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FOREWORD

This initial report, prepared by The Aerospace Corporation for the Environmental Protection Agency, Control Systems Laboratory, Research Triangle Park, North Carolina, presents the results of the first year's work on a study to characterize power plant sludges from nonregenerable flue gas desulfurization processes and to assess and identify methods of sludge disposal that are economically feasible and environmentally sound. At this time all tasks have proceeded through the initial stage of completion and all are continuing into the second year of the current contract.

The study results are given in the Highlights, which briefly present all significant study findings. Section 1 of the body summarizes the total study effort for the first year, and Section 9 describes program status and plans. The other sections present detailed discussions of all work performed, and provide all related data. These discussions cover: (a) the test data and analyses of laboratory characterizations, physical property determinations, and toxicity assessments of selected sludges; (b) technical and economic surveys and assessments of disposal methods including both ponding of untreated sludges and landfilling of chemically treated (fixed) sludges; and (c) reviews of related criteria for water quality and solid waste disposal. The appendices include a listing of companies and individuals contacted for data acquisition, and all backup information relative to the study.

Work completed through November 1973 is reported.

ABSTRACT

This report describes the initial phase of a study: to identify potential environmental problems that may be associated with sludge disposal from non-regenerable power plant flue gas desulfurization systems; to assess potential methods for sludge disposal; to assess technologies and attendant economics for eliminating or minimizing potential environmental problems related to sludge disposal; and to make recommendations for sludge disposal. It includes the following results: laboratory chemical and physical analyses of limestone sludges from two plants, one burning eastern coal and the other, western; a review of power plant sludge production and disposal plans; a survey of pond lining techniques and economics; technical and economic surveys of sludge chemical fixation processes which treat the sludge to produce a suitable landfill material; and a review of water quality and solid waste management regulations.

The report, which discusses the first year's progress on a continuing study, documents the work completed through November 1973.

HIGHLIGHTS

A previous EPA study conducted by The Aerospace Corporation and subsequent EPA and Aerospace studies showed that the near-term projected market for structural products and applications that could use sulfur sludges as an ingredient would consume only a minor portion of the forecast total sludge production. Therefore, emphasis in this study is directed toward disposal rather than commercial applications. Specifically, this study is being conducted to: (a) identify potential environmental problems that may be associated with sludge disposal from nonregenerable (throwaway) power plant flue gas desulfurization systems, (b) assess disposal methods for sludges including technologies and attendant economics for the elimination or minimization of potential environmental problems related to sludge disposal, and (c) make recommendations for sludge disposal. This study does not evaluate the products of regenerable desulfurization systems.

The initial study phase has been completed and accomplished the following: (a) laboratory chemical and physical

characterization of limestone sludges from two plants; (b) reviews of power plant sludge production, disposal programs, and plans; (c) surveys of pond lining techniques and economics; (d) technical and economic surveys of chemical fixation processes that condition the sludge to prevent leaching problems at disposal sites by decreasing the permeability and/or solubility of the sludge; (e) reviews of water quality and solid waste management regulations; and (f) consultations with individuals in industry, research, education, and governmental agencies.

As a result of chemical and physical characterization of selected limestone sludges (sludges from two plants were analyzed --one burned eastern and one burned western coal), the Aerospace analyses identified the presence of trace heavy metals in soluble phases and found significant quantities of dissolved solids, primarily sulfates. In addition, quantitative data were produced that define the large amount of water retention in sludges. Sludge characteristics vary considerably depending on material properties and system applications (e.g., coal chemistry including sulfur content, reactant and system water chemistry, scrubber operating conditions, ash content, and sludge pH). Indications are that raw sulfur sludge disposal in ponds or landfills of the type used for fly ash disposal may pose an environmental problem if they are discharged to streams or allowed to seep through soils to ground water. Also, it appears that raw sludge disposal sites will be unusable as structural or nonstructural landfill unless chemically or physically treated because of the water retention property of the sludges.

Preliminary assessments based on industrial and government programs to develop environmentally sound sludge disposal methods have shown that several technologies exist that may allow disposal without causing water pollution as defined by state water quality

standards or federal drinking water standards; some should produce reclaimable disposal sites. Chemical fixation appears to be the most technically advanced environmentally sound disposal method. Another promising technology, the use of lined ponds, may prevent water pollution for a limited time; however, additional study will be required to ensure permanent protection against water pollution and to permit land reclamation, if desired. The total capabilities of these and the other methods and their attendant costs are to be determined.

Study highlights are presented in this section. These findings may change or be refined during this year's study because of the following: expansion of the technology associated with sludge production and the many facets of sludge disposal, continuation of the current study including analyses of samples from other sources, and assessment of additional disposal technologies. These potential changes or refinements of the study findings should result in firm definitions of sludge assessments and disposal techniques and economics that, when properly related, should be generally applicable to the power industry.

Highlights of the current study findings are as follows:

1. Ponding Without Environmental Protection

Sludge disposal in a pond without providing environmental protection (such as chemical fixation, impervious liners, or the equivalent) against seepage to water supplies constitutes a potential water quality hazard. The degree of hazard characteristic of each site varies depending on the weather, topography, soil characteristics, and proximity of ground and surface waters to the disposal site. In addition, there exist a significant number of other disposal variables (e.g., chemical constituents of the sludge and the condition of sludge disposal) that may impact the potential hazard posed by such

a sludge pond. The potential problems attendant with these conditions are to be determined.

2. Water Quality and Solid Waste Disposal Standards

Currently no water quality or solid waste management standards specifically apply to power plant sludge disposal per se. However, state water quality standards that are approved by the Federal Environmental Protection Agency, are generally applied by state regulatory authorities to the regulation of sludge disposal. This is effected by referring to, or repeating directly, the limitations imposed by the United States Public Health Service (USPHS) Drinking Water Standards - 1962. The use of drinking water standards as a criteria to judge the potential impact of sludges on water quality may be conservative in many cases because a significant reduction of undesirable constituents in the sludge liquors may be obtained through the attenuation capacity of soils (ion exchange). The ion exchange effect applies whether or not dilution effects are considered. The degree of conservatism that may exist depends on the chemistry of the materials involved and the disposal site characteristics mentioned in Highlight No. 1.

The state standards will be modified by requirements of the Federal Water Pollution Control Act Amendments of 1972 that control all waters including ground waters of the United States and that call for new water quality regulations relative to specific industries, including the power industry. Since it was not known what the new standards will be, assessments were made of the potential sludge disposal hazards with respect to the available water quality standards as specifically applied to drinking water supplies. Based on the characteristics of sludges analyzed or reviewed in relation to these

drinking water standards, it is believed at this time that the direct discharge of sludges or any portion thereof to surface waters will not be allowed. Because of a lack of adequate data on the filtering effect of soils on sludge liquors, it is further believed that measures will be required to prevent sludge liquors from leaching through the soil to ground and surface waters.

3. Physical Properties of Sludges

Sludges produced by scrubbing flue gases from eastern and western coals showed variations in physical properties depending principally on the sulfate/sulfite chemistry and the ash content. Typically, sludges tend to retain large quantities of water and are difficult to dewater. They shrink when dried, return to their original wet volume when rewetted, and can be compacted only when dried below a saturation value unique to each sludge. Sludge permeability is relatively similar to that of soils; it ranges from silty sands to sandy clays (10^{-3} to 10^{-5} cm/sec). However, in contrast to soils that will freely drain, percolation of waters through sludge will only occur when a hydraulic head exists over the liquor saturated solids. Based on the analysis of a limestone/eastern coal sludge, it is indicated that the sludge will support personnel when the solids content is greater than 65 percent, will support motorized equipment when solids are greater than 70 percent, and can be pumped when solids are less than 60 percent.

4. Dissolved Solids

The sludges produced by flue gas desulfurization from power plants contain a wide variety of soluble elements. The soluble contents of the sludge liquors are typically 2 percent, but can exceed 10 percent. The soluble ions that constitute the total dissolved

solids are predominately calcium, magnesium, sodium, sulfate, and chloride that exist in concentrations individually or totally in excess of the concentrations allowed in most drinking water standards.

5. Sources of Trace Elements

Coal was found to be the primary source of trace elements in the sludge liquors, but contributions of specific trace elements are also made by limestone and make-up water. Some of these elements (e.g., beryllium, chromium, copper, and lead) enter the system by the collection of fly ash in the scrubber; other elements (e.g., chlorine, cadmium, mercury, and zinc) are scrubbed from the flue gas in the gaseous state. Arsenic, boron, and selenium are suspected to enter the scrubbing system as fine and ultrafine particulates that are normally too fine to be collected in electrostatic precipitators, but are collected in part by the scrubber.

6. Potential Toxicity

Based on the USPHS Drinking Water Standards, several trace metals found in the untreated scrubber liquors are present in excessive concentrations; however, it is not definite from the data obtained so far whether or not a real hazard exists. Because of its relative toxicity, mercury is considered to present the greatest potential problem. Other trace metals found in scrubber liquors, such as arsenic, selenium, and lead are present in excessive concentrations based on drinking water standards, but at a given concentration they are less of a problem than mercury. Other constituents (e.g. boron and chloride) not normally considered hazardous to humans in concentrations found in the sludge liquors could be harmful to plant life.

7. Reduction of Toxicity Potential

The toxicity potential of sludge liquors can be reduced through scrubber system chemical additions and operating alternatives to produce a more alkaline liquor having a low oxidation potential. Other methods of detoxification might include chemical conditioning of the sludge or water treatment of the liquor. The relative cost effectiveness of these methods must be evaluated.

8. Conditioning for Environmentally Sound Disposal

Chemical fixation is the most technically advanced of the several methods available for conditioning sludge to reduce its potential for creating an environmental problem. By reducing the permeability and/or solubility of the sludge, it appears to effectively restrict the loss of soluble components through leaching, and provide a material suitable for landfill and in some cases for structural fill. In addition, sludge drying, sintering, or mixing with nonchemical additives such as soil may produce environmentally acceptable results. However, additional evaluation of these techniques is necessary to determine long-term stability for pollution prevention.

9. Pond Lining

A survey of pond liners, based on industrial experience with ponding of chemical and mining sludges and with cooling system waters, indicates that raw sludges probably can be adequately contained for the operating life of the scrubber system. Many polyvinyl chloride liners used in water retainment ponds are still operable after 20 years of service. Manufacturers of other types of flexible liner materials are currently guaranteeing their products for a service life of 20 to 25 years. Nonflexible liners (e.g., clay) are reported to have a service life beyond 25 years. However, the effects of the chemical

and physical properties of scrubber sludges on the sealing qualities of pond lining materials over long periods of time need to be determined. Although the existing technology can control seepage from operational lined ponds, practical methods need to be determined to control seepage from a lined pond that has exceeded its operational service life or to reclaim the pond for land usage.

10. Disposal Costs

The cost of wet sludge (50 percent solids) disposal by chemical fixation has been estimated based on quotations made by industry. Reasonable costs (excluding major development impacts) vary from $1.50 per wet ton by chemical processors to $7.25 per wet ton by one power plant operator. The costs are affected by many variables such as: sludge characteristics and chemistry including water and ash content; transport distances; land values, ownership, and residual value; type of capitalization; and type of chemical fixation. Because of these variables, a wide range of costs is to be expected for disposal by chemical fixation. Except for unusual conditions, it appears that fixation disposal costs for typical cases should range between $2.50 to $5.00 per ton of wet sludge. As an example of disposal costs in terms of power produced, fixation at $5.00 per wet ton (including ash) will be approximately 1.1 mills per kWh.

Estimates were also made of the cost of disposal in lined ponds. Variations in disposal costs are caused by factors such as: type of liner; pond configuration; transport distance; land cost, ownership, and residual value; type of financing; and time-scaling of pond construction (e.g., build a portion now and the remaining portion(s) later). Preliminary estimates indicate that ponding disposal will cost approximately half that of disposal by chemical fixation. However, some undetermined costs will be incurred to account for

leachate protection after the pond is retired, and to dewater the pond if the land is to be reclaimed; whereas, chemical fixation is intended to provide permanent environmental protection. Some additional costing will be required for both disposal methods when the dumpsite is filled; this is to account for soil cover and/or seeding.

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SECTION 1

INTRODUCTION AND SUMMARY

1.1 INTRODUCTION

1.1.1 Background

The removal of sulfur dioxide (SO_2) from stack gases in compliance with provisions of the Clean Air Act and local regulations will require that the electric power industry use special equipment on many existing and new boilers that burn sulfur-bearing fossil fuels. Currently, the preferred method of SO_2 removal (generally referred to as lime or limestone scrubbing) employs the scrubbing of the stack gas with a slurry of water and an alkaline earth additive, principally lime or limestone. This solution reacts with the SO_2 and produces sulfates and sulfites of calcium and magnesium that are drained from the scrubber. There is no regeneration of the reactants in these systems. If ash collection devices are used upstream of the scrubber, the amount of fly ash entrained in the slurry and collected with the scrubber reaction products will depend on the efficiency of the collection devices.

A previous study of sludges made by The Aerospace Corporation for the Environmental Protection Agency (EPA) and other

EPA investigations identified the existence of dissolved trace heavy metals (e.g., arsenic, magnesium, zinc) and high concentrations of soluble components (e.g., chlorides, sulfates, carbonates) in the scrubber effluent. From these studies it appeared as if it may not be acceptable to either discharge the system waters (liquors) and sludges to water supplies or to allow their percolation through the soil to ground waters.

The SO_2 scrubbing systems that are in use or planned are designed so that the liquors are not directly discharged to watercourses, but are recirculated to avoid water pollution. In this operating mode, called closed loop operation, water leaves the system only by evaporation in the scrubber and by association with disposed sludge. The concern of this study, therefore, is for the characterization of the disposed material and for its environmentally sound disposal. Methods generally considered for ultimate disposal are landfilling and ponding. In both methods, the environmental considerations are for water quality and the potential reuse of the large acreage that will be required to contain the sludge. However, both methods present problems: raw sludge has the potential of leaching potentially undesirable constituents into water supplies from landfills and ponds; raw sludge retains water and, therefore, may not provide strength adequate to allow reuse of the land. Technologies have been developed to provide disposal techniques that will solve these problems; however, none of the technologies have been demonstrated on a large scale over a long period. The more significant of the technologies that are to be assessed in this study are: (a) chemical fixation processes that reduce the solubility and/or permeability of the sludge to minimize or eliminate leachability problems and that produce a material suitable for landfill, (b) pond management including the use of linings that provide impermeable bases, and (c) drying, compacting and covering, or using inert additives to provide the benefits mentioned in (a).

A previous Aerospace Corporation study for the EPA, and other EPA studies strongly indicated that commercial sludge utilization as predicted today indicate that only a small portion of the quantities to be produced will be consumed. Based on that assessment, a characterization and disposal study program was defined by the EPA for The Aerospace Corporation that would consist of laboratory characterization, technical and economic surveys, analyses, assessments, and recommendations.

1.1.2 Objectives

The study objectives are to:

a. Perform chemical characterization and crystalline phase and physical property determinations of selected sludges.

b. Perform toxicity determination of selected sludges and assess methods of detoxification.

c. Evaluate and assess environmentally sound disposal methods, technology, and costs.

d. Relate sludge disposal to water and solid waste environmental regulations.

1.1.3 Study Approach

The study objectives are to be met by: (a) characterizing, as appropriate, the sludges, coals, make-up water, fly ash, and chemically conditioned sludges from specified sources by chemical and physical analyses; (b) surveying technical and economic data, as appropriate, pertaining to sludge production, qualities, and disposal; (c) performing evaluations of all data determined in (a) and (b); (d) reviewing appropriate water quality standards and solid waste management regulations, and correlating this study's technical evaluations with limitations imposed by these regulations; and (e) identifying environmentally sound disposal techniques on the basis of technical and economic evaluations.

1.1.4 Acquisition of Relevant Data

The first year of this study has been completed. Laboratory analyses have been conducted on two limestone/eastern coal sludge samples obtained from the TVA Shawnee Power Station in Paducah, Kentucky, and one limestone/western coal sample from the Mohave Station in Clark County, Nevada, provided by the Southern California Edison Company. Additionally, preliminary reviews have been made of disposal techniques at the following power companies: Northern States Power Company, Sherbourne County Station, Minneapolis, Minnesota; Commonwealth Edison, Will County Station, Joliet, Illinois; Louisville Gas and Electric Company, Paddy's Run Station, Louisville, Kentucky; and Duquesne Light Company, Phillips Station, Pittsburgh, Pennsylvania. Contacts have been made with several other power stations, EPA regional offices, and EPA National Environmental Research Centers (NERC) at Research Triangle Park, North Carolina; Cincinnati, Ohio; and Corvallis, Oregon. Preliminary reviews have been made of fixation techniques at Chemfix, Division of Environmental Sciences, Inc., Pittsburgh, Pennsylvania; Dravo Corporation, Pittsburgh, Pennsylvania; and International Utilities Conversion Systems, Inc., Philadelphia, Pennslyvania. A survey has been made of ponding techniques, and contacts have been made with various ponding contractors, suppliers, and users. Consultation and advice have been obtained from Dr. J.E. McKee, Professor of Environmental Engineering, California Institute of Technology. Discussions have been held with soil sciences personnel from the University of Arizona and the Illinois State Geological Survey, both of whom are supporting the EPA Solid and Hazardous Waste Research Laboratory at Cincinnati, and with sanitation engineers from municipalities and the University of California at Riverside. Federal and

State water quality and solid waste management regulations have been reviewed, as appropriate.

Because of the varied and changing nature of the sludge disposal problem and current technological advancements in industry, all tasks will continue into the second year and samples will be analyzed from other stations to include additional types of sludges.

1.1.5 Organization of This Report

Section 1 summarizes the study findings and provides brief discussions and appropriate tables and figures to support those findings.

Section 2 describes the analytical equipment and procedures used to perform the chemical characterization and crystalline phase determination of sludge samples from two power plants. It also includes the analyses and evaluations of the elements selected because of their potential toxicity, an appraisal of the solubility of these elements, a discussion of the primary sources of trace elements found in the scrubber sludge, and a brief statement about test status and plans.

Sections 3 and 4 discuss toxicity determination and detoxification potential, respectively.

Section 5 describes the measurements made to determine the sludge's physical properties and its physical behavior as applied to disposal. The results are analyzed and evaluated to determine those properties most useful in developing engineering design criteria for sludge disposal technology.

Section 6 contains the analyses of potential disposal methods: raw sludge disposal without environmental protection, lined disposal ponds, and sludge conditioning. The status of

industrial and government sludge disposal development and demonstration programs is also assessed.

Section 7 provides pond lining and disposal cost estimates, sludge conditioning and disposal cost estimates, and ponding and fixation cost comparisons. Water quality and solid waste disposal criteria are discussed in Section 8. Preliminary estimates are made of the effect of these criteria on sludge disposal. Program status and plans are briefly described in Section 9.

Supporting data in the appendices include the identification of data sources, laboratory analysis data sheets, pond construction details, potential commercial utilization of sludges, power plant disposal program descriptions, and some comments about the potential toxic effects of trace elements.

Throughout this report, analytical data are given in units of parts per million (ppm) or parts per billion (ppb). For simplicity of usage, the equivalences of these units are considered to be as follows:

State	ppm	ppb
Liquids	mg/liter	μg/liter
Solids	mg/kg	μg/kg

1.2 SUMMARY

1.2.1 Chemical Characterization and Crystalline Phase Determination

Three separate sets of samples were obtained that represent the input and output constituents of the Turbulent Contact Absorber (TCA) test scrubber at the Shawnee Power Station in Paducah, Kentucky. These sludge samples were produced by scrubbing flue gas from eastern coal with limestone. One set of sludge samples was obtained from the TCA prototype scrubber at the Mohave Power Station,

Clark County, Nevada; it is a sludge produced by scrubbing flue gas from western coal with limestone.

Sample analyses were performed by emission spectroscopy, spark source mass spectroscopy, atomic absorption spectrophotometry, and ion microprobe mass analysis. Standard techniques were used for each type of analysis, and concentration values were determined by comparison with standards prepared for each element.

A representative trace element analysis of Shawnee Power Station sludge liquors is given in Table 1-1. Concentrations of the trace metals were determined at various sampling stations in each system in both the solids and liquid portions of the scrubber systems (the potential environmental impact of these trace metals is discussed in Sections 1.2.3, 1.2.4, and 1.2.10).

In addition to these metals, relatively high concentrations of boron and chloride ions were observed in the sludge liquors. Although these elements do not pose a problem as great as the trace metals mentioned, their high solubilities create a potential water quality condition that is not readily abated by current water treatment practices. Another potential nontoxic problem arises from the oxygen demand of the sulfite phase that further affects the potential water quality impact of supernatant or leachate liquors. This chemical oxygen demand tends to obviate the direct discharge of sludge to streams in some cases even in the absence of any water quality effects due to trace elements.

A major potential water quality problem created by uncontrolled sludge disposal arises from the solubility of the various trace elements in the sludge. The measured concentration of these elements in the liquor provides, in a qualitative sense, a measure of the relative availability of these elements to the environment. A more quantitative evaluation must take into consideration other

Table 1-1. REPRESENTATIVE TRACE ELEMENT ANALYSIS

TVA Shawnee Power Station; TCA Limestone Sludge (parts/million)[a]

Trace element	Scrubber system input			System output (clarifier underflow)	
	Make-up water	Limestone	Fly ash	Liquid	Solids
Arsenic (As)	<0.02	5	20	0.2	15
Beryllium (Be)	0.001	3	5	0.01	4
Cadmium (Cd)	<0.0005	0.5	3	0.005	3
Chromium (Cr) (total)	<0.001	10	15	0.05	15
Copper (Cu)	0.01	3	15	0.05	10
Lead (Pb)	<0.005	1	3	0.1	1
Mercury (Hg)	<0.01	1	4	0.06	2
Selenium (Se)	<0.01	2	5	0.3	4
Zinc (Zn)	<0.2	10	100	0.5	50

[a]Equivalent to mg/liter

factors that take into account the complexity of the chemistry in the scrubber circuit. Nevertheless, analysis of these data indicate that those metals with the greatest observed solubility are also those whose more stable compounds are carbonates or hydroxides. These data suggest that in a limestone scrubber system, the concentration of carbonate ions may be inadequate (and the concentration of hydroxide ions is inadequate) to effectively reduce the concentration of these metals. Chemical treatment that alleviates this inadequacy is discussed in Paragraph 1.2.4. In a lime scrubber system the concentrations of carbonate and hydroxide ions would be greater, and it is expected that they would be more effective in reducing the concentration of trace elements in the liquors.

1.2.2 Sources of Trace Metals of Interest

From the various chemical analyses conducted in this study, determinations were made of the source or sources of each element and the chemical or physical state in which they might be expected in the sludge.

Arsenic in the sludge originates primarily in coals and can be found both as the inorganic sulfides and as the organic components in the coal. During combustion, compounds of arsenic are converted to oxides and carried in the flue gas to the scrubber where a mixture of three arsenious acid complexes are formed, the amount of each depending on the pH. Reaction of these acids with calcium probably produces the most insoluble compound.

The beryllium occurs in both eastern and western coals. Beryllium forms both an insoluble hydroxide and sulfate, and it can be in the sludge probably in either of these forms.

Cadmium usually appears in coals in association with zinc as the sulfide mineral phase. During combustion, cadmium may sublime as the element or as the oxide also in association with zinc. Much of the cadmium is suspected to escape the system in the flue

gas, but if entrained in the scrubber, several insoluble cadmium compounds can form.

Chromium enters the scrubber system from the coal, probably in association with iron as the oxide. It forms an insoluble hydroxide, and this is probably the form in which it is found in the sludge.

Copper originates in coal primarily as the inorganic sulfide phase. It would enter the scrubber as the oxide and would be immobilized as the hydroxide in the sludge.

Mercury is typically found in eastern coals at levels somewhat higher than in western coals. Recent studies suggest that about half of the mercury is organic, the other half is presumed to be a sulfide. Mercury is either sublimed as the metal or as the sulfide, some of which is removed from the flue gas in the scrubber. Few mercury compounds, except the mercurous chloride, are insoluble; this compound may be unstable at points of high oxidation potential. Limestone and make-up water can also contribute some mercury to the scrubber system.

Lead originates in coals as the sulfide and enters the scrubber as the oxide. The lead compounds in the scrubber liquor are all slightly soluble; the sulfate being the most insoluble and probably the compound in which lead is found in the sludge.

Selenium chemically reacts similar to arsenic and probably appears in the scrubber much like arsenic. Selenites of calcium and magnesium are the most insoluble phases and may be the form in which selenium is precipitated from the liquor.

Zinc is also found in coals. The oxide is the product of combustion and enters the system either adsorbed onto the particulates or as a sublimed specie. It reacts with hydroxide and carbonate ions to form insoluble compounds.

1.2.3 Toxicity Assessment

The determination of heavy element toxicity is dependent upon the physiological effects of each element on the natural function of the human body. Many elements existing in nature in trace quantities are essential to man's life or health. Of the potentially toxic elements identified in this study, only cadmium, lead, and mercury have no known biological function and can act synergistically with other substances to increase toxicity. Once in the body, their toxic effects are cumulative and are harmful to the degree that the dosages and resultant concentrations can approach a lethal threshold. Even those trace elements having proven biological functions, when ingested at high concentrations, can produce disease either by their cumulative effect or by inhibition of natural functions.

The primary potential health hazards that may exist from power plant sludge arise from the solubility of arsenic and mercury. Lead and selenium may also be the source of problems under certain environmental conditions.

Although not found at high concentration in coals, mercury poses the most serious problem because of its relative toxicity. Arsenic and selenium are both recognized as micronutrients in the human body; however, their observed availability in the analyzed sludge liquors surpasses standards for human capacitance. Lead is like mercury; it serves no useful purpose in the body.

It is not yet possible to determine whether stack-gas sludge poses a health problem; however, attention is directed to those potentially toxic elements mentioned, all of which were measured in concentrations that exceed Public Health Drinking Water Standards.

For this reason, it appears that sludge disposal should be managed such that liquor, leachate, or runoff from a sludge disposal site will not directly intermingle with drinking water supplies.

1.2.4 Detoxification Alternatives

The potential capability for detoxification of a sludge is a function of the element or group of elements that pose a potential toxic hazard. The elements identified in the limestone system as having the capability most likely to create a toxic hazard are arsenic and mercury, and possibly lead and selenium. Since the potential toxic hazard from a sludge will originate primarily from the sludge liquors, leachate, or runoff, detoxification methods must consider conversion of the potentially toxic components from the liquid phase to a solid, or by concentration in a smaller liquid volume that can then be disposed of by other means.

The most technically advanced sludge detoxification method is the chemical fixation process that coverts sludge from a highly water-retentive material to one that has properties suitable for landfill or structural fill. In this conversion process, soluble components are reported to be chemically combined, and thereby restricted in their availability to the environment.

The concentrations of the most soluble of the potentially toxic elements in the limestone scrubber liquors may be reduced by a chemical treatment or system modifications that increase pH and/or retard oxidation within the scrubber system.

Among the more feasible detoxification schemes is a water treatment of a liquor side stream in which chemical precipitation (lime softening) may precede a secondary water treatment method. Among the possible secondary treatments are: reverse osmosis, flash distillation, electrodialysis, and ion exchange. For any of these

secondary treatment techniques to be effective, a reduction in total dissolved solids must precede their use. These processes are relatively costly; they might be considered cost effective in only rare circumstances. However, since some of these water treatment techniques will also reduce the chloride concentration in scrubber liquors, savings will be realized by their use in corrosion avoidance of major hardware.

A brine of very high dissolved solids content is a by-product in some of these water treatment processes. This brine can be disposed of by chemical fixation processes or by evaporation.

The relative costs of these various processes have not yet been determined.

1.2.5 Physical Properties

Physical properties were determined from the Shawnee and Mohave sludges to provide a more complete characterization of their behavior as related to limitations or restrictions on sludge disposal, handling, and transportation techniques. In each case, the sludge was in the state in which it would be normally disposed of without further processing.

Although these two sludges were the products of scrubbing flue gas from eastern and western coals, their behavior was not a consequence of the coal's geological origin, but rather a consequence of the phase constituents in the sludge. The Mohave sludge is low in fly ash and very high in sulfate content; whereas the Shawnee sludge has about a 40 percent fly ash content and a 20 percent sulfate content. Most behavioral differences between the two sludges can be attributed to the difference in the content of the plate-like sulfite particles.

Many of these sludge's physical properties were found to be strongly dependent on water content; it affects their behavior either while being handled for disposal or after being placed in a disposal site. For the two sludges, equivalent water content did not produce equivalent behavior as revealed in the dewatering results (Figure 1-1). The results are directly attributable to sulfite content and can be summarized as:

Condition	Percent solids Shawnee	Percent solids Mohave
No drainage	45	67
Drain freely	52	
Centrifugation	55	75
Vacuum-assisted filtration	65	80

If disposed of within a pond, the Mohave sludge will settle, or if mechanically dewatered, is expected to attain a solids content great enough to support personnel and should require very little additional air drying to support equipment. In contrast, the Shawnee sludge is not expected to settle or mechanically dewater sufficiently for support of personnel. In either case, sludge support strength for personnel will not be attained until a solids content greater than 65 percent is reached; equipment support will require greater than 70 percent solids. Ponded sludge that has dried will return to its original wet volume when rewetted.

The drainability of the Shawnee or Mohave sludge is similar to that of natural soils. The coarseness of the sulfate particles in the Mohave sludge provides a drainability similar to that of soils with a high sand content; whereas the Shawnee sludge is more typical of silty clay soils because of the high sulfite content.

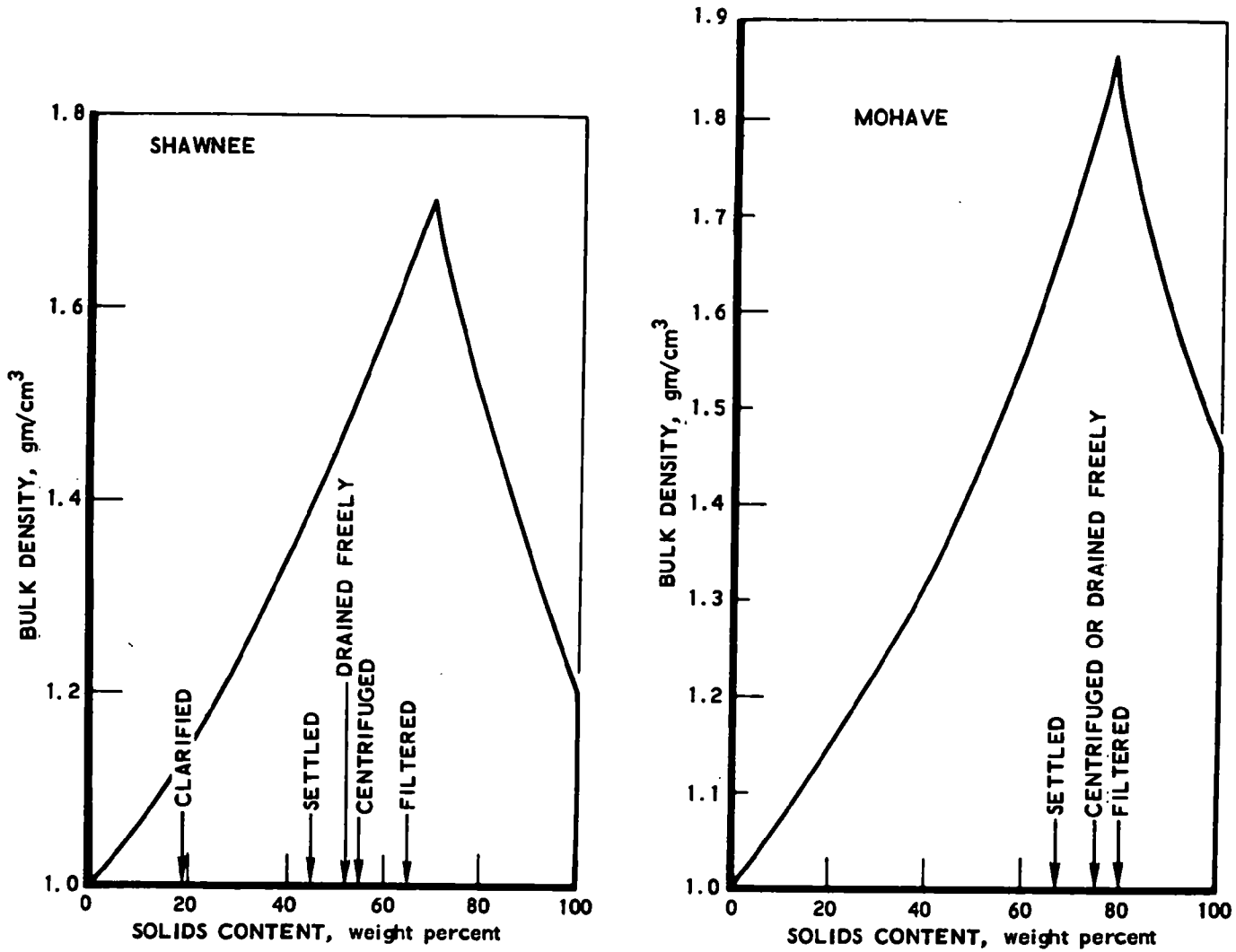


Figure 1-1. Sludge bulk densities

Neither sludge was found to develop strength during settling by pozzolanic reaction or other means. The compaction strength developed during drying or dewatering did not change with time. Without specific chemical additions, the sludges did not develop resistance to subsequent leaching.

Based upon viscosity tests, it was determined that either sludge can be easily pumped at low solids content. As solids content increases, the viscosity of the Shawnee sludge increases regularly and could place an increased demand on the pump; its pumpability appears limited to about 60 percent solids. For the Mohave sludge, viscosity does not vary much with an increase in solids content until a value of about 60 percent is reached; then the viscosity rises rapidly to a point that pump overloading and transfer pipe plugging are possible.

The sludge corrosiveness appears to be pH dependent, and no accelerated growth was observed except when a galvanic reaction was allowed to proceed as a consequence of an oxygen gradient between supernatant liquors and sludge solids. This condition could cause serious corrosion problems if the sludge were transported or stored in steel containers.

The physical property test results indicate that a sludge containing high sulfate content has properties, primarily dewatering behavior, that are desirable for disposal.

1.2.6 Raw Sludge and Ash Disposal Without Controls

The power industry has several alternative methods available for disposal of fly ash and sulfur sludge. Presently fly ash lagoon disposal is contributing to the dissolved solids content of receiving waters. A majority of the nation's power plants are located

along the banks of major watercourses and the contribution from each plant is measured in tons per year. The disposal of ash with sludge reduces the environmental pollution load by eliminating the discharge of waste water from the fly ash lagoon, and containing it within a closed-loop scrubber operation that recirculates the liquor and controls the disposal of separated solids.

If sludge is disposed of in a separate pond, elemental constituents carried in the flue gas (primarily mercury, cadmium, zinc, arsenic, and possibly selenium) will be scrubbed from the flue gas and attain a level of solubility in the pond liquors. By disposing of the fly ash with the sludge, elements that were found soluble in fly ash lagoons are additionally available to the scrubber liquors. Although simultaneous disposal eliminates the continuous disposal of fly ash lagoon waste waters to watercourses, the additional contribution of fly ash constituents to these liquors increases the potential environmental hazard created by the sludge.

Whether sludge and fly ash are disposed of simultaneously, a potential environmental hazard will exist. Sludge disposal without control requires consideration of many conditions that may contribute to seepage to ground waters or discharge to watercourses: the soil (sand/clay content), the disposal site's geological and hydrological location, weather, and disposal site management. Other considerations that may affect the potential impact of sludge intrusion into waters include: the coal's chemical content, scrubber type, and sorbent. Even when sludge disposal sites are being controlled (e.g., by pond linings or chemical fixation), their effectiveness must be determined for long periods.

