, solids settling, and sludge concentration. Figure 16 is a flow sheet of the mine water treatment process.

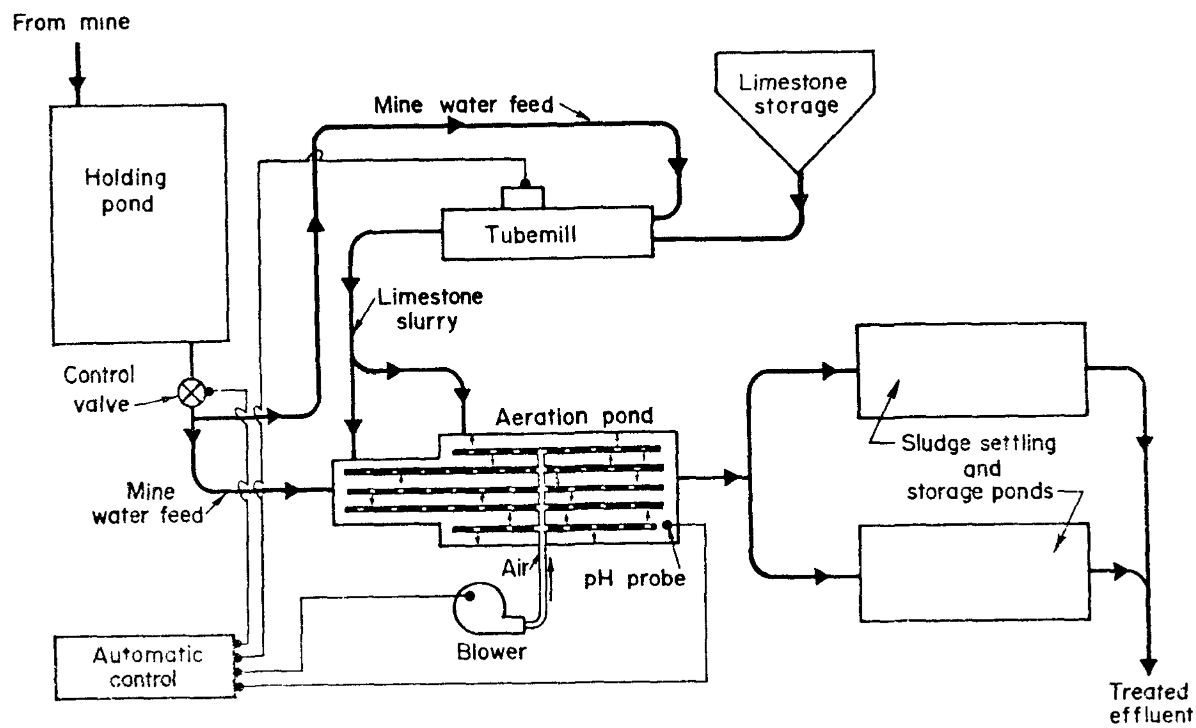


FIGURE 16

FLOWSHEET OF MINE WATER TREATMENT PROCESS
After Mihok, 1970[8]

Mihok[8] describes the process as follows:

Gravity flow in this plant design is utilized throughout the treatment from holding pond to ultimate effluent discharge. Mine water flows from the holding pond through pipes and flumes and is mixed with limestone slurry generated in an autogenous tube mill or grinder. The resulting mixture enters the primary section of the aeration pond where air is applied to remove CO_2 formed from the neutralization of free acidity. As the mixture flows into the main section of the aeration pond, additional limestone slurry is added to neutralize the remaining acidity formed by oxidation and precipitation of iron. Air sparging is continued at a reduced rate through the main section of the aerating pond. The neutralized mixture flows from the pond through flumes to settling ponds designed to provide sufficient time for the suspended solids to settle to the bottom of the pond. The clarified effluent is discharged into a stream or river.

The two settling ponds are designed to hold 10 years of solids accumulation. When the sludge level in the pond approaches within 5 feet of the uppermost water level, solids settling is conducted in the other pond. Water in the first pond is drawn off and the sludge is air dried and allowed to remain in place. When the second pond fills with sludge, the neutralized water is diverted to the first pond which is air dried and settling continues uninterrupted.

Design Criteria and Costs - Design criteria and costs are given for a wide range of volumes and quality of mine water. Volumes range from 100,000 gpd to 6 million gpd, acidity from 100 to 5,000 ppm, ferrous iron from 50 to 1,500 ppm, and neutralized water suspended solids from 250 to 8,000 ppm. Suspended solids concentrations typically consist of calcium sulfate, hydrated metal oxides, silica, unused limestone, and inerts.

Since design criteria and treatment methods affect the cost of construction and operation of a treatment plant, a discussion of important factors affecting costs follows:

a) Holding Pond - The holding pond capacity is at least three times the anticipated maximum daily mine water flow. This additional volume provides safeguards to prevent untreated or inadequately treated water from discharging into streams or rivers in the event of unforeseen increase of acid mine drainage flow and temporary shutdown of neutralizing facilities. It will minimize fluctuations in raw water feed composition and reduce ferrous iron concentrations.

b) Neutralization Treatment - The limestone autogenous tube mill and aeration equipment is designed to treat continuously a 25 percent excess of the anticipated maximum daily mine water acid and ferrous iron load. Process control is maintained by raw mine water feed regulation. Normal operation consists of maximum production of limestone for neutralization of total acidity so that depletion of feed takes place at rated design capacity. When a minimal level of acid mine water in the pond is reached, the tube mill shuts down and is reactivated when sufficient water volume has accumulated.

c) Limestone Storage and Processing - Limestone storage and processing capacity is based on the maximum daily total acidity to be treated. Storage bins are designed to hold at least a five (5) day supply of limestone. A feeder mechanism is included to meet maximum daily limestone requirements. The autogenous grinder provides limestone slurry containing particles of which 99 percent pass through a 400-mesh screen. A consistent uniform slurry is produced when the tube mill operates under constant feed and grinding speed conditions.

The storage bin and feeder costs, including installation, have been obtained from manufacturers of these items.

d) Aeration - Aeration performs three functions in limestone treatment of acid mine drainage; it mixes the reactants, removes CO_2 formed from $CaCO_3$ reaction with acid, and supplies oxygen for ferrous iron oxidation. Mihok[8] believes that this can best be accomplished by diffused air or air sparging.

The design of the aeration system is based on winter operating conditions (air and water temperature 0^{o} to 10^{o} C) when the lowest reaction rates and highest concentrations of ferrous iron prevail. The volume of acid mine water, ferrous iron concentration, and oxidation rate under these conditions dictate the size of the pond and the volume of air to be supplied. Disregarding catalytic oxidation, ferrous iron oxidation rates at pH range of 6.5 to 7.5 and 10^{o} C for various concentrations used in this design are as follows:

Fe^{++} concentrate ppm	Oxidation rate, ppm per min
50..........	3
100..........	4
250..........	5
500..........	6
1,000..........	7.5
1,500..........	10
2,000..........	12.5

Based on results of the pilot plant and laboratory tests, these rates can be achieved with air rate volumes approximately double the water volume flow rate for a period of up to a five (5) minute detention time in the primary section of the aeration unit. Subsequent air, at rates approximately equal to the water volume flow rate, is supplied in the secondary or main section of the aeration unit. A centrifugal blower delivers air at four (4) psi pressure at rated capacity through a PVC pipe equipped with diffuser nozzels or orifices mounted near the bottom of the aeration pond.

Centrifugal blower, motor, and piping costs have been obtained from manufacturers and total costs including installation have been estimated.

e) Sludge Settling and Concentration Ponds - Suspended solids are separated from the treated water by means of duplicate settling ponds. The alternate use of the pond provides for sludge concentration and solids storage in situ. At least a 24 hour settling time is maintained at all times. Capacity is based on the volume occupied by air-dried solids accumulated over a period of 10 years. An average bulk density of dried solids of 50 lbs./cu. ft. has been used to determine the settling pond capacity. A ton of dried sludge cake containing up to 50 percent moisture occupies the volume of approximately 300 gallons of water.

f) Excavation - Pond construction costs depend on many factors but ultimately are expressed in terms of cost per cubic yard of earth handled. The capacity of the pond in gallons equated in terms of cubic yards determines the relative amount of work that must be performed. An estimate of one dollar ($1.00) per cubic yard for excavation was used in determining construction costs for holding, aeration, and sludge settling ponds. Aeration pond costs also include an additional $1.00 per square foot for concrete slab lining of the sidewalls.

g) Water Transport, Flow Control, and Measurement - Mine water is transported by means of open flumes throughout the process, except for water discharged from the holding pond which flows through PVC pipes. Piping and valves are incorporated in the system for a distance of 200 feet from pond to neutralizer. Open, half round, corrugated galvanized pipe flumes carry the water through the rest of the process. Weirs for measuring water flow are located ahead of the neutralizer and at the effluent discharge from the settling pond. Automatic controls are used to regulate the mine water feed instead of regulating the neutralizing agent feed, because generation of limestone fines can be controlled more efficiently and economically with constant-speed grinding.

Hydraulic requirements dictate the size of valves, piping, etc., and the cost of these items was obtained from manufacturers. Included in the total cost of water transport and control are labor and installation estimates.

h) Limestone Fines Generation at Tube Mill - For limestone requirements of up to 10 tons per day, the cost of limestone fines generation is related to the cost of the pilot plant tube mill designed and constructed by the Bureau of Mines. Tube mill cost estimates for greater than 10 tons per day capacities have been obtained from grinding mill manufacturers.

i) Auxiliary Equipment Costs - Included in this item are pH meters, turbidity meters, and process controls. The cost of these items were obtained from the manufacturers. Table 5 gives the estimated costs of these items for treatment plants of various capacities.

j) Other Factors Affecting Costs - The costs of land acquisition, site improvement and pumping water from the mine can be highly variable. It is assumed for this cost estimate that sufficient land is available and mine water is discharging into the holding or equalization pond. It also has been assumed that electric power is available at the site.

k) Capital Costs - The total treatment plant capital costs include all construction costs plus an allowance of 25 percent to cover contingencies.

l) Fixed Costs - Included in the annual operating costs is a fixed charge of 10 percent of the total capital costs. It is expected that the useful life of the plant equipment will be greater than 10 years, but the ponds storage capacity sets this 10 year limit. The plant life can be extended by removing the solids from the pond.

m) Operating Costs -

1. Limestone - The cost of limestone (containing about 75 percent $CaCO_3$) has been set at $2.00 per ton f.o.b. for these calculations.

2. Labor - Labor costs are based on $10,000 per man-year.

3. Power - The power cost is based on a 1 cent per kilowatt-hour rate, with continuous consumption 24 hours per day and 365 days per year.

4. Maintenance - Yearly maintenance costs, including tube mill liner replacement, are estimated at 10 percent of tube mill capital costs.

The detailed breakdown of estimated capital and operating costs for limestone treatment plants of various capacities used in the U. S. Bureau of Mines publication "Mine Water Research - Plant Design and Cost Estimates for Limestone Treatment," 1970, by Mihok [8] is shown on Tables 6 through 11. The cost estimates presented in these tables were made in 1969. It is assumed that the ENR construction cost index was 1305 (December, 1969) when these estimates were made. The estimated costs were updated using an ENR construction cost index of 1700 (April, 1972), and the updated costs were plotted as cost curves on Figures 17 through 24.

A preliminary study conducted by the U. S. Bureau of Mines indicates the aeration step might be supplanted by a catalytic oxidation step prior to neutralization. Extremely rapid ferrous iron oxidation rates have been attained with the use of granular activated carbon. With all the iron in the raw mine water converted to the ferric state, neutralization equilibrium can be quickly established and subsequent aeration is unnecessary. Promising aspects of the catalytic oxidation process are nonrecurring expense and long operational life of the activated carbon. Therefore, further reduction of mine water treatment costs and greater simplicity and control of neutralization are possible.

Bituminous Coal Research, Inc.[4] in their studies also indicated that activated carbon is an effective catalyst and reduces the time required for ferrous iron oxidation to about 60 minutes. However, the short duration (about 24 cycles) for which this activity is maintained requires more frequent regeneration of the activated carbon making the process economically unattractive.

TABLE 5
AUXILIARY EQUIPMENT COSTS

Auxiliary equipment	Plant capacity--gpd					
	100,000	300,000	500,000	1,500,000	2,000,000	6,000,000
Piping, valves, etc....	$ 1,000	$ 1,500	$ 2,000	$ 3,500	$ 5,000	$ 8,000
pH meter.............	1,500	1,500	1,500	1,500	1,500	1,500
Turbidimeter.........	1,500	1,500	1,500	1,500	1,500	1,500
Electricity............	1,000	1,000	3,000	3,000	6,000	6,000
Weir and flumes.......	1,500	1,500	3,000	3,000	4,500	4,500
Automatic controls....	4,500	4,500	5,000	5,000	6,000	6,000
Building	1,500	1,500	2,000	2,000	2,500	2,500
Total Cost.....	$12,500	$13,000	$18,000	$19,500	$27,000	$30,000

TABLE 6. - Limestone treatment plant cost estimates for 100,000 gpd plant capacity

Mine water quality, ppm:															
Acidity........................	500	1,000	2,000	5,000	500	1,000	2,000	5,000	1,000	2,000	5,000	2,000	5,000	3,000	5,000
Iron as Fe^{++}..................	50	50	50	50	100	100	100	100	500	500	500	1,000	1,000	1,500	1,500
Neutralized suspended solids...	500	1,000	2,000	4,000	1,000	1,500	2,500	5,000	2,000	3,000	6,000	4,000	7,000	6,000	8,000
Auxiliary equipment cost....$ M..	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5
Holding pond:															
Capacity...............MM gal..	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Cost......................$ M..	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Neutralization:															
$CaCO_3$ equivalent..........tpd..	0.21	0.42	0.83	2.10	0.21	0.42	0.83	2.1	0.42	0.83	2.10	0.83	2.10	1.25	2.10
Limestone.................tpd..	0.31	0.62	1.25	3.10	0.31	0.62	1.25	3.10	0.62	1.25	3.10	1.25	3.10	1.90	3.10
Limestone...............M tpy..	0.11	0.23	0.46	1.14	0.11	0.23	0.46	1.14	0.23	0.46	1.14	0.46	1.14	0.68	1.14
Annual limestone cost.....$ M..	0.23	0.46	0.91	2.28	0.23	0.46	0.91	2.28	0.46	0.91	2.28	0.91	2.28	1.37	2.28
Storage-feeder capacity..tons..	10	10	10	25	10	10	10	25	10	10	25	10	25	10	25
Storage cost..............$ M..	1.5	1.5	1.5	2.0	1.5	1.5	1.5	2.0	1.5	1.5	2.0	1.5	2.0	1.5	2.0
Tube mill capacity........tpd..	1	1	2	4	1	1	2	4	1	2	4	2	4	2	4
Tube mill motor............hp..	5	5	10	15	3	3	5	15	3	5	15	5	15	10	15
Tube mill cost............$ M..	2.5	2.5	4.0	8.0	2.5	2.5	4.0	8.0	2.5	4.0	8.0	4.0	8.0	4.0	8.0
Annual power cost.........$ M..	0.05	0.1	0.3	0.8	0.05	0.1	0.3	0.8	0.1	0.3	0.8	0.3	0.8	0.3	0.8
Aeration:															
Pond capacity...........M gal..	3.5	3.5	3.5	3.5	5.0	5.0	5.0	5.0	20	20	20	30	30	35	35
Pond cost.................$ M..	1.00	1.00	1.00	1.00	1.10	1.10	1.10	1.10	1.85	1.85	1.85	2.25	2.25	2.40	2.40
Blower capacity...........cfm..	125	125	125	125	150	150	150	150	500	500	500	700	700	800	800
Blower motor...............hp..	5	5	5	5	5	5	5	5	15	15	15	20	20	20	20
Blower-motor cost.........$ M..	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	2.0	2.0	2.0	2.1	2.1	2.1	2.1
Total aeration cost.......$ M..	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	5.0	5.0	5.0	5.5	5.5	6.0	6.0
Annual power cost.........$ M..	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.8	0.8	0.8	1.3	1.3	1.3	1.3
Settling:															
Pond capacity..........MM gal..	0.4	0.6	1.1	2.0	0.6	0.8	1.3	2.5	1.1	1.5	2.9	2.0	3.2	2.9	3.7
Pond cost.................$ M..	2.0	3.0	5.5	10.0	3.0	4.0	6.5	12.5	5.5	7.5	14.5	10.0	16.0	14.5	18.5
Dried solids..............tpy..	75	150	310	620	150	230	390	780	310	460	920	620	1,070	920	1,200
Repair and maintenance......$ M..	0.25	0.25	0.40	0.80	0.25	0.25	0.40	0.80	0.25	0.40	0.80	0.40	0.80	0.40	0.80
Labor......................$ M..	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
Total capital cost..........$ M..	29.4	30.6	35.6	46.9	30.6	31.9	36.9	50.0	35.6	40.0	54.4	43.8	56.9	50.0	60.6
Annual operating cost.......$ M..	8.8	9.2	10.5	13.9	8.9	9.3	10.6	14.2	10.2	11.4	15.1	12.3	15.9	13.4	16.2
Cost per 1,000 gallons....cents..	24.1	25.2	28.7	38.1	24.4	25.5	29.0	38.9	27.9	31.2	41.4	33.6	43.6	36.7	44.4

From Mihok, 1970[8]

TABLE 7. - Limestone treatment plant cost estimates for 300,000 gpd plant capacity

Mine water quality, ppm:															
Acidity........................	500	1,000	2,000	5,000	500	1,000	2,000	5,000	1,000	2,000	5,000	2,000	5,000	3,000	5,000
Iron as Fe^{++}..................	50	50	50	50	100	100	100	100	500	500	500	1,000	1,000	1,500	1,500
Neutralized suspended solids...	500	1,000	2,000	4,000	1,000	1,500	2,500	5,000	2,000	3,000	6,000	4,000	7,000	6,000	8,000
Auxiliary equipment cost....$ M..	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13
Holding pond:															
Capacity...............MM gal..	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
Cost.....................$ M..	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5
Neutralization:															
$CaCO_3$ equivalent..........tpd..	0.62	1.24	2.50	6.2	0.62	1.24	2.50	6.20	1.24	2.50	6.20	2.50	6.20	3.75	6.30
Limestone.................tpd..	0.93	1.86	3.75	9.3	0.93	1.86	3.75	9.30	1.86	3.75	9.30	3.75	9.30	5.40	9.30
Limestone...............M tpy..	0.34	0.68	1.36	3.42	0.34	0.68	1.36	3.42	0.68	1.36	3.42	1.36	3.42	2.05	3.42
Annual limestone cost.....$ M..	0.68	1.36	2.72	6.84	0.68	1.36	2.72	6.84	1.36	2.72	6.84	2.72	6.84	4.10	6.84
Storage-feeder capacity..tons..	10	10	25	50	10	10	25	50	10	25	50	25	50	25	50
Storage cost..............$ M..	1.5	1.5	2.0	4.0	1.5	1.5	2.0	4.0	1.5	2.0	4.0	2.0	4.0	2.0	4.0
Tube mill capacity........tpd..	1.0	2.0	4	10	1	2	4	10	2	4	10	4	10	7.5	10
Tube mill motor............hp..	3	5	15	30	3	5	15	30	5	15	30	15	30	20	30
Tube mill cost............$ M..	2.5	4.0	8.0	20.0	2.5	4.0	8.0	20.0	4.0	8.0	20.0	8.0	20.0	15.0	20.0
Annual power cost.........$ M..	0.2	0.3	0.8	1.9	0.2	0.3	0.8	1.9	0.3	0.8	1.9	0.8	1.9	1.3	1.9
Aeration:															
Pond capacity...........M gal..	10	10	10	10	15	15	15	15	60	60	60	90	90	100	100
Pond cost.................$ M..	1.4	1.4	1.4	1.4	1.6	1.6	1.6	1.6	3.1	3.1	3.1	4.0	4.0	4.2	4.2
Blower capacity...........cfm..	375	375	375	375	450	450	450	450	1,500	1,500	1,500	2,100	2,100	2,400	2,400
Blower motor...............hp..	10	10	10	10	10	10	10	10	40	40	40	50	50	60	60
Blower-motor cost.........$ M..	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	3.3	3.3	3.3	3.7	3.7	3.9	3.9
Total aeration cost.......$ M..	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	8.0	8.0	8.0	9.5	9.5	11.0	11.0
Annual power cost.........$ M..	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	2.4	2.4	2.4	3.3	3.3	3.8	3.8
Settling:															
Pond capacity..........MM gal..	1.0	1.7	3.1	5.9	1.7	2.4	3.9	7.5	3.1	4.5	8.6	5.9	9.6	8.6	11.1
Pond cost.................$ M..	5.0	8.5	15.5	29.5	8.5	12.0	19.5	37.5	15.5	22.5	43.0	29.5	48.0	43.0	55.5
Dried solids..............tpy..	0.23	0.46	0.92	1.84	0.46	0.69	1.17	2.34	0.92	1.38	2.76	1.86	3.21	2.76	3.60
Repair and maintenance......$ M..	0.25	0.4	0.8	2.0	0.25	0.4	0.8	2.0	0.4	0.8	2.0	0.8	2.0	1.5	2.0
Labor......................$ M..	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
Total capital cost..........$ M..	38.1	44.3	58.8	93.8	42.5	48.8	63.8	103.8	58.1	72.5	115.6	70.6	123.8	110.6	135.0
Annual operating cost.......$ M..	10.5	12.1	15.8	25.7	11.0	12.5	16.3	26.7	15.3	19.0	29.7	19.7	31.4	26.8	33.0
Cost per 1,000 gallons....cents..	9.6	11.1	14.4	23.5	10.0	11.4	14.9	24.4	14.0	17.4	27.1	18.0	28.7	24.5	30.1

From Mihok, 1970[8]

TABLE 8. - Limestone treatment plant cost estimates for 500,000 gpd plant capacity

Mine water quality, ppm:														
Acidity........................	500	1,000	2,000	500	1,000	2,000	4,000	1,000	2,000	4,000	2,000	4,000	3,000	4,000
Iron as Fe^{++}..................	50	50	50	100	100	100	100	500	500	500	1,000	1,000	1,500	1,500
Neutralized suspended solids...	500	1,000	2,000	1,000	1,500	2,500	4,000	2,000	3,000	5,000	4,000	6,000	6,000	7,000
Auxiliary equipment cost....$ M..	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0
Holding pond:														
Capacity..............MM gal..	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Cost......................$ M..	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5
Neutralization:														
$CaCO_3$ equivalent..........tpd..	1.04	2.08	4.16	1.04	2.08	4.16	8.32	2.08	4.16	8.32	4.16	8.32	4.16	8.32
Limestone.................tpd..	7.6	3.1	6.2	1.6	3.1	6.2	12.4	3.1	6.2	12.4	6.2	12.4	6.2	12.4
Limestone...............M tpy..	0.57	1.14	2.28	0.57	1.14	2.28	4.56	1.14	2.28	4.56	2.28	4.56	3.42	4.56
Annual limestone cost.....$ M..	1.14	2.28	4.56	1.14	2.28	4.56	9.12	2.28	4.56	9.12	4.56	9.12	6.84	9.12
Storage-feeder capacity..tons..	10	25	50	10	25	50	100	25	50	100	50	100	50	100
Storage cost.............$ M..	1.5	2.0	4.0	1.5	2.0	4.0	6.0	2.0	4.0	6.0	4.0	6.0	4.0	6.0
Tube mill capacity........tpd..	2	4	7.5	2	4	7.5	15	4	7.5	15	7.5	15	10	20
Tube mill motor............hp..	5	15	25	5	15	25	45	15	25	45	25	45	30	60
Tube mill cost............$ M..	4	8	15	4	8	15	25	8	15	25	15	25	20	30
Annual power cost.........$ M..	0.4	0.8	1.6	0.4	0.8	1.6	2.9	0.8	1.6	2.9	1.6	2.9	1.9	3.8
Aeration:														
Pond capacity...........M gal..	7.5	7.5	7.5	10.0	10.0	10.0	10.0	35.0	35.0	35.0	50.0	50.0	60.0	60.0
Pond cost.................$ M..	1.3	1.3	1.3	1.5	1.5	1.5	1.5	2.4	2.4	2.4	2.9	2.9	3.1	3.1
Blower capacity...........cfm..	700	700	700	1,000	1,000	1,000	1,000	2,500	2,500	2,500	3,500	3,500	4,000	4,000
Blower motor...............hp..	20	20	20	30	30	30	30	60	60	60	80	80	100	100
Blower-motor cost.........$ M..	2.1	2.1	2.1	3.1	3.1	3.1	3.1	3.9	3.9	3.9	5.6	5.6	6.0	6.0
Total aeration cost.......$ M..	4.5	4.5	4.5	6.0	6.0	6.0	6.0	8.0	8.0	8.0	12.0	12.0	13.0	13.0
Annual power cost.........$ M..	1.3	1.3	1.3	1.9	1.9	1.9	1.9	3.8	3.8	3.8	5.2	5.2	6.5	6.5
Settling:														
Pond capacity..........MM gal..	1.5	3.0	5.0	3.0	4.0	6.5	10.0	5.0	7.5	12.0	10.0	14.5	14.5	16.5
Pond cost.................$ M..	7.5	15.0	25.0	15.0	20.0	32.5	50.0	25.0	37.5	60.0	50.0	72.5	72.5	82.5
Dried solids..............tpy..	380	760	1,520	760	1,140	1,900	3,040	1,520	2,280	3,800	3,040	4,560	4,560	5,320
Repair and maintenance......$ M..	0.4	0.8	1.5	0.4	0.8	1.5	2.5	0.8	1.5	2.5	1.5	2.5	2.0	3.0
Labor.......................$ M..	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
Total capital cost..........$ M..	53.8	68.8	91.3	65.0	76.9	103.8	140.6	85.6	112.5	165.6	132.1	176.3	171.3	196.3
Annual operating cost.......$ M..	13.5	17.1	23.0	15.2	18.5	24.9	35.5	21.2	27.7	39.9	31.1	42.4	39.4	47.1
Cost per 1,000 gallons....cents..	7.4	9.3	12.6	8.3	10.1	13.6	19.4	11.6	15.2	21.8	17.0	23.2	21.6	26.8

From Mihok, 1970[8]

TABLE 9. - Limestone treatment plant cost estimates for 1,500,000 gpd plant capacity

Mine water quality, ppm:														
Acidity	500	1,000	2,000	500	1,000	2,000	4,000	1,000	2,000	4,000	2,000	4,000	3,000	4,000
Iron as Fe^{++}	50	50	50	100	100	100	100	500	500	500	1,000	1,000	1,500	1,500
Neutralized suspended solids	500	1,000	2,000	1,000	1,500	2,500	4,000	2,000	3,000	5,000	4,000	6,000	6,000	7,000
Auxiliary equipment cost....$ M..	19.5	19.5	19.5	19.5	19.5	19.5	19.5	19.5	19.5	19.5	19.5	19.5	19.5	19.5
Holding pond:														
Capacity..............MM gal..	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5
Cost....................$ M..	22.5	22.5	22.5	22.5	22.5	22.5	22.5	22.5	22.5	22.5	22.5	22.5	22.5	22.5
Neutralization:														
$CaCO_3$ equivalent.........tpd..	3.12	6.24	12.48	3.12	6.24	12.48	24.96	6.24	12.48	24.96	12.48	24.96	18.72	24.96
Limestone...............tpd..	4.7	9.3	18.6	4.7	9.3	18.6	37.2	9.3	18.6	37.2	18.6	37.2	27.9	37.2
Limestone.............M tpy..	1.71	3.42	6.84	1.71	3.42	6.84	13.68	3.42	6.84	13.68	6.84	13.68	10.28	13.68
Annual limestone cost.....$ M..	3.42	6.84	13.68	3.42	6.84	13.68	27.36	6.84	13.68	27.36	13.68	27.36	20.56	27.32
Storage-feeder capacity..tons..	25	50	100	25	50	100	200	50	100	200	100	200	150	200
Storage cost.............$ M..	2	4	6	2	4	6	10	4	6	10	6	10	8	10
Tube mill capacity........tpd..	5	10	20	5	10	20	40	10	20	40	20	40	30	40
Tube mill motor...........hp..	15	30	60	15	30	60	125	30	60	125	60	125	90	125
Tube mill cost...........$ M..	10	20	30	10	20	30	55	20	30	55	30	55	40	55
Annual power cost.........$ M..	0.9	1.9	3.8	0.9	1.9	3.8	8.0	1.9	3.8	8.0	3.8	8.0	5.7	8.0
Aeration:														
Pond capacity..........M gal..	25	25	25	30	30	30	30	100	100	100	150	150	180	180
Pond cost................$ M..	2.1	2.1	2.1	2.3	2.3	2.3	2.3	4.2	4.2	4.2	5.6	5.6	6.3	6.3
Blower capacity...........cfm..	2,100	2,100	2,100	3,000	3,000	3,000	3,000	7,500	7,500	7,500	10,000	10,000	12,000	12,000
Blower motor..............hp..	50	50	50	80	80	80	80	150	150	150	200	200	250	250
Blower-motor cost.........$ M..	3.7	3.7	3.7	5.6	5.6	5.6	5.6	8.0	8.0	8.0	12.0	12.0	13.0	13.0
Total aeration cost.......$ M..	7.5	7.5	7.5	11.0	11.0	11.0	11.0	17.0	17.0	17.0	25.0	25.0	27.0	27.0
Annual power cost.........$ M..	3.3	3.3	3.3	5.2	5.2	5.2	5.2	9.5	9.5	9.5	13.0	13.0	16.0	16.0
Settling:														
Pond capacity.........MM gal..	5	9	15	9	12	19	30	15	22	36	30	42	42	50
Pond cost................$ M..	25	45	75	45	60	90	150	75	110	180	150	210	210	250
Dried solids.............tpy..	1,040	2,280	4,560	2,280	3,420	5,700	9,120	4,560	6,840	11,400	9,120	12,680	12,680	15,960
Repair and maintenance......$ M..	1.0	2.0	3.0	1.0	2.0	3.0	5.5	2.0	3.0	5.5	3.0	5.5	4.0	5.5
Labor......................$ M..	5	5	5	5	5	5	5	5	5	5	5	5	5	5
Total capital cost.........$ M..	107.1	148.1	200.6	137.5	170.3	230.0	335.0	197.5	246.2	380.0	316.3	427.5	408.8	480.0
Annual operating cost.......$ M..	24.3	33.9	48.8	27.4	38.0	53.7	84.1	45.0	59.6	93.4	70.1	101.6	92.1	109.9
Cost per 1,000 gallons....cents..	4.4	6.2	8.9	5.0	6.9	9.8	15.4	8.2	10.9	17.1	12.8	18.6	16.8	20.0

From Mihok, 1970[8]

TABLE 10.- Limestone treatment plant cost estimates for 2 million gpd plant capacity

Mine water quality, ppm:											
Acidity........................	100	500	1,000	500	1,000	1,500	500	1,000	1,500	1,000	1,500
Iron as Fe^{++}..................	50	50	50	100	100	100	250	250	250	500	500
Neutralized suspended solids...	250	500	1,000	500	1,000	1,500	1,000	1,500	2,000	2,000	2,500
Auxiliary equipment cost....$ M..	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0
Holding pond:											
Capacity..............MM gal..	6	6	6	6	6	6	6	6	6	6	6
Cost.....................$ M..	30	30	30	30	30	30	30	30	30	30	30
Neutralization:											
$CaCO_3$ equivalent..........tpd..	0.84	4.16	8.32	4.16	8.32	12.48	4.16	8.32	12.48	8.32	12.48
Limestone................tpd..	1.3	6.2	12.5	6.2	12.5	18.8	6.2	12.5	18.8	12.5	18.8
Limestone..............M tpy..	0.46	2.28	4.56	2.28	4.56	6.08	2.28	4.56	6.08	4.56	6.08
Annual limestone cost.....$ M..	0.92	4.56	9.12	4.56	9.12	12.16	4.56	9.12	12.16	9.12	12.16
Storage-feeder capacity..tons..	10	50	100	50	100	100	50	100	100	100	100
Storage cost.............$ M..	1.5	4.0	6.0	4.0	6.0	6.0	4.0	6.0	6.0	6.0	6.0
Tube mill capacity........tpd..	2	7.5	15	7.5	15	20	7.5	15	20	15	20
Tube mill motor............hp..	5	25	45	25	45	60	25	45	60	45	60
Tube mill cost...........$ M..	4	15	25	15	25	30	15	25	30	25	30
Annual power cost.........$ M..	0.3	1.6	2.9	1.6	2.9	3.8	1.6	2.9	3.8	2.9	3.8
Aeration:											
Pond capacity...........M gal..	25	25	25	35	35	35	75	75	75	150	150
Pond cost................$ M..	2.1	2.1	2.1	2.4	2.4	2.4	3.5	3.5	3.5	5.6	5.6
Blower capacity...........cfm..	2,000	2,000	2,000	3,000	3,000	3,000	5,000	5,000	5,000	10,000	10,000
Blower motor..............hp..	50	50	50	75	75	75	125	125	125	200	200
Blower-motor cost.........$ M..	3.5	3.5	3.5	4.1	4.1	4.1	6.4	6.4	6.4	12.0	12.0
Total aeration cost.......$ M..	7.5	7.5	7.5	9.0	9.0	9.0	16.0	16.0	16.0	25.0	25.0
Annual power cost.........$ M..	3.3	3.3	3.3	4.9	4.9	4.9	8.0	8.0	8.0	13.0	13.0
Settling:											
Pond capacity..........MM gal..	4.5	6.5	11.0	6.5	11	16	11	16	20	20	25
Pond cost................$ M..	22.5	32.5	55.0	32.5	55	80	55	80	100	100	125
Dried solids.............tpy..	760	1,520	3,040	1,520	3,040	4,560	3,040	4,560	6,080	6,080	7,600
Repair and maintenance......$ M..	0.4	1.5	2.5	1.5	2.5	3.0	1.5	2.5	3.0	2.5	3.0
Labor......................$ M..	5	5	5	5	5	5	5	5	5	5	5
Total capital cost..........$ M..	115.6	145.0	188.1	138.1	190.0	227.5	183.7	230.0	260.3	251.3	288.8
Annual operating cost.......$ M..	21.5	30.2	41.6	31.4	43.4	51.6	39.1	50.5	58.0	57.7	65.8
Cost per 1,000 gallons....cents..	2.9	4.2	5.7	4.3	5.9	7.1	5.4	6.9	8.0	7.9	9.0

From Mihok, 1970[8]

TABLE 11.- Limestone treatment plant cost estimates for 6 million gpd plant capacity

Mine water quality, ppm:											
Acidity........................	100	500	1,000	500	1,000	1,500	500	1,000	1,500	1,000	1,500
Iron as Fe^{++}..................	50	50	50	100	100	100	250	250	250	500	500
Neutralized suspended solids...	250	500	1,000	500	1,000	1,500	1,000	1,500	2,000	2,000	2,500
Auxiliary equipment cost....$ M..	30	30	30	30	30	30	30	30	30	30	30
Holding pond:											
Capacity..............MM gal..	18	18	18	18	18	18	18	18	18	18	18
Cost....................$ M..	90	90	90	90	90	90	90	90	90	90	90
Neutralization:											
$CaCO_3$ equivalent..........tpd..	2.5	12.5	25.0	12.5	25.0	37.5	12.5	25.0	37.5	25.0	37.5
Limestone................tpd..	3.8	18.8	37.5	18.8	37.5	56.4	18.8	37.5	56.4	37.5	56.4
Limestone...............M tpy..	1.38	6.84	13.68	6.84	13.68	18.24	6.84	13.68	18.24	13.68	18.24
Annual limestone cost.....$ M..	2.8	13.7	27.4	13.7	27.4	36.5	13.7	27.4	36.5	27.4	36.5
Storage-feeder capacity..tons..	25	100	200	100	200	200	100	200	200	200	200
Storage cost..............$ M..	2	6	10	6	10	10	6	10	10	10	10
Tube mill capacity........tpd..	4	20	40	20	40	60	20	40	60	40	60
Tube mill motor............hp..	15	60	125	60	125	200	60	125	200	125	200
Tube mill cost............$ M..	8	30	55	30	55	70	30	55	70	55	70
Annual power cost.........$ M..	1.3	3.8	8.0	3.8	8.0	13.0	3.8	8.0	13.0	8.0	13.0
Aeration:											
Pond capacity...........M gal..	75	75	75	100	100	100	225	225	225	450	450
Pond cost.................$ M..	3.5	3.5	3.5	4.2	4.2	4.2	7.5	7.5	7.5	10.0	10.0
Blower capacity...........cfm..	5,000	5,000	5,000	7,500	7,500	7,500	12,500	12,500	12,500	20,000	20,000
Blower motor...............hp..	125	125	125	150	150	150	325	325	325	600	600
Blower-motor cost.........$ M..	7.3	7.3	7.3	8.0	8.0	8.0	19.4	19.4	19.4	33.5	33.5
Total aeration cost.......$ M..	16.0	16.0	16.0	17.0	17.0	17.0	35.0	35.0	35.0	55.0	55.0
Annual power cost.........$ M..	8.0	8.0	8.0	9.8	9.8	9.8	21.0	21.0	21.0	38.0	38.0
Settling:											
Pond capacity..........MM gal..	13	20	33	20	33	48	33	48	60	60	75
Pond cost.................$ M..	65	100	165	100	165	240	165	240	300	300	375
Dried solids..............tpy..	2,280	4,560	9,120	4,560	9,120	13,680	9,120	13,680	18,160	18,160	22,800
Repair and maintenance......$ M..	0.8	3.0	5.5	3.0	5.5	7.0	3.0	5.5	7.0	5.5	7.0
Labor.....................$ M..	5	5	5	5	5	5	5	5	5	5	5
Total capital cost..........$ M..	263.8	340.0	475.5	341.3	458.8	571.3	445.0	575.0	669.0	653.8	766.3
Annual operating cost.......$ M..	44.2	66.5	99.9	68.4	101.8	128.4	89.9	124.6	149.4	149.5	176.1
Cost per 1,000 gallons....cents..	2.0	3.0	4.4	3.2	4.6	5.9	4.1	5.7	6.8	6.8	8.0

From Mihok, 1970[8]

FIGURE 17

ESTIMATED CAPITAL COSTS Vs. PLANT CAPACITY
FOR LIMESTONE TREATMENT PLANT-U.S. BUREAU OF MINES (REF. 8)
IRON AS Fe^{++} = 50 PPM

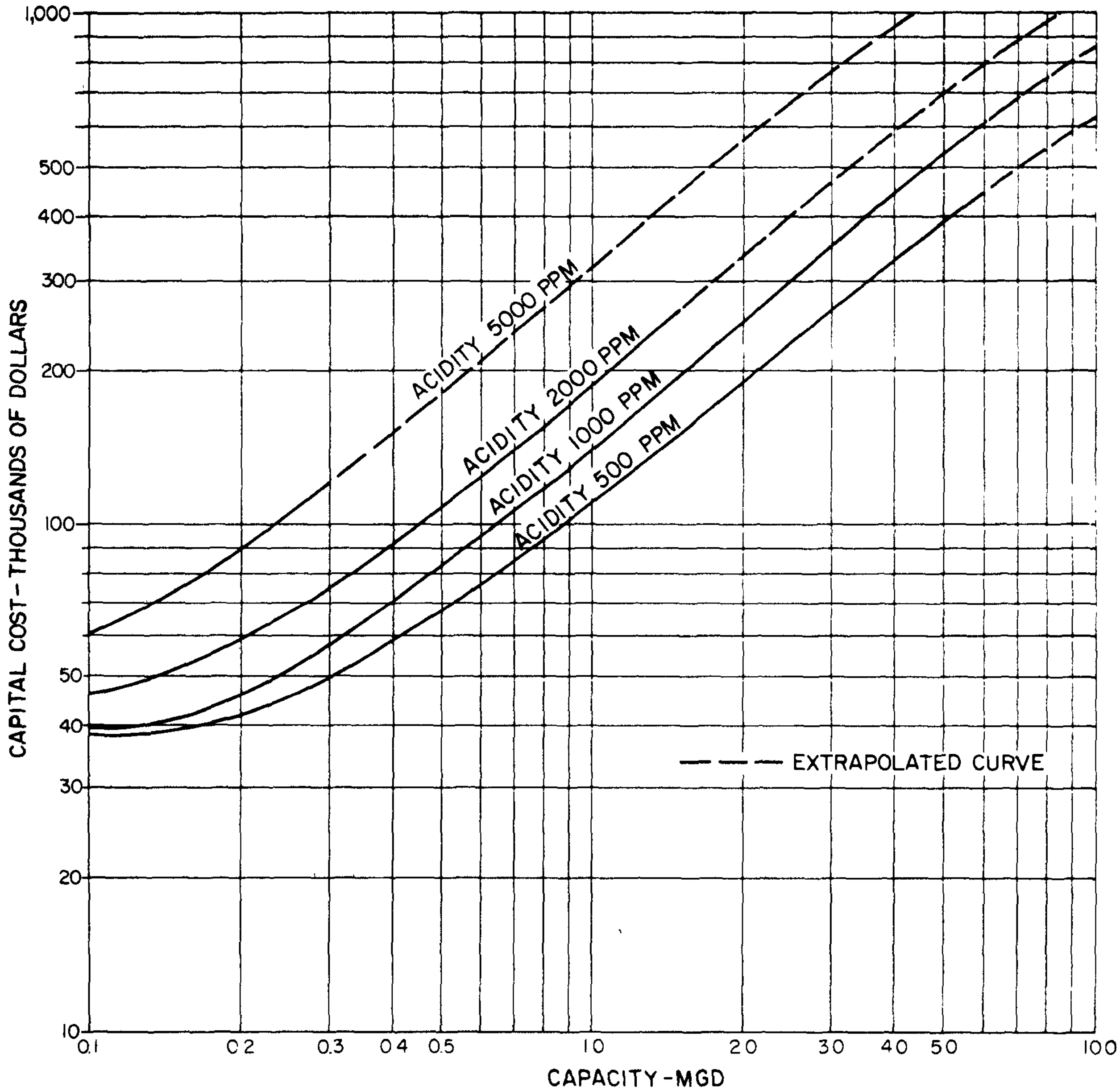


FIGURE 18

ESTIMATED CAPITAL COSTS Vs. PLANT CAPACITY
FOR LIMESTONE TREATMENT PLANT–U.S. BUREAU OF MINES (REF. 8)
IRON AS Fe^{++} = 100 PPM

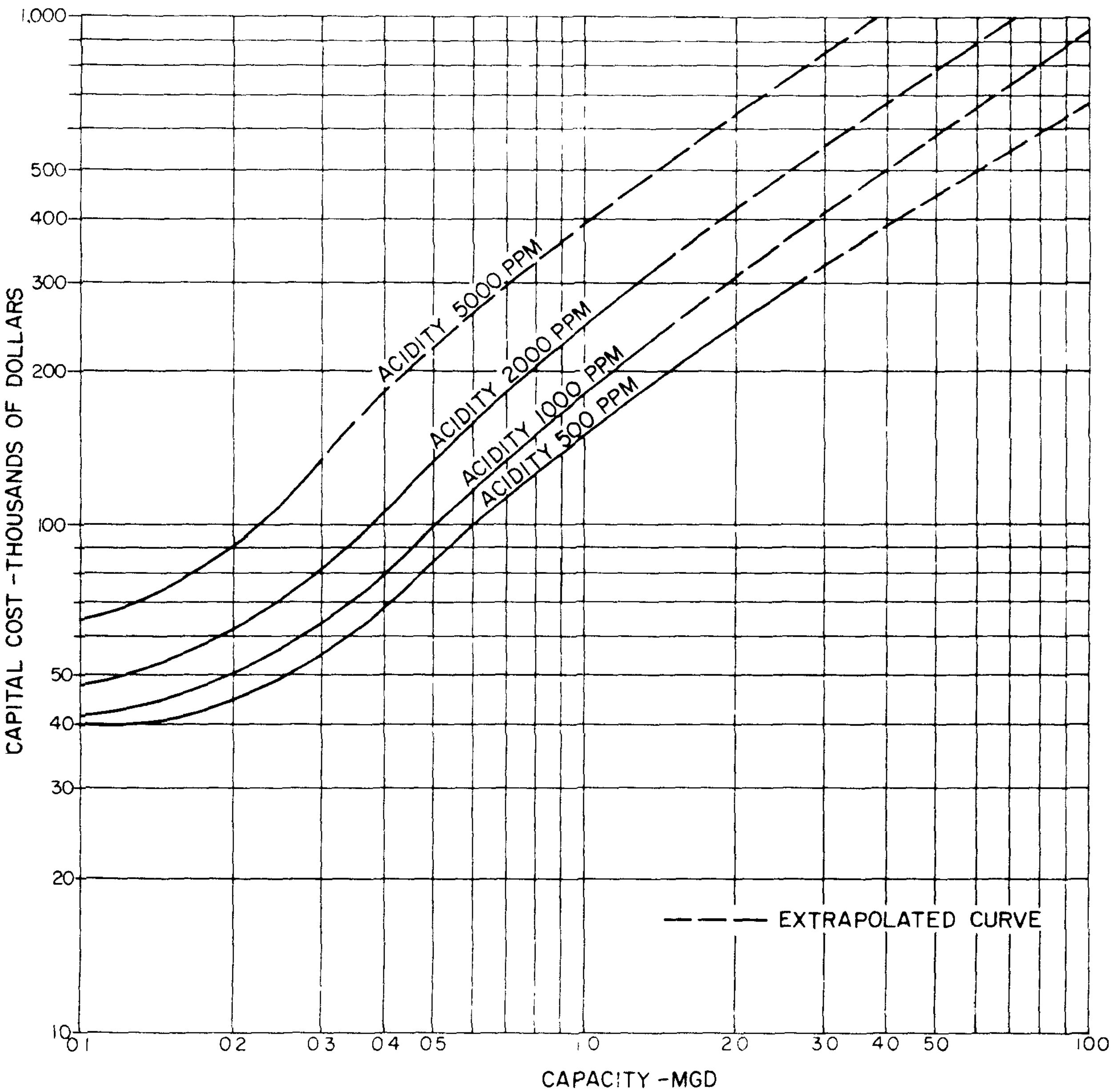


FIGURE 19

ESTIMATED CAPITAL COSTS Vs. PLANT CAPACITY
FOR LIMESTONE TREATMENT PLANT-U.S. BUREAU OF MINES (REF. 8)
IRON AS Fe^{++}=500 PPM

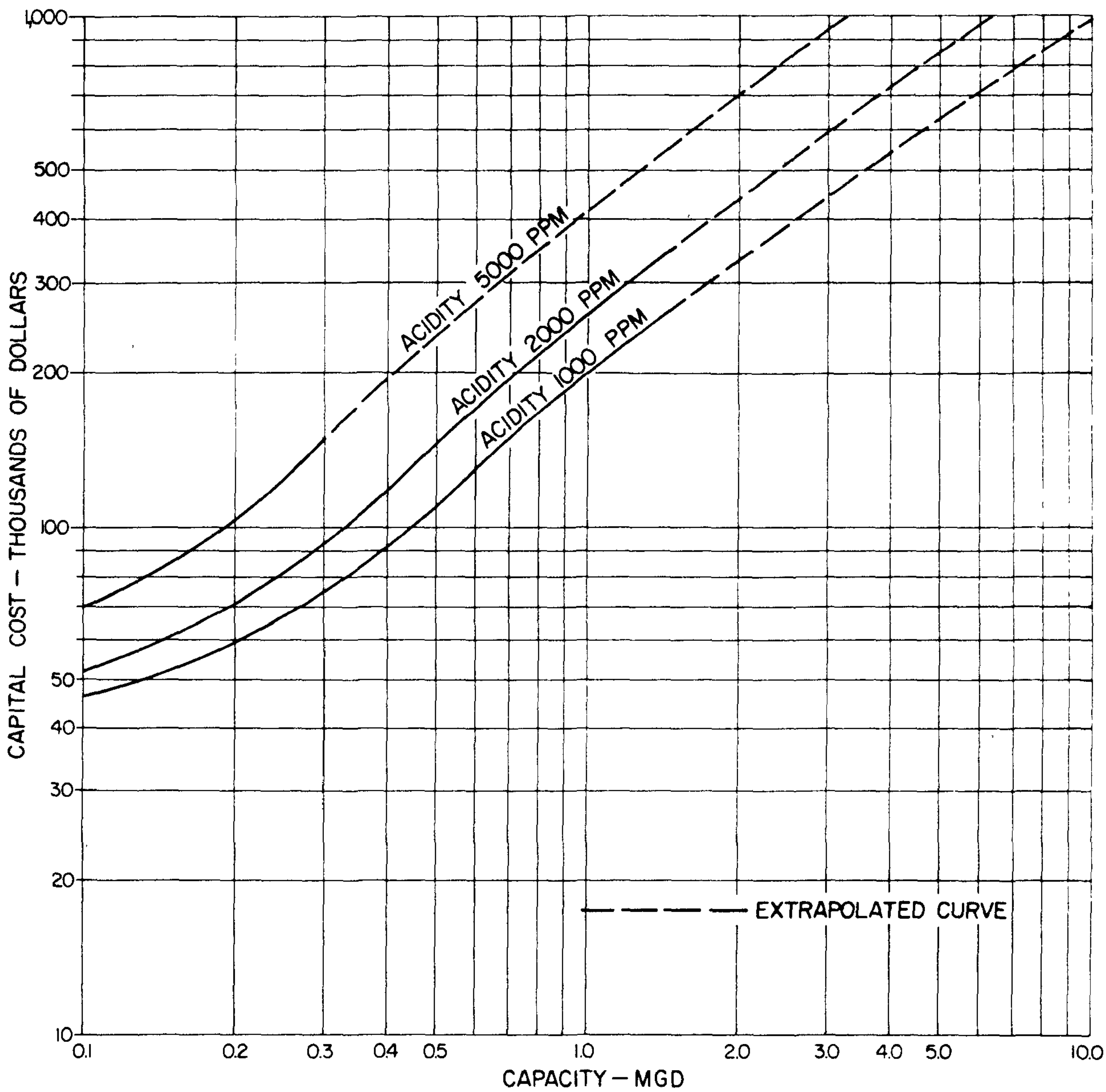


FIGURE 20

ESTIMATED CAPITAL COSTS Vs. PLANT CAPACITY
FOR LIMESTONE TREATMENT PLANT-U.S. BUREAU OF MINES (REF.8)
IRON AS Fe^{++}=1000 PPM

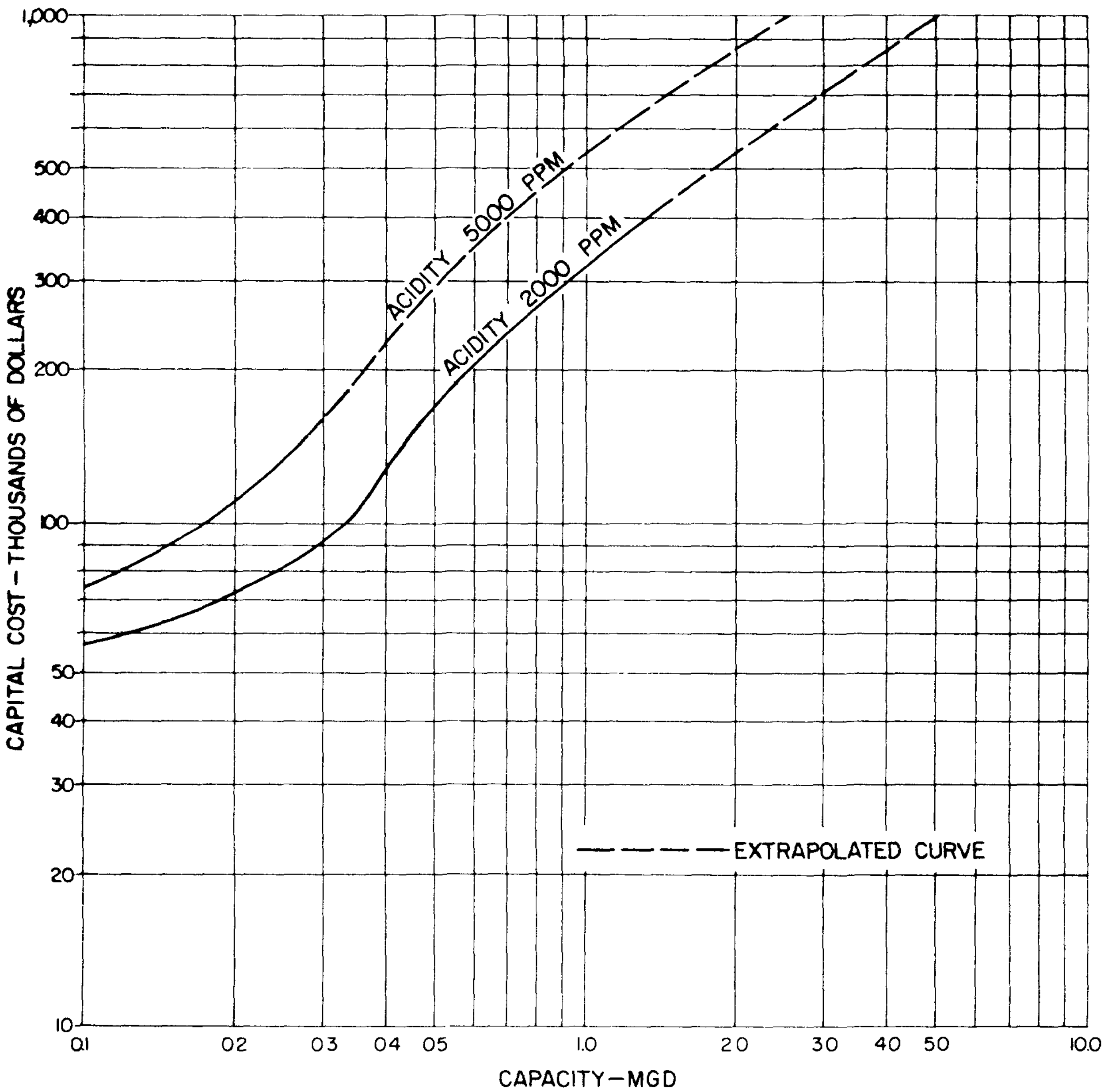


FIGURE 21

ANNUAL OPERATING COSTS Vs. PLANT CAPACITY
FOR LIMESTONE TREATMENT – U.S. BUREAU OF MINES (REF. 8)
IRON AS FE^{++} = 50 PPM

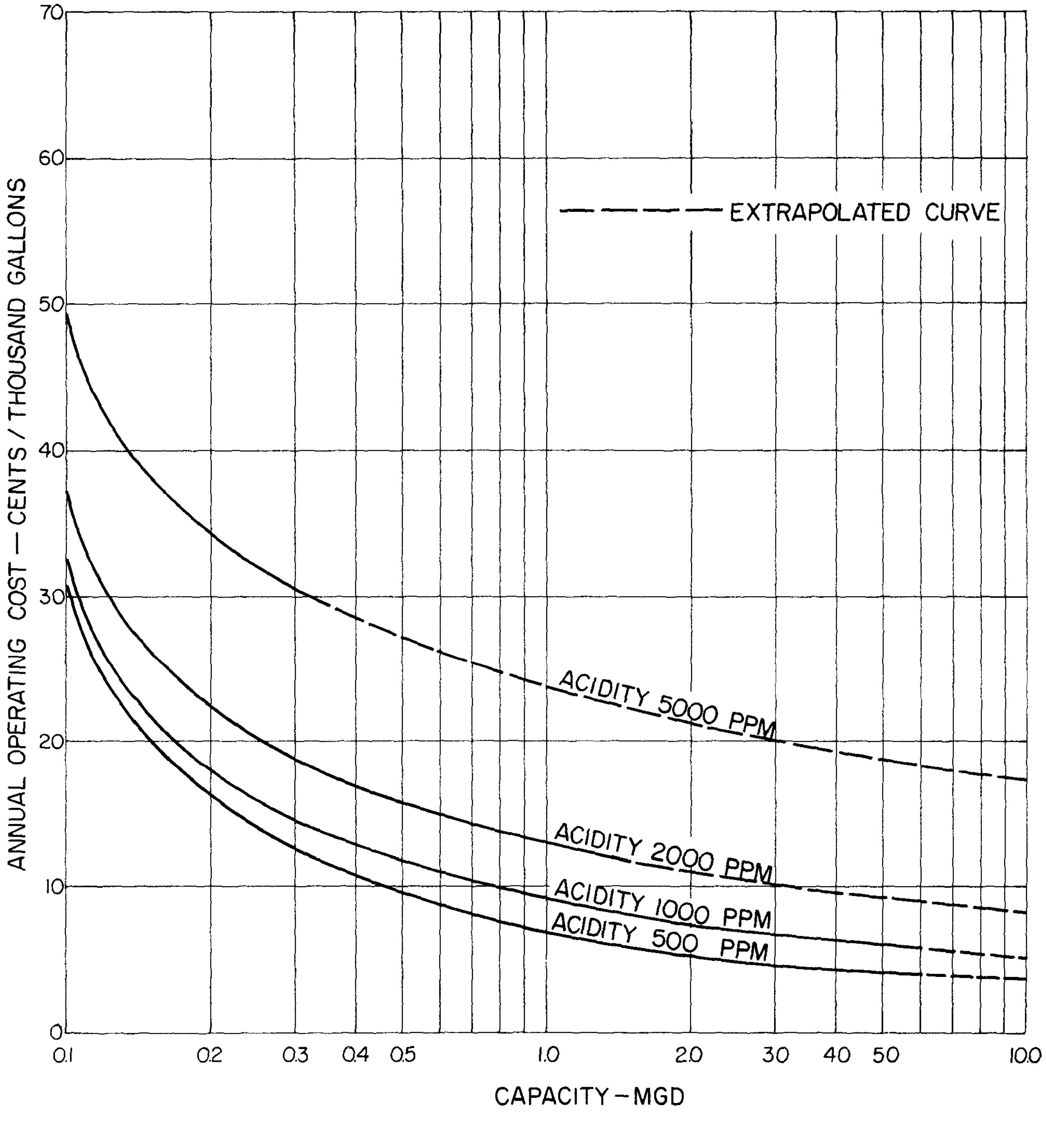


FIGURE 22

ANNUAL OPERATING COSTS Vs. PLANT CAPACITY
FOR LIMESTONE TREATMENT – U.S. BUREAU OF MINES (REF. 8)
IRON AS FE^{++} = 100 PPM

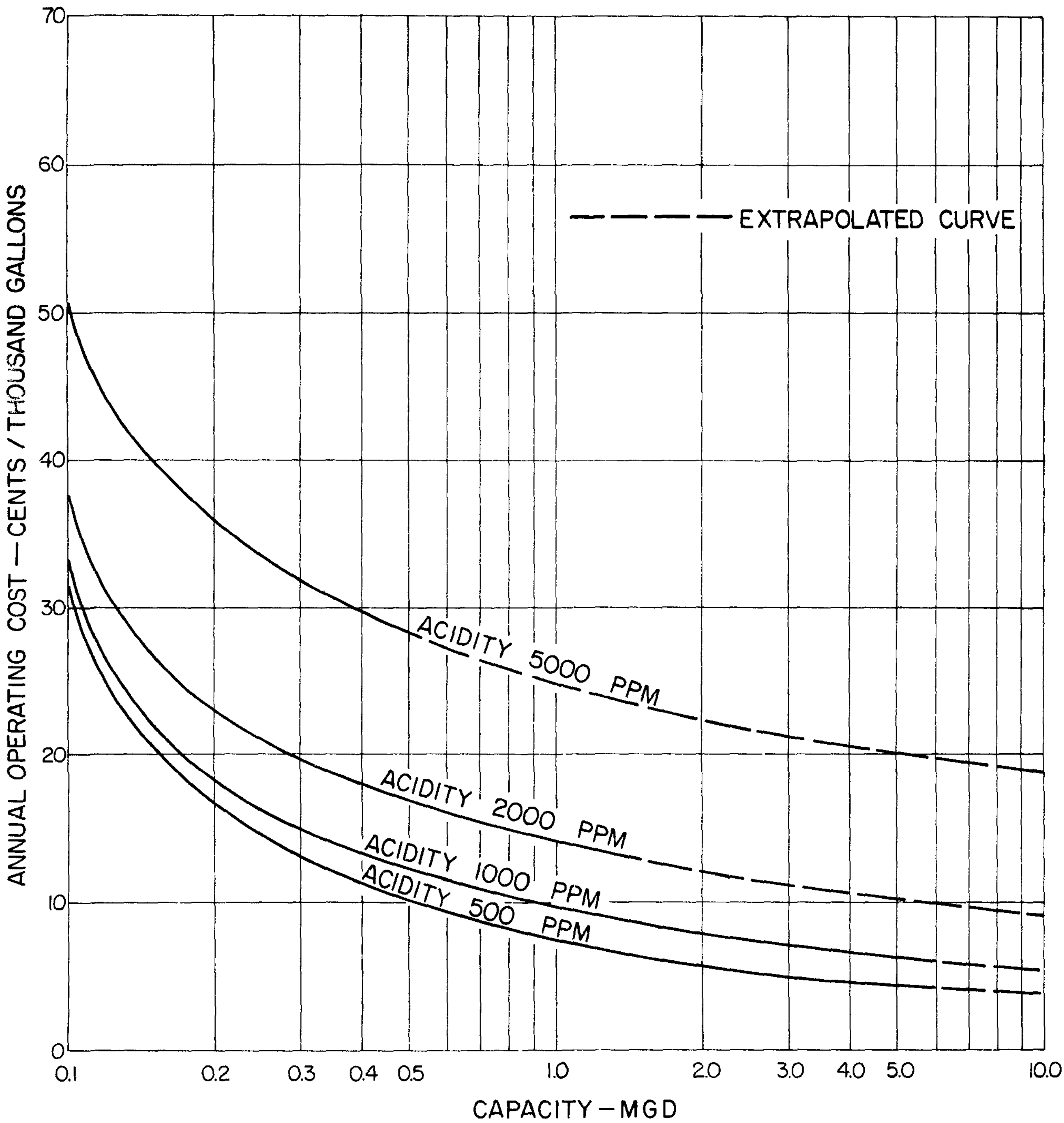


FIGURE 23

ANNUAL OPERATING COSTS Vs. PLANT CAPACITY
FOR LIMESTONE TREATMENT — U.S. BUREAU OF MINES (REF. 8)
IRON AS FE^{++} = 500 PPM

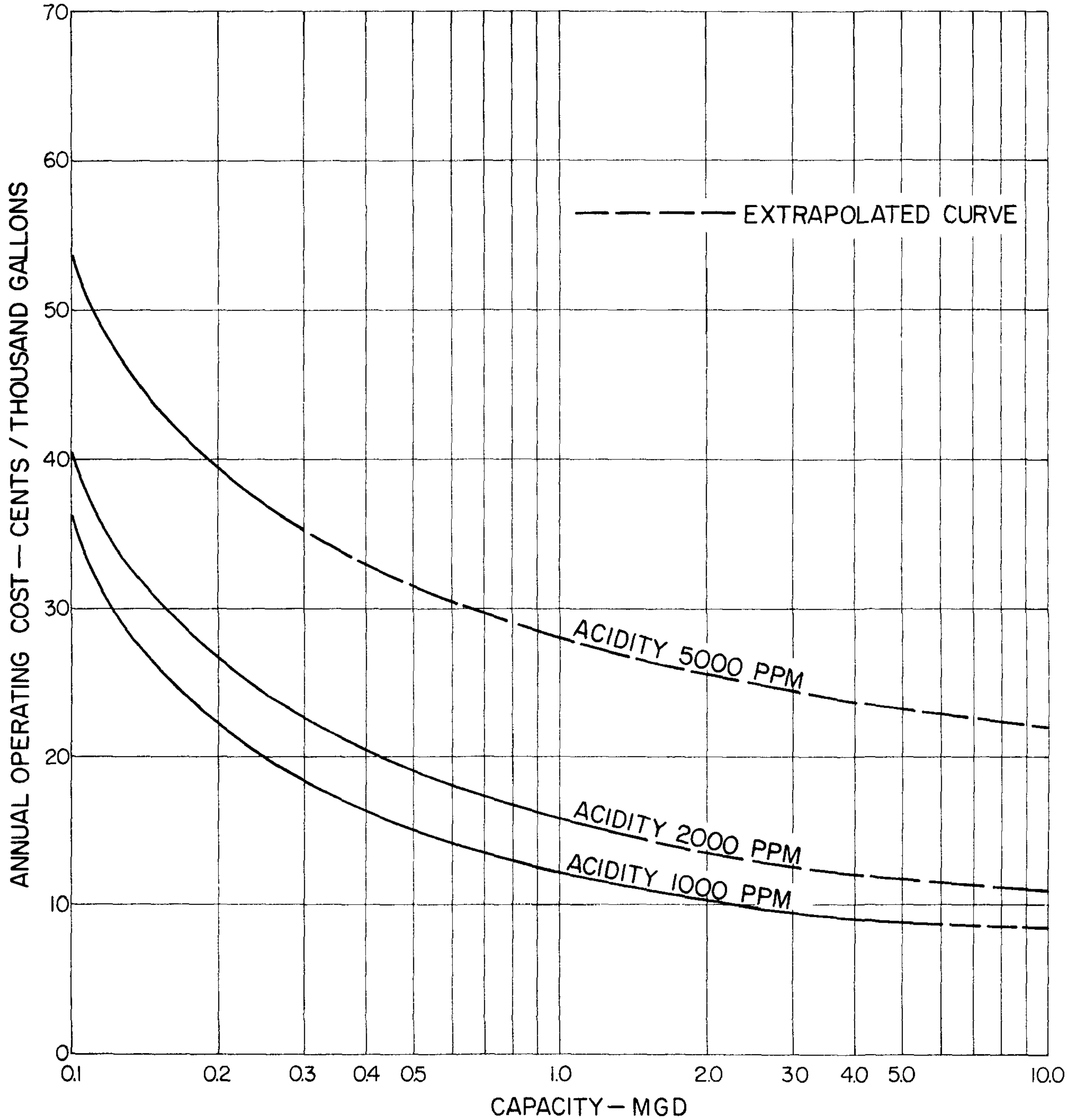
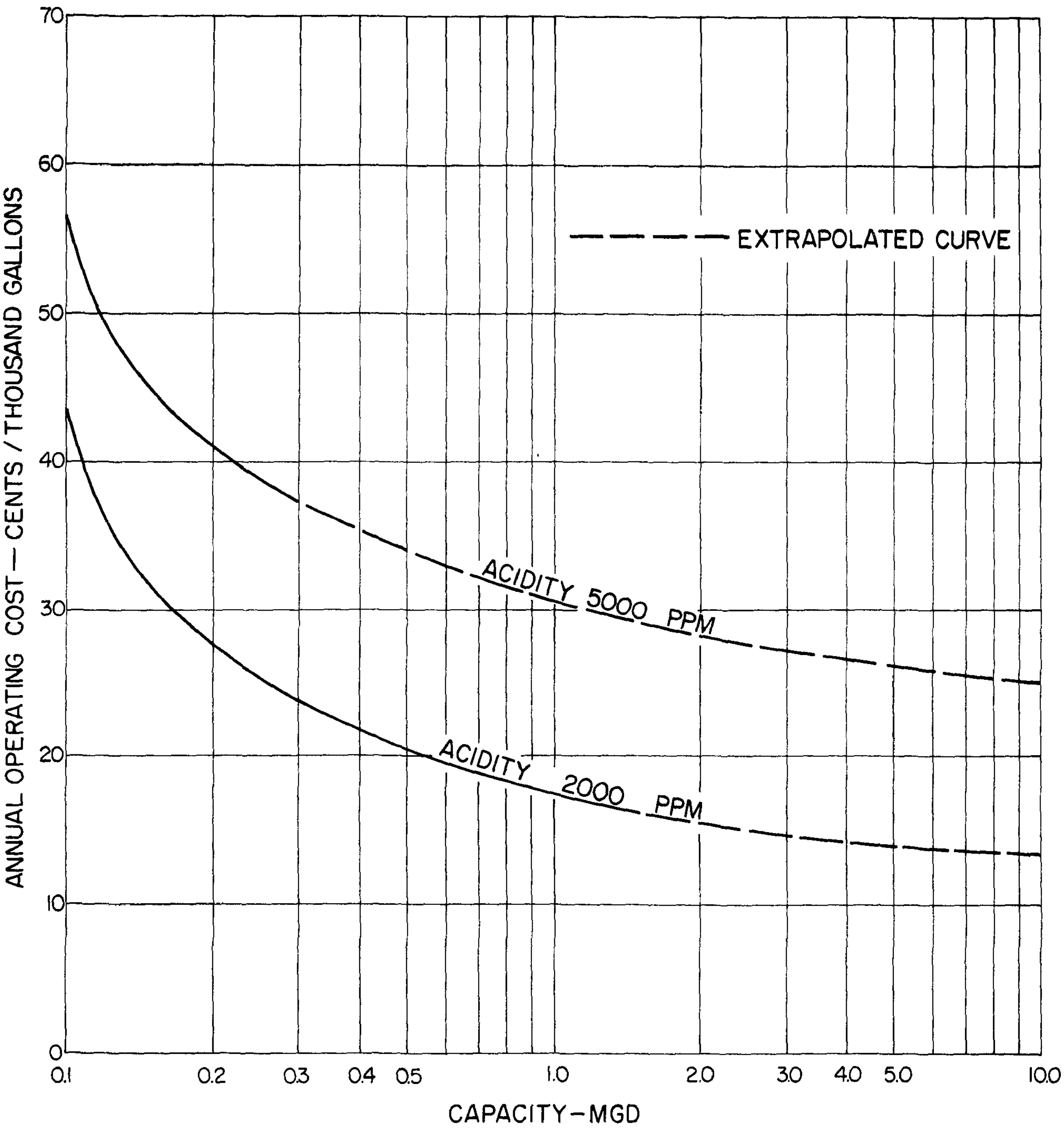


FIGURE 24

ANNUAL OPERATING COSTS Vs. PLANT CAPACITY
FOR LIMESTONE TREATMENT – U.S. BUREAU OF MINES (REF. 8)
IRON AS FE^{++} = 1000 PPM



Combination Limestone - Lime Treatment Process

The major disadvantages of using limestone as a neutralizing agent in treating acid mine drainage are:

1. The relatively inefficient reaction rate, which in many cases, makes lime more economical to use, and

2. The pH's in excess of 7 which are necessary for rapid oxidation of ferrous iron are not produced.

Thus, in spite of recent work to increase the reaction efficiency of limestone, it can only effectively compete with lime when treating ferric iron mine drainage or mine drainage in which the ferrous iron can be cheaply oxidized to ferric iron by biological oxidation or other methods prior to limestone neutralization.