1.2.7 Lined Pond Disposal

Technical reviews were made to evaluate the potential use of fifteen different flexible and nonflexible materials for lining flue gas desulfurization raw sludge disposal ponds. The flexible liners

consist of 10- to 30-mil thick materials such as polyethylene, polyvinyl chloride, Hypalon, and butyl rubber. Nonflexible liners include asphalt, cement products, and pozzolans in 3- to 6-in. thicknesses, and clay with thicknesses varying from several inches to several feet. The liner provides a physical barrier to prevent any seepage of liquors from the disposal ponds into ground or surface waters. Table 1-2 lists the liners considered, thicknesses normally employed, permeability rates, and life expectancy. Figure 1-2 presents the installed costs for the lining materials (disposal costs are discussed in Section 1.2.9).

Although ponding is currently a proven technique for large-scale, low-cost evaporation operations and for waste disposal, the predicted useful life of a potential sludge pond liner still needs to be defined. It is directly dependent upon the aging characteristics of the liner material and its chemical interaction, if any, with the sludge or supporting soil. Flexible liners are generally guaranteed for 20 to 25 years. The life expectancy of nonflexible liners is estimated to be even greater. However, long-term service data applicable to sulfur sludge containment do not exist for either type of liner.

The techniques currently available to monitor pond seepage range from backfilling with sand/gravel to permit the seepage to be piped to an observation well, to using electromechanical soil-moisture measuring devices.

Because practical methods to dewater a raw sludge pond have not as yet been developed, the technologies have not been adequately defined to control leaching from a lined pond after its service life. Therefore, the potential for pond reclamation for future land usage and the considerations necessary for permanent environmental control must be determined.

Table 1-2. POND LINER MATERIAL CHARACTERISTICS

Material	Thickness,[a] mil	Thickness,[a] in.	Permeability, cm/sec	Life expectancy, yr	Dirt cover[b]	Average installed[c] cost, $/sq yd	Notes
Flexible							
Polyethylene	10	-	d	20	Yes	0.70	
Polyvinyl chloride	10 - 20	-	d	20	Yes	1.10 - 1.50	
Hypalon	30	-	d	20+	No	3.25	
Chlorinated polyethylene	30	-	d	20+	No	3.25	
Petromat fabric	-	1/16 - 1/8	d	20+	No	2.00	
Butyl rubber	30	-	d	20	No	2.80	
EPDM rubber	30	-	d	20	No	4.00	
Polyester fiberglass	65	-	d	20+	No	4.75	
Nonflexible							
Soil cement	-	6	About 10^{-6}	20+	No	1.00	e, f
Concrete	-	6	About 10^{-8}	50+[g]	No	3.75 - 4.75	e, f
Clay	-	Up to 18	10^{-5} to 10^{-8}	50+[g]	No	1.00 - 6.00	e, h
Asphalt concrete	-	6	d	50+[g]	No	4.00	e
Gunite	-	3	d	20+[g]	No	6.30	e, f
Pozzolan stabilized base	-	2 - 6	10^{-5} to 10^{-7}	50+[g]	No	3.85	

[a]Commonly used
[b]Protection from ultraviolet rays
[c]See Section 7.1
[d]Superior to clay
[e]Affected by wet/dry and hot/cold cycles
[f]Subject to sulfate attack
[g]Industrial estimates not obtained
[h]Possible breakdown due to ion exchange

To convert from	to	Multiply by
sq yd	sq m	0.8361
mil	cm	0.00254
in.	cm	2.54

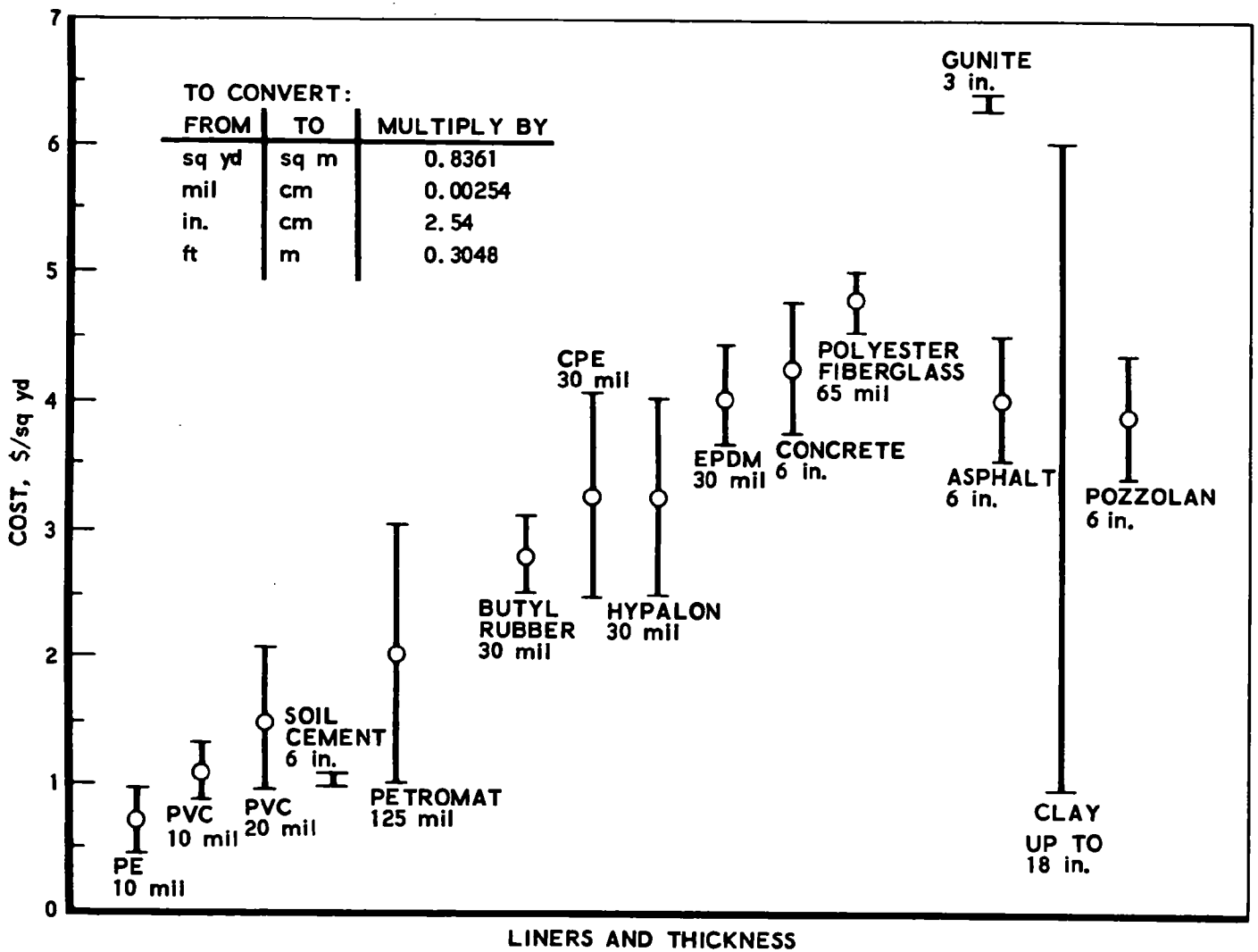


Figure 1-2. Installed liner costs

1.2.8 Sludge Fixation Disposal

Several sludge conditioning methods are available to reduce the sludge's potential as an environmental problem. Chemical fixation is the most advanced method, but other techniques such as sludge drying, sintering, and blending with nonchemical additives may be equally effective. However, none of these other techniques has been extensively developed.

The chemical fixation of power plant sludges produces a material suitable for landfill and a material in which soluble trace elements are chemically bound such that their availability to subsequent leaching is minimal or nonexistent. Chemical fixation converts a typically thixotropic sludge into a material that resembles either concrete, clay, or soil, depending on the particular commercial processing used. These materials are reportedly made suitable for landfill or structural fill depending on the process used. In addition, a chemically fixed sludge offers certain cost and convenience advantages for transporting by truck, rail, or barge.

An additional property of sludge chemical fixation gained by some methods is the conversion of the sludge to a material having very low permeability. By combining the reduction of soluble components with the reduction of permeability gained by chemical fixation, a total reduction of potentially toxic elements available to the environment of 10,000 times or more may be realized.

An example of the degree of reduction attainable in the soluble trace elements is illustrated by the results from a leaching experiment conducted in September 1973 on a chemically fixed sludge. Table 1-3 presents experimental data comparing the concentrations of the trace elements in leachate from the fixed sludge against the original TVA Shawnee Power Plant raw limestone sludge. Further work is under way to refine the values of the concentration of constituents in the leachate and to relate those values to corresponding values that

Table 1-3. COMPARISON OF TRACE ELEMENT ANALYSES BETWEEN RAW SLUDGE AND LEACHATE FROM THAT SLUDGE AFTER CHEMICAL CONDITIONING BY FIXATION (REF. 1-1) (parts/million)

Constituents	TVA Shawnee TCA limestone raw sludge	Leachate water from conditioned sludge
Arsenic (As)	2.2	<0.10
Cadmium (Cd)	0.30	<0.10
Chlorides	2000	64.0
Chromium (Cr) (total)	2.8	<0.25
Copper (Cu)	1.5	<0.10
Iron (Fe)	120	<0.10
Lead (Pb)	26	<0.10
Mercury (Hg)	<0.10	<0.10
Nickel (Ni)	3.5	<0.10
Zinc (Zn)	16	<0.10
Phenol (C_6H_5OH)	<0.25	<0.10
Cyanide (CN^-)	<0.10	<0.10
Sulfate (SO_4^-)	>10,000	400

define concentrations in the sludge leachate that has not been chemically fixed.

An alternative method of sludge conditioning for disposal might employ drying of the sludge so that a solid waste material is disposed of. A major difficulty with dried sludge disposal is based on the capacity of sludge to reabsorb water; thus, disposal by fill and bank techniques may be necessary. In this case, and depending upon both the physical effects and the potential for polluting the environment, an impervious clay cover may be necessary to prevent reabsorption of rain water and the dissolution of trace elements into leachate or run-off waters.

In certain geological areas, conversion of sulfur waste to commercial products may be economically feasible. Technology exists to convert and use power plant sludge for a road-base material or as structural aggregate. In addition, production of structural products (e.g., brick or block) is possible, or these wastes may be used as feed for cement clinker production. The latter is a prime consideration because the sludge can provide the lime originating from the sorbent and the agrillaceous components for cement originating from the fly ash. However, these sintering processes will require a scrubbing system for sulfur removal.

An additional technique for reducing or eliminating the pollution potential of power plant sludge would use nonchemical additives such as industrial waste materials or soils. Soils provide a mechanism for dewatering the sludge, and if they contain clay, provide an ion exchange capacitance that may reduce or eliminate the availability of toxic elements to subsequent leaching waters.

Except for preliminary analyses of chemical fixation, the techniques discussed herein have not been evaluated relative to their environmental acceptability or their cost effectiveness.

1.2.9 Disposal Cost Estimates

1.2.9.1 General

Disposal cost estimates were made for each of the two most prevalent disposal methods: ponding and landfill using chemical fixation. Considerable information was provided by various sources; however, for each method the cost data are widely variant. As a result, the disposal costs are given in wide ranges of values consistent with appropriate qualifications based on the many variable parameters attendant to either disposal method. Although refinements are expected during succeeding disposal cost studies in this program, the disposal cost will always be expressed as a range of values, except when applied to a specific disposal operation. This section summarizes this analysis and includes significant disposal costs and appropriate rationale.

1.2.9.2 Chemical Fixation Disposal Costs

The disposal costs by chemical fixation are dependent upon many factors: the fixation process and the contractor operating efficiency; sludge characteristics including water, ash, and chemical content; disposal site physical characteristics and distance from power plant; sludge transport method; disposal land costs and ownership; residual value of disposal site; and environmental monitoring. Additionally, the costs depend upon whether the power plant uses a disposal contractor or does the work itself. To determine these costs, data were obtained from personal communications, visits, published technical papers, brochures, and testimony from the National Power Hearings of October and November, 1973. Sources of these data were: power companies - Commonwealth Edison Company and Duquesne Light Company; chemical fixation companies - Chemfix, Dravo Corporation, and International Utilities Conversion Systems, Inc.; and the EPA Control Systems Laboratory. Disposal costs quoted by the power companies and fixation companies are listed in Table 1-4.

Table 1-4. SLUDGE FIXATION COSTING ESTIMATES
All values are condition and site dependent

Source	Dollars/ton, 50% solids	Remarks
Commonwealth Edison Company, Will County Station		
	5.91	On-site disposal -- vendor quote
	8.55	Current estimate[a]
	5.25	Best experience[a]
	10.00	Worst experience[a]
	5.00	Target[a]
Duquesne Light Company, Phillips Station	7.25	Total disposal
International Utilities Conversion Systems, Inc.	1.50-2.50	On-site disposal
Chemfix	~5.00	On-site disposal
Dravo Corporation	1.50-3.00	Total cost to customer; includes pumping to 10 mi

[a]Company operation - on-site disposal; excludes capital costs

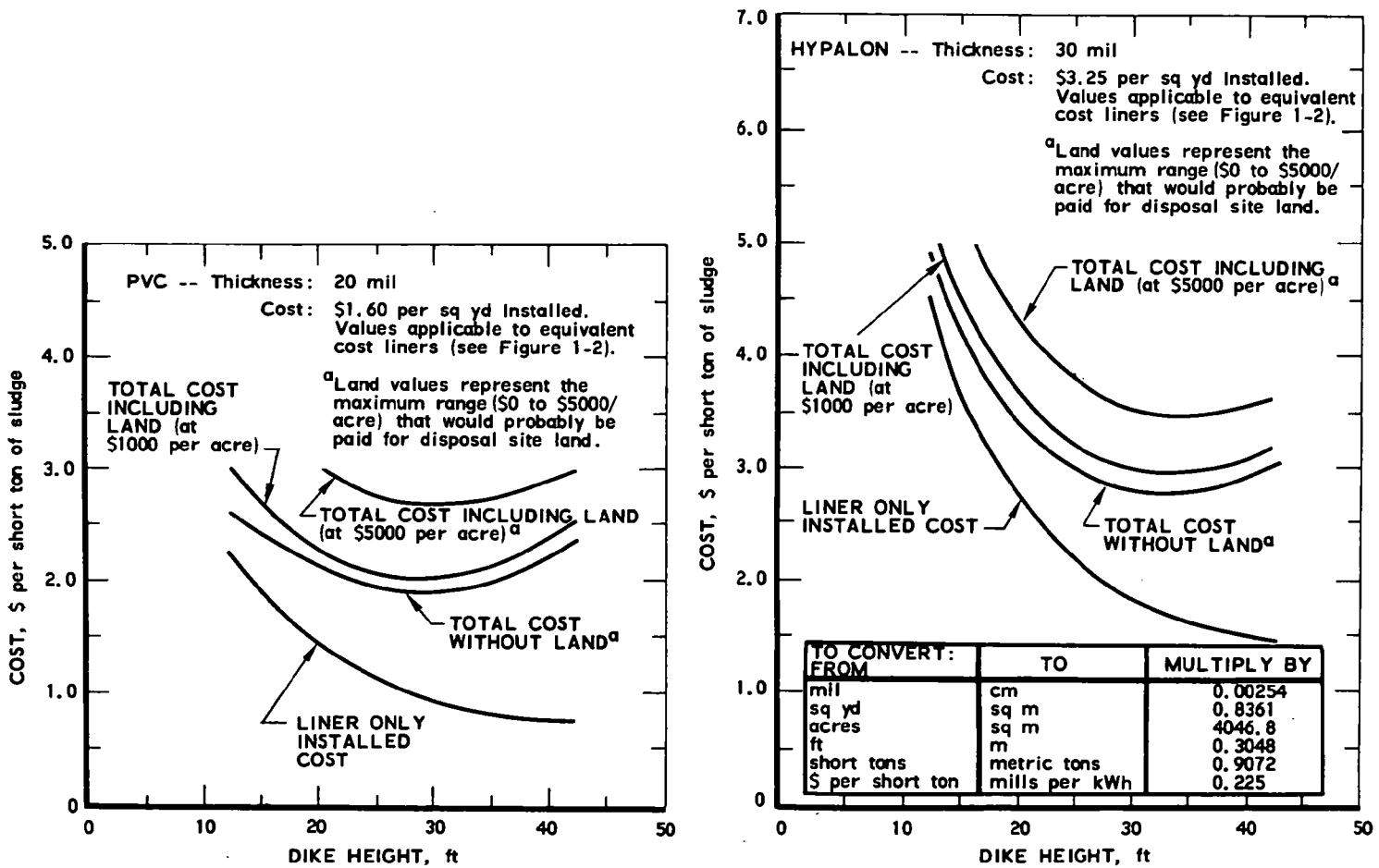
These values, equated to sludges that are 50 percent solids, range from $1.50 to $10.00/ton. All relevant factors pertaining to the values given are not available; however, based on the data given, it appears that except for extreme cases (e.g., development or demonstration sites), the general range of costs is approximately $2.50 - $5.00/ton of sludge on a 50 percent solids basis. Some additional costs may be incurred for topsoil and/or seeding after the disposal site is filled.

1.2.9.3 Ponding Disposal Costs

Ponding costs vary considerably for many of the reasons given for fixation and for others quite different. For example, in addition to the effects of sludge composition, transport, disposal site characteristics and distance from power plant, land costs and ownership, and environmental monitoring, there are effects such as type of liner, liner delivery distance, site construction rates, dike height, and pond capacity constructed within a given period. Based on data provided by liner suppliers, ponding contractors, power companies, and mining companies, cost estimates were made of ponding disposal on a 30-year average basis. These costs (Figure 1-3) are given for ponds constructed with both low and high priced liners and for various land costs, and they indicate that on the basis of 30-year averages, the costs should be in the range of $2.00 to $3.00/ton of sludge (50 percent solids). Liner protection is limited by the liner life expectancy; therefore, if the disposal site is to be usable land after the pond is filled, it will have to be partially dewatered, protected against rewatering, and landscaped. Practical technologies to account for permanent environmental protection or land reuse have not been developed; therefore, costs for these factors are not included.

1.2.9.4 Cost Comparisons - Fixation Versus Ponding

It is apparent that the costs of disposal by fixation or ponding are indefinite and highly variable. This is because sludge disposal by fixation is an emerging industry with little actual practice at this time and, although the use of lined ponds is an established technique in some industries, there is little experience with power plant sludge disposal by that method. Furthermore, currently there is no long-term performance data for either method. Cost comparisons are made by observing the range of values available and making rational comparisons in light of the variations in requirements and



TO CONVERT: FROM	TO	MULTIPLY BY
mil	cm	0.00254
sq yd	sq m	0.8361
acres	sq m	4046.8
ft	m	0.3048
short tons	metric tons	0.9072
$ per short ton	mills per kWh	0.225

Figure 1-3. Sludge disposal costs -- ponding (30-year average)

potential disposal methods. It is believed that the most accurate comparisons (Table 1-5) should be made on a current cost basis, thereby eliminating conjecture as to future costing effects which vary depending on the disposal method considered as well as variations in the economy. The fixation costs are estimates quoted for current operations. The current ponding costs are based on initially purchasing all land and ancillary equipment needed for a 30-year operation and constructing a pond capable of containing a 10-year sludge and ash supply (50 percent solids). This comparison indicates that ponding will cost approximately half that of disposal by chemical fixation. Permanent environmental protection and land reclamation are additional factors that do not appear to favor ponding costs.

1.2.9.5 Disposal Costs Related to Power Produced

The following example considers the cost of fixation/disposal of all sludge and ash produced at a 1000 MW station using a limestone scrubber. A total of 1.44 million tons of 50 percent solid sludge (including ash) is produced per year; it is assumed that the output of the plant is 6.4 billion kWh per year, and that the coal has a 3 percent sulfur and 12 percent ash content. The annual cost of this form of disposal would be 0.56 to 1.12 mills/kWh, using a disposal cost of $2.50 and $5.00/ton, respectively. If a lime scrubber is used, the disposal cost would be from 10 to 20 percent less, principally because the tonnage would be reduced. Also, reductions in disposal costs should be possible by reducing the wet tonnage volume by collecting the fly ash upstream of the scrubber and by reducing the water content of the sludge.

1.2.10 Water Quality and Solid Waste Disposal Criteria

The measure of what conditions constitute the environmentally sound disposal of sludges is defined by authoritative water

Table 1-5. DISPOSAL COST COMPARISONS -- SLUDGE INCLUDING ASH; 50 PERCENT SOLIDS

($ per short ton; 1973 dollars)

Disposal site suitable for reclamation. Soil cover not included. Current price quotes.

Fixation	
Cost, $	Remarks
1.50	Lowest quote Ideal conditions Disposal site adjacent to plant No land cost included
3.00	Maximum quote by two processors Fly ash supplied by plant Disposal site up to several miles distance Land cost included in one case
5.00	Quote by one processor Disposal site up to 1 mile distance Target cost for one processor No land cost included
7.25	Total disposal cost quote by one power company

[a] Values applicable to equivalent cost liners.

[b] Represents maximum that would probably be paid for disposal site land.

First year costs shown. Annual capital charge 26.5 percent first year. Ten-year sludge production capacity pond. Thirty-year land cost included - no residual value. Future effort may be required for permanent environmental protection or land reclamation.

Ponding	
Cost, $	Remarks
PVC liner, 20 mil thick [a]	
1.00 - 1.50	Land cost at $1000/acre
1.50 - 2.70	Land cost at $5000/acre [b]
Hypalon, 30 mil thick [a]	
1.40 - 2.50	Land cost at $1000/acre
1.80 - 3.70	Land cost at $5000/acre [b]

To convert from	to	Multiply by
short tons	metric tons	0.9072
acres	sq m	4046.8

quality standards and solid waste disposal regulations,* or by the judgment of regulatory officials when standards are nonapplicable or nonexistent. The procedure, therefore, in the development of this task effort has been to gather the existing standards to determine what qualities or conditions must be prevented or controlled, and to compare the criteria specified therein with the characteristics of as many sludges as possible, including the effects of the disposal method on the environment. Also, regulatory officials have been contacted for information on methods of standards application. The collection of standards has produced documents from all states for which water quality standards are available at this time (90 percent of all states). Accordingly, solid waste regulations have been obtained from 20 percent of the states. This collection of solid waste regulations is considered representative for an initial determination of status based on information provided by the EPA NERC, Cincinnati. All told, the water quality standards identify numerical criteria for the quality of receiving interstate waters. These criteria when considered in terms of regulations that may be applied to the qualities of sludges include items such as heavy metals, toxic materials, total dissolved solids, pH, and various compounds such as sulfates and chlorides.

Water quality criteria for surface waters vary among the states, but for drinking water supplies, the states generally repeat or refer directly to the U.S. Public Health Service (USPHS) Drinking Water Standards - 1962 that specify concentration limits for chemical substances in a water supply. This portion of the USPHS standards is reproduced in Table 1-6. Also, some states have regulations concerning the quality of ground water. For example, Illinois requires that

*Water Quality Standards consist of four major components: (a) use designations, (b) narrative and numerical criteria, (c) a plan of implementation and enforcement and solid waste regulations that define various types of waste materials with requirements for disposal, and (d) an antidegradation statement.

Table 1-6. EXCERPTS FROM UNITED STATES PUBLIC HEALTH SERVICE DRINKING WATER STANDARDS - 1962

The following chemical substances should not be present in a water supply in excess of the listed concentrations where, in the judgment of the Reporting Agency and the Certifying Authority, other more suitable supplies are or can be made available.

Substance	Concentration (mg/liter)
Alkyl Benzene Sulfonate (ABS)	0.5
Arsenic (As)	0.01
Chloride (Cl)	250.0
Copper (Cu)	1.0
Carbon Chloroform Extract (CCE)	0.2
Cyanide (CN)	0.01
Iron (Fe)	0.3
Manganese (Mn)	0.05
Nitrate (NO_3)	45.0
Phenols	0.001
Sulfate (SO_4)	250.0
Total Dissolved Solids	500.0
Zinc (Zn)	5.0

The presence of the following substances in excess of the concentrations listed shall constitute grounds for rejection of the supply.

Arsenic (As)	0.05
Barium (Ba)	1.0
Cadmium (Cd)	0.01
Chromium (Hexavalent) (Cr^{+6})	0.05
Cyanide (CN)	0.2
Lead (Pb)	0.05
Selenium (Se)	0.01
Silver (Ag)	0.05

underground waters that are a present or potential source of water for public or food processing supply shall meet the general and public and food processing water supply standards. In general, other states, which do not have a specific regulation concerning the quality of underground water, apply stream or drinking water standards to the underground water for lack of more definitive regulations. Finally, according to the EPA, in all cases, stream dilution is not to be considered a substitute for or an extension of a waste treatment facility.

For the regulation of solid waste disposal, standards are much less specific than water quality criteria. Regulations ordinarily limit the disposal of toxic, hazardous, or harmful substances by requiring that those materials not be disposed of on the ground, or underground without the express approval of a designated authority such as the State Department of Health, the State Health Commissioner, County Health Commissioner, or the State Department of Commerce. This survey to date indicates that those offices, when judging the disposal of sludges, base their judgment on sludge quality as related to USPHS water quality criteria.

The limitations imposed on sludge disposal are further intensified by the recent and potential passage of legislation. For example, the Federal Water Pollution Control Act Amendments of 1972 essentially require the revision and reapproval of all state water quality standards: to change applicability from interstate waters to all waters including ground waters, to specifically prohibit or limit direct discharges of pollutants to streams, to limit sub-surface disposal, and to include Federal EPA-prescribed criteria for specific toxic elements. Additionally, the federal drinking water standards are being revised, and legislation is in process to develop new limitations for the land disposal of solid waste.

Chemical analyses conducted in this program have shown untreated sludge properties that make those tested unsuitable

for direct discharge into streams. Because of the wide variations in soil properties and a lack of understanding of the attenuation of harmful or undesirable components in soils, it is believed that untreated sludge disposal on the earth or in an underground cavity may not be allowed because of the potential contamination of ground waters. The characteristics or components of concern in the sludges that have been analyzed so far are: total dissolved solids, sulfates, chlorides, arsenic, mercury, lead, and selenium, and other materials of lesser concentrations. A typical trace metal analysis of a limestone sludge is compared to water quality criteria in Table 1-7.

With current water quality standards and solid waste management regulations that prohibit sludge disposal in water and that are being interpreted to prohibit its disposal on land without safeguards, and with new and pending legislation that is or will be more restrictive, it is apparent that the sludges must be disposed of in such a manner as to prevent direct discharge to streams. It appears that it will be necessary to prevent or control leaching through the soil to ground or surface waters.

Table 1-7. SUMMARY SLUDGE LIQUOR METAL ANALYSIS COMPARED TO WATER QUALITY CRITERIA

TVA Shawnee Power Station; TCA Limestone Sludge (parts/million)[a]

Element	Clarifier underflow liquor
Arsenic (As)	0.2[b]
Beryllium (Be)	0.01
Cadmium (Cd)	0.005
Calcium (Ca)	2500[c]
Chromium (Cr) (total)	0.05
Copper (Cu)	0.05
Lead (Pb)	0.1[b]
Magnesium (Mg)	600[c]
Mercury (Hg)	0.06[d]
Selenium (Se)	0.3[b]
Zinc (Zn)	0.5

[a]Equivalent to mg/liter

[b]Exceeds USPHS Standards - 1962 (see Table 1-6)

[c]Total dissolved solids exceed USPHS Standards - 1962 (see Table 1-6)

[d]Exceeds some state standards

REFERENCES

1-1. Personal Communication, Chemfix, Division of Environmental Sciences, Inc., Pittsburgh, Pennsylvania (September 1973).

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SECTION 2

CHEMICAL CHARACTERIZATION AND CRYSTALLINE PHASE DETERMINATION

2.1 SLUDGE SAMPLING

A set of samples representing the input and output constituents of the TCA test scrubber at the Shawnee Power Station in Paducah, Kentucky, was obtained on three occasions: 21 December 1972, 1 February 1973, and 11 July 1973. The sample set collected on 21 December 1972 was incomplete and, therefore, was not used. Samples were collected by TVA personnel under the direction of Mr. J. B. Barkley and sent by air freight to The Aerospace Corporation in polyethylene bottles. The Shawnee samples represent sludge produced by scrubbing flue gas from eastern coal with a limestone sorbent.

A single sample set of sludge constituents was collected by Bechtel personnel from the TCA prototype scrubber at the Mohave Power Station on 30 March 1973. This set did not include coal,[+] fly ash,[+] or bottom ash. The Mohave samples represent sludge produced by scrubbing flue gas from western coal with a limestone sorbent.

[+]Analytical data reported for western coal and fly ash were obtained from Reference 2-1; averages of two measurements were used.

A description of the samples is given in Table 2-1, 2-2, and 2-3. Flow diagrams showing the sampling stations are given in Figures 2-1 and 2-2.

2.2 ANALYTICAL EQUIPMENT AND PROCEDURES

Suitable aliquots were taken for analyses. Methods employed were emission spectroscopy (designated ES in tables of analytical results), spark source mass spectroscopy (SSMS) and atomic absorption (AA) spectrophotometry. The Perkin-Elmer 303 atomic absorption spectrophotometer with graphite furnace atomization was used for the high precision measurements. Liquid samples were filtered through Whatman 40 filter paper for both ES and AA analyses. Solid samples were reduced (when necessary) to -0.5 mm (-32 mesh), quartered, and dried at room temperature over $CaSO_4$ desiccant for all analyses. All samples were stored in polyethylene containers.

The AA test procedure consists of injecting the liquid samples at full strength into the graphite furnace and comparing absorptions against standard solutions of reagent grade chemicals. For a few analyses samples were diluted with distilled/deionized water to obtain on-scale absorption readings, but whenever possible spectral lines of lesser sensitivity were used when concentrations were high enough to saturate primary absorption bands [e.g., for magnesium (Mg) and zinc (Zn)]. Solid samples were also atomized directly in the graphite furnace, using a tantalum cup and insertion spoon. For some solid samples, particularly limestone and fly ash, the solids were digested in concentrated acids and the resultant solution was analyzed as a liquid sample. Interferences from volatiles hampered the analysis of certain samples, particularly bottom ash and coal, but the use of a deuterium background corrector on subsequent analyses is expected to reduce interference.

Table 2-1. SLUDGE SAMPLES ACQUISITION, SHAWNEE POWER STATION, 1 FEBRUARY 1973

Sample	Sampling station[a]	Quantity	Time of sampling
Process water make-up	7	100 ml	0700
Scrubber effluent slurry, retained as slurry	2	4.40 liter	0700
Scrubber effluent slurry, separated after sampling	2		0700
Liquid portion		100 ml	
Solids portion		20 gm	
TCA inlet fly ash	4	3 gm	0930 - 1130
TCA outlet fly ash	3	3 gm	0930 - 1130
Clarifier effluent	1	22 liter	0700
Bottom ash, Unit No. 10		100 gm	0900
Coal from scale, pulverized and quartered		100 gm	0730 - 0830
Limestone from feed belt, composite sample	6	100 gm	0735 - 0835

Operating conditions:

Bechtel Test Run No.	Gas flow rate	Time
428-2A	420 cu m/min	0700 - 1030
429-2A	700.8 cu m/min	1030 - 1130

Coal consumption to Boiler No. 10	42.5 mt/h av[b]
Power produced	102 MW av
Total ash production	6.66 mt/h av[b]
Bottom ash production	1.33 mt/h approx[b]

[a]See Figure 2-1

[b]mt/h is metric tons/hour

Table 2-2. SLUDGE SAMPLES ACQUISITION, SHAWNEE POWER STATION, 11 JULY 1973

Sample	Sampling station[a]	Quantity, liter	Time of sampling
Process water make-up	7	0.55	0820
Scrubber effluent slurry, retained as slurry	2	4.40	0845
Scrubber effluent slurry, separated after sampling	2		0840
Liquid portion		0.55	
Solids portion		0.55	
TCA inlet fly ash	4	33 g	0730 - 0930
Clarifier effluent	1	0.55	0855
Coal from Unit No. 10 bunker		1.10	During day 7-10-73
Limestone from feed belt	6	0.55	0830
Bottom ash from Unit No. 10		2.20	0800
Soil near limestone pile		4.40	1000

Operating conditions:

Coal consumption to Boiler No. 10	40 mt/h av[b]
Power produced	95.6 MW av
Total ash production	6.21 mt/h av[b]
Bottom ash production	1.54 mt/h approx[b]

[a]See Figure 2-1

[b]mt/h is metric tons/hour

Table 2-3. SLUDGE SAMPLES ACQUISITION, MOHAVE POWER STATION, 30 MARCH 1973

Sample	Sampling station[a]	Quantity
Scrubber input from holding tank	1	1.10 liter
Scrubber effluent	2	4.40 liter
Centrifuge discharge		
Liquid portion	4	1.10 liter
Solids filtered from liquid portion	4	1 gm
Solids portion	3	5 gm
Make-up water	5	1.10 liter
Limestone	6	907 gm

Operating conditions:

Limestone depletion tests

Gas flow rate: 35.4 cu m/min

Time of sampling - 1330 - 1430

[a]See Figure 2-2

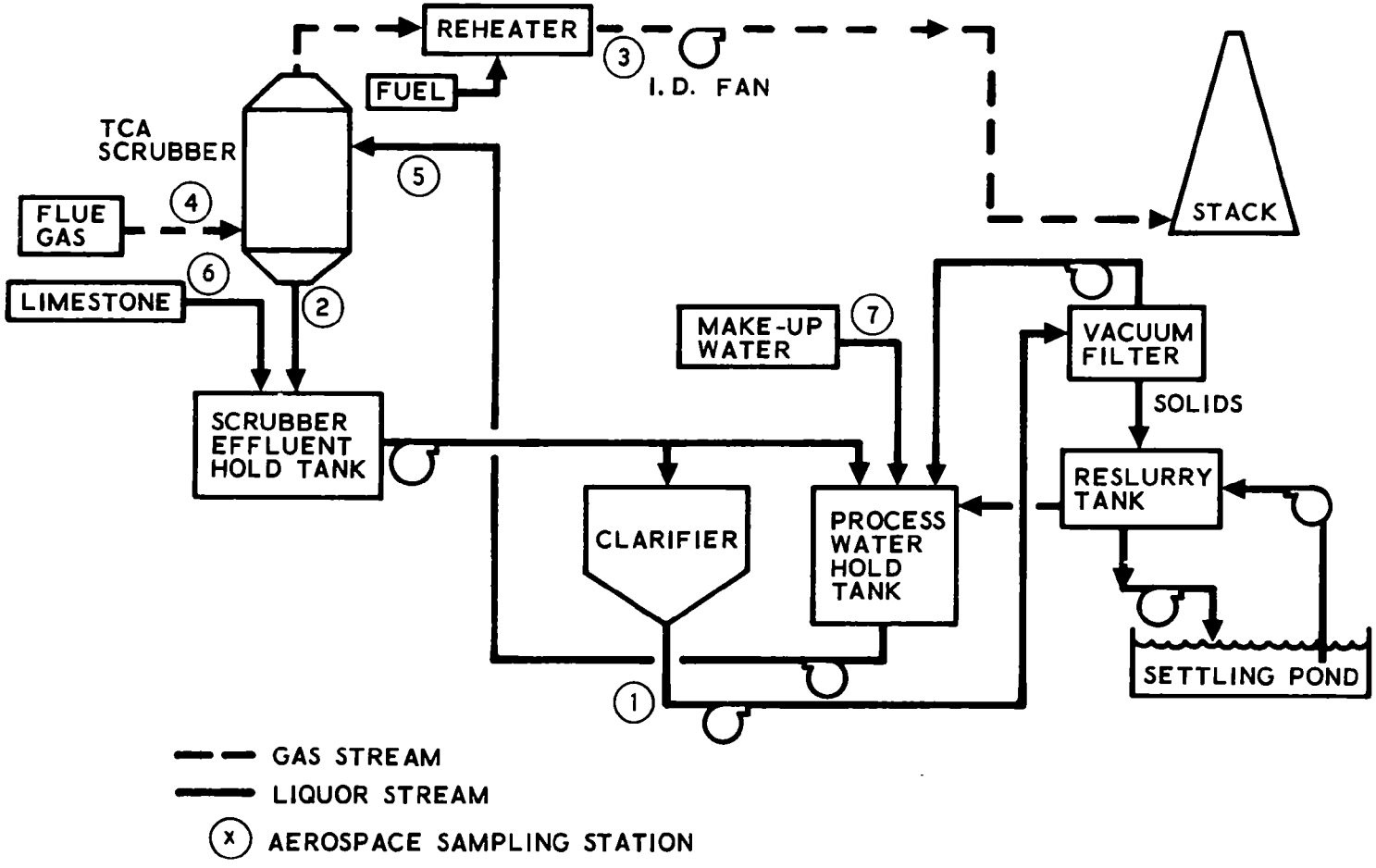

Figure 2-1. Process flow diagram for TCA system at the Shawnee Power Station

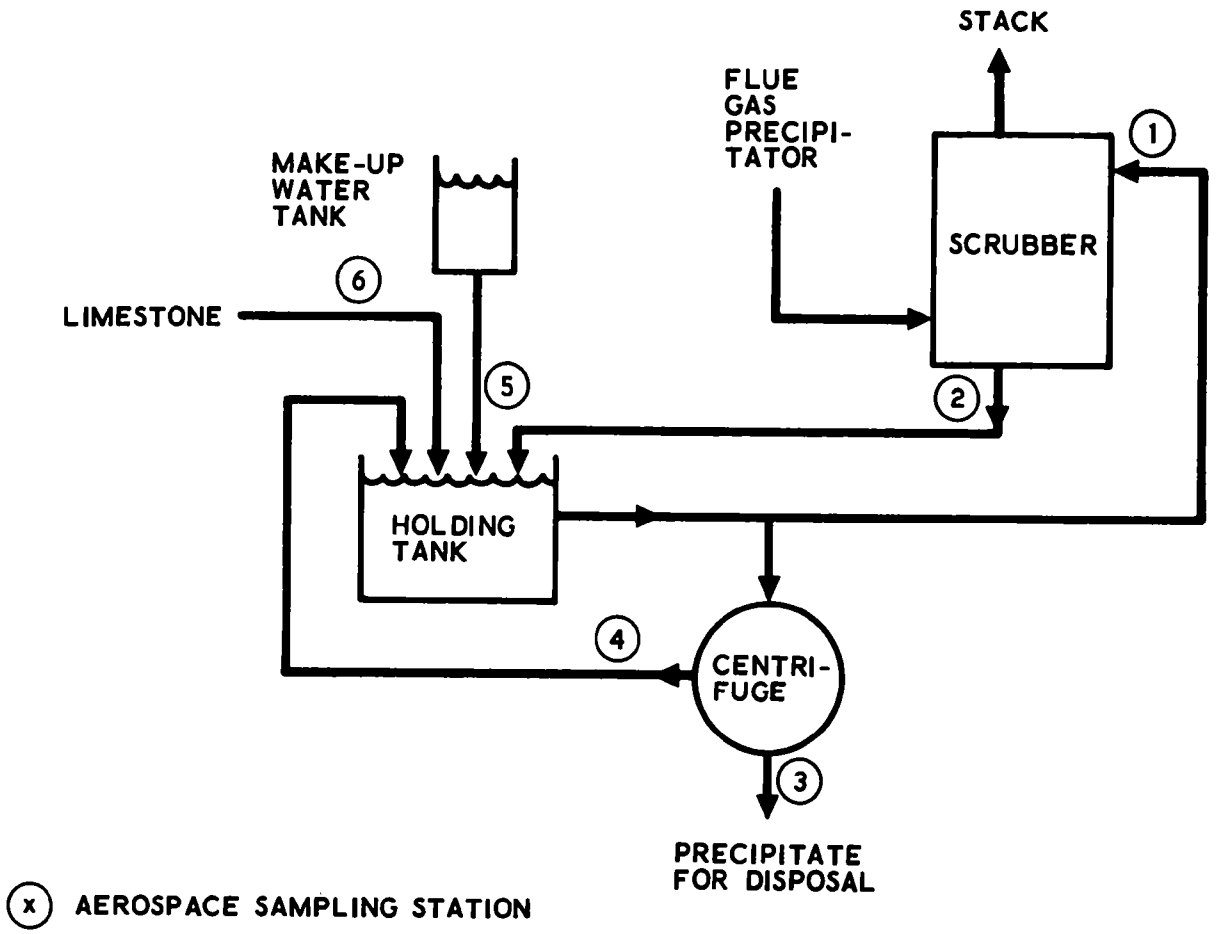

Figure 2-2. Process flow diagram for Mohave station limestone scrubber pilot plant

For the Shawnee samples, the flow sheets in Section 2.4 show that the scrubber effluent slurry is reported in two ways: separated and retained. The separated slurry sample was filtered immediately upon collecting the sample by the TVA personnel taking the sample. By immediately separating the liquid and solid portion, interaction between the two phases is arrested. The retained samples were separated at the time of analysis, 8 months for the 1 February 1973 sample, and 3 months for the 11 July 1973 sample.

In this and subsequent discussions, no distinctions are made among the three analytical methods employed (ES, SSMS, and AA). For purposes of comparison, the preferred method is AA because its greater sensitivity gives it more precision and higher accuracy. In most, if not all cases, when the AA analysis of some elements has low sensitivity, it is still greater than that obtained from the other analytical methods.

The SSMS test procedure consisted of wrapping a nominal 100 mg sample in gold foil that is then sparked against a high purity gold counterelectrode in a CEC 21-110X mass spectrometer. The data are collected on a photographic plate as a function of mass/charge ratio and scanned on a microdensitometer. Quantitative values are determined by integrating line densities and comparing these intensities against standards developed for each element. Trace elements at concentrations less than 5 ppm atomic are not listed.

The ES test procedure uses a sample that is acidified in sulfuric acid and then ashed. Liquid samples are evaporated to dryness, and the remaining residue is analyzed. A nominal 20 mg sample is packed into a spectrographic grade carbon sample holder and sparked against a similar grade carbon electrode. The emission spectra are recorded on photographic film and scanned on a microdensitometer. By comparison of line density with standards, a semiquantitative analysis can be obtained for each element.

2.3 ANALYTICAL RESULTS

The analytical results of these analyses are presented in tabular form in Appendix B.

2.4 ANALYSES AND EVALUATIONS

This section discusses the regional (eastern/western) occurrence of those elements (As, Be, Cd, Cr, Cu, Hg, Pb, Se, and Zn) chosen because of their potential toxicity (Ref. 2-2). The simplified

flow sheets show the level of the toxic element at each sample point and could be used as a basis for a materials balance if appropriate rate data were available.

2.4.1 Arsenic

Coal is an important source of the arsenic (As) observed in the system. No analyses are available for As in the coals used, but concentrations of 10 ppm are typical for eastern coals (Ref. 2-3) and a value of 3 ppm has been reported for western coal, originating from the Black Mesa Range (Ref. 2-1). Make-up water appears to be a significant source of As in the Mohave pilot unit. Under the reducing conditions of coal formation, As, a sulfide-forming chalcophile like most of the metals discussed here could occur as the sulfide (e.g., arsenopyrite, FeAsS; realgar, AsS; and orpiment, As_2S_3). Alternatively, arsenic could be organic in origin as a consequence of the takeup of As by plant tissue, and in its transformation during coalification it could remain organically bound or appear so by forming a sulfide on the molecular scale. In addition, substitutions of As in other minerals also commonly occur. Very high As content in the super-fines of fly ash and the identification of As in the carbon particles of coal by ion microprobe analysis suggest its origin in the organic component of coal. During combustion of the coal, As compounds are converted to oxides and carried in the flue gas as fine particulates. Minor amounts enter the circuit in limestone and make-up water.

Minor build-up of As is evident in the Shawnee circuit (Figure 2-3) from February to July; this possibly implies that the saturation concentration has been reached. The concentration of As in the Mohave liquors (Figure 2-4) reflects the concentration in make-up water.

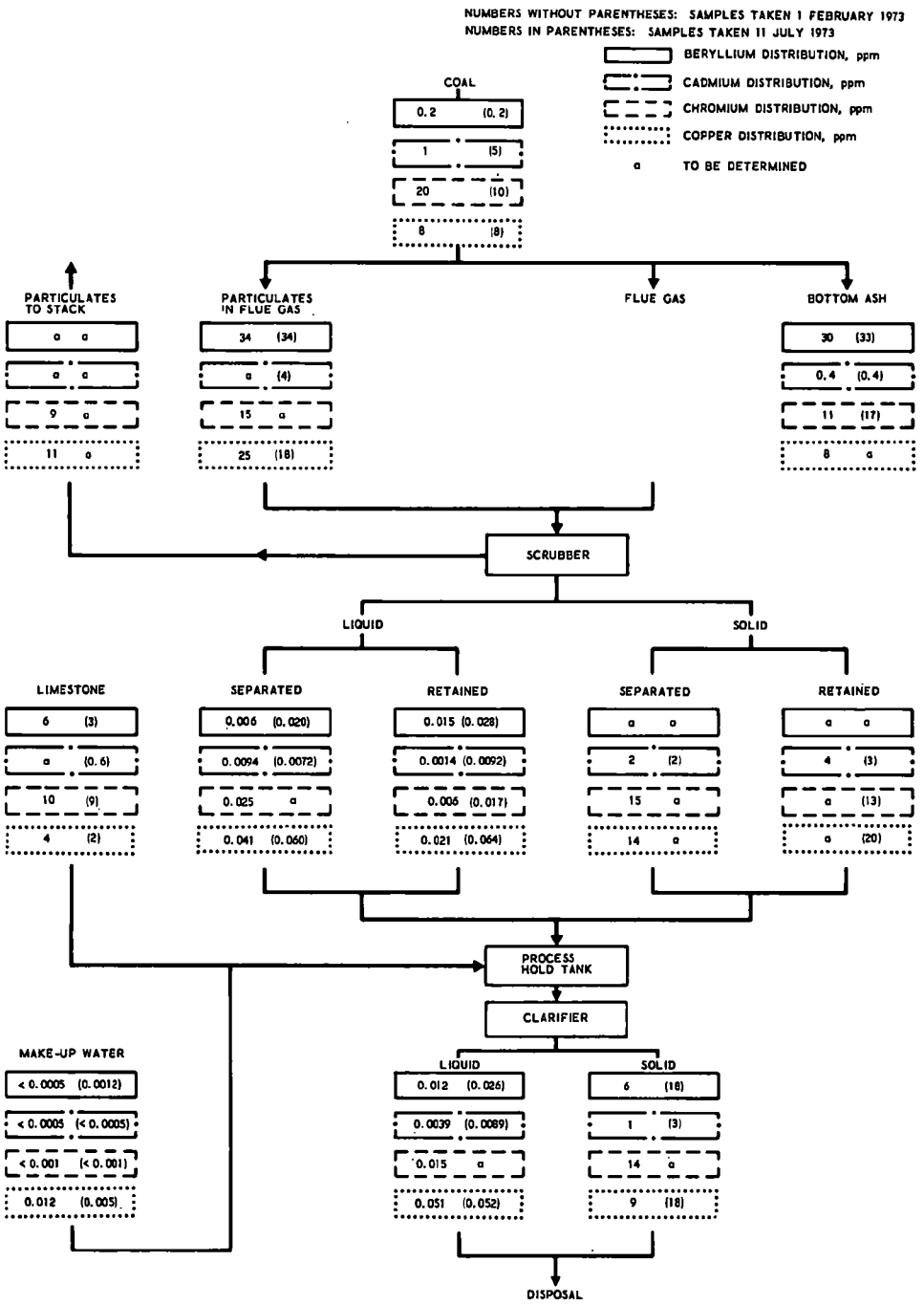

Figure 2-3. Interim status of data development--level of heavy metals at each sample point of the Shawnee Power Station (sheet 1 of 2)

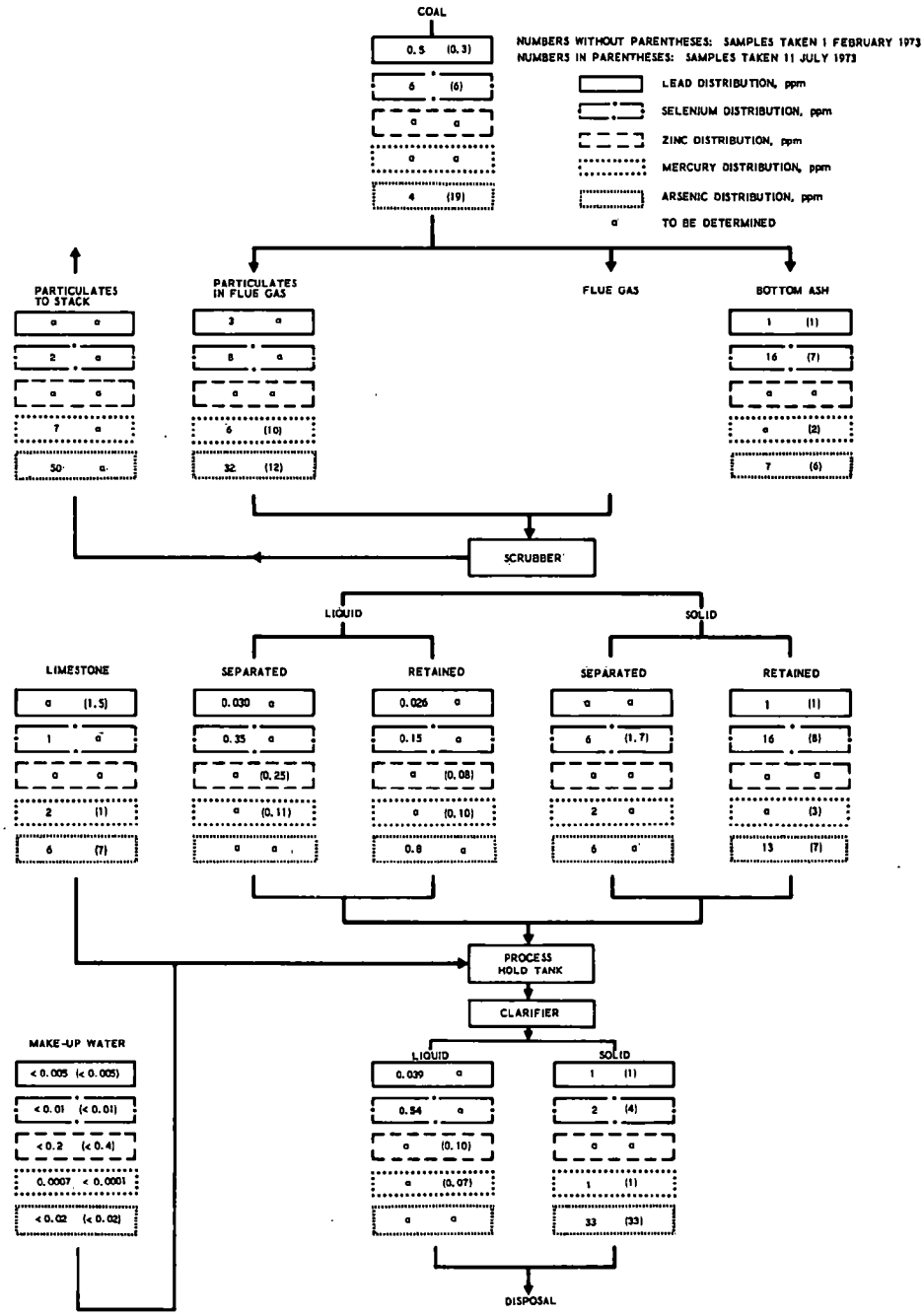

Figure 2-3. Interim status of data development--level of heavy metals at each sample point of the Shawnee Power Station (sheet 2 of 2)

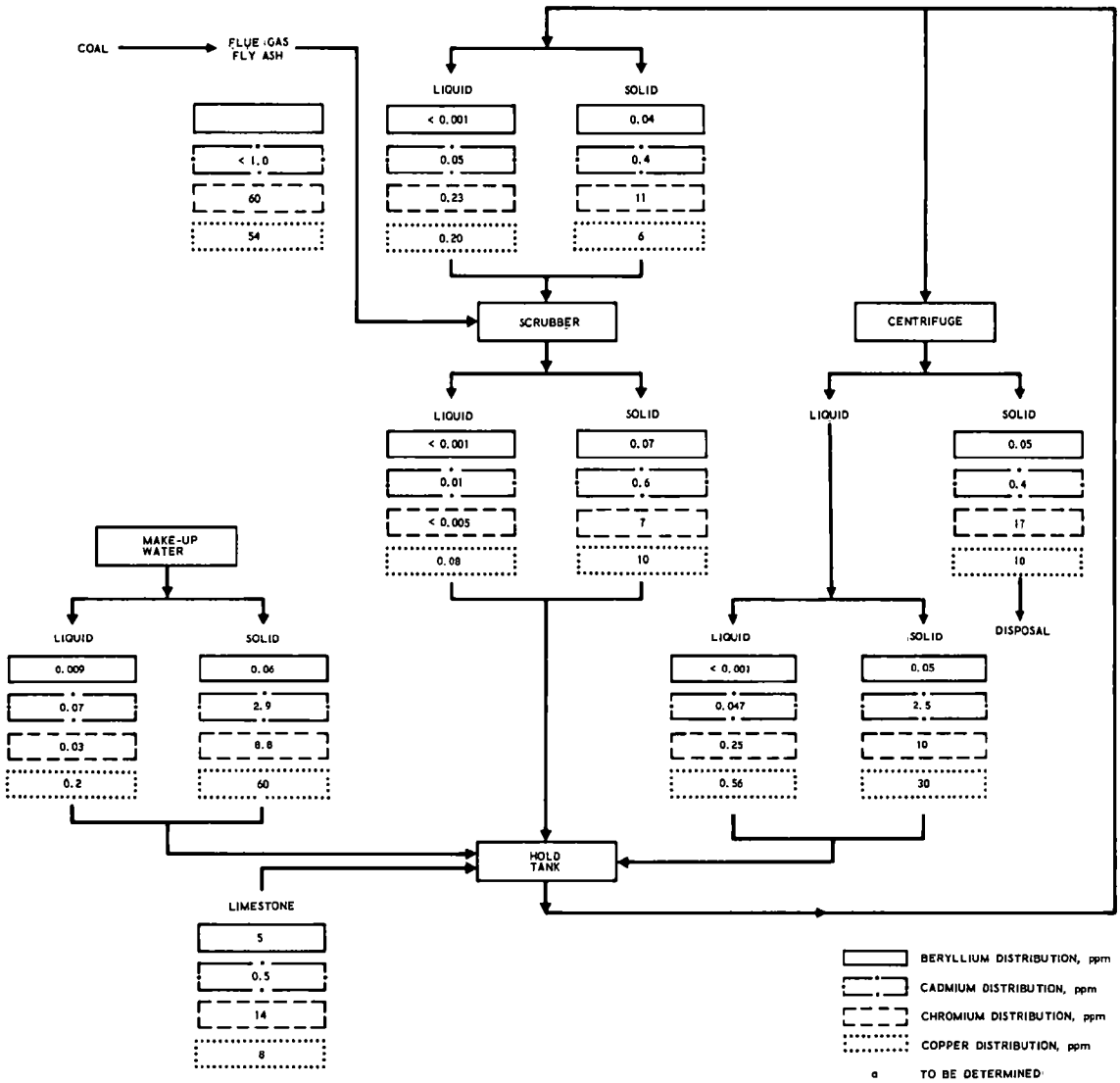

Figure 2-4. Interim status of data development--level of heavy metals at each sample point of the Mohave Power Station on 30 March 1973 (sheet 1 of 2)

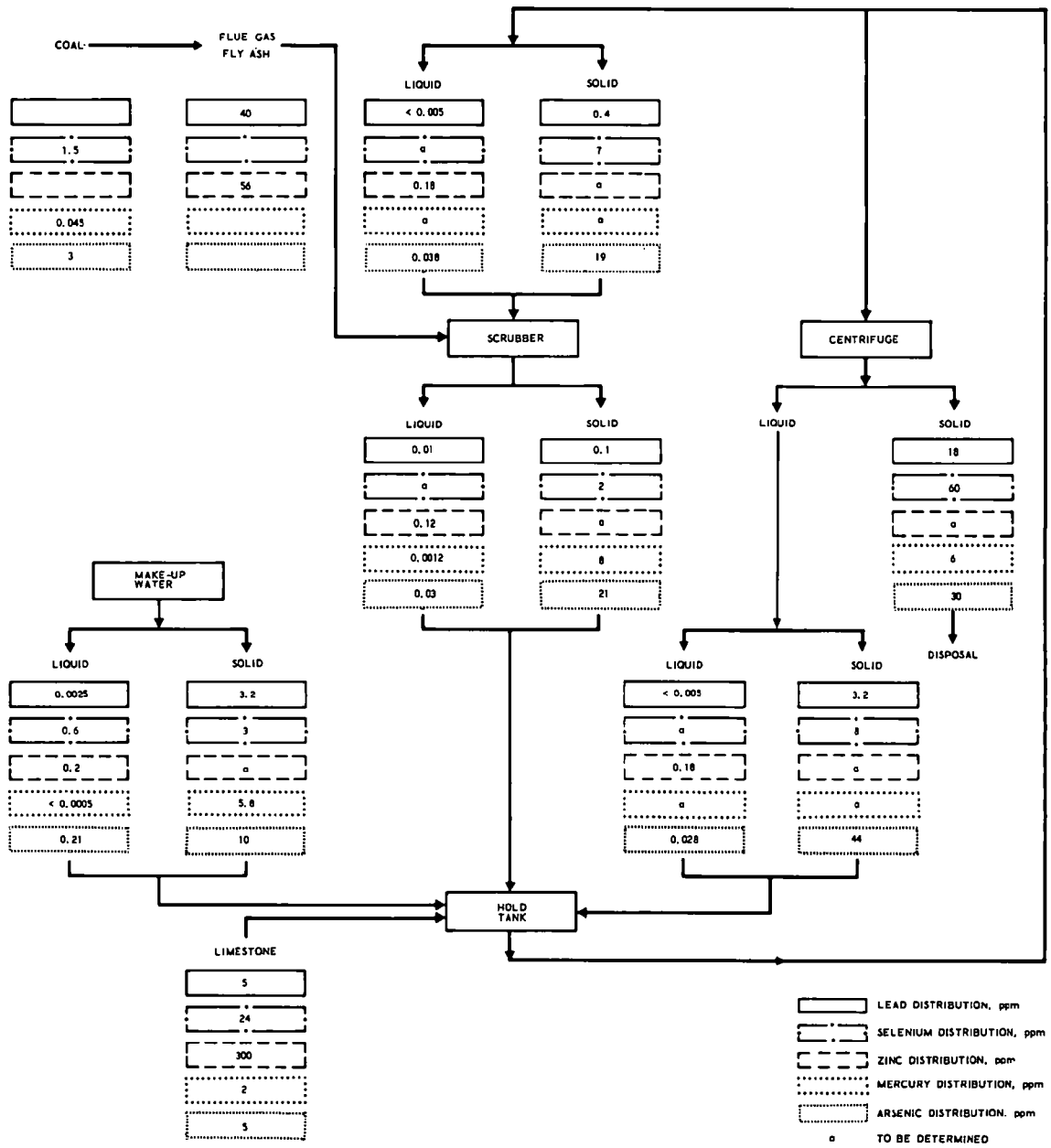

Figure 2-4. Interim status of data development--level of heavy metals at each sample point of the Mohave Power Station on 30 March 1973 (sheet 2 of 2)

Arsenic oxide, As_2O_3, has both acid and base properties. In the scrubber it would form a mixture of the three complexes of arsenious acid, $[H_2AsO_3^-]$, $[HAsO_3^=]$, and $[AsO_3^{\equiv}]$; the proportions would depend on the pH. At high levels of Eh, or oxidation potential, an even more soluble arsenic acid complex, $[H_2AsO_4^-]$, would be formed, though this is unlikely in a sulfite liquor without purposeful oxidation.

2.4.2 Beryllium

Beryllium (Be) is found in both coal and limestone. The content of Be in eastern and western coals averages 1-2 ppm (Ref. 2-1), and either coal or limestone could account for the small amount of soluble Be in the liquors.

Beryllium is found in nature as the mineral beryl, $Be_3Al_2Si_6O_{18}$, but the Be content of the Shawnee samples is so low that it probably occurs in substitution for Al or Mg. Pending further analyses, it is presumed to deposit in the pond. This is desirable as a step in the removal process, but only if we assume that the pond deposits are completely immobilized. All aspects of loss from the pond that might render Be airborne must be carefully studied; these include spillage and flood washouts, breaching of pond walls, and especially deflation of dried-out deposits by wind action. Beryllium identified in Shawnee and Mohave samples is noted in Figures 2-3 and 2-4.

2.4.3 Cadmium

The cadmium (Cd) analyses give little indication of its source or path in the circuit (Figures 2-3 and 2-4). Cadmium in coals averages less than a part per million (Ref. 2-4); however, the Cd content of the limestone is sufficient to produce the observed concentrations. It is uncommon in nature; the sulfide CdS or greenockite is

widely associated with sphalerite, ZnS, primarily in coals. Cadmium is so close to calcium (Ca) in ionic radius and charge that it is probably introduced in the limestone as a Ca substitute. Both the carbonate and oxide of Cd are substantially insoluble, and it appears in the scrubber effluent solids for removal to the pond. Conclusions about the movement of Cd should be deferred, however, until more analyses are made.

2.4.4 Chromium

The substantial chromium (Cr) content of the Shawnee and Mohave coals shows up at all stages of the scrubbing process (Figures 2-3 and 2-4). Chromium is lithophile or oxide-forming in nature; its important ore is chromite, $FeCr_2O_4$, but it substitutes readily for Fe^{+3} having practically the same ionic radius. This substitution probably accounts for its presence in a coal having an Fe content of 4500 ppm. Chromite may hydrolyze in the alkaline circuit to the amorphous species $Cr(OH)_3$, which is insoluble but difficult to remove by clarification processes. This may be the form seen in trace concentrations in the scrubber and clarifier liquids.

The presence of Pb in the circuit introduced the possibility that at least a portion of the Cr may be immobilized in the pond deposit as the highly insoluble mineral crocoite, $PbCrO_4$. This would require an oxidizing regime to convert Cr to the hexavalent form and is not likely to occur unless strong oxidizing conditions were imposed.

2.4.5 Copper

Copper (Cu) introduced into the scrubber system from both eastern and western coals approximates 15 ppm (Ref. 2-3), with minor amounts entering in limestone and water. During coal formation it would form stable sulfides (e.g., chalcocite, Cu_2S, and chalcopyrite, $CuFeS_2$) and oxidize in the furnace to the insoluble oxides

cuprite, Cu_2O, and tenorite, CuO. In this form, it would appear in the scrubber and clarifier solids, and finally the pond deposits with only trace amounts showing up in the various liquid phases.

The Cu content of the Shawnee liquid samples is fairly uniform at around 0.05 ppm (Figure 2-3). The slight increase in Cu from February to July is not considered significant. When the scrubber underflow liquid separated at the time of sampling is compared to that retained in contact with the solids, the latter runs lower in Cu content for the February sample (with a corresponding increase in Cu in the solids), but is unchanged for the July sample. The lower pH seems to be associated with the loss of Cu from solution to solid, but the mechanism is unclear and can only be referred to possible sorption on fine particles. Since copper hydroxide, $Cu(OH)_3$, is quite insoluble, the higher pH of the July slurry liquid (retained) could also be expected to reduce the content of Cu in solution, particularly since the separated sample of July slurry liquid was acidic. Both samples, however, showed about the same content of Cu (0.06 ppm). Hence no conclusions can be drawn about the possible effect of pH on the completeness of Cu separation in the circuit and in the pond. (See Figure 2-4 for Cu distribution in the Mohave sample.)

2.4.6 Mercury

Mercury (Hg) in eastern coals averages about 0.2 ppm and in western coals is about 0.05 ppm (Ref. 2-3). The limestone and make-up water also contribute some Hg to the system. The average Hg content of limestones is 0.04 ppm (Ref. 2-5); make-up water contributes approximately 0.05 ppm. The coal, consequently, is expected to be the major contributor of Hg to the scrubber system.

Cinnabar and metacinnabar, the rhombic and cubic crystalline forms of HgS, are the only common Hg ores. In nature, it associates with Cu and Pb, and particularly with Zn as sphalerite,

ZnS. Concentration of Hg in plant tissue as an organic complex probably preceded the coalification that produced the coal beds.

Mercury is reduced to the vapor of the metal in the boiler and remains in that state until cooled in the scrubber. The amount of vapor escaping from the stack depends on the efficiency of the scrubbing process. The greater part should be trapped, dissolved as the mercurous ion Hg^+, or adsorbed on particulates. Its path can be traced through the circuit only when more complete analyses are available. Mercurous carbonate, Hg_2CO_3, is nearly insoluble (0.05 ppm), but Hg is solvated in the form of various ionic complexes, which may account for the relatively high concentration seen in the slurry liquid. The higher Hg concentration in the liquid retained in contact with the solids is supporting evidence for the gradual solution of Hg from a solid phase. Nothing can be concluded at this time about the saturation level of Hg; future levels may be even higher than those determined so far.

The situation in the pond is modified by the introduction of atmospheric O_2 into the system. This will oxidize the Hg to the mercuric stage, Hg^{2+}, which forms more soluble salts than Hg^+. A basic mercuric carbonate, $HgCO_3 2HgO$, forms in an alkaline circuit that is insoluble and should be retained in the pond deposits. See Figures 2-3 and 2-4 for Hg distribution in Shawnee and Mohave samples.

2.4.7 Lead

Lead (Pb) in eastern and western coals averages 5-10 ppm (Ref. 2-3). There are lesser amounts in limestone and make-up water, but coal is considered the principal contributor. Its mineral galena, PbS, is the most likely form; the trace amount in the limestone may be present as cerussite, $PbCO_3$. Anglesite, $PbSO_4$, is found in an oxidizing regime; the last two forms may be important

in the TCA circuit itself. The combustion product litharge, PbO, is slightly soluble as are the carbonate and sulfite species, hence we see some Pb in the slurry and clarifier liquids, and there is evidence that it is accumulating in the liquid, but these concentrations are not yet considered a serious problem. The small difference between the lead contents of the separated and retained liquids indicates that pH changes do not affect significant amounts of lead solubility.

Lead should be stabilized in the pond deposits as $PbCO_3$ or $2PbCO_3 \cdot Pb(OH)_2$ (white lead) and $PbSO_4$. Precipitation by chromate under oxidizing conditions has been discussed; this would give the least soluble species of those mentioned. Other forms could eventually be leached from the pond, possibly slowly enough to present no hazard. Lead distribution in the Shawnee and Mohave samples is given in Figures 2-3 and 2-4.

2.4.8 Selenium

The selenium (Se) content of coals averages about 1 ppm (Ref. 2-3); this is comparable to the selenium entering the system from the Shawnee limestone (30 ppm) such that the latter is considered an equal contributor to the selenium in the circuit. Like As, Se is amphoteric and may substitute for sulfur in pyrrhotite and chalcopyrite. This substitution may account for its state in coal and possibly in limestone. However, its chemical similarity to arsenic suggests that selenium may also exist in the coal as an organic specie. Analysis has not yet detected the small amounts of selenium in the coal, but it is presumed that its origin is similar to that of As. Under weakly oxidizing conditions it forms soluble selenious acid, H_2SeO_3; this ionizes in two steps, forming $SeO_3^{=}$ and $HSeO_3^{-}$, so that the solubility is pH-controlled. The amount of Se in the sulfite liquors suggests that precipitation or adsorption processes do not take place. Selenites of Ca and Mg are relatively insoluble; this may be the form

in which Se is removed to the pond deposits in the solids. How well it is retained there is open to question, but its stability is at least suggested by the agreement in Se content between the separated and retained slurry liquids in the Shawnee samples. Selenium distribution in the Shawnee and Mohave samples is given in Figures 2-3 and 2-4.

2.4.9 Zinc

Zinc (Zn) found in coals ranges widely (western coals tend to have lower Zn contents than eastern coals), but values between 10 and 100 ppm are typical (Ref. 2-3). Reported analyses range from 20 to 2000 ppm so that the measured value (180 ppm) from the Shawnee coal lies well within this range. Nevertheless, it is likely that coal is the principal source of the Zn in the scrubber systems. Sphalerite, ZnS, is the most likely Zn mineral in an average coal. Smithsonite, $ZnCO_3$, and hemimorphite (calamine), $Zn_4Si_2O_7OH \cdot H_2O$, are of lesser importance as sources of Zn.

The oxide ZnO, the combustion product of ZnS, sublimates readily (a method used in the refining of Zn) and some may escape the scrubbing action. Zinc oxide is soluble only to the extent of about 1 ppm, and the amphoteric nature of Zn may account for the concentrations seen in the sulfite liquors:

$$ZnO + [SO_3^{=}] + H_2O \rightleftharpoons ZnSO_3 + 2[OH^-]$$

The $ZnSO_3$ is soluble to the degree of about 0.15 percent. Some precipitation of $ZnCO_3$ may occur to bring the level of Zn^{+2} in the liquor down to the observed levels. If it were not for carbonate formation, oxidation of the sulfite in the pond might produce the highly soluble zinc sulfate and result in rapid loss of zinc by leaching. Zinc distribution in the Shawnee and Mohave samples is given in Figures 2-3 and 2-4.

2.5 SOLUBILITY APPRAISAL OF POTENTIALLY TOXIC ELEMENTS

To make an overall appraisal of the occurrence of toxic elements in the TCA scrubbing facility at the Shawnee Power Station, certain speculations must be made based on the data presented and the known chemistry of the constituents. No absolute trend toward a build-up of soluble toxic elements in the circuit can be confirmed on the basis of partial analyses. Moreover, in making an assessment the limitations that must be taken into consideration are: (a) samples may be representative of local test conditions and not representative of the system, (b) the high ionic strength of the system affects the solubility of each component in an unknown manner, (c) the possibility of forming soluble complexes is great because of the variety of ions present and the pH and Eh factors, and (d) precipitation of a trace metal may be retarded because of the high ionic concentrations and these elements might remain in a supersaturated state until scavenged or coprecipitated in a major crystalline phase.

Nevertheless, the stability of compounds produced by interaction of the ions of toxic trace elements with the major ionic species present in the slurry can be estimated, at least on a qualitative basis. Compound stability is a major determinating factor controlling the solubility of the various elemental species in the sludge. The solubility or insolubility of a compound is a relative factor and in a dynamic system relates not to how much dissolves but to how much dissolves in a given time. All compounds will completely dissolve given enough leach water and time. Whether these compounds are subject to slow or fast leaching from pond deposits, and to what extent they may be affected by environmental conditions will determine their potential toxicity. An environmentally sound disposal method need not prevent the introduction of the elements into the environment, but rather control their rate of entry such that environmental health

hazards are avoided. Insight into whether toxic elements in the form of oxides, hydroxides, carbonates, sulfites, and sulfates might be sufficiently insoluble in a scrubber system is given in Table 2-4. When compared with the analytical data presented in Section 2.4, these data of known chemical behavior will reveal whether the system is sufficiently buffered with the necessary anions to keep them adequately immobilized for environmentally safe disposal.

Beryllium should precipitate as the sulfate and possibly as the sulfite, but some unknown amount of soluble carbonate complex should also form. The relatively low concentration of Be in the liquor probably represents that fraction existing as the soluble complex; the remainder is sulfate or sulfite. Once in the sulfate or sulfite form, it should remain in pond deposits and not be available to the environment in amounts that warrant environmental concern.