The logical step would be to combine the limestone and lime processes. Since limestone is highly reactive at low pH's, it should be added first to the acid mine drainage. Lime being highly reactive to pH 9 and higher, should be used to "polish" the limestone treated water. In this manner, combination limestone - lime treatment enables both limestone and lime to be employed as neutralizing agents in their most efficient ranges of reactivity. The lower cost of limestone and the improvement in sludge characteristics as a result of using this material are advantages which should lead to an overall cost reduction when both limestone and lime are employed in neutralizing acid mine water.

This approach was investigated by the Environmental Protection Agency[11] at the Norton Mine Drainage Field Site, Norton, West Virginia. The mine drainage used in the batch scale studies and in the later pilot plant operation was from a heavily polluted stream in which it is estimated that 90 percent of the flow is from abandoned mines; about 70 percent of the pollution flows directly out of underground mines. The mine drainage has the following significant chemical characteristics:

		Mean
pH	2.5 to 3.4	2.8*
Acidity	134 to 640 mg/l	430 mg/l
Calcium	18 to 170 mg/l	106 mg/l
Magnesium	21 to 120 mg/l	35 mg/l
Aluminum	18 to 69 mg/l	33 mg/l
Sulfate	76 to 1200 mg/l	590 mg/l
Total Iron	14 to 170 mg/l	92 mg/l

*Median Value

Virtually all the iron present in this mine drainage was in the ferric state.

In order to obtain the smallest particle size commercially available, the "rock dust" form of limestone was used. The cost of the limestone was \$6 per ton and lime was \$18 per ton.

The combination limestone-lime treatment provided greater than 25 percent reduction in material cost for treatment to pH 6.5 of the Norton acid mine drainage as compared to straight lime or limestone treatment. In addition to the materials cost advantage, combination treatment produced a sludge whose solids contents were up to five times higher than sludge produced by lime neutralization, though not as high as sludge from limestone neutralization. The volume of sludge produced by combination treatment was roughly one-third that of lime treatment and slightly less than limestone sludge volume.

Although the study was performed on ferric iron water, the combination limestone-lime treatment should be applicable to virtually all acid mine drainage situations. Whether or not an economic advantage can be realized is a matter which can only be determined by evaluating each individual site and its required process parameter. The variables which must be considered are:

1. Raw material costs of "rock dust" limestone and hydrated lime.
2. Effectiveness of limestone in acid mine drainage treatment (composition of limestone).
3. Reaction time.
4. Treatment pH

To determine the effects of raw material costs for lime and limestone on process economics, the data on Table 12 was chosen by Wilmoth, et. al.[11] as an example. Both the lime and limestone raw material costs were varied and the cost reduction calculated. Their plot of the resulting data is shown on Figure 25. When the lime/limestone raw material cost ratio is less than 1.8:1, the cost advantage of combination treatment over lime treatment no longer exists. As the lime/limestone ratio increased, so did the advantage of combination treatment.

In an example, they assumed the water treated in Table 12 was all ferrous iron mine drainage and a pH in the range of 9.0 would be required for efficient oxidation by aeration. In this example, roughly 20 percent more lime would be required (verified by titration tests) to affect the pH increase from 6.4 to 9.0. Thus, side 2 in Table 12 would require an additional 0.727 lbs./1,000 gallons of lime (20% of 3.634) for a total of 4.361. The amount of limestone required by side 1 would not change but the amount of lime would be increased by the same 0.727 pounds to 2.078 lbs./1,000 gallons of water. The cost reduction due to combination treatment would decrease to 21.4 percent (lime/limestone raw material cost ratio of 3:1 when limestone = 0.30/lb. and lime = 0.90/lb.)

TABLE 12
LIMESTONE-LIME Vs. LIME at 5 GPM

	Side 1 - Combination Limestone & Lime @ 5 gpm							Side 2 - Lime @ 5 gpm			
Date 1971	#/1000 Gallons Limestone	Lime-stone pH	#/1000 Gallons Lime	Final pH	Cost per 1000 gals. Lime-stone Cents	Lime Cents	Total Cents	#/1000 Gallons Lime	Final	Cost per 1000 Gallons Cents	Material Cost Re-duction Percent
7/24	3.345	3.6	1.352	6.2	1.004	1.217	2.221	3.462	6.2	3.116	28.7
7/25	4.447	4.3	1.308	6.5	1.334	1.177	2.511	3.408	6.3	3.067	18.1
7/29	4.297	4.1	1.349	6.2	1.289	1.214	2.503	3.914	6.2	3.523	29.0
7/30	4.093	3.8	1.393	6.5	1.228	1.254	2.482	3.751	6.3	3.376	26.5
Average	4.046	4.0	1.351	6.4	1.214	1.216	2.430	3.634	6.3	3.271	25.7
Example	4.046		2.078		1.214	1.871	3.085	4.361		3.924	21.4

Raw Material Costs:

Limestone = 0.30 cents/lb @ $ 6.00/ton
Lime = 0.90 cents/lb @ $18.00/ton

$$3.924 - 3.085 = 0.839$$

$$0.839/3.924 \times 100 = 21.4\%$$

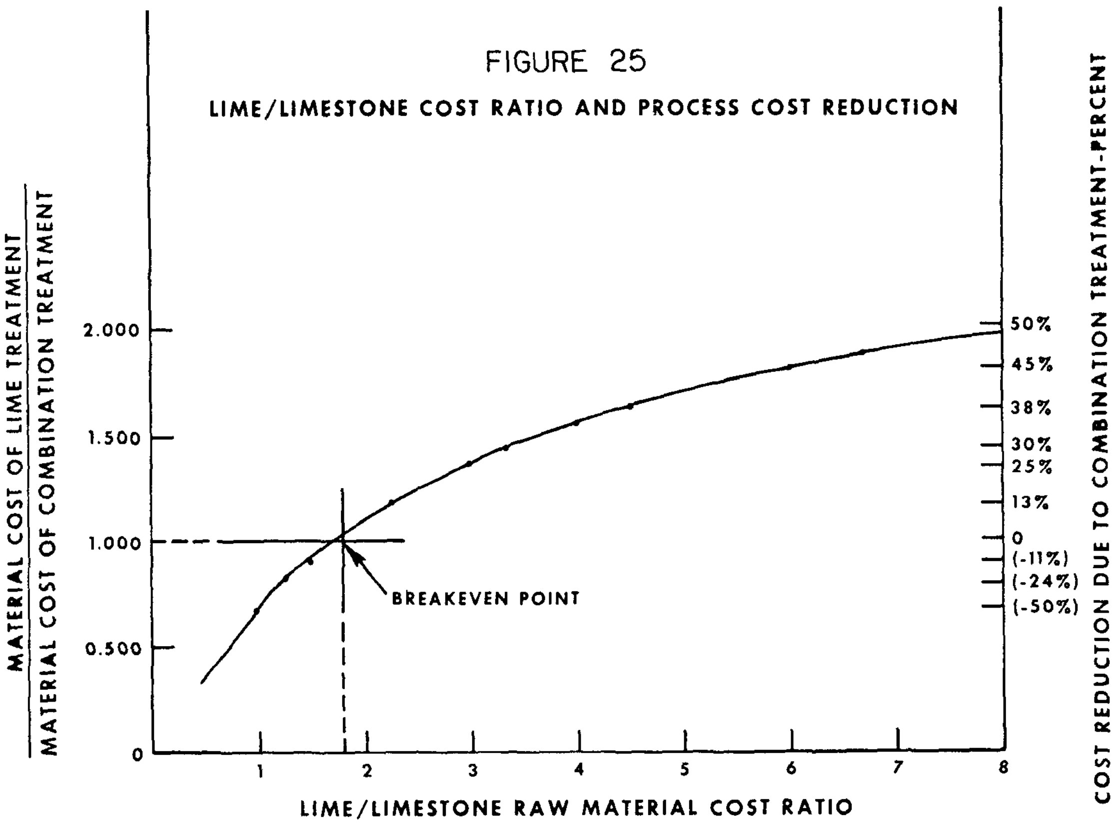
After Wilmoth, et. al., 1972 (11)

If 70 percent more lime were required to increase the pH from 6.4 to 9.0, then the cost advantage of combination treatment over lime would decrease to 15.1 percent (lime/limestone raw material cost ratio of 3:1).

The combination treatment appears to offer nearly as great an economical advantage in ferrous iron situations as in ferric ones. Although combination treatment requires a higher initial investment in equipment, it appears the advantage realized in reagent cost reduction can quickly offset this increased initial expenditure.

FIGURE 25

LIME/LIMESTONE COST RATIO AND PROCESS COST REDUCTION



After Wilmoth, et al., 1972[11]

Combination Lime-Limestone Neutralization with Rotary Precoat Filtration for Sludge Dewatering

The combination lime-limestone neutralization process was employed by Davis, et, al.,[12, 13] in conjunction with rotary precoat filtration for dewatering the sludge produced from neutralization of mine drainage. Pilot plant operation was performed at five sites. A schematic flow-diagram of the process used at Hollywood, Pennsylvania, the fourth site, is shown in Figure 26. The raw water was obtained from the pump well of the Proctor 2 pumping station feeding the Hollywood, Pennsylvania experimental mine drainage treatment facility. The chemical characteristics of the mine drainage treated at this site are: pH - 3.0, total iron - 653 mg/l, ferrous iron - 445 mg/l, total acidity - 1,560 mg/l and total solids - 4,110 mg/l.

The pilot plant treatment system was fabricated from the following equipment:

1. U.S. Bureau of Mines' four foot diameter by 24 foot long tube mill[7] which was used to produce a fine limestone slurry from one-half to two inch rock.

2. The Pennsylvania Department of Environmental Resources' Operation Yellowboy Trailer. This trailer contains a variable capacity feed pump, a 50 gallon flash mixer with agitator and screw feeder, a 1,200 gallon agitated aerator tank with a 17 cfm blower-sprayer unit, a 1,000 gallon thickener, and a variable speed sludge recycle/discharge pump.

3. A Johns-Manville rotary vacuum precoat filter (6 inch face and 36 inch diameter) with a variable speed drum drive, variable speed knife advance and 30 and 50 percent submergence ports in the filter bowl.

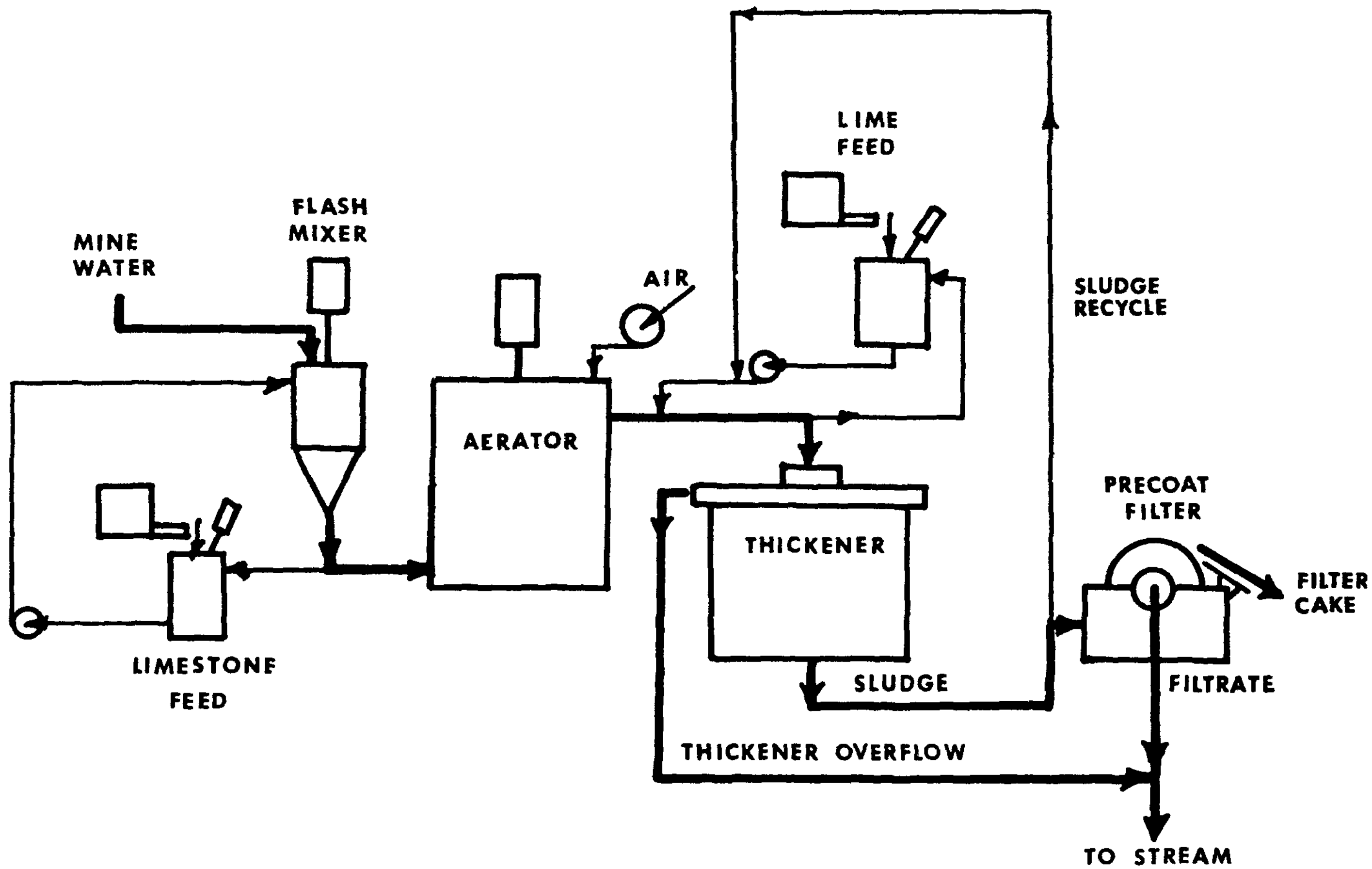
The conclusions reached as a result of this investigation[13] were:

1. The sedimentation and filtration unit processes were found to be the major factors contributing to treatment costs for systems using chemical neutralization followed by solids concentration and dewatering via rotary vacuum precoat filtration.

2. The optimum economic system design for a given chemical process can be found by optimizing the individual unit processes with the exception of the sedimentation and filtration processes. Due to the interaction between these processes, they should be considered as a single-unit process in optimizing the design of the system.

3. The use of polyelectrolytes appeared to offer an economic means of increasing sludge concentration, thereby reducing the sludge volume and the respective filtration costs.

FIGURE 26



LIMESTONE-LIME NEUTRALIZATION
WITH ROTARY PRECOAT FILTRATION OF SLUDGE

From: Johns-Mansville Products Corp., 1971[12]

4. The presence of unreacted limestone appeared to enhance the settleability and filterability of the sludge.

5. Chemical neutralization with a combination of limestone and lime offers a definite cost advantage over lime alone and operational advantages over limestone alone.

6. Production of fine limestone slurry by attrition of rock in a wet mill on-site appeared to be the most economical method for feeding limestone.

7. Optimum conditions for operation of the rotary vacuum filter are a drum speed on one revolution per minute, 30 percent submergence, a CELITE 501* precoat and a knife advance of 0.001 inches per drum revolution.

*A proprietory diatomaceous earth filter.

Cost estimates based on the system shown in Figure 26 are presented in Tables 13 and 14. These cost estimates were computed from values found in the literature and updated to 1970 economics by use of the Marshall and Stevens Equipment Cost Index. For this study, it is assumed the updated cost estimates were equivalent to an ENR Cost Index of 1425 (1970) and they are further updated to reflect an ENR Cost Index of 1700 (April, 1972). The 1972 cost estimates were plotted and the resulting curves are shown on Figures 27, 28 and 29.

TABLE 13
ESTIMATED CAPITAL COSTS FOR VARIOUS SIZE PLANTS
USING INCREASED EFFICIENCY LIMESTONE-LIME PROCESS

Source: Proctor No. 2, Hollywood, Pennsylvania

Item	Plant Size - MGD 0.5	1.0	1.5	2.5	5.0
Raw Feed Pump	$ 3,100	$ 4,400	$ 5,300	$ 6,900	$ 9,700
Limestone Storage Bin	1,500	2,800	4,100	6,500	12,100
Limestone Feeder	7,000	8,800	10,100	11,900	15,000
Limestone Reactor	7,700	10,700	13,000	16,600	23,200
Aeration Pond	600	1,300	1,900	3,200	6,500
Helixors and Blowers	4,500	6,100	7,400	11,000	20,200
Lime Storage Bin	1,600	3,100	4,400	7,000	13,000
Lime Feeder	5,400	6,800	7,800	9,300	11,600
Lime Reactor	7,700	10,700	13,000	16,600	23,200
Thickener	57,200	95,300	152,600	187,100	197,900
Sludge Pump	2,100	2,900	3,400	4,100	6,200
Rotary Precoat Filter	209,000	418,000	586,900	934,700	1,956,200
Sludge Disposal	20,900	41,800	58,700	93,500	195,600
Control Building	20,000	20,000	20,000	20,000	20,000
Instrumentation	17,500	31,600	44,500	66,400	125,500
TOTAL EQUIPMENT	$365,800	$ 664,300	$ 933,100	$1,394,800	$2,635,900
Installation and Piping	$182,900	$ 332,200	$ 466,600	$ 697,400	$1,318,000
Contingencies and Engineering	$ 54,900	$ 99,600	$ 140,000	$ 209,200	$ 395,400
TOTAL CAPITAL COST	$603,600	$1,096,100	$1,539,700	$2,301,400	$4,349,300
Calculated Optimum Sludge Concentration, mg/l	7,000	7,000	8,000	9,000	8,000

After Johns-Manville Products Corp., 1971[12]

TABLE 14
ESTIMATED OPERATING COSTS FOR VARIOUS SIZE PLANTS
USING INCREASED EFFICIENCY LIMESTONE-LIME PROCESS

Source: Proctor No. 2, Hollywood, Pennsylvania

	Plant Size - MGD				
	0.5	1.0	1.5	2.5	5.0
Amortization	$ 52,500	$ 95,400	$133,900	$200,200	$ 378,400
Labor (366 man-hours @ $2.50)	1,000	1,000	1,000	1,000	1,000
Power (1.3 cents/kw-hr)	8,900	35,500	50,000	78,600	153,900
Chemicals					
Limestone	21,900	43,800	65,700	109,500	219,000
Lime	17,900	35,800	53,600	89,400	178,900
Filter Aid	27,700	55,500	77,900	124,000	259,600
Subtotal	$139,900	$267,000	$382,100	$602,700	$1,190,800
Maintenance (10% of above)	$ 14,000	$ 26,700	$ 38,200	$ 60,300	$ 119,100
TOTAL ANNUAL OPERATING COST	$153,900	$293,700	$420,300	$663,000	$1,309,900
Cost per thousand gallons treated	$0.84	$0.80	$0.77	$0.73	$0.72
Cost per 100 pounds acidity treated	$5.81	$5.54	$5.28	$5.00	$4.95

After Johns-Manville Products Corp., 1971[12]

FIGURE 27

ESTIMATED CAPITAL COSTS FOR VARIOUS SIZE PLANTS
USING INCREASED EFFICIENCY LIMESTONE-LIME PROCESS (REF. 12)

ROTARY PRECOAT FILTRATION FOR SLUDGE DEWATERING

FOR MINE DRAINAGE CHARACTERISTICS SEE TEXT

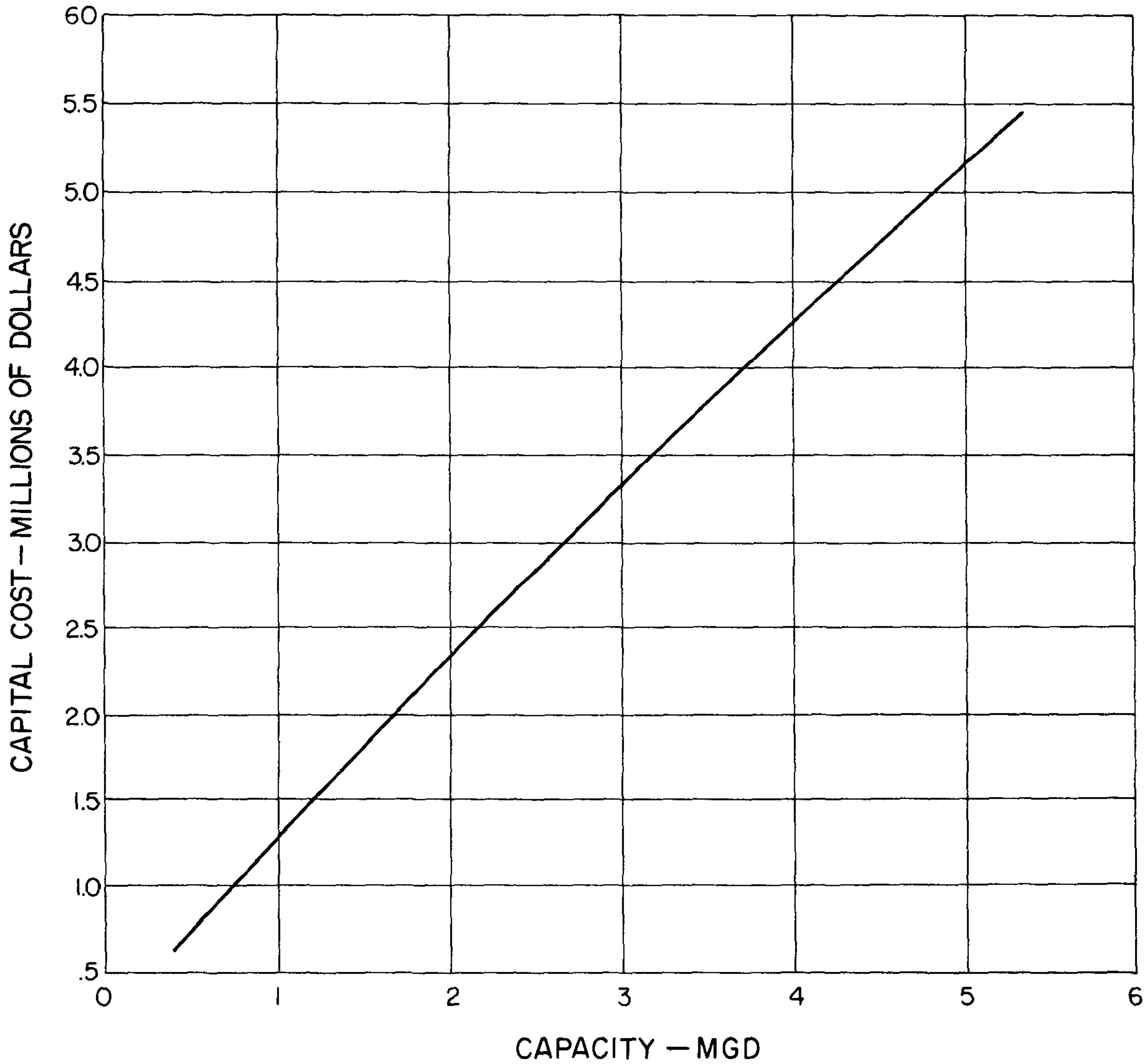


FIGURE 28

ESTIMATED CAPITAL COSTS FOR VARIOUS SIZE PLANT COMPONENTS USING INCREASED EFFICIENCY LIMESTONE-LIME PROCESS (REF. 12)

ROTARY PRECOAT FILTRATION FOR SLUDGE DEWATERING

FOR MINE DRAINAGE CHARACTERISTICS SEE TEXT

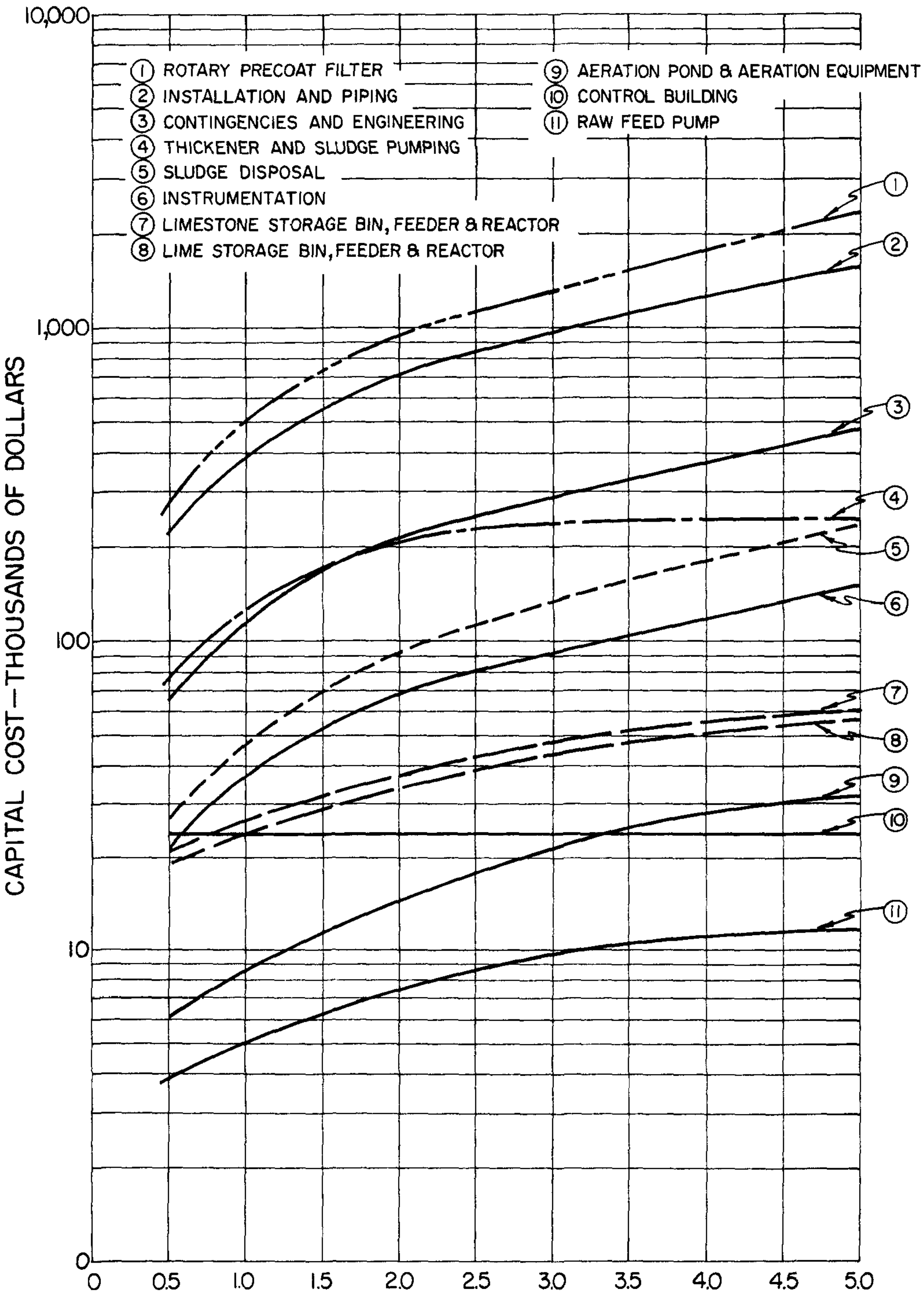
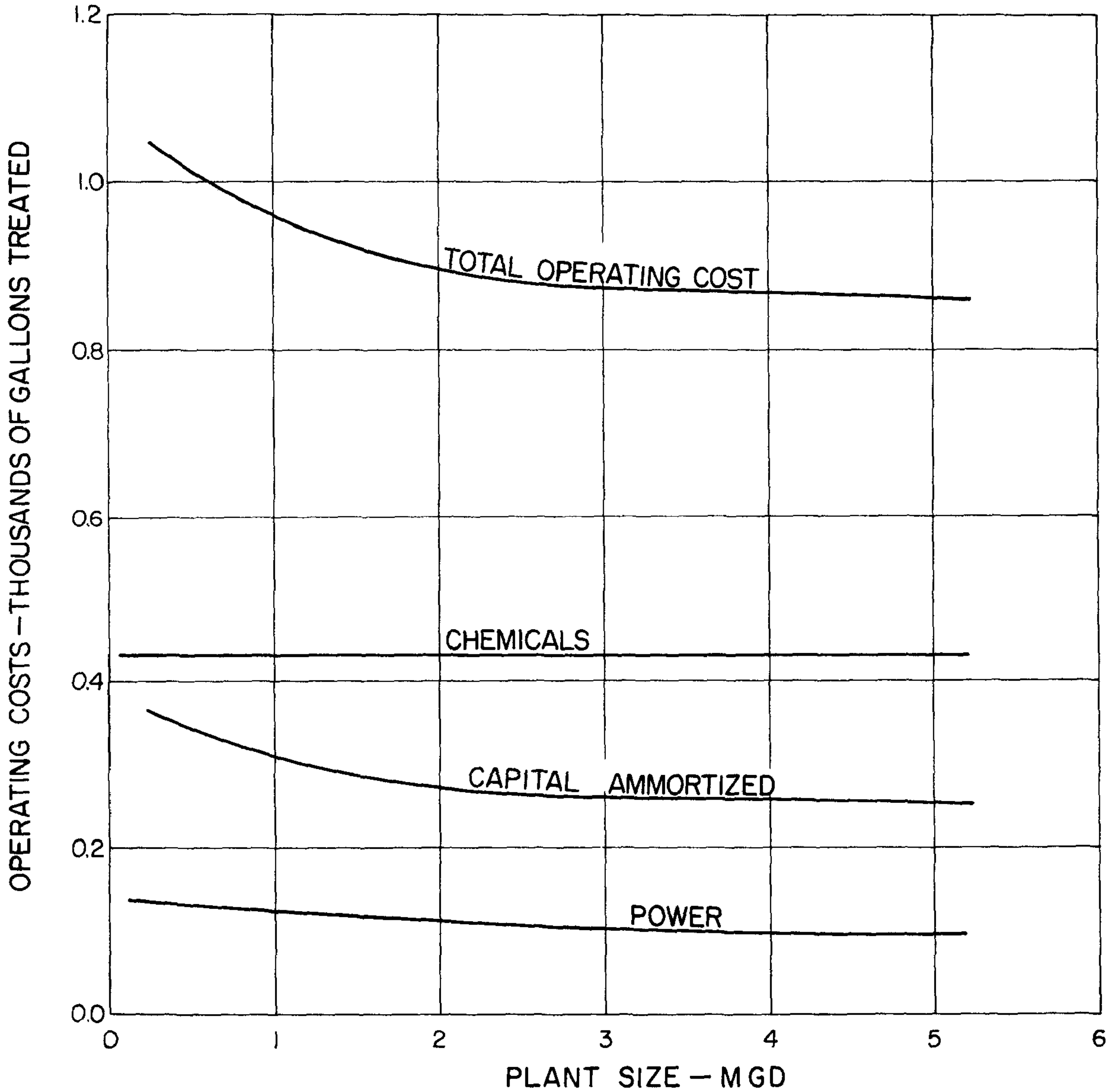


FIGURE 29

ESTIMATED OPERATING COSTS FOR VARIOUS SIZE PLANTS
USING INCREASED EFFICIENCY LIMESTONE-LIME PROCESS (REF. 12)

ROTARY PRECOAT FILTRATION FOR SLUDGE DEWATERING

FOR MINE DRAINAGE CHARACTERISTICS SEE TEXT



Electrochemical Oxidation Followed by Limestone Neutralization

Tyco Laboratories, supported by the Environmental Protection Agency, has developed an electrochemical oxidation process to oxidize ferrous iron before subjecting the mine drainage to limestone neutralization, Gaines, et. al, 1972[14, 15]. The logic being that unlike most waste liquids, the high acid content of acid mine drainage produces a material of reasonable ionic conductivity. In addition to accomplishing the desired oxidation, electrolytic hydrogen is produced as a by-product. At high AMD treatment rates, the recovery of this hydrogen can produce a significant cost savings for the overall treatment process.

Basic Electrochemical Parameters - An acid mine water can contain on the average 500 mg/l of Fe^{2+} and 1,000 mg/l H^+. Also present are variable amounts of aluminum, calcium and manganese. As such, AMD is an electrolytically conducting solution and is capable of being treated electrochemically without resort to additional additives. The pertinent electrochemical reaction

$$Fe^{2+} \longrightarrow Fe^{3+} + e^-$$

is carried out at an inert (nonconsumable) anode. Concurrently, on an inert cathode, the reaction

$$H^+ + e^- \longrightarrow 1/2\ H_2$$

will result in the removal of 1 mole of acid (and the generation of 1/2 mole of hydrogen gas) for every mole of iron that is oxidized.

Carbon anodes, formed from a packed bed of activated carbon (4 x 10 mesh granules), were employed since carbon is inexpensive, readily available in a variety of forms, resistant to chemical attack, and has a wide potential range over which it is electrochemically stable (i.e. does not evolve O_2, H_2 or dissolve). As a cathode, 316 stainless steel perforated sheet was used since this readily available material is highly resistant to corrosion in dilute sulfuric acid solutions. The perforations in the cathode sheet allow the generated hydrgen bubbles to leave the reactor without obstructing electrode area.

Reactor Configuration - Treatment of 6,000 gal./hr. of AMD containing 500 mg/l Fe^{2+} is considered as the base design of the packed bed reactor. The ferrous concentration is to be reduced to five percent (5%) of its original value.

The proposed reactor configuration developed from experimental data is outlined in Figure 30. The reactor is constructed in two series-connected vertical tanks, each 8 feet high by 3 feet wide. Each tank is partitioned by perforated stainless steel sheet into 35 flow channels, 1 inch wide, each treating 170 gal./hr. of AMD. Each unit would thus be about 5 feet long for a total reactor volume of 240 cu. ft.

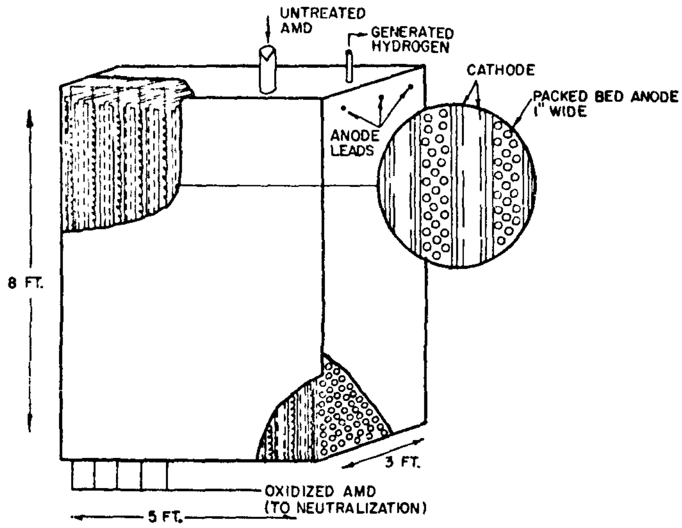


FIGURE 30
Oxidation Unit for Treating 6,000 gal./hr. of 500 mg/l Fe^{2+} AMD

From: Gaines, et al., 1972[14]

Devices capable of treating more than 6,000 gal./hr. of AMD would be simple multiples of the proposed design. Thus the oxidation reactor for a large AMD treatment plant operating at a peak process flow of 1,000,000 gal./day would occupy approximately 1,650 cu. ft.

Capital Costs - The capital cost analysis for a 6,000 gal./hr., 95% conversion, oxidation reactor are as follows:

Reactor		
Stainless steel tank	$10,000	Vendor Quote
Carbon bed @ 0.50/lb.	2,100	
Other	1,400	
	13,500	
Installation and start-up costs	6,700	
Total Cost	$20,200	

Net Capital Cost: 2.6¢/1,000 gal. treated (25 yr. life, 4-1/2% interest charge)

Due to the modular nature of electrochemical devices, the capital charge of 2.6¢/1,000 gal. is generally applicable to all situations where a conversion of 95% is desired. The capital costs for conversion of 90% and 99%, i.e., for initial Fe^{2+} concentrations of 50 mg/l and 1,000 mg/l treated to final ferrous content of 5 mg/l are:

Conversion, %	Capital Charge, ¢/1,000 gal.
90	1.9
95	2.6
99	3.8

Not included in the capital charges are the initial costs associated with the AC-DC rectifying and control circuits required for the operation of the oxidation reactor. These costs are sensitive to both AMD flow rate and initial Fe^{2+} concentration, as well as the desired conversion.

In addition to the capital charges described above, the only other cost peculiar to the direct oxidation concept is the power cost associated with the oxidation reaction. Labor and maintenance charges are not significant. The electrochemical treatment step requires no operating labor and is easily constructed in a failsafe configuration.

The cost of the electrochemical oxidation step is compensated by cost reductions in other parts of the treatment scheme. These cost reductions accrue from the elimination of aeration equipment, the use of cheaper limestone rather than lime to precipitate iron, and a reduction in equipment size and disposal problems due to the denser more rapidly settling sludge produced by the limestone treatment.

The clarifier and/or settling pond requirements for limestone treatment of ferric mine water, containing less than 5 mg/l Fe^{2+} were estimated. Primary settling, performed in a conventional clarifier-settler with a 1 hour residence time, would discharge 10% of the total stream flow to a settling pond/storage basin for final compaction and disposal. The use of a primary clarifier, by reducing the sludge volume and increasing its solids content to 6 to 10% by weight, facilitates sludge disposal in shallow lagoons or abandoned mine shafts. The costs associated with the final storage volume required are, of course, dependent on the initial acidity and iron content of the AMD.

AMD Treatment Plant Design and Economics - Since AMD varies widely in composition as well as flow rate, three flows and three ferrous iron concentrations were selected by Tyco Laboratories in order to represent a variety of possible situations.

AMD Compositions and Flow Rates

Flow Rate, gal./day	Fe^{2+} Concentration, mg/l	Total Acidity mg/l
250,000	1,000	2,000
1,000,000	500	1,000
6,000,000	50	500

The basic treatment scheme proposed was the same in all cases. Under the conservative assumption that no ferrous iron will precipitate during limestone treatment, the oxidation reactor was designed for a final maximum Fe^{2+} concentration of 5 mg/l. Since the flow of mine drainage will vary to some extent, even on a daily basis, a holding pond with a controlled output was provided. For plants with a low flow rate, the holding pond would also be used for AMD storage, thereby reducing labor charges since continuous plant operation would not be necessary.

Limestone slurry would be produced by loading a tumbling mill with bulk limestone and providing a flow of water to give the slurry concentration desired. Limestone containing 75% $CaCO_3$ costing $5/ton F.O.B. was used as a basis for estimating equipment size and operating costs.

The AMD from the holding pond is fed to the electrochemical oxidation reactor. Following oxidation, the limestone slurry is added to the ferric mine water in a simple neutralization reactor. In the absence of ferrous iron, the precipitation is rapid and in a form favorable to rapid settling. A primary clarifier is used to separate the rapidly settling dilute sludge (about 10% of the total stream flow) from the iron free supernate. The underflow from the primary clarifier is sent to settling lagoons for final compaction and storage.

The investment costs for the AMD treatment plants are listed in Table 15. Sizing of the process equipment was based on operating times of 8 hr./day for the 250,000 gal./day rate, 16 hr./day at the 1,000,000 gal./day rate, and continuous operation at 6,000,000 gal./day. Holding pond capacities were adjusted to provide a 30 hour retention volume. Process stream flows are thus 41,600 gal./hr., 104,000 gal./hr. and 250,000 gal./hr., respectively. The capital costs associated with final sludge disposal are considered by Tyco Laboratories to be too variable to be included without reference to a specific location, this investment requirement is not included in the analysis.

The estimated operating expenses (exclusive of final sludge costs) are shown in Table 16. For 500 mg/l Fe^{2+}, the operating costs range from 20¢/1,000 gal. at 6,000,000 gal./day to 55¢/1,000 gal. at 250,000 gal./day. Tyco Laboratories found that comparable figures for current approaches to AMD treatment were not readily available. In the one case where operating data was available(16), a lime cost alone of 13¢/1,000 gal. was reported for a plant treating about 3,000,000 gal./day of 200 mg/l Fe^{2+}, 700 mg/l H^+ AMD. They found reported values for total treatment costs (including capital charges) range from 20¢ to $2/1,000 gal. treated.

The data in Tables 15 and 16 were updated to reflect prices in April, 1972 (from an ENR Construction Cost Index of 1575 to 1700). The updated costs were plotted and the resulting cost curves are shown in Figures 31 and 32.

Credits for hydrogen production can only be estimated. Treatment of 1,000 gal. of AMD containing 500 mg/l Fe^{2+} will result in the generation of 15 cu. ft. of hydrogen. Optimized electrolytic hydrogen plants can produce H^2 at about 30¢/100 cu. ft. Shipping charges will range from 20¢ to $1/100 cu. ft. depending on distance and method. If the by-product hydrogen can be sold at a credit (after collection and packaging costs) of 40¢/100 cu. ft., the credit to the treatment process would be 6¢/1,000 gal. of AMD treated. At AMD flow rates of 6,000,000 gal./day, this by-product return would represent a savings of 30% on total treatment costs. For streams containing 1,000 mg/l Fe^{2+}, the savings approach 50% of total costs.

Although the cost of electrochemical oxidation of ferrous iron followed by neutralization appears attractive, it must be understood that these are estimates developed from bench scale experiments with no supporting data from full scale operations.

TABLE 15
PLANT INVESTMENTS
ELECTROCHEMICAL OXIDATION METHOD

AMD Flow, gal/day	Fe^{2+} Conv, mg/ℓ	Holding Pond, M $	Oxidation Reactor, M $	Electrical Equipment, M $	Limestone Mill, M $	Instru. + Controls, M $	Piping + Tanks M $	Clarifier Settler M $	Equipment Total, M $	Site Preparation, M $	Total Cost, M $
250,000	1000	1.5	160	42	16	3	4	22	251.5	58.5	310
	500	1.5	140	25	6	3	4	22	200	50	250
	50	1.5	70	8.4	4	3	4	22	113	27	140
1,000,000	1000	6	400	84	26	4	5	33	558	142	700
	500	6	351	50	10	4	5	33	459	121	580
	50	6	175	17	6.5	4	5	33	240.5	59.5	300
6,000,000	1000	30	951	168	39	6	6	47	1247	303	1550
	500	30	844	100	15	6	6	47	1048	262	1310
	50	30	422	18	9	6	6	47	538	132	670

After Tyco Laboratories, Inc., 1972[15]

TABLE 16
ESTIMATED OPERATING EXPENSES FOR
DIRECT ELECTROCHEMICAL OXIDATION TREATMENT PLANTS,
¢/1,000 GAL.*

Flow Rate, Gal./Day	250,000			1,000,000			6,000,000		
Fe^{2+}, mg/l	50	500	1000	50	500	1000	50	500	1000
Acidity, mg/l	500	1000	2000	500	1000	2000	500	1000	2000
Treatment Power, 5 V	0.5	5.3	11	0.5	5.3	11	0.5	5.3	11
Plant Power	3	3	3	3	3	3	3	3	3
Limestone	2	4	8	2	4	8	2	4	8
Labor + Overhead	16	16	16	8	8	8	2	2	2
Depreciation	15	27	34	8.2	16	19	3	6	7
Total Costs	37	55	72	22	36	49	11	20	31

Basis: Power at 1¢/KWhr.
Depreciation at 10% of investment
Limestone at $6.67/ton (10% of basis)
Labor + overhead at $5/hr.
Plant On-Stream 8, 12 and 24 hours/day respectively

*Lime treatment range 20¢ to $2/1,000 gal.

After Tyco Laboratories, Inc., 1972(15)

FIGURE 31

ESTIMATED CAPITAL COSTS Vs. PLANT CAPACITY
FOR ELECTROCHEMICAL OXIDATION AND LIMESTONE NEUTRALIZATION TREATMENT
AFTER TYCO LABORATORIES, INC. (REF. 15)

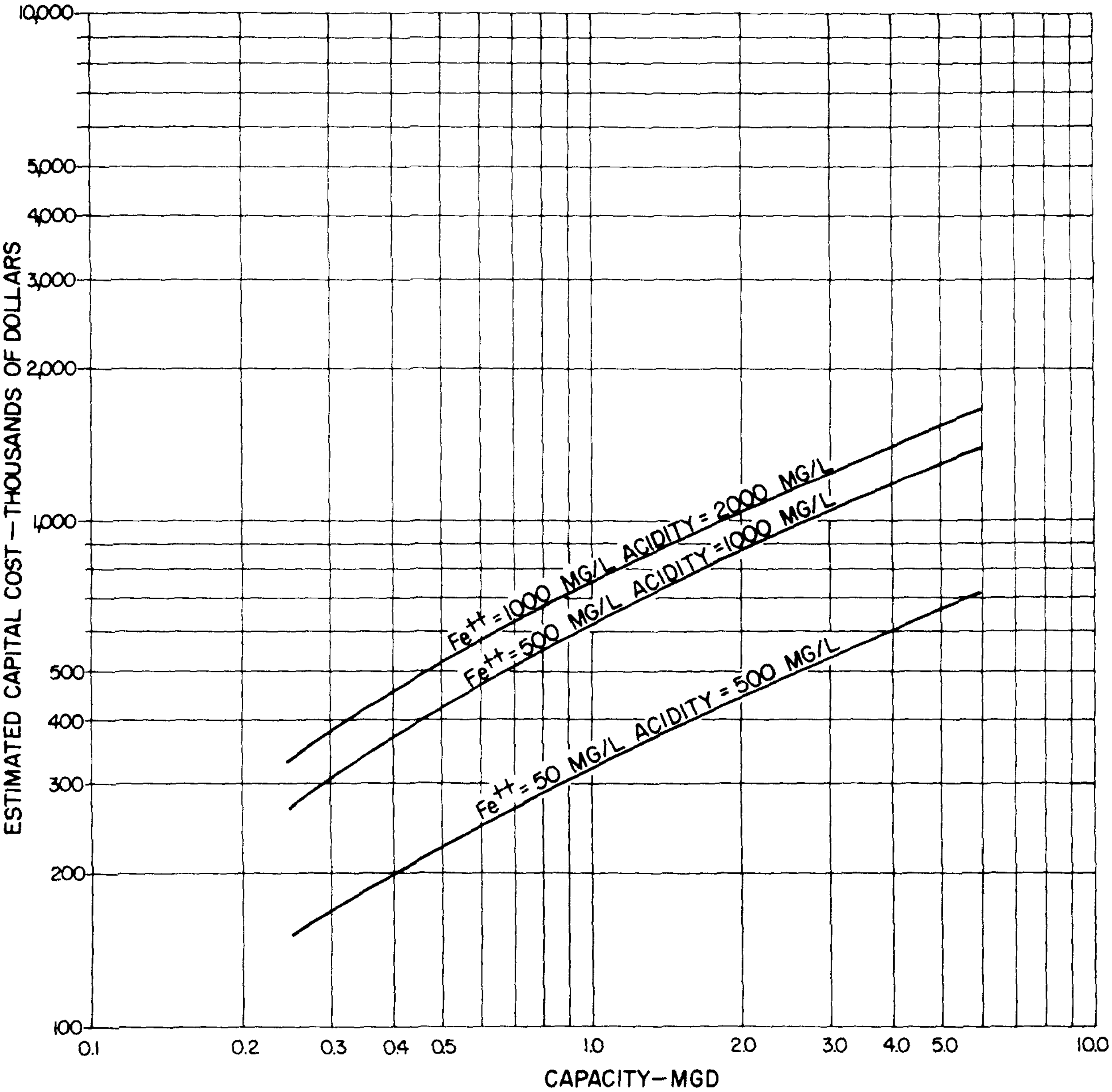
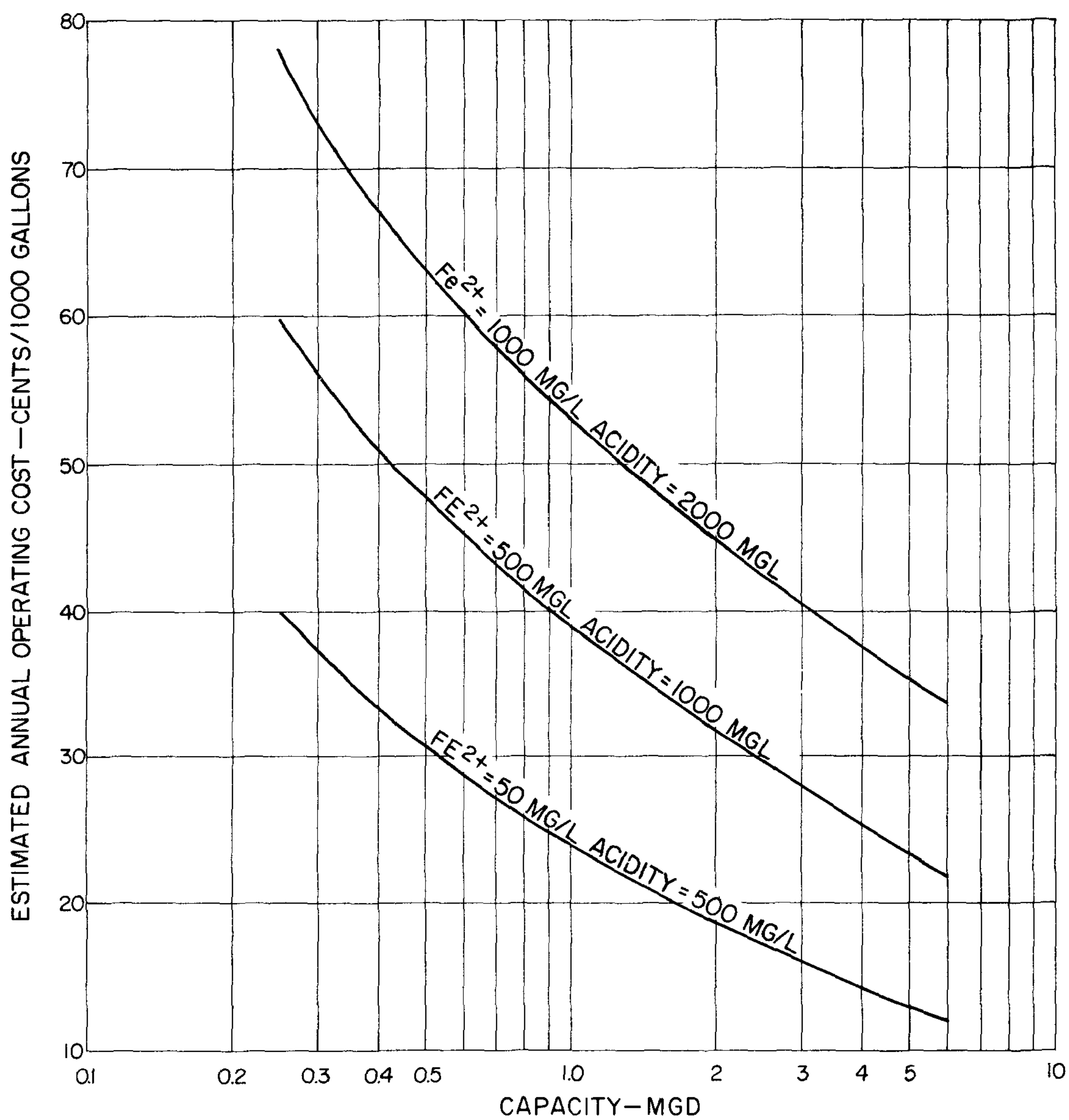


FIGURE 32

ESTIMATED ANNUAL OPERATING COSTS Vs. PLANT CAPACITY FOR ELECTROCHEMICAL OXIDATION AND LIMESTONE NEUTRALIZATION TREATMENT AFTER TYCO LABORATORIES, INC. (REF. 15)



Biochemical Oxidation Followed by Limestone Neutralization

The existence of certain bacteria, commonly known as the acidophilic iron bacteria, that specialize in the oxidation of ferrous to ferric iron at low pH values has been known for years[17]. In fact, these micro-organisms have been isolated from many mine discharge waters.

Acidophilic iron bacteria are autotrophic (do not require organic substances for growth) and are classified as the Thiobacillus-Ferrobacillus group. These bacteria utilize carbon dioxide as their source of carbon and oxidize ferrous iron to the ferric state in order to obtain energy to drive their cell machinery. In addition to carbon dioxide, oxygen and ferrous iron, these organisms also require lesser quantities of nitrogen and phosphorous and trace amounts of other minerals[18].

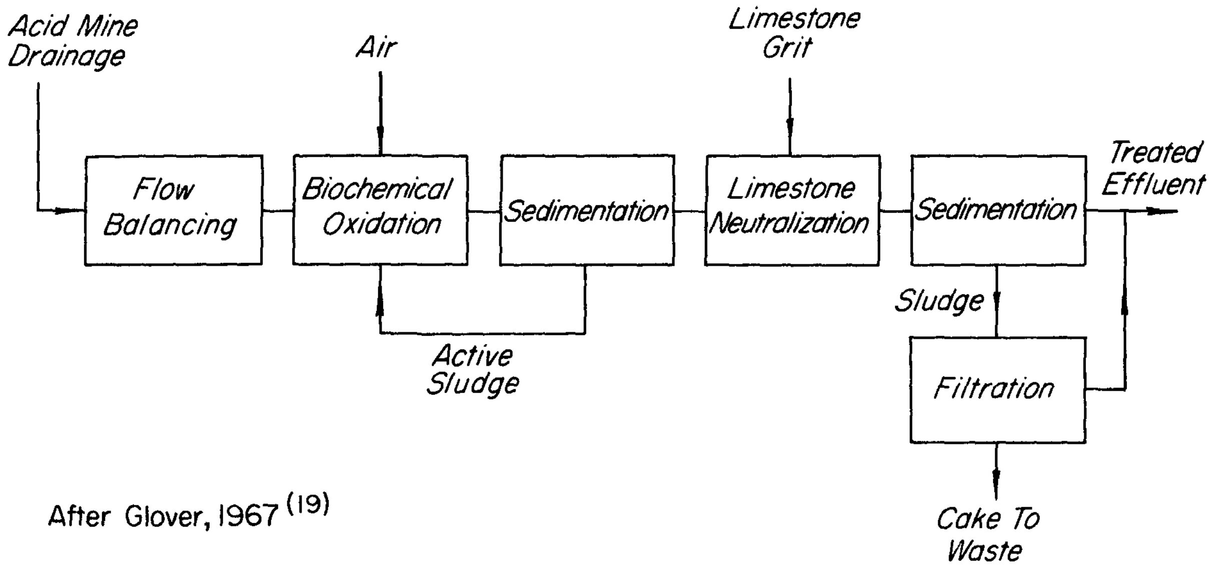
Glover[19] demonstrated that this microbial catalytic activity can be economically utilized to satisfactorily prepare ferrous acid mine drainage water for limestone treatment. His studies indicated that complete treatment of an acid mine drainage could be achieved by preliminary biochemical oxidation to convert ferrous salts to ferric, followed by neutralization with limestone. A pilot plant was constructed in Great Britain to demonstrate the whole process. A flow diagram of the plant is shown in Figure 33 and a dimensioned sketch in Figure 34. The plant includes biochemical oxidation reactors, a new upflow expanded bed limestone reactor, a sedimentation vessel, and a sludge filter. The typical operating characteristics are summarized in Table 17.

Glover's patented process employs recirculation of active sludge containing an active biological culture of acidophilic bacteria and in this respect is similar to the activated sludge treatment of municipal sewage and certain industrial wastes. On the pilot scale, it was possible to find sufficient deposited sludge in the mine drainage feed tank and in the limestone reactor pump feed tank to start the biochemical reactors at a high rate. On the large scale, it should be possible to start a plant by agitating the deposits in the feed channels of the acid mine drainage and by driving the suspension forward into the process where it would be retained[19].

The neutralized drainage discharged from the limestone reactors was found to have relatively poor initial settling characteristics. Lime settling did not occur and it was necessary to design sedimentation basins on a basis of retention time for coagulation. Retention for four hours without any special flocculating equipment or reagents produced a supernate having a suspended solids content of less than 20 mg/l which would be adequate to meet most required standards for discharges to inland watercourses in Great Britain. The supernate contained most of the manganous salts which had been present in the original mine drainage although some of the manganese had been absorbed by the limestone neutralized sludge (Table 17).

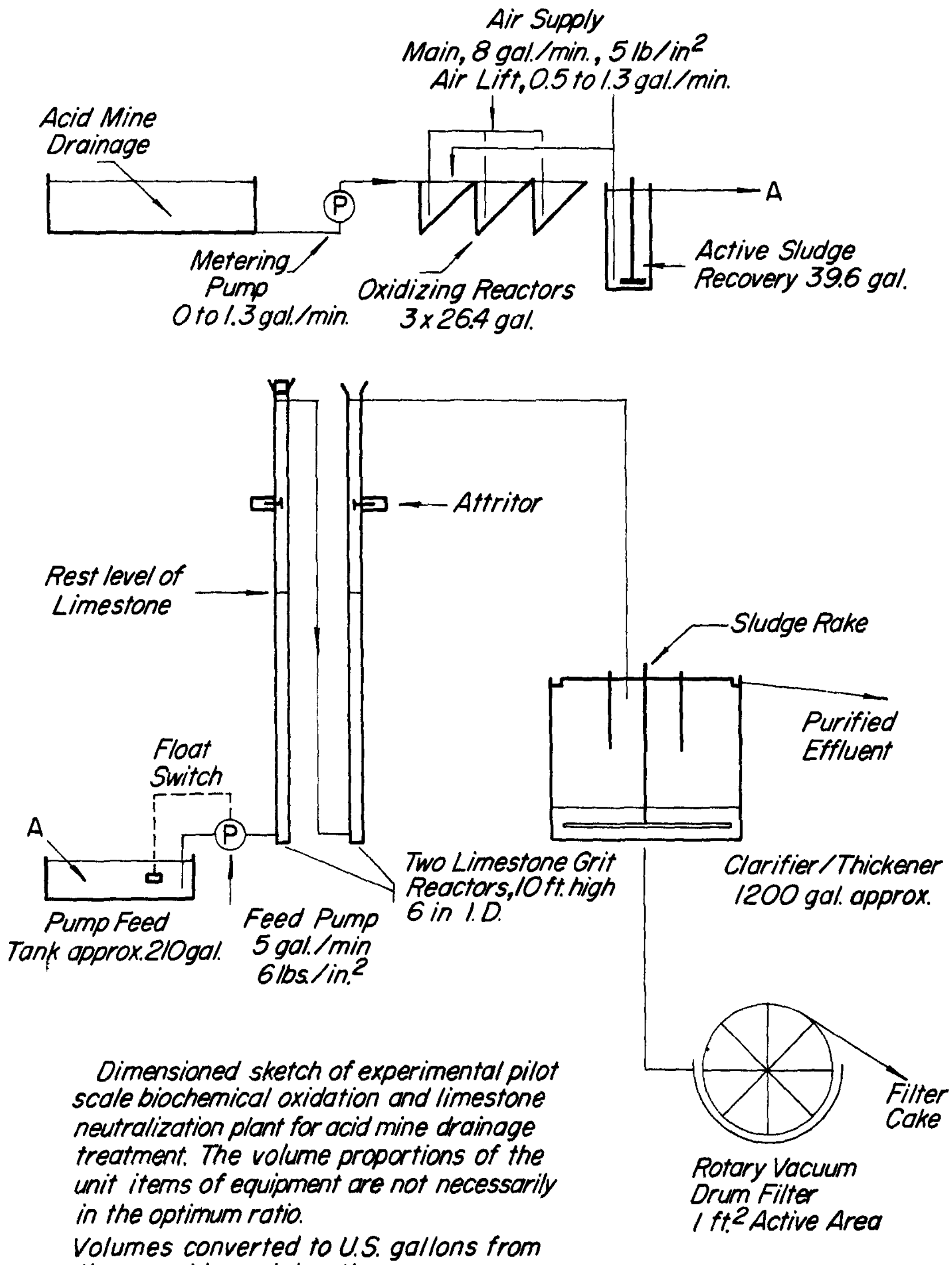
FIGURE 33

Flow Diagram of Complete Biochemical Oxidation and Limestone Neutralization Process



After Glover, 1967 (19)

FIGURE 34



Dimensioned sketch of experimental pilot scale biochemical oxidation and limestone neutralization plant for acid mine drainage treatment. The volume proportions of the unit items of equipment are not necessarily in the optimum ratio.