The elements Cd, Cu, Hg, and Pb form stable carbonates that will remain in pond deposits unless leached by acidic water. Mercury and lead can form insoluble sulfite, and this is probably the principal form in which they exist as a precipitate. Eventually, with an increase in oxidation potential they will convert to sulfates and the Hg will be able to leach away. Lead sulfate is highly stable and will not leach at a rate of environmental concern. In addition, Hg forms an insoluble mercurous chloride that when oxidized will convert to the more soluble mercuric chloride. The high concentration of Hg in the scrubber liquors possibly reflects the soluble potential for Hg either as a chloride or sulfate.

Cadmium and copper also form insoluble hydroxides, and these salts will remain stable in a basic environment. The concentration of Cd and Cu in the scrubber liquors is sufficiently low because both form stable carbonates and hydroxide. Their concentration in an acidic environment could, however, pose a greater toxic hazard.

Table 2-4. RELATIVE SOLUBILITIES IN WEAKLY ALKALINE AND REDUCING SOLUTIONS

Toxic cations	Major anions			
	$CO_3^{=}$	OH^-	$SO_3^{=}$	$SO_4^{=}$
Be^{2+}	Soluble	Insoluble		Insoluble
Cd^{2+}	Insoluble	Insoluble soluble	Slightly	Soluble
Cr^{2+}	a	Insoluble	a	Insoluble
Cu^{+}	Insoluble	Insoluble	Slightly soluble	Not formed in water
Hg^{+}	Insoluble	Insoluble	Insoluble	Slightly soluble
Pb^{2+}	Insoluble	Slightly soluble	Insoluble	Insoluble
Zn^{2+}	Very slightly soluble	Insoluble	Slightly soluble	Soluble

Major cations	Toxic anions	
	AsO_3^-	$SeO_3^{=}$
Ca^{2+}	Slightly soluble	Insoluble
Mg^{2+}	a	Insoluble

[a]Data to be determined

Sources: Refs. 2-6, 2-7, and 2-8

Chromium forms a very stable hydroxide and sulfite in a basic liquor, and its low concentration in the scrubber liquor reflects its immobilization in the system.

Zinc has no highly insoluble salts under the conditions of a scrubber circuit and would be hard to retain as a pond deposit for long periods. The hydroxide has sufficient stability to prevent Zn from accumulating to high concentrations, but insufficient stability to immobilize the metal. The high concentrations of Zn in the scrubber liquor reflect the relative instability of zinc compounds in the system.

The arsenite, AsO_2^-, is difficult to purge from the system. Its calcium salt is slightly soluble; the solubility of the magnesium salt is not known. It forms insoluble compounds with some of the trace metals present in the circuit, but its removal probably depends on the efficiency of being scavenged by $CaSO_3$. Its relatively high concentration in scrubber liquors is undoubtedly a consequence of the relative instability of arsenite compounds in the system. Because of this instability, As is expected to accumulate in a recirculating system.

Selenium is chemically similar to As but the selenites of magnesium and calcium are much more stable than the arsenites. The relatively lower Se content in the scrubber liquor reflects the greater insolubility of the selenites. Selenium is not expected to pose a health hazard in this form, but it may accumulate in a recirculation system.

Among the metals analyzed, As is the only element for which an insoluble compound can not form in the sludge liquors. In spite of this fact, several elements exist at concentrations in excess of that which might be predicted from known chemistry. One explanation might be the formation of complexes; in some cases this is undoubtedly true. The more likely explanation is gained from the observation that those metals with the greatest observed solubility are also

those whose more stable compounds are carbonates. In some respects this observation is also true for elements that form stable hydroxides. This observation suggests, therefore, that a deficiency in carbonate and hydroxide may exist in the liquors relative to the concentrations necessary to precipitate these heavy metals to these equilibrium levels.

In summary, As, Hg, Pb and Se are sufficiently soluble to be of environmental concern. In addition, Be and B may be of concern, but their potential hazard is not clear at this time. The compounds of Cd, Cu, and Cr, are sufficiently insoluble so as not to be of concern at the present state of understanding. This evaluation is based on the precept that liquor waters will not sufficiently change oxidation potential or pH from that measured. A greater health hazard is expected under conditions of high oxidation potential and lower pH, but a quantitative assessment of this hazard cannot now be given.

In addition to the toxic heavy metals discussed, two other highly soluble elements are found in sludge liquors that must be considered. Boron was found in the Shawnee coal at 46 ppm--a value considered typical for both eastern and western coal. Chlorine in the Shawnee coal has been reported as 2000 ppm (Ref. 2-9), but its measured value in this study was 280 ppm. The former value is more consistent with other data. The chlorine content of eastern coals varies from 100 to 5000 ppm with an overall average content of 2000 ppm (Ref. 2-10). Western coals are expected to have a lower chlorine content, but an analysis for these coals has not been found in the literature. Boron is primarily associated with the organic portion of coal whereas chlorine usually originates as soluble salts.

Boron will enter the scrubber as the oxide, B_2O_3, and will hydrolize to soluble boric acid, H_3BO_3. Chlorine enters the scrubber as gaseous hydrogen chloride and is easily entrained in the scrubber liquor as the chloride ion. Neither element forms insoluble

compounds with any major component within the scrubber system. As a consequence, these elements will build up in the liquors or if allowed to reach subsoils will percolate to the water table. The concentration to which these elements can build up is that at which the loss from the system through the liquor component in sludge will just balance the system intake. At the Shawnee TCA scrubber, this value reached 7000 ppm in the liquor in a system operating not fully closed-loop. For many coals, this value could exceed 1 percent of the scrubber liquor.

Although these elements are not specifically toxic to man, they do pose problems of concern. Boron is toxic to many forms of plant life, many of them are part of the human diet. Only the gaseous borane is known to be toxic to man, but when assimilated in organic matter, there is an uncertainty as to whether this form of boron may be toxic to man or animal. Nevertheless, agricultural lands exposed to boron by runoff, spillage, or other inadvertent mishap may be poisoned for further agricultural use for many years.

Chloride ions are highly corrosive to metals; thus, the high chloride build-up that could take place may severely shorten the life of the scrubber and auxiliary parts. Besides the economic consequence of corrosion the possibility exists of metal components from the scrubber hardware entering the scrubber chemistry. Elements such as manganese, cobalt, chromium, nickel, vanadium, molybdenum, and others are typically found in the steels used in power plant construction. The solution of these elements in the liquor might aggravate the hazards that originate in these sludge materials.

The high degree of uncertainty that exists with respect to ionic species, solubilities, and solution rates of any of the elements prevents evaluation of ionic concentration under conditions with varied pH, Eh, or temperature. The occurrence of soluble complexes makes

this evaluation even more difficult because complex chemistry is an area that is just now being understood. Further evaluation of the toxic hazard will require analyses under varied environmental conditions.

2.6 SOURCE OF POTENTIALLY TOXIC ELEMENTS

The primary source of trace elements found in scrubber sludge is the fossil fuel--coal in these cases--but some significant contribution of specific elements to the system enter from the limestone and make-up water. Trace elements from the coal are the consequence of combustion and enter the system either as a gas, in particulates, or as adsorbed species on the particulates. Analyses of trace elements as a function of the size of fly ash particulates have indicated that certain elements are nonuniformly distributed. Other trace elements found in the scrubber system are not found by analyses among the particulates, and it is rationally presumed that their entry into the system is through the flue gas. Some of the gaseous species are physically adsorbed on the particulates, but their concentration in this form cannot solely account for the quantity determined to be present in the sludge.

Various methods were used in an attempt to reveal the source of trace elements. Among the more successful was the ion microprobe technique whereby the chemical analysis was determined for individual particles. Particles of coal, sludge, and fly ash were analyzed individually and in clusters. Lead and chromium were found heavily concentrated in fly ash particles rich in iron. The inference to be made by this observation is that these elements are associated with iron either as a substitute ion or as a coprecipitated compound, most probably as the sulfide. Beryllium and copper could not be detected in individual particles of fly ash but were observed when a cluster of particles was analyzed. Because they exist in the system at lesser concentration, their correlation with more major elemental

species could not be made and their origin in the system, therefore, has not yet been determined.

Zinc was also found in the analysis of fly ash particles, but its occurrence was dissimilar to that of lead and chromium even though it exists at similarly high concentrations. The interpretation of the data suggests that Zn is adsorbed on these particles, probably as the oxide. Zinc oxide is the combustion product of zinc sulfide, the most probable zinc compound in the coal, but some zinc may be present as an organic fraction. The oxide sublimed during combustion is believed to condense on the fly ash particles as the flue gases cool. Furthermore, its presence as an adsorbed specimen gives it ready accessibility that probably partially accounts for the relatively high concentration of zinc in the liquor.

Arsenic and boron were found in the SSMS analysis of fly ash but were not found by ion microprobe techniques of individual particles. Particle cluster analyses by ion microprobe indicated their presence, but specific correlation was not made. It was noted, however, that concentration of these elements in the fine dust collected downstream of the demister was greater than in the inlet particles to the scrubber. Since the fines in the fly ash particulate distribution are primarily the ash content of the organic fraction of the coal rather than the mineral content, this distribution implies that B and As originate as organic species. Ion microprobe analysis of coal particles supported the association of these elements with the organic content rather than with the inorganic content of coal. Electron diffraction analysis of coal particles rich in organic content has revealed crystalline inorganic matter in particle sizes as small as 0.01 and as large as 1 micron. However, since neither element was observed in individually large mineral particles of raw coal, it is concluded that B and As originate within the organic portion. Selenium, although not detected by any of these techniques, is believed to originate also

in the organic portion of coal because of its strong chemical similarity to arsenic.

Cadmium and mercury are chemically similar to zinc, and much of their origination in the coal is in association with Zn, especially Cd. The combustion product for both Cd and Hg is the oxide, but the oxide of Hg is unstable at the temperature to which the flue gas is cooled. The stability of the oxide of Cd lies between that of Zn and Hg and may enter the scrubber as either the metal or oxide. In either case, these metals enter the system as vapors in the flue gas and become entrained in the scrubber liquors possibly with the help of the carbonate and chloride ion.

Chlorine enters the scrubber as gaseous hydrogen chloride in the flue gas. This gas is easily and efficiently scrubbed by the liquor, and contributes to the source of hydrogen ions and chloride ions.

In summary, the elements Be, Cr, Cu, and Pb enter the system as particulates of fly ash; As, Se, and B also enter the system as particulates, but they are more heavily distributed in the fines and superfines. Cadmium, chlorine, mercury and zinc are carried in the flue gas either as metal vapors, oxide vapor or as gas. Possibly because of their gaseous dispersion, those elements carried in the flue gas appear to be efficiently scrubbed by the liquors.

2.7 TEST STATUS AND PLANS

Sample sets from Shawnee (2 sets) and Mohave have been analyzed by various chemical techniques. Since these analyses are not yet complete, full chemical characterization is not now available; however, the data to date indicate that several toxic trace elements are or can be sufficiently soluble to cause environmental concern in the handling and disposal of power plant sludges. The data further suggest that a greater potential health hazard may exist under conditions of greater oxidation potential and/or lower pH.

Two additional sample sets from Shawnee will be obtained as well as a set from a lime scrubber system and one from a double alkali system. In addition, analyses will be conducted on samples exposed to simulated environmental conditions of high Eh and low pH, and on sludges chemically conditioned by several different processes.

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SECTION 3

TOXICITY DETERMINATION

3.1 INTRODUCTION

The determination of heavy element toxicity is dependent upon observed physiological effects resulting from either carefully controlled experiments or from an environmental catastrophe of epidemic proportions. Clinical experiments rarely if ever precede the observed consequence of illness and death that often results from acute exposure to specific element intoxication. Moreover, health hazards from clinical testing preclude these experiments so that the relationship between exposure and the effects on human beings is most often evaluated from the effect on animals. Thus, the resulting threshold or exposure limits for humans are not always established with the certainty that may be desired. The role of trace elements in man's biological processes is only now beginning to be understood: many elements toxic to man in relatively high concentrations are essential to his health in trace quantities.

Nine elements found in nature in trace quantities (chromium, cobalt, copper, iodine, iron, manganese, molybdenum, selenium, and zinc) are essential to man's life or health; all are probably

important catalysts for differing biological functions. In addition, vanadium, nickel, fluorine, and arsenic are suspected of having a useful biological function. Other elements, which are now considered inert, are found in human tissue and may perform useful roles in the body, but the study of their biological activity has not been undertaken. Cadmium, mercury and lead have no known biological function and can act synergistically with other substances to increase toxicity. Once in the human system, their toxic effects are cumulative and are harmful to the degree that the dosages and resultant concentrations approach a lethal threshold. Even those trace elements having proven biological function, when ingested at high concentrations, can produce disease either by their accumulative effect or by inhibition of natural functions.

From the two known accumulative diseases, hepatolenticular degeneration from copper and idiopathic hemochromatosis from iron, accumulative diseases are suspected for other essential cations--chromium, manganese, cobalt, and possibly zinc and vanadium. The medical profession has long recognized that all essential trace elements are toxic in excess. If it were not for homeostatic mechanisms that reject excesses and conserve deficiencies, man would have to regulate his intake voluntarily. For elements such as cadmium, lead, and mercury to which man has experienced only recent exposure, it is unlikely that adequate homeostatic mechanisms have developed. In these cases trace elements are absorbed, accumulated, and eventually they lead to the development of disease. Cadmium represents one of the more serious toxic elements because it causes kidney and liver dysfunction, and it also interferes with the natural function of zinc leading to arterial hypertension and toxemia of pregnancy.

In making an assessment of the toxicity created by stack-gas scrubber sludge, a literature search was conducted to determine the toxic limits of the trace elements present in fossil

fuels and limestone. Appendix F provides a short review for some of these elements; this review is continuing.

3.2 TOXICITY ASSESSMENT

The primary potential hazards to water quality that may exist from power plant sludge arise from the solubility of arsenic and mercury. In addition, lead and selenium may present problems under certain environmental conditions.

Mercury, of all the potentially hazardous elements, poses the most serious health problem. It is not found in coals at high concentrations, but it is apparently efficiently scrubbed from the flue gases. Although it can form insoluble compounds, the analysis of mercury suggests that these are not easily formed. Mercury, when exposed to anaerobic aquatic environments, will easily and readily methylate, thereby becoming increasingly more hazardous. The scrubbing of mercury from flue gases can reduce the overall environmental load if this mercury can be contained within the sludge. As a soluble component, mercury has the potential of being released to the environment at concentrations in excess of limitations for water quality.

Although the preliminary data suggest that selenium may be building up in the recirculation liquors, it is typically found in low concentration in coal. Therefore, it is expected to reach a saturation equilibrium in the system at a level that does not pose a health problem. Since selenium is a micronutrient, homeostatic mechanisms within the human body will be able to eliminate surpluses over those required for good health.

Arsenic is an element used by the human body, but its availability in coal can be 10 to 100 times that of selenium. Although arsenic and selenium both have similar chemistry, arsenite's greater solubility and its higher concentration poses a more serious problem.

The full measure of this problem is not apparent in these preliminary results.

Lead is an element much like mercury in that it serves no useful purpose in the body and accumulates in the liver and kidneys. Lead can pose a serious health hazard if consumed in high concentrations, and it has appeared in some liquors at concentrations that exceed drinking water criteria. However, lead forms relatively insoluble compounds with many of the anions in the scrubber system and is expected to be controlled by them under most scrubber operating conditions.

For each of the elements discussed, the analyses on which these evaluations were based are preliminary and subject to change. Thus, these assessments must also be considered as tentative and subject to further evaluation.

3.3 ANALYSES AND EVALUATION

It is not yet possible to determine unequivocally whether stack-gas sludge poses a health problem. Certainly, situations can be presented whereby sludge can be a health hazard. Specifically, sludge liquors contain concentrations of dissolved salts that are very high relative to Public Health Department drinking water standards. It is herein presumed that the liquors will be managed to prevent their being directly intermingled with drinking water supplies. Hence, it is one of the study objectives to define minimum disposal technology that will prevent these sludges from becoming a health hazard. It will become easier to define those conditions wherein the sludge does not pose a health hazard rather than where it does.

Since reasonable precautions undoubtedly will be undertaken to ensure these sludges are not introduced directly into public waterways, access to the environment by more indirect means are being considered. Examples might be through the percolation of

leachate through the disposal site subsoils to reach the water table and thereby enter a river or wells, or by pond overflows or pipeline ruptures that permit liquors to enter a watercourse or poison agricultural lands. The inadvertent access to the environment might be the most dangerous situation because it might be detected only after health problems are noted among the affected populous. It is the intent of this study, therefore, to identify environmentally safe disposal technology and the potential hazard created by the alternative sulfur dioxide scrubbing processes.

Whereas sludge liquors may contain dissolved heavy metal contents posing specific toxic hazards, the liquors also contain soluble components that when ingested will render them noxious. Specifically, high chloride contents will make them salty, sulfates have a purgative effect, and carbonates give rise to gas generation. In addition, many dissolved cations (calcium, magnesium, boron, etc.) although not harmful to humans, are noxious when consumed in high concentrations. Liquors are, therefore, not acceptable discharges when they can enter a drinking water supply. The alternatives are to allow precolation to the water table or provide for complete containment. Defining the extent and safety of these alternatives is essential to this study.

The presence of sulfate, sulfite, carbonate, chloride, and hydroxide ions in the sludge liquors provides a high probability that insoluble compounds will form with most toxic heavy metals thereby reducing their availability to the environment, even under inadvertent situations. The toxic problem now appears to be primarily associated with arsenic and mercury because their chemistry includes some soluble compounds in scrubber liquors. This task is continuing so that determinations can be made of the full extent of this potential health hazard and the potential toxicity of other elements.

3.4 STATUS AND PLANS

Specific attention will be addressed to a build up in liquor concentrations of arsenic and mercury in the recirculation system of the Shawnee Power Station TCA scrubber system. In addition, other elements will be monitored either to determine their toxic potential or to provide insight into the scrubbing operation. An explanation of the system's chemistry with respect to the concentration of dissolved elements will be attempted relative to the operation variables.

Samples obtained from other power plants will be analyzed and compared with the Shawnee data to determine the chemical similarities and differences existing as a consequence of materials and system design variables. The objective of this task will be satisfied by identifying the toxic potential of power plant sludges and the situations in which these conditions exist.

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SECTION 4

DETOXIFICATION POTENTIAL

4.1 TOXIC CONDITIONS CONSIDERED

The potential capability for detoxification is a function of the element or groups of elements that pose the toxic hazard (Section 3). From the observed and known chemistry of the important toxic elements in power plant sludges the heavy elements that are most likely to create a water quality hazard are arsenic, mercury, zinc, and possibly lead and selenium. Arsenic and selenium are expected to form soluble acid complexes in the scrubbing operation. Although the data are still incomplete, the preliminary analysis suggests, at least in the case of selenium, that an insoluble phase forms and immobilizes the heavy element. Whether a similar precipitate also takes place with arsenic is still uncertain. Mercury appears principally as the relatively insoluble mercurous chloride that is stable in the liquor at low oxidation potential, but becomes unstable at high oxidation potential relative to the more soluble mercuric chloride. Zinc is relatively insoluble as hydroxides, but the concentration of hydroxide ions is low for the limestone scrubbing system. Lead is insoluble as the hydroxide and as the sulfate.

4.2 POTENTIAL DETOXIFICATION METHODS

Since the toxicity hazard from a sludge will originate primarily from the sludge liquors or leachate, detoxification methods must consider conversion of toxic components from the liquid phase to a solid, or by concentration in a smaller liquid volume that can be disposed of by water treatment or chemical fixation (Section 6.6). A variety of detoxification methods is theoretically available for consideration, but few of them are economically feasible. Because of the large volume of water used in a scrubber, any water treatment process (e.g., a lime water softening treatment combined with other methods such as reverse osmosis, flash distillation, or electrodialyses is possible) must be applied to a side stream. However, the cost of these treatment processes would be prohibitive in most cases. Except for those situations where the treatment of a side stream may be necessary to control and/or reduce chloride content to prevent corrosion, alternative detoxification methods such as chemical fixation of sludges would be more economical. Other methods might include ion exchange, oxidation, pH change, thermal decomposition, etc.

4.3 ASSESSMENT OF POTENTIAL DETOXIFICATION

The potential capability for detoxification of a sludge is a function of the element or group of elements that pose a potential toxic hazard. The elements identified in the limestone system as having the capability most likely to create a toxic hazard are arsenic and mercury and possibly lead and selenium. Since the potential toxic hazard from a sludge will originate primarily from the sludge liquors, leachate, or runoff, detoxification methods must consider conversion of the potentially toxic components from the liquid phase to a solid, or by concentration in a smaller liquid volume that can then be disposed of by other means.

The most technically advanced sludge detoxification method is the chemical fixation process that converts sludge from a highly water-retentive material to one that has properties suitable for landfill or structural fill. In this conversion process, soluble components are reported to be chemically combined, and thereby restricted in their availability to the environment.

The concentrations of the most soluble of the potentially toxic elements in the limestone scrubber liquors may be reduced by a chemical treatment or system modifications that increase pH and/or retard oxidation within the scrubber system.

Among the more feasible detoxification schemes is a water treatment of a liquor side stream in which chemical precipitation (lime softening) may precede a secondary water treatment method. Among the possible secondary treatments are: reverse osmosis, flash distillation, electrodialysis, and ion exchange. For any of these secondary treatment techniques to be effective, a reduction in total dissolved solids must precede their use. These processes are relatively costly; they might be considered cost effective in only rare circumstances. However, since some of these water treatment techniques will also reduce the chloride concentration in scrubber liquors, savings will be realized by their use in corrosion avoidance of major hardware.

A brine of very high dissolved solids content is a by-product in some of these water treatment processes. This brine can be disposed of by chemical fixation processes or by evaporation.

The relative costs of these various processes have not yet been determined.

4.4 STATUS AND PLANS

The most probable potentially toxic elements have been identified, and several alternative detoxification methods have been

given cursory consideration. The element's detailed chemistry will be defined further, and the alternative detoxification methods will be considered further. In addition, detoxification techniques for other elements that appear to pose a toxic hazard will be assessed when the extent of their hazard has been identified.

SECTION 5

PHYSICAL PROPERTIES DETERMINATION

5.1 IDENTIFICATION AND DESCRIPTION OF SAMPLES

A number of physical properties were determined from the Shawnee and Mohave sludges to provide a more complete characterization of their behavior as they may limit or restrict sludge disposal, handling, and transportation techniques. The material used from the Shawnee sludge was the solids content of the underflow from the clarifier. This is the material that might be normally disposed of in a pond or lagoon if a secondary dewatering process were not used. The centrifuge cake was used from the Mohave sludge as it would have been disposed of. In each case, tests were conducted to reveal specific behavioral characteristics that might limit disposal or handling during disposal. Since, in each case, the information desired was not necessarily the physical property but rather physical behavior as applied to disposal, tests were designed to reveal this behavior in the most direct and expedient manner. Standard procedures were changed without compromising test results whenever and wherever these changes appeared to be desirable.

5.2 PHYSICAL PROPERTY MEASUREMENTS

5.2.1 Bulk Density

Knowledge of the variation in bulk density of sludge as a function of its solids content is important in estimating the volume required to dispose of a certain quantity of sludge. Transportation handling problems may be eased by moving sludge as a slurry, although it may require a subsequent dewatering step. Bulk density/solids content data are essential to evaluate the alternative methods of sludge transport and disposal.

5.2.1.1 Physical Model

Equations based on the rule of mixtures may be employed to predict the relation of bulk density to solids content when the true solid density and the dry packed bulk density are known. When water is added to dry packed sludge, voids and interstices are progressively filled and the density of the mixture increases until the sludge is saturated. At this point, all excess volume between sludge particles is filled with water, and the mixture is at its peak density. Further addition of water dilutes the mixture and reduces its density.

The bulk density ρ of a sludge may be calculated as a function of weight fraction solids content S_c, in terms of the bulk density of dry packed sludge ρ_B, the true density of sludge particles ρ_s and the density of water ρ_w. For a sludge with solids content less than the saturation (peak density) value

$$\rho = \frac{\rho_s \rho_w}{\rho_w S_c + \rho_s (1 - S_c)} \qquad (5\text{-}1)$$

For a sludge containing less water than the saturation value

$$\rho = \frac{\rho_B}{S_c} \tag{5-2}$$

Both density expressions coincide at the saturation value defined by

$$(S_c)_{Sat} = \frac{1}{1 + \rho_w\left(\frac{1}{\rho_B} - \frac{1}{\rho_s}\right)} \tag{5-3}$$

Values of ρ_B and ρ_s are the only measurements required to produce the smooth curve of bulk density versus solids content.

5.2.1.2 Experimental Procedure

The bulk density of dry sludge and the true density of sludge solids were determined experimentally to obtain the values necessary to evaluate Eqs. (5-1), (5-2), and (5-3).

Bulk density was obtained by casting sludge into a 2.54 cm^3 (1 $in.^3$) block mold, allowing it to air dry, and measuring the geometrical volume and weight of the casting. This value corresponds to settled and dried packing obtained without mechanical compaction.

True density of sludge solids was determined using an air pycnometer for measuring the total volume of individual grains of sludge in an oven-dried weighed sample. The air pycnometer operates on the principle of Boyle's law to measure the volume of air displaced by the sample from a container of known dimensions.

Data points were also obtained to verify the predicted relationship. Sludges of established water content were placed in preweighed graduated cylinders for subsequent weight and volume determinations. Dried sludge cakes were progressively re-wet, and the weight and geometrical volumes were determined. Additional data

points were determined from some of the dewatering study measurements that could provide simultaneous bulk density/solids content values.

5.2.1.3 Bulk Density Test Results

The true density of solids of the Shawnee sludge sample is 2.48 gm/cm^3. Packed dry Shawnee sludge solids have a bulk density of 1.20 gm/cm^3. The variation of bulk density versus solids content as calculated is shown in Figure 5-1. The sludge-water mixture attains a peak density of 1.7 gm/cm^3 at 70 percent solids. At this point, all the solid particles remain packed together, with water completely filling all the voids and interstices between particles.

Agreement is excellent with subsequently determined bulk density/solids content values. Levels of solids content obtained by different dewatering steps are also shown on the figure. Practical dewatering methods do not remove sufficient water to obtain maximum bulk densities in this sludge.

The variation of bulk density with solids content for Mohave sludge with a solids true density of 2.53 gm/cm^3 and a bulk density of 1.46 gm/cm^3 is shown in Figure 5-2. The saturation (peak) density (1.87 gm/cm^3) corresponds to slurry containing 78 percent solids. Levels of dryness obtained by various dewatering methods on Mohave sludges are also shown in this figure. In this sludge, maximum bulk densities can be obtained by dewatering.

5.2.2 Corrosion

The useful life of sludge handling machinery and piping may be limited by corrosion. Bench scale tests were performed to determine if any particularly corrosive behavior might be observed in handling the Shawnee sludge.

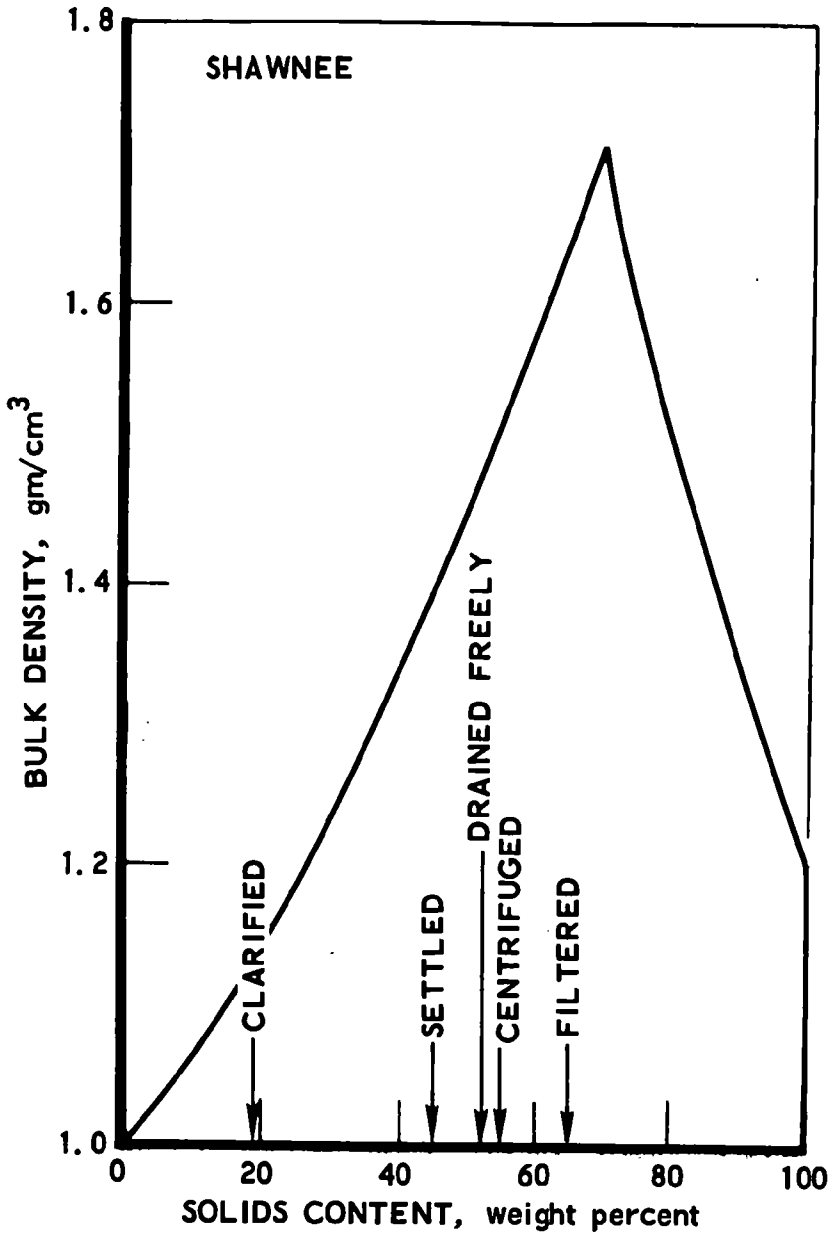

Figure 5-1. Shawnee sludge bulk densities

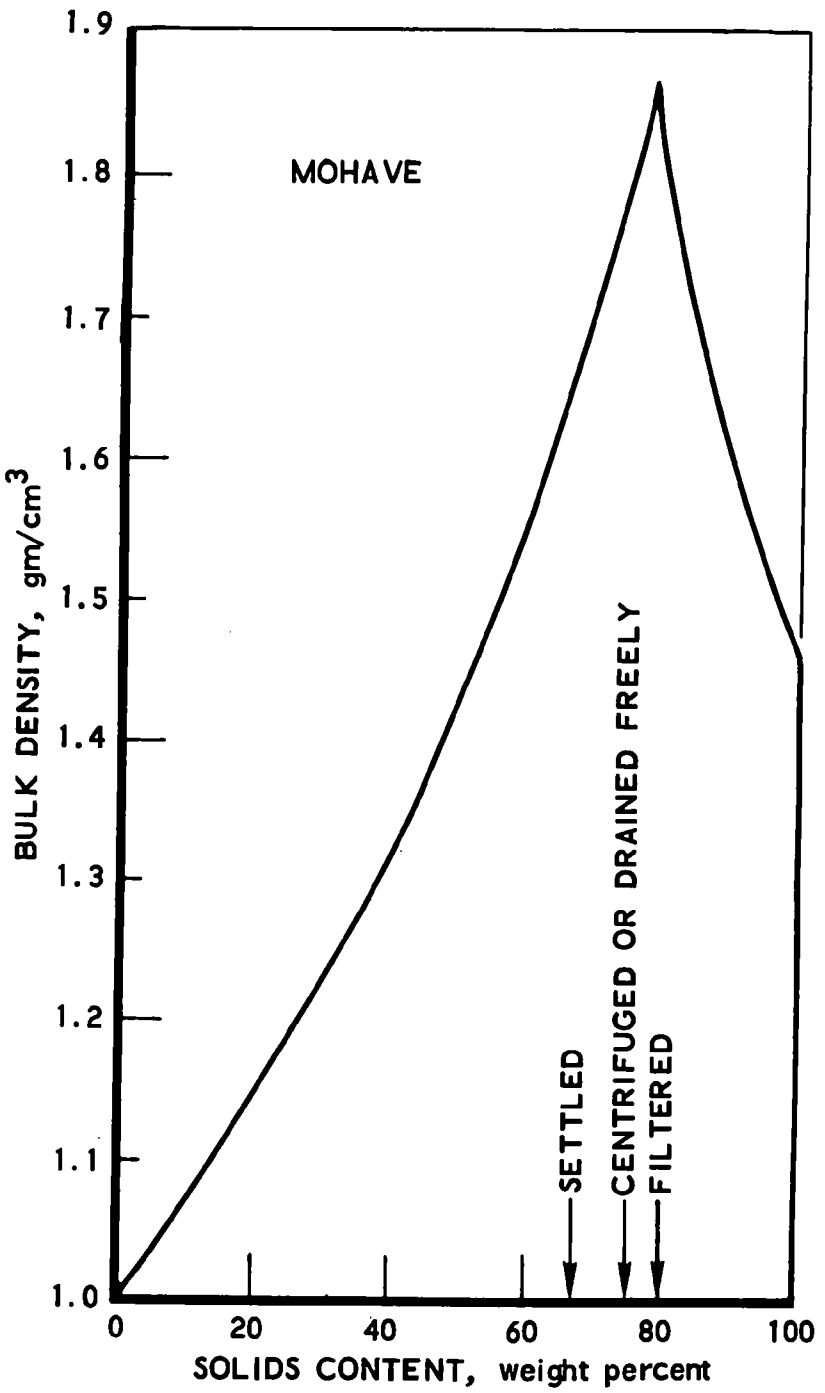

Figure 5-2. Mohave sludge bulk densities

5.2.2.1 Experimental Procedures

Test strips of 1100 aluminum and 1010 mild steel were numbered, cleaned, and preweighed. The strips were mildly etched in 0.1 N solutions of HCl for mild steel and 0.1 N NaOH for aluminum to remove residual oxide layers. The sliding sludge would effect a similar oxide removal (polishing action) in sludge handling systems.

A group of test strips was immersed in sludge for a 4-month period. At 1-month intervals, some test strips were removed from the sludge, rinsed, dried, and weighed.

5.2.2.2 Corrosion Test Results

Aluminum samples showed only about 0.2 percent weight loss over this period. Aluminum exhibited corrosion resistance due to formation of an adhering protective oxide that was not breached by action of any chemicals in Shawnee sludge. Localized minor pitting, which was confined to small areas, undoubtedly proceeds at an impurity inclusion.

Mild steel samples were more generally attacked. Corrosion products would act to cement sludge particles to the test strips and, by this effect, weight gains to 26 percent were observed after 4 months. Earlier in the study, insufficient corrosion had taken place to provide enough corrosion products to bind sludge particles, and a minor weight loss was observed.

Attack of mild steel does not appear to be caused by the chemical nature of the sludge. Exposure of test strips to sludge liquor alone was equivalent to the exposure by total immersion in wet sludge solids. Accelerated attack was observed, however, if a test strip spanned a region of solids to liquor. This effect is due to an oxygen concentration gradient between the area of sample exposed to the liquor and the area immersed in the sludge solids. A similar

reaction accounts for the rusting of nails in wood. Anodic reaction proceeds in the oxygen-deficient sludge region dissolving iron, and the iron salts eventually serve to bind sludge particles. Cathodic reaction proceeds at the steel surface in the water region, and iron rust as $Fe(OH)_3$ precipitates there. This rust is nonadhering and rinses from the steel strip prior to weighing.