Volumes converted to U.S. gallons from liters and imperial gallons.

After Glover, 1967[19]

Not To Scale

TABLE 17

TYPICAL OPERATING CHARACTERISTICS OF PILOT SCALE BIOCHEMICAL OXIDATION AND LIMESTONE NEUTRALIZATION PROCESS (COMPONENTS IN SOLUTION UNLESS OTHERWISE SPECIFIED)

Parameter		Influent	After oxidation and Sedimentation	After Neutralisation	Water Phase after Second Sedimentation	Sludge Phase after Second Sedimentation	Sludge Phase after filtration
pH value		3.0	2.8	5.8-6.5	6.0-6.5	-	-
Ferrous	mg/l Fe	100-300	< 5	< 5	< 1	-	-
Ferric	mg/l Fe	100-300	200-600	0	0	-	20% (dry cake)
Aluminium	mg/l Al	20-50	20	0	0	-	-
Manganese	mg/l Mn	20	20	16	11	-	-
Calcium	mg/l Ca	200	-	-	-	-	-
Magnesium	mg/l Mg	150	-	-	-		-
Sodium	mg/l Na	100	-	-	-		-
Potassium	mg/l K	15	-	-	-		-
Sulphate	mg/l SO_4	1500-2000	-	-	-	-	-
Chloride	mg/l Cl	40	-	-	-	-	-
Silica	mg/l SiO_2	30	-	-	-	-	-
Carbon dioxide	mg/l CO_2	200	1	-	-	-	-
Combined Nitrogen	mg/l N	1-3	-	-	-	-	-
Arsenic	mg/l As	<0.02	-	-	-	-	-
Total solids (dissolved)	mg/l	2500	-	-	-	-	-
Suspended solids	mg/l	0-10,000	10	1000	<20	9-12%	45%
Flow rate, max 0°C	l/min	0.5 (cont)	-	18 (int)	18 (int)	0.005 (cont)	-
Flow rate, max 10°C	l/min	2 (cont)	-	18 (int)	18 (int)	0.02 (cont)	-
Flow rate, max 20°C	l/min	5 (cont)	-	18 (int)	18 (int)	0.05 (cont)	-

After Glover, 1967[19]

After consolidation for a few days, the sludge from the neutralization process had a relative volume of about one percent (1%) of the volume of mine drainage processed, and a solids content of 9 to 12 percent. This was a considerable improvement compared to the sludge accumulation from lime treatment of the same acid mine drainage which had a relative volume of about ten percent (10%) and a solids content of about one percent (1%). The tenfold reduction in the volume of sludge produced is considered to be the main advantage of the biochemical oxidation/limestone neutralization process.

The filtration rate of the sludge averaged 7 gal./$ft.^2$/hr. From this data it was calculated that vacuum filters of a total filtration area 250 $ft.^2$ operating 10 hr./day, 7 days/week, would be sufficient to dewater the sludge produced by biochemical oxidation/limestone neutralization of 1,000,000 gal./day of acid mine drainage containing about 300 mg/l of dissolved iron[19].

The lower limit of acidity of an acid mine drainage which can be treated by this process is determined by the pH value of the drainage after it has been oxidized. The pH value of the drainage as discharged from the mining operation may be an insufficient guide since, for example, ferrous sulfate solutions containing hundreds of mg/l of iron are stable at almost neutral pH values. The process should be applicable to mine drainages which contain at least 10 to 20 mg/l of dissolved iron and a total acidity of 25 mg/l ($CaCO_3$) or more.

The upper limit of acidity which can be treated by the process would be determined by the sulfate tolerance of the limestone process. It would probably be safe to assume that the upper limit will be 5,000 mg/l SO_4, but it is possible that higher limits may be acceptable due to the effect of the attritors[19]. Higher limits would be possible if the reaction temperature was less than 15° C.

The extreme temperature limits for the complete process are expected to be 0° C to 35° C, with a preferred working range of 5° C to 25° C. Temperatures up to 30° C would increase the activity of the biochemical oxidation stage, but temperatures down to 5° C would raise the sulfate tolerance of the limestone stage.

The inability of the process to remove manganese salts from an acid mine drainage is a distinct disadvantage which would be more acute at some sites than others. In general, manganese salts are as much a pollutant as are ferrous salts, although manganese salts do not produce such an obvious discoloration of the stream bed.

The physical limitations of Glover's process are: 1) the mine drainage must be at least slightly acidic, but not seriously contaminated with acidity, 2) the temperature must not be extreme, and 3) the manganous salt content should not be excessive.

A cost estimate was made by Glover[19] for treatment of an acid mine drainage discharge from a shallow underground coal mine. The discharge having a peak flow rate of 840,000 gal./day*, a maximum consecutive period of 21 days at peak flow, and an average flow rate of 240,000 gal./day*. The quality of the influent, effluent and cake from the biochemical limestone process are as shown in Table 17. The quality of products from the lime process are as near as possible similar.

**Estimated Costs $1/Year	Lime Process	Biochemical/Limestone Process
Highest Probable		
Capital	$332,575	$154,760
Operating	53,000	31,005
Lowest Possible		
Capital	52,470	31,138
Operating	58,035	33,920

*Converted from imperial to U. S. gallons
**Converted from British Pounds - One Pound Sterling = U.S. $2.65

It is evident the process, based on the above cost estimate, would have a distinct cost advantage over the lime treatment process at the particular degree of contamination represented by the sample mine drainage. It is expected the cost advantage would increase as the mine drainage became less contaminated since the lime process becomes progressively more difficult to operate with the less contaminated mine waters. Conversely, the lime process increases in efficiency as the degree of contamination rises. The break point at which the lime process becomes cheaper than the biochemical limestone process is not known, but it may be above the upper limit for the sulfate content of the biochemical limestone process, in which event it could conceivably be cheaper to dilute the acid mine drainage to bring it within range of the biochemical limestone process, although this would increase the load of dissolved calcium salts discharged from the process.

As a generalization, it may be concluded that the biochemical limestone process will find its application in the purification of the less contaminated acid mine drainage, and that the conventional lime process will be more applicable to the most highly contaminated acid mine drainages. The two processes are thus to some extent complementary rather than competitive[19].

Continental Oil Company[18] conducted studies to determine the abilities of acidophilic bacteria to oxidize ferrous iron or to convert sulfate to hydrogen sulfide and reached conclusions similar to that of Glover. They also found that series multistaging of microbial oxidation vessels offers operational efficiency over a single oxidation vessel. However, attempts of Continental to go from a 1-1/2 gallon bench size microbial oxidation system to a 1,000 gallon pilot plant oxidation vessel were not successful. As a result of their experiments, they also found that although sulfate-reducing bacteria are present in acid mine drainage water, they will not grow or produce H_2S at pH values below 5.5.

Lovell[20] conducted studies at the Pennsylvania State University Experimental Mine Drainage Research Facility, Hollywood, Pennsylvania, and effectively treated waters containing up to 100 mg/l iron II in a limestone system without a separate iron oxidation step. Waters containing between 100 and 500 mg/l iron II were successfully oxidized biochemically to levels well below 100 mg/l iron II and subsequently they responded satisfactorily to the limestone reaction.

A bacterial strain, designated "Z," was cultured from Hollywood waters and utilized in these studies. It was presumed to be Ferrobacillus ferrooxidans. Advantages in initiating the biochemical oxidation system were experienced from inoculation with laboratory cultures, but continued introduction of inoculant need not be maintained. Similarly, the addition of bacterial nutrients was helpful to initiate growth but need not be continued. A bacterial culture at a minimum level of 10^6 cells/ml appeared necessary and was maintained for the study.

At Hollywood, Lowell[21] employed an oxidation reactor in the form of a trickling filter similar in design to a conventional sewage trickling filter (Figure 35). It was filled with inert, minus four inch (-4") argillite to a depth of five (5) feet. Hydraulic loading rates to this reactor were maintained at levels up to 0.16 GPM/square foot. There were no power or labor requirements for this operation which is an obvious advantage. A disadvantage to using a stone-filled trickling filter is that it is liable to get plugged with sludge build up; experimental work on plastic filter media with high void ratio is expected to solve this problem. A rotary tube mill is utilized as the limestone reactor and the water retention time in the reactor was slightly over two minutes. Reactor power requirements ranged between 0.5 and 1.2 cents/1000 gallons with power priced at 1.7 cents/KWH. The rotary reactor was continuously charged with limestone. The most satisfactory limestone appeared to be a quarry waste which was relatively soft and degradable. Effluent from the limestone reactor goes to an upflow clarifier. Frequently limestone sludges with solids content as high as 15 percent by weight were obtained. Porous bottom sludge drying beds dry this sludge to one-fourth of its original volume, 95 percent of the drying taking place in the first 48 hours. Similarly, the dry solids rate of limestone sludges from precoat vacuum filtration ranged from 300-1,200 lbs./ft.^{2}/24 hours. At 25 - 50 percent moisture in contrast to 30 - 40 lbs./ft.^{2}/24 hours obtained with lime-produced sludges. Detailed cost estimates have not been developed for these facilities.

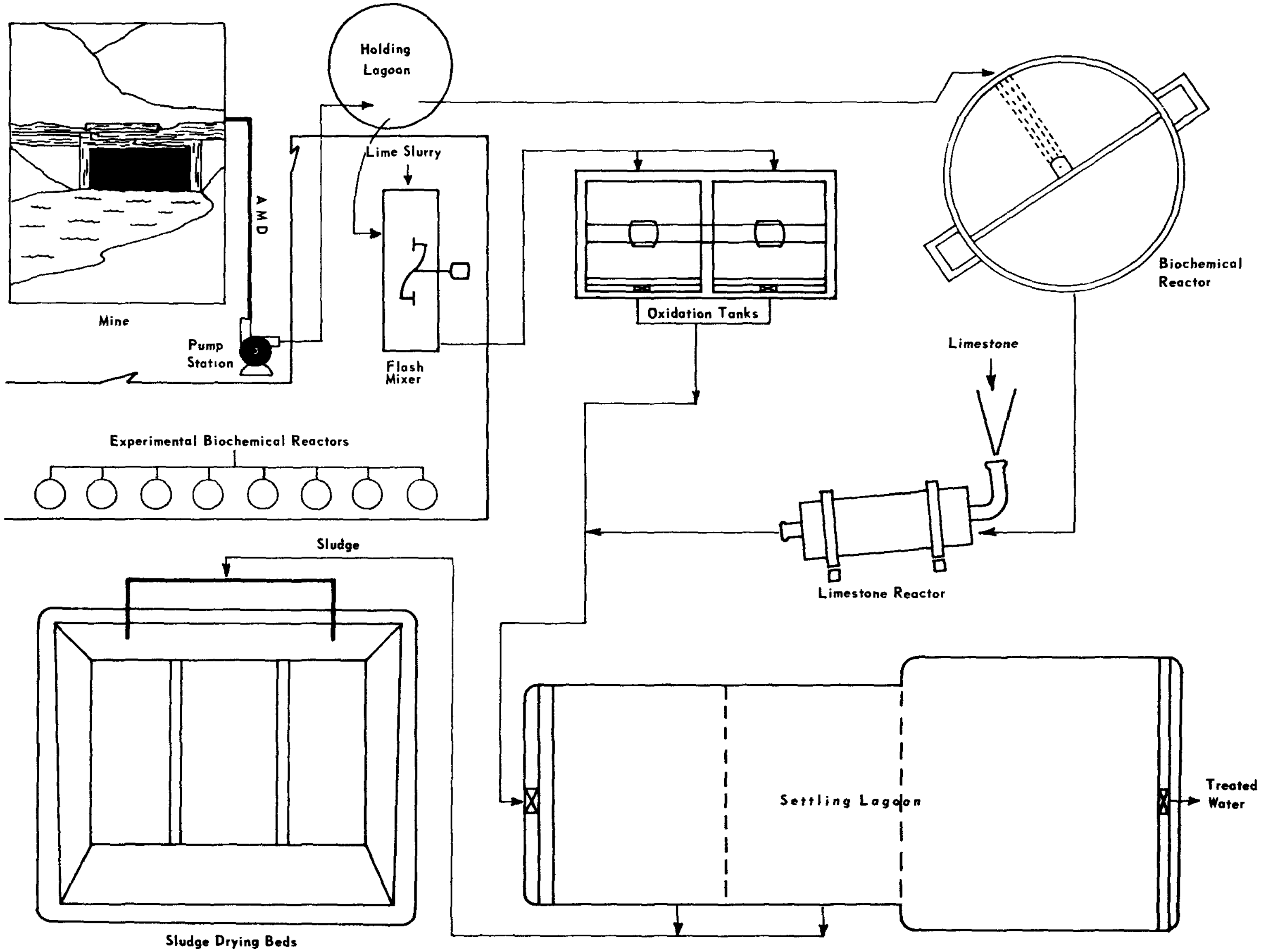


Figure 35 FLOWSHEET - BIOCHEMICAL IRON OXIDATION LIMESTONE TREATMENT PROCESS
(After Lovell, 21)

Ozone Oxidation Followed by Limestone Neutralization

An engineering design and economic study to evaluate the feasibility of ozone oxidation and limestone neutralization of acid mine drainage was performed by Beller, Waide and Steinberg(23) at Brookhaven National Laboratory. The chemistry of using ozone for oxidation in low pH solutions is expressed by the following equations:

(1) Oxidation

$$2\ Fe^{+2} + O_3 + 2\ H^+ \rightleftharpoons 2\ Fe^{+3} + H_2O + O_2$$

(2) Hydrolysis

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

(3) Neutralization

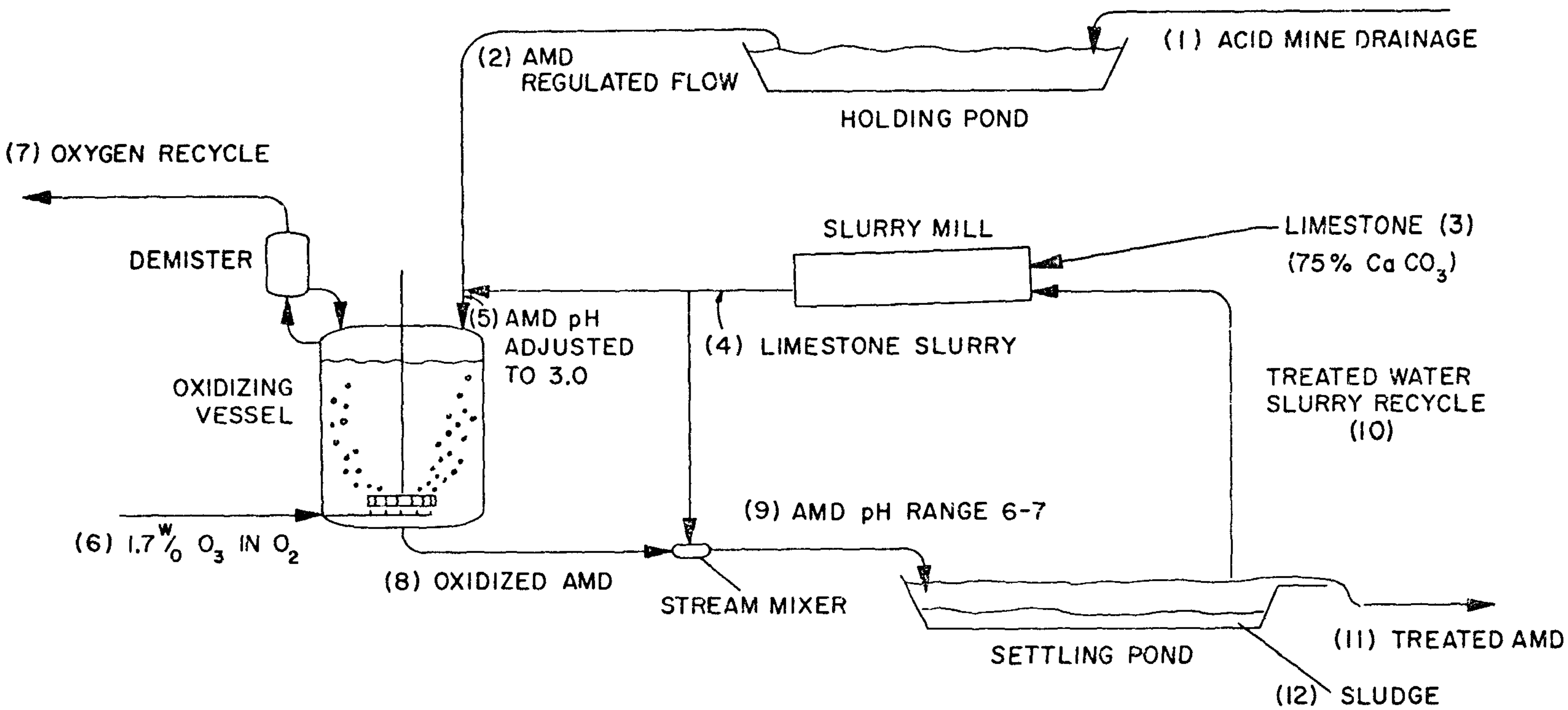
$$3\ H^+ + 3\ OH^- \rightleftharpoons 3\ H_2O$$

Because acid mine waters range widely in flow rate and composition, three flows and ferrous iron compositions were selected for the study which generally encompass the conditions at typical acid mine drainage sites. The acid mine drainage flow rates chosen are 250,000, 1,000,000 and 6,000,000 gallons per day, containing ferrous iron contents of 50,300 and 1,000 parts per million. The Fe^{+2} and total acidity used for the study are summarized below. For simplicity, any acid resulting from the hydrolysis of metal ions other than iron was ignored.

Fe^{+2} Conc. ppm	pH	Total Acid (mg/l $CaCO_3$)
1,000	2.5	1,900
300	2.5	650
50	2.5	200

Figure 36 shows the acid mine drainage oxidation neutralization process system using ozone for oxidation of ferrous iron. The ozone is produced as a mixture containing 1.7 percent by weight of ozone (1% by volume) in a gaseous oxygen stream. It is supplied to the oxidizing contactor, and after reacting with the AMD, is recycled to the ozone production unit. A turbine type mixer is used in the oxidizing vessel as the contact device.

Ozone requirements for the various cases on which the study was based are as follows:



AMD OXIDATION & NEUTRALIZATION PROCESS SYSTEM

FIGURE 36

After Beller, et. al., 1970[23]

Ozone Requirements for AMD Streams
lbs./day Ozone

	AMD Stream Flow-gal./day		
Fe^{+2} Conc.-ppm	250,000	1,000,000	6,000,000
50	52	208	1,248
300	312	1,248	7,488
1,000	1,040	4,160	24,960

The ozone requirements are based on the stoichiometry of the oxidation reaction:

$$2\ Fe^{+2} + O_3 + 2\ H^+ \longrightarrow 2\ Fe^{+3} + H_2O + O_2$$

The following methods of ozone production were examined in the study for their economic feasibility.

1. Electric discharge in oxygen.

2. Electric discharge in air.

3. Chemonuclear (Fission Fragment)

4. Isotopic sources (Gamma)

Tables 18 through 24 present the cost estimates worked out by Beller et al.(23), which are plotted in the form of cost curves in Figures 37 through 40.

Beller et al.(23), also worked out the investment cost necessary to treat the entire acid mine drainage of southwestern Pennsylvania, estimated at 486,000,000 gal./day. The cost of $182,000,000 is based on the use of a 200-ton per day central chemonuclear ozone plant. The investment cost includes ozone storage and shipment facilities and AMD treatment equipment at each of the approximately 2,160 sites in the region. Each site was assumed capable of handling an average flow of 250,000 gallons per day. A central electric discharge plant would require an investment of about $191,000,000. Table 25 gives this cost breakdown.

The cost estimates in this study were made about March, 1970 (U.S. Average ENR Construction Cost Index 1314). They should be multiplied by a factor of (1700/1314) = 1.3 to arrive at the ENR Construction Cost Index of April, 1972.

The study consisted of an analysis of available methods of ozone production and theoretical assumptions of acid mine drainage oxidation by ozone. The conclusions reached in the study were not verified by actual laboratory or plant scale tests. Therefore, the cost estimates arrived at as a result of the study, provide at the best, an indication of the probable costs should ozone oxidation materialize as a proven and tested method for acid mine drainage treatment.

TABLE 18

AMD PLANT COST IN THOUSANDS OF DOLLARS

Case	AMD Flow gal/day	Fe^{+2} conc. ppm	Oxidation vessels	Agitators	Limestone mill	Piping & neutr T	Misc., Instr.& control	Holding pond	Settling pond	Total equipM&L) indirects	Total cost	¢/1000 gal.
1	6×10^6	1000	545	45	39	6	6	24	48	713	855	3.6
2	"	300	545	45	20	6	6	24	48	694	830	3.4
3	"	50	545	45	9	6	6	24	24	659	790	3.2
4	1×10^6	1000	102	9	16	4	3	4	8	146	175	4.3
5	"	300	102	9	6	4	3	4	5	136	163	4.0
6	"	50	102	9	4	4	3	4	4	130	156	3.8
7	$\frac{1}{4} \times 10^6$	1000	29	3	4	3	1	1	3	44	53	5.2
8	"	300	29	3	4	3	1	1	3	44	53	5.2
9	"	50	29	3	4	3	1	1	2	43	52	5.1

After Beller et al, (23)

TABLE 19

AMD TREATMENT PLANT OPERATING COSTS* - ¢/1000 GAL.

AMD Flow Gal./Day	0.25×10^6			1×10^6			6×10^6		
Fe^{++}, ppm.	50	300	1000	50	300	1000	50	300	1000
Depreciation @ 7.3%	5.1	5.2	5.2	3.8	4.0	4.3	3.2	3.4	3.6
Power @ 8 mil.Kw-Hr	3.2	3.3	3.5	3.2	3.3	3.5	3.2	3.3	3.5
Limestone @ $5/Ton	0.5	1.6	4.4	0.5	1.6	4.4	0.5	1.6	4.4
TOTAL	8.8	10.1	13.1	7.5	8.9	12.2	6.9	8.3	11.5

*Not including ozone.

After Beller et al, (23)

TABLE 20

AMD TREATMENT TOTAL OPERATING COST

¢/1000 Gal.

AMD FLOW, GPD	0.25×10^6			1.0×10^6			6.0×10^6		
Fe^{++}, ppm	50	300	1000	50	300	1000	50	300	1000
OZONE GENERATED ON SITE-ELECTRIC DISCHARGE OZONIZERS									
A. ONCE-THROUGH AIR FEED, 7.25 KW-Hr/lb									
OZONE	3.6	20.1	61.1	3.4	18.1	55.0	2.8	16.0	51.7
AMD PLANT	8.8	10.1	13.1	7.5	8.9	12.2	6.9	8.3	11.5
TOTAL	12.4	30.2	74.3	10.9	27.0	67.2	9.7	24.3	63.2
B. ONCE-THROUGH AIR FEED, 9.75 KW-Hr/lb									
OZONE	4.2	24.8	75.3	4.2	22.2	67.9	3.7	19.6	62.5
AMD PLANT	8.8	10.1	13.1	7.5	8.9	12.2	6.9	8.3	11.5
TOTAL	13.0	34.9	88.4	11.7	31.1	80.1	10.6	27.9	74.0
C. OXYGEN FEED WITH RECYCLE, 3.75 KW-Hr/lb									
OZONE	4.9	21.2	56.5	3.7	16.5	45.7	2.7	12.6	35.8
AMD PLANT	8.8	10.1	13.1	7.5	8.9	12.2	6.9	8.3	11.5
TOTAL	13.7	31.3	69.6	11.2	25.4	57.9	9.6	20.9	47.3
D. OXYGEN FEED WITH RECYCLE, 5.0 KW-Hr/lb									
OZONE	5.5	24.1	65.2	4.3	19.1	52.9	3.2	14.5	42.1
AMD PLANT	8.8	10.1	13.1	7.5	8.9	12.2	6.9	8.3	11.5
TOTAL	14.3	34.2	78.3	11.8	28.0	65.1	10.1	22.8	53.6

After Beller, et al, (23)

TABLE 21

OZONE GENERATED IN 40 TON/DAY CENTRAL PLANT, SHIPPED TO AMD SITE

¢/1000 Gal.

AMD FLOW, GPD	0.25×10^6			1.0×10^6			6.0×10^6		
Fe^{++}, ppm	50	300	1000	50	300	1000	50	300	1000
A. ELECTRIC DISCHARGE OZONIZERS, RECYCLED O_2, 5 KW-Hr/lb									
1. 5 MIL./KW-Hr POWER COST									
OZONE	1.2	7.0	23.3	1.2	7.0	23.3	1.2	7.0	23.3
AMD PLANT	8.8	10.1	13.1	7.5	8.9	12.2	6.9	8.3	11.5
DISTRIBUTION	0.9	5.4	14.0	0.9	5.4	14.0	0.9	5.4	14.0
LABOR	2.0	2.0	2.0	1.0	1.0	1.0	0.5	0.5	0.5
TOTAL	12.9	24.5	52.4	10.6	22.3	50.5	9.5	21.2	49.3
2. 6 MIL./KW-Hr POWER COST									
OZONE	1.5	8.0	26.0	1.5	8.0	26.0	1.5	8.0	26.0
AMD PLANT	8.8	10.1	13.1	7.5	8.9	12.2	6.9	8.3	11.5
DISTRIBUTION	0.9	5.4	14.0	0.9	5.4	14.0	0.9	5.4	14.0
LABOR	2.0	2.0	2.0	1.0	1.0	1.0	0.5	0.5	0.5
TOTAL	13.2	25.5	55.1	10.9	23.3	53.2	9.8	22.2	52.0
B. CHEMONUCLEAR OZONE, RECYCLED O_2									
1. G = 15, E = 0.20									
OZONE	1.0	5.8	19.5	1.0	5.8	19.5	1.0	5.8	19.5
AMD PLANT	8.8	10.1	13.1	7.5	8.9	12.2	6.9	8.3	11.5
DISTRIBUTION	0.9	5.4	14.0	0.9	5.4	14.0	0.9	5.4	14.0
LABOR	2.0	2.0	2.0	1.0	1.0	1.0	0.5	0.5	0.5
TOTAL	12.7	23.3	48.6	10.4	21.1	46.7	9.3	20.0	45.5
2. G = 10, E = 0.20									
OZONE	1.3	6.8	22.5	1.3	6.8	22.5	1.3	6.8	22.5
AMD PLANT	8.8	10.1	13.1	7.5	8.9	12.2	6.9	8.3	11.5
DISTRIBUTION	0.9	5.4	14.0	0.9	5.4	14.0	0.9	5.4	14.0
LABOR	2.0	2.0	2.0	1.0	1.0	1.0	0.5	0.5	0.5
TOTAL	13.0	24.3	51.6	10.7	22.1	49.7	9.6	21.0	48.5

After Beller et al, (23)

TABLE 22

OZONE GENERATED IN 200 TON/DAY CENTRAL PLANT, SHIPPED TO AMD SITE

¢/1000 Gal.

AMD FLOW, GPD	0.25×10^6			1.0×10^6			6.0×10^6		
Fe^{++}, ppm	50	300	1000	50	300	1000	50	300	1000
A. ELECTRIC DISCHARGE OZONIZERS, RECYCLED O_2, 5 KW-Hr/lb									
1. 5 MIL./KW-HR POWER COST									
OZONE	1.1	6.4	21.3	1.1	6.4	21.3	1.1	6.4	21.3
AMD PLANT	8.8	10.1	13.1	7.5	8.9	12.2	6.9	8.3	11.5
DISTRIBUTION	0.9	5.4	14.0	0.9	5.4	14.0	0.9	5.4	14.0
LABOR	2.0	2.0	2.0	1.0	1.0	1.0	0.5	0.5	0.5
TOTAL	12.8	23.9	50.4	10.5	21.7	48.5	9.4	20.6	47.3
2. 6 MIL./KW-HR POWER COST									
OZONE	1.2	7.2	24.0	1.2	7.2	24.0	1.2	7.2	24.0
AMD PLANT	8.8	10.1	13.1	7.5	8.9	12.2	6.9	8.3	11.5
DISTRIBUTION	0.9	5.4	14.0	0.9	5.4	14.0	0.9	5.4	14.0
LABOR	2.0	2.0	2.0	1.0	1.0	1.0	0.5	0.5	0.5
TOTAL	12.9	24.7	53.1	10.6	22.5	51.2	9.5	21.4	50.0
B. CHEMONUCLEAR OZONE, RECYCLED O_2									
1. G = 15, E = 0.20									
OZONE	0.7	4.1	13.7	0.7	4.1	13.7	0.7	4.1	13.7
AMD PLANT	8.8	10.1	13.1	7.5	8.9	12.2	6.9	8.3	11.5
DISTRIBUTION	0.9	5.4	14.0	0.9	5.4	14.0	0.9	5.4	14.0
LABOR	2.0	2.0	2.0	1.0	1.0	1.0	0.5	0.5	0.5
TOTAL	12.4	21.6	42.8	10.1	19.4	40.9	9.0	18.3	39.7
2. G = 10, E = 0.20									
OZONE	0.9	5.2	17.3	0.9	5.2	17.3	0.9	5.2	17.3
AMD PLANT	8.8	10.1	13.1	7.5	8.9	12.2	6.9	8.3	11.5
DISTRIBUTION	0.9	5.4	14.0	0.9	5.4	14.0	0.9	5.4	14.0
LABOR	2.0	2.0	2.0	1.0	1.0	1.0	0.5	0.5	0.5
TOTAL	12.6	22.7	46.4	10.3	20.5	44.5	9.2	19.4	43.3

After Beller et al, (23)

TABLE 23

TOTAL INVESTMENT COSTS FOR AMD TREATMENT
USING ON-SITE OZONE WITH RECYCLED OXYGEN FEED

5.0 KWH/LB OZONE

COSTS IN THOUSANDS OF DOLLARS

AMD FLOW, GAL./DAY	250,000			1,000,000			6,000,000		
Fe^{+2} CONC'N ppm	50	300	1000	50	300	1000	50	300	1000
OZONE PLANT	14	60	190	40	220	530	220	810	2130
AMD PLANT	52	53	53	156	163	175	790	830	855
TOTAL $	66	113	243	196	383	705	1010	1640	2985

After Beller et al, (23)

TABLE 24

COMPARISON OF AMD TOTAL TREATMENT COSTS

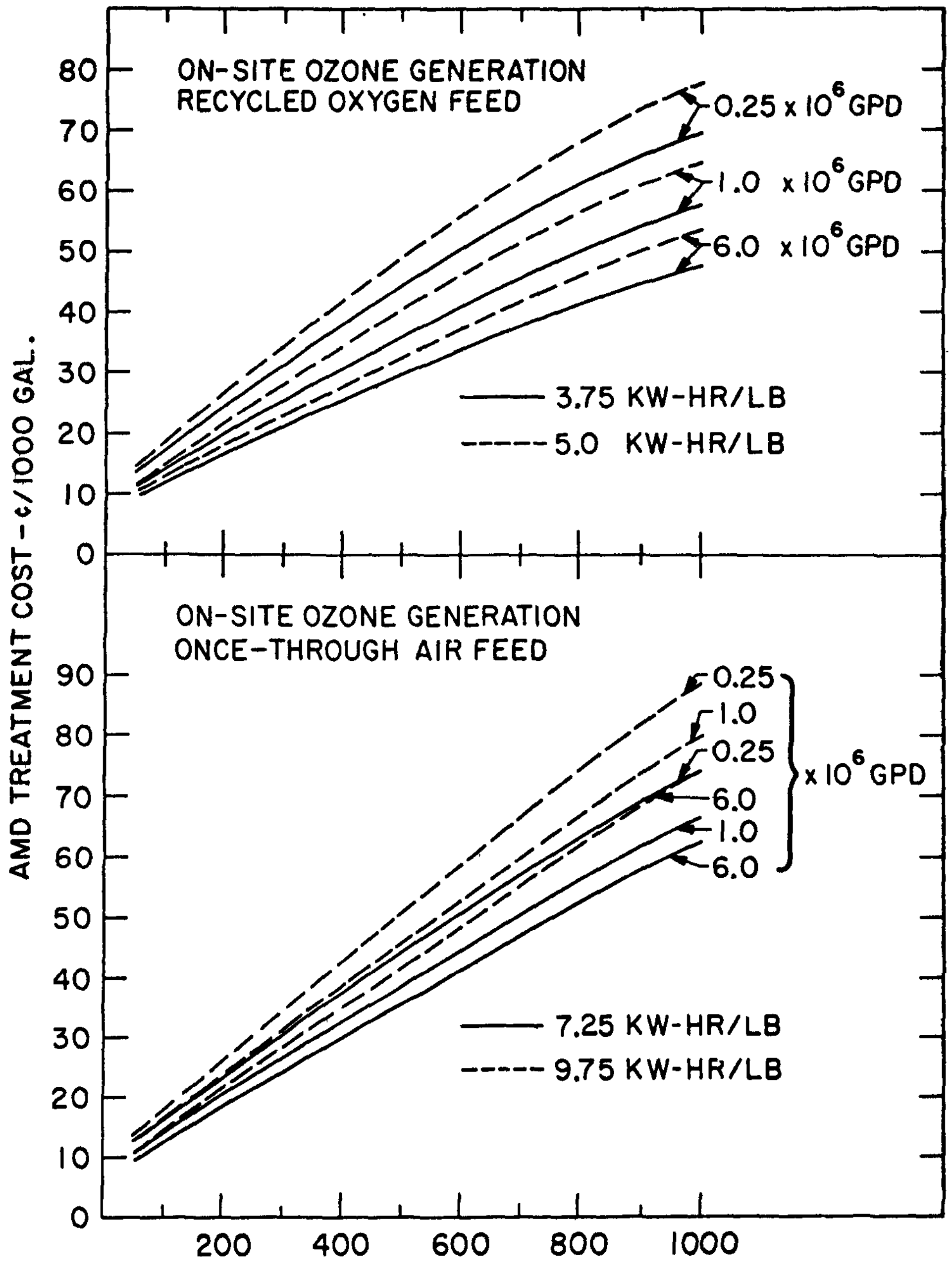
COSTS IN CENTS PER 1000 GAL.

AMD FLOW - GAL. PER DAY

	0.25×10^6			1.0×10^6			6.0×10^6		
Fe^{++} CONTENT-ppm	50	300	1000	50	300	1000	50	300	1000
1. ELECTRIC DISCHARGE WITH RECYCLED OXYGEN FEED, ON-SITE OZONE GENERATION									
@ 3.75 Kwh/lb.	14	31	70	11	25	58	10	21	47
@ 5.00 Kwh/lb.	14	34	78	12	28	65	10	23	54
2. ELECTRIC DISCHARGE WITH ONCE-THROUGH AIR FEED, ON SITE OZONE GENERATION									
@ 7.25 Kwh/lb.	12	30	74	11	27	67	10	24	63
@ 9.25 Kwh/lb.	13	35	88	12	31	80	11	28	74
CENTRAL OZONE PLANTS WITH DISTRIBUTION SYSTEMS									
3. ELECTRIC DISCHARGE, 40 TON/DAY OZONE									
@ 5 mil/Kwh power	13	24	52	11	22	50	10	21	49
@ 6 mil " "	13	26	55	11	23	53	10	22	52
4. ELECTRIC DISCHARGE, 200 TON/DAY OZONE									
@ 5 mil/Kwh power	13	24	50	10	22	48	9	21	47
@ 6 mil/ " "	13	25	53	11	23	51	9	21	50
5. CHEMONUCLEAR, 40 TON/DAY OZONE									
G=10, E=0.20	13	24	52	11	22	50	10	21	48
G=15, E=0.20	13	23	49	10	21	47	9	20	45
6. CHEMONUCLEAR, 200 TON/DAY OZONE									
G=10, E=0.20	13	23	46	10	21	44	9	19	43
G=15, E=0.20	12	22	43	10	19	41	9	18	40

After Beller et al, (23)

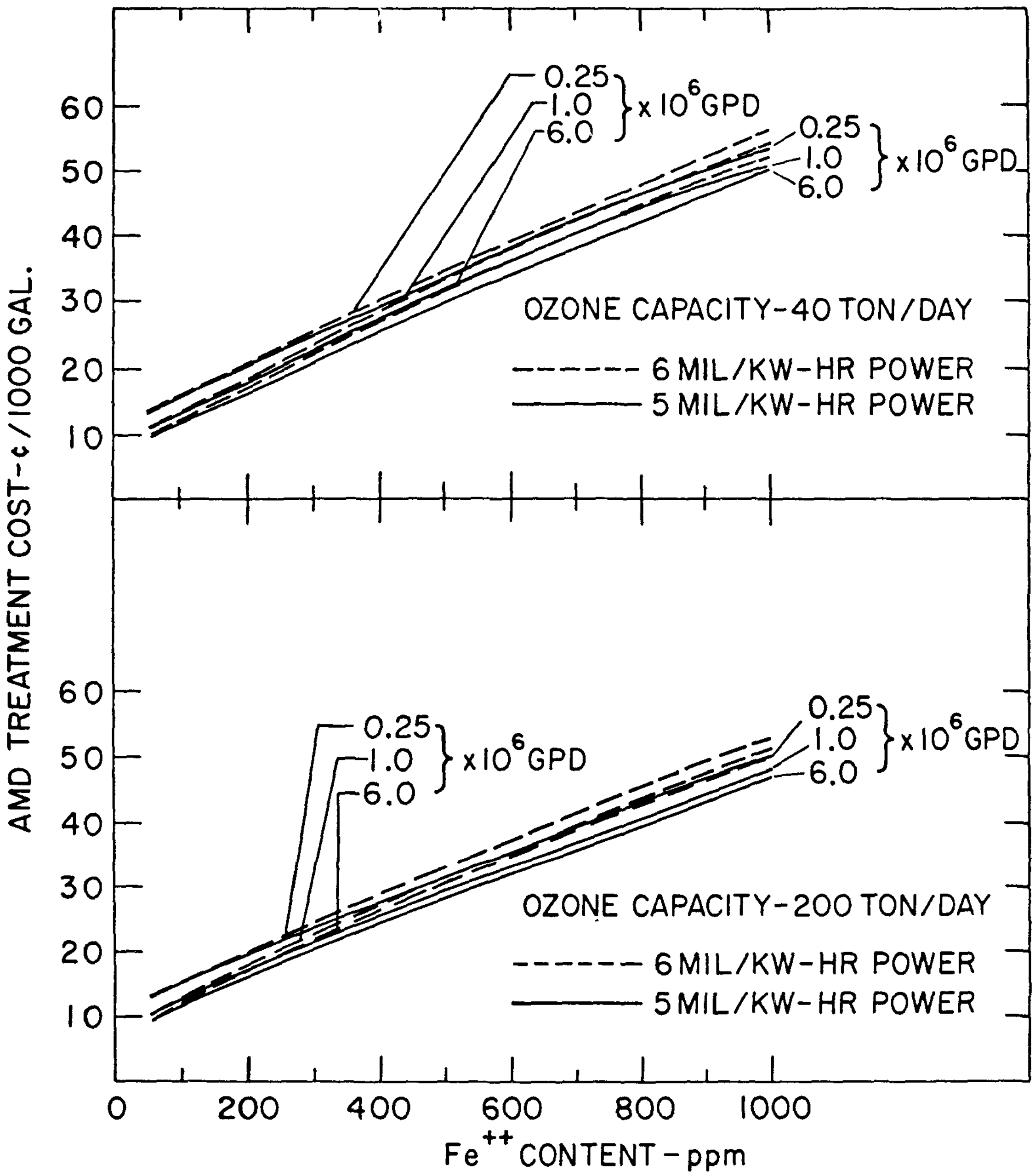
FIGURE 37



TOTAL AMD TREATMENT COSTS USING OZONE
ELECTRIC DISCHARGE OZONIZERS

After Beller et al, (23)

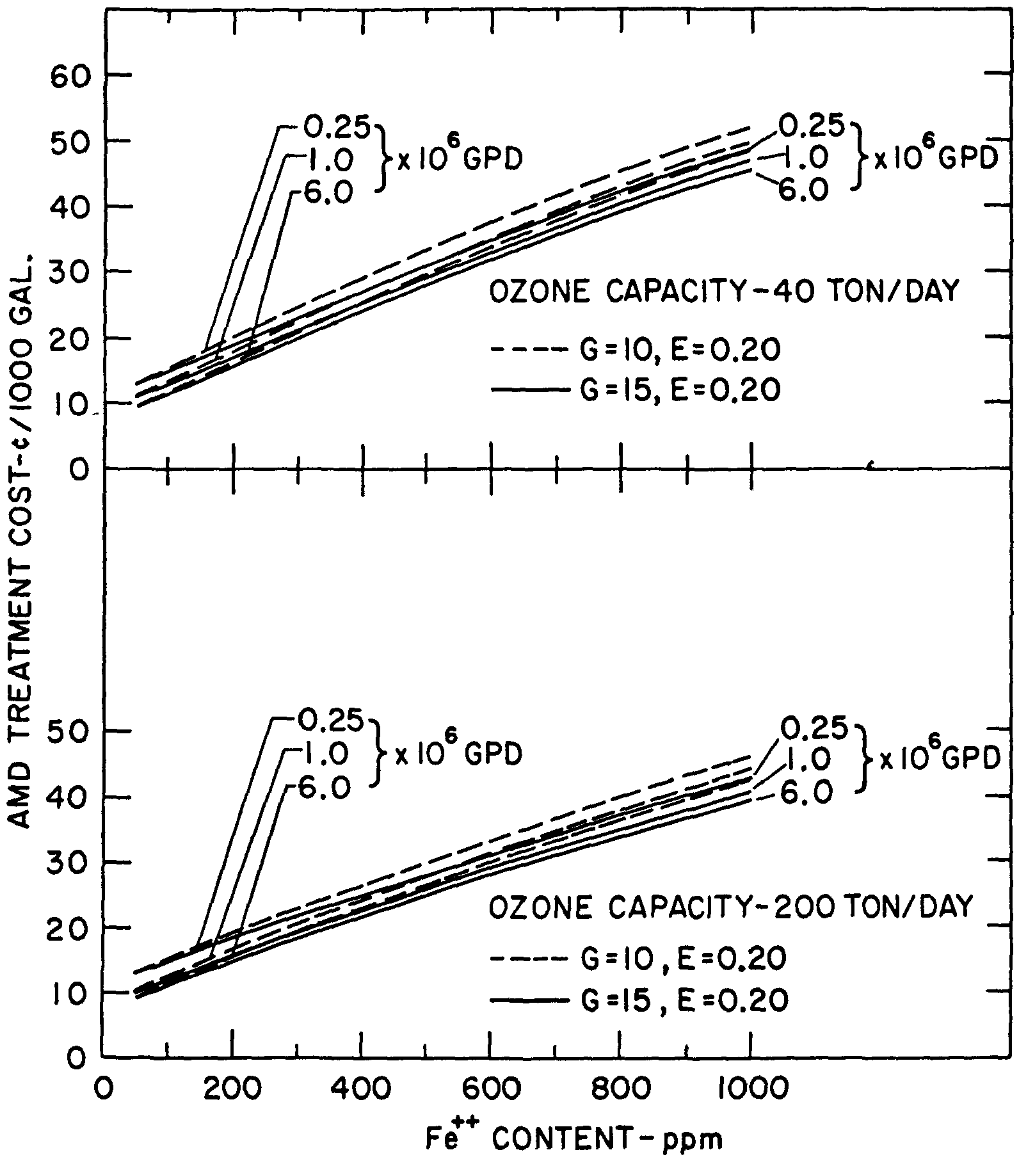
FIGURE 38



TOTAL AMD TREATMENT COST USING ELECTRIC-DISCHARGE OZONE
CENTRAL PLANT OZONE GENERATION, SHIPPED TO AMD SITE
5 KW-HR/LB O_3 POWER CONSUMPTION

After Beller et al, (23)

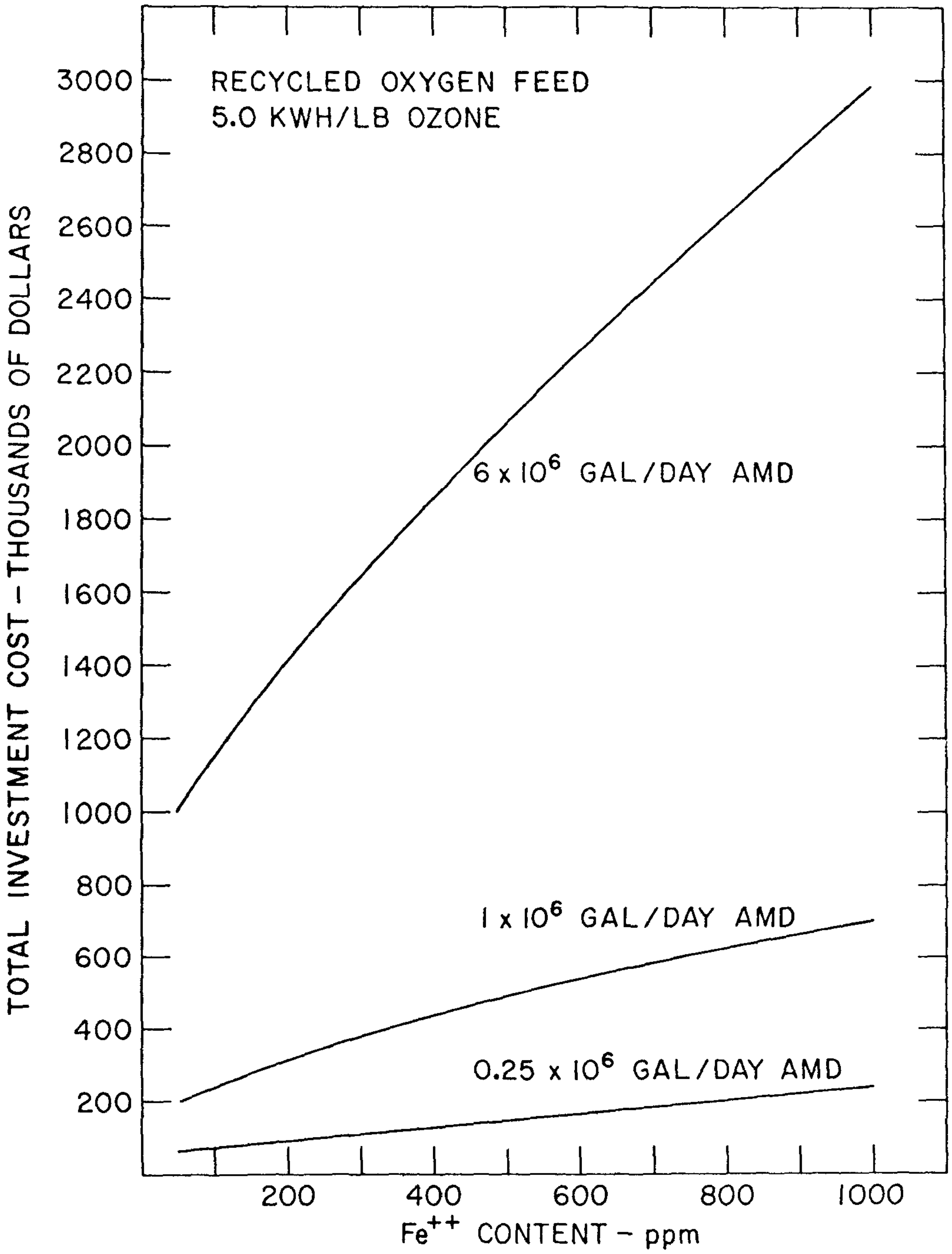
FIGURE 39



TOTAL AMD TREATMENT COST USING CHEMONUCLEAR OZONE CENTRAL PLANT OZONE GENERATION, SHIPPED TO AMD SITE

After Beller et al, (23)

FIGURE 40



TOTAL PLANT INVESTMENT COST FOR AMD TREATMENT USING ON-SITE ELECTRIC DISCHARGE OZONE

After Beller et al, (23)

TABLE 25

COST BREAKDOWN FOR TOTAL AMD TREATMENT OF PENNSYLVANIA AMD STREAMS

486 MILLION GALLONS PER DAY

Investment Costs - Million Dollars

	Central Chemo-nuclear	Central Elec. Disch.	On-Site Elec. Disch.
Ozone Plants	26.0	34.8	99.5
AMD Neutralization*	156.0	156.0	113.0
Total Investment	182.0	190.8	212.5

Operating Costs - ¢/1000 Gal.

	Central Chemo-nuclear	Central Elec. Disch.	On-Site Elec. Disch.
Depreciation-7.3%	9.1	9.6	10.6
Nucl. Fuel Cycle	0.9	-	-
Labor	2.1	2.1	1.0
Power	3.9	6.3	7.2
Maintenance	0.1	0.1	1.0
Purchased Oxygen	-	-	5.4
Distribution	0.8	0.8	-
Limestone	1.2	1.2	1.2
Total Operating Costs	18.1	20.1	26.4
Annual Operating Costs	$26.4x10^6$	$29.3x10^6$	$38.5x10^6$

*Assumes 2,160 AMD treatment sites with average flow rates of 250,000 gpd.

After Beller et al, (23)

Neutralization of Mine Drainage with High Ferric Iron Content

Neutralization of mine drainage with high ferric iron content can be accomplished more easily and at less cost compared to treatment of mine drainage high in ferrous iron. Equipment, chemicals and methods necessary for oxidation of ferrous iron can be eliminated with consequent reduction in cost and simplification of treatment.

Wilmoth and Hill[24] conducted continuous flow and batch test studies utilizing lime, limestone and soda ash to treat acid mine drainage having a high ferric/ferrous ratio. Some of their conclusions and recommendations were:

1. Chemical costs for treating by the three methods were: soda ash - 0.049 cents, limestone - 0.010 cents, and lime - 0.005 cents per mg/l acidity per 1,000 gallons. These costs updated to April, 1972, using the ENR Construction Cost Index, would be respectively: 0.075 cents, 0.015 cents and 0.0075 cents per mg/l acidity per 1,000 gallons.

2. Lime is a very reactive material and the neutralization reaction goes to completion in less than half an hour. The limestone reaction requires 24 to 48 hours to go to completion and therefore, requires a long detention time before discharge, however, aeration will reduce the detention time to one comparable to lime.

3. The limestone reaction is not very sensitive quantitatively, i.e., small changes in limestone feed rate or water quality do not cause large changes in product water quality so the accuracy with which constituents are fed into the reactor need not be controlled with the precision required by lime. Accidental overtreatment is not the pollution problem with limestone that it would be with lime.

4. Lime is capable of attaining high pH's which may be necessary in some cases for desired water quality, whereas with limestone, pH's above 7.0 are very difficult to attain.

5. All three neutralizing agents were capable of treating the high ferric acid mine drainage. Lime costs were half that of limestone for treating the same acid mine drainage because of the low utilization of limestone. However, the characteristics of the limestone sludge were superior; it occupied approximately two-thirds of the volume of lime sludge and had a higher solids content. The limestone sludge also had a large residual alkalinity which would be beneficial when disposed into an acid environment (although this residual alkalinity is expensive and of questionable value to the treatment process).

6. Studies should be made to develop methods of increasing the efficiency of limestone as a neutralization agent in acid mine drainage treatment because of the lower initial cost and low sludge volume. Studies should be made on:

   a) Sludge return to take advantage of the residual alkalinity within the sludge.

   b) Increasing the detention time in the reactor to allow more limestone to go into solution.

   c) Increasing the shearing action in the reactor to break the calcium sulfate and iron coating of the limestone.

   d) Combination limestone-lime to utilize the strong points of each, i.e, limestone for low pH's to around pH 5 (the most efficient portion of the limestone curve) and then the use of lime to further increase the pH.

   e) Developing methods to produce a rapid settling and dense sludge, e.g., the use of coagulating aids.

Calhoun[25] in discussing the design and operation of a limestone treatment plant for the Rochester & Pittsburgh Coal Company, Indiana, Pennsylvania, expressed the opinion that the limestone treatment method should always be investigated prior to installation of a permanent treatment plant because some types of mine drainage can be treated with a limestone system. The reasons given are: 1) most economical, 2) a lesser volume of sludge for disposal, and 3) there is no danger of overtreatment. He also said, it appears a combination limestone-lime treatment method would be most economical for treatment of a difficult water with a high ferrous iron content. These statements are in agreement with the studies of Wilmoth and Hill.

At the Rochester & Pittsburgh Coal Company treatment site the mine drainage has the following average characteristics: pH - 3.1, acidity - 350 mg/l, iron - 56 mg/l (less than 10% in the ferrous state), dissolved solids - 1,600 mg/l, and a volume of 150/gpm.

The treatment facility consists essentially of a rotating drum as a reactor to tumble the limestone and a settling pond. The average quality of the effluent from the settling pond in 1967 was: pH - 6.9, alkalinity - 18 mg/l, and iron - 1.4 mg/l.

It is estimated capital costs for new equipment for the treatment plant would be close to $20,000. Actual costs were somewhat lower because second hand equipment was utilized. Operating costs, including limestone, power, maintenance and labor was estimated to be about 6¢/1,000 gal. treated (escalated to 1972 price levels it would be about 10¢/1,000 gal. treated).

Mine Drainage Treatment Using Hydrated Lime

In 1970, Heine and Giovannitti[26] said, "The science and technology of mine drainage treatment is in its infancy in the United States with the most significant recent advancements occurring in Pennsylvania." This is still the case two years later. Mine drainage technology is undergoing a period of rapid growth. The pace of research and development is so rapid, that some treatment plants can be said to be obsolete before they go into operation.

There are now probably close to three hundred plants treating mine drainage. Most of these plants are in Pennsylvania and many of them have been in operation for less than three years. The majority of the treatment plants use lime as the neutralizing agent. In the next few years, this domination by lime neutralization could conceivably change as the results of recent limestone and limestone-lime treatment technology are put into effect.

In estimating costs for mine drainage treatment, it should be recognized that much of the actual cost data developed to date is based on lime neutralization. Because of the newness of mine drainage treatment technology the capital and operating costs of existing treatment plants may not be an indication of future costs in mine drainage treatment. It is obvious when one reviews recent research and development that if the information was available at the time many of the existing plants were planned, the design and operation would be considerably different. Although most of the lime neutralization plants in operation today are effectively treating acid mine drainage at costs that are relatively economical, they are at best primitive examples of mine drainage treatment in the dawn of a developing technology. Further economies can accrue from more efficient operation and design as a result of the progress being made in mine drainage treatment technology.

Hydrated Lime Process - Basically this process involves four steps in treating acid mine drainage.

1. Neutralization which entails the conversion of

   a) Sulfuric acid to calcium sulfate

   $$Ca(OH)_2 + H_2SO_4 \longrightarrow CaSO_4 + 2\ H_2O$$

   b) Ferrous sulfate to ferrous hydroxide and calcium sulfate

   $$Ca(OH)_2 + FeSO_4 \longrightarrow Fe(OH)_2 + CaSO_4$$

2. Aeration - The oxidation of ferrous hydroxide to ferric hydroxide

   $$O_2 + 4\ Fe(OH)_2 + H_2O \longrightarrow 4\ Fe(OH)_3$$

3. Clarification - Thickening

4. Sludge Dewatering and Disposal

The advantages of lime treatment are: 1) removal of acidity, 2) removal of iron and aluminum salts, 3) reduction in sulfate ion concentration, 4) relative simplicity and control, and 5) ready availability of lime.

The disadvantages are: 1) addition of hardness to effluent, 2) gypsum scale on plant equipment and possibly in effluent, 3) difficulty in sludge handling and dewatering, 4) volume of sludge production and disposal, and 5) possibility of overtreatment with detrimental effects.

Engineering Cost Factors - The following engineering cost factors should be considered in estimating costs of lime treatment facilities.

1. Treatment Plant Capacity - The capital cost of a plant is determined by its construction cost which to some extent is affected by the acidity and iron content of mine drainage to be treated. The operating costs are more affected by the acidity and iron content than by the plant size.

2. Lime Storage Facilities - These facilities depend for their sizing on acidity characteristics as well as the volume of mine drainage to be treated.

3. Mixing and Aeration - The purpose of mixing is two fold: 1) it must disperse the solid hydrated lime in mine water and 2) it must produce turbulence of high intensity around the hydrated lime particles in order to promote a mass transfer between the two phases. Dorr-Oliver, Inc. reports(27, 28) that with a separate flash mixing operation, a detention time of one minute was found sufficient to ensure neutralization.

4. Aeration - "Operation Yellowboy" data(29) indicates a detention time of about 30 minutes with efficient aeration equipment is sufficient.

5. Settling and/or Thickening - Sludges formed in lime treatment are typically slow in settling from solution. In this respect, lime treatment is at a disadvantage in comparison with limestone treatment, which produces a more rapidly settling sludge of less volume. "Operation Yellowboy"(29) used a thickener to separate the iron oxide-gypsum sludge mixture, and subsequent centrifugation as a sludge dewatering process. Also, according to "Operation Yellowboy" data, settling and thickening may represent a significant cost in capital plant expenditures.

   The sludge volume typically produced in lime treatment represents a high percentage of the influent volume and the solids content ranges from 1 to 10%. The solids content does increase with time. Polymeric flocculants improve the settling characteristics of sludge, but they do not increase the solids concentration.

Kostenbader and Haines[30, 31] report the development of a high-density sludge (HDS) process which, in addition to the usual lime treatment process, involves recycling a controlled volume of the settled sludge and mixing the recycled sludge with lime slurry in a reaction tank prior to the neutralization and separation steps. Figure 41 shows the flow diagram of the HDS process. Depending mainly on the oxidation state of iron in the mine water, the sludges produced can contain 15 to 40% solids. The HDS process is claimed to be inherently well-suited for treating acid mine drainage with high ferrous/ferric iron ratios.

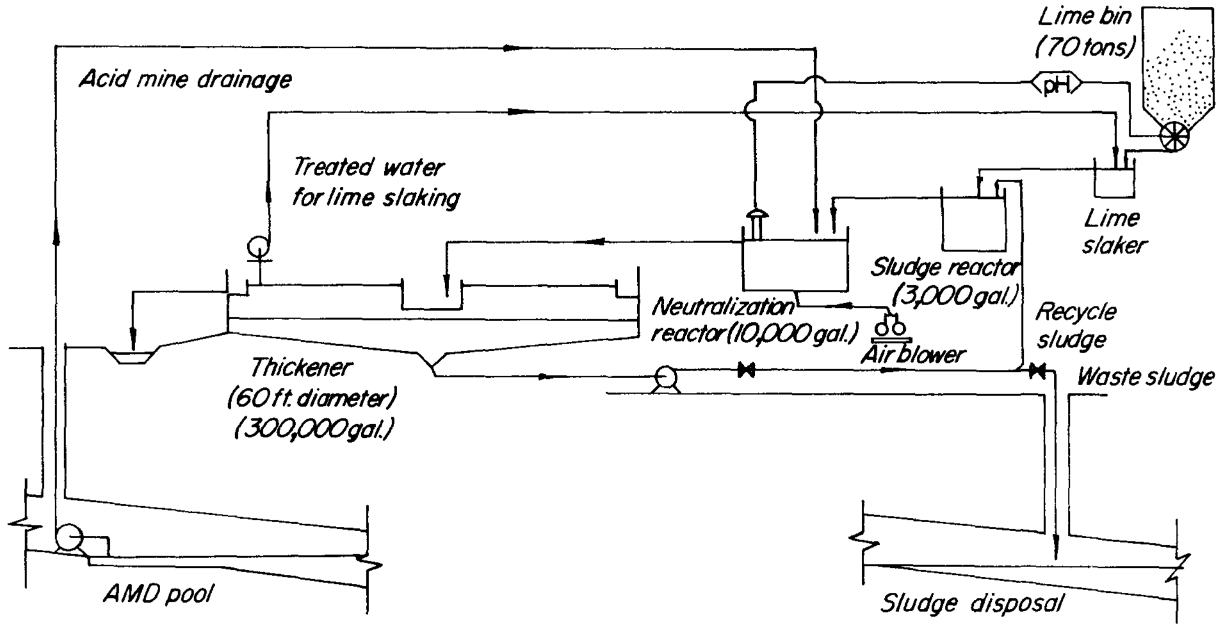
If land space is available, lagoons could be used for sludge settling as an alternative to mechanical thickening. Two or more lagoons or basins could be used, and after sludge settling, the supernatant may be removed by pumping, or the sludge may be allowed to dry in the lagoon.

6. Sludge Dewatering - The "Operation Yellowboy" projects employed various dewatering techniques, including centrifugation and filtration. A drum filter process increased solids concentrations from initial ranges of 0.9 to 5 percent to final solids concentrations of 21 to 27 percent.

   Rotary precoat filtration, centrifugation, pressure filtration, freezing, cycloning, CO_2 pretreatment, and other methods of sludge densification and dewatering have also been studied[32, 33].

7. Sludge Disposal - The disposal of sludge is a major problem in mine drainage treatment. Holland et al.[3], estimated costs of disposing of sludge in lagoons. These estimates show costs may amount to 13 to 15 percent of the total annual plant operating costs for treating highly acid mine drainage, 11 to 13 percent for moderately acid discharges and 7.5 to 10 percent for weakly acid discharges. Holland points out that the cost could be higher because the cost of sludge disposal in lagoons is markedly affected by land availability, soil type, underlying rock, ground water, etc. He also suggests the possibility of using nearby abandoned mines for sludge disposal.

   Where possible, sludge should be pumped to abandoned mines. Deep injection wells cannot be used where the subsurface geology is unfavorable and it is questionable whether this method is practical for acid mine drainage sludge disposal. Evaporation ponds are not functional in areas where annual rainfall exceeds annual evaporation. Rinne[34] provides costs for evaporation ponds and for deep well disposal of brine (Tables 26 and 27). Steinman[35] reports that at the Thompson Mine Drainage Treatment Plant of Jones and Laughlin's Vesta Shannopin Coal Division, it was found more economical to truck the sludge rather than acquire land and construct a large sludge lagoon. Dean[36] describes methods of sludge disposal in detail. Osman et al.[37], investigated mine drainage sludge utilization. Their research covered: 1) additives used in the building materials industry, 2) recovery of iron, 3) the application of gypsum technology to the sulfate portion of the sludge, and 4) separation of the major chemical components. They found that manufacture of synthetic light-weight aggre-



After Kostenbader & Haines[31]

FIGURE 41

FLOW DIAGRAM, HDS DEMONSTRATION PLANT AT MINE 32
BETHLEHEM STEEL CORPORATION

TABLE 26
COST OF BRINE DISPOSAL IN EVAPORATION PONDS
(Assuming PVC Liner at $0.30 per sq. ft.)
1.0 MGD Brine

	Arkansas City, Ark.	Gallup, N.M.	Midland, Texas
Net Avg. Annual Pond Evaporation (inch)	14	30	40
Pond Area (acres)	960	468	343
Pond Construction Cost ($ x 10^6)	15.27	7.34	5.38
Total Annual Operation Cost ($/yr. x 10^6)	1.73	0.84	0.62
Cost per 1,000 gals. of brine	$5.20	2.50	1.92
90% recovery of feed ($/1,000 gallons) fresh water	0.52	0.25	0.19

TABLE 27
ESTIMATED COSTS OF DEEP WELL DISPOSAL

	Arkansas City	Midland	Ft. Morgan
Prod. Vol. (MGD)	7.0	5.0	3.0
Brine Vol. (MGD)	1.27	0.8	1.0
Well Construc. Cost ($ x 10^6)	0.195	0.157	0.787
Total Cap. Cost ($ x 10^6)	0.258	0.401	1.775
Total Annual Cost ($/yr. x 10^6)	0.063	0.120	0.384
Product Water Bases			
Total Unit Cap. Cost ($/gal./day)	0.369	0.080	0.591
Total Unit Oper. Cost ($/1,000 gallons)	0.025	0.066	0.35

After Rinne, 1970[34]
Costs not updated to 1972.

gates and structural bricks utilizing small percentages of sludge was technically feasible and recovery of iron was also generally successful. The high-iron content sludge (alkaline) can be pelletized and used directly as a blast furnace feed after dewatering. The high-sulfate sludge (acid), when pre-reduced at high temperature to decompose the calcium sulfate, can be agglomerated into a blast furnace feed. Additional research is needed before these results can be considered commercially attractive.

"Operation Yellowboy" projects(27, 28, 29, 38, 39), Holland, et al.(3) and Selmeczi(40) provide useful design information for lime neutralization treatment plants.

Tables 28, 29 and 30 give the actual costs of five "Operation Yellowboy" projects. Tables 31, 32 and 33 give the estimated costs using hydrated lime as taken from the work of Holland, et al.(3). These costs were updated to April, 1972 price levels using the ENR Construction Cost Index and plotted as cost curves in Figures 42, 43 and 44.

TABLE 28

Acid Mine Drainage Treatment Plant
Capital Expenditures

Item	Marianna bore hole	Young & Son gravity discharge	Morea Strip Pit	Loomis bore hole	Scrubgrass Creek	Warwick bore hole
Flow Rate, MG/D	0.240	0.180	4.00	5.76	4.15	0.60
Water storage and transportation facilities	$ 22,800	$ 15,300	$ 42,500	$ 8,000	None	$ 17,000
Control-Filter						
Building	223,000	160,000	275,500	614,000	8,600	144,000
Aeration	6,000	6,200	18,400	34,000	None	9,200
Thickening	45,000	26,600	254,000	342,000	None	84,000
Sludge Holding	9,500	2,500	7,500	9,000	None	10,000
Piping and Site Preparation	40,900	19,300	59,500	87,000	1,250	35,000
Total Capital Cost	$347,200	$229,900	$657,400	$1,094,000	$9,850	$282,700

After Charmbury, et al [29]

TABLE 29

Annual Operating Costs

Item	Marianna bore hole	Young & Son gravity discharge	Morea Strip Pit	Loomis bore hole	Scrubgrass Creek	Warwick bore hole
Flow Rate, MG/D	0.240	0.180	4.00	5.76	4.15	0.600
Amortization	$25,550(1)	$16,900(1)	$ 48,371(1)	$ 80,500(1)	$ 2,275(2)	$ 22,000(1)
Labor and Supervision	36,500	20,000	42,500	108,000	730	43,000
Power	4,700	3,200	8,700	100,000	87	15,000
Chemicals (lime)	22,000	2,300	20,000	152,000	7,045	29,000
Total Annual Operating Costs	$95,250	$47,400	$126,571	$475,500	$10,236	$117,500

(1) 20 years amortization @ 4% interest

(2) 5 year amortization @ 5% interest

After Charmbury, et al [29]

TABLE 30

Total Annual Unit Costs

Item	Marianna bore hole	Young & Son gravity discharge	Morea Strip Pit	Loomis bore hole	Scrubgrass Creek	Warwick bore hole
Flow Rate, MG/D	0.240	0.180	4.00	5.76	4.15	0.600
Cost per 1,000 gal., treated	1.09	0.72	0.087	0.226	0.0068	0.537
Coal Marketed-tons/D	5,000	40	None	None	None	5,000
Cost per ton of Coal	0.052	3.25	None	None	None	0.095
Cost per ton of dry solids	$ 27,780	$ 333,000	$ 302,600	$ 50,700	None	$ 17,133
Cost per ton of iron	$425,500	$1,362,000	$6,780,000	$126,700	$428,260	$158,640
Cost per ton of acid	$ 85,000	$ 397,000	$ 207,200	$ 81,400	$ 6,610	$ 90,319

After Charmbury, et al [29]

TABLE 31

Estimated Costs of Neutralizing Highly Acid Mine Water Using Hydrated Lime
(All Costs in Cents per 1000 Gallons of Water Treated)

Plant Capacity Gallons/Day	Labor	Lime	Plant Cost Except Sludge Disposal	Sludge Disposal Cost	Repair	Misc.	Total	Accumulation of Sludge in One-Year Acre-Feet
300,000	10	28	9.5	8	4	3	62.5	9.8
900,000	5	26	8.5	7	3	3	52.5	30.1
2,700,000	2.5	25.5	7.25	7.75*	2.5	3	48.5	91.0
8,100,000	2	25.5	7.25	7.50*	2.5	3	47.75	273.0

Acidity 2800 - 4000
Iron 900 - 1200

Bag Lime $24.00/Ton
Bulk Lime $22.00/Ton

TABLE 32

Estimated Costs of Neutralizing Moderately Acid Mine Water Using Hydrated Lime
(All Costs in Cents per 1000 Gallons of Water Treated)

Plant Capacity Gallons/Day	Labor	Lime	Plant Cost Except Sludge Disposal	Sludge Disposal Cost	Repair	Misc.	Total	Accumulation of Sludge in One-Year Acre-Feet
300,000	8	12.9	9.5	4	3	3	34.8	4.9
900,000	4	11.5	8.5	3.5 *	2.5	3	33.0	15.4
2,700,000	2	11	7.75	3.75*	2	3	29.5	45.5
8,100,000	1.6	11	7.25	3.75*	2	3	28.6	136.5

Acidity around 1400 PPM
Iron around 600 - 700 PPM

Bag Lime $24.00/Ton
Bulk Lime $22.00/Ton

TABLE 33

Estimated Costs of Neutralizing Weak Acid Mine Water Using Hydrated Lime
(All Costs in Cents per 1000 Gallons of Water Treated)

Plant Capacity Gallons/Day	Labor	Lime	Plant Cost Except Sludge Disposal	Sludge Disposal Cost	Repair	Misc.	Total	Accumulation of Sludge in One-Year Acre-Feet
300,000	6	6.1	8.5	2	2.5	2.5	27.60	2.8
900,000	3	5.7	7.5	1.8	2	2.5	22.50	7.7
2,700,000	1.8	5.5	6.75	1.9*	1.5	2.5	19.95	23.1
8,100,000	1	5.5	6.5	1.9*	1.5	2.5	18.90	68.6

Acidity around 600 - 700,
Iron 322,

Bag Lime $24.00/Ton
Bulk Lime $22.00/Ton

After Holland, et al [3]
*These costs allow for excavating some hard rock.

FIGURE 42

CAPITAL COST Vs. PLANT CAPACITY

HYDRATED LIME TREATMENT PLANT WITH SLUDGE DISPOSAL

REFERENCES: 29 & 41

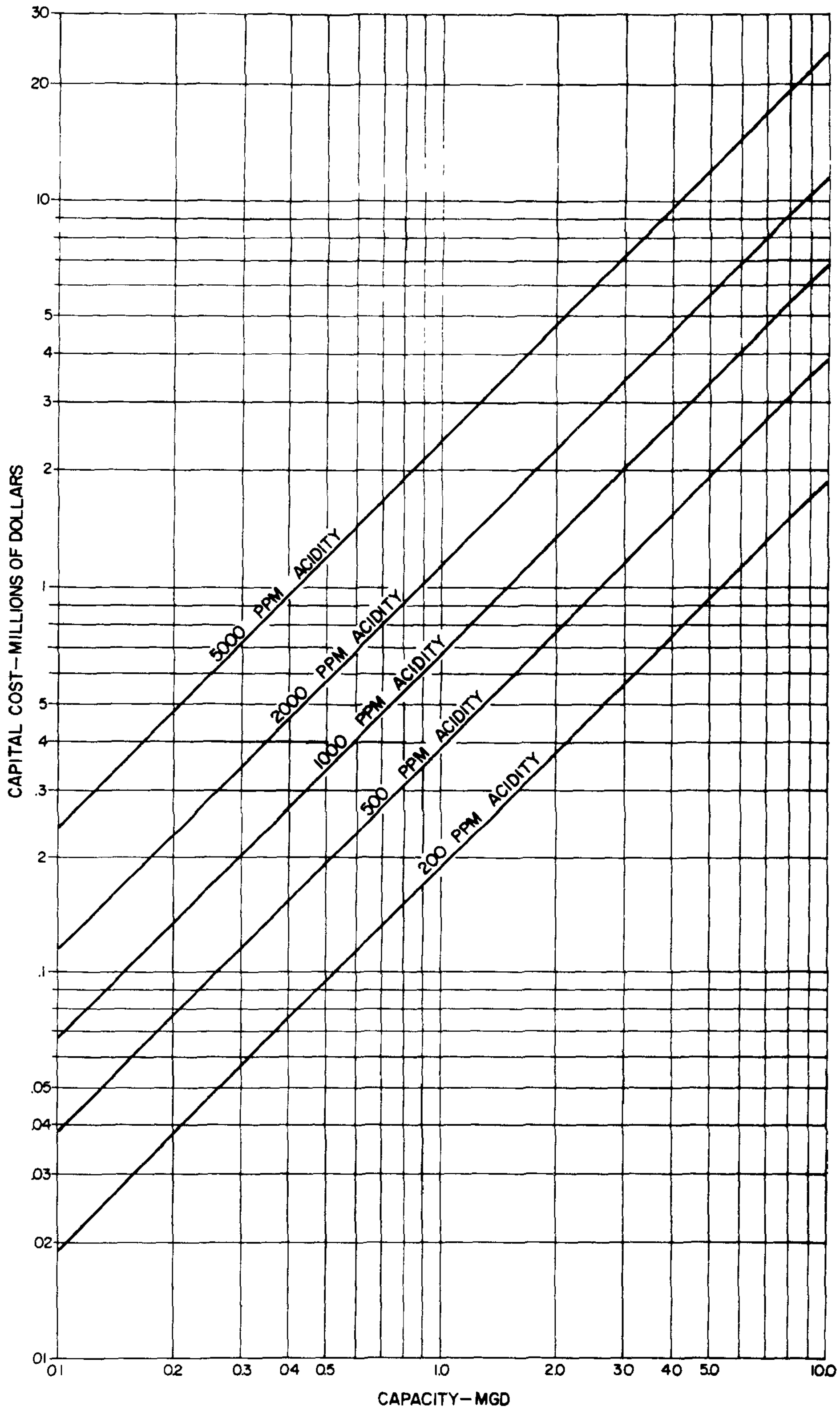


FIGURE 43

TOTAL CAPITAL COST Vs. PLANT CAPACITY
HYDRATED LIME TREATMENT PLANT
(WITHOUT SLUDGE DISPOSAL) REF. 3

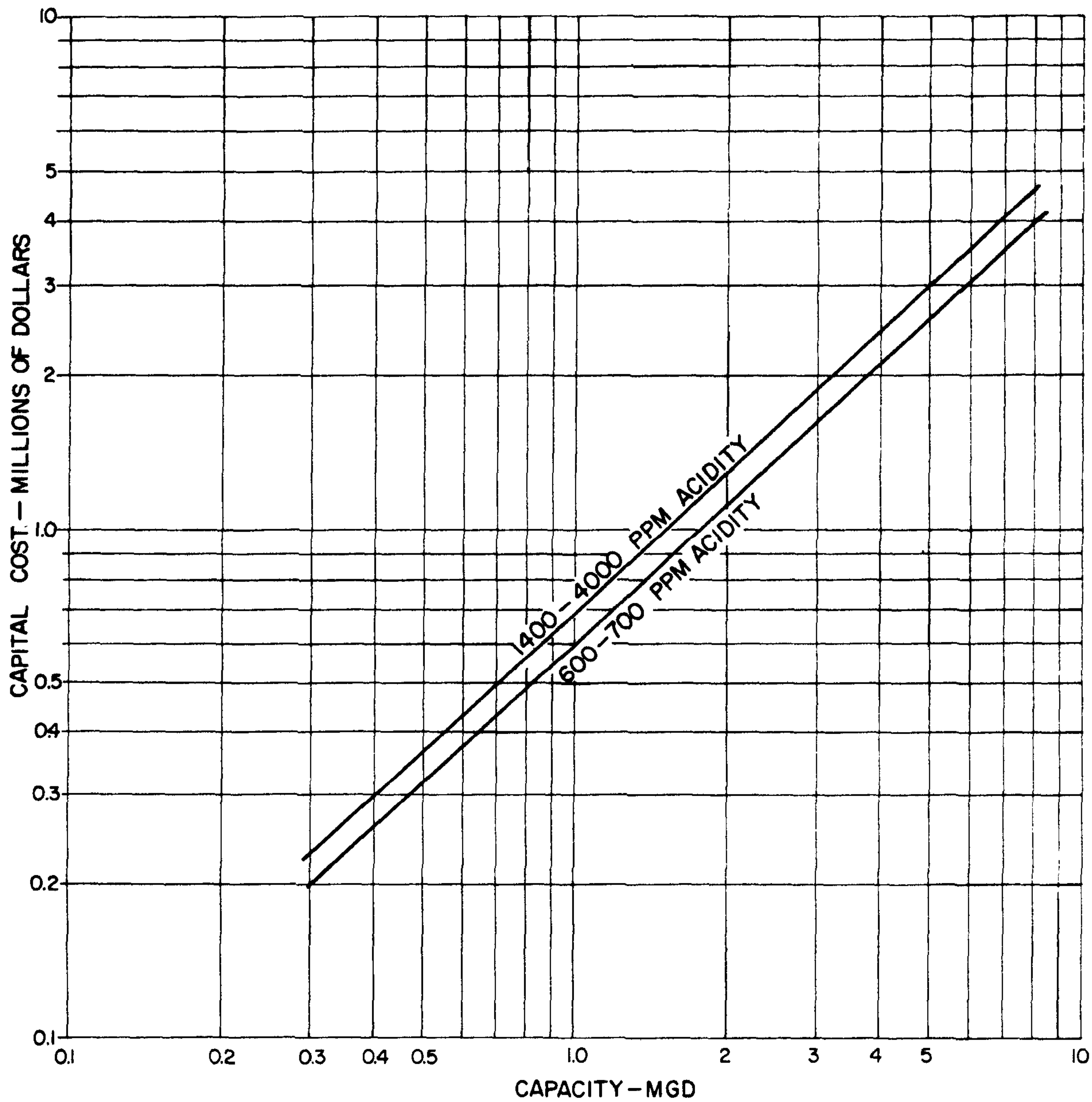
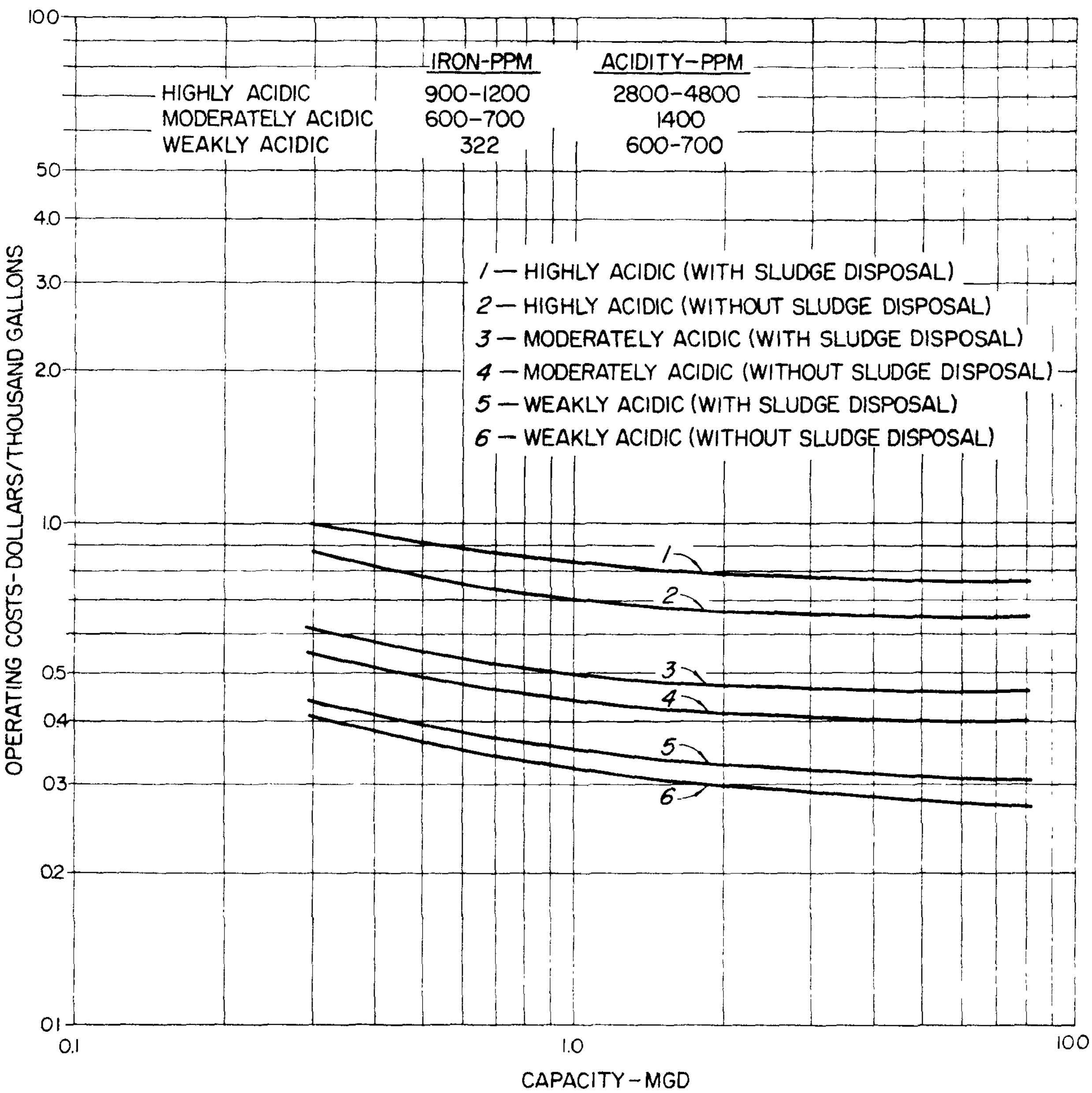


FIGURE 44

TOTAL OPERATING COST (Including Capital Costs)

HYDRATED LIME TREATMENT (REF. 3)



Cost of Lime Neutralization of Mine Drainage - Mine drainage is a complex waste which varies in quality, quantity and inherent characteristics from mine to mine and even within the same mine from place to place and with time. The cost of treating mine drainage, therefore, will vary with the quantity of drainage requiring treatment, the initial quality and the desired final quality, and other factors, such as, availability of land for the treatment plant and methods of sludge disposal.

More than two hundred mine drainage treatment plants are presently in operation in Pennsylvania alone and many of the plants are operated by captive coal companies. Because coal mining is a highly competitive industry, most companies have shown reluctance to supply information on their treatment costs for use in this study. Treatment costs are available for some plants built for the Commonwealth of Pennsylvania and a few cost figures are available in the literature on mine drainage treatment for plants operated by coal companies.

Since little actual cost data is available, a case history approach will be used in describing selected lime neutralization plants, their characteristics and costs, in order to get an idea of the present cost of mine drainage treatment by lime neutralization. The case histories are as follows:

1. Duquesne Light Company, Warwick Mine No. 2

In 1969, the Duquesne Light Company began operating a 3 MGD mine drainage treatment plant at the Warwick Mine No. 2, Greene County, Pennsylvania. Figure 45 is a flow sheet for this plant. According to Draper[42], mine drainage discharges from this Pittsburgh Seam mine were consolidated to the area of lowest seam elevation and all mining in this area was completed so that it could act as a natural sump.

Draper describes the plant operation as follows:

Three deep well turbine pumps with a capacity of about 4,400 gpm were installed from the surface through boreholes into the area. The raw mine water is discharged from the mine pumps into a flume, which conducts it to a four million gallon raw water equilization pond. To prevent leakage of raw water into the ground or into the nearby stream, this pond was lined with over three feet of a compacted special impervious clay trucked from some distance. The mine water is pumped from the equalization pond into the reaction and aeration tank where it is retained some 20 minutes.

Lime is delivered to the plant lime bin in pneumatic tank trucks of approximately 22 tons capacity. When the pH control probe signals for lime, the rotary and screw feeders under the bin start to feed lime into the lime slurry tank, the water pump starts to put water into the same tank and the lime slurry pump starts to pump milk of lime from the tank

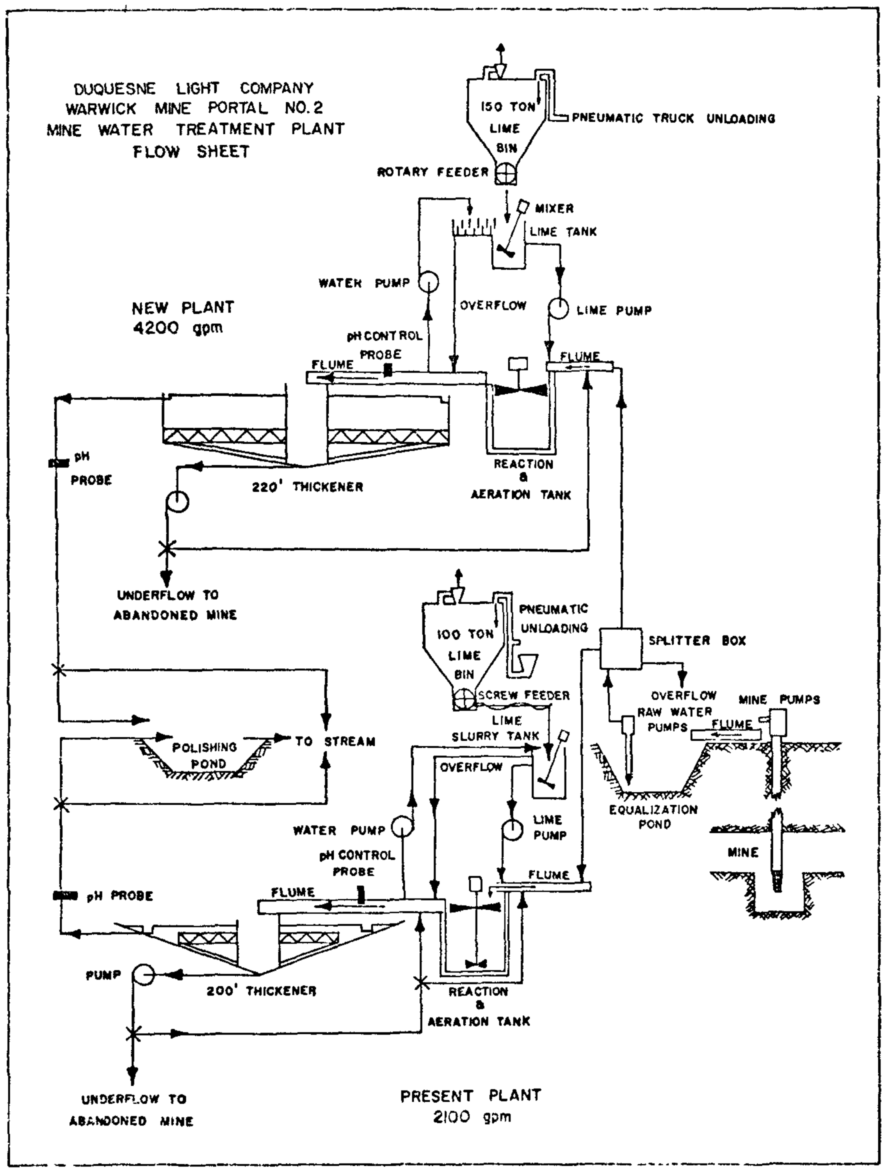


FIGURE 45

After Draper, 1972[42]

into the mine water as it enters the reaction and aeration tank. When the pH of the water rises to the preset level, the control shuts off both lime feeders and both pumps.

The limed and aerated mine water discharges into a flume, passes by the pH control probe and is discharged into the center well of the 200 foot diameter earthen wall thickener. The overflow from this thickener is collected in a trough near the periphery and conducted in a flume either directly to the stream or to a polishing pond, which will retain the water for some 12 hours before discharging it to the stream. The underflow of the thickener is pumped to a shaft or one of several boreholes for disposal in an abandoned mine in the Sewickley Seam. The discharge from this seam percolates to the Pittsburgh Seam, which is 100 feet below and from which the raw water is pumped.

The total cost of the plant in 1969 was $582,000 including the polishing pond which was installed in December, 1969. For the purpose of deriving cost, a life of 10 years was assumed. The annual operating costs are about 19¢ per thousand gallons. The mine drainage treated in 1971 had an average chemical analysis of: pH - 4.20, acidity - 1,557 mg/l, and total iron - 573 mg/l (Fe^{+2} - 424 mg/l).

The low cost of the plant operation can be attributed to: 1) sludge disposal in abandoned mines, 2) completely automated operation of the plant eliminating most of the labor costs and, 3) favorable topography and ground conditions permitting construction of earthen walled tanks and ponds thus eliminating costly construction of tanks of concrete or other structurally strong walls.

2. Slippery Rock Creek Mine Drainage Treatment Plant

Probably the most interesting studies made to date on the effect of acid mine drainage on an entire watershed, are those studies made for Slippery Rock Creek. In addition to construction of a mine drainage treatment plant, as a result of these studies, mine sealing and strip mine reclamation projects were completed. The latter projects are discussed in the appropriate sections of this report.

In 1963, the basin was chosen by the Pennsylvania Department of Health, Division of Sanitary Engineering (now Pennsylvania Department of Environmental Resources, Bureau of Water Quality Management) for its first intensive mine drainage study of a large watershed(43). One of the reasons for choosing Slippery Rock Creek was the complete change in water quality that occurred downstream within months after the closing of a limestone processing plant. Although the large number of mines in the watershed had an adverse effect on stream quality, particularly in the headwaters which were extensively mined, the highly alkaline discharge of waste water from the limestone plant effectively neutralized the stream's acid load, making it alkaline downstream of the limestone plant discharge. Figure 46 shows the effect that closing the limestone processing plant had on Slippery Rock Creek water quality.

In July, 1964, a high runoff occurring as a result of heavy rainfall caused a serious fish kill in Slippery Rock Creek. The acid condition of the stream during and immediately following the runoff was the direct cause of death of fish and other aquatic life. Approximately two million fish were killed over the entire length of the stream. It was concluded that the slugs of acid responsible for the fish kill were flushed out of swamps and impoundments in the extensively mined headwaters of North Branch Slippery Rock Creek and that acid mine discharges from other sources contributed to and prolonged the acid condition of the stream[43].

Drainage from Slippery Rock Creek normally has a high natural alkalinity because much of the watershed is underlain by 20 or more feet of Vanport Limestone, a high calcium limestone. This availability of $CaCO_3$ is responsible for the chemical character of the mine drainage which is weakly acidic in spite of the extensive mining which has occurred in parts of the watershed. The mine drainage has a pH of around 4, acidities of less than 100 mg/l, a low iron content, a manganese concentration equal to or greater than iron, and a relatively high solids content when compared to other water quality parameters. The mine drainage can be classified as Class II and some of the tributaries may have Class III mine drainage (Table 1).

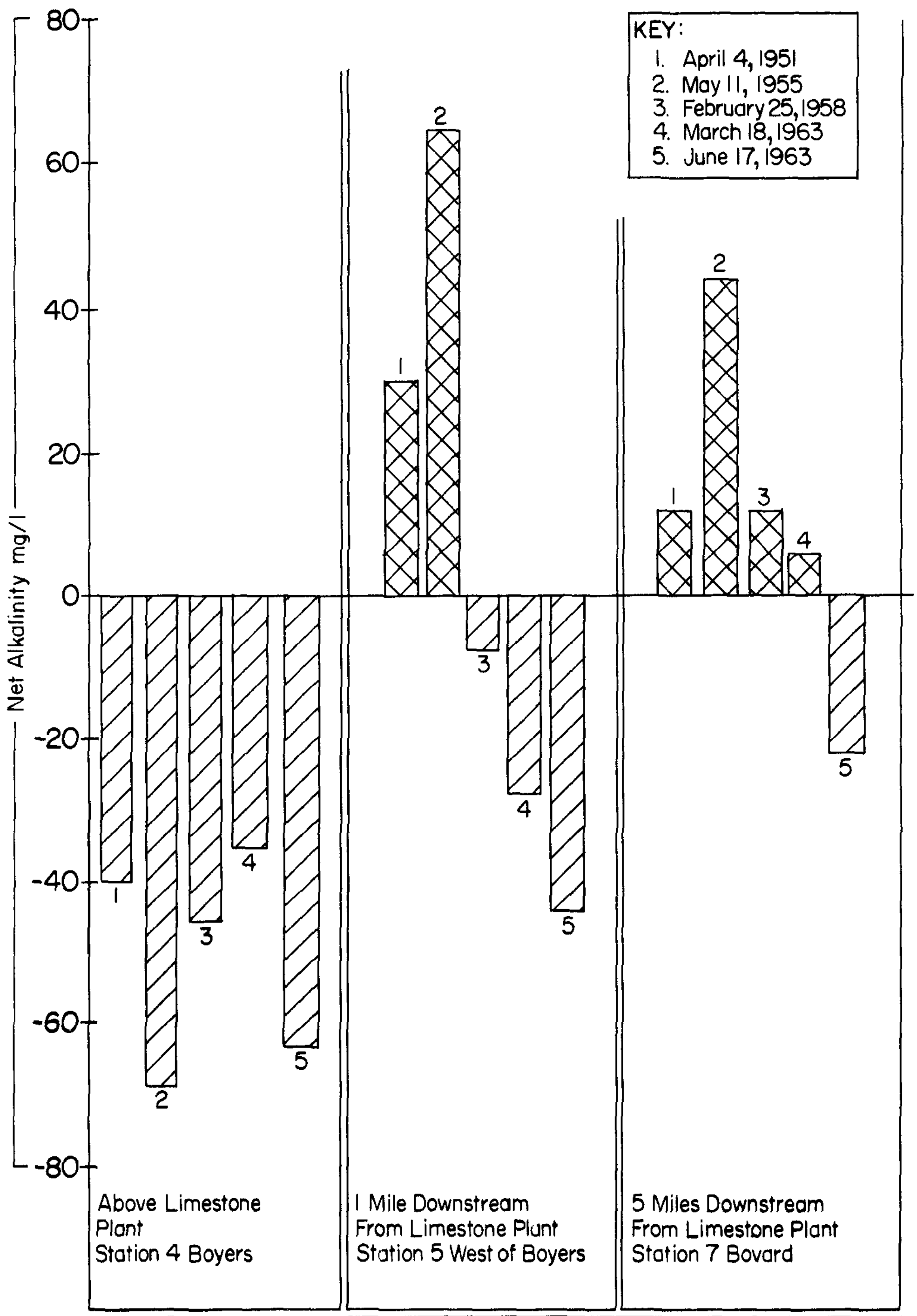
The mine drainage treatment plant is located near the headwaters of North Branch Slippery Rock Creek, which is in turn the headwaters for Slippery Rock Creek drainage area, a watershed of some 400 square miles. Tributaries which comprise less than 25 percent of the total watershed are responsible for mine drainage pollution in the main stream, and the bulk of this acid load is from the headwaters. More than 83 percent of the acid mine drainage originates in abandoned mine workings.

The treatment plant is designed not only to improve the water quality of the headwaters of North Branch Slippery Rock Creek, but also to minimize the effect of acidity contributed by acid tributaries at some distance downstream. Table 34 showing treatment plant operating data for 1971 has a tabulation of pH ranges in the stream below the treatment plant.

To accomplish the objective of making North Branch Slippery Rock Creek a clean stream, it was necessary to neutralize all the acid mine drainage and in addition, to remove all the insoluble by-products of that neutralization. According to Lisanti, et al.[44], the treatment of a major portion of a stream watershed of three square miles and the removal of settleable solids was not done before this undertaking.

FIGURE 46

EFFECT OF THE CLOSING OF THE MICHIGAN LIMESTONE CO. PLANT AT BOYERS IN DECEMBER 1957 ON WATER QUALITY IN SLIPPERY ROCK CREEK



After Pennsylvania Department of Health, Division of Sanitary Engineering, 1965[43]

TABLE 34

TREATMENT PLANT OPERATING DATA - 1971
SLIPPERY ROCK CREEK NORTH BRANCH

Month	Flow (gpm)	Influent pH Range	Effluent pH Range	Stream Below Plant pH Range	Influent Iron (mg/l)	Effluent Iron (mg/l)	Influent Acidity To pH 8.3 as measured with phenolphthalein endpoint (mg/l $CaCO_3$)	Effluent Alkalinity To pH 8.3 as measured with phenolphthalein endpoint (mg/l $CaCO_3$)
Jan.	3322	4.1-4.4	8.0-9.2	7.2-7.9	2.6	0.0	51.3	17.1
Feb.	4350	4.1-4.5	7.3-9.8	7.1-7.6	2.7	0.0	34.2	17.1
March	6050	4.3-4.6	7.5-9.8	7.0-9.0	2.4	0.0	34.2	17.1
April	2170	4.3-4.6	7.2-8.3	7.0-7.4	2.2	0.0	40.0	17.1
May	2612	4.2-4.4	7.3-8.4	6.9-7.5	2.0	0.0	34.2	13.7
June	2060	4.0-4.1	7.1-9.5	7.0-7.2	2.0	0.0	34.2	17.1
July	500	3.9-4.1	7.5-9.0	7.2-7.4	1.5	0.0	40.0	13.7
Aug.	340	3.8-4.0	7.0-7.6	6.7-7.3	1.8	0.0	40.0	13.7
Sept.	660	3.9-4.2	7.2-9.1	7.1-7.8	1.6	0.0	45.5	17.1
Oct.	352	3.9-4.1	7.2-8.0	7.2-7.6	1.2	0.0	41.0	17.1
Nov.	3842	3.8-4.1	7.1-9.0	6.9-7.5	2.0	0.0	59.9	13.7
Dec.	3989	3.9-4.6	7.0-10.5	6.8-10.0	2.3	0.0	90.6	17.1
Avg.	2520						47.7	16.3

Monthly averages based on 3 grab samples per day

From Lisanti, et al., 1972[44]

The flows, acidity, iron and manganese concentrations in the stream may vary considerably with intensity of rainfall, therefore, average figures in design have little meaning. The peak flow of the stream is in the order of 1,550 MGD. The treatment plant objective is satisfied if 6,000 lb./day of acidity is neutralized and as much as 50,000 lb./day of solids is removed from the neutralized water. The peak design flow rate was set at 10 MGD and a median flow rate of 3 MGD was the basis of design for the treatment plant. An average lime use of 1,900 lbs./day was estimated.

A flow diagram of the plant is shown in Figure 47 and the principal unit processes are as follows:

a) Flow Diversion - A concrete dam to divert the peak design flow to the plant. The dam, spillway and downstream channel are designed to take peak stream flow, i.e., 3,450 cfs.

b) Equalization - A 2 million gallon impoundment lagoon serves to lessen shock loads to the plant.

c) Neutralization - The stream flows by gravity to a well agitated tank where lime slurry is automatically added under pH control. A back-up pH and lime feed system is provided at the clarifiers center wall for emergency use. Dry hydrated lime delivered in tank trucks is made into a 30 to 35 percent by weight slurry by pneumatically unloading and mixing it with water in a storage tank provided with a turbine mixer. The specific gravity of the slurry is controlled in a dilution tank and fed to the treatment tank by means of proportioning weirs.

d) Wastewater Pumping - The head loss through the plant made it necessary to lift stream water. This is accomplished with screw pumps because they are essentially surge-free, will handle highly variant flow rates, have non-clogging characteristics, and have an efficiency of about 85 percent which remains relatively constant regardless of variations in volume. The pumps are located between the flash mix neutralization tank and the clarifier.

e) Clarification - A 75 ft. diameter, solids-contact type clarifier is used which is capable of handling the varying loading and settling rates. A 200,000 gallon lagoon is provided for emergency use.

f) Solids Handling - A 30 ft. diameter thickener is provided to reduce the water content of the clarifier sludge and to temporarily store the sludge. The thickened sludge is pumped to one of two sludge lagoons, each 150,000 gallons, for further dewatering and storage.

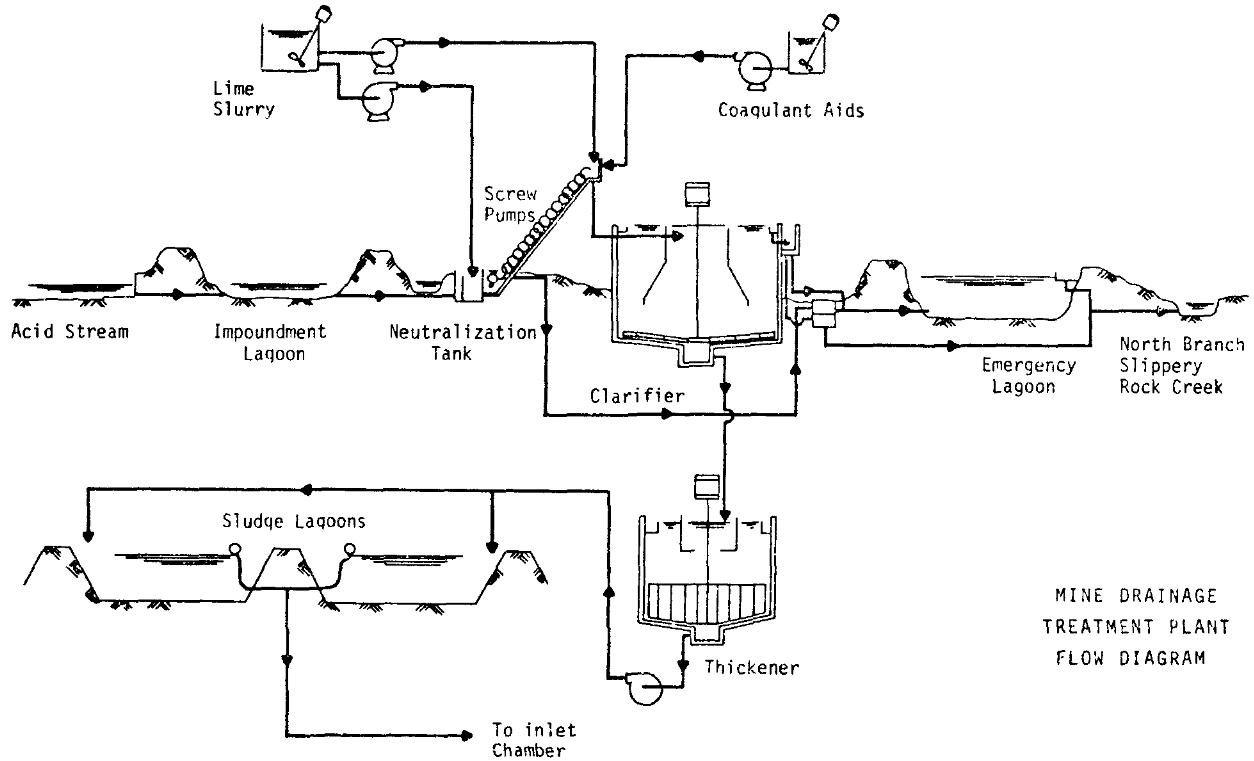


FIGURE 47

Flow Diagram - Slippery Rock Creek Mine Drainage Treatment Plant

After Lisanti, et al., 1972(43)

g) Miscellaneous - Also included in the plant are: a polymeric flocculant feeding system; filtration of treatment plant effluent for potable water use; process water system which uses the plant effluent without further treatment; compressed air system; and a sanitary sewage treatment system.

The plant is manned by two operators during the day shift, usually one during the second shift, and is unattended during the night shift, operating, therefore, completely automatically.

Construction of the plant was completed in December, 1969 and the total cost was $750,000. Engineering costs were $53,000. The annual operating cost is about $51,000 (chemicals - $5,000, electricity - $7,000, wages - $34,000, telephone and alarm services - $1,500, and the balance for miscellaneous items.

3. Mountaineer Coal Company Mine Drainage Treatment Plant

Kosowski and Henderson(45) reported some of the design features and capital expenditures for a mine drainage treatment plant at the Mountaineer Coal Company operation in Harrison County, West Virginia. The mine drainage is an alkaline type discharge containing substantial amounts of dissolved iron. A typical analysis of the influent is: pH - 6.5, alkalinity - 252 mg/l and iron - 109 mg/l.

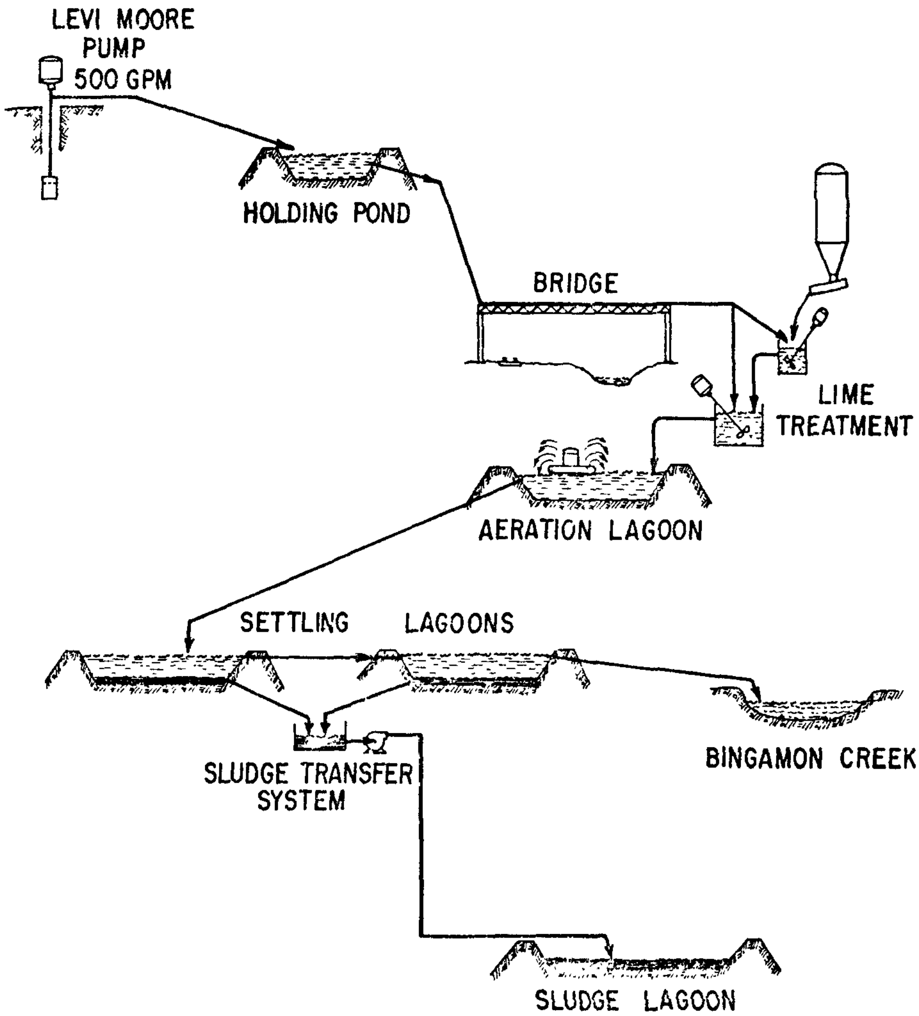
The treatment plant is designed to treat 0.72 MGD of mine drainage on a 24 hour basis. A schematic flow sheet is presented in Figure 48. The steep mountainous terrain in the immediate vicinity of the discharge together with other natural and man made obstacles, limited the available land for a treatment plant to a single tract of land approximately 100 feet below and 2,000 feet away from the discharge.

The design features of the treatment plant are as follows:

a) The mine drainage flows from the Levi Moore borehole discharge in an open ditch to a 300,000 gallon earthen holding pond. The Georgia V-type ditch is approximately 1,450 feet long, 16 feet wide and has a fall of 1/2 percent. The ditch also serves as an access road to the discharge pump.

b) From the holding pond, the mine drainage flows by gravity through a 10 inch pipe, down the side of the mountain, across a railroad track, and across a creek, a total length of 520 feet to the treatment building.

c) At the treatment building the mine drainage is mixed with a lime slurry prepared from bulk hydrated lime. The lime system is a standard unit consisting of a pneumatic bulk lime storage bin of 30 ton capacity, a bin shaker, screw feeder, lime slurry tank with mixer and a flash mix tank with mixer.



MOUNTAINEER COAL CO. - WILLIAMS MINE
LEVI MOORE DISCHARGE

FIGURE 48

From Kosowski and Henderson, 1968[45]

d) The treated drainage then flows into an earthen aeration lagoon of about 100,000 gallon capacity. Aeration is accomplished by spraying the water into the air using a floating surface aerator.

e) The water then flows into two earthen settling lagoons arranged in series where the insoluble iron compounds drop to the bottom of the lagoon while the clear treated water overflows into the creek. The settling lagoons have a combined capacity of almost 3 million gallons.

f) Flocculating chambers of reinforced concrete construction were built into the inlet of each of the settling lagoons. The mechanical flocculator is a standard unit, equipped with one five-blade flocculating turbine with stabilizing ring and powered with a 1.5 HP motor with variable speed drive. Only one flocculator is used since it is physically moved from one settling lagoon to the other. According to Kosowski and Henderson[45], this is a unique feature of the treatment plant design and probably the first of its kind in the mine drainage field. The flocculating units are expected to reduce significantly the retention time, therefore, huge lagoons are not needed to provide retention time for precipitation of iron compounds as under normal circumstances.

g) A concrete sludge sump, with sludge pumps and piping was installed between the two settling lagoons to permit draining the contents and pumping the sludge into a sludge lagoon.

h) Transfer of treated water from the treatment building to the aeration lagoon, through the two settling lagoons and into the creek is by open flared concrete flumes.

Another unique feature of this treatment plant is the installation of a complete bulk lime system, even though the water is not acidic. The lime system is used to obtain basic information on a large-scale treatment plant under a variety of actual operating conditions and seasonal fluctuations.

The treatment facilities are capable of discharging treated mine drainage containing no more than 10 mg/l of iron, 30 mg/l of aluminum, 200 mg/l of suspended solids and having a pH of 5.5 to 8.5.

The estimated capital expenditures at the Levi Moore treatment facilities are $120,000. A breakdown of these expenditures are:

a) Excavation and Grading	$23,000
b) Mechanical Equipment including Electrical	13,000
c) Concrete, Piling, Erection of Steel and Bridge	59,000
d) Piping	6,000
e) Sludge Pump and Piping	15,000
f) Contingencies	4,000
Total	$120,000

4. Little Scrubgrass Creek Lime Treatment Plant

Based on the results obtained from research using the lime neutralization technique with the "Operation Yellowboy" trailer, the Pennsylvania Department of Mines and Mineral Industries (now part of the Pennsylvania Department of Environmental Resources) decided that from a technical and economic viewpoint, it would be most effective if neutralization of "low iron" streams was accomplished using a fully automated neutralization process (46, 47).

A prototype treatment plant was designed and installed on Little Scrubgrass Creek, Venango County, Pennsylvania. The plant did not include any facility for liquid solid separation and this type of installation may only be used in those cases where iron, aluminum, manganese and other precipitable salts are present in low or insignificant quantities. There does not appear to be a limit to the acid content of the mine water which can be treated by the plant. It may be possible to operate a plant of this type at sites where the stream velocity is such that any precipitates which might form would be carried away and dispersed and would not create any appreciable sedimentation or siltation problems.

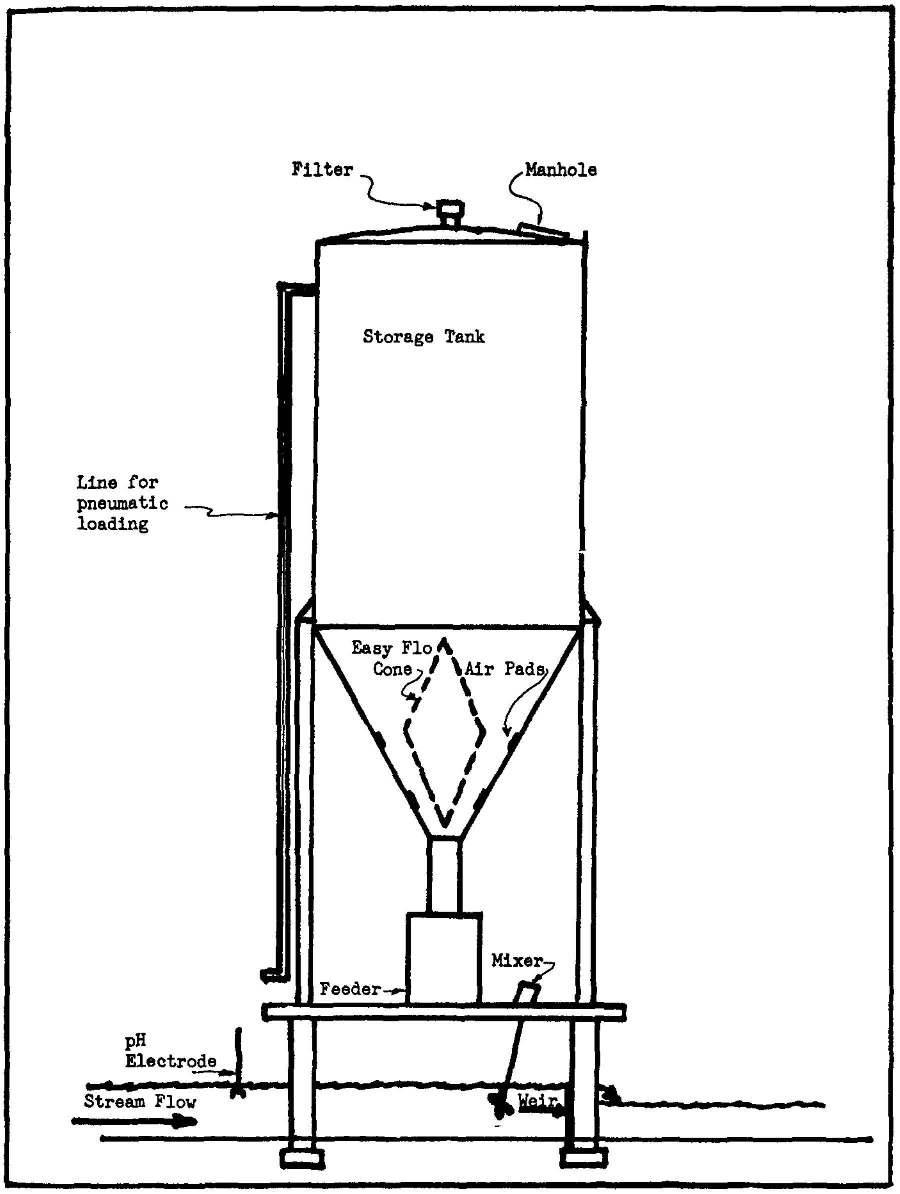
The treatment plant operated 24 hours per day, 365 days per year and treated the entire flow of Little Scrubgrass Creek. A schematic diagram of the plant is shown on Figure 49. A float mechanism suspended from the treatment plant into the creek rises and falls with the flow of the water beneath the plant. The stream flow is highly variable, but the quality of the water remains nearly constant, therefore, the float mechanism needs only to feed a quantity of lime directly proportional to the quantity of water flow beneath the plant.

Similar plants were later constructed on other streams in Pennsylvania. The capital costs have ranged from $40,000 to $54,000 depending on site conditions and the specific requirements of the mine drainage.

The Little Scrubgrass Creek mine drainage has an iron content of approximately 1 mg/l and an average acidity of 68 mg/l. Neutralization is the only treatment required of this stream. Aeration and dewatering were not warranted. Costs for treating 1,000 gallons of this specific water by lime neutralization varied between $0.0068 (high flow) and $0.0573 (low flow). Table 35 gives the monthly operating expenses for high and low flows.

FIGURE 49

SCHEMATIC DIAGRAM
LITTLE SCRUBGRASS TREATMENT PLANT
VENANGO COUNTY, PENNSYLVANIA



From Charmbury, et al., 1968[46]

TABLE 35

LITTLE SCRUBGRASS CREEK LIME TREATMENT PLANT
Monthly Operating Expenses

	Low Flow*	High Flow**
Lime (Tons @ $15.65/Ton)	$116.46	$557.50
Electricity	12.35	18.00
Man Hours	160.00	160.00
Repairs	5.50	5.50
Total	$300.31	$741.00

*Summer-Fall Low Flow

**Winter-Spring High Flow

5. Rausch Creek Mine Drainage Treatment Plant

A report submitted by the Anthracite Research and Development Company[49] to the Pennsylvania Department of Environmental Resoruces indicated there are 28 active mining operations on the east and west branches of Rausch Creek together with six abandoned workings on the west branch and an overflow from a mine pool on the east branch contributing to mine drainage pollution of the stream.

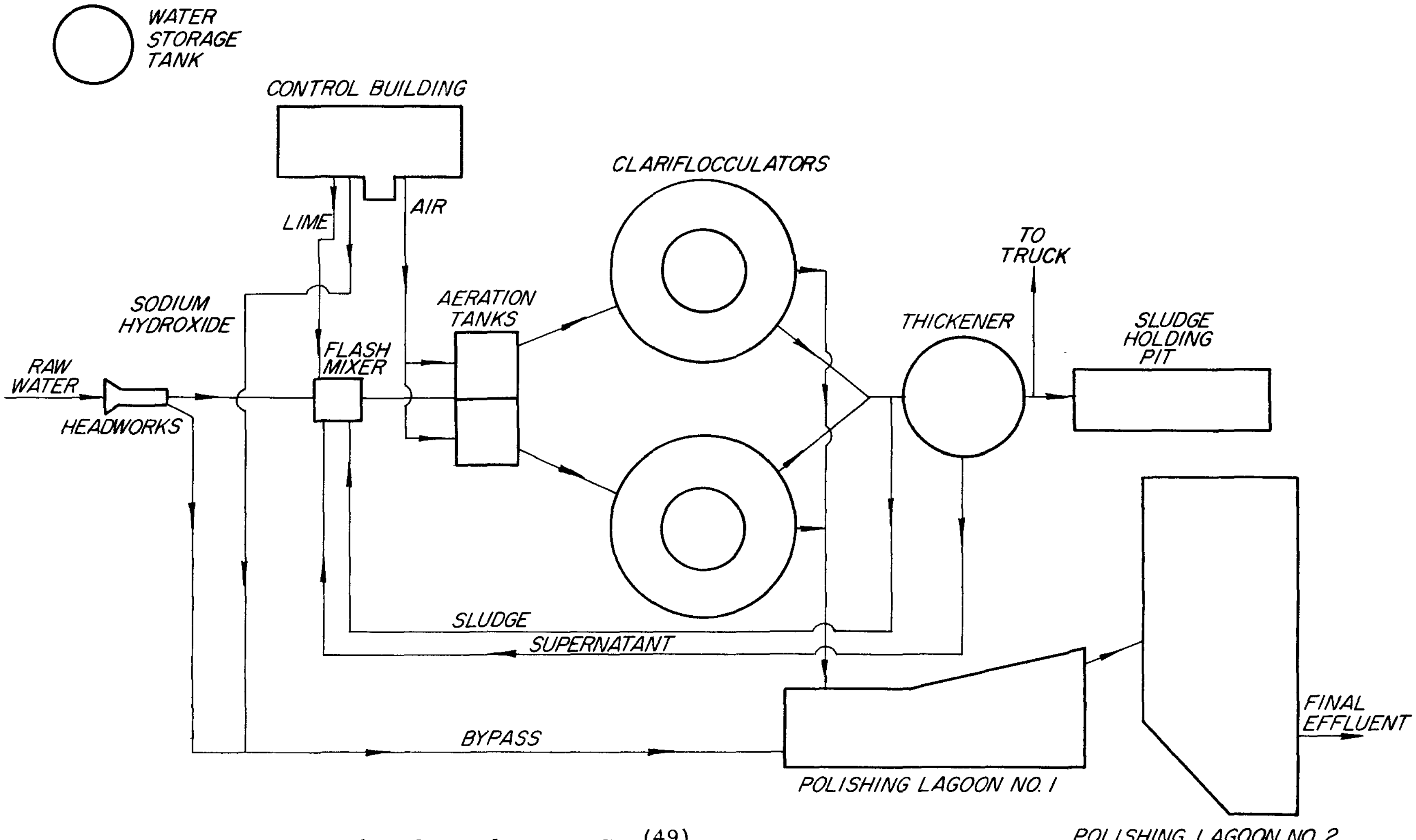
A treatment plant was designed to treat the entire flow of Rausch Creek located in Schuylkill County, Pennsylvania and construction is nearing completion. Figure 50 is a flow sheet of the treatment plant. Operators of active mines contributing mine drainage to Rausch Creek are required to pay a fee for operating expenses of the treatment plant.

The plant is designed for a flow of 10 MGD with a hydraulic capacity of 20 MGD and is provided with flash mixing, aeration, flocculation and clarification, and thickening and polishing lagoons. Flows larger than 20 MGD are automatically bypassed to Polishing Lagoon No. 1. In the event of such large flows, facilities have been provided for addition of sodium hydroxide to the polishing lagoon. Also the large holding capacity of the lagoons should be able to absorb excess flows without any appreciable change in alkalinity of the effluent. Provision has been made for trucking the sludge for final disposal. The total construction cost of the project is $1,747,380 and engineering design costs amount to an additional $314,700. Since the plant has not gone into operation yet, no operating costs are available[50].

6. Altoona Mine Drainage Treatment Plant

The treatment plant was designed by Gwin, Dobson & Foreman, Inc., to eliminate acid mine drainage contamination of the area west of Altoona, Pennsylvania and to improve the supply of potable water to the Altoona Water System[51].

The major sources of potable water for the City of Altoona are located in drainage areas west of the city. One stream, Kittanning Run is bypassed because it is highly contaminated with acid mine drainage. Glen White Run is contaminated to a lesser extent and is used for water supply. Sugar Run was formerly used as a supply of potable water, but it is now highly contaminated by acid mine drainage. Two other drainage areas, Mill Run and Homer's Gap, are not affected by mine drainage. A general summary of water quality parameters of the streams is as follows:



After Anthracite Research and Development Co.(49)

FIGURE 50

FLOW DIAGRAM OF RAUSCH CREEK TREATMENT PLANT

	pH	Acidity mg/l	Iron mg/l	Manganese mg/l
Glen White Run	3.8	60	5.5	3.3
Kittanning Run	2.9	420	70.0	11.0
Sugar Run	3.5	140	12.0	2.0
Mill Run	7.1	0	0.2	0.0

On the basis of laboratory and field investigations, it was decided that these flows could be neutralized with a combination of lime treatment, mixing, aeration and sedimentation. Additional studies were carried out to determine the most feasible means of further treatment to render the water potable for use in the Altoona Water System. The studies indicated that a lime-soda process be used as it provided more flexibility and is more adaptable to changing conditions which might occur. The combined water treatment plant is under construction and has separate facilities for neutralization and for softening and filtering a water supply. Neutralization facilities are designed for a capacity of 15 MGD and the softening and filtration portion is designed for a capacity of 7 MGD. A schematic flow diagram is shown in Figure 51. Sludge will be disposed of in abandoned deep mines.

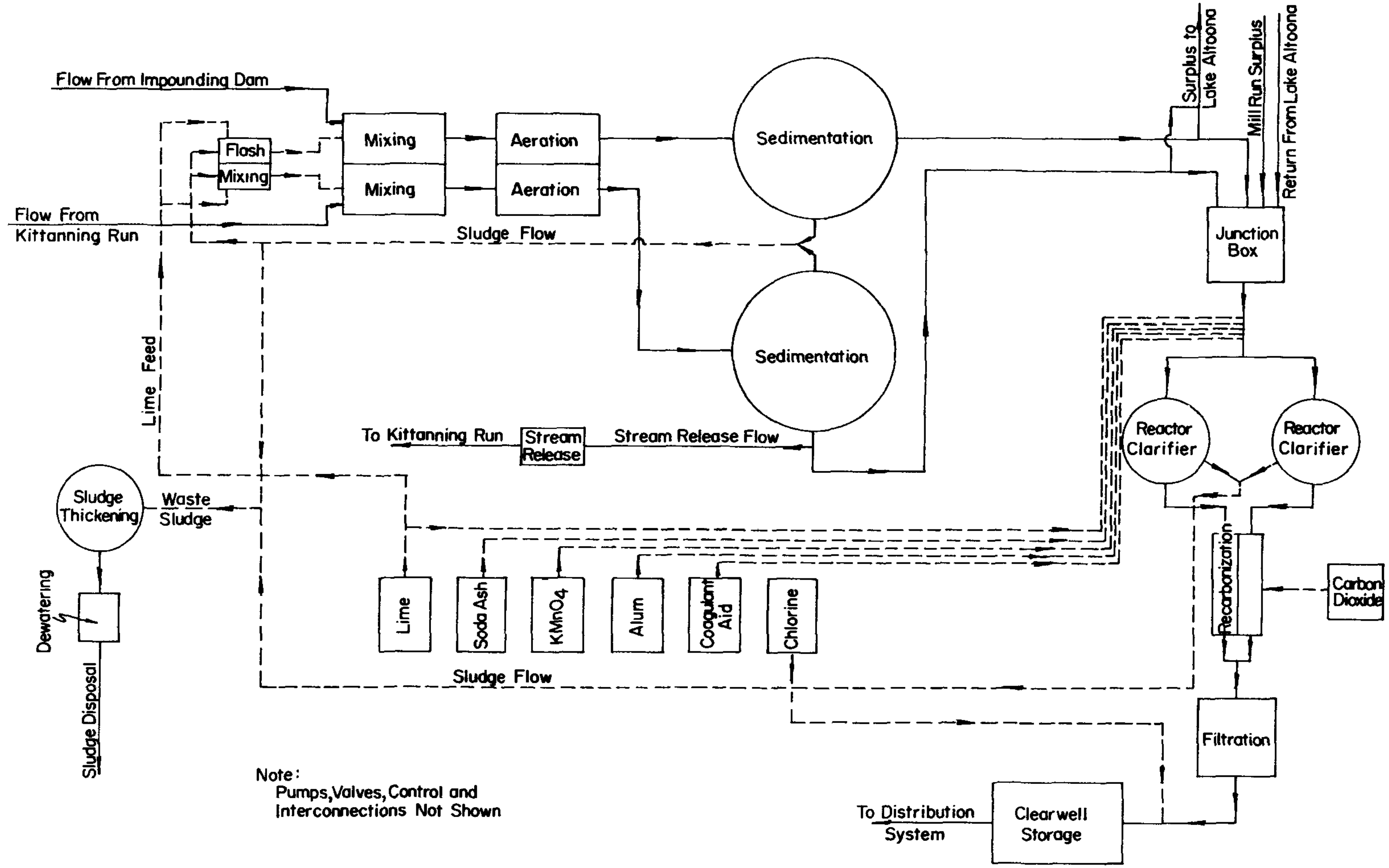
The total construction cost of the project as contracted will be about $4,590,000. Engineering design and supervision costs are about $172,000. The operating costs for the treatment plant, excluding capital ammortization, are expected to be about $156,000[50].

7. Shirley Machine Company "Mixmeter"

A package slurry making and discharging plant is available in several models with the trade name "Mixmeter" from the Shirley Machine Company, a Division of Tasa Corporation, Pittsburgh, Pennsylvania[52]. The plant comes complete with pH recordings and controlling instruments. A typical installation arrangement of one of the models is shown in Figure 52.

The Mixmeter provides continuous variable feed under automatic control and is capable of feeding 500 to 3,000 lbs./hr. of hydrated lime in slurry form with 20 percent solids. Plants with higher feed capabilities have been designed and are available on order. The Mixmeter system monitors the result of treatment downstream of the treatment plant, relays a signal to the Mixmeter which responds to maintain the desired pH of the effluent. In this concept the pH (a specific and constant pH) of the treated effluent is the object of the treatment process. It automatically compensates for volume and quality of the influent and the quality of neutralizing agent being used.

Coal operators and other industrial sites in Pennsylvania, West Virginia and Ohio with acid pollution problems have a number of these plants in operation.



FLOW SCHEMATIC
ALTOONA MINE DRAINAGE TREATMENT PLANT
ALTOONA PENNSYLVANIA

FIGURE 51

OPERATION SCARLIFT PROJECT SL-116
GWIN, DOBSON & FOREMAN, INC.