Common iron rusts to destruction because its oxide is nonadhering. No chemical acceleration of rusting was observed in this study with Shawnee sludge relative to a control blank immersed in water adjusted to the pH of the sludge liquor. However, a corrosion couple (formed by contact with both the highly anaerobic sludge solids and liquor containing some dissolved oxygen) will lead to accelerated corrosion of the portions in contact with the solids.

5.2.3 Viscosity

The viscosity of a fluid affects the steady-state power requirements for pumping it. In addition, the rheological behavior of a fluid must be appreciated if problems are to be avoided in handling non-Newtonian fluids. Since the solids content of a sludge is the parameter that may be most practically used to adjust its viscosity, the viscous behavior of sludges was measured as a function of solids content.

5.2.3.1 Experimental Procedure

The measurements were performed at room temperature using a viscometer having a cylindrical sleeve immersed in the fluid and rotated at 64 rpm, representing a shear rate of 7.9 cm/sec (15.6 ft/min) at the surface of the 2.4-cm-diameter (15/16 in.) rotating sleeve.

Prior to measurement, the solids content of the sludge was adjusted to the desired value, and the mixture was homogenized by hand stirring. The measuring cylinder was immersed in the sludge

and left undisturbed for 1 minute at which time the viscometer was turned on and the initial (peak) viscosity was noted. As the viscometer cylinder continued to turn, the measured viscosity (rotational resistance) decreased. When the viscometer was turned off for a short period (about 1/2 minute) and restarted, the viscometer reading immediately returned to that value recorded just prior to being turned off and not to the original higher value. If the viscometer was turned off for longer times (typically in excess of 1 minute), the initial peak viscosity was again recorded.

5.2.3.2 Viscosity Test Results

The peak viscosity of the Shawnee sludge with water content adjusted from 40 to 50 percent varied from 120 to 20 poise as shown in Figure 5-3. For the stiffer (higher viscosity) suspensions, the measured viscosity decreased within 1 minute to an equilibrium value 40 percent less than the peak value. The measured viscosity of the more fluid mixtures decreased only 20 percent in 1 minute. When the viscometer was turned off, the torque on the rotor did not return to zero. This behavior is representative of a Bingham solid in which a critical shear stress must be exceeded to initiate flow.

Measurements were not extended to sludges with water content outside the 40 - 50 percent range. Slurries with a water content greater than 50 percent would not remain homogenized long enough to attain a measurement of viscosity because of a rapid settling of particles. Values dropped to those approaching water as a function of settling time and not as a function of the shear stresses created by the viscometer cup. Stiffer suspensions of water content lower than 40 percent would require the use of a different viscometer rotor which, instead of a cylinder, uses a disc rotated about its normal axis. The disc rotor broke free of the suspension too readily, and

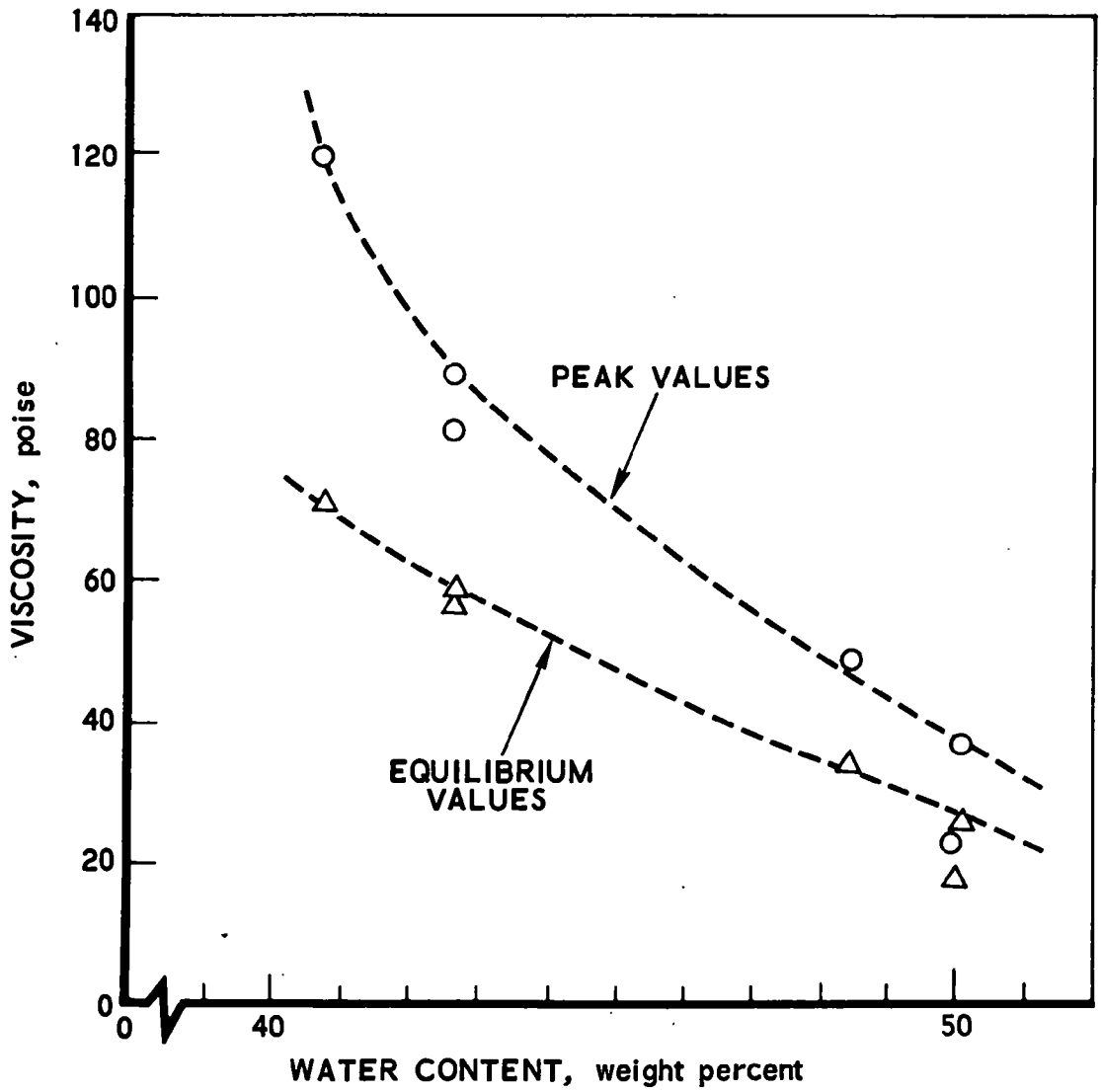

Figure 5-3. Viscosity of Shawnee sludges

erroneously low measurements were obtained. Attempts to correlate viscosity measurements obtained by using the two rotors where their ranges overlapped were unsuccessful because of this effect.

Fluids that exhibit a viscosity which decreases with time after shear is initiated are called thixotropic. Fluids may exhibit thixotropic behavior when intermolecular bonds are broken by shearing forces, creating smaller, less intertwined molecular structures and allowing flow more easily past one another. Sludges, however, are two-phase mixtures of small clumps of particles (or discrete particles) and water. The thixotropic behavior appears when the two components of a homogeneous mixture are separated by shear stresses, and the more fluid component (water) concentrates along the shear boundary layer defined by the viscometer cup and sludge interface.

Procedures used to measure the viscosity of Mohave sludge slurries differ from those used on Shawnee sludge slurries in one notable exception. The Mohave sludges are clay-like in that they flocculate readily and are difficult to mix into a suspension because they coalesce and settle rapidly. Mixing the sludges into a slurry suspension requires scraping a small amount of sediment from the bottom of the mixing containers and thoroughly stirring it into the fluid phase. Then an additional scraping of sediment is dispersed, and so on, until the entire mixture is in suspension. The viscometer rotor is then introduced into the sludge and quickly (before the particles settle) the viscometer is turned on to obtain the peak reading. Operationally, the chief difference is the time allowed for the viscometer rotor to assimilate to the sludge--1 minute for the Shawnee sludge, 5 seconds for the Mohave sludge.

Viscosity values for Mohave sludges at several water contents are shown in Figure 5-4. The difficulty in stirring stiff mixtures and their fast settling tendencies limited measurements to

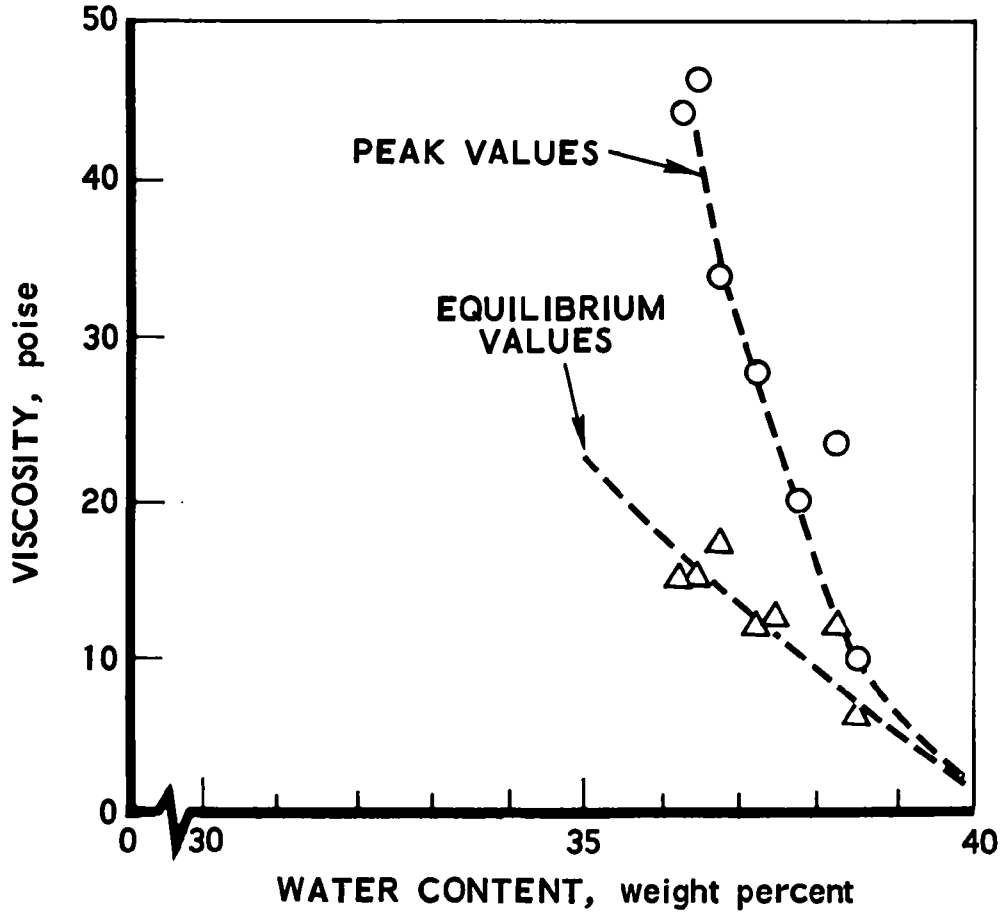

Figure 5-4. Viscosity of Mohave sludges

viscosities less than 50 poise, whereas Shawnee sludge viscosities were measured to values as high as 120 poise. Equilibrium values, after stirring by the viscometer for 1 minute, are also shown on Figure 5-4.

Curiously, the viscosity measured after 1 minute stirring is subject to fluctuations. Occasionally, during long stirring periods, the measured viscosity temporarily increased by as much as 50 percent from the "equilibrium" value. This sporadic rheopectic

behavior could overload a pumping system designed for the lower equilibrium value. Fortunately, this effect is only found in the stiffer mixtures having less than 35 percent water content.

In contrast to the Shawnee sludges which showed a gradual increase in viscosity as the water content of the sludges varied from 50 to 40 weight percent, the Mohave sludges rapidly become more viscous at water contents below 40 weight percent. This would be expected due to the clay-like properties of the Mohave sludges--enough water allows the material to slip readily, and slightly less water allows the clay-like particles to bond together.

The high initial viscosity value represents more nearly the "viscosity" of the sludge suspension. Continued turning of the viscometer rotor draws lubricating water to the viscometer sludge interface, reducing the apparent viscosity similar to the behavior observed with Shawnee sludges.

5.2.4 Compaction Strength

Criteria for safe access to a pond by personnel or equipment can be based on the compaction strength of the sludge. Monitoring the mechanical stability of the sludge is facilitated if the compaction strength can be determined by correlation with convenient elementary measurements.

The parameter most significantly affecting the compaction strength of a given sludge is its water content; therefore, measurements were made to correlate the variation of compaction strength with water content of the sludges examined in this work. In addition to establishing a basis for convenient compaction strength monitoring, the determination of most physical properties parametric in water content provides a common basis for comparison and cross-correlation.

5.2.4.1 Experimental Procedure

Compaction strength was measured by determining the penetration resistance of a 0.95-cm-diameter (3/8 in.) rod pushed into the sludge at a rate of 1.27 cm/min (1/2 in./min). An Instron testing machine was used to determine load for these measurements. The sludge was retained in a 3.8-cm-diameter (1-1/2 in.) cylinder of sufficient depth that edge and bottom effects were negligible. For the penetration depths employed, buoyancy effects were insignificant.

Sludge was poured into the cylindrical container and allowed to settle, excess water was siphoned or wicked off the top of the settled sludge, and the sludge was allowed to dry to the desired water content. Measurement of this value was determined by weight loss after each test.

After the water content had been adjusted for each test run, the test rod was brought into contact with the sludge, and penetration was begun. After the rod had penetrated 0.6 cm, a constant compressive resistance was attained which persisted as the rod sank deeper into the sludge. Penetration depths to 2.5 cm were employed in these experiments. This procedure was repeated to obtain a set of compaction strength values at several water contents for both the Shawnee and Mohave sludges; these data are presented in Figure 5-5.

5.2.4.2 Compaction Strength Test Results

Sludge of low water content, capable of supporting loads in excess of 30 psi, showed compaction behavior more like a restrained solid--increasing penetration required increasing force. Under these conditions, geometry and dimensions of the confining container become significant. However, it was shown that load carrying capacities of this magnitude occur when the strength is increasing rapidly with decreasing water content, and detailed correlation of strength and water content is difficult and of little value.

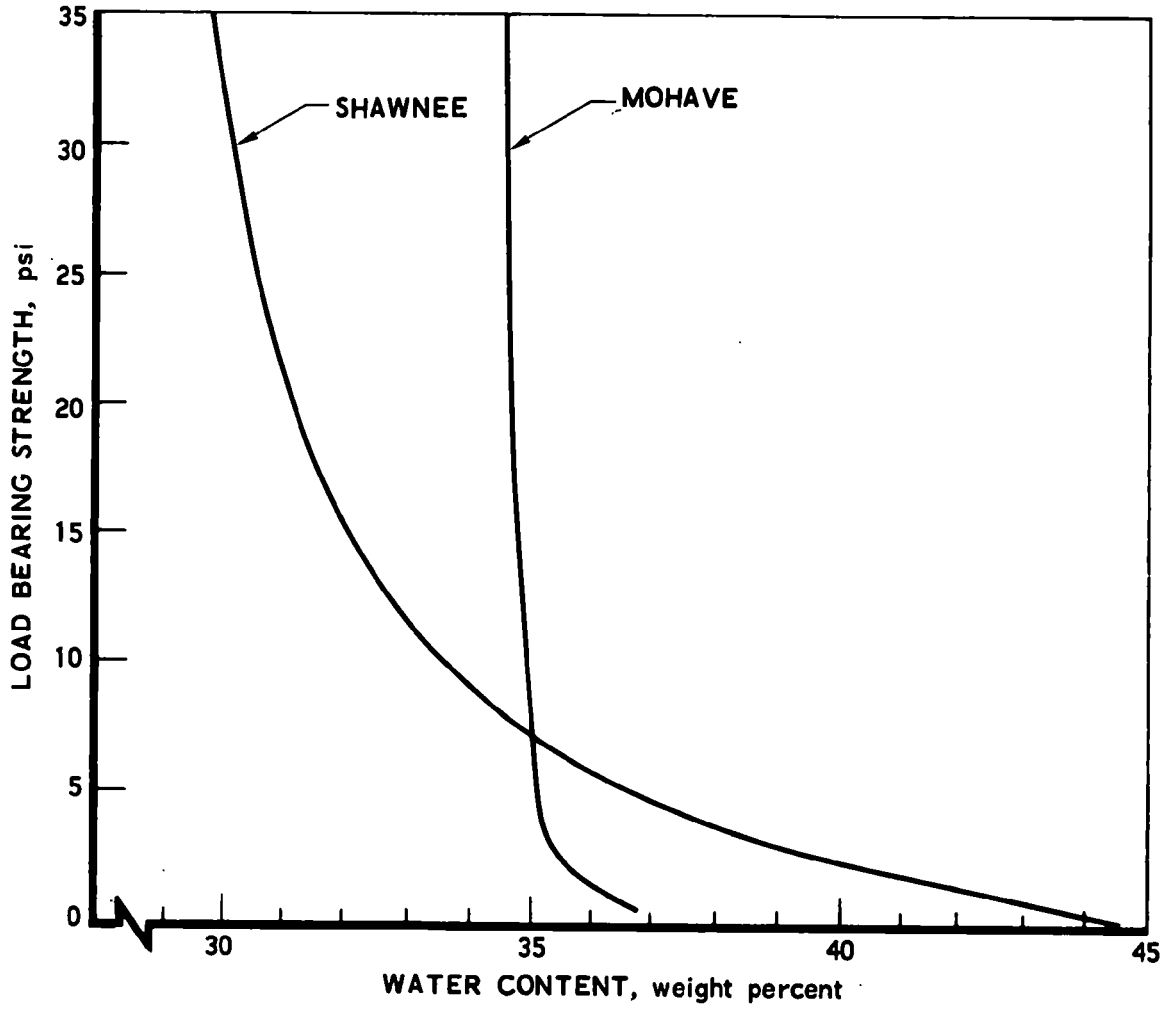

Figure 5-5. Sludge compaction strength

Compaction strength was measured for Shawnee sludges of water content from 45 to 30 percent. At 45 percent water content, the sludge can sustain virtually no load, while at 30 percent water content, a load bearing capacity of 2.1 - 2.4 $\times 10^6$ dyne/cm^2 (30 - 35 psi) exists. The variation of compaction strength with water content for Shawnee sludge is shown in Figure 5-5. It is estimated

that a person exerts approximately 2×10^5 dyne/cm^2 (3 psi) while standing. Support of this level by Shawnee sludge would be attained at 39 percent water content.

At 30 percent water content, where the strength is increasing rapidly, the sludge is just at its saturation point. (This is the peak density point on the bulk density versus solids content curve, Figure 5-1.) Removal of additional water reduces the lubrication between sludge particles and accounts for the dramatic increase in strength.

It is interesting to note that compaction strength and viscosity measurements overlapped the water content range from 40 to 45 percent.

Safe access for personnel can probably be granted if the water content is less than 35 percent, at which point a load bearing capability of 5.5×10^5 dyne/cm^2 (8 psi) is expected. It should be noted that this corresponds to the dryness obtained by vacuum filtering--the most effective water removal process. Access to vehicles could probably be granted when the water content was less than 30 percent. However, it should be noted that around 30 percent the strength varies rapidly with water content.

Compaction strength measurements for the Mohave sludge do not vary smoothly with water content. Instead, 35 percent water content marks a sharp change in compaction strength (Figure 5-5); at that value, compaction strengths range from 2 to 20×10^5 dyne/cm^2 (3 to 30 psi). Pressure from the penetrating plunger squeezes water from the plastic clay-like sludge and packs sludge particles firmly together.

Water content less than 35 percent can be attained with Mohave sludges using any of the dewatering processes--settling, centrifuging, or vacuum filtering. Consequently, if no free standing

water is present, a pond of Mohave sludge is probably safe for personnel and most equipment.

5.2.5 Pozzolanic Strength

The structural integrity and draining characteristics of sludge used for land fill depend on the degree to which the sludge particles fit and bind together. Pozzolanic reaction, if it were to cement sludge particles together, would enhance the compressive strength of packed dried sludge as a function of time. Pozzolanic reaction is that reaction which takes place in the cure of concrete when a pozzolan such as fly ash is added to the mix.

5.2.5.1 Experimental Procedure

To measure pozzolanic effects in sludge samples, cylindrical test specimens were cast for evaluation by compressive loading. Specimens 1.3 cm (1/2 in.) in diameter by 5 - 8 cm (2 - 3 in.) long were tested after curing for various periods after casting. Initial "uncured" strength is measured after 5 days when the excess moisture has been drained and the samples can be unmolded. Additional curing took place in a humid environment with samples being removed for testing at 1-month intervals. The specimens were tested on an Instron test machine using a cross-head speed of 8.4×10^{-4} cm/sec (0.02 in./min).

5.2.5.2 Pozzolanic Strength Test Results

Shawnee sludge samples crushed under less than a 2.3 kg (5 lb) load, representing a negligible strength of 1.8×10^6 dyne/cm^2 (26 psi) at each consecutive test over four monthly intervals.

Mohave sludge samples showed reasonable strength of 12×10^6 dyne/cm^2 (170 psi) for uncured, damp specimens. Test specimens cured for longer periods and allowed to dry before testing crumbled under a stress of only 7×10^6 dyne/cm^2 (100 psi). This

behavior has been interpreted as a function of water content and is completely analogous to the strength characteristics expected of clay-bonded fine aggregate.

Neither the Shawnee nor Mohave sludge examined in this work shows any characteristics of pozzolanic reaction that would lead to increased bonding between sludge particles and increased compressive strength. It should be noted that the Mohave pilot scrubber was downstream of electrostatic precipitators, while the Shawnee scrubber was not. Consequently, the solids portion of the Shawnee sludge contained fly ash (approximately 40 percent by weight). A pozzolanic strength effect might be expected because of the fly ash content; however, as noted previously, it did not appear after 4 months.

5.2.6 Drainability

Drainage characteristics of sludge are particularly significant for proper pond design or in its use as a landfill by environmentally sound disposal techniques. Laboratory-scale experiments were designed to provide information on the rate of water permeation through sludge beds as a function of the bed thickness and the head of water over the bed. These data are suitable for extrapolation to predict field conditions.

5.2.6.1 Experimental Procedure

The experiment was configured about a 3.8-cm-diameter (1.5 in.) column of sludge established over four sheets of Whatman 40 filter paper supported on a glass frit filter. This arrangement provided support for the sludge, yet permitted water to drain freely from the bottom of the column. The rate of permeation of water through the filter paper/glass frit filter combination alone exceeded by at least 100-fold the rate of permeation through sludge columns. Sludge columns of Shawnee sludge with nominal heights of

5, 12.5, and 25 cm (2, 5, and 10 in.) were employed in this study. Hydraulic heads to 2.5 m (6 ft) were established over the sludge columns. Water drained from the column was collected in a graduated cylinder from which the amount drained was recorded as a function of time. A head loss of 2 cm (3/4 in.) was typical for each run.

Some settling and tighter packing occurs as the water drains through a freshly established column. A nonlinear draining curve is obtained until the sludge settles to a more fully dense position.

5.2.6.2 Drainability Test Results

Drainage rates at steady state are plotted in Figure 5-6 as a function of the height of water head over the sludge. As expected, a short column of sludge poses less resistance than a tall column and drains at a faster rate. When water is poured on top of damp, freely drained sludge, water immediately begins to drip from the bottom of the column. This suggests that the sludge acts as a wick. When excess water is supplied at the top, the water is immediately transmitted through the column. When no head exists over the sludge, no water will drain; only excess water drains.

An additional head of water inducing drainage appears to be in the sludge itself. This hidden pressure is shown by the negative intercept on the pressure axis in Figure 5-6. If the height of the sludge column were added to the pressure head, all lines would intersect at the origin--zero drain rate at zero head. The supernatant head, when corrected to an effective head by adding the height of the sludge column, will give a sludge permeability (cm/sec) in terms of

$$\left[\frac{\text{Head Recession Rate}\left(\frac{\text{cm}}{\text{sec}}\right)}{\text{Effective Head (m)}}\right] \times \text{Bed Height (m)} \qquad (5\text{-}4)$$

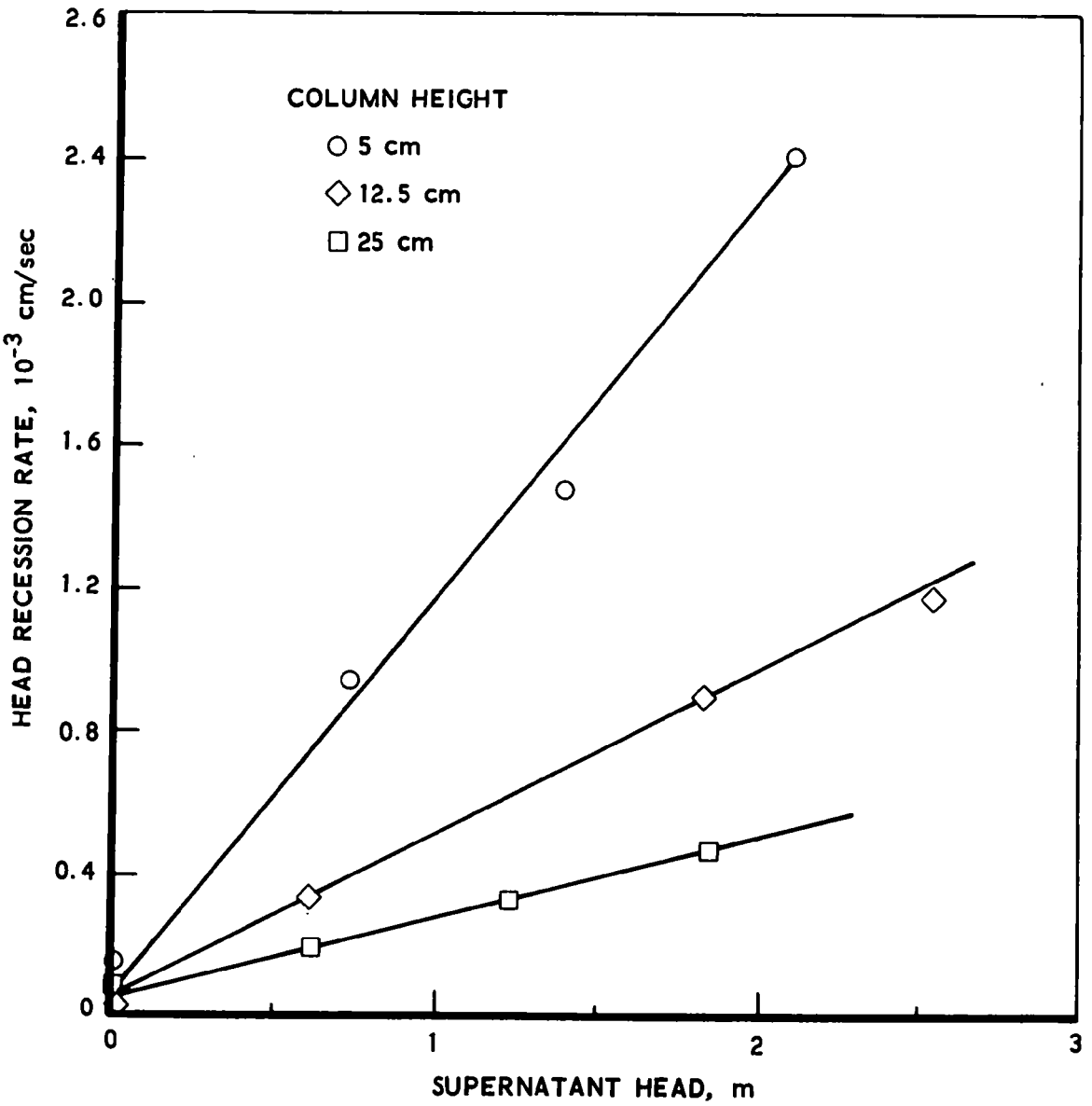

Figure 5-6. Drainability of Shawnee sludge

For the 5, 12.5, and 25 cm experimental columns, the sludge permeability determined as above is 2.23, 2.27, and 2.31×10^{-4} cm/sec for each column, respectively. The permeation rate (head recession rate) for a given pond of sludge would be given by multiplying this specific sludge permeability by the effective head height (m) and dividing by the sludge bed thickness (m). The effective head is, of course, the bed thickness plus the height of standing water.

When only a thin film of water covers the sludge, the factors of bed thickness and effective head height are identical and mutually cancel. This represents the wicking condition alone that predicts that the rate of water transport by wicking is independent of the bed thickness.

5.2.7 Water Retention

Minimizing land required as a disposal site and conditioning the sludge for disposal will ultimately require dewatering of sludge at some stage in handling; therefore, information on the capability to dewater sludge by common techniques is necessary in the assessment of sludge disposal problems.

5.2.7.1 Experimental Procedure

Dewatering of Shawnee and Mohave sludge was performed by techniques of settling, centrifuging, and filtering. An additional water content is also considered that was obtained by the Shawnee "clarifier" stage and as a result of free draining.

Sludge-water slurry was settled in a graduated cylinder and the supernatant decanted, leaving sludge dewatered by settling. Sludge was also dewatered using a laboratory centrifuge to settle the sludge, after which the water was decanted. Water separated from sludge using vacuum assisted filtering and Whatman 40 filter paper produced a filter cake. A water aspirator was used as the vacuum

source, and care was taken not to draw air through the dewatered cake which would cause extra drying. Sludge freely drained in the drainability experiments furnished additional dewatering data.

Water content in each case was determined by weight of sludge before and after oven drying.

5.2.7.2 Dewatering Test Results

Consistency of Shawnee and Mohave sludges dewatered by various means is shown on the respective bulk density/solids content curves (Figures 5-1 and 5-2). For both sludges, the most effective water removal process considered is vacuum filtering followed in rank by centrifuging, free draining, and settling. A 5 - 10 percent difference in attainable sludge dryness separates the different processes applied to a given sludge.

Dewatering of Shawnee sludge (Figure 5-1) only removes water in excess of the amount required to saturate the sludge. By contrast, filtering of Mohave sludge removes water from between the sludge particles, resulting in a filter cake containing less than the saturation amount of water. Approximately 20 weight percent more water is removed from Mohave sludge than from Shawnee sludge, using the same dewatering techniques.

5.3 ANALYSIS AND EVALUATION

The physical properties of sludges may limit or restrict the possible methods of handling and disposal. The two sludges thus far investigated were produced by eastern and western coals. However, the observed sludge behavior was not a consequence of the geological origin of the coal, but rather was a consequence of the phase constituents in the sludge. In the Mohave system, an electrostatic precipitator exists upstream of the scrubbing unit; thus, the sludge contained less than 3 percent fly ash. The Shawnee system does not

have a precipitator upstream of the scrubbers, and the resulting sludge contains about 40 percent fly ash. In addition, the Mohave sludge is more than 75 percent oxidized to the sulfate, whereas the Shawnee sludge is oxidized to only 20 - 25 percent sulfate. Most of the behavioral differences between the two sludges can be attributed to the degree of fly ash and sulfite content. The Mohave sludge has characteristics much like sandy clay; this can be related to a high percentage of bulky sulfate particles surrounded by platey sulfite particles. The Shawnee sludge behaves more like a silty clay and can be understood in terms of the presence of bulky sulfate particles, fly ash, and residual limestone that constitutes more than 60 percent of the total quantity of sludge.

Many of the physical properties determined on these sludges were found to be strongly dependent on water content. The behavior of sludge either while being handled for disposal or after being placed in a disposal site will be strongly affected by its water content. Moreover, for the two sludges investigated, equivalent water content did not produce equivalent behavior. If a sludge is to be disposed of by ponding, the bulk density of the Shawnee sludge would reach only 45 percent solids if placed in an impervious liner such as clay or plastic, but if allowed to drain freely, it would reach about 52 percent solids. The Mohave sludge settles to 67 percent solids irrespective of its ability to freely drain. Centrifugation with a laboratory centrifuge produces a material containing 55 percent solids from the Shawnee sludge and 75 percent solids from the Mohave sludge. (Centrifugation in a porous cup would be expected to give a solids content 10 percent greater than that resulting from an impervious cup. Centrifugation with an industrial centrifuge is expected to give a product somewhere between these two values and will depend somewhat on centrifugation rate.) By vacuum assisted filtration, the Shawnee sludge dewatered to a value of 65 percent solids whereas the

Mohave sludge reached a value of 80 percent. In this case, filtration with an industrial filter is not expected to be as effective as laboratory filtration.

In each case, the Mohave sludge attained a higher solids content than the Shawnee sludge regardless of the dewatering method. These results were expected when the relative amounts of sulfite in the two sludges were considered.

In a pond disposal method, the Mohave sludge will settle or if dewatered, will attain a solids content great enough to support personnel. A very small amount of subsequent drying would be adequate to support equipment. In contrast, the Shawnee sludge will not settle or be dewatered sufficiently for support of personnel until a solids content of 65 percent is reached. Support of equipment would require greater than 70 percent solids; this could be accomplished if the sludge were dried after dewatering. This drying could take place in the pond during dry seasons. Rewetting during rain could return the pond to the condition in which personnel and equipment could not be supported. These values represent the minimum support loads and do not represent recommended working consistencies.

The drainability of the Shawnee sludge is similar to many natural soils. If the disposal site were such that liquors and rain water were allowed to pass through it, the sludge would provide no hindrance. Although drainability experiments on the Mohave sludge are not yet completed, its drainage rate is greater than that of the Shawnee sludge and more typical of soil with a high sand content. Rain waters would easily percolate through such a sludge and would not collect on the surface.

Neither sludge was found to develop strength during settling by pozzolanic reaction or other means. Thus, except for the compaction strength that develops during drying or dewatering, no property change is observed to take place with time. Without

specific chemical additions, the sludge does not develop resistance to subsequent leaching.

Whereas the lack of strength build-up with time may not aid in its use as a landfill, it does provide a material that can be easily removed or transported regardless of time. For this purpose, pumping the sludge as a slurry is the most economical means of transportation. For the Shawnee sludge, the viscosity rises regularly with an increase in solids content. Pump requirements can be easily determined from the measured relationship. In contrast, for the Mohave sludge, the slurry behaves much like water up to 60 percent solids, but between 60 and 65 percent solids the viscosity rises very fast. In this case, optimum pumping could be done at 60 percent solids, but close control of the solids content must be maintained to prevent the solids content from getting too much higher to prevent pump overloading or the possibility of plugging a transfer pipe.

The tests on corrosion revealed that the corrosiveness of the sludge is related to the pH of the liquor and that no enhancement takes place except for one condition. If a metal container is in simultaneous contact with both sludge solids and liquor in a stagnant condition where an oxygen solution gradient can be maintained, an anodic reaction takes place that releases iron from that portion of the steel in contact with the solids. The iron subsequently reacts with the dissolved sulfate ions in the liquor and results in the deposition of sulfate compounds that form an encrustation on the metal part.

The physical property measurements on the Shawnee and Mohave sludges have revealed differences in their behavior that can be ascribed, at least in part, to the sulfate content and the presence or absence of fly ash in the sludge. The Mohave sludge has some properties, primarily dewatering behavior, that are more desirable for disposal. These properties should be useful in the development of engineering design criteria for sludge disposal technology.

5.4 STATUS AND PLANS

All physical property measurements have been made on both Shawnee and Mohave sludges, except for completion of drainability measurements on the Mohave sludge. The physical properties relating to sludge disposal technology will be determined for the sludges from a lime scrubbing system and the double alkali system.