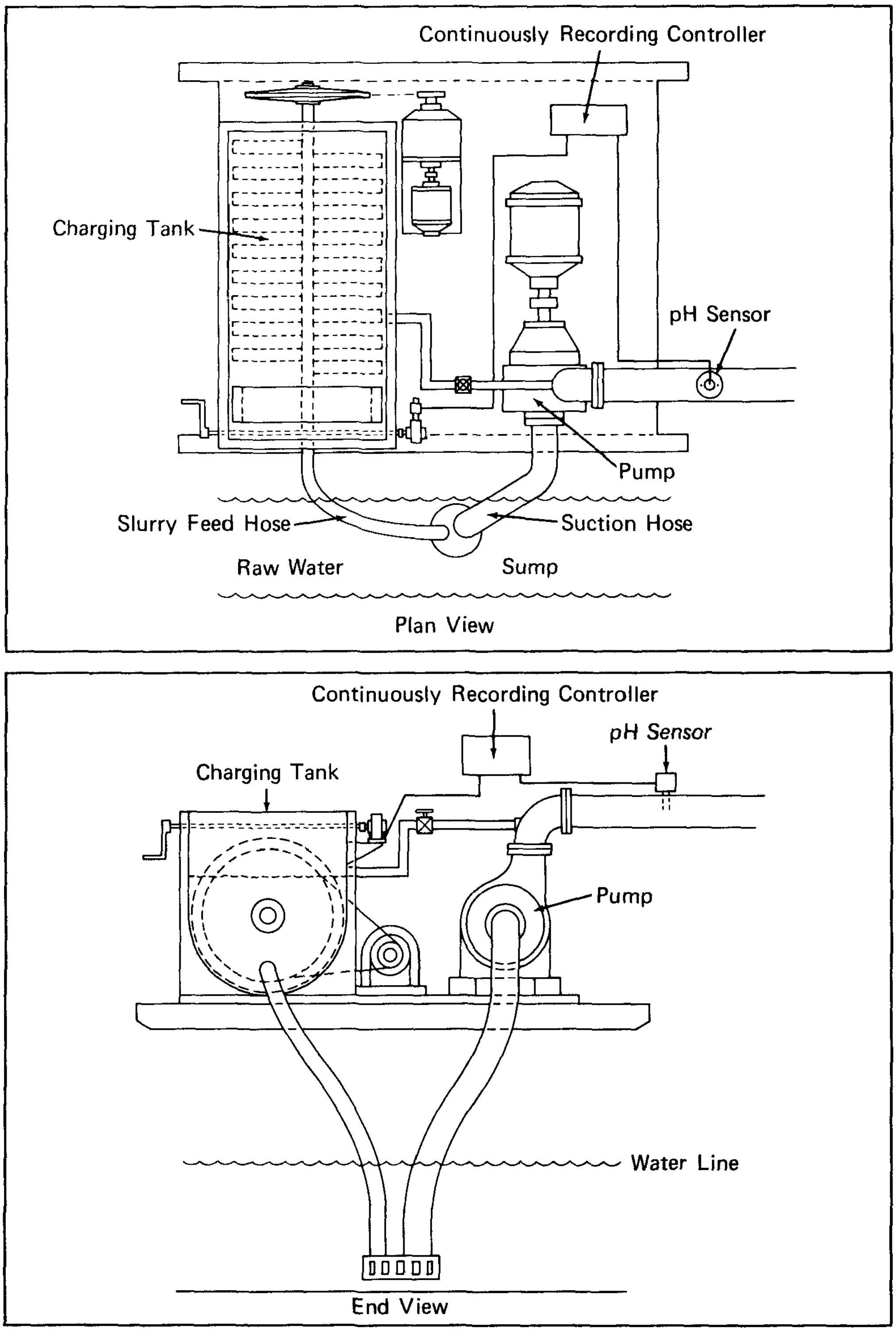


FIGURE 52
MIXMETER MODEL 65AE - TYPICAL INSTALLATION ARRANGEMENT

From Shirley Machine Company, Information Manual, 1972[52]

FLASH DISTILLATION PROCESS

Flash distillation is a vaporization and condensation process. The feed in liquid state is heated to the vaporization point in an enclosed chamber and subsequently flashed, in a series of chambers or columns, operated at successively low pressures and temperatures (Figure 53). The basic process has been utilized for years by the chemical industry for the processing of petroleum, organic chemicals, and inorganic chemicals. The principal items of equipment include evaporators, deaerators, air ejectors, heat exchangers, pumps, air compressors and stream generating systems.

Within the last five years, the process has been investigated, evaluated and used for processing saline and brackish waters for production of potable water for domestic use. Recently the process has been investigated as a method for the treatment of acid mine waters and at the same time for the production of high quality potable water.

The basic idea of a concentrating evaporator is to reduce the volume of contaminant ions by removing the H_2O as vapor and leaving all the contaminants behind. Drastic reduction in volume of material to be disposed of is the chief benefit of this method, with the production of ultrapure water being a close second.

Westinghouse Electric Corporation under a contract with the Coal Research Board, Commonwealth of Pennsylvania, evaluated the flash distillation process for treating of acid mine water[53, 54, 55, 56]. Preliminary tests were made with a small scale pilot plant to determine the optimum operating conditions and to assess the engineering and economics of the process as applied to acid mine water. The data obtained from these tests were used to design a 5 MGD treatment plant. Capital investment and operating costs were estimated for the plant based on the data from the pilot plant operation (Tables 36, 37, and 38).

The operating costs in Tables 37 and 38 do not include capital cost amortization and cost of sludge disposal. The demineralization plant was scheduled to be completed about January, 1973. Since the new U.G.I. steam plant was not scheduled to be completed until at least June, 1975, it would have been necessary to operate the flash distillation plant for at least two years on temporary oil-fired boilers.

The disposal of solid wastes from the Westinghouse Plant posed many problems. Each day of full operation would yield about 150 tons of residue which would be extremely caustic. Plans called for the disposal of this material in a plastic-lined pit at the plant site but because of the chemical composition of the plant residue, the Pennsylvania Department of Environmental Resources felt contamination of the groundwater could occur if the plastic lining failed.

Because of projected excessive operating costs and questions about environmental impact, plans to construct a plant have been abandoned.

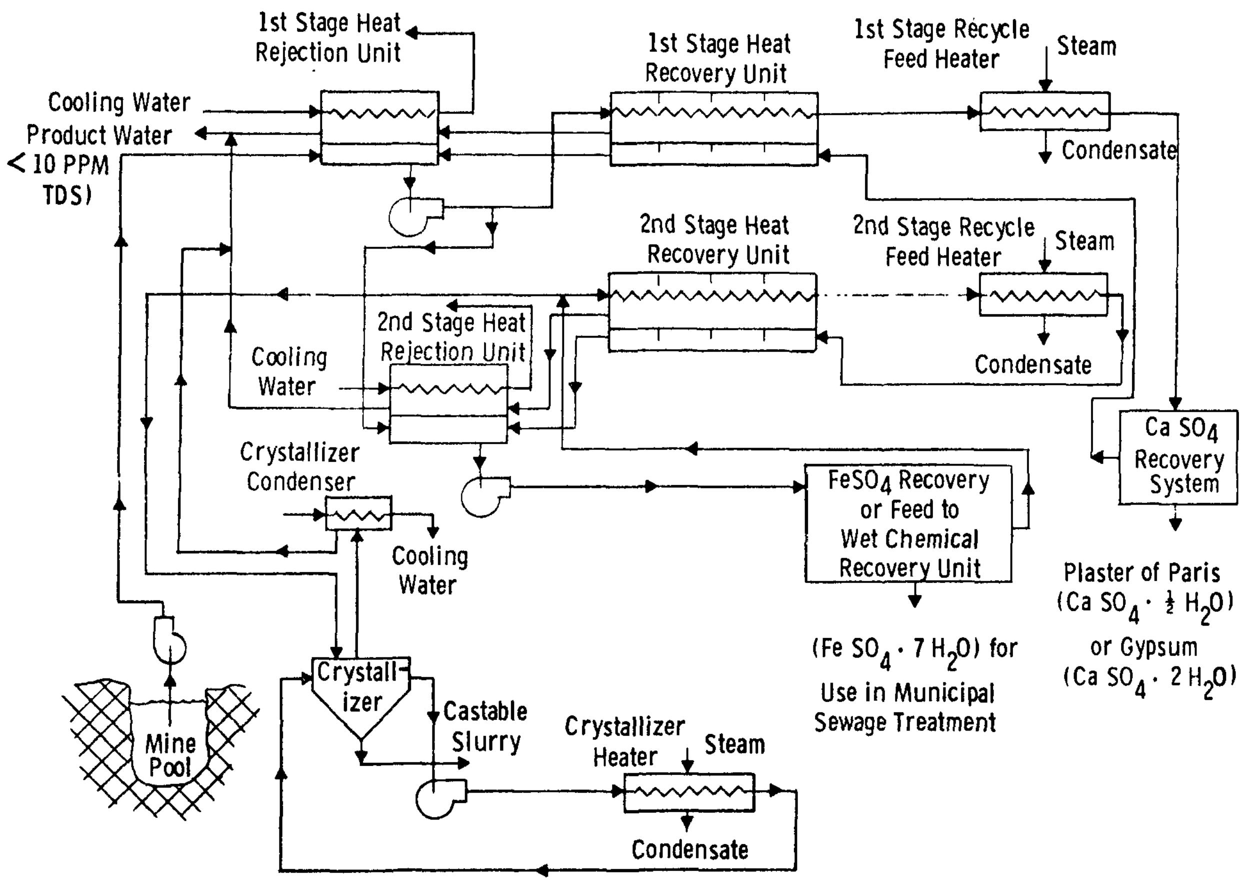


FIGURE 53

LOW TEMPERATURE MSF EVAPORATOR PROCESS FOR TREATMENT OF AMD
(SELECTIVE RECOVERY OF DISSOLVED MINERALS)

From Westinghouse Electric Corp., 1969[53]

TABLE 36

MULTIPLE STAGE FLASH DISTILLATION
ACID MINE DRAINAGE TREATMENT PLANT

Cost Estimate
(1971)

1. Principal Items of Equipment	
Evap. & Brine Heater	$ 6,024,000.00
Air Ejector	10,000.00
Pumps and Drivers	425,124.00
Misc. Tanks	50,000.00
Crystalizer	---
Evap. Field Erection	567,000.00
2. Process Facilities	
Site Development	567,000.00
Piping	655,200.00
Electrical	459,527.00
Instruments	195,300.00
Insulation	126,000.00
Painting	50,400.00
Building	264,600.00
Equipment Erection	347,760.00
3. Other Plant Costs	
Engineering (Purchases)	577,041.00
Interest During Construction	
Start-Up Expenses	214,200.00
Engineering W	446,000.00
4. Other Facilities	
AMD Pumping System	597,996.00
Cooling Tower	432,180.00
Temporary Boiler (s)	1,007,760.00
Prod. Water Post-Treat	63,000.00
Sludge Disposal	6,300.00
Plant Cost Total	13,086,388.00
5. Operation and Maintenance	447,000.00
6. Plant + Operational Cost	13,533,388.00
7. Contingency on Prototype Plant	666,612.00
8. Grand Total Plant + Operation for 1st Year	$14,200,000.00

After Westinghouse Electric Corp., 1971[55]

TABLE 37

SUMMARY OF OPERATING COSTS

Plant Capacity = 1,750,000 KGAL/year

	1971 Engineering Cost Estimate Yearly	Cost/1000 Gal.
<u>Direct Operating Costs</u>		
1. Steam Cost	$ 505,050.00	28.9¢
2. Electric Cost	344,064.00	19.7¢
3. Maintenance	69,600.00	4.0¢
4. Oper. Labor/Supv.	93,600.00	5.4¢
Subtotal	$1,012,314.00	58.0¢
<u>Indirect Operating Costs</u>		
1. General and Administrative Payroll	$ 28,080.00	1.6¢
2. Payroll Extras for Op. Labor	12,500.00	.7¢
Subtotal	$ 40,580.00	2.3¢
Total	$1,052,894.00	60.3¢

"Interim Cost of Water" is presented in Table 38. This cost can be anticipated until operation with the U.G.I. plant commences.

After Westinghouse Electric Corp., 1971[55]

TABLE 38

INTERIM OPERATING COSTS

	1971 Interim Cost Estimate Yearly	Cents/1000 Gal.
Direct Operating Costs		
1. Steam Cost	$3,968,800.00	226.7¢
2. Electric Cost	602,760.00	34.4¢
3. Maintenance	75,000.00	4.3¢
4. Operating Labor and Supervision	126,880.00	7.2¢
Subtotal	$4,773,440.00	272.6¢
Indirect Operating Costs		
1. General and Administrative Costs	$ 125,000.00	7.1¢
2. Payroll Extra for Operating Labor	17,472.00	1.0¢
Subtotal	$ 142,472.00	8.1¢
Total	$4,915,912.00	280.7¢ =
		$2.81

After Westinghouse Electric Corp., 1971[55]

ION EXCHANGE PROCESSES

The basic process for the treatment of acid mine water by ion exchange (deionization) consists of the reaction of metal salts and hydroxides in water with specific anionic and cationic resins.

Various forms of ion exchange processes can be used to remove undesirable constituents from mine drainage. Either alone or in combination with neutralization, softening, and aeration, ion exchange can produce water of high quality suitable for either domestic or industrial use. There is an indication that the sludges and other residues produced by this process may be more amenable to disposal than those produced by neutralization.

Burns and Roe, Inc., in a proposal to the Pennsylvania Department of Environmental Resources(57), describe the two fundamental reactions involved in the ion exchange process. They can be expressed by the following equilibrium equations:

$$C_1 + R_1^-C_2^+ = C_2^+ + R_1^-C_1^+$$

$$A_1^- + R_2^+A_2^- = A_2^- + R_2^+A_1^-$$

Where C_1^+, C_2^+ are cations of different species

A_1^-, A_2^- are anions of different species

R_1^-, R_2^+ are cationic and anionic exchange materials.

The normal sequence in the treatment of industrial waters by the ion exchange process is to pass the flow first through a cation exchanger and then through an anion exchanger. If softening is the desired objective, the following reaction applies:

$$\left.\begin{matrix} Ca^{++} \\ Mg^{++} \end{matrix}\right\} + Na_2R_1 \longrightarrow \left.\begin{matrix} Ca^{++} \\ Mg^{++} \end{matrix}\right\} R + 2\ Na$$

After the resin is exhausted; i.e., all of the exchange sites have been used, it is regenerated with concentrated salt solution as follows:

$$\left.\begin{matrix} Ca^{++} \\ Mg^{++} \end{matrix}\right\} R_1 + 2\ Na^+ \longrightarrow \left.\begin{matrix} Ca^{++} \\ Mg^{++} \end{matrix}\right\} + Na_2\ R_1$$

The calcium and magnesium ions are contained in the waste regenerant as the chlorides. The treated water contains sodium ions and all of the anions originally present.

Applied to mine drainage, the softening reaction has several limitations. The process removes none of the anions, specifically, sulfates, and the waste regenerant contains the same cations, still in soluble, albeit more concentrated, form. A third limitation is that the ion exchange reactions involving iron and manganese cations may not be as easily reversible as those involving calcium and magnesium. Finally, the total waste problem is actually aggravated by the load represented by the regenerant.

If the conventional demineralization process is utilized, the reactions are as follows:

$$\left.\begin{matrix}2\,Na\\Ca\\Mg\\Fe\\Mn\\Al\end{matrix}\right\}\left\{\begin{matrix}SO_4\\Cl_2\end{matrix}\right. + H_2R_1 \longrightarrow \left.\begin{matrix}2\,Na\\Ca\\Mg\\Fe\\Mn\\Al\end{matrix}\right\} R_1 + \begin{matrix}H_2SO_4\\2\,HCl\end{matrix}$$

$$\left.\begin{matrix}H_2SO_4\\2\,HCl\end{matrix}\right\} + 2\,R_2OH \longrightarrow R_2\left\{\begin{matrix}SO_4\\Cl_2\end{matrix}\right. + 2\,H_2O$$

The regeneration reactions are as follows:

$$\left.\begin{matrix}2\,Na\\Ca\\Mg\\Fe\\Mn\end{matrix}\right\} R_1 + H_2SO_4 \longrightarrow \left.\begin{matrix}2\,Na\\Ca\\Mg\\Fe\\Mn\end{matrix}\right\} SO_4 + H_2R_1$$

$$R_2\left\{\begin{matrix}SO_4\\Cl_2\end{matrix}\right. + 2\,NaOH \longrightarrow 2\,Na\left\{\begin{matrix}SO_4\\Cl_2\end{matrix}\right. + R(OH)_2$$

The limitations of the normal demineralization sequence are the same as those of the softening process, plus the relatively high cost of the regeneration chemicals, which makes the process uneconomical as compared to alternate processes as soon as the total solids level exceeds 500-1,000 mg/l.

The criteria used in selecting ion exchange processes for the treatment of mine drainage are therefore the following:

1. To convert the contaminating soluble ions present in mine drainage into insoluble forms.

2. To achieve this conversion either utilizing low cost chemicals as regenerants or to develop process sequences which allow for the recovery and reuse of the regenerant.

A promising process for treatment of acid mine drainage wastes was described by Pollio and Kunin[58]*. The principal process steps are expressed in these reactions:

Treatment:

$$M(SO_4) + 2\ RHCO_3 \longrightarrow R_2SO_4 + M(HCO_3)_2$$

Regeneration:

$$R_2SO_4 + 2\ NH_4OH \longrightarrow 2\ ROH + (NH_4)_2SO_4$$

$$2\ ROH + 2\ H_2CO_3 \longrightarrow 2\ RHCO_3 + 2\ H_2O$$

The ion exchange process is followed with aeration and coagulation with lime to precipitate iron, manganese and aluminum and to reduce calcium and magnesium hardness.

The advantage of this process is that most of the metallic sulfates are converted into soluble bicarbonates which pass through the resin bed without forming precipitates. The insoluble salts then are formed downstream in the aerator and softener and are removed by coagulation and sedimentation. The regenerants used in this process are ammonia and carbon dioxide, both of which are relatively low cost bulk chemicals. Furthermore, the process appears to be suited to either regenerant recovery and reuse or the development of marketable by-products from the spent regenerant. The process therefore has the potential of meeting the objectives of elimination of pollution and of the ultimate disposal of the waste products.

Another promising ion exchange process for treatment of acid mine drainage waters takes advantage of sulfate-bisulfate equilibria and is currently being explored for processing brackish waters. This process** uses 1) a strong acid cation exchange resin, and 2) a strong base anion exchange resin which operates on the sulfate-bisulfate cycle.

The fundamentals of this process are as follows: In the first step, the water is contacted with a strongly acidic ion exchange resin, converting the salts to their corresponding free acids. These are passed through the sulfate form of a strong anion exchanger. The divalent sulfate counter ions remove hydrogen ions from the water and are converted to the monovalent bisulfate ion. This frees half the anion exchange sites for absorption of anions from solution. The water is thereby effectively demineralized. For example, a solution of ferrous sulfate passed through the resin acids will react as follows:

*Desal Process ®
**Sul-biSUL process ®

Cation Exchanger

$$FeSO_4 + 2\,RH \rightleftharpoons R_2Fe + H_2SO_4$$

Anion Exchanger

$$H_2SO_4 + R_2SO_4 \rightleftharpoons 2\,RHSO_4$$

Regeneration is a simple process. The anion resin is regenerated with water, or water made slightly alkaline with lime, which, because of its higher pH, reverses the sulfate bisulfate reaction:

$$2\,RHSO_4 \xrightarrow{H_2O} R_2SO_4 + H_2SO_4$$

The liberated acid is partially recovered using it to regenerate the cation resin.

$$R_2Fe + H_2SO_4 \longrightarrow 2\,RH + FeSO_4$$

The regenerant chemicals are inexpensive; i.e., sulfuric acid and lime. This process is reportedly more efficient at higher salt concentrations, and it could be very economical if the natural acidity of mine waters could be used as a source of regeneration acid. It seems possible that this process could be more economical than bicarbonate cycle processes for certain acid mine drainage waters. Therefore, the choice of ion exchange process would depend on the concentration and composition of the acid mine drainage water to be processed.

Burns and Roe, Inc.[59, 60], designed an ion exchange treatment plant to treat acid mine drainage at Hawk Run near Philipsburg, Pennsylvania. The plant utilizes the "Modified desal process"® developed by Rohm and Haas Company, Philadelphia, to remove mineral acidity. This is followed by aeration, softening, and filtration to remove iron, other metals and hardness to produce water meeting the U.S. Public Health Service standards for drinking water. A schematic flow diagram of the treatment plant is shown on Figure 54. Burns and Roe, Inc.[60] gives a summary of operating data and the design water quality as shown in Table 39.

The estimated construction cost of the plant is about $2,485,000 including engineering design costs.

Chester Engineers[61, 62] designed a 0.5 MGD ion exchange treatment plant for Smith Township about 20 miles west of Pittsburgh. The capital costs of the plant is borne solely by the Commonwealth of Pennsylvania and the Smith Township Municipal Authority in conjunction with the Smith Township Supervisors will operate and maintain the plant.

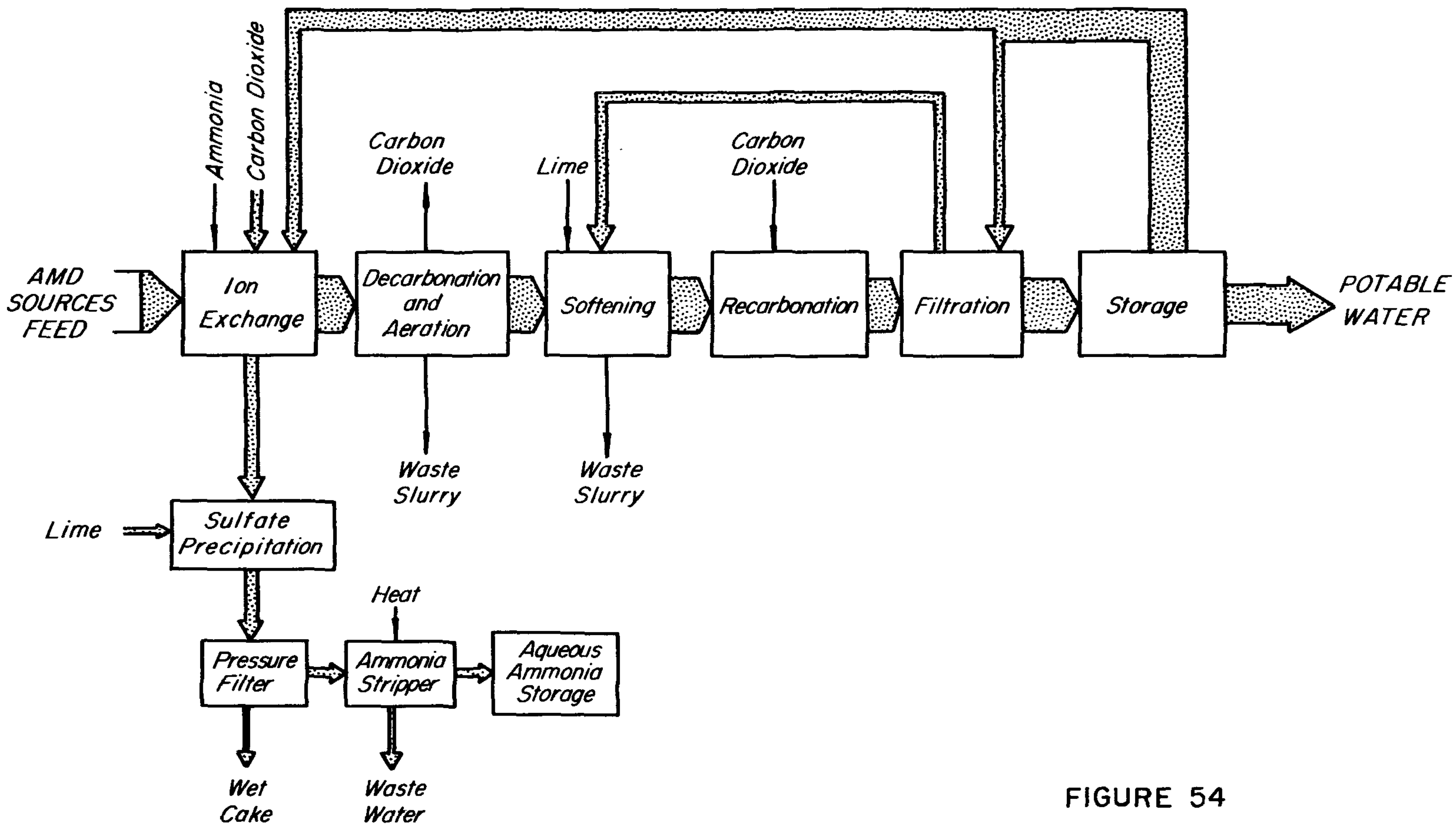


FIGURE 54

ACID MINE DRAINAGE TREATMENT PLANT
PHILIPSBURG, PENNSYLVANIA
SCHEMATIC OF PROPOSED TREATMENT PLANT

After Burns and Roe, Inc., 1969[60]

TABLE 39

SUMMARY OF OPERATING DATA AND DESIGN WATER QUALITY

Summary of Operating Data

Nominal Plant Capacity, Normal Operating Conditions	500,000 GPD
AMD Water Treated	684,000 GPD
In-Plant Use and Waste	64,000 GPD
Treated Water Produced	620,000 GPD
Maximum Output of Ion Exchange Resin When Supplied with AMD Water of Design Conditions	820,000 GPD
Chemical and Fuel Requirements	
Ammonia (5% Makeup)	160 Lb./Day
Carbon Dioxide	6,180 Lb./Day
Lime	6,430 Lb./Day
Fuel Oil	350 GPD
Waste Products (Dry Basis)	19,160 Lb./Day

Design Water Quality

	AMD Feed	Product
Sulfate	1,000 mg/l	50 mg/l
Hardness	550 mg/l	70 mg/l
Total Iron	250 mg/l	0.3 mg/l
pH	3 - 4	8.5
Total Solids	1,000 mg/l	300 mg/l

The water in Dinsmore Reservoir, the source of potable water for the Township, is alkaline but contains more than 1,000 mg/l of sulfates, largely calcium sulfate, and several hundred mg/l of carbonates. Mine drainage from strip mines within the area flows through limestone and calcareous shales. This results in the production of a calcium sulfate near-neutral water product as the acidity and iron is removed. A typical analysis of raw water in the reservoir would indicate a pH of 6.5 to 8.4, sulfates from 400 to over 1,300 mg/l, and total dissolved solids of 1,500 to 2,000 mg/l.

Prior to the installation of the ion exchange treatment plant, raw water was treated by coagulation to remove turbidity, some soda lime softening followed by filtration and chlorination. Hardness was only partially removed by this treatment and the high total dissolved solids discouraged industrial use. Water treatment costs using the lime and soda ash process was about 0.50¢/1,000 gal. and it is believed that water treatment costs using the new ion exchange process will be brought down to 0.20¢/1,000 gal[63].

The ion exchange process for the treatment plant is based on Sul-biSul® technology of the Dow Chemical Company and on a resin handling system developed by Chemical Separations, Inc. It employs two ion exchange steps and an intricate method for regenerating and transporting ion exchange resins. Figure 55 is a flow diagram of the process. A product water with a pH of 8 to 9, a dissolved solids concentration of less than 500 mg/l, and a total hardness of 150 mg/l should result from treatment. The total capital cost of the project including engineering design is estimated at $730,000.

The Culligan International Company[64] made an extensive study for the Environmental Protection Agency on treatment of mine drainage using ion exchange processes. They studied two complete processes in detail for production of potable water. One process, the utilization of a strong acid cation exchanger (H^+ form) with a weak base anion exchanger (free base form) is a conventional ion exchange process which has never been applied to the treatment of mine drainage. The process utilizing a weak base anion in the bicarbonate form with lime treatment had been studied before. Their study compared the two processes. It is demonstrated that these processes are capable of producing a potable effluent from acid mine drainage and that the chemical costs are about the same. Wastes from the conventional ion exchange process will contain acid materials while the bicarbonate form-weak base process does not. Three plant sizes for each process are being designed for production of 0.1, 0.5 and 1.0 MGD of potable water so that a comparison can be made of each of the two processes.

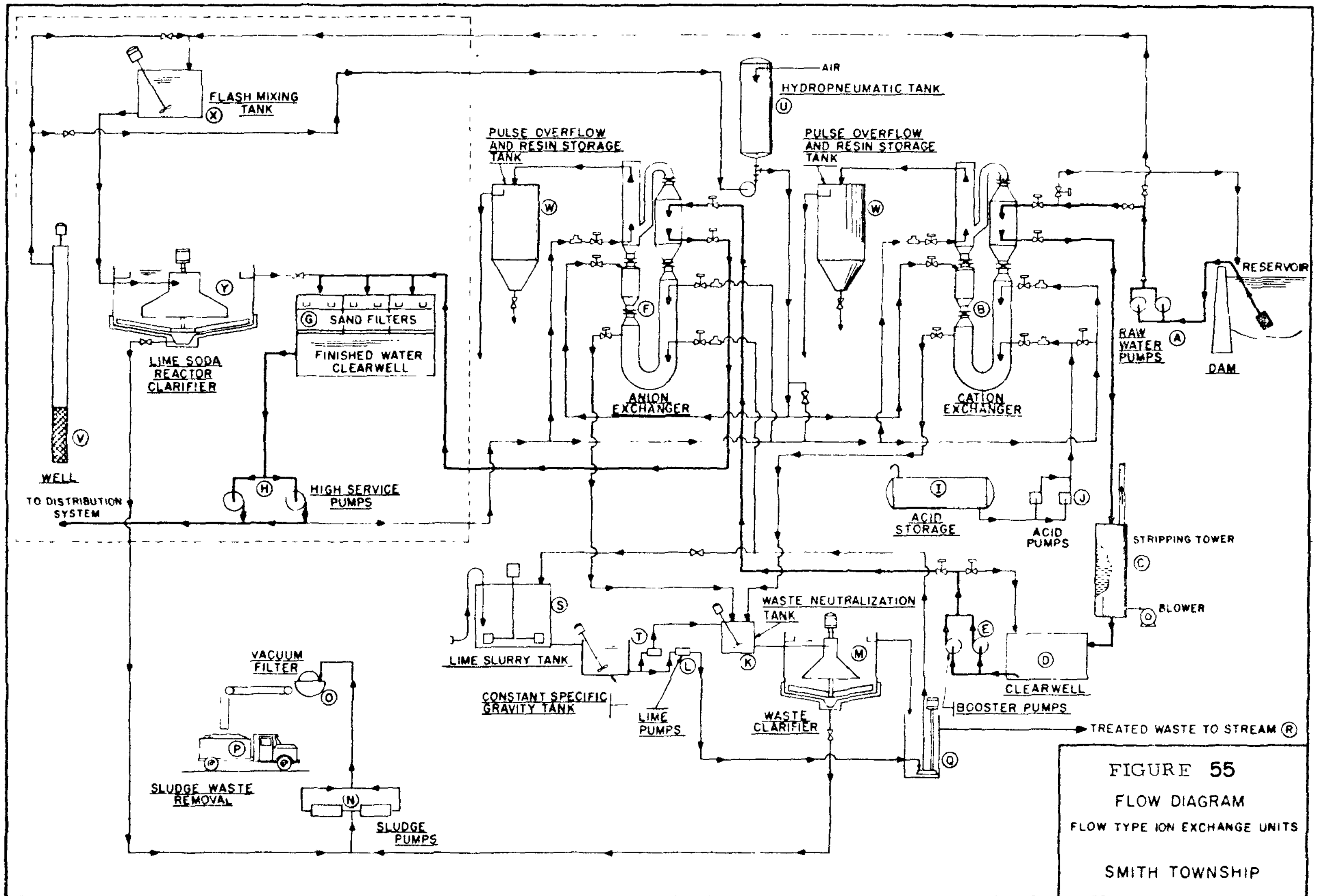


FIGURE 55

FLOW DIAGRAM

FLOW TYPE ION EXCHANGE UNITS

SMITH TOWNSHIP

From Zabban, et al., 1972[62]

REVERSE OSMOSIS PROCESS

A concise definition of the fundamentals of reverse osmosis is included in "Treatment of Acid Mine Drainage by Reverse Osmosis," a study by Rex Chainbelt, Inc. for the Environmental Protection Agency[65].

"Osmosis occurs if two solutions of different concentrations in the same solvent are separated from one another by a membrane. If the membrane is semipermeable, i.e., permeable to the solvent and not to the solute, solvent flow occurs from the more dilute to the more concentrated solution. This solvent flow continues until the two solutions are of equal concentration or the pressure on the more concentrated side of the membrane rise to a value called the osmotic pressure. If a pressure in excess of the osmotic pressure is applied to the more concentrated side of the membrane, the solvent can be caused to flow into the more dilute solution. This is termed reverse osmosis."

Golomb and Besik[66] describe five broad categories of osmotic membrane modules as follows:

Tubular Units - There are several design concepts of tubular modules on the market. Their chief advantage over other systems is that they can handle liquids containing suspended particles or dissolved substances likely to precipitate out as the feed solution becomes more concentrated. In the tubular unit, provision is made for maintaining a good flushing action throughout the system during operation. As the solution becomes more concentrated, it is often possible to prevent fouling or plugging of the membrane simply by adjusting the proper hydrodynamic conditions. This is an easy operation in tubular systems, but hardly possible in others. Nevertheless, there are also some disadvantages: 1) the large number of connectors with the resulting expense in making and assembling the array; 2) the small membrane surface area/unit volume ratio; 3) the necessity for enclosing the tube exteriors to protect the purity of the permeate; and 4) the expensiveness of the support media.

Spiral-Wound Units - Developed by Gulf General Atomic Co., the spiral-wound unit consists of a "sandwich" arrangement consisting of two layers of membrane, with a porous backing material at the center, at one end of which is a perforated plastic pipe. The edges of the membrane are sealed, with the porous backing material inside the resulting envelope, which with suitable mesh spacers is rolled spirally around the central pipe. The whole is placed inside a cylindrical pressure container, thus completing the modular unit. Typically, several modules can be placed in series. The feed liquid flows axially, and as water permeates the membrane it flows through the porous backing material to the central pipe which acts as collector for the product water. The concentrated solution continues to flow axially through the roll, emerging at the mesh spacer gaps at the other end.

A principal advantage of this design is that it has a high membrane surface area/unit volume ratio compared with the tubular configuration. Disadvantages in comparison with tubular units are: 1) severe problems in handling high-solids feed; 2) short feed flow paths; 3) high pressure losses; and 4) difficulty in recirculating concentrate.

Plate and Frame Units - The plate and frame concept, the earliest design of RO unit, has an obvious similarity to the filter press, and provides a convenient solution to the pressure-containing problem. A system of this type has been developed by Aerojet-General Corp. It is particularly attractive for small, low-pressure plants.

The membrane is supported on a flat circular plate, and plates are stacked on top of each other. Product water emerges at the edge of the plates in the smaller units; in the larger units (over 1,000 gpd* capacity) product water is channelled to a central shaft. Feed and product liquid streams are kept separate by O-ring seals. Turbulent flow of the feedstream is induced by means of baffles located near the membrane surfaces.

The following disadvantages can be ascribed to the plate and frame design: 1) expensive to install and maintain (labor costs); 2) distribution and short circuiting problems; 3) narrow flow channels; 4) multiple membrane handling, which increases the probability of failure; and 5) low surface area/ unit volume ratio. Notwithstanding these limitations, large numbers of complete units have been used for water purification on a scale up to 40,000 gpd.

Plate and Frame (Ultrafiltration) Units - Dorr-Oliver, Inc. has developed a somewhat unique ultrafiltration module, less costly and easier to maintain than other devices now available in regard to membrane replacement. The membrane is supplied in the form of replaceable cartridges, which are inserted into a polyester/fiberglass molded rectangular shell-and-cover arrangement. The unit has typical operating pressures of 10-50 psi. The Dorr-Oliver unit utilizes high flux, non-cellulosic anisotropic membranes, developed by the Amicon Corp., and tailor-made for retention of large molecules and colloids. These membranes are well-suited to operation under more strongly acidic or alkaline conditions than the cellulosic membranes can withstand, and also at higher temperatures. Currently, this system is being developed for industrial and domestic wastewater purification.

Hollow-Fiber Units - A somewhat novel approach to RO equipment is being pursued by the DuPont Co. and by Dow Chemical Co., who have pioneered the use of fine hollow fibers as osmotic membranes.

Modules based on this concept contain an astronomically large number of hollow filaments, ca. 50μ o.d. and 25μ i.d., assembled into a cylindrical bundle, the open ends of which have been potted into a plug of resin serving as

*Gallons of Permeate per Day

a header. This bundle is inserted into a cylindrical shell which serves as a pressure vessel. Pressurized liquid is pumped into the shell side of the assembly, permeate being collected from the ends of the hollow fiber bundle. These units contain an enormous membrane surface area/unit volume ratio, so that high intrinsic membrane permeabilities (in terms of gfd) are unimportant. Present systems are designed primarily for water demineralization. Dow's fibers are spun from cellulose acetate; DuPont's from nylon and other polymers.

Advantages of the hollow fiber configuration are: 1) enormous surface area/unit volume ratio; and 2) the hollow fibers withstand the high operating pressures required for RO and eliminate the need for space-consuming porous support media essential to other module designs.

The disadvantage of this configuration is that it is not applicable where an appreciable level of suspended solids is present in the feed solution. Filtration is necessary to prevent clogging of the fiber bundle.

The DuPont hollow-fiber unit, based on nylon fibers, is operational in the pH range 1.5 - 12.0, as compared with the recommended pH range 3 - 8 for modules utilizing cellulose acetate membranes.

A reverse osmosis plant for treating acid mine waters would consist of a raw water intake, pumps, and filters for removal of particulate matter from the raw water. Filter effluent passes to the reverse osmosis pressure vessel and is exposed to the membrane cells. The concentrated brine after completing its circuit through the reverse osmosis unit passes to a collection pond or tank for disposal by deep well injection or by a lime neutralization process. Product water is collected and held in storage tanks for ultimate utilization.

A plate and frame type reverse osmosis unit was briefly operated on acid mine waters at two mines near Kittanning, Pennsylvania in 1965, by Gulf General Atomic, Inc.[(67)] under the sponsorship of the Office of Saline Water in cooperation with the Bureau of Mines. The spiral-wound configuration was then extensively tested by Gulf General Atomic, Inc.[(68)] at the Environmental Protection Agency mine drainage treatment laboratory in Norton, West Virginia. These tests showed utilization of reverse osmosis with acid mine drainage feed was feasible and that the product water was of potable quality. On the basis of the test results, it was reasonable to conclude the process would be most applicable for Class I acid mine waters which are highly acidic and have low pH's, and that Class III mine waters which contain no iron and are alkaline would be suitable.

The principal advantage of reverse osmosis for acid mine drainage treatment is the recovery of potable water as a byproduct.

Disadvantages are: 1) high cost of acid mine drainage treatment and brine disposal; 2) reverse osmosis by itself does not eliminate acid mine drainage water; 3) fouling of membranes with consequent necessity of periodic replacements; 4) operation with the acid solutions required for the prevention of scaling makes it necessary to construct the plant of corrosion resistant materials which significantly increase capital cost requirements; and 5) pre-filtration of acid mine drainage is required for feed to a reverse osmosis process unit.

Cyrus Wm. Rice and Company in their report to the Appalachian Regional Commission[41] developed tabulated costs and plots based on the studies of Keilin[69] and Schroeder, et al.[70]. Tables 40 to 52 and Figures 56 to 59 show the tabulated costs and cost curves as worked out by this company. No attempt has been made to update these cost figures for the present study because of rapid technological developments in the reverse osmosis field with resulting reductions in the cost of RO units.

Cyrus Wm. Rice and Company[41] list the elements of capital and operating costs which must be considered in design, construction and operation of reverse osmosis treatment plants.

<u>Elements of Capital Cost</u>

1. Principal Items of Equipment

    a) Reverse Osmosis Cells
    b) Filters
    c) Pumps
    d) Pressure Vessels

2. Process Facility Costs

    a) Site Development
    b) Piping
    c) Electrical
    d) Instruments
    e) Buildings
    f) Others

3. Other Plant Costs

    a) Contingencies
    b) Engineering
    c) Interest during construction
    d) Startup expense
    e) Cost of Site

4. Other Facilities Costs

   a) Raw Water Intake
   b) Product Water Storage
   c) Deep well or lime neutralization facilities for brine disposal

Elements of Operating Costs
(Excluding Taxes and Insurance)

1. Reverse Osmosis Processing

   a) Power
   b) Membrane Replacement
   c) Operating Supplies
   d) Operating and Maintenance Labor
   e) G & A and Overhead
   f) Fixed Charges (Amortization and Interest)

2. Lime Neutralization Brine Disposal

   a) Hydrated Lime
   b) Limestone

3. Deep Well Brine Disposal

TABLE 40

REVERSE OSMOSIS CAPITAL COSTS

Summary of Reference Conditions Used as a Basis for Tables 41, 42, 43, 45, 46, 47, 48, 49, 50, 51

	Moderately Acidic			Strongly Acidic			Seawater	
	Case A-.1	Case A-1[1]	Case A-10	Case B-.1	Case B-1[1]	Case B-10	Case C-.1	Case C-1[1]
Capacity (product water), MGD	0.1	1.0	10.0	0.1	1.0	10.0	0.1	1.0
Water recovery, %	80	80	80	60	60	60	33	33
AMD treated (Feed), MGD	0.125	1.25	12.5	0.167	1.67	16.7	0.3	3.0
Effluent brine, MGD	0.025	0.25	2.5	0.067	0.67	6.7	0.2	2.0
Total dissolved Solids in feed, ppm	1500	1500	1500	5000	5000	5000	35,000	35,000
Total acidity in feed, ppm[2]	500	500	500	1667	1667	1667	---	---
Total dissolved solids in brine, ppm	7500	7500	7500	12,500	12,500	12,500	52,500	52,500
Total Acidity in brine, ppm[2]	2500	2500	2500	4167	4167	4167	---	---
Product quality, ppm	250	250	250	250	250	250	250	250
Operating pressure, psig	750	750	750	750	750	750	750	750
Electrical efficiency, %	80	80	80	80	80	80	80	80
Flux, average, GFD	50	50	50	20	20	20	10	10
Membrane life, years	1	1	1	1	1	1	.5	.5
Availability, days/year	330	330	330	330	330	330	315	315

Note: 1. Cases A-1, B-1, and C-1 are taken from (69) and were used as a basis for other plant sizes.
2. Acidity was assumed to be equal to TDS/3

From Cyrus Wm. Rice & Co., 1969[41]

TABLE 41

ESTIMATED CAPITAL COSTS FOR REVERSE OSMOSIS PROCESS
IN THOUSANDS OF DOLLARS (FOR CASES CITED IN TABLE 40)

		A-.1[4]	A-1[3]	A-10[4]	B-.1[4]	B-1[3]	B-10[4]	C-.1[4]	C-1[3]
I.	Principal Items of Equipment	76	430	3100	134	760	5470	255	1450
II.	Process Facilities	27	153	1100	47	268	1930	88	500
III.	Other Plant Costs	26	146	1050	45	257	1850	86	490
	Sub-Total	129	729	5250	226	1285	9250	429	2440
IV.	Other Facilities Costs (excluding brine disposal)	33	188	1350	35	200	1440	42	240
	Total	162	917	6600	261	1485	10,690	471	2680

Note:

3. Reference (69) was used as a basis for A-1, B-1, and C-1 costs. Since the original data cited was not for AMD plants, cost multipliers for AMD service (1.76X to 2.04X) were obtained from (70). A multiplier of 2.04 was used in the above for items I, II, and III. Item III was omitted from the (69) data. Again (70) was used to estimate Item III at 25% of Items I and II total. Item IV was estimated from (70) data.

4. Costs for 100,000 GPD and 10,000,000 GPD plants were estimated from size range costs defined in (70).

From Cyrus Wm. Rice & Co., 1969[41]

TABLE 42

ESTIMATED CAPITAL COSTS FOR REVERSE OSMOSIS PROCESS WITH LIME NEUTRALIZATION FOR BRINE DISPOSAL IN THOUSANDS OF DOLLARS (FOR A AND B SERIES CASES CITED IN TABLES 40 & 41)

	A-.1	A-1	A-10	B-.1	B-1	B-10
Total RO plant (Items I-IV, Table B)	162	917	6600	261	1485	10,690
Total Capital Cost for Lime Neutralization Facility$_5$	200	240	480	200	290	1,000
Total	362	1157	7080	461	1775	11,690

Note:

5. Costs obtained from curves developed by Cyrus Wm. Rice & Co., 1969[41]

From Cyrus Wm. Rice & Co., 1969[41]

TABLE 43

ESTIMATED CAPITAL COSTS FOR REVERSE OSMOSIS PROCESS WITH DEEP WELL BRINE DISPOSAL IN THOUSANDS OF DOLLARS

	Special Case-A_6	Special Case-B_7
Total RO plant (from plotted data)	560	416
Total Capital Cost of Deep Well Brine Disposal Facility	600	600
Total	1160	1015

Note:

6. Special Case A is based upon data obtained from as follows: TDS = 1500 ppm, well depth = 4000 feet, total cost basis = \$150/ft., injection pressure = 700 psi, injection flow = 100 gpm. Data developed on the foregoing is as follows: AMD treated = 720,000 GPD (from 1500 ppm inlet solids and 100 GPM disposal flow), product flow = 575,000 GPD, Total well cost = \$600,000.

7. Special Case B is based upon data in 6 above with the exception: TDS = 5000 ppm. Data developed on the foregoing is as follows: AMD treated = 358,000 GPD (from 5000 ppm inlet solids and 100 GPM disposal flow), Product flow = 214,000 GPD, Total well cost = \$600,000.

From Cyrus Wm. Rice & Co., 1969[41]

TABLE 44

ESTIMATED CAPITAL COSTS VS. CAPACITY FOR REVERSE OSMOSIS PROCESS WITH DEEP WELL BRINE DISPOSAL
(From Schroeder, et al., 1966[70])

Product Flow in gpd	Capital Cost
100,000	$248,000
1,000,000	$1,407,000
10,000,000	$10,120,000

Total Dissolved Solids in Feed - 1638 ppm

From Cyrus Wm. Rice & Co., 1969[41]

TABLE 45

ESTIMATED OPERATING COSTS FOR REVERSE OSMOSIS PROCESS
IN DOLLARS PER THOUSAND GALLONS OF AMD TREATED
(FOR CASES CITED IN TABLES 40 & 41)

	A-.1	A-1	A-10	B-.1	B-1	B-10	C-.1	C-1
Power (@ $.007/ kw-hr)[9]	.054	.054	.054	.051	.051	.051	.054	.054
Membrane replacement[10]	.006	.006	.006	.009	.009	.009	.020	.020
Operating Supplies[10]	.005	.005	.005	.007	.007	.007	.007	.007
Operating and maintenance labor[11]	.544	.054	.011	.407	.041	.008	.680	.068
G&A and overhead[11]	.176	.018	.004	.144	.014	.003	.234	.023
Sub-Total	.785	.137	.080	.618	.122	.078	.995	.172
Fixed charges[12]	.227	.129	.093	.274	.156	.103	.288	.164
Total	1.012	.266	.173	.892	.278	.181	1.283	.336

Note:

9. 7 mils per kw-hr power cost is universally used. It is, however, considered unrealistic since range of electrical load is A-1 = 38.4 kw + B-10 = 5,000 kw and range of annual consumption is A-1 = 304,000 kw-hr + B-10 = 39,600,000 kw-hr.

10. Costs are considered linear independent of plant capacity.

11. Costs are considered non-linear for various capacity plants. Assumption is that actual labor staff, G&A and overhead are the same for .1 MGD and 1 MGD plants and double for 10 MGD plants.

12. Fixed charges were estimated on the basis of 30 year life, 4% interest, equal payments.

From Cyrus Wm. Rice & Co., 1969[41]

TABLE 46

ESTIMATED OPERATING COSTS FOR REVERSE OSMOSIS PROCESS WITH LIME NEUTRALIZATION FOR BRINE DISPOSAL IN DOLLARS PER THOUSAND GALLONS OF AMD TREATED (FOR CASES CITED IN TABLES 40 & 42 USING HYDRATED LIME)

	A-.1	A-1	A-10	B-.1	B-1	B-10
Sub-Total (Table A)	.785	.137	.080	.618	.122	.078
Neutralization Operating Costs	.182	.180	.161	.605	.595	.500
Fixed Charges	.507	.162	.099	.484	.186	.123
Total	1.474	.479	.340	1.707	.903	.701

TABLE 47

ESTIMATED OPERATING COSTS FOR REVERSE OSMOSIS PROCESS WITH LIME NEUTRALIZATION FOR BRINE DISPOSAL IN DOLLARS PER THOUSAND GALLONS OF PRODUCT WATER (FOR CASES CITED IN TABLES 40 & 42 USING HYDRATED LIME)

	A-.1	A-1	A-10	B-.1	B-1	B-10
Total	1.840	.599	.425	2.856	1.510	1.171

From Cyrus Wm. Rice & Co., 1969[41]

TABLE 48

ESTIMATED OPERATING COSTS FOR REVERSE OSMOSIS PROCESS WITH LIME NEUTRALIZATION FOR BRINE DISPOSAL IN DOLLARS PER THOUSAND GALLONS OF AMD TREATED (FOR CASES CITED IN TABLES 40 & 42 USING LIMESTONE)

	A-.1	A-1	A-10	B-.1	B-1	B-10
Sub-Total (Table A)	.785	.137	.080	.618	.122	.078
Neutralization Operating Costs	.140	.139	.121	.312	.305	.230
Fixed Charges	.507	.162	.099	.484	.186	.123
Total	1.432	.438	.300	1.414	.613	.431

TABLE 49

ESTIMATED OPERATING COSTS FOR REVERSE OSMOSIS PROCESS WITH LIME NEUTRALIZATION FOR BRINE DISPOSAL IN DOLLARS PER THOUSAND GALLONS OF PRODUCT WATER (FOR CASES CITED IN TABLES 40 & 42 USING LIMESTONE)

	A-.1	A-1	A-10	B-.1	B-1	B-10
Total	1.791	.548	.375	2.360	1.023	.720

From Cyrus Wm. Rice & Co., 1969[41]

TABLE 50

ESTIMATED OPERATING COSTS FOR REVERSE OSMOSIS PROCESS
WITH DEEP WELL BRINE DISPOSAL IN
DOLLARS PER THOUSAND GALLONS OF AMD TREATED
(FOR SPECIAL CASES A & B IN TABLE 42)

	Special Case A	Special Case B
Power (@ $.007/kw-hr)$_{14}$	.063	.069
Membrane replacement	.006	.009
Operating supplies	.005	.007
Operating and maintenance labor	.095	.190
G and A and overhead	.030	.067
Well maintenance	.025	.051
Fixed Charges	.282	.497
Total	.506	.890

TABLE 51

ESTIMATED OPERATING COSTS FOR REVERSE OSMOSIS PROCESS
WITH DEEP WELL BRINE DISPOSAL IN
DOLLARS PER THOUSAND GALLONS OF PRODUCT WATER

	Special Case A_{16}	Special Case B_{17}
Total	.634	1.49

Note:

14. Deep well injection pump power added to reverse osmosis power.
15. Based upon $6,000/year maintenance estimated by
16. Product flow = 575,000 GPD
17. Product flow = 214,000 GPD

From Cyrus Wm. Rice & Co., 1969[41]

TABLE 52

ESTIMATED OPERATING COSTS VS. CAPACITY FOR REVERSE OSMOSIS PROCESS WITH DEEP WELL BRINE DISPOSAL IN DOLLARS PER THOUSAND GALLONS OF PRODUCT WATER (FROM SCHROEDER, et al., 1966[70])

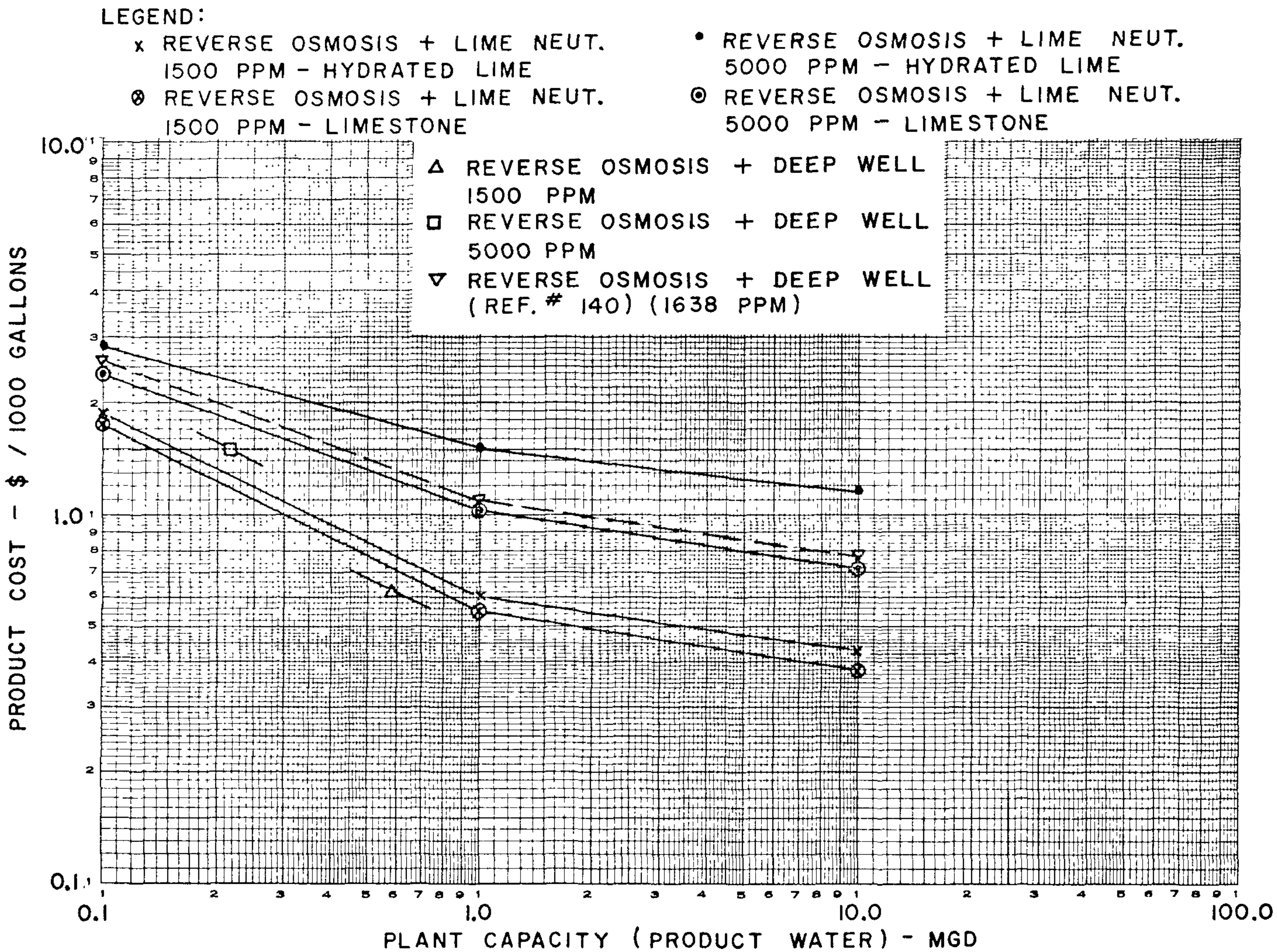
Product Flow in gpd	Cost
100,000	$2.57
1,000,000	$1.09
10,000,000	$0.77

Total Dissolved Solids in Feed - 1638 ppm

From Cyrus Wm. Rice & Co., 1969[41]

FIGURE 56

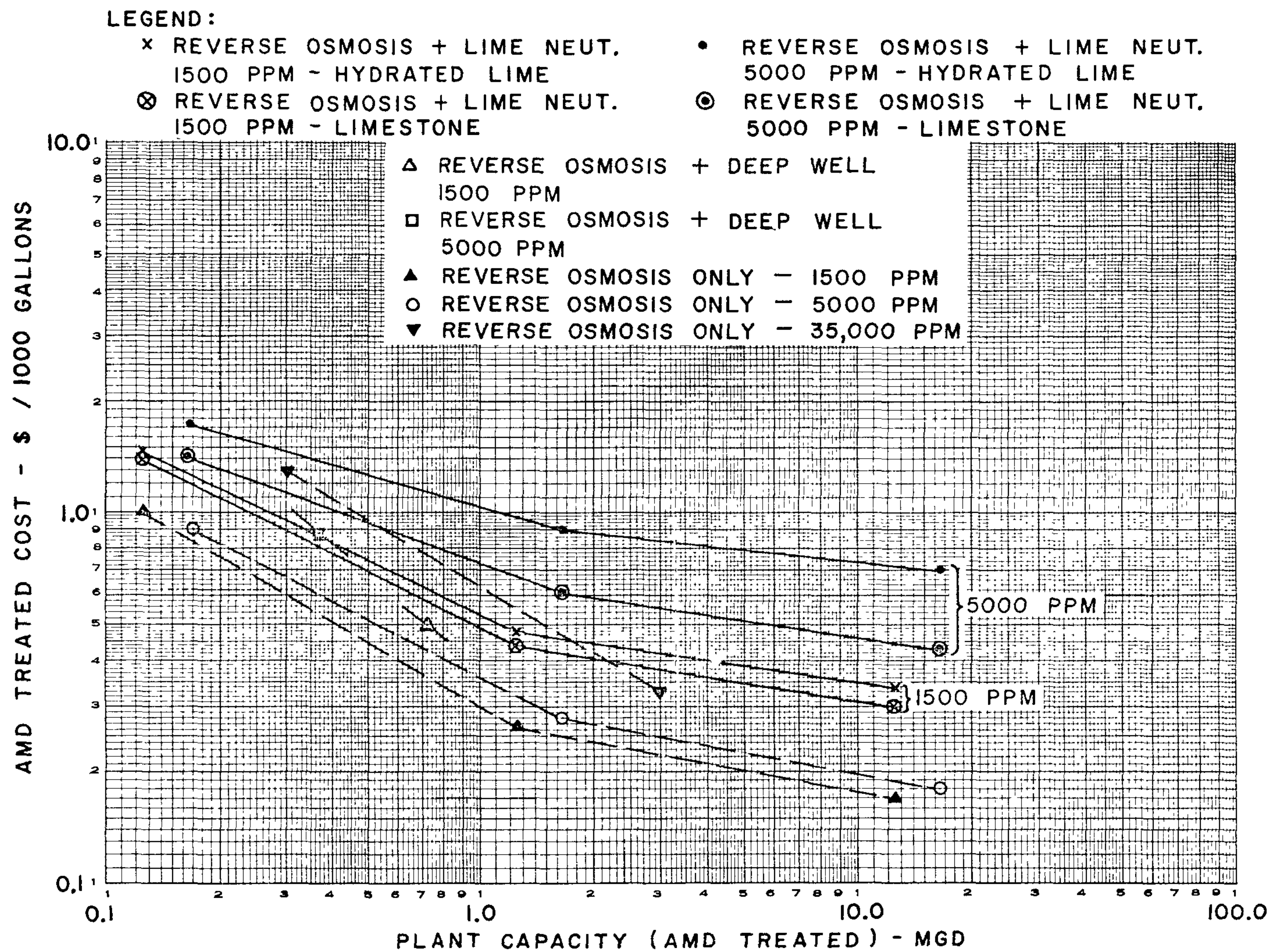
OPERATING COST IN $ / 1000 GALLONS VS. PLANT CAPACITY
REVERSE OSMOSIS + BRINE DISPOSAL (PRODUCT WATER)



From Cyrus Wm. Rice & Co., 1969(41)

FIGURE 57

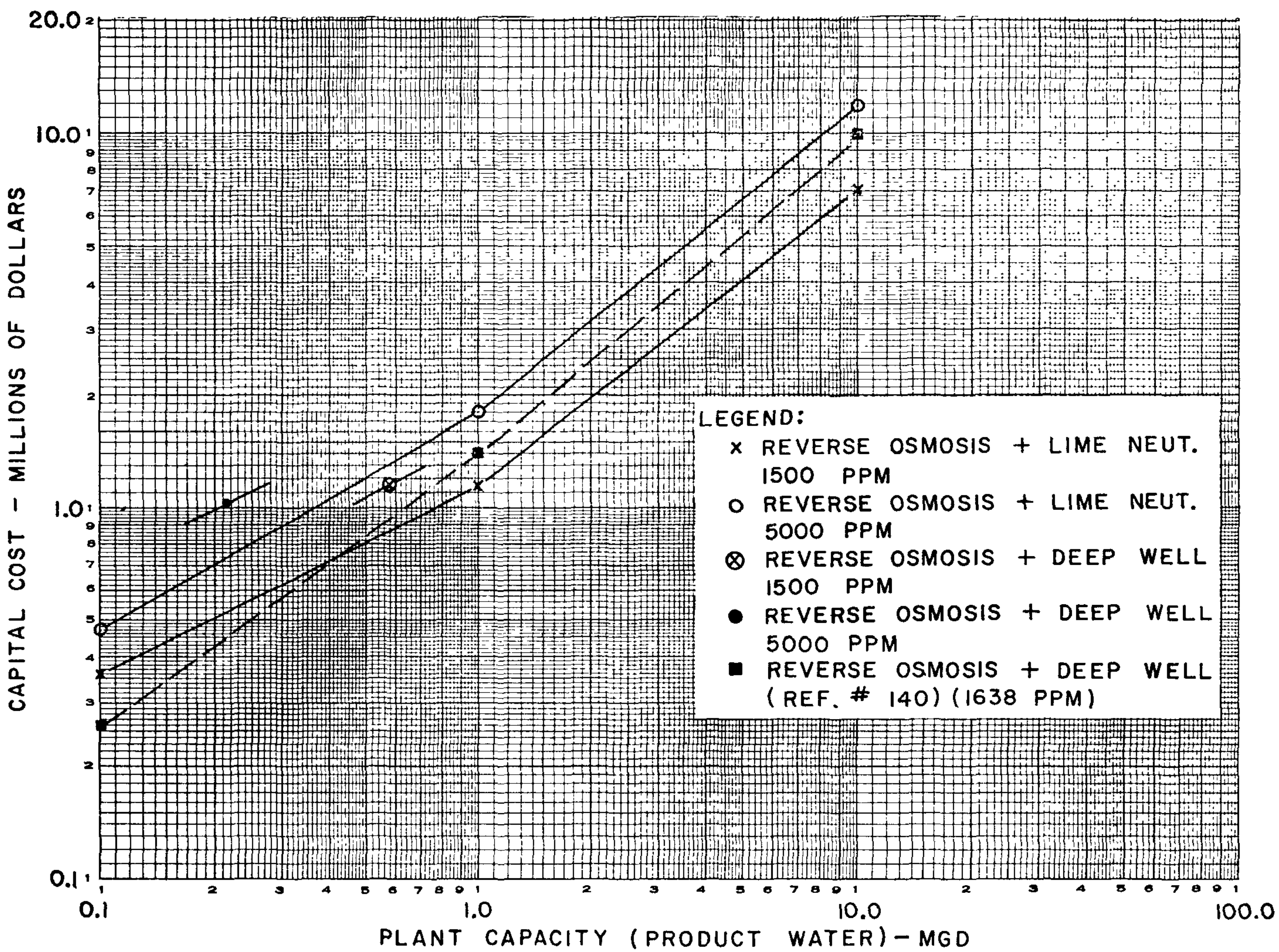
OPERATING COST IN $ / 1000 GALLONS VS. PLANT CAPACITY
REVERSE OSMOSIS WITH & WITHOUT BRINE DISPOSAL (AMD TREATED)



From Cyrus Wm. Rice & Co., 1969(41)

FIGURE 58

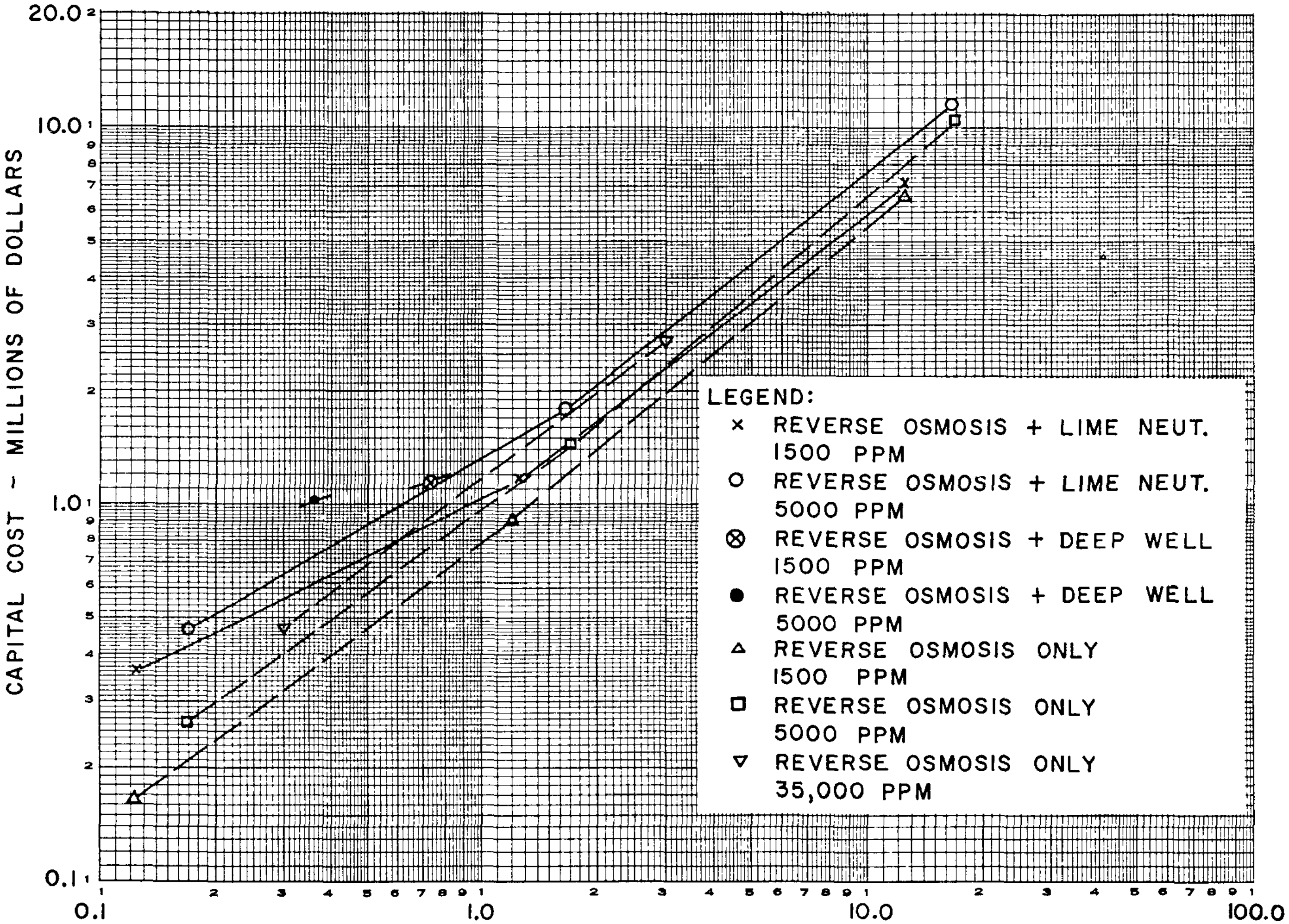
CAPITAL COST OF REVERSE OSMOSIS PLANT
WITH BRINE DISPOSAL VS. PLANT CAPACITY (PRODUCT WATER)



From Cyrus Wm. Rice & Co., 1969(41)

FIGURE 59

CAPITAL COST OF REVERSE OSMOSIS PLANT
WITH BRINE DISPOSAL VS. PLANT CAPACITY (AMD TREATED)



From Cyrus Wm. Rice & Co., 1969(41)

Studies were conducted by Rex Chainbelt, Inc. and the Environmental Protection Agency[65, 71, 72, 73] with tubular, hollow fiber and spiral-wound systems of reverse osmosis and the following conclusions were reached:

1. Under proper operating conditions, reverse osmosis can be used to treat ferrous iron acid mine drainage without major iron and calcium sulfate fouling problems.