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SECTION 6

DETERMINATION OF ENVIRONMENTALLY SOUND DISPOSAL METHODS

6.1 STATEMENT OF PROBLEM

The surveys and analyses made to date in this program, including reviews of technical papers published in the industry, have indicated strongly that stack gas sulfur dioxide (SO_2) scrubbing is cause for major concern for the environmentally sound disposal of the resultant sludge. With the production of sludge and fly ash of up to 1.4 million tons/year/1000 MW capacity, massive quantities of materials will have to be dealt with when the scrubbers become fully operational (Ref. 6-1). If the sludge is treated so that it may be used in the production of commercial products or used otherwise in some form of commercial application, the disposal problem could be minimized. However, based on surveys of marketing and commercial planning activities in this country it appears that commercial utilization will consume only a small and inconsequential percentage of the total sludge that will be produced. Several research programs by both industry and the federal government have determined technical applications that would consume reasonable amounts of sludge if those

materials could be marketed. A brief summary of the potential commercial utilization status is given in Appendix D. The conclusion drawn in that assessment is that, "indications are that the potential sludge products will not compete well enough in the near term to consume an appreciable portion of the projected (sludge) supply and that the principal concern for the sludge will be disposal and not utilization." Even if commercial utilization could absorb a large percentage of the sludge supply, the disposal process would still be a major problem requiring technical solutions. The difference would be that somewhat smaller amounts would have to be dealt with in the disposal area.

This section discusses the various methods by which power plant sludges may be disposed of, the problems associated with each method, progress being made, potential solutions, and costs. These discussions center around the fact that lime and limestone sludges present problems of considerable magnitude because of the following factors:

a. The sludges contain many trace elements and dissolved solids that are not allowed in surface or ground waters from which drinking water supplies are withdrawn.

b. Quantities of total wastes are involved up to as much as three times the tonnage of fly ash normally produced at a given power station.

c. The ability for the soil to prevent the leaching of harmful constituents to ground or surface waters is not well understood such that the impoundment of sludges without using specific safeguards to prevent seepage is considered a high risk approach.

Presently, the disposal alternatives being considered are ponding and landfilling; both disposal operations will require the establishment of procedures that avoid hazards related to health and safety. The requirements for disposal of a particular sludge will be strongly dependent upon whether or not it is found to be toxic. If the sludges are found not to be toxic, the problem of disposal may be

simplified, but the problem of water quality and possibly land use must still be addressed. An untreated sludge will retain a considerable quantity of water. Laboratory tests on a limestone sludge containing a relatively high sulfate content will settle only to 45 percent solids content if underdrainage is not provided, but if drainage to subsoil is allowed, the settled sludge will reach a content greater than 50 percent solids. A maximum particle packing equivalent to a value of about 70 percent solids content is reached upon air drying.

When a dried sludge is rewetted, the sludge can bloat and decrease its bulk density depending upon the quantity of water absorbed by the sludge. When a sludge contains a high sulfite content, the sludge will settle to a value of about 35 percent solids whether underdrainage is provided or not. A sulfite sludge does not dry as readily or settle as much during drying as a sulfate sludge.

A sulfate sludge for which underdrainage is provided will produce savings relative to one with no such provision because the higher packing density allows for the disposal of about 20 percent more sludge in the same ponding volume. However, if the subsoil is the only means of underdrainage, the possibility for soil plugging exists especially in the case of sulfate sludges containing high concentrations of dissolved solids. Depending upon soil type, salts will precipitate within the soil, fill the pores, and prevent further water passage. Thus, the advantage of underdrainage would be lost. The more reliable system is one in which underdrainage is provided. Although in this case the sludge is assumed not to be toxic, it is very likely that the leachate would not be of a quality to be acceptable for discharge to a water course because of the high content of dissolved solids in the sludge liquors.

Ponding can be used not only for the final disposal of the sludge, but also as an interim measure to allow settling before

removing the material to a landfill site. The most fundamental problem in the environmentally sound disposal of the sludge arises when the hazard exists for leaching toxic elements or soluble salts to ground or surface waters, or drainage to surface waters. The immediate solution to this potential problem may require dewatering and/or fixation of the sludge and/or storing it in a clay-lined pond so that permeation to the subsoil is minimized. Overdrainage and underdrainage return liquor waters to the scrubber system thereby eliminating direct discharge to surface waters. Such a pond can serve as a final disposal site, but in some cases because of the large volumes of sludge and water to be handled, the pond can serve as a primary settling basin from which the sludge can be periodically removed and placed in a landfill. A fixation treatment applied to the sludge prior to placing it in the pond is an alternative technique generally applicable only if the sludge is to be removed to a landfill after curing. This treatment has two purposes: removing water and increasing strength qualities, and minimizing leaching by decreasing the permeability of the material.

If a sulfate sludge is found to be toxic, it may be adequate to store it untreated in a pond having an impervious base. The use of underdrainage and overdrainage would minimize inadvertent leaching and the possibility of overflow, especially in areas where rainfall exceeds evaporation. This, of course, requires the lining of a large area pond, monitoring, and maintenance, as necessary. A further problem would be faced when a point in time is reached where the generating plant can no longer accept all drainage originating from rainfall from all its disposal ponds and direct discharge to streams would not be allowed, or where the plant is to be abandoned. Under either of these conditions, encapsulation by covering with an impervious material may be the best solution.

Numerous alternatives for ponding with or without pond lining or sludge conditioning may be possible. Surveys of the industry have shown that many of these alternatives are presently being considered and employed. Alternatives, such as treatment processes mentioned earlier, produce a high solids content sludge material having acceptable structural qualities for a landfill usage; also, a process for producing aggregate has been developed.

Based on the considerations just mentioned, this program has investigated various disposal techniques including chemical fixation and pond linings, either of which may be adequate to contain the sludge indefinitely. These two methods, though not technically proven for long-time service, are considered to be the best technically and economically feasible approaches for solving the sludge disposal problem. Their characteristics, problems, potential solutions, and the characteristics of disposal without environmental protection are the bases for the following discussions.

6.2 POTENTIAL DISPOSAL METHODS

6.2.1 Raw Sludge Disposal Without Environmental Protection

The disposal of raw sludge into a pond, impoundment basin, ravine, or water course without some form of environmental protection is not considered sound at this time. However, attempts are being made at power plant sites in Kansas, Alabama, and Kentucky to dispose of raw sludge in ponds without providing a chemical fixation of the sludge or a pond lining. The Kansas sites, which include the disposal of raw sludge into ponds in a manner similar to that in which fly ash is commonly disposed of, are being monitored to determine changes in the quality of ground waters in the immediate area. At the Alabama site the sludge will be sluiced to the pond and allowed to settle in a clay deposit. This site will also be monitored

with regard to potential ground and surface water pollution. At the Kentucky site the sludge is dewatered by filtration, and dumped and compacted into the disposal site. It has been estimated by many members of the power and environmental regulatory community that these approaches will not be environmentally sound because of the potential leaching of heavy metals and dissolved solids to the ground or surface waters. These sites have not been investigated in detail during the first phase of this study; however, they will be surveyed and assessed later in this program. A discussion is given in Section 6.4 of raw sludge disposal without pollution controls and the environmental impact of fly ash on sludge disposal.

6.2.2 Lined Ponds

Raw sludge can be impounded in ponds that are lined by various materials to a high degree of impermeability such that leaching to water is minimal. Linings can be made from materials ranging from compacted clays to concrete, plastics, or even some types of chemically fixed sludge. In each case the liner prohibits leaching and generally surface waters are recycled to the scrubber system to minimize the volume of impoundment required while allowing reuse of the pond liquors as an absorbent in the scrubber. The principal problems associated with this form of disposal are: (a) the lack of technical data to establish the ability to restrict excessive leaching for very long times, and (b) the build up of a high water retentive mass that may require special, yet undefined consideration for the reclamation of this land after disposal is completed. Additionally, such a pond may require continual monitoring for leaks and in some cases, depending on the demands of the local regulatory authorities, special construction to channel and contain any leakage. The details associated with ponding design are given in Section 6.5.

6.2.3 Sludge Conditioning

The fixation of sludges through chemical conditioning processes offers the greatest environmentally sound approach to their disposal. The purpose of the conditioning processes is to create a material that is: easy to handle, highly impermeable and/or insoluble such that the problem of contamination from leaching is eliminated, and amenable to land reclamation. At this time considerable research and development have been carried out by private industry, and some of these developers are under contract to perform either partial or full-scale sludge disposal operations at power plants now operating or soon to be operating stack-gas scrubbers on a full-scale basis. Considerable monitoring of these disposal sites will be performed by the site operator and randomly by state or local regulatory authorities. Monitoring is considered mandatory at this time because the long-term effects of the conditioning process have not been proven. Discussion of these processes, problems, and potential solutions and costs are given in Section 6.6

6.3 INDUSTRIAL AND GOVERNMENT PROGRAMS

Since the purpose of this portion of the Aerospace study is to assess the status of the technology related to the environmentally sound disposal of sludges, it has been necessary to visit many industrial organizations and government agencies to gather the necessary data. Contacts have been made with electric power companies, sludge conditioning processors, federal and state environmental agencies, and universities. Although some of the developments are similar, it can be said that no two are alike at this time. Many of the power companies involved in disposal program developments have been contacted; however, no company is operating continually on a full-scale basis. Some are in the pilot stage phase, others are operating prototype units, and a few are operating or building full-scale units. A listing of the

scrubber units now being developed or operated in the United States, with an identification of flue gas desulfurization techniques, is given in Tables 6-1 through 6-6. Also descriptions of current developments in some of the power industries are given in Appendix E. These include: Commonwealth Edison, Will County Station, Joliet, Illinois; Northern States Power Company, Sherbourne County Station, Minneapolis, Minnesota; Louisville Gas and Electric, Paddy's Run Station, Louisville, Kentucky; and Duquesne Light Company, Phillips Station, Pittsburgh, Pennsylvania. The developments in these stations are all different and include the following approaches, respectively:

a. Chemical fixation performed by the power company and material dumped in an unlined landfill

b. Raw sludge to be dumped in clay-lined basins

c. Dried sludge dumped in an unlined basin

d. Sludge chemically conditioned by a commercial process and to be dumped in unlined ponds

None of these four has demonstrated its selected processes on a continuing operational basis. During the remainder of this program, contact will be made with these stations to determine their progress, and problems and solutions. Additionally, other stations now planning or developing similar operations for sludge disposal will be contacted (e.g., the Ohio Edison Company's Bruce Mansfield Plant, a 1650 MW station, which will probably have all of its sludge chemically fixed and pumped to a disposal ravine approximately 6 to 8 miles away). Contacts will also be made with Kansas City Power and Light, and Kansas Power and Light, both of which are investigating the disposal of raw sludge in unlined ponds. Other stations to be contacted include, but are not limited to, the following: Detroit Edison, St. Clair Station; TVA, Widow's Creek Station; Montana Power, Colstrip Station; and Arizona Public Service, Cholla Station.

Table 6-1. PLANNED AND OPERATING FLUE GAS DESULFURIZATION (FGD) UNITS ON U.S. POWER PLANTS AS OF SEPTEMBER 1973--LIMESTONE SCRUBBING SYSTEM

Source: EPA Control Systems Laboratory, Nonregenerable Processes Section

Utility company and power station	New or retrofit	Size of FGD unit (MW)	Process vendor	Fuel and sulfur content, %	Status (start-up date)
Commonwealth Edison Will County No. 1	R	156	Babcock and Wilcox	Coal, 3.5	Operational (February 1972)
Kansas City Power and Light Hawthorn No. 4	R	100	Combustion Engineering	Coal, 3.5	Operational (August 1972)
Kansas City Power and Light LaCygne Station	N	820	Babcock and Wilcox	Coal, 5.0	Operational (June 1973)
Arizona Public Service Cholla Station	R	115	Research Cottrell	Coal, 0.4 - 1.0	Under construction (October 1973)
Detroit Edison St. Clair No. 6	R	180	Peabody Engineering	Coal, 3.7	Under construction (December 1973)
Southern California Edison (operating agent) Mohave Station	R	160	Universal Oil Products	Coal, 0.5 - 0.8	Under construction (March 1974)
Tennessee Valley Authority Widow's Creek No. 8	R	550	Tennessee Valley Authority	Coal, 3.7	Under construction (May 1975)
Northern States Power Sherbourne County No. 1	N	680	Combustion Engineering	Coal, 1.0	Under construction (May 1976)
Public Service of Indiana Gibson Station	N	650	Combustion Engineering	Coal, 1.5	Planned (1976)
Northern States Power Sherbourne County No. 2	N	680	Combustion Engineering	Coal, 1.0	Planned (May 1977)

Table 6-2. PLANNED AND OPERATING FLUE GAS DESULFURIZATION (FGD) UNITS ON U.S. POWER PLANTS AS OF SEPTEMBER 1973--LIME SCRUBBING SYSTEM

Source: EPA Control Systems Laboratory, Nonregenerable Processes Section

Utility company and power station	New or retrofit	Size of FGD unit (MW)	Process vendor	Fuel and sulfur content, %	Status (start-up date)
Union Electric Co. Meramec No. 2	R	140	Combustion Engineering	Coal, 3.0	Abandoned (September 1968)
Kansas Power and Light Lawrence No. 4	R	125	Combustion Engineering	Coal, 3.5	Operational (December 1968)
Kansas Power and Light Lawrence No. 5	N	430	Combustion Engineering	Coal, 3.5	Operational (November 1971)
Kansas City Power and Light Hawthorn No. 3	R	100	Combustion Engineering	Coal, 3.5	Operational (November 1972)
Louisville Gas and Electric Paddy's Run No. 6	R	70	Combustion Engineering	Coal, 3.0	Operational (April 1973)
Duquesne Light Co. Phillips Station	R	100	Chemico	Coal, 2.0	Under construction (November 1973)
Southern California Edison (operating agent) Mohave Station	R	160	SCE/Stearns-Roger	Coal, 0.5 - 0.8	Under construction (December 1973)
Ohio Edison Mansfield Station (2 units)	N	1650	Chemico	Coal, 4.3	Under construction (Early 1975)
Montana Power Colstrip Nos. 1 and 2	N	720	Combustion Engineering	Coal, 0.8	Under construction (May 1975)
Columbus and Southern Conesville Nos. 5 and 6	N	750	Not selected	--	Planned (1976)

Table 6-3. PLANNED AND OPERATING FLUE GAS DESULFURIZATION (FGD) UNITS ON U.S. POWER PLANTS AS OF SEPTEMBER 1973--LIMESTONE OR LIME SCRUBBING NOT SELECTED

Source: EPA Control Systems Laboratory, Nonregenerable Process Section

Utility company and power station	New or retrofit	Size of FGD unit (MW)	Process vendor	Fuel and sulfur content, %	Status (start-up date)
Salt River Project Navajo No. 1	N	750	Not selected	Coal, 0.5 - 0.8	Construction start, November 1974 (March 1976)
Salt River Project Navajo No. 2	N	750	Not selected	Coal, 0.5 - 0.8	Construction start, October 1975 (October 1976)
Arizona Public Service Four Corners No. 1	R	175	Not selected	Coal, 0.75	Construction start, October 1975 (October 1976)
Arizona Public Service Four Corners No. 2	R	175	Not selected	Coal, 0.75	Construction start, November 1975 (December 1976)
Southern California Edison (operating agent) Mohave Nos. 1 and 2	R	1180	Not selected	Coal, 0.5 - 0.8	Planned (December 1976)
Arizona Public Service Four Corners No. 3	R	229	Not selected	Coal, 0.75	Construction start, June 1976 (March 1977)
Salt River Project Navajo No. 3	N	750	Not selected	Coal, 0.5 - 0.8	Construction start, March 1976 (March 1977)
Arizona Public Service Four Corners No. 4	R	800	Not selected	Coal, 0.75	Construction start, September 1975 (April 1977)
Arizona Public Service Four Corners No. 5	R	800	Not selected	Coal, 0.75	Construction start, November 1976 (June 1977)

Table 6-4. PLANNED AND OPERATING FLUE GAS DESULFURIZATION (FGD) UNITS ON U.S. POWER PLANTS AS OF SEPTEMBER 1973-- MAGNESIUM OXIDE SCRUBBING SYSTEM

Source: EPA Control Systems Laboratory, Nonregenerable Process Section

Utility company and power station	New or retrofit	Size of FGD unit (MW)	Process vendor	Fuel and sulfur content, %	Status (start-up date)
Boston Edison Mystic No. 6	R	150	Chemico	Oil, 2.5	Operational (April 1972)
Potomac Electric and Power Dickerson No. 3	R	100	Chemico	Coal, 2.0	Operational (September 1973)
Philadelphia Electric Eddystone No. 1	R	120	United Engineers	Coal, 2.5	Under construction (December 1973)

Table 6-5. PLANNED AND OPERATING FLUE GAS DESULFURIZATION (FGD) UNITS ON U.S. POWER PLANTS AS OF SEPTEMBER 1973--OTHER SULFUR DIOXIDE CONTROL SYSTEMS

Source: EPA Control Systems Laboratory, Nonregenerable Process Section

Control system, utility company, and power station	New or retrofit	Size of FGD unit (MW)	Process vendor	Fuel and sulfur content, %	Status (start-up date)
Catalytic Oxidation (Cat-Ox)					
Illinois Power Co. Wood River No. 4	R	110	Monsanto	Coal, 3.2	Operational (October 1972)
Wellman-Lord					
Northern Indiana Public Service D.H. Mitchell No. 11	R	115	Davy Powergas/ Allied Chemical	Coal, 3.5	Under construction (Early 1975)
Aqueous Sodium Base Scrubbing, Nonregenerable					
Nevada Power Reid Gardner Nos. 1 and 2	R	250	Combustion Engineering	Coal, 0.5 - 1.0	Under construction (December 1973)
Nevada Power Reid Gardner No. 3	R	125	Combustion Engineering	Coal, 0.5 - 1.0	Under construction (1975)
Dry Adsorption					
Indiana and Michigan Electric Tanner's Creek Station	R	150	Babcock and Wilcox/Esso	Coal	Under construction (1974)

Table 6-6. PLANNED AND OPERATING FLUE GAS DESULFURIZATION (FGD) UNITS ON U.S. POWER PLANTS AS OF SEPTEMBER 1973--PROCESS NOT SELECTED

Source: EPA Control Systems Laboratory, Nonregenerable Process Section

Utility company and power station	New or retrofit	Size of FGD unit (MW)	Process vendor	Fuel and sulfur content, %	Status (start-up date)
Public Service of New Mexico San Juan No. 2	R	100	Not selected	Coal, 0.8	Planned (November 1974)
Potomac Electric and Power Chalk Point No. 3	N	630	Not selected	Oil	Planned (1975)
Potomac Electric and Power Chalk Point No. 4	N	630	Not selected	Oil	Planned (1976)
Potomac Electric and Power Dickerson No. 4	N	800	Not selected	Coal, 2.0	Planned (1976)
Potomac Electric and Power Dickerson No. 5	N	800	Not selected	Coal, 2.0	Planned (1977)

The status of the development of sludge fixation technology has been reviewed with three companies: The Dravo Corporation, International Utilities Conversion Systems, Inc. (IUCS), and Chemfix. Each of these produces a "nonleachable material suitable for landfill usage." At this time Dravo is providing the chemical fixation admixture for a sludge disposal program at the Duquesne Light Company, Phillips Station, Pittsburgh, Pennsylvania, and to perform a demonstration program at the Mohave Station in Nevada. They are also negotiating to dispose of the Ohio Edison Bruce Mansfield Plant's sludge using the Dravo fixation process and pumping the sludge to the disposal ravine. They would maintain and monitor this disposal site and pump pond liquor back to the scrubber. Conversion of some sludge from the Mohave Station's limestone scrubber to an artificial aggregate will be demonstrated by IUCS; they will haul the aggregate away for commercial usage. Chemfix, though commercially conditioning industrial sludges at this time, is not yet conditioning any sludges for the power industry. Continuing contacts with these three companies and others who may become significant in this field will be made throughout the remainder of this program. More detailed descriptions of these three fixation processes are given in Section 6.6.

6.4 RAW SLUDGE AND ASH DISPOSAL WITHOUT POLLUTION CONTROLS

6.4.1 Introduction

Several alternative methods are available to power plants with regard to disposal of fly ash and SO_2 sludge. Of the two dozen power stations in the United States that are committed to lime or limestone scrubbers, the method of disposal of fly ash and sludge is either not fully defined or, if defined, each differs in both philosophy and practice from any other station. Whereas most power companies are taking some precaution in the disposal of their sludge relative to the

prevention of environmental pollution, others are not. In considering the many alternative disposal methods possible, it is conceivable that a relatively large number of power stations that will eventually use a lime or limestone scrubber will attempt not to provide environmental control of their waste products. It is the potential hazard created at these power plants that the following discussion addresses.

A majority of the nation's power plants are located along the banks of a major watercourse. The most prevalent method of fly ash disposal has been by sluicing it to lagoons, usually using cooling tower blowdown, and returning the water to the watercourse after the suspended solids have settled out. Chemical analyses of discharges have been made from EPA Region V Power Plants, and specific attention has been paid to the discharge originating from ash ponds. One large power plant (Ohio Power, Muskingham River Plant) located along the Ohio River is of particular interest because the chemical characteristics of its pond discharge are considered typical for that region. This plant, which represents about 2 percent of the electrical power generated along the Ohio River and its tributaries, returns 1.4 million gallons of water to the Ohio River daily through its ash pond discharge. In each year there is emitted with this water: 19 lb of antimony, 390 lb of boron, 1.3 lb of beryllium, 104,000 lb of calcium, 9 lb of chromium, 4.7 lb of copper, 6.4 lb of lead, 25 lb of selenium, and 8 lb of zinc. The chemical trace analysis of the fly ash lagoon outflow from this plant is given in Table 6-7. It is unfortunate that the important toxic elements, arsenic and mercury, were not included in the list of elements analyzed by this plant; therefore, the total extent to which the industry's fly ash lagoons contribute to pollution is unknown.

Using this plant as an example, we examined the effluent emitted under the following two conditions that are possible if lime or

Table 6-7. OHIO POWER, MUSKINGHAM RIVER PLANT ASH POND DISCHARGE

Discharge	Amount	Discharge	Amount
pH	7.5	Sodium (Na)	171.0 ppm
		Tin (Sn)	32.0 ppb
		Zinc (Zn)	18.0 ppb
Aluminum (Al)	190.0 ppb		
Antimony (Sb)	45.0 ppb		
Barium (Ba)	120.0 ppb	Acidity	4.0 ppm
Beryllium (Be)	3.0 ppb	Alkalinity	164.0 ppm
Boron (B)	920.0 ppb	Ammonia	6.0 ppm
		Chloride	310.0 ppm
Bromide (Br)	0.13 ppm	Nitrate	1.13 ppm
Calcium (Ca)	243.0 ppm	Nitrite	0.18 ppm
Chromium (Cr)	21.0 ppb	Sulfate	110.0 ppm
Cobalt (Co)	17.0 ppb		
Copper (Cu)	11.0 ppb	Total dissolved solids	1170 ppm
Iron (Fe)	190.0 ppb	Total suspended solids	53 ppm
Lead (Pb)	15.0 ppb		
Magnesium (Mg)	46.0 ppm	Total volatile solids	469 ppm
Manganese (Mn)	233.0 ppb		
Nickel (Ni)	24.0 ppb	Total solids	1237 ppm
Nitrogen (N)	18.0 ppm		
Phosphorus (P)	0.24 ppm		
Potassium (K)	12.0 ppm		
Selenium (Se)	58.0 ppb		
Silver (Ag)	5.0 ppb		

limestone scrubbers are installed on the flue stacks, and no controls are used to protect the quality of ground or surface waters:

a. Fly ash and SO_2 sludge are collected separately and disposed of in a fly ash lagoon and a sludge pond, respectively.

b. Fly ash and SO_2 sludge are collected separately or together, and both are disposed of in a sludge pond.

Additionally, a discussion is given of a variation of (b), as follows: fly ash is used as the SO_2 sorbent; the sludge (containing fly ash) is disposed of in a sludge pond.

These three cases are discussed in Sections 6.4.2, 6.4.3, and 6.4.4, respectively.

6.4.2 Separate Ash and Sludge Collection and Separate Disposal

It is presumed that the sludge pond would be enclosed, and that no liquor could flow directly into the river. However, since the plant is located near the river bank, the pond would be just above or possibly into the water table. The sludge will contain about 50 percent of its mass as water, but experiments have shown that sludge does not offer resistance to drainability; thus, leachate liquors from the sludge pond have direct or nearly direct access to the water table and, thereby, access to the river. The metal loading from the ash pond discharge to the river remains unchanged.

The sludge pond will contain liquors high in dissolved solids with total concentrations approaching 2 percent. Combined calcium ions and sulfate ions are expected to be present at a concentration of 0.4 percent, chloride ions at 0.5 - 1.0 percent, and other cations represented by Na, K, B, Mg, Mn, and others at 1 percent or greater. Among these others, arsenic (As), mercury (Hg), and, to a lesser extent, cadmium (Cd) are expected as dissolved solids in

the liquor. The origination of these three cations and chloride ions--all products of coal combustion--is a consequence of scrubbing flue gas.

Normally, elemental Hg and Cd are volatilized in the combustion of coal and enter the atmosphere with the flue gas. In addition, the chlorine in the coal forms gaseous hydrogen chloride and will also be emitted with the flue gas. When the flue gas is scrubbed by either a lime or limestone sorbent, hydrogen chloride (HCl) is readily scrubbed from the gas. Existing data suggest that SO_2 scrubbing units are at least 90 percent effective in removing HCl from the flue gas. Since chlorine forms so few insoluble salts, chloride ions will not precipitate as a solid. It is assumed that the scrubbing liquor remains in a closed-loop system with the only purge being the water that is disposed of in the sludge. The chloride ion will then build up to a concentration of equilibrium such that the amount of chlorine entering the scrubbing system from the flue gas will be balanced by the chlorine disposed of in the liquor fraction of the sludge. For typical concentrations of chlorine in coal this value will approach 1 percent in a well regulated closed-loop system.

The chloride ion serves a useful purpose in the scrubbing operation because its presence in the liquor will promote the solution of elemental Hg scrubbed from the flue gas and will result in the precipitation of the highly insoluble mercurous chloride (Hg_2Cl_2); the flue gas is thereby effectively scrubbed of Hg by chloride ions in the scrubber. However, Hg is easily oxidized and when the Hg_2Cl_2 precipitate is subsequently disposed of in the pond, the higher oxidation potential that exists there relative to the scrubber or hold tank will convert the Hg to mercuric chloride ($HgCl_2$), a salt that is highly soluble. Data thus far obtained, indicate that this oxidation readily takes place. Since most, if not all, ponds are being provided with a liquor recovery system as part of the closed loop, the Hg-ion laden liquors

will be recirculated to the scrubber. The consequence will be a build-up of Hg ions in the recirculation liquors. The equilibrium concentration at which the system will come into balance has the potential of being appreciably high (>50 ppm) depending on scrubber design parameters and Hg content of coal; the consequence can be a highly toxic pond liquor.

Cadmium too can be scrubbed from the flue gas, but in this case, the carbonate ion is the effective sorbent. Cadmium carbonate is an insoluble salt that will precipitate in the scrubbing system. Since the equilibrium concentration of carbonate ion in the system is at least one or more orders of magnitude greater than the Cd content, the soluble Cd content is expected to be very low. Moreover, liquor recirculated to the pond would be expected to reach equilibrium with CO_2 in the atmosphere; resolubility, as in the case of Hg, would not be expected to take place.

A third element, As, is also scrubbed from the flue gas; however, As does not enter as a gas but as a solid. Approximately 1 percent by weight of the total particulates produced during combustion passes through the precipitators. These particles constitute the super-fines having very high surface areas. Analyses of these particles indicate that they contain about 20 percent of the As originating from the coal. Wet scrubbing removes these particles from the flue gas and the As becomes easily dissolved in the scrubbing liquor. Arsenic does not form stable (insoluble) compounds with the anions in the lime-limestone system and builds up within the liquor as a dissolved solid. Analysis of liquors from a closed-loop recirculation system has shown that a level of dissolved As in excess of safe limits is possible, and this value may not even have reached the equilibrium saturation level.

The foregoing arguments reveal that flue gas scrubbing for SO_2 removal can also remove Hg and As that might otherwise be

distributed to the atmosphere. In so doing, however, the recirculation liquors can reach high levels and create a potential hazard in sludge disposal. Thus, sludge liquors having access to the watercourse can easily and readily create a problem of water pollution as a consequence of air pollution prevention. In the present case, typical of a majority of power plants using eastern coal, Hg and As would be leachable to the river (see Section 6.4.3) as contaminants in addition to those originating from the fly ash lagoon. The net effect is not known, except that the following case can be more severe.

6.4.3 Ash and Sludge Mixed and Disposed of in Sludge Pond

Fly ash can be collected in the scrubber or it might be collected separately and added to the sludge at the sludge pond. Either way, soluble elements that otherwise enter the river are now collected in the sludge pond. However, recirculation of liquor will allow each element to build up to an equilibrium concentration. The total level of dissolved solids can reach and surpass 10 percent depending on the particular elements in the system and their chemistry. Some elements (e.g., Pb and Be) will be controlled by sulfate or sulfite ions; others (e.g., Mn and Cu) form insoluble carbonate salts. Other elements [e.g., B and chlorine (Cl)] do not form insoluble salts and will accumulate in the recirculation liquors. The chemistry of other elements is not yet understood. Although these elements are not directly discharged to the river, their presence in an uncontrolled sludge pond makes them available by passage through the water table to the river.

An important aspect of this indirect discharge must be considered. The surface of a sludge pond will normally lie above the water table such that a hydraulic head from the pond can effect an order of magnitude increase in the permeability of the leachate through the aquifer. While access to the river is a function of many variables

(such as geological location of the pond, subsurface soils, and flow rate within the table), a major disadvantage exists for the typical pond site. At pond locations adjacent to power plants located along a riverbank, subsurface water lateral flow tends to be relatively rapid compared to vertical flow. During summer months when the river level is low, a major source of river rejuvenation can originate from drainage of the water table. At this time, the pond discharge potential to the river is greatest because of the hydraulic head of the pond, and the reduced or nonexistent hydraulic head effect of the river. The drainage to the river from the pond through a saturated base soil contains high concentrations of soluble elements accumulated throughout the year, but discharged to the river during a period of low volume and reduced flow rate.

In summary, the collection or combination of fly ash with sludge and disposal in a single basin as part of a closed-loop system, prevents the continuous pollution of river waters that results from a fly ash lagoon operation. However, a periodic pollution problem can be created that is much more severe than that occurring from separate ash lagoon and sludge pond operations if environmental controls are not exercised on this disposal site.

6.4.4 Fly Ash Sorbent--Disposal in Sludge Pond

A further alternative for sludge disposal may consider the use of fly ash as the sorbent. This is a situation that exists when high-lime western coal is used. These coals often contain high limestone such that there is sufficient lime in the fly ash to obviate the need for lime or limestone additions to the scrubber. In addition, the sulfur content of the coal is low; therefore, high flue gas scrubbing efficiency need not be obtained to meet environmental standards. The consequence is that the scrubber could be operated at lower than stoichiometric that produces highly acidic sludge. The potential for

environmental pollution created by this sludge is greater than that if the sludge were neutral or basic. The major solid components in the sludge--sulfites, sulfates, and carbonates--are all more soluble in an acid condition than in a base condition. Quantitative increase in solubility is not possible to predict in such a complicated chemical system, but values ranging from a few percent to orders of magnitude would be expected among the various heavy metal compounds typically found in these sludges.

6.4.5 Comments

In each of the cases considered, the potential hazard exists for environmental pollution as a consequence of disposing of SO_2 sludge in an uncontrolled condition that is state-of-the-art for ash disposal in the electrical power industry. Conditions relating to the soil (sand/clay content), the geological and hydrological location of the disposal site, weather, disposal site management, chemical contents of the coal, scrubber type, and sorbent each have an effect on the real pollution hazard. This hazard originates primarily as a consequence of the concentrating capacity of sludge liquors and the further possibility of these liquors being discharged inadvertently to the environment.

Even in cases where sludge disposal sites are being controlled by linings on ponds or by chemical fixation, there presently exists a measure of uncertainty. Laboratory evidence has indicated that sulfate ions can saturate clays so as to render them ineffective in their ion exchange capacity and thereby make them ineffective, in time, as a holding basin for sludge. Furthermore, the reliability of plastic lining materials over long times is uncertain. Neither sufficient data nor experience with these materials presently exists to provide a quantitative measure of reliability of any type of pond lining material. As an environmental alternative there is the choice of chemical fixation, but these techniques also have not been proven with time. The evaluation of the alternative disposal techniques relative to their capability for environmental protective capacity is now under study in this program.

6.5 LINED PONDS

6.5.1 Study Approach

Analyses were made to determine the technical and economic details relating to disposal ponds capable of containing sludge from the desulfurization scrubbers of power plant flue gases.

In the technical analyses, examinations were made of the engineering design of sludge ponds with emphasis on 15 liner materials, liner installation techniques, liner maintenance and techniques for repair, any limitations on pond usage, effects of the environment on the liner materials, determination of ancillary equipment needed to control the flow of sludge into or the effluent from the pond, and the instrumentation and methods used for monitoring pond leakage or seepage.

The economic analysis was directed toward determining the initial investment for the sludge ponds (including both the liner installation and general contractor work) and the required ancillary equipment, and the cost of the pond as a function of the kWh of electricity produced.

To acquire the data needed for the technical and economic analyses, detailed discussions were held with representatives from the liner fabricators, general contractors, power utility companies, and other industries using evaporation and sludge disposal ponds. These discussions were with companies operating throughout the United States so as to obtain a full insight into the techniques used in different parts of the country.

In all discussions it was assumed that present day technology would be used for the pond design and construction, and that all costs are based upon 1973 prices.

6.5.2 Pond Design

6.5.2.1 General

During the technical evaluation phase of the study it became evident that the useful life of a sludge disposal pond is dependent upon the aging characteristics of the seepage barrier material. The flexible liners have an age life of 20 to 25 years depending upon the material and how it is used. The age life of the nonflexible liners (e.g., asphalt and concrete) may be more than 50 years, again depending upon the design of the pond and degree of earth movement. Only the clays may possibly have a longer, indefinite life cycle. When selecting the specific liner material to be used as a seepage barrier, consideration must be given to the following factors:

> What is to be done with the pond after it has been filled to capacity? Will it be treated further and converted into a park or used for structural purposes? Should plans be made at the time the ponds are constructed to allow for removing the sludge every 20 to 30 years and replacing the flexible liner so as to ensure the integrity of the seepage barrier? Should the philosophy be that the pond liner is a permanent installation and no replacements are to be made unless forced to do so because there is contamination of the surface or ground waters? Or, should dewatering drainage be built into the pond?

At this time, the capabilities of the pond lining as to permanent environmental protection are not known, and the considerations that would be required if the disposal site is ever to be converted to structural or nonstructural land usage have not been determined.

Because each pond is designed to perform a specified function, the designs vary in accordance with the immediate soil conditions, topography, weather conditions, the state and local pollution control regulations, traffic within and surrounding the ponds, and with the material to be contained.

The sludge pond configuration considered in this study is essentially an excavated pit or basin with the soil graded into embankments or dikes to add to the heights of the sidewalls. Figures 6-1 through 6-3 illustrate some of the general characteristics and key features of typical ponds that use a flexible liner system for seepage control.

The pond bottom is usually flat, but may be contoured or pitched to drain off the liquid if so desired. The embankment slopes are 2 to 1 or shallower for ease of construction, and the tops of the embankments (berms) are at least 45.7 cm (18 in.) wide to provide sufficient structural support for the sides. In many cases the berms are sufficiently wide and steady enough to support vehicles.