2. Flux declines observed during optimized flow schemes were tolerable for all three units but the spiral wound and hollow fiber were slightly superior in flux stability.

3. Although salt rejections were near 99 percent for all three units, product water would still need further treatment for iron and manganese removal and pH adjustment before potable standards could be met.

4. An intolerable flux decline rate was observed for the tubular system when high salt passage (1.5 percent) membranes were utilized, while lower salt passage (0.4 percent) membranes had significantly improved flux stability.

5. Oxidation of ferrous iron by bacteria can be inhibited by ultraviolet disinfection and/or by lowering the pH to 2.9 by acid injection.

6. Water recovery was limited to slightly above 75 percent due to calcium sulfate precipitation which occurred when brine $CaSO_4$ molar solubility product values were in the range 35-50 x 10^{-5}.

7. No observable loss in membrane salt rejection capability occurred during a six-month study.

8. The tubular system had significantly lower productivity and higher initial cost as compared to the hollow fiber and spiral-wound system in this application.

Table 53 shows the typical raw water quality characteristics of the Mocanaqua discharge at Mocanaqua, Pennsylvania, where the three systems of reverse osmosis were evaluated. Tables 54 and 55 compare the water production capabilities and relative cost of the three reverse osmosis systems.

TABLE 53

TYPICAL RAW WATER QUALITY CHARACTERISTICS OF MOCANAQUA DISCHARGE

pH	3.4
Conductance	1100 Mmhos/cm.
Acidity	230 mg/l as $CaCO_3$
Calcium	120 mg/l
Magnesium	90 mg/l
Total Iron	80 mg/l
Ferrous Iron	68 mg/l
Aluminum	11 mg/l
Sulfate	800 mg/l
Manganese	15 mg/l
Silica	10 mg/l
TDS	1200 mg/l
Dissolved Oxygen	$<$ 1 mg/l
Temperature	54° F.

TABLE 54

Comparison of Water Production Capabilities

System	Pressure Vessel Volume ft^3	Enclosed Membrane Area ft^2	Membrane Packing Density ft^2/ft^3	Avg. Flux GFD @ 77° F & 400 psi net	Total Vessel Flux per Day Gal/Day @ 77° F & 400 psi net	Output per Cubic Foot of Vessel Volume	
						per day @ 77°F & 400 psi net	per Min. @ 77°F & 400 psi net
				(19.28 @ 600)	(2892 @ 600)	(2559 @ 600)	(1.78 @ 600)
Spiral Wound (Phase I)	1.13	150	133	12.86	1929	1707	1.19
Spiral Wound (Phase II)	1.13	186	165	12.31	2290	2026	1.41
Hollow Fiber (Phase II)	0.65	1500	2308	2.48	3720	5723	3.97
Tubular (Phase II)	0.63	16.9	26.8	(15.60 @ 600) 10.40	(264 @ 600) 176	(418 @ 600) 280	(0.29 @ 600) 0.19

TABLE 55

Relative Cost

System	Cost for One Pressure Vessel and Membrane	Observed Output (Gal. per Vessel per day @ 77° F & Indicated Net Pressure)	Initial Cost per Unit Output (gal/day)
Spiral Wound Phase I	$ 850.[11]	2892 @ 600	$0.29
Spiral Wound Phase II	$ 850.[11]	2290 @ 400	$0.37
Hollow Fiber Phase II	$1000.[12]	3720 @ 400	$0.27
Tubular Phase II	$ 255.[13]	264 @ 600	$1.00

From Wilmoth, et al., 1972[73]

In a report for the Environmental Protection Agency, Rex Chainbelt, Inc.[72] worked out cost estimates for a 0.75 MGD reverse osmosis acid mine drainage treatment plant. Figure 60 shows the flow sheet used for the cost estimates. The following assumptions were made to arrive at costs:

1. Hollow fiber RO modules are utilized.

2. RO product water capacity is 0.75 MGD.

3. Chemical additive costs are based on field testing results.

4. Diatomaceous earth filtration is utilized.

5. No costs for buildings or land are included.

6. The product water from the plant meets USPHS standards.

7. No costs are included for disposal of residuals.

8. Operating manpower includes a plant manager and a three man crew. (Total salary and administrative costs - $50,000 per year.)

9. Power costs are 1.0¢/kwh.

10. Chemical additives include acid, diatomaceous earth, lime, chlorine, flushing chemicals for RO membranes, potassium permanganate.

11. RO module life is four years - replacement cost is 28¢/gpd capacity.

12. The brine treatment system is of concrete construction with high speed floating aerators.

13. The product water treatment system utilizes a portion of the sedimentation tank overflow for neutralization and potassium permanganate for manganese oxidation, followed by filtration and chlorination.

Table 56 shows the major cost items for the treatment system. The cost estimates were based on vendor quotations or purchase prices at the time the report[72] was written. Advancement in reverse osmosis technology is likely to bring about price reductions in RO equipment. Also it must be considered that two tasks are being performed, i.e., treatment of acid mine drainage and production of potable water.

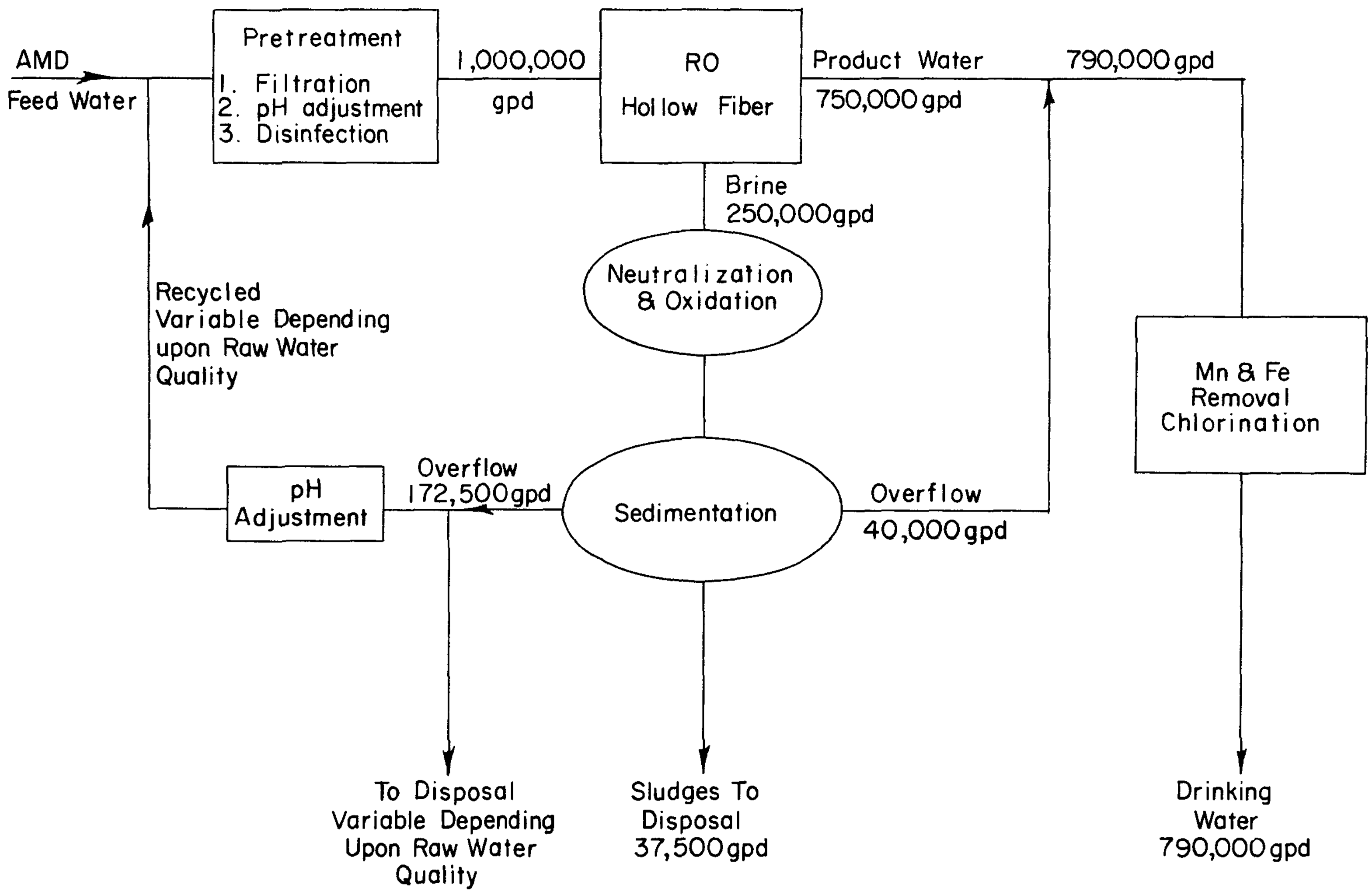


FIGURE 60

FLOW SHEET USED FOR COST ESTIMATES

After Rex Chainbelt, Inc., 1972[72]

TABLE 56

MAJOR COST ITEMS FOR 0.75 MGD
REVERSE OSMOSIS TREATMENT PLANT

I. CAPITAL COSTS

A. Pretreatment

Filtration (diatomaceous earth)	
pH Control	
Disinfection	$ 29,000

B. RO System

Modules	
Pumps and Plumbing	
Instrumentation	$385,000

C. Brine Treatment System

Aeration Unit (high-speed surface aerator)	
Sedimentation Unit	
Chemical Feeders and Controls	$ 58,000

D. RO Product Water Treatment

Iron and Manganese Removal	
Final Filtration	
Chlorination	$ 31,000
Total Capital Cost	$503,000

Amortized @ 6% - 20 years, = 15¢/1,000 gallons of Product Water

II. OPERATING COSTS IN ¢/1,000 GALLONS OF PRODUCT WATER

A. Chemical Additives	4.8
B. RO Modules	17.4
C. Power	7.0
D. Maintenance-Materials	2.0
E. Operating Manpower	17.3
Total	48.5

After Rex Chainbelt, Inc., 1972(72)

Gulf Environmental Systems Company performed studies[74] to evaluate the reverse osmosis process for treating acid mine drainage with high ferric iron content. They found it possible to attain water recoveries of 80 to 90 percent. Environmental Protection Agency personnel carried out neutralization and decantation operations followed by recycling of the supernatant through the reverse osmosis unit. This resulted in effective 98 percent water recovery based on feed volume, with maintenance of excellent quality in the recovered permeate water. This process combining reverse osmosis and neutralization has been termed "neutrolosis" by Hill, et al.[75]

SUBMERGED COAL REFUSE COMBUSTION PROCESS

Black, Sivalls and Bryson, Inc.[76] performed engineering, laboratory and economic studies on a two-stage coal refuse combustion process for the treatment of acid mine water. The process utilizes coal refuse as fuel to generate steam for the conversion of acid mine water to potable water. Energy for steam generation to operator evaporators for distillation or to drive pumps for reverse osmosis, is derived from a two-stage coal refuse combustion process. In the first stage of combustion, high-sulfur coal refuse or similar low-cost fuel is dissolved in a molten iron bath. In the second stage of combustion the fuel carbon is burned with air at the surface of the iron bath, generating hot carbon monoxide which can be further burned to release additional heat in a boiler.

Two-stage combustion makes it possible to use high sulfur bearing fuels without polluting the air. Fuel sulfur is trapped in the iron from which it is removed via a lime-bearing slag in the form of calcium sulfide, without generating sulfur oxides. Sulfur is also recovered from the reduction of the sulfate content of the acid mine water. Sulfates contained in the sludge generated by distillation or reverse osmosis units are dried and added to the combustor as part of the slag. Sulfur is extracted from the calcium sulfide in the slag by treating the hot slag with steam and air to recover elemental sulfur.

The recovery of sulfur from the acid mine water and the fuel, coupled with the utilization of coal refuse as a fuel, provides the economic incentive for treatment of acid mine water using this process.

Figure 61 presents a flow chart of the process. The dotted lines on the flow chart indicate the acid mine water may or may not be partially neutralized. Partial neutralization will be required for concentrated acid mine water to prevent excessive corrosion of the flash distillation equipment, but for moderately concentrated acid mine water the process economics are more attractive without neutralization. Referring to Figure 61, if neutralization is required, acid mine water is introduced intc a neutralizer (1) where it is contacted with finely divided limestone to partially neutralize the acid mine water to a pH of 3 or more. The limestone used for partial neutralization reduces the amount of flux introduced into the dryer (4) for use in combustor (5). The neutralized water which contains suspended solids is pumped to a flash distillation unit (7) to produce potable water and a concentrated brine slurry which is subsequently fed to the rotary kiln dryer (4). If acid mine water is not neutralized, it is fed directly into the distillation unit.

The rotary kiln dryer serves three functions: 1) to dry the concentrated brine slurry from the distillation unit, 2) to calcine dolomitic limestone to produce lime and magnesia for use as flux in the combustor, and 3) to preheat the portion of the desulfurized spent slag from the desulfurization unit. The contents of the dryer are fed to the combustor (5) to minimize the quantity of dolomitic limestone required in the process.

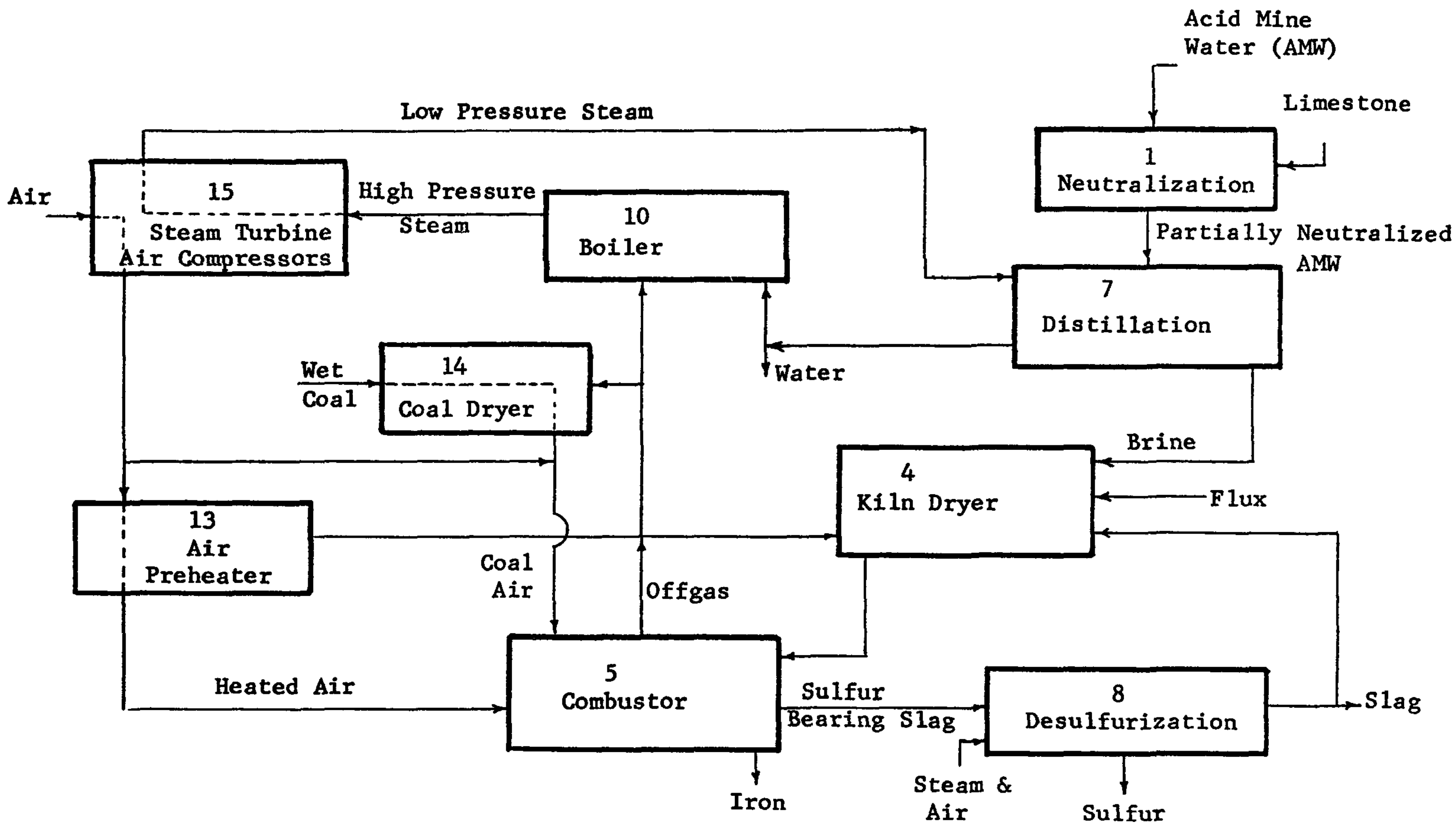


FIGURE 61
FLOW CHART ACID MINE WATER TREATMENT PROCESS
USING TWO-STAGE COAL REFUSE COMBUSTION PROCESS

From: Black, Sivalls & Bryson, Inc., 1971[76]

The combustor is a refractory-lined steel vessel that contains molten iron. Coal or coal refuse is pneumatically injected beneath the surface of the iron bath where the carbon is dissolved to free its sulfur for ultimate reaction with the flux floating on the molten iron surface. Air is then injected slightly below the surface of the bath and reacts with carbon to produce a carbon monoxide rich offgas. Heat generated during the combustion of the coal provides the necessary heat of reaction to reduce calcium sulfate contained in the dryer solids to calcium sulfide. In addition, the combustor provides the energy required to produce iron from iron compounds contained in the dryer solids and pyrite contained in the coal. Molten elemental iron is continuously removed from the combustor. Slag containing calcium oxide, magnesium oxide, ash and calcium sulfide is continuously removed from the combustor and sent to the slag desulfurization unit (8) where it is contacted with steam and air to produce a sulfur-rich gas. Elemental sulfur is condensed out of this gas and sent to storage.

Desulfurized spent slag exiting the desulfurization unit is divided into two streams which proceed to the dryer, and to a spent slag storage pile. Spent slag consists of a dry mixture of silica, alumina, magnesium hydroxide and calcium hydroxide.

Carbon monoxide rich offgas generated in the combustor is used to supply energy for operation of auxiliary equipment. A large fraction of the combustor offgas is sent to the waste heat boiler (10) which provides high pressure steam for the steam turbine-air compressors (15) and the exiting low pressure steam for the flash distillation unit. Steam generated in the waste heat boiler undergoes a pressure reduction through the steam-turbine air compressors before entering the distillation unit. In the study, steam from the waste heat boiler was assumed to enter the distillation unit directly. Steam turbine air compressors are used to generate pressurized air for combustion and coal pneumatic conveying. Combustor offgas is also used to provide the energy requirements for air preheating (13), for drying and calcining the dryer contents, and drying the incoming coal (14).

Laboratory experimentation was conducted on those areas which could profoundly affect the process. Engineering studies show that the process has potential for supplying inexpensive energy for distillation and permits the recovery of sulfur so that distilled water is economically produced. Depending upon the acid mine water composition and a sulfur selling price ($20 to $30/ton) the break-even price of water for a 5 MGD plant varies between $0.42 and $0.16/1,000 gallons when a 14 percent capital interest charge is used.

Table 57 shows the acid mine water compositions used in the studies and Table 58 gives an analysis of the coal refuse selected as representative of a high sulfur coal. Table 59 shows the capital investment needed for various sizes of treatment plants using the two-stage coal refuse combustion process. The break-even price or the cost per 1,000 gallons of product water for a 5 MGD plant is shown in Table 60. Figure 62 indicates that the capital investment is not a linear function of plant capacity and economies can be realized by using higher plant capacities. This infers that the plant should be located at a large source of acid mine drainage provided coal refuse is located in the vicinity. All costs are based on mid-1970 prices.

TABLE 57

ACID MINE DRAINAGE COMPOSITIONS USED IN STUDY OF TWO-STAGE COAL REFUSE COMBUSTION PROCESS

	Dilute (ppm)	Moderately Concentrated (ppm)
Acidity (as ppm $CaCO_3$)	400	1,200
Sulfate	1,061	3,183
Total Iron	200	600
Calcium (as Ca)	80	240
Aluminum (as Al)	5	15
Magnesium (as Mg)	24	72

TABLE 58

ULTIMATE ANALYSIS OF COAL REFUSE
(% By Weight)

Carbon	40.6
Hydrogen	2.9
Oxygen	3.7
Nitrogen	0.7
Sulfur	10.0
Moisture	3.0
Ash	39.3

From: Black, Sivalls, & Bryson, Inc., 1971[76]

TABLE 59

CAPITAL INVESTMENT FOR VARIOUS SIZE
ACID MINE DRAINAGE TREATMENT PLANTS
USING THE TWO-STAGE COAL REFUSE COMBUSTION PROCESS

Equipment Complex Cost	0.5 MM GPD	1 MM GPD	2 MM GPD	5 MM GPD	10 MM GPD
Coal Handling	53,000	81,000	122,000	213,000	321,000
Neutralization	-0-	-0-	-0-	-0-	-0-
Steam Turbine Air Compressor	16,000	25,000	38,000	66,000	100,000
Direct Fired Furnace	41,000	63,000	95,000	164,000	249,000
Waste Heat Boiler	39,000	59,000	90,000	156,000	236,000
Rotary Kiln Dryer	144,000	218,000	330,000	572,000	867,000
Desulfurization	38,000	57,000	87,000	150,000	229,000
Combustor	27,000	40,000	61,000	106,000	161,000
1. Total Purchased Equipment	358,000	543,000	823,000	1,427,000	2,163,000
Installation, 40% of 1	143,000	218,000	330,000	571,000	865,000
Piping, 10% of 1	36,000	54,000	82,000	143,000	216,000
Electrical, 10% of 1	36,000	54,000	82,000	143,000	216,000
Instrumentation, 15% of 1	54,000	82,000	124,000	214,000	324,000
Utilities, 10% of 1	36,000	54,000	82,000	142,000	216,000
2. Physical Plant Cost	663,000	1,005,000	1,523,000	2,640,000	4,000,000
Engineering & Construction, 30% of 2	199,000	302,000	457,000	792,000	1,200,000
3. Direct Plant Costs	862,000	1,307,000	1,980,000	3,432,000	5,200,000
Contractor's fee 5% of 3	43,000	65,000	99,000	172,000	260,000
Contingency, 10% of 3	86,000	131,000	198,000	343,000	520,000
4. Fixed Capital Investment	991,000	1,503,000	2,277,000	3,947,000	5,980,000
5. Installed Cost, Distillation	1,045,000	1,583,000	2,400,000	4,158,000	6,304,000
Total Capital Investment	2,036,000	3,086,000	4,677,000	8,105,000	12,284,000

From: Black, Sivalls & Bryson, Inc., 1971[76]

TABLE 60

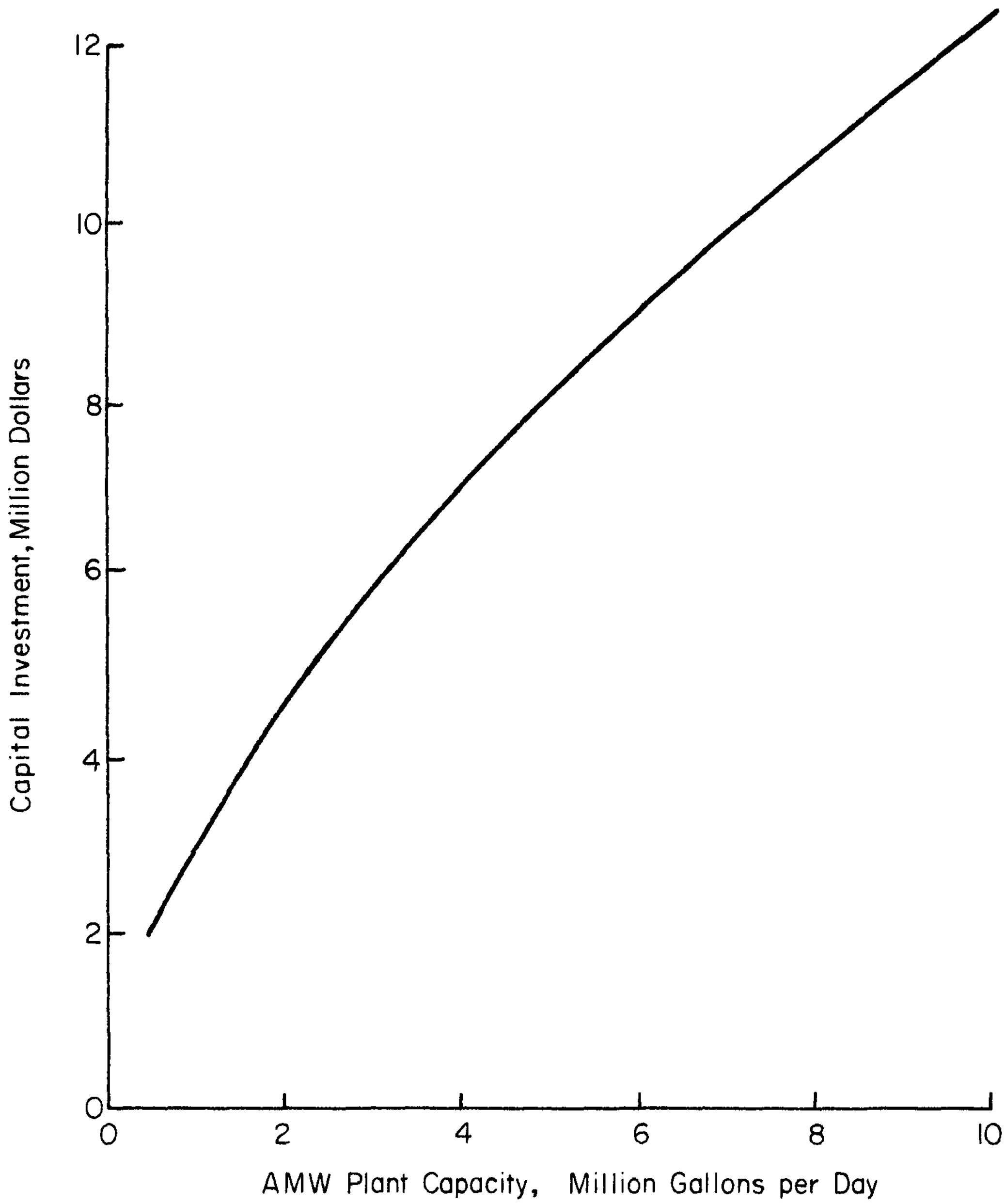
DETERMINATION OF BREAK-EVEN PRICE OF WATER**
5 MGD ACID MINE DRAINAGE TREATMENT PLANT
USING TWO-STAGE COAL REFUSE COMBUSTION PROCESS

Investment Cost		$8,100,000
Potable Water Production		4,975,000 GPD
Daily Production Cost		
Capital Interest Charge*, (14%)		3,150
Flux, 1105 Tons @ $2/ton		2,210
Coal Refuse, 1427 Tons @ $0.25/ton		357
Labor		300
Maintenance, 3% of Investment		675
	$	6,692
Daily Production Credits (not including potable water credit)		
Sulfur, 126 tons @ $25/ton	$	3,150
Iron, 60 tons @ $20/ton		1,200
Slag, 1082 tons @ $.5/ton		541
	$	4,891
Operating Revenue (not including potable water credit)		(1,801)
Break-even Price of Water	$\frac{\$1,801 \times 1,000}{4,975,000}$ =	$0.36/1000 of water
Potable Water Credit	$	1,801
Operating Revenue		0

*Capital Interest Charge = $8,100,000 x .14/360 days

**Assume: 1) Moderately concentrated acid mine drainage, 2) eight (8) percent sulfur refuse, and 3) a heat rate of 3.25 million BTU per 1,000 gallons of acid mine drainage.

FIGURE 62



EFFECT OF PLANT CAPACITY ON CAPITAL INVESTMENT
TWO STAGE COAL REFUSE COMBUSTION PROCESS

From: Black, Sivalls, & Bryson, Inc., 1971 (76)

FREEZING (CRYSTALLIZATION) PROCESS

Hill, 1968[1] discusses the principles of crystallization treatment and says crystallization processes have a distinct energy advantage over many other methods of demineralization because the freezing (heat of fusion) of water only requires 144 btu per pound of water, or less than one-sixth of the heat of vaporization. In his opinion, two methods of crystallization appeared applicable to the treatment of mine drainage, i.e. the freezing method and the gas hydration method, although, these techniques had not been tested on actual mine drainage. He points out that the immediate research need in the area of crystallization is a study to determine if the more troublesome ions found in mine drainage, such as ferrous iron, ferric iron, sulfate, calcium, aluminum, magnesium and manganese can be removed efficiently and economically.

Applied Science Laboratories, Inc.[77] under contract to the Environmental Protection Agency performed a series of over 50 batch experiments in a study of the freezing process in 1970. In these experiments four-liter quantities of acid mine water were subjected to partial freezing to the extent of up to 50 percent conversion to ice. After partial freezing, the ice and unfrozen water (mother liquor) were separated. The ice was melted and these melts (product water) were found to have a reduction of metal and acid components of 85 to 90 percent. In experiments in which both ferrous iron and total iron were determined, the product water had about the same ratio of ferrous iron to total iron as the original acid mine water, so it appears there is little oxidation of ferrous iron during the partial freezing. Difficulties with analytical results prevented a firm conclusion as to the reduction of sulfate.

Similar percent reductions of metal ions occurred in freezing experiments using acid mine water that had been treated with lime. Reduction in hardness of the lime-treated water was nearly 100 percent, but the pH remained substantially unchanged.

As a result of these experiments, Applied Science Laboratories, Inc., proposed a partial freezing process described in Figure 63 consisting of the following three steps:

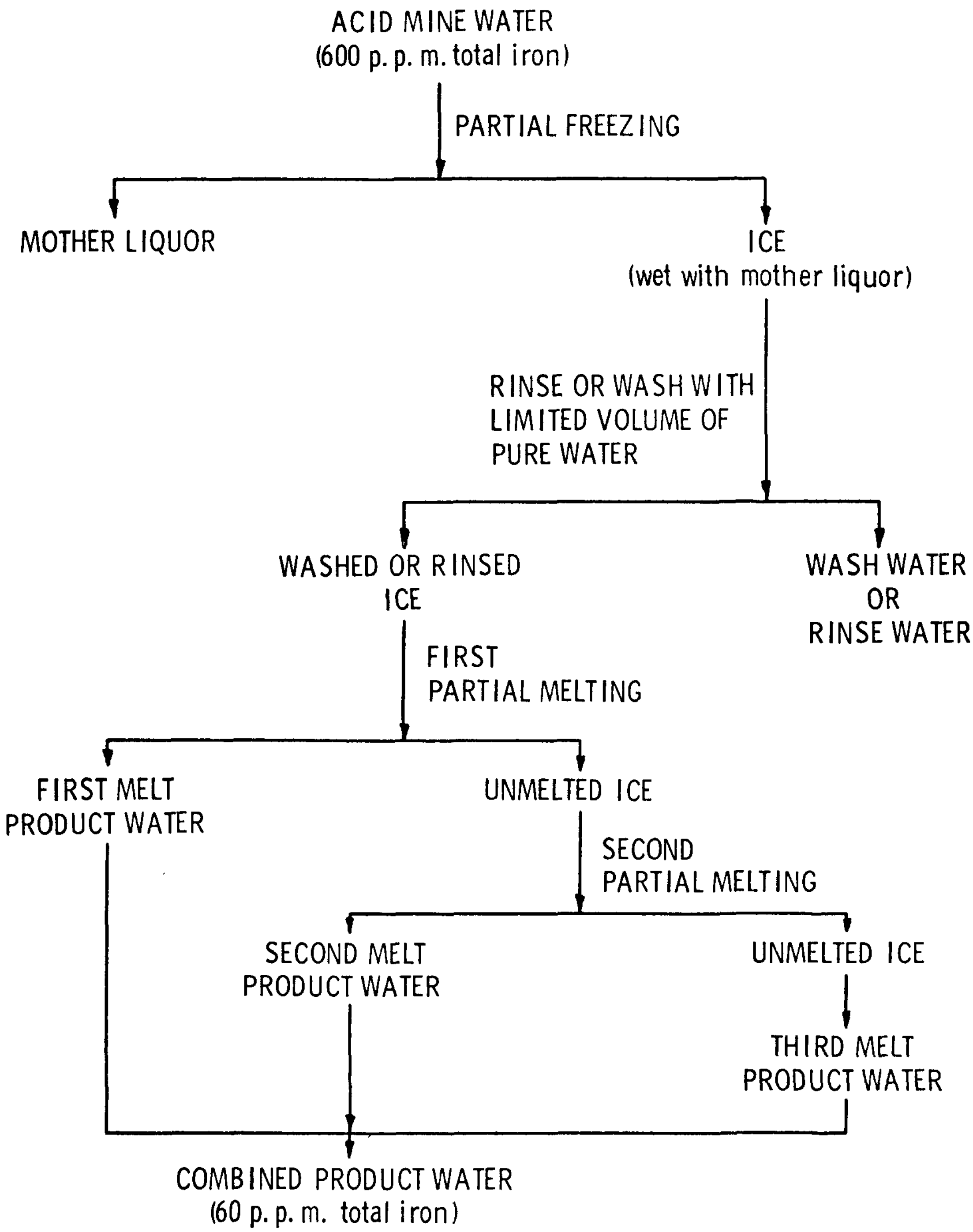
1. The mineralized water is refrigerated to convert a considerable fraction of it into ice.

2. As much as possible of the mother liquor is drained off the ice, almost all the salts remain in the mother liquor.

3. The ice is melted to produce product water.

Partial freezing as a crystallization process appears to be technically feasible for treatment of mine drainage, but studies have not advanced beyond laboratory batch tests. It is yet to be proven that this method would be applicable to mine drainage treatment in large scale studies, i.e., technically or economically feasible.

FIGURE 63



FLOW DIAGRAM FOR PARTIAL FREEZING
OF ACID MINE WATER

From: Applied Science Laboratories, Inc., 1971[77]

The Office of Saline Water has been studying the separation of salts from water by crystallization for a number of years, but these studies are concerned with treatment of brackish water and not mine drainage. Several pilot plants are in operation. Schroeder, et al.[70], in 1966 wrote a report for the Office of Saline Water in which they analyzed the application of saline water conversion processes to acid mine waters. They estimated the cost of treating mine drainage from Kittanning Run, Pennsylvania by vacuum freezing, secondary refrigerants (N-Butane) and the hydrate process. These costs for plant investment and operation are calculations only, based on the assumption that the desalinization data are applicable to acid mine drainage. The capital and operating costs are presented in Table 61 and they have not been updated since it is felt that updating these costs would serve no purpose.

TABLE 61

SUMMARY OF CRYSTALLIZATION COSTS USING KITTANNING RUN, PENNSYLVANIA, WATER AS FEED

Capital Costs

Plant Capacity (millions of gal./day)	Direct Freezing	Secondary Refrigerant	Hydrate Process
0.1	$ 434,900	$ 456,800	$ 465,900
1.0	2,219,000	2,198,000	2,273,000
10	12,945,000	11,970,000	12,572,000
100	81,608,000	70,362,000	74,940,000

Operating Costs (dollars per 1,000 gallons)

Production (millions of gal./day)	Direct Freezing	Secondary Refrigerant	Hydrate Process
0.1	3.10	3.18	3.23
1.0	1.32	1.34	1.38
10	0.85	0.85	0.89
100	0.68	0.67	0.71

Note: (1) Plants operate at a load factor of unity
(2) Product water is about 400-500 mg/l total dissolved solids

After Schroeder, et al., 1966[70]

ELECTRODIALYSIS PROCESS

Considerable work has been accomplished by the Office of Saline Water in using electrodialysis for production of fresh water from brackish water. The electrodialysis process, like the reverse osmosis process, utilizes membranes, however, electricity is the driving force in electrodialysis.

An electrodialysis unit would consist of a number of narrow compartments separated by closely spaced membranes. Each compartment is bound by a cation and an anion membrane which are permeable to positive and negative ions respectively. A positive electrode is located at one end of this "stack" and a negative electrode is located at the other end. The intermediate channels between each pair of membranes is filled with the solution to be processed. When the electrodes are energized, thereby causing an electric current to pass through the solution and the stack of membranes, the ions contained in solution migrate through the various channels. Cations migrate through the cation membranes and anions through the anion membranes. Considering a group of three channels separated by two membranes (one anion permeable and one cation permeable), it can be seen that the cations and anions migrate from the center channel through the respective membranes enclosing the channel reducing the concentration of salts in this center compartment. Since the entire stack of membranes consists of alternate anion and cation elements, a succession of fresh water and brine channels is found to exist(41).

The principle energy requirement of the electrodialysis process is electrical energy to the electrodes in the stack. Energy is also used for pumping the feedwater through the system. The total electric energy required is a function of the salt reduction which must be accomplished in producing fresh water. An electrodialysis plant for treatment of acid mine drainage would consist of 1) a coagulation-filtration pretreatment processing unit to reduce iron, manganese, and suspended solids concentrations and to adjust pH, 2) a circulating pump, 3) electrodialysis unit, 4) product water recovery and storage system, and 5) provisions for brine disposal(41).

Bench scale studies of electrodialysis for mine drainage treatment were performed by the Environmental Protection Agency at Norton, West Virginia, in cooperation with the Office of Saline Water(78). When used on water receiving no pretreatment, the cathode cell quickly became fouled with iron. In those cases where the mine drainage was pretreated by lime neutralization for iron removal, the unit operated satisfactorily.

Schroeder, et al.(70) calculated capital and operating costs for various size treatment plants in their 1966 analysis of the application of saline water conversion processes to acid mine drainage treatment. It should be pointed out that these costs are assumptions based on the application of a process effective in saline water conversion, but not tested for acid mine drainage treatment. Table 62 presents these capital and operating costs which are not updated for this study.

TABLE 62

ELECTRODIALYSIS TREATMENT PLANT
USING KITTANNING RUN, PENNSYLVANIA
WATER AS FEED

Plant Capacity (Millions of Gal./Day)	Capital Cost	Operating Costs ($/1,000 Gallons)
0.1	$ 249,000	2.52
1.0	1,309,000	1.01
10.	8,760,000	0.68
100.	65,709,000	0.58

Note: 1) Plants operate at a load factor of unity.
2) Product water is about 400-500 mg/l total dissolved solids.

After Schroeder, et al., 1966[70]

FOAM SEPARATION (FRACTIONATION) PROCESS

Foam separation (fractionation) is based on the phenomenon of surface activity which results from the ability of certain solutes (surfactants) to reduce the surface free energy of their solutions, and therefore the total free energy of the system, by accumulating at an interface. Surface activity as it relates to foam separation process is described using the concept of Gibbs surface excess[79].

In practice, foam separation consists of passing bubbles through a solution of surface active solute(s) with the aim to adsorb the solute(s) onto the gas-liquid interfaces and to remove these surfaces intact as foam, thus effecting a separation. Further, by coadsorption of non-surface active with surface active solutes, the former can be separated from solution with the latter. This is the case in the treatment of acid mine drainage[79].

Horizons Incorporated[80], conducted laboratory studies of continuous flow foam separation to determine the optimum operating conditions of maximum extraction of dissolved metal cations (Fe, Ca, Mg, Mn and Al) from acid mine drainage. Continuous flow foaming experiments were conducted in a 6 inch diameter glass column capable of liquid flow rates of 3 to 12 gallons per hour. The approach to foam separation taken was the production of persistent foams which allowed protracted foam drainage to reduce liquid carry-over in the foam. The effects of pH, chelate addition, surfactant type and concentration, air sparging rate, metal concentration and foam drainage were investigated in relation to metal extraction.

The low extraction capacity of foam separation (fractionation) makes the process unattractive for the treatment of acid mine drainage.

NEUTRADESULFATING PROCESS

This process essentially involves 1) neutralization of mine drainage feed and precipitation of iron and aluminum using soda ash or sodium bicarbonate as the neutralizing agent and 2) treatment of the effluent which is now free from iron and aluminum by an ion exchange system to remove sulfate. The resin is loaded in the barium form, and the barium sulfate precipitate is removed. Catalytic, Incorporated[81] conducted laboratory studies on acid mine drainage and developed the conceptual neutradesulfating process shown in Figure 64.

The advantages claimed for the process are:

1. A substantial reduction in the concentration of major pollutants in the acid mine water. Virtually a complete removal of iron and aluminum and a large reduction in sulfate content.

2. Sludge disposal is at a minimum.

3. Operating costs for labor are low.

4. Almost all of the chemicals produced are reused in the process.

5. Production of a high-purity water.

However, as reported by Catalytic, Inc., based on the projected or scaled up technology, the treatment cost for a 1 MGD plant would be $2.69/1,000 gallons of treated water based on a 30 year payback period at 4.6%. The total capital investment was estimated at 4.96 million dollars and represents about 35% of the unit cost or $0.94/1,000 gallons.

Because of the high projected cost of acid mine drainage treatment by this method, the project was terminated.

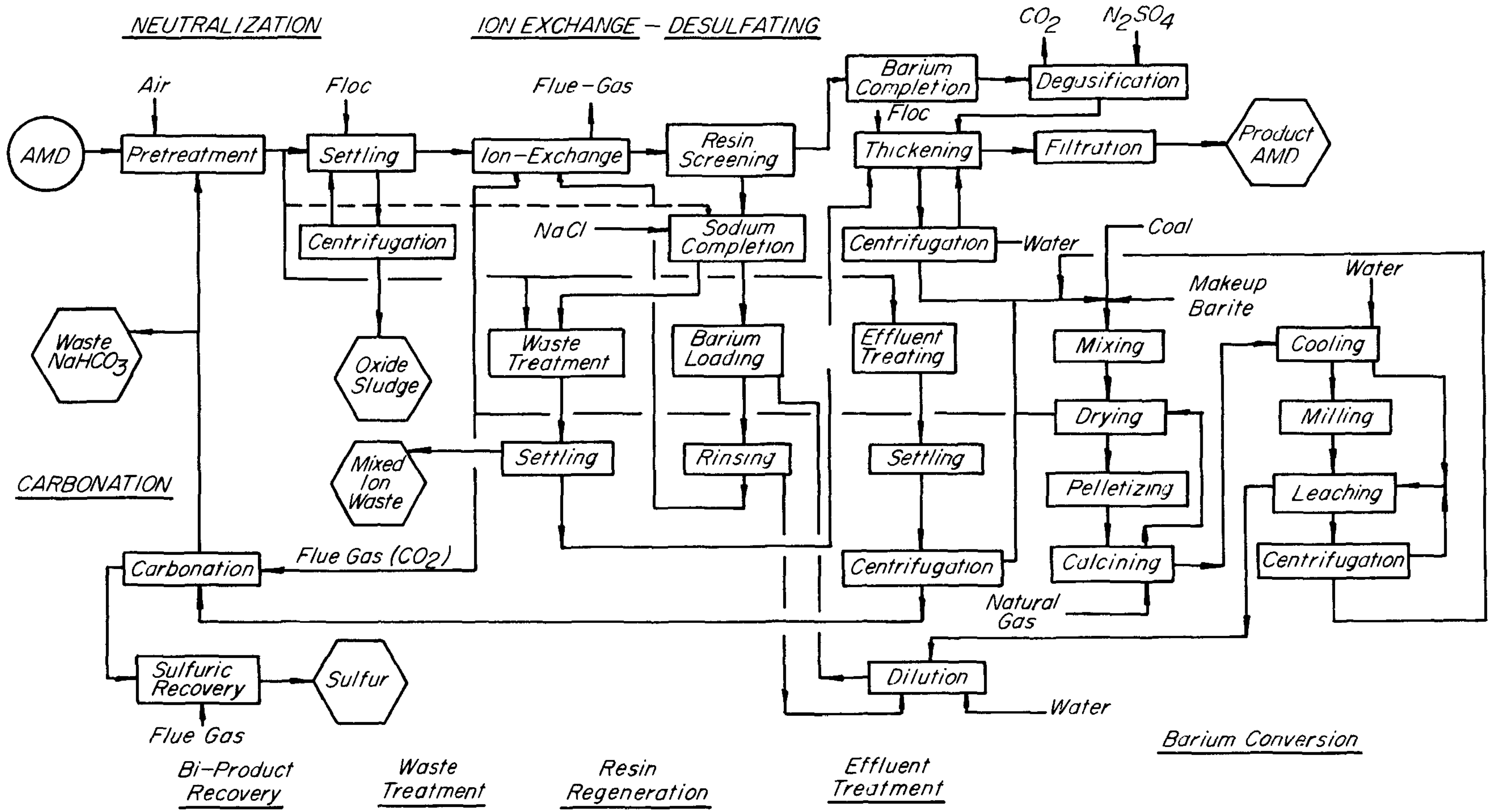


FIGURE 64

SCHEMATIC FOR AMD NEUTRADESULFATING

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OTHER MINE DRAINAGE ABATEMENT PROCEDURES

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OTHER MINE DRAINAGE ABATEMENT PROCEDURES

Limestone Barriers Across Streams

It has long been known that acid mine waters flowing through a limestone terrain become neutralized. The construction of limestone barriers across streams is an attempt to create similar environmental conditions in alkaline poor stream basins.

This method of stream neutralization was tried on Sandy Run in Vinton County, Ohio in the early 1950's[1]. Sandy Run is an acid stream feeding Lake Hope, a center for extensive water-oriented recreation. A low dam was constructed across Sandy Run and the upstream side of the structure filled with granular limestone. The path of natural stream flow was directed through the limestone bed. The limestone was initially effective in raising the pH of the water, but in less than one month, a heavy rain and resulting high stream flow largely covered the limestone bed with sand and reduced its effectiveness. The sedimentation problem grew progressively worse so that within six months, it was necessary to move the limestone from behind the dam to the stream bed below the structure. Again, an initial improvement in water quality was noted at normal stream flow rates. As before, this improvement gradually diminished as sediment accumulated in the voids of the limestone bed. The project was abandoned.

Recently, under Operation Scarlift Project SL 121, a series of six limestone barriers were constructed across Trough Creek in Huntingdon County, Pennsylvania. The project was designed by Africa Engineering Associates, Inc. for the Pennsylvania Department of Environmental Resources and the cost of construction was funded by a grant from the U. S. Environmental Protection Agency[2].

The barriers were constructed of coarse limestone aggregate having a high calcium-low magnesium carbonate composition. The aggregate is held in place by a blanket of heavy stone riprap on the upstream and downstream sides of the limestone barrier. Riprap was also placed along the stream banks for erosion control. The total cost of construction was \$191,270.00 and engineering design costs were \$22,198.00. Contract items and costs are as follows:

Item	Quantity	Unit	Unit Price	Cost
Site Clearing	Job	L.S.	---	$ 15,000.00
Excavation and Disposal	9,306	C.Y.	$ 2.40	$ 22,334.40
Rolled Embankment	1,109	C.Y.	$ 1.80	$ 1,996.20
Furnishing and Placing Riprap Creek Bank Linings	552	S.Y.	$12.00	$ 6,624.00
Furnishing and Placing Grouted Stone Riprap	798	S.Y.	$18.00	$ 14,364.00
Furnishing and Placing Concrete Masonry	153	C.Y.	$80.00	$ 12,280.00
Furnishing and Placing Rock Fills	1,552	C.Y.	$12.00	$ 18,624.00
Furnishing and Placing Limestone Media	3,336	C.Y.	$24.00	$ 80,064.00
Other Misc. Items	---	---	---	$ 19,983.40
Total Cost				$191,270.00

The average cost for a limestone barrier on this project was $31,878.33. The limestone barriers are still undergoing evaluation for their effectiveness in neutralizing the acid flow. It appears remedial construction will be necessary because of erosion and siltation of the barriers and it is possible this problem may occur annually.

Major factors affecting costs on projects of this nature are:

1. Accessibility of project area.
2. Time of construction.
3. Complexity of design.
4. Availability of riprap materials.
5. Haulage distance of suitable crushed limestone.
6. Nature of stream bottom.
7. Frequency and magnitude of stream flooding.
8. Stream water quality.
9. Degree of neutralization desired.

Insitu Precipitation of Ferric Hydroxide

Laboratory studies performed by the Parsons-Jurden Corporation[3] indicated insitu neutralization of mine water with the resulting precipitation of sludge would be effective in mine sealing. Water slurries of alkaline reactants such as limestone or fly ash if injected directly into the water in a mine would form a sludge. The sludge formed should eventually fill the mine and effectively seal it. The advantage of filling with sludge, is that sludge is a balking type precipitate, taking up more volume than that occupied by the unreacted material used to treat the mine water.

In 1968 the Parsons-Jurden Corporation received a contract from the Pennsylvania Department of Mines and Mineral Industries, now the Department of Environmental Resources, for mine sealing by insitu precipitation of ferric hydroxide. The actual work performed consisted of the construction of rubble barriers within three mine headings of the inactive Driscoll No. 4 mine near Vintondale, Pennsylvania. The barriers were constructed of available materials from within the mine and injection pipes extended through the barriers to the interior of the mine. A lime slurry was injected into the mine to neutralize the mine water and precipitate iron hydroxide. Clogging of the rubble barriers with iron hydroxide did not occur and the project was abandoned.

The mine drainage effluent was alkaline during pumping operations, but whenever the injection of lime slurry was stopped the effluent became acidic. The reasons for the failure of sludge to form have not been documented, but it appears the alkaline effluent did not precipitate iron hydroxide until after it left the mine. Cost figures are not available, but it is estimated the total project cost exceeded $250, 000.

Spoil Pile Neutralization

Spoil pile neutralization by drilling and grouting a pulverized limestone - lime slurry has recently been completed near Toms Run in Clarion County, Pennsylvania. This work was performed for the Pennsylvania Department of Environmental Resources under Operation Scarlift Project SL 165[4].

If mine refuse is grouted with powdered limestone and lime, an alkaline reserve should be available for neutralization of the acid salts produced by pyrite oxidation. In addition to this effect, pyrite may become sealed from the air when surrounded by the grout slurry. A third mechanism may also operate to reduce the amount of pyrite undergoing chemical reaction; the sudden change in pH of the spoil material may decrease the activity of iron oxidizing bacteria.

The costs for this project are as follows:

	Description	Unit Price	Quantity	Cost
1.	Slurry Injection Holes	$ 1.00/Each	453.	$ 453.00
2.	Driving Grout Sleeves	0.50/L.F.	9,778.	4,889.00
3.	Pulverized Limestone	11.45/L.F.	5,234.4	59,933.88
4.	Hydrated Lime	35.00/L.F.	504.13	17,644.55
5.	Flume Drains	3.25/L.F.	1,400.	4,550.00
	Total Cost			$87,407.43

Pollution abatement using this method would have the advantage of producing immediate and significant results. There is some doubt, however, as to the lasting effect of this type treatment.

The main factors affecting costs of spoil pile neutralization are:

1. Accessibility of the project area.
2. Unit Costs of materials.
3. Haulage distance for materials.
4. Number of drill holes required.
5. Degree of abatement desired.

Deep Mine Water Diversion

Mine water diversion work is in progress at the Ernest Mine Complex, Operation Scarlift Project No. SL 107-4, in Indiana County, Pennsylvania(4). The purpose of the project is to divert mine drainage flows from various locations in the mine to a central point where a water treatment plant will be constructed in the future.

In order to achieve this goal, it is necessary in several areas of the extensive mine workings to impound water to a design elevation so that mine waters can flow over drainage divides or humps within the mine to the central treatment location. The necessary work includes sealing of numerous shafts, drifts and boreholes, the placement of an 18 inch mine water transfer pipe within the mine, removal of a mine barrier, installation of permanent valves and concrete structures as well as other items.

The original contract estimate for this diversion work was $266,815, however, a total of five change orders to date have increased the total estimated cost to $333,790 and additional change orders may be necessary. Some reasons for the additional cost are as follows and they provide an insight into the types of problems that can be expected in deep mine water diversion:

1. Additional boreholes were discovered during exploratory shaft excavation and they required sealing.

2. Dewatering of some areas was not practical and the 18 inch transfer pipe had to be installed under water in these areas.

3. Two mine dams were found to be unsatisfactory and additional work was required.

4. A subsidence cave-in developed during construction which required removal of material and support to prevent a total collapse which would have damaged the 18 inch transfer pipe.

5. The sealing of some parts of the mine created hydraulic heads which caused boreholes and nearby water wells to develop artesian flow. These boreholes and water wells will have to be sealed.

6. Some contract items, such as calipering and reaming of boreholes, appear to be unnecessary and may have added to the project cost.

Insitu Neutralization of Acid Mine Water by Injecting Fly Ash into Deep Mines

The Duquesne Light Company is sluicing alkaline fly ash from the Colfax power station into an abandoned section of the Harwick Mine. The mine and power station, both owned by Duquesne Light Company, are about 14 miles northeast of Pittsburgh. The idea of this unique system was conceived, in part at least, because of space limitations for fly ash disposal at the adjacent site for the new Cheswick plant under construction. The Harwick Mine will be completely worked out about the time the new power station goes into service.

The engineering study for Cheswick plant indicated there were distinct economic advantages in disposing of fly ash into the Harwick Mine. Cost of removal of fly ash to a landfill area is 80 - 90¢/ton. Capital investment proposals for conventional ash disposal varied from $500,000 to over $1,000,000 and annual operation and maintenance cost was estimated at $250,000.

Cost estimates for the proposed fly ash disposal system, including mine modifications, pumps, an electrical substation and the necessary controls, were less than the amounts for conventional fly ash disposal methods. Savings for the new Cheswick plant are estimated at $700/day, after allowances for mine dewatering costs.

In addition to treatment of acid mine water, deep mine disposal of fly ash has the distinct added advantage of eliminating completely the air pollution problems associated with landfill disposal.

The disposal system using both fly ash and bottom ash from the Colfax plant has operated for 18 months, with only minor problems (as of December, 1968). The ash is pumped as a slurry through a borehole into the mine. Dams have been constructed in the mine to form a large sedimentation basin to settle the fly ash out of the mine water.

The water quality characteristics of the effluent have been well within the quality limits prescribed by the Pennsylvania Sanitary Water Board. The amount of water pumped from the ash disposal basin has averaged over 2 million gallons/day. In the 18 months the ash disposal system has been in operation, the suspended particulate content of the effluent has never approached the permissible maximum of 200 mg/l; the highest observed value was 97 mg/l. Average values for water quality characteristics are: pH - 7.2, Fe - 2.5 mg/l and suspended solids - 9.4 mg/l.

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REFUSE BANK AND MINE FIRES

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REFUSE BANK AND MINE FIRES

Introduction

Our present day environmentally oriented society is constantly on the alert for new ways and means to combat all forms of pollution. In the Appalachian region, a recurring and everpresent source of pollution has been the sulfur-emitting, smoldering coal waste banks and deep mine fires. The population has been able, only in recent years, to make their voices heard regarding the detrimental effects of these fires and urge that measures be taken to eliminate this source of pollution.

The deep mine fires are usually extinguished or brought under control in a relatively short period of time, only if they associated with actively producing coal properties, fires in abandoned mines have been allowed to burn unattended, but not unnoticed for decades.

Coal refuse or waste banks have never seemed to warrant the attention of the deep mine fires, even though they are a public nuisance and an environmental hazard.

Over the many years these fires have existed, sporadic attempts have been made by coal companies, municipal and other governmental bodies to control them. It was not until the establishment of the Appalachian Regional Commission which was created by the Appalachian Regional Development Act of 1965 that sufficient funds were made available to put forth a concentrated effort to combat refuse bank and mine fires. This effort is not only helping to reduce pollution, but is protecting a valuable national resource.

National Surveys of Burning Refuse Banks

In 1963, the U.S. Bureau of Mines, through a cooperative agreement with the Public Health Service, Department of Health, Education and Welfare, conducted the first nationwide reconnaissance survey of burning coal refuse banks. This survey noted 495 burning coal refuse banks in the United States[1,2].

Another survey conducted in late 1968 and early 1969 noted 292 burning coal refuse banks in 13 of the 26 coal-producing states. This total includes only refuse banks that were determined to be smoldering or buring through visual indications such as flames or "fire glow," thermal waves above the refuse bank, smoke, fumes, or a combination of these conditions. Seven states in the Appalachian region accounted for 264 burning banks, or 90 percent of the total. States that had reported burning refuse banks in the past, but in which none were known to be burning in 1969, include Alaska, Indiana, Iowa, New Mexico, Tennessee and Wyoming[2].

Coal refuse fires have proven to be extremely hazardous to the environment and its inhabitants. At least 55 persons have lost their lives as a result of burning banks. The health and safety of nearby residents, particularly children and elderly persons, is threatened as a result of the impairment of air quality caused by the airborne pollution generated by burning waste banks. Vegetation and building materials are also severely damaged or destroyed when the gases are heavily concentrated in an area nearby these sulfur-emitting banks[2].

Ignition of Refuse Banks

Ignition of a refuse bank can be initiated in several ways. A recent U.S. Bureau of Mines report outlines the following possible sources of combustion (Maneval[1]):

1. Spontaneous ignition

    a. Sufficient air must enter the refuse dump to oxidize the coal and other combustible materials.

    b. Air must be insufficient in quantity to carry away the heat generated during the oxidation, thus permitting the heat to accumulate.

2. Careless burning of trash on or near the bank.

3. Forest fires

4. Camp fires left burning

5. Intentional ignition to create residue which may be used for road base materials.

Spontaneous combustion is a common cause of coal refuse fires. Sixty-six (66) percent of the 292 refuse banks found burning in 1968 are believed to have started by heat generated within the pile. This phenomenon results from the flow of air through combustible refuse material and consequent oxidation. When sufficient oxidation occurs, heat is generated, and the combustible components in the pile ignite[2].

Methods of Controlling and Extinguishing Fires

Federal and State governments have undertaken research projects to control and extinguish coal waste bank and deep mine fires. Various techniques have been tried, some of which are listed as follows:

Coal Refuse Bank Fires[1]

1. Accelerated Combustion and Quenching
2. Isolation
3. Foam Covering
4. Vermiculite and Sodium Bicarbonate Injection and Coating
5. Injection of Fine Mineral Matter
6. Mine Drainage Sludge Injection
7. The Use of Anti-Oxidants
8. Saturation Through Serpentine Canals
9. Ponding Technique (Rice Paddy)
10. Cooling and Dilution
11. Blanketing with Clay and Cement Waste
12. Blanketing - Quarry Wastes
13. Use of Explosives Followed by Quenching
14. Hydraulic Jets (Water Cannon Technique)
15. Water Sprays

Deep Mine Fires

1. Dry Fly Ash Injection with Surface Seals
2. Isolation Plug Barrier and Surface Seal
3. Fly Ash Injection (Wet and Dry)
4. Sand Flushing (including sand barriers)
5. Trenching and Sand Barrier
6. Underground Dam with Water Flooding
7. Smothering with Isolation Seal

Prevention of Coal Refuse Bank Fires

McNay[2] discusses the problems associated with coal refuse disposal and indicates refuse bank fires can be prevented if more attention is directed toward: 1) Site selection and preparation, 2) Refuse bank design, and 3) Site reclamation and abandonment. The following factors and requirements are important when considering these items of refuse disposal planning:

1. Site Selection and Preparation

    a. Terrain suitable for intended type and quantity of refuse disposal
    b. Geologic investigation of site
    c. Evaluation of drainage in area
    d. Source of non-combustible material nearby
    e. Clearing of all combustible material from the site
    f. Adequately seal off all coal outcroppings

2. Refuse Bank Design

    a. Slope of terrain and foundation materials

b. Site drainage
c. Compaction methods (soil mechanics principles employed)
d. Control of material segregation, sizing and grading
e. Outside slope sealing

3. Site Reclamation and Abandonment

a. Bank properly graded, compacted and sealed
b. Final layer of non-combustible material placed over bank
c. Establish vegetative cover
d. Fencing and signing
e. Periodic inspection or regular patrols

Prevention of Deep Mine Fires and Explosions(3)

The down-time of a mine as a result of a fire or explosion can be long and the cost of recovery and reconditioning can be extremely high. Some companies have been forced into bankruptcy as a result of such disasters. Every individual working in a coal mine should be educated as to the cause and preventative measures designed to prevent disasters. They must see that the measures are adequate, are maintained, and are enforced.

With the advent of mine mechanization, changes in mining methods and transportation have been revolutionary and the use of electricity has multiplied many times. Electric power sources must be effectively controlled at all times, because a mine environment is not favorably suited to electrical installations - saturated atmospheres, dust in suspension, roof falls, poor lighting, restricted areas, constant jarring of unit-mounted sensitive control or detecting equipment, shock waves from blasting, abrasive use and makeshift repairs, all of which complicate the electrical, operational and maintenance problems.

Deep mine fires may be initiated in may ways, the following is a list of possible causes of ignition:

1. Rock falls knocking down bare electrical conductors.
2. Faulty tracks and rolling stock triggering energized trolley wires into igniting dust or other combustiles as the result of wrecks.
3. Arcs and sparks from trolley skids or wheels.
4. Overloaded power cables and conductors.
5. Failure to properly maintain permissible electrical equipment.
6. Conveyor belt fires, often due to stuck rollers.
7. Sparks from continuous mining machines cutting through pyrite inclusions.
8. Mishandling of explosives used for production blasting.
9. Smoking or open lights in gassy mines.
10. Welding operations not properly conducted.
11. Spontaneous combustion due to poor housekeeping and inadequate ventilation.

The majority of the above causes can be eliminated through compliance with the existing Federal and State mining laws, in addition to a company or mine owner following a regular strict inspection and maintenance program performed by reliable and capable personnel.

Cost Figures for Refuse Bank and Mine Fire Projects

Since the majority of the efforts directed toward the extinguishment and control of refuse bank and deep mine fires has taken place in the Pennsylvania anthracite and bituminous coal regions, the cost figures for bank and mine fire abatement projects presented in this section are from Pennsylvania projects.

Table 1 is a compilation of information on nine (9) mine fire extinguishment projects performed in the bituminous region of Pennsylvania. The unpublished data obtained from the U.S. Bureau of Mines[4] presents information on project and unit costs, and the method of extinguishing the fire is indicated.

Data on nine (9) refuse bank and stripping fires was obtained from the Pennsylvania Department of Environmental Resources[5, 6] for the anthracite region of Pennsylvania. This information is presented in Table 2 and includes project and unit costs, method of extinguishment and other pertinent data.

TABLE 1

APPALACHIAN MINE FIRE CONTROL PROJECTS(4)

(U.S. Bureau of Mines - Pittsburgh, Pennsylvania)

Pennsylvania - Bituminous

PROJECT NO. 9 January, 1972

Upper Whyel, Sewickley Township, Westmoreland County, Pennsylvania

Method: Dry Fly Ash Injection - Surface Seal - Emergency Drainage - Erosion Prevention

(Contractor - Dragan & Son)

Unit Cost	Project Costs		
	Remove Vegetation		$ 5,000.00
$ 21.00/hr.	Angle Dozer	2,082 hrs.	43,722.00
3.15/ft.	Vertical Boreholes	1,142 ft.	3,597.30
2.00/ton	Loading, Transporting and Discharging Fly Ash	29.09 tons	58.18
21.50/hr.	Dragline	408-1/2 hrs.	8,782.75
23.90/ton	Agricultural Limestone	20.45 tons	409.00
100.00/ton	10-6-4 Fertilizer	5 tons	500.00
1.00/lb.	Grass Seed	500 lbs.	500.00
1.00/bale	Hay or Straw	700 bales	700.00
			$63,269.23
	16 Percent (Supervision-Administration-Engineering)		10,123.08
			$73,392.31

TABLE 1 (continued)

PROJECT NO. 10 — September, 1970

Carpentertown, Mt. Pleasant Township, Westmoreland County, Pennsylvania

Method: Backfilling and Erosion Prevention

(Contractor: Yelinek & Smail, Inc.)

Unit Cost	Project Costs		
$13.75/hr.	Angle Dozer	806 hrs.	$10,276.50
5.00/hr.	Laborer	16 hrs.	80.00
7.00/ton	Limestone	16 tons	112.00
70.00/ton	Fertilizer	4 tons	280.00
40.00/100# unit	Grass Seed	4 100# units	160.00
0.75/bale	Hay or Straw	300 bales	225.00
			$11,133.50
	16 Percent/Administration & Engineering		1,781.36
			$12,914.06

PROJECT NO. 11 — August, 1968

Lloydsville, Unity Township, Westmoreland County, Pennsylvania

Method - Dry Ash Injection Method

(Contractor - Dragan & Son)

Unit Cost	Project Costs		
$ 1.25/ft.	Drilling Boreholes	6,449 ft.	$ 8,061.25
20.00/ft.	Casings	123 ft.	2,460.00
2.80/ton	Fly Ash	6,237.54 tons	17,465.12
	Total Cost Including Labor, Fertilizer, Seed, Lime, etc.		
	(Including 16 Percent for Administration)		$ 5,234.16
			$38,600.13

TABLE 1 (continued)

PROJECT NO. 17 December, 1970

Near Pennsylvania Turnpike - Plum and Monroeville Boroughs, Allegheny County, Pennsylvania

Method: Fly Ash Injection and Revegetation

(Contractor: Dragan & Son)

Unit Cost	Project Costs		
$ 3.70/ft.	Drilling	3,546 ft.	$13,120.20
20.00/unit	Casing with Caps (Inject. Holes)	31 units	620.00
25.00/unit	Casing Adapters	1 unit	25.00
1.50/ton	Fly Ash	78.33 tons	117.50
5.00/ton	Top Soil	70 tons	350.00
10.00/ton	Limestone	1/5 ton	2.00
50.00/100# unit	Grass Seed	1-100# unit	50.00
	Laborers	220 hrs.	1,100.00
			$15,384.70
	24 Percent Allowance for Administration and Engineering		3,692.33
			$19,077.03

PROJECT NO. 18 March, 1970

Peters Creek, Jefferson Borough, Allegheny County, Pennsylvania

Method: Surface Seal and Isolation Plug Barrier

(Contractor: Dragan & Son)

Unit Cost	Project Costs		
$ 4.00/hr.	Laborer	748 hrs.	$ 2,992.00
9.00/hr.	Dragline	256 hrs.	2,304.00
16.00/hr.	Straight Blade Dozer	1,068 hrs.	17,088.00
17.00/hr.	Angle Blade Dozer	2,583 hrs.	43,911.00
2.00/ft.	Drilling 6" Boreholes	819 ft.	1,638.00
	16 Percent Administration - Engineering - Planning and Direction		$12,133.28
	Total Cost (Including Fertilizer, Seed, Lime, Dynamite, etc.)		$87,966.28

TABLE 1 (continued)

PROJECT NO. 20 September, 1970

City of Monongahela, Washington County, Pennsylvania

Method: Removal of Vegetation - Installation of Surface Seal - Injection of Fly Ash - Prevention of Erosion

(Contractor: Dragan & Son)

Unit Cost	Project Costs		
$16.80/hr.	Dozer	1,079-1/2 hrs.	$18,351.50
12.00/hr.	Hi-Lift	404 hrs.	4,848.00
5.00/hr.	Chain Saws	1,092 hrs.	5,460.00
4.00/hr.	Laborers	1,720 hrs.	6,880.00
1.60/ft.	6" Vertical Boreholes	13,784 ft.	22,054.40
1.60/ft.	6" Angle Boreholes	418 ft.	668.80
2.00/ton	Fly Ash	2,284.075 tons	4,568.15
4.00/ton	Top Soil	304 tons	1,216.00
8.00/hr.	Truck	412 hrs.	3,296.00
	Misc. (Fertilizer, Seed Limestone, Casing, etc.)		
			$68,209.10
	24 Percent Allowance for Supervision and Administration		16,370.18
			$84,579.28

TABLE 1 (continued)

PROJECT NO. 33 — August, 1969

Ken Ridge Drive, Kennedy Township, Allegheny County, Pennsylvania

Method: Dry Fly Ash Injection - Fly Ash Slurry - Revegetation

(Contractor: Construction Methods, Inc.)

Unit Cost	Project Costs		
$18.00/hr.	Hi-Lift	236 hrs.	$ 4,248.00
5.60/hr.	Laborers	202-1/2 hrs.	1,113.75
0.95/ft.	6" Boreholes	6,822 ft.	6,480.90
10.00/unit	Basings w/caps (injection holes)	34	340.00
15.00/unit	Casing Adapters	2	30.00
1.85/ton	Fly Ash	297.25 hrs.	549.91
0.50/lb.	Grass Seed	250 lbs.	125.00
3.00/ton	Top Soil	325 tons	975.00
10.00/hr.	High Pressure Slurry Pump	110 hrs.	1,100.00
20.00/hr.	Challenge Truck Mixer	170 hrs.	3,400.00
	Misc.		
			$18,371.56
	24 Percent Administration and Engineering		4,409.17
			$22,780.73

PROJECT NO. 38 — December, 1970

Peferman's Corners, Penn Hills Township, Allegheny County, Pennsylvania

Method: Fly Ash Injection (Wet and Dry) - Revegetation

(Contractor: Allied Asphalt Company, Inc.)

Unit Cost	Project Costs		
$1.25/ft.	Vertical Boreholes	9,530 ft.	$11,912.50
1.25/ft.	Angle Boreholes	1,322 ft.	1,652.50
2.00/ton	Dry Fly Ash	340.81 tons	681.63
6.50/C.Y.	Fly Ash - Water Slurry	5,968.85 C.Y.	38,797.50
	Misc. Costs plus		
	24 Percent Allowance - Supervision and Administration		$34,671.77
			$87,715.90

TABLE 1 (continued)

PROJECT NO. 39 January, 1972

Upper Tyrone Township, Fayette County, Pennsylvania

Method: Fly Ash Injection - Revegetation

Contractor: Allied Asphalt Company, Inc.)

Unit Cost		Project Costs	
$24.00/hr.	Dozer (D8)	8 hrs.	$ 192.00
15.00/hr.	Dozer (Tractor)	96-1/2 hrs.	1,447.50
7.00/hr.	Laborers	2,040 hrs.	14,280.00
1.00/ft.	6" Boreholes	15,418 ft.	15,418.00
20.00/unit	Casing w/caps (injection holes)	34	680.00
20.00/unit	Casings w/caps (inspection holes)	3	60.00
2.35/ton	Fly Ash	4,444.86 tons	10,445.42
6.00/ton	Top Soil	204.75 tons	1,228.50
18.00/ton	Limestone	3-1/2 tons	63.00
80.00/ton	Fertilizer	3-1/4 tons	260.00
3.00/ft.	3" Boreholes	620 ft.	1,860.00
50.00/100# unit	Grass Seed	3-1/2 100# units	175.00
12.00/C.Y.	Wet Fly Ash	1,961.45 C.Y.	23,537.40
			$69,646.82
	24 Percent Supervision and Administration		16,715.24
			$86,362.06

TABLE 2

REFUSE BANK AND STRIPPING FIRES[5, 6]

(Pennsylvania - Anthracite)

Site	Project No.	Date	Area	Contractor	Method Used	Material Quantity-C.Y.	Project Cost	Unit Price Cost/C.Y.	Type
Marvine (South)	SL-201-2	1969-70	Scranton	Dixon Contracting	Sluicing with water cannon into lagoon	1,731,600	$1,523,808	$0.88	Bank
Eddy Creek	SL-207	1971-72	Olyphant and Throop Boros	Dixon Contracting	Sluicing with water cannon into lagoon	3,154,905	$2,650,886	$0.84	Bank
Laflin (Keystone)	NR-75	1966	Wilkes-Barre	---	Trenching	25,000	$ 5,975	$0.24	Bank
Plymouth	NR-88A-8	1969	Plymouth	Empire Contracting	Dozing into lagoon	15,888	$ 38,000	$2.39	Bank
Pittston Landfill	A-22	1969	Pittston	---	Hose Quenching	41,481	$ 8,680	$0.21	Stripping
Washington Street	SL-203	1970	Taylor	No. 1 Contracting	Rice Paddy	270,656	$1,381,850	$5.10	Bank
*Mt. Carmel	SL-304	1969	Mt. Carmel	Kerris and Helfrick Elycon Corp.	Stripping	8,000,000		$1.28	Stripping
**Kehley Run	SL-309	1970	Shenandoah	No. 1 Contracting	Stripping				Stripping Deep Mine Fire Surfaced
***Baker Bank	U.S.B.M. Demonstration Project	1969	Scranton	---	Sluicing with water cannon & dozing			$0.44	Bank

TABLE 2 (continued)

*<u>Mt. Carmel</u> (Project SL 304)

8,000,000 cu. yds. @ $1.28 per c.y. This figure includes drilling, blasting, loading, hauling, spreading, quenching, backfill, mobilization and demobilization.

A coal credit of $4.50 to $4.75 per ton was allowed for approximately 360,000 tons of coal. (deduct)

**<u>Kehley Run</u> (Shenandoah) Project SL 309

1,100,000 cu. yds. refuse and spoil material @ $1.65/c.y.
4,300,000 cu. yds. consolidated & solid material @ $1.65/c.y.
2,600,000 cu. yds. backfill @ $0.50/c.y.
14" pipeline and deep well pump installation (including power costs) $70,000
85,000 cu. yds. of clay seal @ $3.20/c.y.
40,000 cu. yds. of deep mine flushing @ $3.60/c.y.
2,400 linear ft. 6" diameter boreholes @ $9.00/foot
600,000 tons coal credit @ $4.35/ton (deduct)

***<u>Baker Bank</u> (Scranton) U.S. Bureau of Mines Demonstration Project

Bank contained an estimated 3.5 million cubic yards of refuse, the section of the bank used for the demonstration project contained an estimated 1.1 million cubic yards. Two techniques were employed: 1) Quenching and sluicing the hot material with available mine water, then bulldozing the cooled refuse into an adjacent strip pit; 2) Quenching the hot refuse with water cannons and a sprinkler system, a bulldozer was then used to rip the quenched material and a tractor-scraper transported, spread and compacted the extinguished material.

For technique No. 1 the cost was $0.66/c.y., costs for technique No. 2 were $0.44/c.y.

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MINE SUBSIDENCE CONTROL

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MINE SUBSIDENCE CONTROL

Introduction

The prevention and limitation of subsidence caused by underground mining is an art which is rapidly becoming an exact science as recent application and observation technology for controlling the damaging effects of surface subsidence are put into effect. Most of the really significant technological developments have occurred in Pennsylvania as a result of the funding available under the Operation Scarlift Program which permitted rapid development of the needed technology.

Surface subsidence as a result of coal mining has been a problem in the United States for over one hundred years, and in 1864, hydraulic stowing was "invented" in the anthracite region of Pennsylvania to control subsidence(1). Numerous papers have been published on mine subsidence, but probably one of the most useful to the engineer is a recently reprinted publication (1972) by the British Institution of Civil Engineers titled "Report on Mining Subsidence"(2). This report prepared by the Mining Subsidence Committee of the Institution in 1959 discusses the types of subsidence movements and the effects of mining subsidence on the stability and durability of all types of civil engineering works and structures on or near the surface. It recommends precautionary measures to be taken and methods of construction for structures, bridges, roads and public utilities in areas where subsidence is or can be a problem. An extensive bibliography of pertinent publications is included.

To satisfy the ever increasing demand for energy, more and more land is being undermined to obtain coal, a prime energy source. As the areal extent of undermined land increases along with a growing population which is expanding into areas that were formerly mined or now being mined, the necessity for effective control of mine subsidence becomes a pressing need.

Several methods of subsidence control are discussed in this section of the report. In recent years, the Commonwealth of Pennsylvania and the U. S. Bureau of Mines have developed a great deal of experience in pneumatic and hydraulic injection of fly ash and prepared coal mine refuse into mine voids for ground stabilization. Other methods such as drilled caissons and grouted aggregate piers have been used in areas where heavy or valuable structures are constructed on undermined land.

Pressure Grouting of Mine Voids

Pressure grouting of mine voids and the roof rock with cement grout has been technically feasible for many years. The drawbacks have been several, most notably, the high unit cost of the medium and the almost impossible task of accurately estimating the grout take and thereby the total project cost. If cost is not a factor, pressure grouting is the most positive stabilization procedure, particularly with the addition of modern inspection tools such as the borehole camera and television.

Construction of Concrete Piers

A relatively simple technique, the construction of concrete piers within the mine void is somewhat less expensive than pressure grouting, but, has many important limitations on its applicability. Among these are the need for a relatively competent roof strata and, most important, access to the void to permit standard construction procedures to be carried out in the dry.

Drilled Caissons

Drilled piers (caissons) have been utilized to support structures over mine voids by drilling from the surface into the mine floor at the location of the building column, placing shells, and then, filling the shells with concrete. After the concrete has set, the structure can be framed in normal fashion. It is necessary, however, that the floor be constructed as a structural floor, supported on grade beams between the piers, since only the column points are dependably supported. The average cost for a 30-inch drilled pier, in medium hard rock, is about $40.00 per lineal foot, including all supplemental costs. The unit cost of these units appears to be high, however, the available bearing capacity is subject to so many factors controllable in design that almost any conceivable load can be supported by varying the characteristics of each caisson within a relatively narrow range. The drilled caisson is becoming a standard method of supporting high and valuable loads over mines within a 50 foot depth. It is believed that further development of the controlled fly ash flushing method will soon lead toward package projects wherein both structural and ground loads can be supported by a combination of drilled piers and fly ash backfill of voids.

Grouted Aggregate Piers

The grouted aggregate pier method of mine void stablization is probably the most efficient technique yet devised for construction of valuable structures on undermined land. The process has been applied sufficiently often that considerable expertise has been developed, along with the efficient observation and application tools. In this method six inch borings are made to the floor of the void. Gravel or slag is placed in the mine void and spread with the assistance of compressed air into a truncated conical form until the top surface of the truncated cone achieves a minimum diameter of six feet against the roof of the mine. The aggregate cone and the rock over the void are then pressure grouted to an approximate diameter of six feet. The grouted aggregate piers are normally spaced on 25 foot centers throughout the area of concern, although the spacing can sometimes be increased to as much as 40 feet depending on mine void conditions and the proposed use of the property(3).

Estimated unit costs for the grouted aggregate pier method are:

Drilling (6 inch diameter hole)	$ 2.75 L.F.
Casing (6 inch O.D.)	1.50 L.F.
Photography (For job planning and control)	175.00/Day
Grouted Aggregate Pier	700.00 to 1,000.00 Ea.

When it is considered that approximately 75 piers per acre are required under standard conditions, it can be seen that this process is not cheap. It does, however, provide a method of almost guaranteed stability that is well within the cost structure of almost any significant development, particularly since location may be an important factor in the economic consideration of a project site. Granted the importance of location, then the approximate cost of $75,000 per acre for grouted aggregate piers becomes an easily handled item in the overall cost-benefit ratio of the project.

Fly Ash Injection Method

The stabilization of mine voids by pneumatic injection of fly ash or hydraulic injection of a fly ash slurry is a process employed by the Pennsylvania Department of Environmental Resources to the level of a "Standard Specification" type of work. Significant cost reductions have occurred in this method as contractors have gained experience in equipment usage and the cost factors involved. The present overall cost of fly ash injection is estimated at $4.20 per cubic yard. This cost includes all supplemental costs and offers, potentially, a low cost approach to stabilization, particularly since the application cost is not apparently a function of depth with the exception of the cost of borings.

There are several minor questionable features to the system, principally, the surface supporting capacity of pneumatically injected fly ash is somewhat conjectural. The take at any particular site is difficult to predict and finally there is some question as to whether the supply of fly ash is adequate within the areas of need. This could result in increased overall costs because of transportation costs. It would be desirable to see experimental projects carried out to determine the consolidation properties of the fly ash after being placed in a mine. This information could provide reassurance that fly ash is the ultimate mine void stabilizer that so many believe. If so, this method could be applied in place of other methods which are much more expensive, but have been shown to offer stability under heavy imposed loads.

Table 1 is a tabulation of recent fly ash injection mine stabilization projects performed under Pennsylvania's Operation Scarlift Program. The projects cover a period from 1968 to 1971 and are arranged in order of decreasing cost per acre of stabilization. When project location, areal extent of stabilization, depth and thickness of void is considered, it is apparent that no cost trend can be developed from the information presented in the table. The best unit cost estimates for fly ash injection obtained from individuals familiar with this method ranged from $4.00 to $4.50 per cubic yard. Allowance must be made for extra deep borings, difficult site conditions, haulage distances and other factors which could increase costs(4).

TABLE 1

MINE STABLIZATION PROJECTS USING FLY ASH
PENNSYLVANIA

Rank in Cost Per Acre	Rank in Total Cost	Project No. (SL)	County	Area (Acres)	Cost Per Acre	Void Thickness	Depth	Total Cost
1	9	423	Allegheny	0.2	$110.k	6'	80'	$ 22,000
2	7	404-2	Allegheny	0.4	$101.k	6'	85'	$ 60,500
3	8	402	Allegheny	0.4	$ 72.k	6'	90'	$ 28,600
4	1	417-1	Beaver	6.8	$ 68.8k	14'	220'	$468,000
5	3	415	Luzerne	3.0	$ 59.k	N.A.	110'	$178,000
6	2	401	Luzerne	7.2	$ 40.3k	N.A.	N.A.	$290,500
7	4t	422	Allegheny	5.5	$ 22.7k	6'	160'	$120,000
8	5	407	Westmoreland	4.5	$ 21.5k	6'	45'	$ 96,500
9	6	408-1	Allegheny	4.0	$ 17.5k	6'	160'	$ 69,000
10	10	413-2	Allegheny	0.5	$ 17.k	6'	103'	$ 8,500
11	4t	403-A	Lackawanna	7.7	$ 16.k	N.A.	N.A.	$120,000

Flushing Coal Mine Refuse

A number of mine stabilization projects have been completed in the Northern Anthracite Field of Pennsylvania using anthracite breaker refuse crushed to minus one-half inch as the fill material(5). The cost of the projects were borne jointly by Federal and State government and were part of a program called "Operation Backfill." The work consisted of the filling of mine voids by the application of the "controlled flushing" and "blind flushing" techniques. Table 2 presents cost data and volumes of coal refuse utilized in 14 of these projects.

Quantities of various "pay items" used for Project ASP-1, the Pine Brook Mine Project at Scranton, Pennsylvania were as follows:

Cubic yards placed by controlled flushing	491,955
Cubic yards placed by blind flushing	7,956
Linear feet six (6) inch diameter boreholes	12,053
Linear feet six (6) inch O.D. casing pipe	4,885
Linear feet 12 inch diameter boreholes	396
Linear feet 12 inch O.D. casing pipe	173
Linear feet 28 inch diameter boreholes	202
Linear feet 28 inch O.D. casing pipe	220

This project was started in 1966 and completed in 1968. "Pay items" are those which the Contractor submitted unit prices in his bidding proposal and they are the only items for which payment was made. The price contracted for per cubic yard of flushing included all costs for the crushing plant, preparation of flush material, haulage, labor and materials incident to actual placement underground. The price per foot of drilling the flushing boreholes includes all labor and materials incidental thereto, likewise the installation of casing pipe. Cost of installing hoisting equipment, headframes, fan, etc., is included in the unit price of the large diameter boreholes. Therefore, the total amount paid for the entire project is the sum of the amounts obtained by multiplying each of the few quantities bid on a unit price basis in the contract(5).

This was mostly a "controlled flushing" project and the cost on a per cubic yard basis was $1.75. Project ASP-2, completed on the other side of Scranton, the Morse School Project, had a cost of $3.65 on a cubic yard basis. Approximately 70 percent of the flushing on this project was "blind flushing" which accounted for a much greater borehole footage, over 200,000 linear feet of borehole.

Another, newer method of backfilling abandoned mine workings is the so-called Dowell System(6), a slurry hydraulic injection process. In this system locally available permeable materials, usually mine wastes, are crushed and then pumped through a central borehole under pressure until the void is filled. The method has several advantages, it results in removal of unsightly surface wastes and requires only one injection point which makes the process,

TABLE 2

MINE STABILIZATION PROJECTS
UTILIZING COAL MINE REFUSE
NORTHERN ANTHRACITE FIELD, PENNSYLVANIA

Project No.	Location	Volume Filled (Cubic Yards)	Total Cost	Cost Per Cubic Yard
NRD-3	Pittston	271,122	$239,974	$0.89
NR-32	Scranton	50,008	82,372	1.65
NR-32A	Scranton	23,985	35,187	1.47
NR-33	Scranton	49,613	74,780	1.51
NR-34	Scranton	169,392	240,165	1.42
NR-37	Scranton	92,680	130,531	1.41
NR-39	Scranton	54,931	75,274	1.37
NR-46	Scranton	61,977	85,975	1.39
NR-55	Scranton	399,368	445,431	1.12
NR-56	Scranton	10,181	23,753	2.33
NR-10	Pittston	70,348	146,884	2.09
PH&S-2	Scranton	291,077	364,293	1.25
ASP-1	Scranton	491,911	858,865	1.75
ASP-2	Scranton	259,306	946,474	3.65

aesthetically, far more acceptable than other methods. On the other hand, the process requires such extensive physical plant and pumping time that the application cost appears high, even with the advantage of cost free materials. One project, at Rock Springs, Wyoming, was completed with injection of 20,000 cubic yards of sandy waste at a cost of $8.65 per cubic yard. Another project is being performed at Scranton, Pennsylvania. This project will involve about 300,000 cubic yards of anthracite mine waste and application costs are estimated at $5.60 per cubic yard of, again, cost free material. The process is not inexpensive, it does, however, seem to have a very real place in urban areas and in other areas where disruption from multiple injection points has high economic importance.

Controlled Mine Subsidence

For many years little was known about the nature of ground movement and subsidence calculations were therefore very approximate. But in recent years, affected areas have been carefully measured and observed and the principles of ground movement cause by extraction of stratified deposits are now more fully understood.

There is a new mining technique that was brought to this country from Germany during the last decade and has only recently been put to use in bituminous coal mines(7). This technique uses a special machine, known as a long-wall miner, which removes all of the coal as the machine advances through the seam; a set of automatic advancing jacks holds up the mine roof immediately behind and parallel with the cutting bits. As the operation moves farther along the coal deposit, the jacks are also moved, leaving behind a completely mined-out area. The surface over this area settles, but because 100 percent of the coal has been removed, the settling or subsidence is uniform.

Uniform subsidence seldom causes damage to any surface structures which lie directly and entirely above the mining operation. The damage occurs where there are variations in the degree of subsidence. Where, for example, one part of a house stays at the same level and the rest of the house drops several inches. Traditional mining techniques, with their coal pillars interspersed throughout the post-mining cavity, can and do cause this variable subsidence; the long-wall miner does not. In virtually all cases where the long-wall method has been used, little or no damage to surface structures has been reported, although there are frequently cases where wells run dry because of the fracturing of aquifers caused by subsidence.

Formulas have been worked out to determine how much subsidence will occur as the result of a given long-wall mining operation. If a six foot thick coal seam lying 100 feet beneath the surface is removed, for example, the overlying surface will sink six inches; if the seam is thinner or lies deeper, the subsidence will be less.

Since there will be a drop-off of the land surface at the perimeter of each long-wall mining operation, care must be taken to plan the operation so that there is no surface structure sitting athwart this perimeter. For this reason, the new mining method is most suitable in areas which are rural and where the coal deposits occur in large blocks.

Only a brief mention has been made of pillar mining in previous paragraphs. In room and pillar mining, it is not possible to predict the development of subsidence, since there is such a great variety of pillar sizes and depths. Pillars may fail after years have elapsed, the amount of movement depending on the room space available into which they can crush. Or the pillars may be forced into a soft floor such as fireclay. This will result in a lowering of the surface just as though the pillars had been crushed and spread. Where the floor is soft the limiting factors are the thickness of the soft floor stratum and the space available in the rooms into which the pillars can be forced. In general it has been found that the smallest safe dimension for pillars is about one-tenth the depth of the coal seam.

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PART B

ABATEMENT OF POLLUTION FROM SOURCES OTHER THAN COAL MINING

COST ESTIMATES FOR AIR POLLUTION CONTROL EQUIPMENT

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COST ESTIMATES FOR AIR POLLUTION CONTROL EQUIPMENT

Cost estimates performed without the benefit of design or technical specifications are nebulous at best. Stricter emission standards and rapidly changing technology in the field of air pollution control have brought into play far too many variables to enable accurate predictions. The year data was compiled is very important, since equipment, material and labor costs have risen each year. The data used in this section of the report ranges from less than a year to four years in age. However, before a cost comparison was made for a fixed size unit, costs were updated to a July, 1972 base using "Marshall and Stevens Index" as published in Chemical Engineering Magazine.

The volume of gas to be cleaned is the single most important factor in determining the cost of an air pollution control device and the removal efficiencies for contaminants are paramount in deciding which type of equipment is to be used. The unit selected must be able to produce an effluent capable of meeting the National Ambient Air Quality Standards established by the Environmental Protection Agency (Table 1).

Two other factors affecting equipment costs are system design and process control. Their importance cannot be overemphasized. A poor design will increase emissions or amounts of exhaust gas to be treated, thus making cleaning more difficult and more expensive. Improper operation of the best design possible will result in the same outcome.

Figure 1 summarizes the most important factors affecting the final net cost of an air pollution control system.

Classes of Air Pollution Control Equipment

Four classes of pollution control equipment are analyzed as well as odor control devices which are considered separately. They are as follows:

1. Mechanical Collectors - This type of collector is used for removal of particulate emissions only. They rely on gravity, particle inertia or centrifugal force to effect removals. The types of units included in this category are: 1) settling chambers, 2) inertial separators and 3) cyclones. Efficiencies depend heavily upon the particle characteristics, removal percentages decreasing rapidly with decreasing particle size. These units are most effective in collecting particles ten microns in size or larger. Efficiencies can vary from 20-90 percent. Overall, mechanical collectors are the least expensive equipment to purchase and operate. However, low removal efficiency and large space requirements make this equipment undesirable as a single unit installation. Generally, they are used in series with other kinds of units as a pretreatment stage. Contaminants are collected in a dust bin, further disposal being to a landfill or similar area.

2. Wet Scrubbers - This class of devices uses a liquid, usually water, to aid in the removal of contaminants. They are effective in removing gas and vapor phase pollutants as well as particulates. The units are effective at high temperature and are not significantly affected by particle size or loadings. Efficiencies for particles ranging in size from submicron to ten microns vary from 80-99.5 percent. According to Cross(3), scrubbers are the most widely used control equipment and have been recommended as the only economical and effective control device for moderately sized incinerators (less than 1,000 lb./hr. capacity). Sulfur dioxide can also be controlled with scrubbers. The disadvantage of wet collectors include corrosion problems, wastewater disposal, contamination of the exhaust gas by liquid entrainment, freezing in cold weather and visibility of water vapors from stacks during certain weather conditions. Costs vary with respect to the amount of pressure drop through the unit, the construction materials and the unit size.

3. Electrostatic Precipitators - This type of device employs the principle of particle ionization by a discharge electrode and then entrapment by a collecting plate consisting of a grounded electrode. They are most effective with particles ranging from one to ten microns. Efficiencies start at 60 percent and can exceed 99.5 percent. A mechanical collector generally precedes a precipitator because large particles can cause damage to the discharge electrodes. Agglomerates of particles are formed and these are collected below the grounded electrodes. Disposal to a landfill or a similar site is easily accomplished. Unit capacities can be as high as three million cubic feet per minute (CFM), pressures can approach 150 pounds per square inch of gas (PSIG) and gas temperatures can be as high as 1,200° F. Electrical power is consumed at the rate of 50 to 500 watts per 1,000 CFM. Electrical costs in Western Pennsylvania are between $0.01 and $0.02 per kilowatt hour for units of 50,000 CFM capacity.

4. Filters - In this type of unit an exhaust gas is passed through a porous structure. The units operate effectively on all sizes of particles, efficiency being determined by the type of filtering material used. Removal values can approach 99.99 percent in some instances. This type of unit is particularly valuable when the contaminant can be recycled for use elsewhere. Temperatures usually must be kept below 550° F, however, this limitation is a function of filter material properties. The filter material or fabric is subject to chemical attack and collection efficiency is affected by humidity. Unit costs vary with the type of shaker (used to clean filter material), the reuseability of filter material, unit size and the amount of pressure drop.

Cost Estimates for Pollution Control

Table 3 is a tabulation of cost estimates for the four classes of pollution control equipment based on a 50,000 actual cubic feet per minute (ACFM) unit with average to high efficiency. The results are in dollar cost for purchase and installation of the unit per 1,000 ACFM size. An "average" unit is assumed. Capital costs would be affected by special design factors, unusual installation problems, a requirement for very high efficiencies, construction with other than steel and other variables. The cost estimates in Table 3 are for a fixed size unit. Variations in cost relative to size for each class of equipment are shown in Figures 2 through 5.

Table 4 from Ernst & Ernst[1] presents installation costs as a percentage of capitalized purchase cost. When capitalized purchase costs are added to the capitalized installation cost, the sum is the annual capital cost. Table 5, also from this publication, is based on information from several sources which suggests maintenance costs can be approximated by using the cost factors in the table. Local labor cost and price conditions can cause wide departures from the factors shown and should be used when available.

Table 6, reproduced from Stern[4] shows relative cost and characteristics of dust and mist collection equipment. A summary of important industries, their pollutant sources, particulate pollutants, and air cleaning techniques is presented in Table 7. Table 8 lists advantages and disadvantages for each of the general types of collection devices. Tables 7 and 8 were reproduced from Kerbec[5].

Actual 1971-72 capital and operating costs, design data, and other pertinent information for air pollution control equipment is presented in Table 9. This unpublished information covering various industries was obtained from Mr. Douglas Lesher, Pennsylvania Department of Environmental Resources[6].

Lund[7] presents data on expenditures for air pollution control by 330 firms in various industries for 1967. The cost figures are five years old and air quality standards and equipment design have changed considerably since then. On the average, each firm spent:

Capital Equipment Costs	$88,400
Installation Costs	53,200
Operating Costs	46,550

The breakdown in operating costs and percent of total for each item is:

Power, fuel and water	$19,840	43%
Materials and spare parts	5,100	10-11%
Maintenance and labor	7,100	15-16%
Collected waste disposal	14,510	31%
	$46,550	

Incinerator Emissions and Control of Odors

Emissions from incinerators are not constant in character or amount. The amounts and kinds of emissions will vary with the character of the material being burned. Incinerators are capable of producing all six of the categories of pollutants recognized by the Environmental Protection Agency. Table 2 shows typical amounts of incinerator emissions, and as a basis of reference, they are compared with open burning. Odor can also be a problem in incineration, especially when the material incinerated has a high organic content, a condition to be expected in municipal waste incineration.

The control of odors from organic sources is usually accomplished by heating the exhaust gas to 1400^{o} F for a period of 0.5 second. For practical purposes, three types of equipment are available to achieve odor control.

1. Afterburner
2. Afterburner with Energy Recovery
3. Thermal Regenerative System

A fuel cost comparison was presented by Mueller(8) to show the significance of thermal energy and system exhaust temperature (Table 10).

Stacks for Air Pollution Control

Stacks are air pollution control equipment since their purpose is to 1) reduce temperatures of exhaust gases, 2) increase the dispersion of contaminents to achieve lower ground concentrations, and 3) reduce sulfur dioxide concentrations. According to First(9), current estimating practice for construction costs of tall stacks is $1, 000 per foot for the first 600 feet and $2, 500 for each additional foot.

TABLE 1

NATIONAL AMBIENT AIR QUALITY STANDARDS
ENVIRONMENTAL PROTECTION AGENCY

PRIMARY STANDARDS - are to protect public health.
SECONDARY STANDARDS - are to protect against effects on soil, water, vegetation, materials, animals, weather, visibility and personal comfort and well-being.

I. SULFUR OXIDES - primarily from the combustion of sulfur containing fossil fuels.

PRIMARY - 80 micrograms/cubic meter (0.03 ppm) annual arithmetic mean.
- 365 micrograms/cubic meter (0.14 ppm) as a maximum 24 hour concentration not to be exceeded more than once a year.

SECONDARY - 60 micrograms/cubic meter (0.02 ppm) annual arithmetic mean.
- 260 micrograms/cubic meter (0.1 ppm) maximum 24 hours concentration not to be exceeded more than once a year.
- 1300 micrograms/cubic meter (0.5 ppm) as a maximum three hour concentration not to be exceeded more than once a year.

II. PARTICULATE MATTER - Industrial processes or human activity.

PRIMARY - 75 micrograms/cubic meter annual geometric mean.
- 260 micrograms/cubic meter as a maximum 24 hour concentration not to be exceeded more than once a year.

SECONDARY - 60 micrograms/cubic meter annual geometric mean.
- 150 micrograms/cubic meter as a maximum 24 hour concentration not to be exceeded more than once a year.

III. CARBON MONOXIDE - by product of incomplete burning of carbon containing fuels.

PRIMARY/SECONDARY - 10 milligrams/cubic meter (9 ppm) maximum eight hour concentration not to be exceeded more than once a year.
- 40 milligrams/cubic meter (35 ppm) maximum one hour concentration not to be exceeded more than once a year.

IV. PHOTOCHEMICAL OXIDANTS - chief source is when hydrocarbons and nitrogen oxides are exposed to sunlight.

PRIMARY/SECONDARY - 160 micrograms/cubic meter (0.08 ppm) as a maximum one hour concentration not to be exceeded more than once a year.

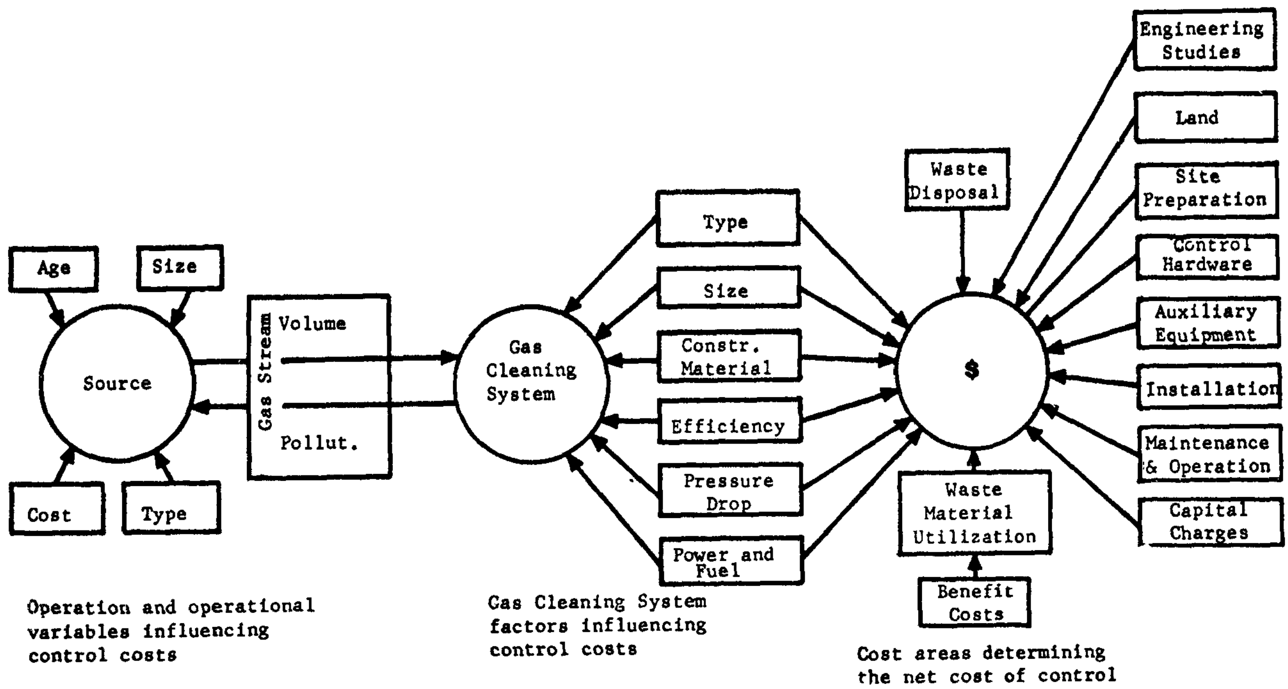
V. HYDROCARBONS - Processing, marketing and use of petroleum products.

PRIMARY/SECONDARY - 160 micrograms/cubic meter (0.24 ppm) as a maximum three hour concentration (6 to 9 AM) not to be exceeded more than once a year.

VI. NITROGEN OXIDES - originate from high temperature combustion processes.

PRIMARY/SECONDARY - 100 micrograms/cubic meter (0.05 ppm) annual arithmetic mean.

FIGURE 1



GAS CLEANING SYSTEMS COST FLOW DIAGRAM

Source: Ernst & Ernst, 1968[1]

TABLE 2

TYPICAL INCINERATOR EMISSIONS COMPARED TO OPEN BURNING

Type of Emission	Incinerator Emissions Pounds/Ton Refuse Fired	Open Burning Emissions Pounds/Ton Refuse Fired
Particulate	30	16
SO_x	1.5	1
CO	1	85
HC	1.5	30
NO_x	2	6
Photochemical	NA	NA

Source: Engdahl, 1968[2]

TABLE 3

POLLUTION CONTROL COSTS FOR 50,000 ACFM UNITS*
(DOLLARS/1,000 ACFM)

	Mechanical Separators	Electrostatic Precipitators	Filters	Scrubbers
Purchase Cost	194	814	544	556
Installation Cost	97	570	440	526
Total Capital Cost	291	1,384	984	1,082
Annual Operating Cost	17	20	60**	46
EFFICIENCIES	50-90%	98-99+%	98-99+%	95+%

*From various sources, Updated to July, 1972 using Marshall and Stevens Index

**Variable depending on type of filter media used.

TABLE 4

INSTALLATION COSTS AS A PERCENTAGE OF PURCHASE COSTS FOR FOUR GENERIC TYPES OF CONTROL DEVICES - 1968

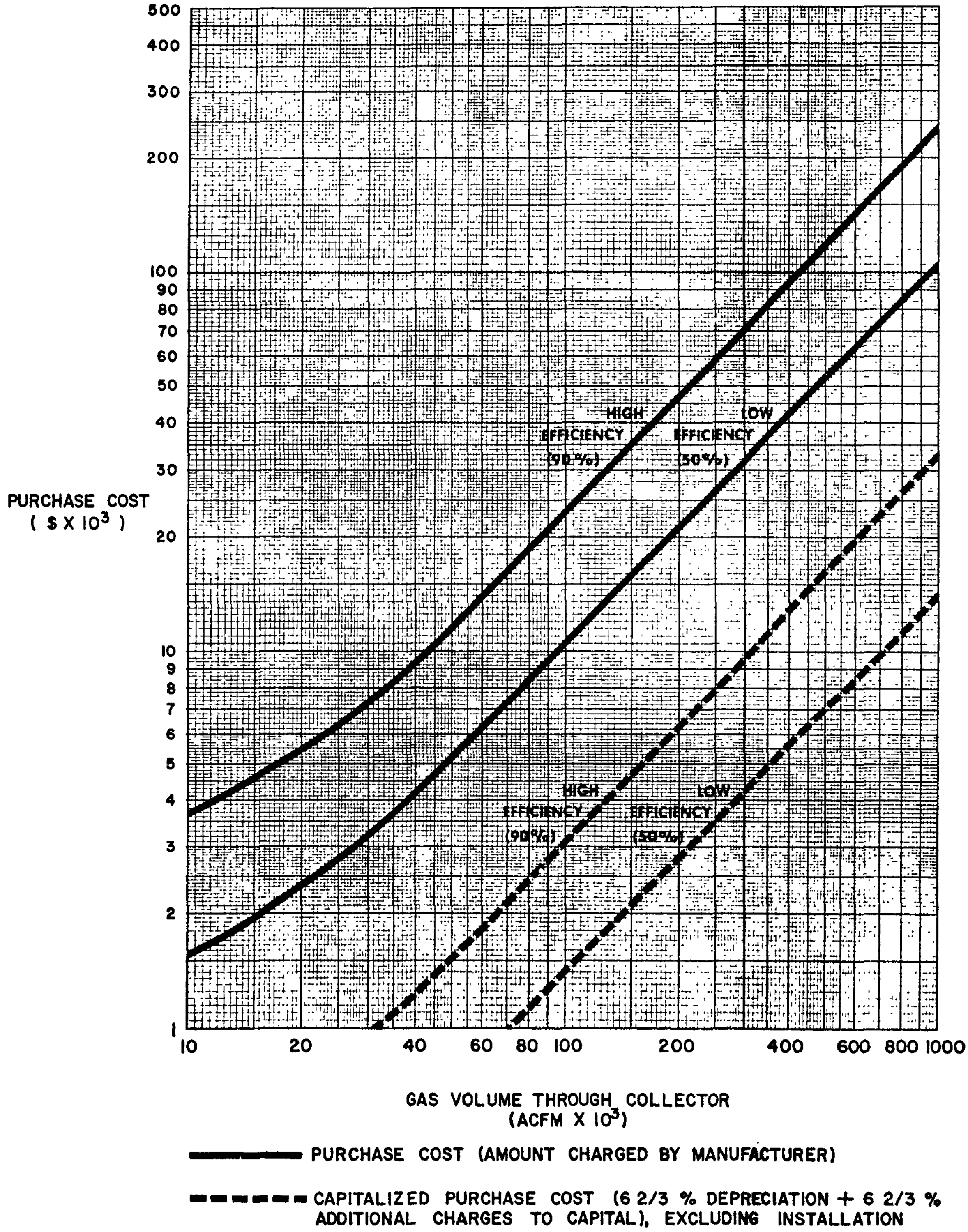
Generic Type	Low Percent	Mean Percent	High Percent	Extreme High Percent
Mechanical Collector	40	50	100	400
Wet Scrubber	50	100	200	400
Electrostatic Precipitator	35	70	100	400
Fabric Filter	75	80	100	400

Reproduced from: Ernst & Ernst, 1968[1]

FIGURE 2

ESTIMATED 1967-68 PURCHASE COSTS FOR FABRIC FILTERS

(LOG SCALES)

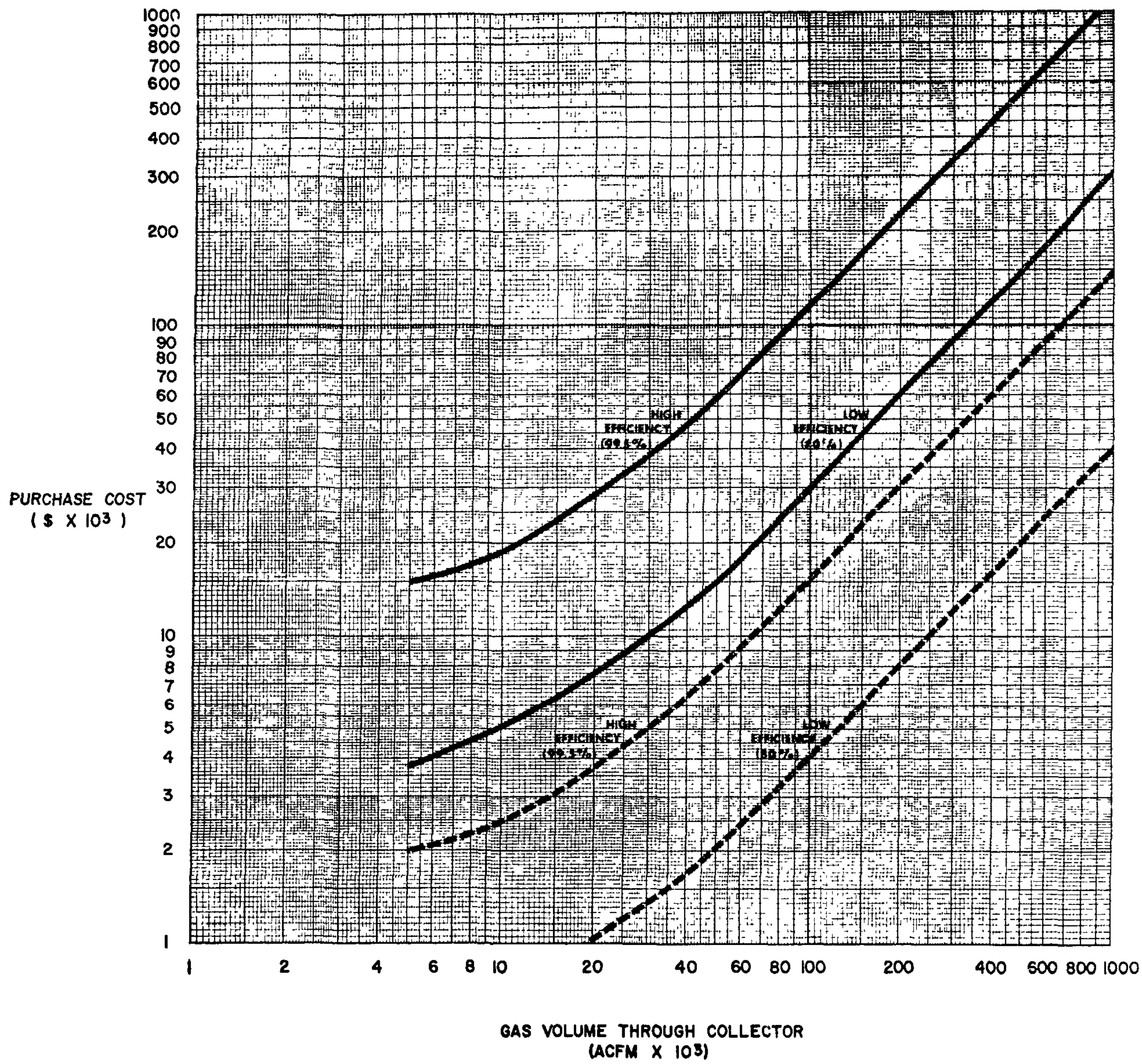


Reproduced From: Ernst & Ernst, 1968[1]

FIGURE 3

ESTIMATED 1967-68 PURCHASE COSTS FOR WET SCRUBBERS

(LOG SCALES)



——— PURCHASE COST (AMOUNT CHARGED BY MANUFACTURER)

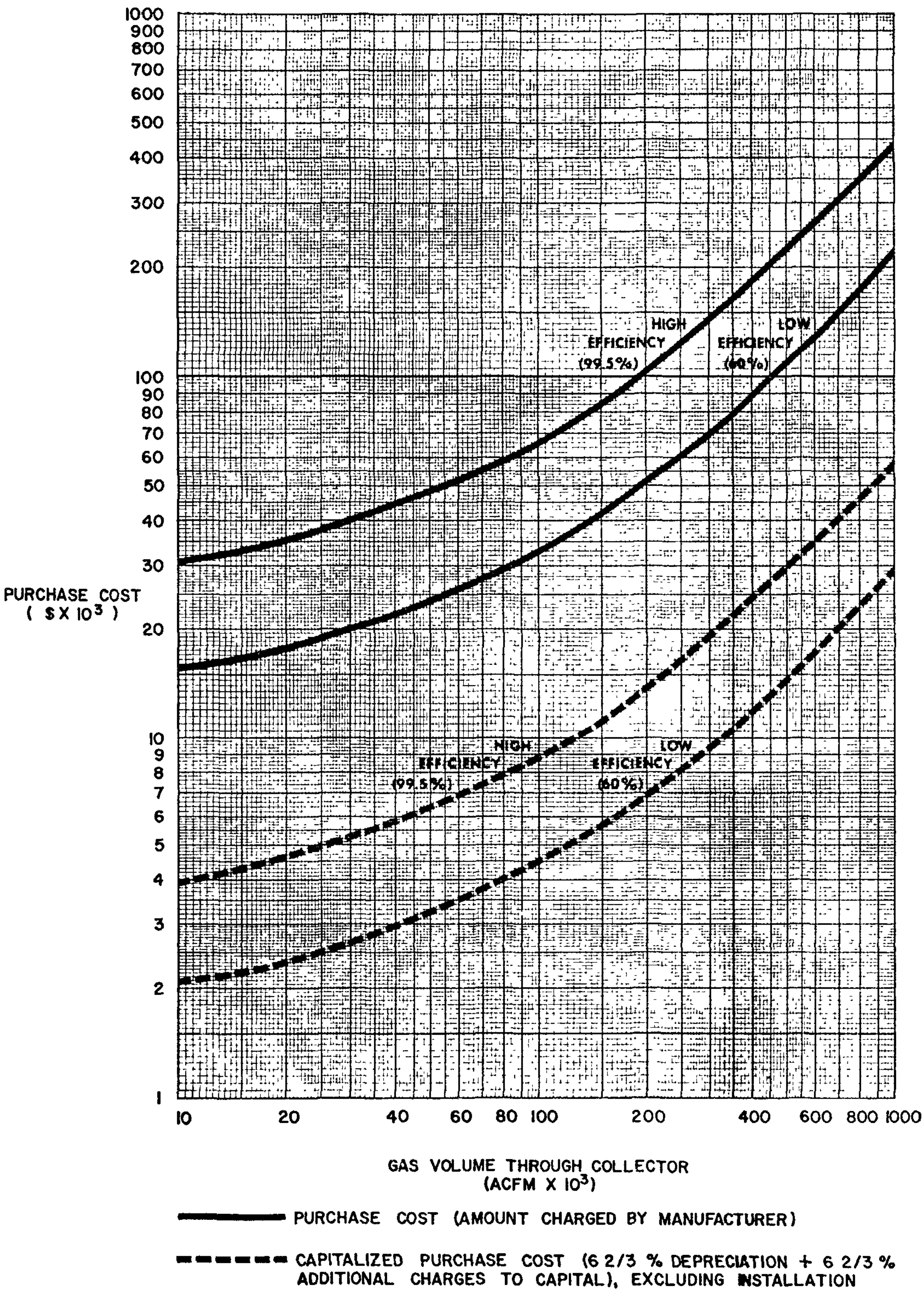
- - - - CAPITALIZED PURCHASE COST (6 2/3 % DEPRECIATION + 6 2/3 % ADDITIONAL CHARGES TO CAPITAL), EXCLUDING INSTALLATION

Reproduced From: Ernst & Ernst, 1968[1]

FIGURE 4

ESTIMATED 1967-68 PURCHASE COSTS FOR ELECTROSTATIC PRECIPITATORS

(LOG SCALES)

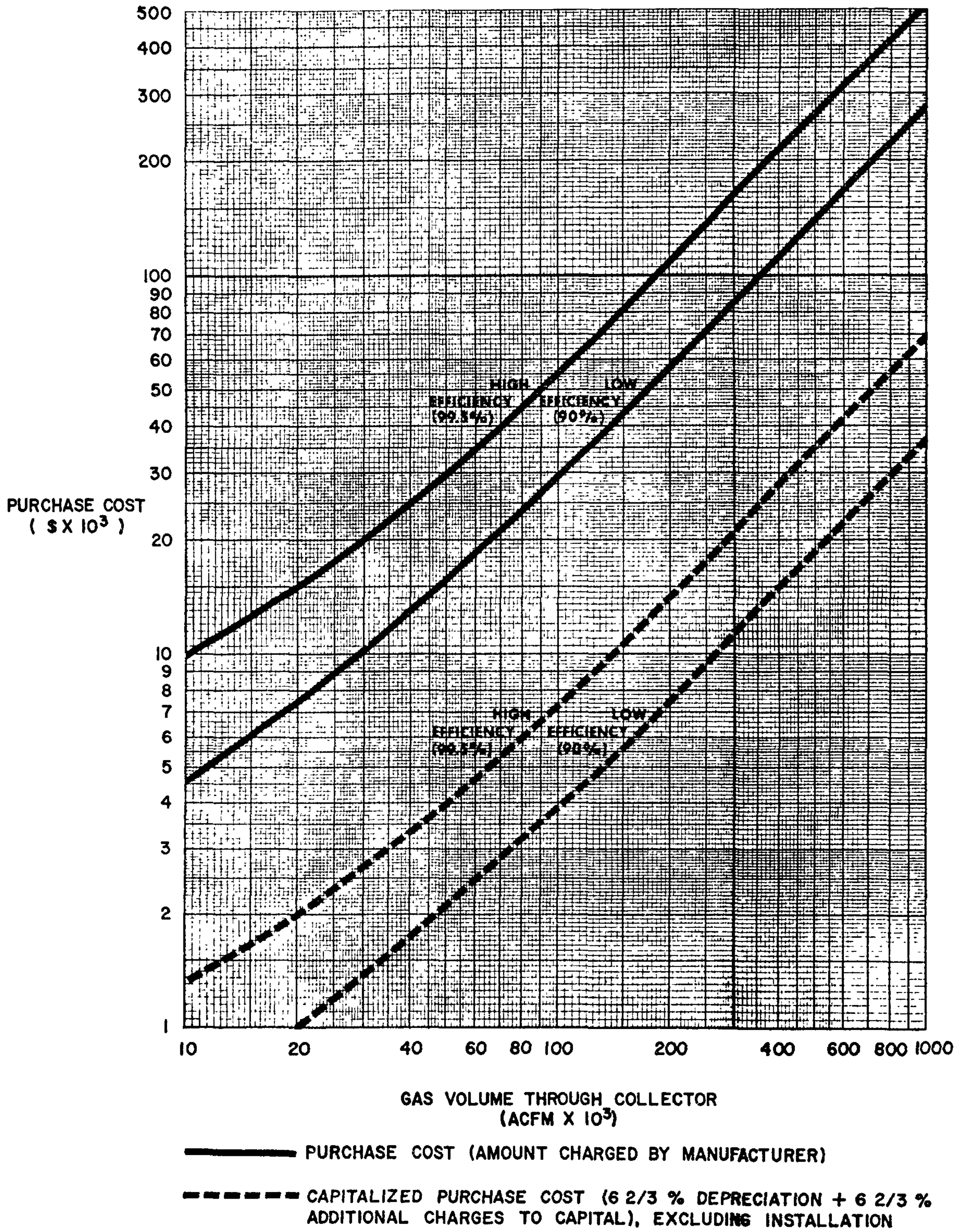


Reproduced From: Ernst & Ernst, 1968(1)

FIGURE 5

ESTIMATED 1967-68 PURCHASE COSTS FOR MECHANICAL COLLECTORS

(LOG SCALES)



Reproduced From: Ernst & Ernst, 1968(1)

TABLE 5

ANNUAL MAINTENANCE COST FACTORS FOR FOUR GENERIC TYPES OF CONTROL DEVICES IN 1967-1968

Generic Type	Cost ($/ACFM)		
	Low	Mean	High
Mechanical Collectors	0.005	0.015	0.025
Wet Scrubbers	0.02	0.04	0.06
Electrostatic Precipitators	0.01	0.02	0.03
Fabric Filters	0.02	0.05	0.08

Reproduced From: Ernst & Ernst, 1968[1]

TABLE 6

APPROXIMATE CHARACTERISTICS OF DUST AND MIST COLLECTION EQUIPMENT

Equipment Type	Relative Cost[a]	Smallest Particle Collected (u)[b]	Pressure Drop (Inches H_2O)	Power Used[c] $\frac{kw}{1000\ ft^3/min}$	Remarks
A. Settling Chambers					
1. Simple	1	40	0.1-0.5	0.1	Large, low pressure drop, precleaner
2. Multiple Tray	2-6	10	0.1-0.5	0.1	Difficult to clean, warpage problem
B. Inertial Separators					
1. Baffle Chamber	1	20	0.5-1.5	0.1-0.5	Power plants, rotary kilns, acid mists
2. Orifice Impaction	1-3	2	1.3	0.2-0.6	Acid mists
3. Louver Type	1-3	10	0.3-1	0.1-0.2	Fly ash, abrasion problem
4. Gas Reversal	1	40	0.1-0.4	0.1	Precleaner
5. Rotating Impeller	2-6	5	---	0.5-2	Compact
C. Cyclones					
1. Single	1-2	15	0.5-3	0.1-0.6	Simple, inexpensive, most widely used
2. Multiple	3-6	5	2-10	0.5-2	Abrasion and plugging problems
D. Filters					
1. Tubular	3-20	0.1	2-6	0.5-1.5	High efficiency, temperature and humidity limits
2. Reverse Jet	7-12	0.1	2-6	0.7-1.5	More compact, constant flow
3. Envelope	3-20	0.1	2.6	0.5-1.5	Limited capacity, constant flow possible
E. Electrical Precipitators					
1. One-Stage	6-30	0.1	0.1-0.5	0.2-0.6	High efficiency, heavy duty, expensive
2. Two-Stage	2-6	0.1	0.1-0.3	0.2-0.4	Compact, air conditioning service
F. Scrubbers					
1. Spray Tower	1-1	10	0.1-0.5	0.1-0.2	Common, low water use
2. Jet	4-10	2	---	2-10	Pressure gain, high velocity liquid jet
3. Venturi	4-12	1	10-15	2-10	High velocity gas stream
4. Cyclonic	3-10	5	2-8	0.6-2	Modified dry collector
5. Inertial	4-10	2	2-15	0.8-8	Abrasion problem
6. Packed	3-6	5	0.5-10	0.6-2	Channeling problem
7. Rotating impeller	4-12	2	---	2-10	Abrasion problem

[a]Including necessary auxiliaries.

[b]With 90-95 percent efficiency by weight.

[c]Includes pressure loss, water pumping, electrical energy.

Reproduced From: Stern, 1968(4)

TABLE 7
INDUSTRIAL PROCESS AND CONTROL SUMMARY

Industry or Process	Source of Emissions	Particulate Matter	Method of Control
Iron and steel mills	Blast furnaces, steel making furnaces, sintering machines.	Iron oxide, dust, smoke	Cyclones, baghouses, electrostatic precipitators, wet collectors.
Gray iron foundries	Cupolas, shake out systems, core making.	Iron oxide, dust, smoke, grease, metal fumes.	Scrubbers, dry centrifugal collectors.
Metallurgical (non-ferrous)	Smelters and furnaces	Smoke, metal fumes, oil, grease.	Electrostatic precipitators, fabric filters.
Petroleum refineries	Catalyst regenerators, sludge incinerators.	Catalyst dust, ash from sludge.	High-efficiency cyclones, electrostatic precipitators, scrubbing towers, baghouses.
Portland cement	Kilns, dryers, material handling systems.	Alkali and process dusts	Fabric filters, electrostatic precipitator, mechanical collectors.
Kraft paper mills	Chemical recovery furnaces, smelt tanks, lime kilns.	Chemical dusts	Electrostatic precipitators, venturi scrubbers.
Acid manufacture-phosphoric, sulfuric	Thermal processes, phosphate rock acidulating, grinding and handling systems.	Acid mist, dust	Electrostatic precipitators, mesh mist eliminators.
Coke manufacturing	Charging and discharging oven cells, quenching, materials handling.	Coal and coke dusts, coal tars.	Meticulous design, operation, and maintenance.
Glass and glass fiber	Raw materials handling, glass furnaces, fiberglass forming and curing.	Sulfuric acid mist, raw materials dusts, alkaline oxides, resin aerosols.	Glass fabric filters, afterburners.
Coffee processing	Roasters, spray dryers, waste heat boilers, coolers, conveying equipment.	Chaff, oil aerosols, ash from chaff burning, dehydrated coffee dusts.	Cyclones, afterburners, fabric filters.

Reproduced From: Kerbec, 1971[5]

TABLE 8
ADVANTAGES AND DISADVANTAGES OF COLLECTION DEVICES

Collector	Advantages	Disadvantages
Gravitational	Low pressure loss, simplicity of design and maintenance.	Much space required. Low collection efficiency.
Cyclone	Simplicity of design and maintenance.	Much head room required.
	Little floor space required.	Low collection efficiency of small particles.
	Dry continuous disposal of collected dusts.	Sensitive to variable dust loadings and and flow rates.
	Low to moderate pressure loss.	
	Handles large particles.	
	Handles high dust loadings.	
	Temperature independent.	
Wet collectors	Simultaneous gas absorption and particle removal.	Corrosion, erosion problems.
		Added cost of wastewater treatment and reclamation.
	Ability to cool and clean high-temperature, moisture-laden gases.	Low efficiency on submicron particles.
	Corrosive gases and mists can be recovered and neutralized.	Contamination of effluent stream by liquid entrainment.
	Reduced dust explosion risk.	Freezing problems in cold weather.
	Efficiency can be varied.	Reduction in buoyancy and plume rise.
		Water vapor contributes to visible plume under some atmospheric conditions.
Electrostatic precipitator	99+ percent efficiency obtainable.	Relatively high initial cost.
	Very small particles can be collected.	Precipitators are sensitive to variable dust loadings or flow rates.
	Particles may be collected wet or dry.	Resistivity causes some material to be economically uncollectable.
	Pressure drops and power requirements are small compared to other high-efficiency collectors.	Precautions are required to safeguard personnel from high voltage.
	Maintenance is nominal unless corrosive or adhesive materials are handled.	Collection efficiencies can deteriorate gradually and imperceptibly.
	Few moving parts.	
	Can be operated at high temperatures (550° to $850^{\circ}F$.)	

TABLE 8 (Continued)

Collector	Advantages	Disadvantages
Fabric filtration	Dry collection possible.	Sensitivity to filtering velocity.
	Decrease of performance is noticeable.	High-temperature gases must be cooled to 200° to 550°F.
	Collection of small particles possible.	Affected by relative humidity (condensation).
	High efficiencies possible.	Susceptibility of fabric to chemical attack.
Afterburner, direct flame.	High removal efficiency of submircon odor-causing particulate matter.	High operational cost. Fire hazard.
	Simultaneous disposal of combustible gaseous and particulate matter.	Removes only combustibles.
	Direct disposal of nontoxic gases and wastes to the atmosphere after combustion.	
	Possible heat recovery.	
	Relatively small space requirement.	
	Simple construction.	
	Low maintenance.	
Afterburner, catalytic.	Same as direct flame afterburner.	High initial cost.
	Compared to direct flame: reduced fuel requirements, reduced temperature, insulation requirements, and fire hazard.	Catalysts subject to poisoning.
		Catalysts require reactivation.