Many different types of pond liner materials are currently being used depending upon the specific purpose of the pond, area to be covered, material to be contained in the pond, and the local environmental conditions. The liners used and included in this study are:

Flexible	Nonflexible
Polyethylene (PE)	Soil cement
Polyvinyl chloride (PVC) (10 and 20 mil)	Asphalt
Petromat fabric	Concrete
Butyl rubber	Pozzolan stabilized base
Chlorinated polyethylene (CPE)	Gunite
Hypalon	Clay
EPDM rubber	
Fiberglass polyester	

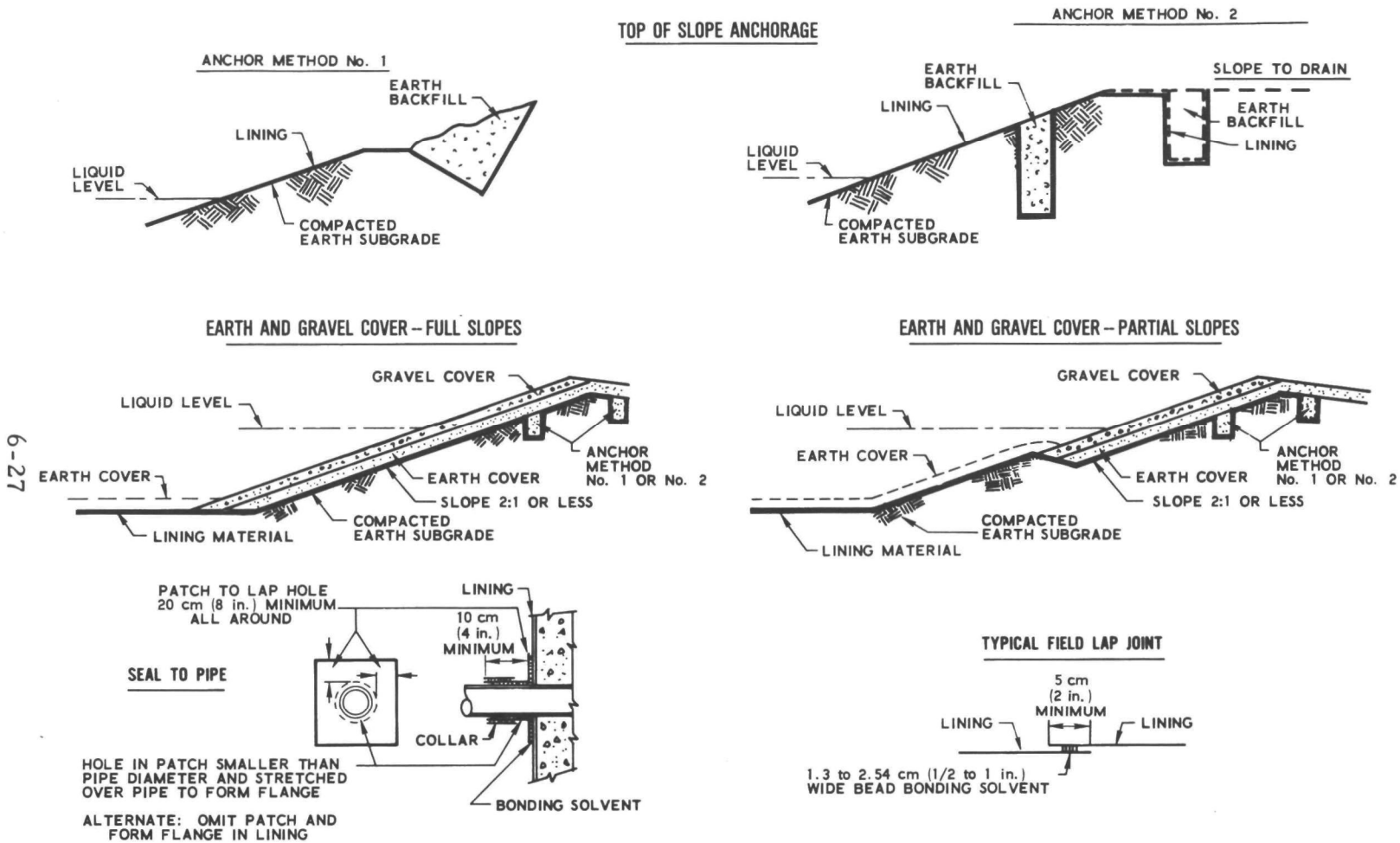

Figure 6-1. Typical pond features--flexible liner system

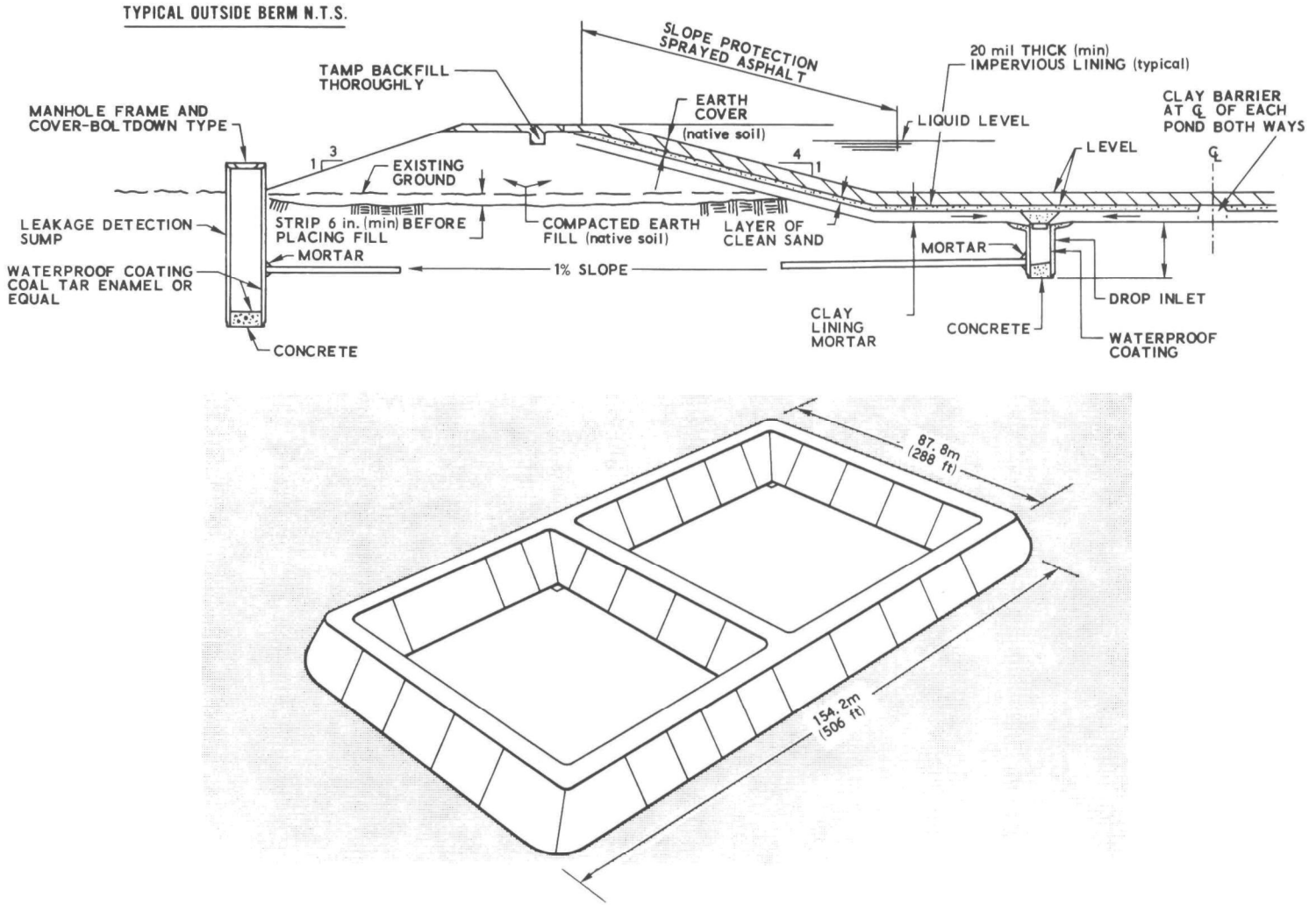

Figure 6-2. Pond with underdrainage (not to scale)

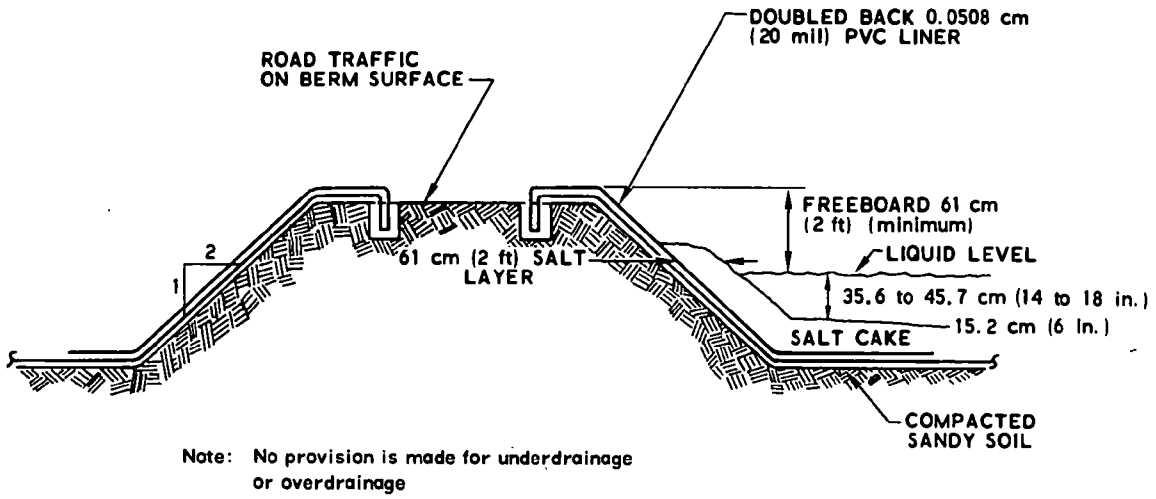

Figure 6-3. Potash evaporation pond features--Texasgulf, Inc. (not to scale)

Properties of these liners are given in Appendix C.

Leakage detection devices are sometimes incorporated into the pond design. These devices vary from a simple underdrainage basin, to an electrical system designed to measure the electrical resistivity of the ground in the pond area. Some pond installations monitor the nearby surface and ground waters to determine if there is leakage or seepage from the ponds.

6.5.2.2 Influence of Locale

The basic design features of disposal ponds are generally uniform throughout the country. However, there may be local ordinances and environmental regulations that must be considered. For example, if flexible liners are installed over decomposing materials or in areas of fluctuating water tables that pump air, bubbles could develop, come to the surface, and be unable to escape because of the liner's impermeability. Where these conditions exist, designs

must be incorporated to vent the gases, and provisions must be made to cover the flexible liner with soil to add weight and reduce the opportunity for it to float prior to adding sludge. Fencing is necessary around all pond areas, but the size and type of fence will vary depending upon the vehicular, pedestrian, and animal traffic in the area.

6.5.3 Technical Data

The many different types of barriers that have been developed over the years and employed to prevent seepage of liquids into the ground include such varied materials as flexible liners, clays, soil cement, asphalt, concrete, wood, and metals. Each type of material in turn is composed of a number of items specifically designed for a special application. Although all materials have a tendency to reduce the liquid seepage rate from a pond or basin, the degree of seepage through the material is a function of: material thickness, material permeability, material to be contained, and amount of supplemental covering over the liner.

6.5.3.1 Thickness

It is generally accepted that the thicker the barrier the less opportunity a liquid has to penetrate the material. This is true providing the barrier is a dense, homogeneous mass without porosity or fissures. In designing disposal ponds, detailed trade off studies are generally made; however, decisions appear to have been somewhat arbitrary in some cases that were examined. Thicknesses most commonly used are: flexible: 0.0254 - 0.0762 cm (10 - 30 mil); clay: 30.4 - 45.7 cm (12 - 18 in.); and asphalt or concrete: 15.2 cm (6 in.).

6.5.3.2 Permeability

Every material is permeable to some degree, the amount depends upon such items as material density; the absence

of cracks, pinholes, and foreign matter; and the head or pressure forcing the liquid through the barrier. Factors such as the liquid permeability, weatherability of the barrier, age life, fungus attack, and fabrication/installation techniques can affect the permeability over the operating life of the pond.

6.5.3.3 Material to be Contained

The material to be contained in a sludge pond directly influences the pond configuration and the construction materials. Problems sometimes develop in sludge disposal ponds that are designed to contain materials with pH values of under 4 or over 8, or if there are organic compounds present that could act as a solvent for the liner or be a basis for bacterial action. Fortunately, the chemical precipitates of the effluent from the flue gas scrubbers are not generally reactive to the standard flexible liner materials, asphalt base liners, or clays. The sulfates in the sludge could react with the soil cement and concrete and cause a breakdown of these liners.

6.5.3.4 Covering Over the Liner

When considering the amount of seepage through a liner, consideration is given to any supplemental covering over the liner that would enhance the barrier effect. There are two general types of covering: an artificial cover such as clay, soil, or secondary membrane liner and the gradual build up and accumulation of solids being contained in the pond. Although an artificial cover increases the pond complexity and cost, this concept may be the only solution to reducing the seepage rate to the desired level or to protect the liner from aging effects and mechanical damage. The exact cover type and thickness will depend upon the liner to be protected, the head of liquid, the permeability of the liner and cover, and the material to be contained. In some situations the material to be disposed of will flocculate to a

degree sufficient to add to the liner barrier effect and thereby reduce the seepage rate. Every case is entirely different and must be evaluated on its own basis.

6.5.4 Flexible and Nonflexible Liners

The materials that have been used for pond linings can be broadly classified as plastics or rubbers, soils, and asphalt/concretes. Appendix C contains descriptions of the key features of some of these types of liners; cost data for the appropriate liners are discussed in Section 7.1. Table 6-8 summarizes the more significant factors relating liner materials to sludge pond requirements.

6.5.5 Seepage Monitoring

6.5.5.1 General

Regardless of the type of pond construction and seepage barrier used for containing sludge, there is always the possibility of a crack occurring in the barrier material with a resultant leachate flow. In some areas, the local ordinances and environmental regulations require that stringent monitoring systems be installed to signal if there is any discharge of liquid from the disposal ponds that could flow into the surface or ground waters. The degree of sophistication of the monitoring systems is a function of the material to be contained, local laws, integrity of the contractor operating the disposal pond, potential damage to surrounding areas and inhabitants, and funds available for instrumentation and/or construction.

Table 6-9 (Ref. 6-2) briefly tabulates the advantages and disadvantages of a number of monitoring techniques. Two general types of monitoring techniques that are currently being used have been investigated: visual and soil resistivity.

Table 6-8. POND LINER MATERIAL CHARACTERISTICS

Material	Thickness,[a] mil	Thickness,[a] in.	Permeability, cm/sec	Life expectancy, yr	Dirt cover[b]	Average installed[c] cost, $/sq yd	Notes
Flexible							
Polyethylene	10	-	d	20	Yes	0.70	
Polyvinyl chloride	10 - 20	-	d	20	Yes	1.10 - 1.50	
Hypalon	30	-	d	20+	No	3.25	
Chlorinated polyethylene	30	-	d	20+	No	3.25	
Petromat fabric	-	1/16 - 1/8	d	20+	No	2.00	
Butyl rubber	30	-	d	20	No	2.80	
EPDM rubber	30	-	d	20	No	4.00	
Polyester fiberglass	65	-	d	20+	No	4.75	
Nonflexible							
Soil cement	-	6	About 10^{-6}	20+	No	1.00	e, f
Concrete	-	6	About 10^{-8}	50+[g]	No	3.75 - 4.75	e, f
Clay	-	Up to 18	10^{-5} to 10^{-8}	50+[g]	No	1.00 - 6.00	e, h
Asphalt concrete	-	6	d	50+[g]	No	4.00	e
Gunite	-	3	d	20+[g]	No	6.30	e, f
Pozzolan stabilized base	-	2 - 6	10^{-5} to 10^{-7}	50+[g]	No	3.85	

[a]Commonly used
[b]Protection from ultraviolet rays
[c]See Section 7.1
[d]Superior to clay
[e]Affected by wet/dry and hot/cold cycles
[f]Subject to sulfate attack
[g]Industrial estimates not obtained
[h]Possible breakdown due to ion exchange

To convert from	to	Multiply by
sq yd	sq m	0.8361
mil	cm	0.00254
in.	cm	2.54

Table 6-9. POTENTIAL TECHNIQUES FOR MONITORING LIQUID SEEPAGE FROM PONDED AREAS (SHEET 1 of 3)

Method	Description	Field application	Advantage	Disadvantage
Evaporation	Pond evaporation losses are compared to pond inflow.	Documentation required for all ponds.	Easy to monitor, inexpensive, low maintenance.	Indirect determination: does not monitor actual seepage, assumes pond evaporation to be equal to nearest comparative pond. Since pond evaporation varies with depth and size, method is subject to error.
Deep wells	Ground water wells--domestic or agricultural. Equipment: electrical conductivity meter.	Monitoring quality for back-up data and possible changes in quality for nearby ponds.	Records easily available, history may be traced.	After-the-fact method. Wells too far away or absent.
Shallow observation wells	Shallow wells with perforated casings, gravel backfilled. Possible equipment: electrical conductivity meter.	Detection of lateral water movement from ponded areas over restricting substrata.	Quantity and quality can be monitored, fairly inexpensive, low maintenance, permanent installation.	Suitable for monitoring water table conditions only--unsaturated flow cannot be detected
Auger	Hand or power augered holes (usually following soil sampling). Equipment: auger.	Preliminary soil investigation of all ponds; determination of seepage in and adjacent to ponds.	Quantity and quality can be monitored, inexpensive.	Difficult to maintain, unsaturated flow cannot be detected.
Soil sampling	Soil sampling to incremental depths pending textural changes. Equipment: auger.	Measurement of soil profile moisture and its quality in all ponds when necessary.	Minimum equipment required, offers wide range of quality and moisture monitoring.	Expensive laboratory analyses, requires repetitive and background sampling.
Infiltrometers	Plastic covered ring infiltrometers 22.9 - 61 cm (9 - 24 in.) diameter, double or single, manometer equipped. Equipment: special driving hammer.	Measurement and pond infiltration both inside and outside ponded areas for all ponds.	Fairly easy to monitor, inexpensive, no special maintenance required, permanent	Requires some expertise for installation; chance of errors--short circuiting, evaporation losses, and mismeasurement.

Table 6-9. POTENTIAL TECHNIQUES FOR MONITORING LIQUID SEEPAGE FROM PONDED AREAS (SHEET 2 of 3)

Method	Description	Field application	Advantage	Disadvantage
Piezometers	6.35 - 9.52 mm (1/4-3/8 in.) metal pipe; perforated at end. Equipment: driving hammers, rivets, rods, pump, tubing, soundbell.	Detection and measurement of moisture movement under ponds overlying restricting layers.	Very inexpensive, simple to install, easy to read, no special maintenance or calibration required, both quality and quantity of special zones can be determined.	Measures only saturated zones, relies on impervious subsoil conditions, cannot determine unsaturated flow.
Gypsum blocks (Bouyoucos blocks)	Unit: gypsum, nylon, or fiberglass blocks; plate electrode. Other equipment: resistance meter.	Detection of changes in soil moisture under all ponds.	Easy to install, easy to monitor, very little maintenance required.	Not capable of measuring quality or quantity of seepage, calibration required--low sensitivity in moist and wet range. Subject to deterioration.
Porous	Ceramic porous suction cups. Equipment: vacuum pumps, lines, etc.	Detection of pond seepage quality in wide moisture range for nearly all ponds.	Samples can be obtained easily, rather inexpensive, low maintenance, permanent installation.	Measures best under saturated conditions--normally measures near the available moisture range, depth limited.
Neutron probe	Neutron scattering moisture meter: includes radioactive source, transmission lines, counter. Other equipment: dummy probe, access tubes, etc.	Detection of vertical moving moisture fronts under and surrounding ponds.	High reliability, access tubes permanent, good for frequent checking.	Very elaborate and expensive, requires special expertise, frequent calibration, special access holes, high maintenance, does not detect quality, requires special storage and licensing by AEC.
Remote sensing	Infrared photographic detection of changes in the radient energy status of a discharge area.	Detection of changes in the growth rate of plants in and around a discharge area as compared to native areas.	Monitor at any time without prior notice, permanent record, interpretation easily delineated.	Expense not well established, subject to weather, does not tell quantity or quality of drainage water.

Table 6-9. POTENTIAL TECHNIQUES FOR MONITORING LIQUID SEEPAGE FROM PONDED AREAS (SHEET 3 of 3)

Method	Description	Field application	Advantage	Disadvantage
Salinity sensors	Salinity sensing device to detect dynamic changes in salt concentration in the soil profile.	Quick detection method of changes in salt concentration in the soil profile.	Simple to set up and operate. Quick response to new equilibrium conditions.	Initial expense is high. Does not measure quantity and individual ions.

6.5.5.2 Visual

As noted in Section 6.5.5.1, the type and degree of monitoring of the ponds depends upon a number of specific factors.

In the case of the Texasgulf, Inc., potash facility at Moab, Utah, which consists of 23 evaporation ponds totaling 1,618,800 sq m (400 acres), the company has taken the philosophy of monitoring only the terrain and surrounding area near the pond site for any obvious seepage.

These ponds are lined with 0.0508 cm (20 mil) PVC, and the facility has been operating for about 3 years. Figure 6-3 shows the key features of the ponds. The evaporation ponds do not have any underdrainage or run-off system to collect any liquid that might seep through the PVC liner. It was stated (Ref. 6-3) that Texasgulf keeps a 6-in.-thick compacted cake of KCl/NaCl salt on the bottom of the pond at all times, and they feel that this salt cake acts as a complete barrier to the flow of any liquid. A 2-ft-thick salt cake is also maintained along the inside slope of the pond. Texasgulf can pump the liquid from one pond to any other one in the event of an emergency (e.g., a leak in the liner). It has not yet been necessary to do this.

The facility is located in the deep canyon country overlooking the Colorado River. In keeping with the concept of monitoring the surrounding area rather than the pond underdrainage, the local streams flowing into the river are checked daily. The potash solution is a bright white color with a long staying power on the ground, and if there should be any leakage it shows up very fast. Small dams have been built around all pipeline connections to and from the ponds to retain any leakage and also at various locations at which the potash solution could possibly flow into the streams.

There is a natural outcropping of potash in the Moab, Utah, area near the Texasgulf facility. The company personnel

reported that before the evaporation ponds were originally filled, many detailed photographs were taken of the local area with special emphasis directed toward these points of potash outcropping. The photographs were legally notarized by the local pollution control district personnel and the company's legal department. Periodically the area is resurveyed and the results compared with the original photographs. Thus far, there has been no noticeable change in the area to indicate any seepage or leaking taking place. The Texasgulf personnel emphasized that because their plant is near a national park area, all employees are extremely cautious and do everything possible to retain the natural beauty of the landscape.

American Magnesium Company is installing five solar ponds for a total of 424,000 sq m (105 acres) near Gail, Texas, for evaporating water from a high solids content magnesium salt solution. There are no provisions for underdrainage or for any type of monitoring system to signal leakage or seepage from the ponds. The dirt contracting work has been completed, and a flexible lining is being installed by Staff Industries, Upper Montclair, New Jersey (Ref. 6-4). The key features of these ponds are:

a. The five ponds range in size from 60,600 to 121,200 sq m (15 to 30 acres) and from 1.52 to 3.66 m (5 to 12 ft) in depth.

b. The magnesium salt solution is fed into Pond No. 1 for concentrating the solids to a certain percentage and the effluent overflowed to Pond No. 2 for further concentration. This process is repeated through Pond No. 5. The effluent from each pond is controlled by a circular weir that can be adjusted to the flow rate as required. Liquid from Pond No. 5 is pumped through a 5-in. pipeline to the magnesium processing plant located about 7 miles away.

c. The bottom surface of the pond is lined with 0.0508 cm (20 mil) PVC; the slopes, which are graded to a 2:1 ratio, are lined with 0.0762 cm (30 mil) CPE.

d. The soil is compacted to 90 - 95 percent, and all roots, grass, and large rocks are removed to provide a relatively smooth surface for the liner.

e. A freeboard of about 1 m is planned.

f. The sludge remaining in the ponds will be mainly NaCl plus impurities. When the sludge builds up to a predetermined level, it will be cleaned out, and attempts will be made to sell it for industrial use.

The Pacific Gas and Electric Company (PG&E) (Refs. 6-5 and 6-6) also uses a visual monitoring system to determine if their evaporation pond located at Barstow, California, is leaking. The pond is for evaporation of coolant water blowdown for the gas compressor coolers. A cutaway view of the pond configuration as used at this location is shown in Figure 6-2. The sketch illustrates the "underdrainage/flow/containment" design. The base of the pond is divided into quadrants sloped (contoured) to a single central down pipe. A clay liner of 20.3 cm (8 in.) is installed over the compacted soil. Above the clay there is a 5.08-cm-thick (2-in.) layer of clean sand. A flexible liner of 0.0508 cm (20 mil) PVC is placed over the sand and the pond bottom is topped with about 30.5 cm (1 ft) of native soil. The clay liner projects from the compacted soil to the PVC liner at the quadrant barrier locations. This clay barrier serves as a retaining wall if there should be a leak; liquid should flow through the sand layer to the down pipe. From the down pipe there is a horizontal outrigger pipe to a leak detection sump. These sumps have manhole openings and are visually inspected on a routine basis for any water accumulation. Because the pond has been designed in such a manner as to separate the total area into distinct quadrants, it is immediately obvious which quadrant of the pond has sustained a leak. Appropriate repairs can then be made.

Although this technique of pond leakage monitoring was expensive to install, PG&E personnel feel that there are no moving parts or electrical connections to go out of order, that this concept

would provide them with a positive indication if there should be a leak, and that it would show them exactly where the leak has occurred.

6.5.5.3 Soil Resistivity

The concept of measuring soil resistivity is an accepted technique in many agricultural, construction, and geology based industries. In applying this method to the determination of leakage or seepage of liquid from the disposal ponds, individual ground rods (pins) are located on a grid or patterned basis beneath the liner (or off to the side of the pond) with insulated conductors leading to a control room. The spacing between rods is normally limited to about 152 m (500 ft) depending upon the soil conditions at the pond site. A multipoint recorder selects a pair of electrodes and records the measured conductivity between the electrodes. Upon initial system installation prior to filling the ponds with liquid, a baseline conductivity for the soil in the pond area is determined. Anytime the conductivity between a pair of the electrodes increases above a preselected value, an indication is provided to notify the pond operating personnel of a possible leak.

There are two disadvantages that must be evaluated when considering this type of leak detection system. They are:

a. There is always the possibility of a false alarm signifying a leak that has not occurred; or vice versa, a leak may have occurred that is not registered. In either situation, the consequences could be not only costly but potentially disastrous.

b. Over the years the repair and maintenance on this system could be higher than on a visual inspection system.

6.5.5.4 Summary

It is necessary that any pond leak detection system be evaluated thoroughly during the early design phases prior to

construction. Consideration is given to major aspects of the problem, such as: cost, maintenance, federal/state/local laws and ordinances, and the consequences of not having a reliable detection system. Emphasis is placed on system reliability; if the installed system is unreliable, it is worse than no system at all because it gives a false sense of security.

6.5.6 Sludge Flow to Pond Site

6.5.6.1 Piping

Sludge at a temperature of less than 100°C (212°F) is pumped from the scrubber or thickener to the disposal pond. Pumping slurries at this temperature and 50 percent solids content appears to be common practice within the mining and chemical process industries and does not require a breakthrough in technology or the development of new equipment.

Various piping construction materials are currently available; each material has been fabricated into pipes of many different sizes and wall thicknesses for pumping fluids at different pressures. No attempt was made in this study to evaluate all the many varieties of piping materials (plastic, rubber lined, steel) or sizes potentially suitable for moving the sludge to the disposal pond. The precise selection is the detail designer's choice based upon his local situation.

For this study, it was assumed that a 1000 MW power plant will require six scrubbers to accommodate all of the flue gases coming from the boilers. It was further assumed that when the power plant is operating at capacity and for 6400 hr/year, the sludge output is at the rate of 218,000 metric tons (240,300 short tons) per scrubber for a sludge of 50 percent solids (including ash). The exact pipe diameter will depend upon the local head loss design conditions and the

desired fluid velocity. Experience has shown that the sludge velocity in the pipes should be about 2.14 - 3.05 m/sec (7 - 10 fps) to prevent any settling out of the precipitate.

6.5.6.2 Pumps

Three of the most common types of pumps available to move the sludge to the disposal pond are: centrifugal, reciprocating and rotary. Any one of these pumps properly designed for the specific pumping conditions (e.g., amount of head loss, velocity, and rate) could perform the required function. A type readily adaptable to this task is a rubber lined centrifugal pump now being used in high abrasive work in the mining industry.

6.5.6.3 Flow Measurement

Numerous flow measuring devices were investigated to ascertain the types of instrumentation needed to determine and control the amount of fluid flowing from the scrubber to the disposal pond. A Parshall Flume, which operates on the principle of upstream head buildup caused by downstream venturi restriction, appears to be suited for this task. This head change is in turn measured by either a capacitance, sonic, or bubbler system and transmits a signal to a device that produces an output signal to be integrated and recorded. The Parshall Flume was considered a better choice for this function than a weir design because the buildup of solids in the bottom of the channel could give an erroneous reading. The flume also has a relatively large head change compared to flow rate change. This feature makes the flow transmission device less critical, and furthermore, the flume can be easily cleaned or repaired.

6.5.6.4 Pond Level and Temperature Indicators

Consideration was given to the potential need for a pond level indicator and a temperature recording instrument. Sonically

operated level indicators are available from many manufacturers. This technique would work satisfactorily for this task because there is no contact with the sludge and, therefore, no contamination problem.

Thermocouples embedded in the sludge flow stream can provide the means for measuring the temperature of the fluid flowing into the pond. The thermocouples can be connected to an indicating thermometer or to a recording device.

6.6 SLUDGE CONDITIONING

The conditioning of sludge for its environmentally sound disposal may be performed by several techniques. The most well developed technique is chemical fixation, and data presently exist that allow this technique to be evaluated. Other conditioning techniques that might be used are drying, sintering, and nonchemical additives. In each of these other fixation methods for sludge conditioning, commercial processes have been or can be developed, but little or no research into these areas has been made by the power industry. While none of these latter methods are included in plans for operational applications, they provide alternative disposal processes that may be suitable for specific problem cases. The following sections describe and discuss the various methods that are technically feasible for conditioning sludge to make it suitable for disposal.

6.6.1 Fixation

The chemical fixation processing of power plant sludges offers an alternative disposal method that may serve several purposes. The processors assert that soluble trace elements become chemically bound such that their availability to subsequent leaching is minimal or nonexistent. As an example of the chemical bonding that fixation processing can provide, Table 6-10 shows an analysis of the leachate obtained from the Shawnee Power Plant sludge, chemically fixed by one

Table 6-10. COMPARISON OF TRACE ELEMENTS ANALYSES BETWEEN RAW SLUDGE AND LEACHATE FROM THAT SLUDGE AFTER CHEMICAL CONDITIONING BY FIXATION (REF. 6-7)

Constituents	TVA Shawnee TCA limestone raw sludge	Leachate water from conditioned sludge
Arsenic (As)	2.2	<0.10
Cadmium (Cd)	0.30	<0.10
Chlorides (Cl^-)	2,000	64
Total Chromium (Cr)	2.8	<0.25
Copper (Cu)	1.5	<0.10
Iron (Fe)	120	<0.10
Lead (Pb)	26	<0.10
Mercury (Hg)	<0.10	<0.10
Nickel (Ni)	3.5	<0.10
Zinc (Zn)	16	<0.10
Phenol (C_6H_5OH)	<0.25	<0.10
Cyanide (CN^-)	<0.10	<0.10
Sulfate (SO_4^-)	>10,000	400

of the processors and compared with raw sludge. Thus, the use of chemical fixation might be an effective and convenient method for sludge detoxification (however, further assessments are necessary to determine long-term effects under operational conditions). In addition to chemical bonding of heavy metals, the treated material is rendered more serviceable as a landfill material and, if properly treated by any of the processes, it can be used as structural fill. The disposal of a material that serves as landfill is made markedly more simple because a much larger selection of disposal sites is available, especially in and near densely populated areas. In comparison with a

thixotropic sludge disposal in a pond, a chemically fixed sludge renders a disposal basin suitable for land reclamation in the future. In addition, if the material must be transported by truck, rail, or sometimes even by barge, a chemically fixed material offers certain advantages in cost and convenience.

To date, three companies have been visited that have developed technology for chemical fixation of sludge materials: Chemfix, Division of Environmental Sciences, Inc., Pittsburgh, Pennsylvania; Dravo Corporation, Pittsburgh, Pennsylvania; and International Utilities Conversion Systems, Inc. (IUCS), Division of International Utilities, Philadelphia, Pennsylvania. Whereas all three processors claim to produce a material that chemically binds soluble components, their processes and products are distinctly different. In each case, process details and additives are considered proprietary; the brief description of these processes presented in the following sections gives some of the fundamental differences that exist between them. These differences are also apparent by the nature of the product of fixation. Specifically, the Chemfix process produces a material that has soil-like characteristics, the Dravo process produces a clay-like material, and the IUCS process produces a material that resembles low-strength concrete.

None of these processors has operational field experience with power plant sludges, but each has sufficient experience in the fixation of sludge materials to give credence to its claims. Chemfix has gained wide field experience in chemical fixation of solid and liquid wastes produced by the automotive, chemical, mining, paint, petrochemical, steel, and metals industries. Their process can handle sludges with all possible solids content. The product of their process is a soil-like material through which rain waters can easily and readily percolate. The Dravo Corporation process is now being

used to establish the sludge disposal system for the lime scrubber at the Phillips Station, Duquesne Light Company, and Dravo will process others (see Section 6.3). They have gained extensive laboratory experience on sludges from various air pollution control devices that include but are not limited to power plant sulfur dioxide scrubbers and are now starting to gain field experience in the fixation of sulfur sludges. This process can chemically fix sludges at various solids contents. The IUCS process has been field tested on the sludge produced by wet scrubbing effluent gases on a lead smelter using hydrated lime as the absorbent. This sludge has many properties similar to power plant sludges and produces a hardened composition when chemically fixed. Laboratory tests have verified the similarity of sludge behavior between this experience and power plant sludges. Curing requires the control of excess water and additives. The suitability of cured material as a structural material was demonstrated at the International Transportation Exhibit (Transpo '72) where the material was placed and compacted as part of a 110 acre parking lot. Known planned operations of IUCS are mentioned in Section 6.3.

6.6.1.1 The Chemfix Fixation Processes

The Chemfix process involves the reaction of at least two chemical components with the waste material to form chemically and mechanically stable solids. The reaction occurs at normal, ambient temperatures and is not affected by temperature variations. A series of inorganic chemicals is used that has proven stability when in contact with the elements of the environment: soil, water, air, micro-organisms and sunlight. The particular chemical choice, chemical ratios, and reagent quantities depend on the type of waste, required speed of reaction, and the end use of the fixed material. Either reactive or nonreactive wastes can be treated with the Chemfix process. The reaction process involves a gelation state followed by a hardening

period. Controlling the gelation time is a factor that depends on the distance the treated material must be pumped to the disposal site.

The treated waste can be made either hard or soft with varying textures depending on its ultimate disposal. The chemical system reacts with all polyvalent metal ions producing stable, insoluble, inorganic compounds. The resulting material can be used as landfill and when properly nourished, grasses and plant life will readily thrive.

6.6.1.2 The Dravo Fixation Process

The Dravo process chemically fixes sludge by the inclusion of a proprietary admixture called Calcilox. The additive is mixed with the sludge usually by feeding through a pumping system while being pumped to a disposal basin. The solids fraction of the sludge is allowed to settle (probably with the aid of a flocculating agent) and curing takes place over a 30-day period. Excess sludge liquor is provided over the curing material during this time. After curing, these liquor waters can be recirculated to the scrubbing system, and the solids can be removed to a permanent disposal site. Alternatively, the material can be cured in the permanent disposal basin.