Reproduced From: Kerbec, 1971[5]

TABLE 9
ACTUAL COSTS FOR AIR POLLUTION
CONTROL EQUIPMENT

Particulars	Case # 1	2	3
1. Nature of Problem	Particulate	Particulate	Asphalt fume emissions
2. Process Controlled	Asphalt Plant	Two-tone Asphalt Plant	Asphalt
3. Manufacturer's Name	Barber-Greene Co. Aurola, Illinois	Interstate Amiesite Corp.	Combustion Equipment Associates
4. Model Number	CF-04	---	Modified PAO-B Special Duty 2.9 - 3.5 MKB
5. Type	Fabric Filter	Venturi	CEA. S.D. #8518 Burning of gaseous matter
6. Design Efficiency Tested	99.97% - 99.99%	99.8%	Almost 100%
7. Rated SCFM	14,500 CFM @ 250°F.	25,000 CFM @ 200°F.	8,800 - 9,850 ACFM
8. Cost of Equipment	$60,000.00	$25,000.00	$10.700.00
9. Installation Cost	---	---	$13,700.00
10. Approximate Annual Operating Cost	$6,000.00	$2,500.00	$15,000.00
11. Operating Period Hrs./Day - Days/Wk. - Wks./Yr.	8-5-25	8-5-25	8-6-52
12. Estimated Weight Discharge Reduction	6,112 lbs./hr.	6,000 lbs./hr.	200 lbs./hr. - 250 tons/yr.
13. Date of Installation	April 1, 1972	April 20, 1972	March 31, 1972

TABLE 9 (continued)

Particulars	Case #	4	5	6
1.	Nature of Problem	Particulate Smoke	Smoke and soot from coal burning	Wood fines
2.	Process Controlled	Grey iron cupolo	Boiler	Sanders, planers, saws
3.	Manufacturer's Name	Air Pollution Industries; Englewood, New Jersey	Crane Co., New York	Pangborne Division Carborundum Co. Hagerstown, Maryland
4.	Model Number	Serial #371	---	456-CT
5.	Type	Wet scrubber	Replaced with oil fired boiler #2 oil	Baghouse in conjunction with cyclones
6.	Design Efficiency Tested	97%	---	99%+
7.	Rated SCFM	29,700 SCFM	---	20,178 CFM
8.	Cost of Equipment	$39,000.00	$3,500.00	$15,496.00
9.	Installation Cost	$88,000.00	Included	$7,400.00
10.	Approximate Annual Operating Cost	$4,000.00	$500.00	%2,000.00
11.	Operating Period Hrs./Day - Days/Wk. - Wks./Yr.	3-5-50	24-7-26	8-5-50
12.	Estimated Weight Discharge Reduction	233 lbs./hr.	10 lbs./hr.	50 lbs./hr.
13.	Date of Installation	---	March 1972	July 1971

TABLE 9 (continued)

Particulars	Case #	7	8	9
1.	Nature of Problem	Rubber Particulates	Particulate	Particulate
2.	Process Controlled	Tire Buffers	Asphalt Plant	Asphalt Plant
3.	Manufacturer's Name	Quinn Brothers, Inc. Philadelphia	Western Precipitation Co. Los Angeles, California	Barber Greene
4.	Model Number	QCC-5	MS8-450	CF 11 X 136
5.	Type	Cyclone collector	Baghouse	Fabric collector
6.	Design Efficiency Tested	90%	99.9%	99.9%
7.	Rated SCFM	4,000 CFM, 6,000 FPM Conoajing velocity	30,000 SCFM	37,000 SCFM
8.	Cost of Equipment	$5,500.00	$60,000.00	$60,000.00
9.	Installation Cost	$2,000.00	$10,000.00	---
10.	Approximate Annual Operating Cost	$480.00	$5,000.00	$5,000.00
11.	Operating Period Hrs./Day - Days/Wk. - Wks./Yr.	10-5-51	8-5-24	4-5-24
12.	Estimated Weight Discharge Reduction	36 lbs./hr.	35 lbs./hr.	70 lbs./hr. 4% minus 200 mesh
13.	Date of Installation	June 25, 1972	1972	April 1972

TABLE 9 (continued)

Particulars	Case #	10	11	12
1.	Nature of Problem	Particulate	Grease	Wood fines
2.	Process Controlled	Asphalt Plant	Fryers	Dust collection bin
3.	Manufacturer's Name	Dusty Dustless Baldwindsville, N.Y.	Heat and Control S. San Francisco	Mircrotron Corp. York, Pa.
4.	Model Number	1-JA-480	#4 vent scrubber	1,000 TP, 115-85
5.	Type	Fabric collector	Spray Tower	(2) drum filters
6.	Design Efficiency Tested	99.9%		99%
7.	Rated SCFM	42,000 SCFM	10,000 CFM @ 225^{o}F.	30,000 SCFM
8.	Cost of Equipment	$65,000.00	$4,500.00	$75,000.00
9.	Installation Cost	---	$2,000.00	Incl.
10.	Approximate Annual Operating Cost	$5,000.00	Operating 5 HP motor 1/2" waterline	---
11.	Operating Period Hrs./Day - Days/Wk. - Wks./Yr.	4-5-24	9-5-50	16-5-51
12.	Estimated Weight Discharge Reduction	15 lbs./hr. 4% minus 200 mesh	---	760 lb./hr.
13.	Date of Installation	---	August 1971	January 1972

TABLE 9 (continued)

Particulars	Case #	13	14	15
1.	Nature of Problem	Smoke emissions	Stone dust	Aluminum oxides and chlorides
2.	Process Controlled	Boiler	Batch Asphalt Plant	Secondary Aluminum Reverberatory Furnace
3.	Manufacturer's Name	J. Brinjac and Assoc. Harrisburg, Pa.	Barber-Greene Co. Aurora, Illinois	F. Walsh and Sons, Inc. Cleveland, Ohio
4.	Model Number	---	CF 11	2088
5.	Type	Pneumatic System and Blowers	Baghouse replaces scrubber	Parsons Baghouse
6.	Design Efficiency Tested	(Higher Efficiency burning)	99.9%	99%+
7.	Rated SCFM	---	37,000 SCFM	40,000 SCFM
8.	Cost of Equipment	$7,100.00	$70,000.00	$38,860.00
9.	Installation Cost	Incl.	---	---
10.	Approximate Annual Operating Cost	$500.00	---	---
11.	Operating Period Hrs./Day - Days/Wk. - Wks./Yr.	8-5-50	6-5-20	24-6-50
12.	Estimated Weight Discharge Reduction	Reduction to within regulations	80 lbs./hr.	490 lbs./hr.
13.	Date of Installation	June 1971	April 1972	March 1972

TABLE 9 (continued)

Particulars	Case #	16	17
1.	Nature of Problem	Black smoke	Smoke
2.	Process Controlled	Open burning	Open burning
3.	Manufacturer's Name	Homemade adapted from wire reclamation incinerator specifications of Air Pollution Manual, H.E.W.	Penn Central Infrared Inc. Dubois, Pennsylvania
4.	Model Number	---	Smokatral 200
5.	Type	---	Incinerator 150 lbs./hr.
6.	Design Efficiency Tested	---	80% (Est.)
7.	Rated SCFM	---	---
8.	Cost of Equipment	$19,500.00	$4,180.00
9.	Installation Cost	Incl.	---
10.	Approximate Annual Operating Cost	$11,250.00	---
11.	Operating Period Hrs./Day - Days/Wk. - Wks./Yr.	8-5-52	3-6-52
12.	Estimated Weight Discharge Reduction	800 lbs./yr.	1 lb./hr. (Est.)
13.	Date of Installation	1971	---

Source: Lesher,[6]

TABLE 10

FUEL COST COMPARISON FOR CONTROL OF ODORS

Equipment Type	Afterburner	Afterburner with Heat Recovery	Thermal Regenerative System
Thermal recovery efficiency	0%	40%	75%
Process gas volume	16,000 scfm	16,000 scfm	16,000 scfm
Purification temperature	1400 F	1400 F	1400 F
System exhaust temperature	1400 F	920 F	500 F
Energy required for purification (Btu/hr)	21,920,000	13,150,000	5,472,000
Gross fuel energy (Btu/ft^3)	1036	1036	1036
Fuel unit cost ($/1000 scf)	$0.86	$0.86	$0.86
Available energy from fuel	61%	72.5%	81%
Cubic feet of gas required	34,700 scfh	20,808 scfh	6,520 scfh
Fuel Cost	$29.82/hr	$15.06/hr	$5.61/hr

Reproduced From: Mueller, 1971[8]

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SOLID WASTES HANDLING AND DISPOSAL COSTS

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SOLID WASTES HANDLING AND DISPOSAL COSTS

The primary purpose of this section is to analyze presently available solid waste handling and disposal techniques and determine unit costs for each such technique discussed. The study is intended to provide information necessary to evaluate the cost of solid waste management remedial programs in the Monongahela River Basin. Although many of the cost analyses given are developed for areas other than the Monongahela River Basin, the capital and operating cost figures are applicable to the region with the exception of land acquisition requirements and labor costs which may be unique to the particular area reported.

Solid waste management involves the following elements: collection and transportation, processing and ultimate disposal.

Collection and Transportation

In urban and suburban areas, the most common methods of collection include municipal collection, contract with a private firm and private collection service. In any case, refuse is normally collected in a compactor truck which transports the wastes to either the processing and disposal site or to a central transfer station. Toftner and Clark(1) recommend the use of transfer stations and size reduction techniques to reduce costs when long hauls are necessary or when large areas are serviced. Another study by Kramer(2) suggests the use of transfer stations if the disposal facility is more than ten miles from the collection area. Kramer lists advantages of transfer stations as: 1) reduced cost of transportation; 2) more efficient use of collector trucks; 3) modest capital cost; and 4) reduced vehicle requirement. The capital costs for such a station including one tractor and two trailers is given as $1,620 per ton per day capacity. Estimated operating costs for a 15 mile haul using a transfer station are given as $0.17 to $0.27 per ton-mile while the cost of packer truck hauling over the same distance is estimated as $0.18 to $0.40 per ton-mile.

In rural areas, collection and disposal are more difficult and more costly than in urban and suburban areas. Inadequate collection services in rural areas lead to unsightly dumping or open burning of refuse. In areas of Pennsylvania infrequent or nonexistant collection services have led to the infestation of the State with over 2,600 roadside dumps and allowance of open burning of domestic refuse in many municipalities (Toftner and Clark(1)). Andres and Cope(3) recommend a system of containerized storage and transfer for rural areas. The stated goal is to eliminate several existing dumps by promoting individual refuse disposal in 8 to 40 cubic yard containers placed at central locations and transfer of the containerized waste to a single centrally located sanitary landfill weekly. The annual cost per ton including amortization for containers and transfer to landfills was estimated to range from $13.63 to $17.89 as compared to a $17.39 annual cost for operation and maintenance of individual community modified sanitary landfills. A similar study was conducted in Vermont (Cacioppi, et al.[4]). Costs were estimated on the basis of the number of cubic yards of compacted waste transported to sites various distances from the collection point in 35 cubic yard containers. Compactor and container leasing costs were estimated at $235 per month, and the charge for disposal at $25 per container. An average of one hour travel time for 30 miles and a time of one-half hour for unloading was assumed. On the basis of 500 pounds per cubic yard compacted, a cost per container load is given. For this study the costs have been converted to a cost per ton of compacted waste. The data is reproduced in Table 1.

TABLE 1

Container Site Distance from Disposal Site (Miles)	Cost/Ton @ 8.75 Ton per Container		
	Times Per Week Containers Emptied		
	1	2	3
3	10.23	6.67	5.64
6	10.43	6.88	5.88
9	10.64	7.09	6.05
12	10.85	7.29	6.26
15	11.05	7.50	6.48
18	11.26	7.71	6.67
21	11.47	7.98	6.88
24	11.67	8.11	7.08
27	11.87	8.32	7.29
30	12.08	8.53	7.49

Source: Solid Waste Section, Environmental Protection Division Agency of Environmental Conservation, State of Vermont in Cacioppi et al., 1970[4]

The data may be extrapolated to greater distances at a rate of $0.07 per ton-mile. The report states that the containerization system is highly suitable for rural areas and small communities and is sanitary, flexible and economic.

Disposal Methods

The conventional solid waste disposal methods include open dumping, sanitary landfill, incineration and composting. Some advanced disposal and recovery or recycling techniques are also known, such as pyrolysis, biological fractionation, and various separation processes; however, most of these techniques are still in the experimental stage.

Open and Covered Dumping

Open dumping is the most common method of solid waste disposal in some areas of the United States, although it is by far the least desirable method. No direct cost figures are available for open dumping; however, the intangible costs of unsanitary conditions, ground and surface water pollution, air pollution, insect and rodent problems, and aesthetic degradation may be associated with this method.

Covered dumping is similar to open dumping except that the refuse is periodically covered with soil. The disadvantages of covered dumping are the same as those mentioned for open dumping. Vermont has estimated costs for closing and sealing dumping sites to be $8,000 per acre (Cacioppi, et al.[4]).

Sanitary Landfills

Sanitary landfill techniques are the most practical and economical methods of solid waste disposal in many areas. Two basic methods of sanitary landfill exist, trench fill and area fill. The area landfill involves the filling of large low-lying areas with cells of refuse compacted and covered with soil at regular intervals. The trench method involves excavation of trenches, filling with refuse and recovering the trenches with soil. The soil cover should be two feet deep over the refuse cells (Golueke[5]). The refuse layers should not exceed five to six feet in depth and should be compacted before being covered.

In several areas of the anthracite and bituminous coal regions of Appalachia, abandoned strip mines are used for sanitary landfills. The use of strip mines not only solves local solid waste disposal problems, but may also lead to restoration of the strip mine areas. Emrich and Landon[6] investigated five strip mine landfill sites in Western Pennsylvania. They found little or no ground or surface water pollution where care is taken to avoid permeable or fractured rock.

For either the area fill or trench fill method equipment requirements range from a single crawler tractor with dozer blade or bullclaw attachment for smaller operations to one bulldozer, compacting equipment, water trucks and earth movers for larger sanitary landfills. One bulldozer of the 4,700 pound gross weight size will handle 250 tons of solid waste per day (Golueke[5]).

Sanitary landfill costs will depend on the population served, size of the landfill, and the equipment required. Initial investments are variable depending on the price of the property acquired. The initial land costs may be partially or completely offset by restoration of the completed landfill for development purposes. Operating costs are more definable, and several costs of operation are given in the literature. Kramer[2] gives operating costs of $1.65 to $2.10 per ton for a 300 acre site handling 96,000 to 150,000 tons per year. In Vermont, sanitary landfill operation costs are estimated to range from

$0.60 to $3.00 per ton depending on the amount of waste to be disposed (Cacioppi, et al.[4] Ralph Stone and Company[7] gives costs of $1.50 per ton for sanitary landfill disposal. Sorg and Hickman[8] have stated that wages account for 40 to 50 percent of costs; equipment, 30 percent; and cover material, administration and overhead, 20 percent. Operating costs developed by Sorg and Hickman are presented in Figure 1.

Incineration

Modern incineration involves controlled burning of solid wastes in a closed vessel at high temperatures. The solid waste may be batch fed or continuously fed onto agitating grates where primary combustion occurs. Ashes and noncombustables are fed into hoppers for disposal. The smoke, exhaust gases and fly ash are directed into a secondary combustion chamber where they are burned at temperatures of 1,500 to 1,800 degrees F (Flower[9]). The gases then flow through settling chambers for removal of heavy particulates and then through various gas cleaning devices to the exhaust stack.

Incineration reduces the volume of waste to be disposed of to 10 to 30 percent of its original volume (Engdahl[10]). The residues may be landfilled directly or separated by mechanical and/or magnetic devices for recovery of ferrous metals and glass. Gilbertson and Black[11] have found landfill or ash residues to cost approximately $1.00 per ton.

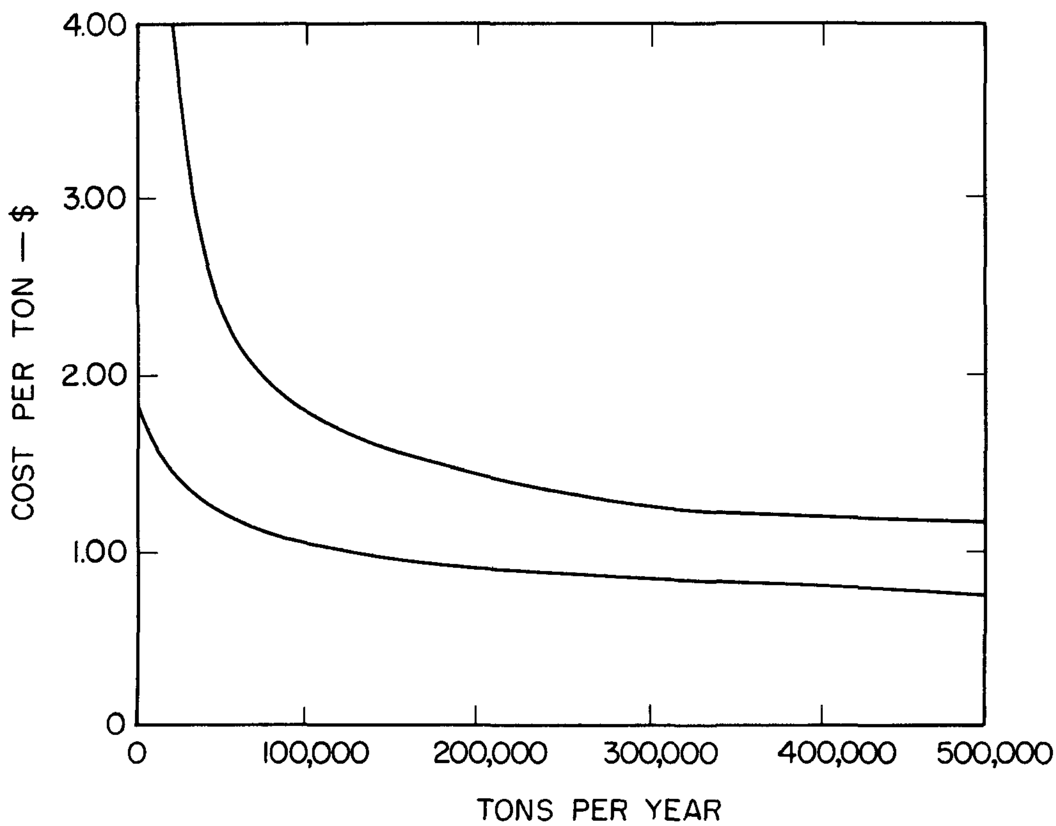
Gouleke[5] has listed equipment needed for incineration of municipal solid waste. A storage pit or hopper holding an amount equal to 24 hours of burning capacity is needed for receiving and storing refuse. A bridge crane, a charging hopper, a feeding and drying stoker and a burning stoker are needed for charging the incinerator. The incinerator should have primary and secondary combustion chambers lined with refractory materials and various gas cleaning chambers, flues and dampers. Ash hoppers and conveyors must be provided for removal of residues. Various instrumentation for temperature measurement, draft gaging and stack gas monitoring should also be provided. Finally, a landfill site is necessary for disposal of the incinerator residues.

Michaels[12] in 1956 reported the capital costs of municipal incinerators to range from $3,000 to $4,000 per ton of 24 hour capacity with buildings accounting for 40 to 76 percent, furnaces and auxilary equipment accounting for 18 to 24 percent and stacks accounting for 4.5 to 11 percent of the total capital cost. More recently, Cacioppi, et al., 1970[4] reported capital costs to range from $8,000 to $11,000 per ton of 24 hour capacity.

Greeley[13] listed the capital costs of municipal incinerators for New York City by component. These unit capital costs are reproduced in Table 2.

FIGURE 1

SANITARY LANDFILL OPERATING COSTS



Reproduced From "Sanitary Landfill Facts"
Thomas J. Sorg and H. Lanier Hickman, Jr. 1970
P H S Publication No. 1792

TABLE 2

PRINCIPAL COMPONENTS OF A MUNICIPAL INCINERATOR AND COSTS

Item	Unit Cost Per Ton Of Rated Capacity
Scales, roadways, dumping rail and enclosing wall	$ 100
Storage bin	200
Cranes	225
Flues and fly ash removal facilities	400
Chimneys	300
Furnaces	1,200
Inside Flues	85
Building and enclosure	1,415
Miscellaneous	75
Total	$4,000

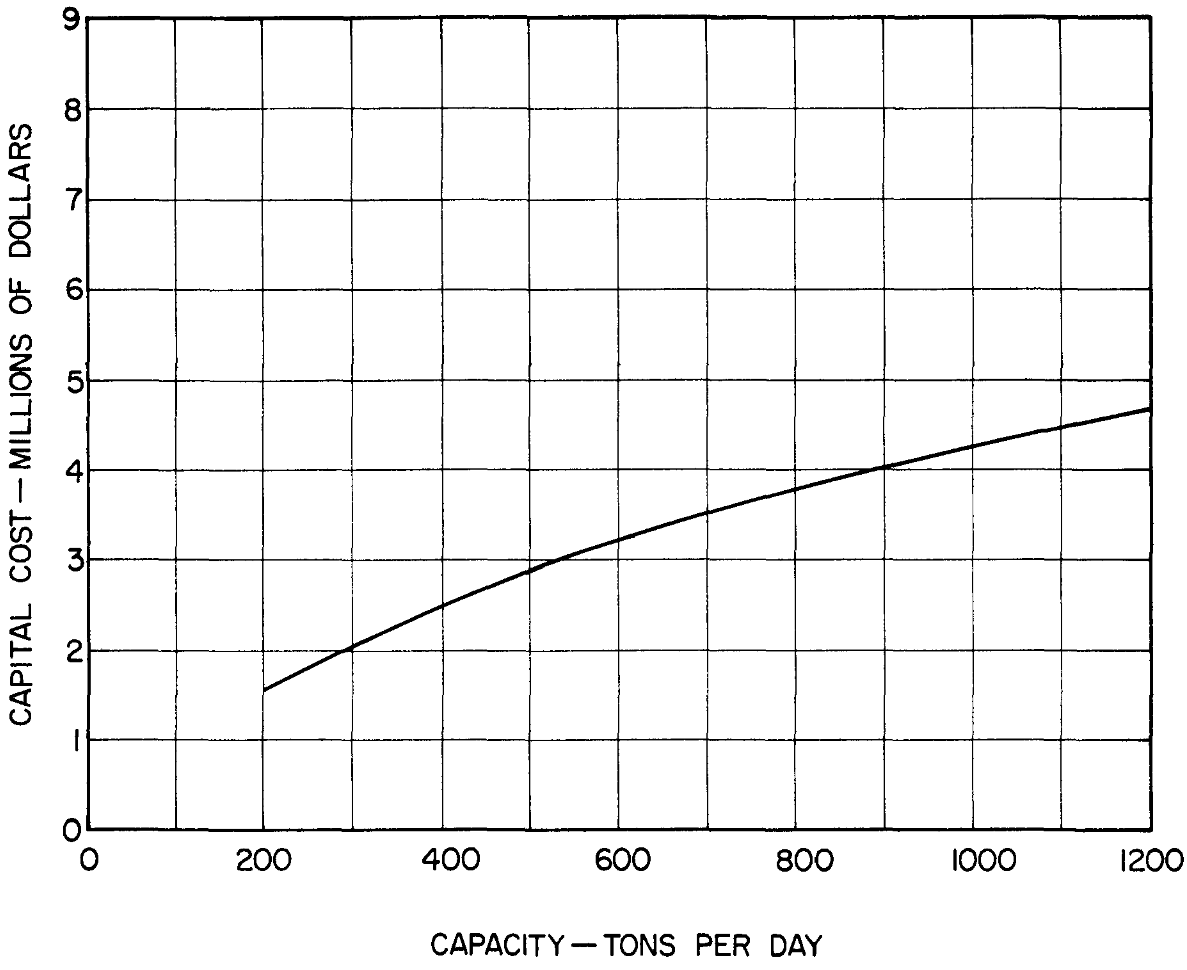
Source: Greeley, S. A., "Background of Design Criteria for Municipal Incinerators - The Designer's View," JAPCA 6(3)133-9, 1956.

Further, Drobny, et al.[14] give total capital costs of various sizes of municipal incinerators based on conventional engineering estimating factors. A portion of their data is reproduced in Figure 2 for construction of incinerators with conventional refractory and no waste heat recovery.

Operating costs for municipal incinerators are highly variable and primarily related to the size capacity of the units and the percent of capacity use per day. Several authors have reported operating costs for municipal incinerators. Rogus[15] reporting on large incinerators of approximately 1,000 ton per day capacity in New York found costs to vary from $4.78 per ton for older plants to $2.39 per ton for newer design plants. Gilbertson and Black[11] found operating costs to average $3.00 per ton in the Washington, D. C. area. The Committe on Refuse Disposal, APWA[16] reported unit costs for municipal incineration in six major U.S. cities to range from $2.28 to $6.49 per ton on a 1959 base. A unit cost of $8.53 per ton including the cost of disposal of ash and inerts was estimated for incineration by the City of

FIGURE 2

CAPITAL COSTS OF MUNICIPAL INCINERATORS



From Drobny, N. L. et al. Recovery and Utilization of Municipal Waste U.S. EPA 1971

Santa Clara, California (Ralph Stone and Company[7]). Golueke[5] found incineration costs to vary from $4.00 to $12.00 excluding pollution control devices in the Oakland, California area. Unit costs estimated by Kramer[2] ranged from $6.50 to $8.40 per ton for two 300 ton per day capacity incinerators for Clark County, Ohio. Costs for incineration in the state of Vermont were estimated to range from $7.00 to $11.00 per ton (Cacioppi, et al.[4]).

Composting

Composting, presently more common to Europe than to the United States, is a biological digestion process whereby the organic components of refuse are degraded into a humus-like product. The process involves the screening of refuse to remove nonorganic materials and biological oxidation of the remaining organics for a period of two to five weeks. The cured compost may be used as a soil conditioner, but because its nutrient content is low, it does not make a good fertilizer.

In the United States composting has not been too attractive because it is not economically competitive with other disposal methods and because no major United States markets have yet developed for compost. Additionally, since the bulk of solid waste is produced in large urban areas and compost would be utilized in rural areas, the transportation costs to move large volumes long distances would often be prohibitive.

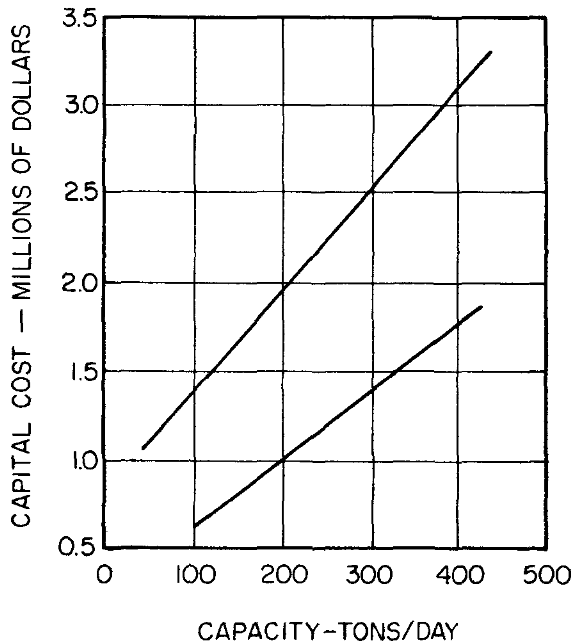
Estimated costs for composting operations in Vermont were estimated to average as high as $8.00 per ton. A composting demonstration plant in Gainesville, Florida had operating costs of $6.25 per ton. Goleuke[5] gives estimated operating costs for composting of $7.00 to $8.50 per ton to serve a population equivalent of 100,000. Kramer[2] estimates compost costs to range from $7.00 to $8.00 per ton of solid waste. Engdahl[10] reported on pilot studies on composting municipal garbage at San Diego, California. Costs of operation excluding administration, overhead and capital amortization ranged from $1.56 per ton where no grinding or other preparation occurred to $20.48 per ton where the garbage was course ground and straw was added. The report further states that grinding accounted for 30 to 60 percent of the total cost per ton.

Drobny, et al.[14] reported on the operation of six privately owned compost operations. Estimates of the capital and operating costs of the systems have been summarized based on operation of a 25 ton per day pilot plant in Altoona, Pennsylvania and Houston, Texas. These costs are illustrated graphically in Figures 3 and 4 for various capacity plants. Operating costs include payroll, utilities and supplies and administration. The reasons for the large range of operating costs are not clear.

Composting in Europe was reported by Hart[17]. He found European refuse more amenable to composting by virtue of its composition. Composting costs were reported as $2.00 per metric ton or $1.80 per short ton.

FIGURE 3

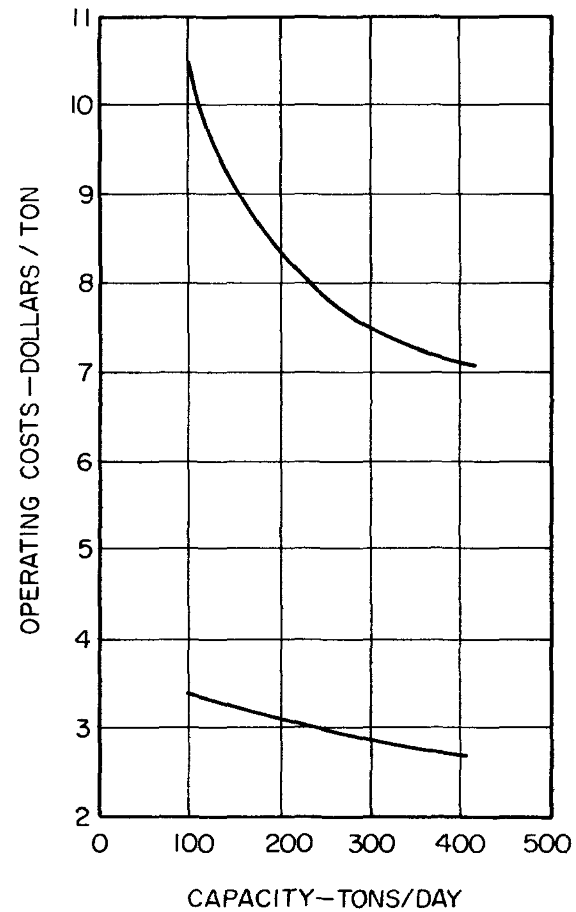
CAPITAL COSTS
OF COMPOST SYSTEMS



ADOPTED FROM DROBNY et al [14]

FIGURE 4

OPERATING COSTS
FOR COMPOST SYSTEMS



Experimental Solid Waste Disposal and Recovery Techniques

There are a number of experimental techniques for solid waste processing now in the research and pilot study stages. Most of these processes now under development are oriented toward the recovery of some economically useful component of solid waste for reprocessing or reuse.

A few of the existing solid waste processes may be modified for recovery of salvageable materials; however, the economics have not been thoroughly defined at this time. The U.S. Bureau of Mines has been the most active organization in developing these recovery methods. A Bureau of Mines pilot plant erected in 1967 has successfully separated metallic iron, non-ferrous metal, glass and ash tailings from incinerator residues (Davis[18]). The plant has an operating cost of $2.00 per ton of residue processed and produces $10 to $12 in recoverable products per ton of residue, Kenahan[19] reports. Drobny, et al.[14] discusses similar recovery systems applicable to compost operations.

Pyrolysis

Pyrolysis, or destructive distillation, is a process of heating a material to about 1,500 degrees F without air to break down the organics into component parts. The process was originally developed by the U.S. Bureau of Mines for coal and coke research; however, the process is now finding limited applications in the solid waste field for the production and recovery of tars, fuel gases and liquids, alcohols, acetic acid, charcoal ash and other organic chemicals (Sanner, et al.[20]). Drobny, et al.[14] has estimated the net operating costs to be about $5.70 per ton of refuse; however, because of the retort residence time requirement of 23 hours, the process appears unprofitable on a large scale.

Biological Fractionation

Biofractionation involves the processing of organic components of solid wastes in a manner similar to aerobic digestion to produce a solid residue with nutrient value for animal feed. The system is highly experimental and costs now average over $40 per ton of refuse processed (Golueke[5]).

Recycling

The ultimate solution to solid waste disposal problems will be utilization. Several community groups and some commercial organizations are salvaging metals, glass, and paper by voluntary sorting the components of solid waste. To date, the majority of operations recycling municipal refuse have been on a very limited scale. However, the role of the organizations in acting as a catalyst to bring about changes in attitudes toward waste in general has been of great value.

Since the majority of organizations involved in recycling use volunteer labor, no cost estimates are available. Methods of economically separating and concentrating urban refuse must be developed before large scale applications of this method are possible. Central storage areas must be developed and minimum daily supplies to recovery industries must be insured (Clark[21]). Conversion of solid wastes into only a few marketable products critically limits the number of markets which can be reached and increases the possibilities of oversupply. Gentile[22] stated, "It is important to combine the element of 'separation' and 'salvage' into a complete conversion system in order to develop a greater variety of by-products and distribute the resultant items and raw material to the most diversified markets possible."

Even though the recycling of urban refuse may be uneconomical in itself at the present time, it may be economically attractive when considering the total cost to the consumer for producing and discarding a particular product. Not only are the natural resources used in the production and disposal of a product utilized, but new natural resources must be developed and utilized to replace the discarded product. When considering reclamation costs, possible devaluation of affected lands and decrease in aesthetic value, a net savings may be incurred from recycling of a majority of urban refuse. A national effort will have to be exerted, however, before the true economic advantages of recycling can be fully realized.

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ABANDONED AUTOMOBILE REMOVAL COSTS

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Introduction

According to the National Industrial Pollution Control Council[1], approximately 21% of the automobiles produced in the United States since 1959 are either abandoned or in automobile graveyards. The wide use of the basic oxygen furnace in the steel industry is the major factor responsible for this accumulation of unused automobile scrap (Dean, et al.[2]). The oxygen furnace is limited to an initial charge of 26 percent scrap compared to 48 percent in the open hearth process. As a result, the market value of ferrous scrap has decreased proportionately. Although the chief component by weight of the average automobile is steel and iron (95%), other metals present in recoverable amounts are lead (1%), copper (1%), aluminum (1%) and zinc (2%) as reported by the Bureau of Solid Waste Management[3] and Dean and Sterner[4].

Besides being a serious waste of natural resources (Shapiro[5]), unused automobile scrap is responsible for health and safety problems and environmental degradation (Dean[6]). Environmental damage not only occurs as a result of the physical presence of an unused automobile, but also because of the increased amount of ore, coal, limestone, and other raw materials necessary to replace the metals discarded. Even though automobile production requires 20 percent of the steel produced and imported by this country (Javits[7]), reprocessed automobile scrap accounts for only nine percent of total scrap utilized (Ralph Stone and Company[8]).

The recycling of rubber used in automobile production, approximately 60 percent of the total U.S. production, has presented similar problems. The primary deterrent to rubber product reuse in the form of automobile tires has been storage and shipping costs (Hassell[9], Pettigrew and Roniger[10]).

Proposed Federal Legislation

Proposed federal legislation that could alleviate future problems associated with abandoned automobiles and automobile graveyards was recommended in 1970 by Javits[11] and Gurney[12] in Senate Bills S4204 and S4197 respectively.

Senate Bill 4204 proposes the use of a "disposal deposit" on all new automobiles. This deposit would be transferrable and refunded at the time the automobile is deposited at an authorized scrap center. If the car was illegally abandoned, a public agency or authorized scrap dealer would remove the vehicle and collect the disposal fee. This bill is also designed to decrease the number and size of junk car lots since a dealer would not receive the disposal deposit until the automobile is actually sent to a reprocessing center. Except for initial organizational expenses, the program should be self-financing. This abatement method possibly could be applied to other items such as tractors, industrial equipment, refrigerators and other househould appliances.

Senate Bill 4197 proposes financial aid to states and would allot funds based on motor vehicle registration in the state. The additional revenues provided to salvage operators in the form of a "bounty payment" would be an incentive to scrap any unusable automobile.

A similar system is already in operation in Maryland where licensed scrap processors receives $10 for each car certified as actually reused as scrap (Leib[13]). Another method involves collection and accumulation of abandoned automobiles by municipal agencies with aid of state funds (Karr[14]).

Other Abandoned Automobile Recycling Recommendations

Other recommendations designed to make automobile scrap recycling economically attractive are:

1. A uniform title clearance procedure which will make abandoned automobile reprocessing easier.

2. Restrictions on the importation of iron ore and steel to encourage the use of scrap.

3. Financial incentives to automobile reprocessors in the form of guaranteed loans and tax write-offs.

4. Manipulation of freight rates to favor scrap reuse.

5. Federally controlled stockpiling of scrap to limit fluctuations in market demand and scrap availability.

6. Development of recycling districts with reprocessing centers.

7. Elimination of "built in" obsolescence in the automobile industry.

8. Development of more efficient methods of nonmetallic waste separation in abandoned automobile reprocessing.

9. Acceleration and expansion of research devoted to the increased use of automobile scrap.

10. Initiation of legislation prohibiting abandonment of vehicles and restrictions on ownership of wrecked, nonoperating or discarded vehicles as outlined in the "Model Ordinance" prepared by the National Institute of Municipal Law Officers[15].

The Need for a Comprehensive Field Survey

A comprehensive field survey is necessary to insure the success of an abandoned vehicle collection program. Information from such a survey should include type of automobile, general condition, amount of surrounding rubble, and if possible, the owner of the land on which the vehicle is located. Location is probably best facilitated by assigning the vehicle a number and marking it on an appropriate map.

Many surveys have been performed utilizing community service organizations such as the Boy Scouts of America, YMCA and other groups. Sometimes local and state agencies can be utilized in the compilation of abandoned automobile data. West Virginia used the state police to locate and obtain release of discarded vehicles. In some communities, it may be possible to have "phone-in" campaigns such as in Michigan where citizens were informed of the program through the local news media as reported by General Motors Corporation[16].

Chase[17] mentioned a bounty system where students were given a $1 reward for each automobile reported and accompanied by a certificate of release. Some commonly accepted title clearance procedures must be developed before a program such as this could be applied on a large scale. Another possible method that may be economically feasible in locating abandoned automobiles is aerial reconnaissance. Two people is all that is necessary to complete such a survey and large areas can be viewed in a relatively short period of time.

Cost of Retrieving Abandoned Automobiles

After an adequate survey has been prepared and certificate of release or title clearance is accomplished, actual removal of discarded vehicles will be possible. In the West Virginia program, the National Guard were used to retrieve vehicles. Reported costs were $40 per automobile, but it was estimated this cost would be 50 percent less if the program was conducted when weather conditions were more favorable (Gandee[18]).

In a cleanup campaign in Columbia County, New York, the County Health Department collected 12,000 automobiles at a unit cost of $1.67. In programs conducted by the Vermont Motor Vehicle Department 13,151 vehicles were collected at an average cost of $10 per car. Both projects used trucks to pick up vehicles. Automobiles were deposited in a central collection area where salvage operators disposed of the accumulated scrap.

Steen[19] reported that the Tennessee Valley Authority has developed a feasible method of collecting derelict vehicles in rural areas. The focal point of this method according to Steen[20] is the use of a modified truck which require only one man to pick up, deliver, and deposit a vehicle with or without wheels. A summary of the results of this program based on available information is as follows:

Location	Number of Automobiles	Total Expenditures	Unit Cost
Anderson Co., N.C.	648	$4,183.59	$6.46
Loudon Co., Tenn.	300	450.00	1.50
Towns Co., Georgia	450	1,450.00	3.22
Murphy, N. C.	179	736.36	4.11
TOTALS	1,577	$6,819.95	$4.32

The average reported unit cost of $4.32 per vehicle compares favorable with the estimate of $4.50 made by the TVA during initial stages of the program.

Little data exists concerning the cost of vehicle retrieval labor, impoundment, and subcontractor cost breakdown. Rothman(21) estimates the total cost of disposing of abandoned automobiles in New York City is $40 to $60 per vehicle. In areas where impoundment is not necessary, automobiles may be removed by licensed processors free of charge.

Better cost estimates will be possible when a standard format is developed for reporting results of an abandoned automobile removal program. The information form should include descriptions of:

1. Field Survey Methods
2. Advertisement Methods
3. Removal Techniques (including equipment, average haul distance, condition of abandoned automobiles, source of labor and other pertinent factors)
4. Storage Facilities
5. Final Disposition of Scrap

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EROSION AND SEDIMENTATION CONTROL COSTS

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Sediment is the greatest single pollutant of streams, lakes, ponds and reservoirs. Sediment lowers the quality of water for municipal and industrial uses and for boating, fishing, swimming, and other water based recreation; it increases the wear on equipment, such as turbines, pumps and sprinkler irrigation systems. Sediment carries with it pesticides, phosphates and other chemical pollutants(1).

Each year more than a million acres of land in the United States are converted from agricultural use to urban use. Studies show that erosion on land going into use for highways, houses, shopping centers and other commercial or residential uses is about 10 times greater than on land in cultivated row crops, 200 times greater than on land in pasture and 2,000 times greater than on land in timber. The nationwide damage caused annually by sediment has been estimated at more than $500 million. Much sediment comes from agricultural land, but the amount contributed by land undergoing urban development is high in proportion to the acreage(1).

Severe sediment problems occur when covering vegetation is removed in construction areas, when the flow regime in channels is altered by realignment or by increased or decreased flow, or when fill, buildings, or bridges obstruct the natural flowway(2). Sediment movement and deposition are part of the natural environment, but the average sediment yield from the landscape and the condition of stream channels tend to change with the advancing forms of man's land-use activity. A major problem is that the scientist or engineer, because of his relatively narrow field of investigation, cannot always completely envision the less desirable effects of his work and communicate alternative solutions to the public(2). Recent publications, Powell, et al.(3), West Virginia Department of Natural Resources(4), Pennsylvania Department of Environmental Resources(5), and Soil Conservation Service(1) indicate that governmental agencies are becoming very much concerned with damages caused to the environment by erosion and sedimentation.

Urbanization tends to increase both the flood volume and the flood peak as pointed out by Leopold(6) in his study summarizing existing knowledge of the effects of urbanization on hydrologic factors. Much of the erosion occurs during the construction period, but areas below a construction site may erode more after construction is completed because of the rapid runoff from impervious pavement, parking lots, or compacted soil. Increased runoff erodes stream banks and channels and causes flooding below the construction site.

Surface mining activities are responsible for serious erosion and sedimentation problems in some areas because of the highly erodable nature of spoil banks(7) and the usual sparseness of vegetation as compared to "undisturbed" areas(8). In other areas, timbering operations, with attendant logging and haul roads and removal of a forest canopy which causes increased runoff, can be the most damaging environmental problem, particularly downstream of the operation. The major source of sedimentation pollution in some areas is the "right-of-way" for a powerline, pipeline or other utility.

Prevention and Control of Erosion and Sedimentation

As with most stream pollutants, sediment can best be prevented at the source, i.e., control erosion and runoff at or near the area undergoing urbanization, deforestation or surface mining. Temporary or emergency "back-up" precautions can be employed using sedimentation and storage collection structures. The structures must be designed to insure there is no danger of failure which could cause downstream damage. On large projects, a comprehensive survey must be performed to evaluate geologic, hydrologic and engineering design considerations. This survey is necessary to insure that the structure will provide adequate sediment and storage capacity and be of safe design.

Since urbanization and other land uses tend to increase flood volume and the flood peak, provision for flood storage upstream will decrease flood peaks and sedimentation yield and compensate for the increased flow caused by land use. Reservoir storage installed on a river reduces the magnitude of peak discharge by spreading the flow over a longer time period. Channels themselves provide temporary storage and act as if they were small reservoirs. Overbank flooding on the flat flood plain is a way that natural rivers provide temporary storage and thus decrease flood peaks downstream.

Flood storage for urban areas can take many forms including the following[6]:

1. Drop inlet boxes at street gutter inlets.
2. Street-side swales instead of paved gutters and curbs.
3. Check dams, ungated, built in headwater swales.
4. Storage volumes in basements of large buildings receiving water from roofs or gutters and emptying into natural streams or swales.
5. Off channel storage volumes such as artificial ponds, fountains or tanks.
6. Small reservoirs in stream channels such as those built for farm ponds.

The following factors determine the amount of erosion that occurs in an area:

1. Soil types
2. Slope of the terrain
3. Rainfall intensity
4. Infiltration capacity of the soils
5. Amount and kind of vegetation
6. Construction methods

Erosion and sedimentation can be controlled effectively, and at reasonable cost, if certain principles are followed in the use and treatment of land.

1. Know the soil characteristics, geology, hydrology and topography of the area. Information on soils can be found in the Soil Conservation Service (SCS) soil survey report of the area. If there is no report, information may be available in the "open files" of the SCS District Office or the Agricultural Extension Service. Soil surveys describe the characteristics and properties of each kind of soil in the area - its texture, slope, depth, erodibility, permeability, degree of wetness, presence of impervious or porous layers and other information useful in construction. The soils information found in these reports, though very useful for an understanding of soils problems, is general in nature. It does not replace the need for professional assistance in the design of structures where failure would cause loss of life and property damage.

2. Have a site development plan that includes provisions for control of runoff, erosion and sedimentation and reclamation of areas disturbed by the land use.

3. Do not grade or strip more land than needed for immediate use. In this way, soil is left bare for the shortest period of time. This calls for developing large tracts in small workable units. In the case of strip mining and timbering operations, reclamation of disturbed areas should be performed concurrently with development.

4. In construction projects, keep grading at a minimum and remove only undesirable trees wherever possible. Protect critical areas with mulch or temporary cover crops and with mechanical methods such as diversions and prepared outlets.

5. Reduce velocity and control the flow of runoff by detaining runoff on the site to trap sediment by constructing sediment basins. Consideration should be given to offsite measures that may be needed to prevent damage to downstream land and property by either erosion or sediment.

6. During construction use soils that are suitable to the development.

7. Establish permanent vegetation and install erosion control structures as soon as possible.

Cost of Erosion and Sediment Control Structures

Normally no two erosion or sediment control structures are alike. Each facility has to be individually designed to suit site conditions and to satisfy hydrological requirements. Therefore, no standard cost estimate per unit of watershed or other commonly accepted method of basing cost on unit area is practical without first considering site conditions and hydrological requirements. Some of the variables that affect construction costs for these structures are presented in Table 1.

Most of the reported costs for erosion and sediment control in Pennsylvania and West Virginia were for structures constructed in conjunction with highway projects. These structures are usually designed for a limited life and require frequent dredging or cleaning out to maintain operating efficiency. The unit cost estimates reported by the highway departments are presented in Table 2. The design of these structures conforms to design requirements given in publications by West Virginia Department of Natural Resources(4), Soil Conservation Service(9) and Pennsylvania Department of Forests and Waters(10).

On small projects, the largest cost may be mobilization of equipment. It may, therefore, be advantageous to perform reclamation on a watershed basis so as to reduce individual mobilization costs and possibly the number of structures required.

TABLE 1

VARIABLES AFFECTING EROSION AND SEDIMENT CONTROL COSTS

1. Type of Installation
   A. Dams - Embankment, rockfill, concrete, log and pole/brush or other type of dam structure
   B. Ponds - Excavated, natural or embankment
   C. Diversions - Channel, ditch or other methods
   D. Riprap for slope, shore or channel protection
   E. Other types of installations

2. Size of Installation Required

3. Hydrological Requirements - Design Flood

4. Design Life of Installation

5. Site Preparation
   A. Access roads
   B. Clearing and grubbing
   C. Water diversion and dewatering
   D. Other site preparation requirements

6. Availability and Haul Distances for Construction Materials

7. Building Code Specifications, Inspection Fees, Performance Bond Requirements and Legal Requirements

8. Post Construction Reclamation

TABLE 2

SUMMARY OF SEDIMENT COLLECTION FACILITY CONSTRUCTION COSTS

Structure Type	Unit	Cost
Excavated Dams or Ponds	C.Y.	\$7 - \$8
Embankment Dams	C.Y.	\$4 - \$6
Stone Check Dams	$Ft.^2$	\$10 - \$30
Log and Pole/Brush Dams	Dam	\$150
Riprap		
Dumped	C.Y.	\$5.50 - \$6.75
Placed	C.Y.	\$12 - \$16
Diversion Ditches (2' Deep x 6' Wide)	L.F.	\$1 - \$2.75
Sand Bags	Bag	\$2.50
Maintenance		
Sediment Dredging	C.Y.	\$5 - \$7
Hauling . . . . First Mile	C.Y.	\$.55 - \$.70
. . . . Each Additional Mile	C.Y.	\$.20 - \$.25

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INDUSTRIAL WASTES "ORPHAN" AND OTHER ENVIRONMENTAL PROBLEMS IN THE PUBLIC SECTOR

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INDUSTRIAL WASTES "ORPHAN" AND OTHER ENVIRONMENTAL PROBLEMS IN THE PUBLIC SECTOR

Introduction

This section is concerned with accumulations of solid wastes other than municipal, abandoned automobiles, and earth materials from the coal mining industry. Further, the solid wastes are abandoned and are now a public responsibility; they may be more a public nuisance than a source of air or water pollution; and one can reasonably expect to find these wastes in the Monongahela River Basin. The solid waste accumulations are from manufacturing, mining, timbering, transportation and other abandoned activities of man in the Monongahela River Basin.

Many of the wastes have littered the landscape and stream beds for a long period of time, a hundred years or more, although, the volume of solid waste has increased rapidly in the last 50 years. The solid wastes fall into three main categories of materials:

1. Materials of metal manufacture which can be classified as scrap metal.

2. Wood product materials including timbering and manufacture.

3. Soil and rock type materials including brick, coke breeze, fly ash, slag and other materials resulting from production and manufacture.

Types of Solid Wastes

Other than coal mine refuse, abandoned automobiles and municipal wastes, there is very little information on the types, characteristics and quantities of abandoned industrial and other solid wastes that can be found in the Monongahela River Basin. The following list is based on a knowledge of the history of industrial development within the area and, for each industry or activity the type or solid wastes that can be expected are given.

1. Coke Making Industry - Coke breeze, beehive ovens, abandoned buildings, track and other metal equipment associated with coke manufacture.

2. Coal Fired Power Plants - Fly ash, bottom ash, boiler slag, abandoned buildings and metal plant equipment.

3. Coal Processing Plants and Other Mining Equipment - Tipples, hoists, engines, pumps, track, mine cars, scales, abandoned buildings and other wood and metal equipment.

4. Railroad Industry - Abandoned track, ties, signalling equipment, water towers, bridges and other wood and metal equipment.

5. Glass Industry - Slag, cullet, buildings and equipment.

6. Pottery and Stoneware Manufacture - Broken crockery, refractories, platermolds, abandoned buildings and equipment.

7. Brick Manufacture - Broken brick, molds, ovens, plant and equipment.

8. Foundries - Stone furnaces, refractories, waste products and metal working equipment.

9. Chemical Industry - Plant wastes, abandoned buildings and equipment.

10. Forest Products Industry - Slashings and bark from timbering operations, and sawdust, sawmill slabs and scrap wood from sawmill operations.

11. Petroleum Industry - Abandoned pumps, feeder lines, pipe, derricks and other equipment from oil and gas production. Wastes, trash, spent catalysts, scrap lumber and dense sludges from refinery operations.

12. River Navigation - Abandoned piers, wharfs, buildings, barges, boats and other wood and metal equipment.

13. Metal Smelting and Refining - Slag, obsolete or abandoned plant and equipment, residues from refining iron, lead, zinc, aluminum and other metals.

14. Demolition Contractors - Refuse, concrete, brick, lumber and scrap metal usually in piles.

Cost Analysis and Methods of Disposal

An in depth survey has not been made on location and quantities of solid wastes discussed in this section, but it appears, that for many of these wastes, the methods of disposal and costs discussed in the section "Solid Wastes Handling and Disposal Costs" could be used for estimating purposes.

Most of the scrap metal would be iron and steel and could have salvage value, the value depending on tonnage and size of pieces at a specific location. Scrap metal dealers may be willing to salvage this material if permission is granted by property owners.

There is no information on abandoned chemical wastes in the Monongahela River Basin. It may be hazardous to disturb chemical wastes and each occurrance of this type material will have to be investigated prior to disposal to prevent water pollution and handling problems.

Fly ash, bottom ash and boiler slag does have limited use and old disposal areas are being worked for construction materials and other uses. Table 1 based on a publication by Sikes and Kolbeck[1] tabulates ash collection and utilization in the United States in 1971. The percent of ash utilization has risen from 12.1 in 1966 to 20.1 in 1971.

TABLE 1

ASH COLLECTION AND UTILIZATION IN THE UNITED STATES - 1971

Type of Ash	Fly Ash (Tons)	Bottom Ash (Tons)	*Boiler Slag (Tons)	Total Ash (Tons)
Ash Collected	27,751,054	10,058,967	4,970,786	42,780,807
Ash Utilized				
1. Used in Type 1-P Cement ASTM 595-71	16,536	---	---	16,536
2. Mixed with raw material before forming cement clinker	104,222	---	91,975	196,197
3. Partial replacement of cement				
a) Concrete products	177,166	35,377	76,563	289,106
b) Structural concrete	185,467	---	---	185,467
c) Dams and/or other mass concrete	71,411	---	---	71,411
4. Stabilization	36,939	7,880	49,564	94,383
5. Lightweight aggregate	178,895	13,942	---	192,837
6. Fill material	363,385	533,682	2,628,885	3,525,932
7. Filler in asphalt mix	147,655	2,833	81,700	232,188
8. Miscellaneous	98,802	475,417	428,026	1,002,245
Sub-Total Items 1 to 8	1,380,478	1,069,131	3,356,713	5,806,322
Ash Removal from Power Plant Sites (At no cost to Utility)	1,872,728	542,895	381,775	2,797,398
Total Ash Utilized	3,253,206	1,612,026	3,738,488	8,603,720
Percent of Total Ash Utilized	11.7	16.0	75.2	20.1

*If separated from Bottom Ash

Source: Sikes and Kolbeck, 1972

Disposal of much of the solid waste can best be handled at the local level. A community action program designed to clean up the local environment would remove many of these public nuisances. If approached, scrap dealers and property owners may be more than willing to cooperate in disposing of solid wastes littering the landscape. Clean up programs similar to those initiated for removal of abandoned automobiles may be effective. Most of the solid wastes are not sources of air and water pollution, therefore, the part played by the Appalachian Regional Commission should be to encourage community action programs.

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ADDENDUM

Air Pollution Control and Wastewater Treatment

Because of increasingly stringent SO_2 emission regulations and a limited reserve of low cost, low sulfur fuels, a SO_x removal process operated in an efficient and economic manner is urgently needed. A new process designed to control atmospheric pollution in industries with the recovery of useful products has been developed by Lin(1) in the laboratory.

The new SO_x removal system is described briefly as follows:

The combustion gases from the furnace containing SO_2, SO_3 and suspended solid particles are passed through a dust collector for removal of fly ash. The flue gas containing SO_x is then passed through a catalytic oxidation converter to oxidize SO_2 into SO_3. The flue gas then goes to a lime reactor where lime is purposely fed in excess of the amount required for complete conversion of SO_3 to $CaSO_4$. Since the flue gas from the catalytic oxidation converter contains moisture, the following reactions take place:

$$SO_3\ (g) + H_2O\ (g) \rightleftharpoons H_2SO_4\ (g)$$

$$H_2SO_4\ (g) + CaO\ (s) \rightleftharpoons CaSO_4\ (s) + H_2O\ (g)$$

SO_3 is a very reactive gas and may also combine directly with CaO to form $CaSO_4$:

$$SO_3\ (g) + CaO\ (s) \rightleftharpoons CaSO_4\ (s)$$

Dust particles in the gas discharged from the lime reactor are further separated by a dust collector and the effluent will be substantially free from dust and SO_x. Nearly 100 percent SO_3 removal has been achieved in the laboratory. The reacted lime particles are discharged from the lime reactor into a powder processing unit. After treatment, a new product is released from the unit which has been named "Linfans."

The important feature of this process is that the reactions in the lime reactor are between gaseous and solid reactants, accompanied by a molecular diffusion in the solid reactant. Since the reactant (CaO) added to the system is in a solid form, the rate of application needed may not be high and can easily be controlled.

Laboratory investigation has shown the solid product, Linfans, containing anhydrous $CaSO_4$ and unspent lime has the following uses:

1. It can be combined with fly ash for production of construction materials.

2. Used for flooring plaster and hard finish plaster.

3. Used in wastewater treatment for acid neutralization and for phosphate and turbidity removal.

A series of laboratory experiments were performed to compare Linfans produced from different SO_x removal systems with high calcium lime in regard to sludge volume produced in neutralization of acid solutions. The tests were conducted on one percent (1%) by volume sulfuric acid solutions. In all cases, Linfans produced the least sludge volume. The percentage of sludge volume produced from neutralization was dependent on the percent of unspent lime in Linfans. The percent of unspent lime should be neither extremely high or low.

The sludges from neutralization of acid solutions by high calcium lime have poor compaction characteristics which are attributed to the typical acicular shape of the crystals that are formed. By contrast, the $CaSO_4$ crystals from neutralization by unspent lime in Linfans are in rhombic form. It is believed the insoluble anhydrous $CaSO_4$ in Linfans serves as nuclei for accelerated growth of $CaSO_4$ particles. This results in higher settling velocities, a considerable reduction in sludge volume and a shorter retention time in a sedimentation tank. Therefore, it is indicated that sludge handling and disposal problems can be greatly minimized if Linfans is used.

It must be emphasized the information given in the publication by Lin(1) indicates a limited amount of laboratory testing has been performed. It appears a great deal more laboratory testing will have to be accomplished before pilot studies can be considered.

Linfans possibly can be used in treatment of wastewater from pickling processes used in basic steel making, metal working and plating. It is not known whether Linfans would be suitable for treatment of acid mine drainage. The laboratory experiments were performed using strong sulfuric acid solutions (over 18,000 mg/l of H_2SO_4) and there were no interfering metallic ions. This sulfate concentration exceeds that of most mine drainage discharges. Calcium sulfate ($CaSO_4$) is not normally a precipitate in sludge from mine drainage treatment because sulfate ions are removed only when the solubility product of calcium sulfate is reached (about 2000 mg/l $CaSO_4$). It appears Linfans would add additional hardness to the mine drainage effluent and cause gypsum scale on plant equipment and possibly in the effluent. The possibility of seeding high sulfate mine drainage to promote larger crystal growth and therefore dense sludge should be investigated.

Quicklime (CaO) does not react rapidly and efficiently with acids to neutralize them. It must first hydrate (convert to $Ca(OH)_2$) before it reacts readily and efficiently. There are hazards connected with the use of quicklime. It is a very caustic irritant to human skin, eyes and mucuous membranes. A quantity of quicklime suddenly dumped into an influent can cause a steam explosion.

Erosion and Sedimentation Control

Two recent publications, one by Thronson[2] and the other by Becker and Mills[3] contain a wealth of information on erosion and sedimentation control.

Thronson comes to the conclusion the cost of effective erosion and sediment control is probably minimal and that the principal problem lies in achieving effective administrative control and enforcement by concerned agencies involved in erosion and sediment control programs. It is extremely difficult to obtain reliable information regarding the cost of temporary erosion and sediment control used only during construction. Normally the costs are hidden in unit costs for excavation and compaction, pipe and other equipment. It is difficult to define the temporary and permanent portion of a facility. Temporary erosion and sediment control for highways with average construction costs of $1,000,000 per mile were estimated at $10,000 to $15,000 per mile. The cost for control in housing developments was given as $40 per lot by engineering and geologic consultants and $100 per lot by developers.

A basin-wide task force, which includes representatives from all concerned organizations within the basin, probably has the best chance of developing and carrying out a successful control program. Trained manpower can be made available by utilizing specific qualified personnel such as geologists, hydrologists, agronomists, engineers, planners, lawyers and managers from the various participating groups within the task force. The crucial element of a sedimentation control program is the enforcement of adopted standards.

The publication by Becker and Mills presents a comprehensive approach to the problem of erosion and sediment control from beginning of project planning to completion of construction. The "Guidelines" is designed and intended for use by both technical and lay personnel. It provides:

1. A description of how a preliminary site evaluation determines what potential sediment and erosion control problems exist at a site being considered for development.

2. Guidance for the planning of an effective sediment and erosion control plan.

3. Procedures for the implementation of that plan during operations.

Technical information on 42 sediment and erosion control products, practices, and techniques is contained in four appendices.

Strip Mine and Refuse Bank Reclamation

Heine and Nickeson(4) recommend the use of substantially increased quantities of limestone in reclaiming old strip mines in alkalinity-poor watersheds. The cost of limestone is essentially defrayed by limiting backfilling to the degree necessary to improve surface runoff and reduce erosion.

Studies have shown there is less probability of success in backfilling and planting old strip mines than in reclamation of current active operations. This is principally due to the mixture of acid materials and topsoil in the spoil. The problem is further complicated by the stony nature of old spoils. Spoil segregation and burial of acid materials are no longer possible and there are no concentrations of "soil type" material. The stony material forming the top layer after reclamation of an old strip mine will be of the same general chemical composition as the old surface and be as permeable (to both air and water) as it was prior to grading. Since there is little soil type material in the top layer, it is difficult to establish a dense ground cover. Trees are the only vegetation that can be readily established and they do not rapidly form a soil profile. The surface of many reforested strip mines planted with trees as long as 30 years ago are almost as stony as the surface of a new unreclaimed strip mine.

Many old strip mines have developed excellent tree growths on some portions of the disturbed areas while other portions remain "hot" and devoid of vegetation. An important practical advantage to "limestone reclamation" is that areas with well established tree growth can be left undisturbed except for application of lime, fertilizer and seed to accelerate vegetation growth.

In the Alder Run and Muddy Run watersheds, Clearfield County, Pennsylvania, Heine and Nickeson recommended the use of quarry limestone (Class 2RC). It is an aggregate of particle sizes ranging from dust to 3/4 inch. They recommend an average layer of one inch thickness be spread over the entire strip mine (approximately 200 tons per acre). In practice the limestone will not be evenly distributed, but will be spread thicker in areas of thick spoil and maximum recharge. The limestone is spread at the completion of grading and disked into the top layer of the spoil.

The presence of this relatively fine grained material will decrease the stoniness of the top layer, making it more acceptable for grass growth. The top layer will be alkaline for many years, allowing grasses to become well established and a soil profile to develop.

The cost of quarry limestone (Class 2RC) was given as $1.15 per ton by bulk, $2.80 delivered, for the Alder Run and Muddy Run projects.

The U. S. Bureau of Mines(5, 6) has demonstrated the use of fly ash in strip mine and refuse bank reclamation. The addition of large quantities of fly ash (150 to 800 tons per acre) will not only dilute the surface materials and neutralize acids, but produce physical changes in the material that will enhance plant survival and growth. The bulk density of the mixture is decreased, thereby increasing pore volume, moisture availability, and air capacity, hence improving conditions for root penetration and growth.

Fly ash resembles soil in certain physical and chemical properties and it is mostly in the silt size range. Beside often being alkaline, it contains plant nutrients and possesses moisture-retaining and soil conditioning capabilities. Analyses indicate fly ash contains many trace elements essential to plant growth.

The use of fly ash in reclamation of strip mine and refuse banks helps solve the fly ash disposal problem. According to Sikes and Kolbeck(7) more than 27,000,000 tons of fly ash were produced in 1971 by power plants and less than 12 percent was utilized. Fly ash can be obtained from power plants at no cost in many areas. The only costs attributed to using fly ash would be hauling the fly ash from the power plant site to the reclamation area and those associated with spreading and disking.

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ACKNOWLEDGMENTS

The purpose of this publication is to provide data which will enable the Appalachian Regional Commission to estimate costs of pollution abatement in the Monongahela River Basin. In order to perform this function, the Appalachian Regional Commission needed an effective, workable handbook on pollution control costs and factors effecting these costs.

This study was performed by Michael Baker, Jr., Inc., for the Appalachian Regional Commission under ARC Contract No. 72-87/RPC-713 titled "Analysis of Pollution Control Costs." Support came from the U.S. Environmental Protection Agency under Grant 14010 HQC.

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6.

8. Performing Organization Report No.

Analysis of Pollution Control Costs

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In August, 1971, the Environmental Protection Agency convened the Monongahela Enforcement Conference in Pittsburgh, Pennsylvania. At this meeting the Appalachian Regional Commission was assigned the task of developing a comprehensive environmental improvement program for the Monongahela River Basin. The study is one of several performed for the Commission as part of this assignment and provides data which will enable it to estimate costs of pollution abatement in the Monongahela River Basin.

The report fulfills requirements for an effective, workable handbook on pollution control costs and factors effecting these costs. The information in the report is based on the latest technological developments and cost analyses of recent reclamation projects.

Although the report was developed for the Monongahela River Basin study, the cost estimates and supporting data should prove useful for all of Appalachia and other areas with similar topography, mine drainage pollution problems and mining history.

*Coal mine drainage abatement and treatment, *Refuse bank and mine fires, *Mine subsidence control, *Abatement of pollution from sources other than coal mining, surface mines, coal refuse banks, mine sealing, mine drainage treatment, air pollution, solid waste, erosion and sedimentation control, abandoned automobiles

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