The result of the Dravo process is a fixed sludge made firm and convenient for disposal. By adding 3 percent Calcilox (based on sludge solids) the conditioned sludge has properties that compare with silty clay with water permeation of 2×10^{-5} cm/sec; the stiffness as determined by compressive yield is much like clay, but it does not have the cohesiveness as determined by shear strength, and it is stable on a 35-45 deg slope. However, more clay-like properties like remaining stable on steeper slopes, lower permeability, and greater stiffness are now being obtained with Calcilox additions of 5 percent.

6.6.1.3 The IUCS Fixation Process

The IUCS process uses fly ash and a lime additive as ingredients in their chemical fixation of sulfite/sulfate sludges. The quantity of either of these additives depends on the water content of the sludge and the reactivity of the fly ash. In most cases, some amount of dewatering of the sludge is necessary for the desired reactions to take place at economical amounts of the additive. The technology is best applied to lime-scrubbed sludge because reactions are most favored by the high pH. Three primary reactions take place: (a) the reaction of lime with soluble sulfate that originates in either the fly ash or sludge water so as to form calcium sulfate (sulfite also works, but the reaction takes longer), (b) the reaction of lime, sulfate, and iron or aluminum oxide present in the fly ash glass forms complex sulfoferrites or sulfoaluminates (this reaction results in the formation of the crystalline phase ettringite that contains substantial quantities of water within the crystalline structure), and (c) the reaction of lime with the glassy silica of fly ash results in the well-known pozzolanic reaction that proceeds slowly to form calcium silicate, tobermorite.

The result of this process is a material that can develop strengths as much as 300 psi in 7 days and greater than 1000 psi after 1 month. Falling head permeability shows that leaching of this material during the first week of curing changes from 10^{-5} to 10^{-7} cm/sec. The low permeability is a consequence partly of the expansive nature of ettringite which tightly seals the set mass and prevents shrinkage crack formation that may otherwise allow some leakage. Besides low leach rate, the water quality of the leach rate has a reduced quantity of trace elements approximating two orders of magnitude. Thus, as a consequence of chemically combining trace elements into new crystalline phases and the reduction in leaching rate, a total reduction of

soluble salts or toxic contaminants that are available to ground waters can be reduced by about 10,000 times over sludge not fixed by this process. Moreover, the application of this material in embankment-type structures results in preferential run-off rather than permeation, and further reduces the toxic hazard relative to ponding. An additional application for the fixed sludge is the manufacture of synthetic aggregate that has properties suitable for usage in concrete.

6.6.2 Drying

An alternative method of sludge conditioning for disposal might use drying of the sludge so that a solid material is disposed of. By drying a sludge, many of the problems associated with sludge are avoided and ultimate disposal can proceed by using techniques developed for sanitary landfill. Moreover, in some localities, disposal in such landfill sites would be acceptable. The Koch drier is one of the commercial machines designed for sludge drying that are available for this process technique. A major difficulty with the dried sludge is based on its ability to reabsorb water. To alleviate this problem, disposal by using a fill and bank technique might be used. The problems that could arise by leaching toxic components from the dried sludge are avoidable by designing run-off ways such that rain waters are not available to rejuvenate the ground waters by passing through the disposal site. Further assessments will be made of this.

6.6.3 Sintering

Although no specific technological development has demonstrated its feasibility, sintering of the sludge offers another alternative method of disposal. It is presumed here that this method of disposal would be performed not solely for the sake of disposal but rather because of useful product results from the sintering operation. These products might be finished products such as bricks or blocks but more likely they would be synthetic raw material like aggregate

for concrete or feed for cement clinker. The latter is a prime consideration because the sludge can provide not only the lime originating from the sorbent, but also the argillaceous components for cement originating from the fly ash. Such a sintering process will require a subsequent scrubbing system for sulfur removal. The concentration of sulfur dioxide in the effluent gas would be high enough that an efficient sulfur dioxide recovery plant can be installed to economically make sulfuric acid or elemental sulfur. The unique marketing conditions necessary to make this use of sludge economically feasible will limit its application to single, isolated locations.

6.6.4 Nonchemical Additives

The alternative method of sludge disposal using nonchemical additives is an alteration of the ponding/landfill concept. In this method, low-cost materials, such as sand, soil, or clay, are mixed with the sludge that is disposed of by being placed in a disposal basin. The role of these additives is primarily to dewater the sludge, but additional utility is derived if clay is the additive. Clay has a high ion exchange capacity and when intimately mixed with the sludge could reduce the availability of toxic elements to subsequent leaching waters. The superb water absorptive capability of sands and slit and the ion exchange capacity of clay make most soils ideal additives for this disposal technique.

6.6.5 Sludge Conditioning Assessment

The chemical fixation of sludge is the most advanced conditioning technique presently available for sludge disposal. It offers one of the more secure methods for detoxification and provides a material suitable for landfill and, in some cases, also for structural fill. Disposal by drying or by using nonchemical additives is less expensive, but their use is limited by the uncertainty of the toxic

hazard that may be introduced. Sintering is a technique by which sludge is converted to a saleable product and depends on favorable market conditions to implement.

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SECTION 7

ENVIRONMENTALLY SOUND DISPOSAL COST DETERMINATION

7.1 POND LINING AND DISPOSAL COST ESTIMATES

7.1.1 General

The cost for constructing a sludge pond will depend not only on the many technical details discussed in Section 6.5, but it will also depend upon its location. The cost for shipping the liner materials to the site from the factory or processing center will vary with the distances traveled, and the labor cost for construction and liner installation varies with the different areas of the country. The engineering analysis undertaken in this study considers these variations and uses average values such that the costs presented can be considered typical, but not necessarily specific.

Cost data were obtained from users and builders of sludge ponds to provide as true a cost value as possible without requiring the preparation of detailed engineering drawings for a specific configuration pond at a definitized site location.

The following ground rules or methods were used:

a. The annual operating time (hours) of the power plant is a function of the age of the facility (Table 7-1). Limestone sludge without the ash added would be about half of this annual production quantity.

Table 7-1. SLUDGE PRODUCED AS A FUNCTION OF POWER PLANT AGE AND OPERATING HOURS

Age of power plant, yr	Plant operating hours per year at rated capacity	Sludge at 50 percent solids including ash--annual production, tons $\times 10^6$	
		Metric tons	Short tons
0 - 1	6400	1.305	1.438
1 - 10	5850	1.188	1.315
11 - 20	4580	0.923	1.025
21 - 30	3200	0.651	0.719

b. Engineering, experimentation, or design costs for the sludge ponds are not included.

c. In many of the calculations, the cost for the land is kept separate from the initial investment to permit comparisons to be made of the ponding costs using various liners. When incorporated, the land costs are assumed to be $1000 or $5000 per acre. The higher value represents the probable maximum cost value for disposal site land.

d. The annualized cost on a 30-year average basis is defined as 18 percent of the initial capital investment (Ref. 7-1). This value includes such items as interest, depreciation, insurance, replacements, maintenance, and taxes.

e. Costs have not been included for the following items and/or equipment that might be needed or installed as part of the overall sludge disposal operations: engineering costs, operating utilities, and security alarm systems.

f. All costs are as of October 1973.

g. The ponds are located 1.6 km (1 mile) from the power plant and are included as a portion of a closed-loop system.

h. There are six scrubbers per a 1000 MW capacity power plant with all scrubbers operating at the same efficiency.

i. To compare the costs of various types of lined ponds and to obtain total estimated ponding disposal costs, 30-year averaging is used. Economic comparisons between fixation and ponding processes are on the basis of first year costs.

7.1.2 Flexible Liners

Figure 7-1 presents a composite cost summary for the various flexible liner materials considered in this study. The data were obtained from either the manufacturer of the sheeting material or the liner installation contractor (Refs. 7-2 through 7-12). The values shown are to be considered for planning purposes only and are typical of the range of costs that might be expected for the fabricated panels installed at the pond sites. For this study, however, the mid-point of the quoted price range has been used as the installed prices that are listed in Table 7-2.

The values shown do not include any installation (spreading) of soil over the polyethylene or PVC film that would require it, whereas the others may not. This particular cost was omitted to permit a direct comparison among the different materials. The cost for adding 15.2 to 30.4 cm (6 to 12 in.) of soil was quoted to be in the range of 4.19 to 12.55 ¢/sq m (5 to 15 ¢/sq yd) (Refs. 7-2 and 7-13).

The widespread variations in liner costs have resulted because of the inclusion of the following factors:

a. Cost of transportation from the panel manufacturer's facility to the field site within a radius of about 1609 km (1000 miles)

b. Variations in the cost of labor to install the panels.

c. Discounts and lower unit costs for purchasing large quantities of the sheeting materials.

Discussions with the liner installation contractors revealed that, because of the vast quantities of material to be involved in the sludge ponds, it is expected that the flexible liner materials could probably be purchased and installed at the lowest cost values indicated in Figure 7-1; however, those lower limit values were avoided as a precautionary measure against data which may not be reliable.

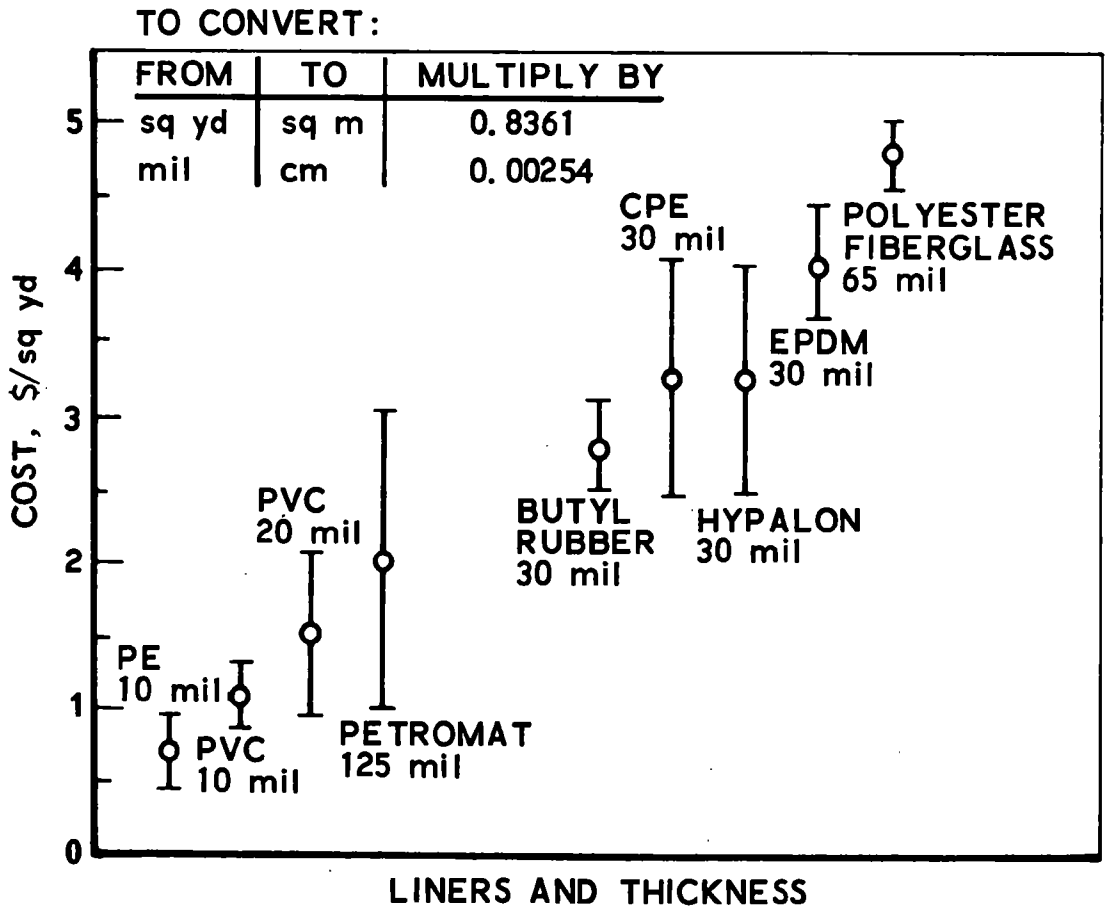


Figure 7-1. Relative costs of flexible liners (installed)

Table 7-2. FLEXIBLE LINER COST DATA MIDPOINT PRICE RANGE VALUE--INSTALLED

Material	Thickness, mil	Cost, $/sq yd
Polyethylene (PE)	10	0.70[a]
Polyvinyl chloride (PVC)	10	1.10[a]
Polyvinyl chloride (PVC)	20	1.50[a]
Petromat fabric	125	2.00
Butyl rubber	30	2.80
Chlorinated polyethylene (CPE)	30	3.25
Hypalon	30	3.25
EPDM rubber	30	4.00
Fiberglass polyester	65	4.75

[a]Does not include soil on top of the liner at $0.10/sq yd.

To convert from	to	Multiply by
sq yd	sq m	0.8361
mil	cm	0.00254

7.1.3 Nonflexible Liners

The costs for the nonflexible liners installed in a pond are shown in Table 7-3. These values were obtained from installation contractors and are considered for comparative purposes only.

7.1.3.1 Clay

The cost for bentonite type clay was quoted from $10 to over $25/ton (FOB the clay processing plant) with about $20/ton as a typical value (Refs. 7-2 and 7-13). The cost variations are a function

Table 7-3. NONFLEXIBLE LINER COST DATA--INSTALLED

Material	Thickness, in.	Cost, $/sq yd
Soil cement	6	1.00
Asphalt	6	4.00
Concrete	6	3.75 - 4.75
Pozzolan stabilized base	6	3.85
Gunite	3	6.30
Clay	Up to 18	1.00 - 6.00

To convert from	to	Multiply by
sq yd	sq m	0.8361
in.	cm	2.45
short tons	metric tons	0.9072
ft	m	0.3048
acre	sq m	4046.8

of the clay quality, degree of processing, and quantity purchased. In addition to the basic cost of the clay, unless the pond site is located near the clay processor, there is the additional high cost for shipping the material to the pond site. The shipping costs[a] are a direct function of the mode of transportation and distance traveled.

[a]Examples of rail shipping costs in bulk lots from clay pits in Wyoming are:

Ship to	Cost, $/ton
Buffalo, New York	28
Galveston, Texas	21
Chicago, Illinois	22
Los Angeles, California	28

For estimating purposes the contractors suggested that a shipping cost of $30/ton be used. This value would include transportation costs and costs for loading and unloading the clay at the rail heads. With the transportation cost added to the cost of the clay, the contractors recommended that processed bentonite type clay be estimated at $50/short ton installed. The use of clay would be prohibitive as a pond liner unless it can be found locally or used in thicknesses of 1 - 2 in.

It was reported that the projected cost for an 18-in.-thick clay liner installed in several large ponds being constructed in the midwest is about $6.00/sq yd. It was further stated that the local clay was transported by truck about 30 miles from the clay pits directly to the pond site. Therefore, to be realistic in this study, a cost of $6.00/sq yd installed was used as the basis for the clay liner calculations. It must be noted, however, that if clay suitable for pond lining is available on the pond site, the cost could be as low as $1.00/sq yd for a comparable liner thickness if the clay could be moved into position by merely bulldozing.

7.1.3.2 Wood and Steel

Quotations were obtained for large wood and steel tanks and for creosote impregnated plywood panels (Refs. 7-14 and 7-15). Because of their high cost, this study did not evaluate these materials as a potential sludge pond liner. Values obtained are given in Table C-9, Appendix C.

7.1.3.3 Asphalt

During discussions with the contractors (Refs. 7-16 and 7-17), prices of $1.75 - $2.25/0.836 sq m (1 sq yd) were quoted for 7.6-cm-thick (3 in.) "asphalt coatings" installed in the ponds. However, to be consistent with the contractor's recommendations and

users of ponds constructed from asphalt liners, it was decided to use a 15.2 cm (6 in.) liner at a cost of $4.00/0.836 sq m (1 sq yd) installed (see Table 7-3). This cost includes any extra grading and compaction of the asphalt required for the ponding application that might be needed to prevent erosion from weathering or wave action.

7.1.3.4 Soil Cement, Concrete, Gunite, and Pozzolan

The thicknesses and costs for the cement-based products (Refs. 7-11 and 7-18 through 7-21) used in this report are as shown in Table 7-3. Soil cement was assumed to be disked into place in a thickness of about 6 in. Concrete was also assumed to be installed in a 15.2 cm (6 in.) thickness, but the Gunite was sprayed on in a 7.6 cm (3 in.) coating. Three inches of Gunite was selected because company representatives indicated that Pacific Gas and Electric Company has had high success with this thickness of Gunite for lining dam surfaces and water canals.

Several companies have mixed appropriate quantities of fly ash as a pozzolan together with sand, lime, aggregate, and water to form a cementitious material for use in road beds, embankments, and reservoirs. This material has been considered as a possible sludge pond liner. It has been estimated that a 6-in.-thick liner could serve as an excellent leachate barrier. Further information on pozzolan products is given in Section C.3.9.

7.1.4 Engineering Costs

The detailed engineering costs for a power plant sludge pond will depend somewhat on whether the engineering work is performed by an independent engineering firm or by the company's in-house engineering department. In the latter case it is further influenced in the manner in which the overhead accounting charges are applied to a project.

If it is an in-house effort, normally overhead expenses are not added onto the project cost. There is also the possibility that the in-house engineering department is considered completely within the overhead account of the company, and then the project is not charged directly with any engineering costs.

Other variables affecting the design cost are: charges for any study effort prior to the detailed design phase, soil borings, experimentation to ascertain the quality and permeability of the compacted native soil, and the amount of detail design data required to be provided to each of the supporting contractors.

It is realized that the engineering phase of the pond design must be accomplished regardless of the type of pond liner to be used, and that corporate funds must still be made available for this effort.

Because of the uncertainties in the variables associated with charging off the engineering and/or experimentation expenses, and because these expenses are not directly related to the specific type of pond liner used, no costs have been included in this study for the engineering and related experimental work.

Any quality control laboratory testing required, on the effluent from the scrubber or intake water to the cooling tower, is charged against the operation of the scrubber or tower, respectively.

7.1.5 General Contractor Costs

The costs for the general contractor to construct the ponds (Refs. 7-2 and 7-11), the access roads, and related dirt moving tasks will depend to a large extent on the terrain, soil conditions, and local labor market. However, an average value for a balanced cut and fill operation to form the side walls and to compact the soil in the pond is quoted as \$0.635 - 0.764/cu m (\$0.75 - \$1.00/cu yd) of dirt moved. A number of the general contractors indicated that they would

install a limited amount of unpaved access roading within the $1/cu yd cost number. Limited access road construction includes bulldozing, grading, and compacting a road of only a few miles primarily to permit the movement of earth handling equipment needed for the pond construction.

This cost number includes all of the bulldozing, scraping, piling the soil to one side then using this soil to construct the dikes around the ponds, compacting the pond sidewalls and bottom, and preparing any slope roads into the ponds.

7.1.6 Ancillary Equipment

7.1.6.1 Piping and Pumping

As indicated in Section 6.5.6.1, the exact size of the pipe to handle the flow of the sludge from the scrubbers to the pond and of the effluent from the pond will depend upon the specific design conditions related to each pond. In this study it was assumed that the pond was 1.6 km (1 mile) from the power plant and that the effluent discharge line would also be of that length. There would be six scrubbers per 1000 MW power plant. The cost for the piping, valves, fittings, etc., assumed that the pipe is laid along the surface of the ground with proper supports added, but it does not include items such as crossing of a major road that must be ditched and repaired.

The cost for the purchase (Ref. 7-22) and installation of nine pumps (six from the scrubbers and three return water pumps or spares) is about $20,000. All pumps are to be located in a single pump house. The cost for the pump house and installation of associated utilities was estimated to be $50,000.

7.1.6.2 Flow, Temperature, and Level Instrumentation

Sections 6.5.6.3 and 6.5.6.4 briefly describe the types of instrumentation that might be installed to monitor the flow of the

limestone sludge to the pond. The cost for the Parshall Flume flow transmitter, temperature, and level indicators and the associated instrumentation has been quoted from the instrument contractors at about $5000 installed (Ref. 7-23). It was assumed that the instrumentation could be located on a single centralized control panel to permit operation of the sludge pond facility from a single location, such as the pump house.

7.1.6.3 Soil Resistivity

Section 6.5 reviews some potential types of seepage monitoring systems that might be used to determine if any pond leakage occurs. For this study, it was assumed that a soil resistivity system would be used with the rods (pins) positioned on 152.5 m (500 ft) centers. The cost for each copper rod was estimated to be $100 installed. An instrument to measure and record the soil resistivity (Ref. 7-23) has been included in the system costs; the total cost was estimated to be $15,000 for a 888,000 sq m (220 acre) size pond.

7.1.7 Labor Costs

An estimate was made of the cost for operating personnel to monitor and control the total disposal pond operations; the estimate was $80,000/year.

7.1.8 Cost Comparisons

7.1.8.1 Initial Investment

Fifteen types of liners of different thicknesses were investigated relative to disposal ponds capable of containing the sludge from the scrubbing of flue gases. The costs for ponds constructed with these liners are summarized in Table 7-4. The costs are shown for a pond with a 3-year production capacity and for one with a

Table 7-4. LINER MATERIAL COMPARISONS

All costs are rough order of magnitude only. Dike height is 13 ft, including 3 ft freeboard.

Material	Index of installed liner costs[a]	Sludge production capacity, years			
		3	3	3	10
			Initial investment		
		Installed liner cost,[b] $\$ \times 10^6$	Pond cost,[c] \$/acre	Total cost,[c] $\$ \times 10^6$	Total cost,[c] $\$ \times 10^6$
Flexible					
Polyethylene (10 mil)	1.0[d]	0.90[d]	5,300	1.19	3.28
Polyvinyl chloride (10 mil)	1.49[d]	1.34[d]	7,400	1.63	4.60
Polyvinyl chloride (20 mil)	1.98[d]	1.78[d]	9,400	2.07	5.93
Petromat fabric (125 mil)	2.48	2.23	11,500	2.52	7.27
Butyl rubber (30 mil)	3.46	3.11	15,500	3.40	9.91
Chlorinated polyethylene (30 mil)	4.04	3.61	17,800	3.91	11.49
Hypalon (30 mil)	4.04	3.61	17,800	3.91	11.49
EPDM rubber (30 mil)	4.94	4.45	21,500	4.74	13.89
Fiberglass polyester (65 mil)	5.88	5.29	25,300	5.58	16.44
Nonflexible					
Soil cement (6 in.)	1.26	1.13	6,400	1.42	3.98
Pozzolan stabilized base (6 in.)	4.53	4.08	19,800	4.37	12.79
Asphalt (6 in.)	4.94	4.45	21,600	4.74	13.89
Concrete (6 in.)	5.25	4.73	22,800	5.02	14.74
Clay (18 in.)	7.38	6.63	31,400	6.92	20.49
Gunite (3 in.)	7.81	7.02	33,200	7.31	21.64

[a]Liner index: \$/sq yd installed/0.80

[b]Excludes land, pond construction, and ancillary equipment costs

[c]Excludes land costs

[d]Includes cost of covering liner with soil

To convert from	to	Multiply by
mil	cm	0.00254
in.	cm	2.54
acre	sq m	4046.8
ft	m	0.3048

10-year capacity. Also shown is the cost for the installed liner only and the cost per acre based upon the 3-year capacity size pond.

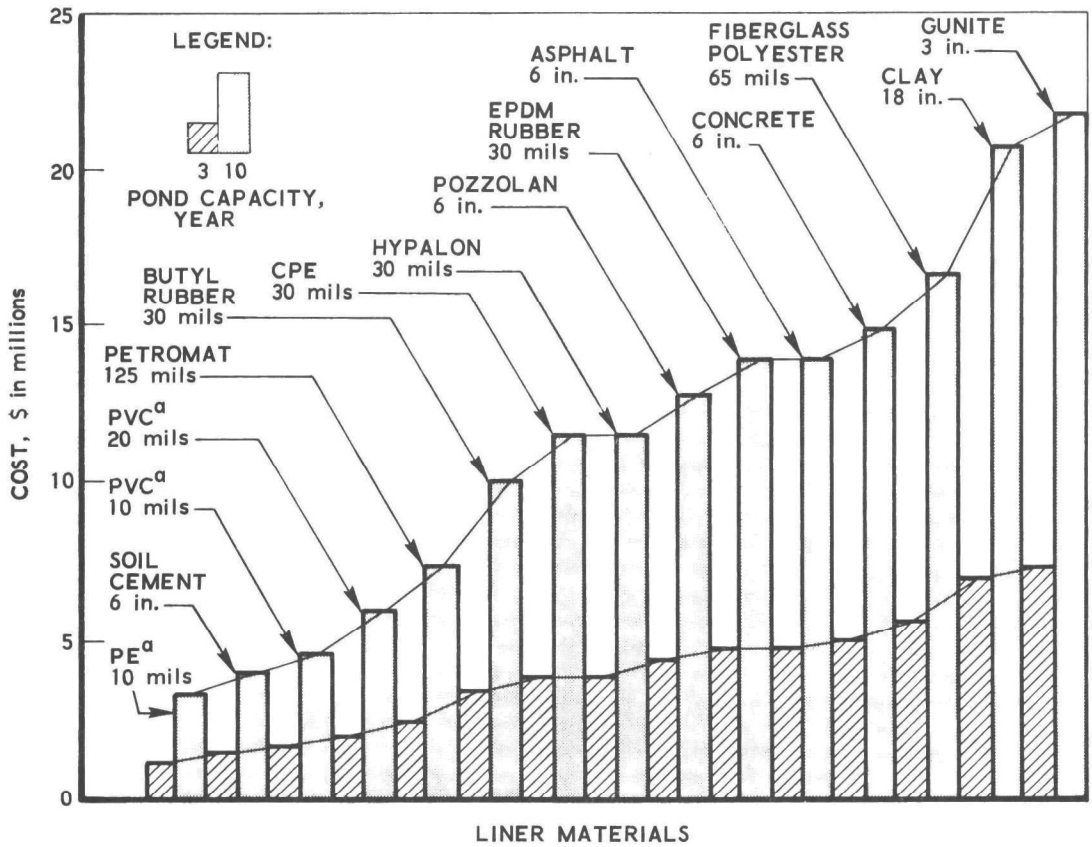
Table 7-4 also shows the relative cost for the different liners using 10-mil-thick polyethylene as the datum base. Figure 7-2 is a graphic representation of the initial investment of total pond costs tabulated in Table 7-4.

The ponds were configured with 3.96-m-high (13 ft) dikes including a 0.9 m (3 ft) high freeboard. The pond bottom was sized to be 888,000 sq m (220 acres) for the 3-year production capacity pond and 2.71 million sq m (669 acres) for the 10-year capacity pond.

The ratio of surface area-to-depth of pond to contain a constant volume (acre-feet) of sludge will affect the cost of the individual ponds. Table 7-5 shows the breakdown of initial investment for ponds with 3.96-, 7.01-, 13.10-m-high (13, 23, 43 ft) dikes including a 0.9 m (3 ft) freeboard for a 3-year and a 10-year capacity pond. The two liners selected are 20-mil-thick polyvinyl chloride and 30-mil-thick Hypalon. The dike construction costs increase as the height increases; however, there is a corresponding liner material cost decrease because of a decreasing total surface area to be covered.

It was assumed that all of the land needed to contain the sludge during the full 30-year life of the power plant would be purchased initially. However, the sludge ponds would be constructed periodically. Land cost was estimated at $1000 and $5000/acre. The higher value represents the probable maximum cost value for disposal site land. The land cost decreases as the dike height increases because of a smaller area needed for the ponds.

Figure 7-3 illustrates the variations of capital investment for the liner only, ancillary equipment, and land as a function of dike height when a 20-mil-thick PVC liner is used and land costs are $1000 per acre. From these curves it is evident that for each



NOTE:

DIKE HEIGHT IS 13 ft INCLUDING 3 ft FREEBOARD.

[a]INCLUDES COST FOR SOIL OVER LINER.

TO CONVERT FROM FEET TO METERS MULTIPLY BY 0.3048.

Figure 7-2. Initial investment, total pond cost

Table 7-5. POND INITIAL INVESTMENT COSTS
($\$ \times 10^6$)

Cost breakdown[a]	3-year capacity			10-year capacity		
	Dike height,[b] ft			Dike height,[b] ft		
	13	23	43	13	23	43
Pond						
Dike construction	0.199	0.497	1.194	0.482	1.224	2.941
Piping/pumping	0.076	0.076	0.076	0.088	0.088	0.088
Instrumentation	0.005	0.005	0.005	0.005	0.005	0.005
Resistivity monitoring	0.015	0.013	0.010	0.017	0.014	0.012
Subtotal	0.295 0.295	0.591 0.591	1.285 1.285	0.592 0.592	1.331 1.331	3.046 3.046
PVC (20 mil) liner installed[c]	1.776	0.955	0.560	5.340	2.910	1.704
Hypalon liner installed[c]	3.608	1.939	1.137	10.845	5.910	3.461
Total	2.071 3.903	1.546 2.530	1.845 2.422	5.932 11.437	4.241 7.241	4.750 6.507
Land[d]						
At $1000/acre	1.660	0.952	0.639	1.660	0.936	0.608
At $5000/acre[e]	8.300	4.760	3.195	8.300	4.680	3.040

[a]All costs are rough order of magnitude.

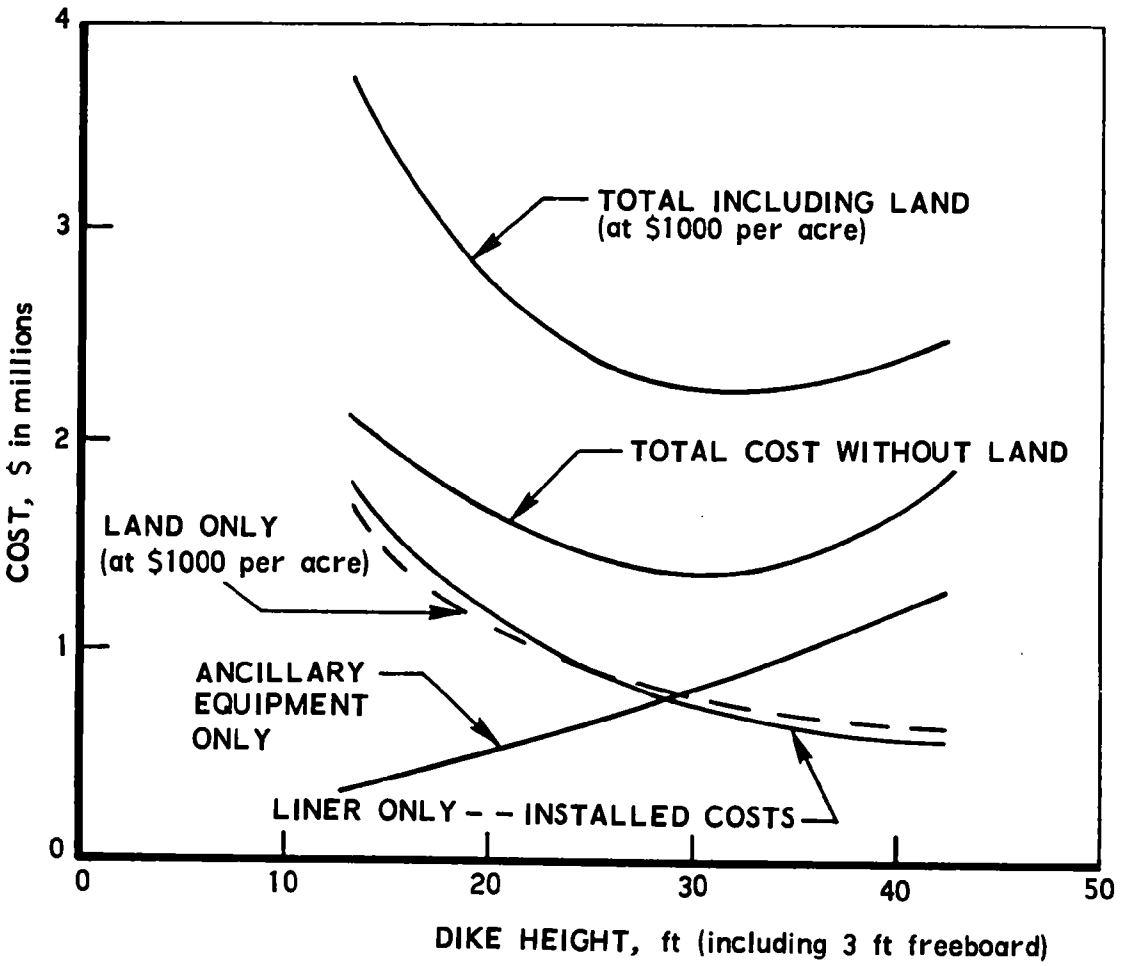
[b]Side walls have 2:1 slope for 13 ft height; 2-1/2:1 for 23 and 43 ft heights

[c]Values applicable to equivalent cost liners

[d]Land cost for 30-year capacity

[e]Represents maximum that would probably be paid for disposal site land.

To convert from	to	Multiply by
ft	m	0.3048
acres	sq m	4046.8



Notes: Sufficient land purchased for 30-year capacity
All costs are rough order of magnitude

To convert:

From	To	Multiply by
ft	m	0.3048
acres	sq m	4046.8

Figure 7-3. Capital investment for 3-year capacity pond--example for 20-mil-thick PVC liner

pond concept there is an optimum point on the capital cost curve that represents the minimum investment.

The function of the pond influences the height of the dikes. For example, the American Magnesium Company facility at Gail, Texas, is being built with dikes of 1.52 - 3.66 m (5 - 12 ft) to provide a large surface area for water evaporation. Whereas, a planned Northern States Power Company disposal pond in Minnesota will not require the evaporation surface and will contain sludge to a depth of 12.19 m (40 ft).

7.1.8.2 Leasing Alternative

McKittrick Mud Company, Bakersfield, California, has proposed (Ref. 7-2) an alternative concept to the need for the utility companies to invest its capital in sludge disposal ponds. McKittrick personnel stated that their company would build the sludge disposal ponds and then lease them to the power plant operators. Furthermore, McKittrick would assume all risks in any potential contamination from pond leakage. The utility companies might then charge off the pond lease rental fee as part of the power plant's direct annual operating expense. This concept was not evaluated in this study, but consideration will be given in a continuation of these analyses, to leasing ponds or pond services rather than purchasing and operating ponds.

7.1.8.3 Disposal Costs

Table 7-6 shows the average 30-year disposal cost in dollars/short ton (50 percent solids) for the installation and operation of the sludge ponds. The ponds selected for this example have PVC or Hypalon liners, and dike heights range from 13 to 43 ft. Land costs have been assumed at $1000 or $5000/acre. The higher value represents the maximum that would probably be paid for disposal site land. From this table and Figure 7-4 it can be seen that the cost for disposal is a function of: land cost, liner used, and dike height.

Table 7-6. AVERAGE DISPOSAL COSTS--30 YEAR

Total land purchased for 30-year sludge capacity. Pond capacity of 22,000 acre-ft required for 30 years of 50 percent solids sludge with ash included. About 1025 million short tons produced per year--average over 30 years. Costs based on an annual charge of 18 percent capital investment. Includes operating labor costs. Based on 1973 dollars. About 4560 operating hours per year average over 30 years.

Pond Components					Polyvinyl chloride[b] Thickness: 20 mil Cost: $1.60/sq yd installed		Hypalon[b] Thickness: 20 mil Cost: $3.25/sq yd installed	
Liner only	Ancillary equipment only	Land cost, $/acre		Dike height, ft	Mills/kWh produced	$/ton of sludge	Mills/kWh produced	$/ton of sludge
		1000	5000[a]					
x	-	-	-	13	0.51	2.27	1.02	4.54
x	x	-	-	13	0.59	2.63	1.10	4.89
x	x	x	-	13	0.66	2.92	1.16	5.16
x	x	-	x	13	0.92	4.08	1.43	6.46
x	-	-	-	23	0.28	1.25	0.55	2.45
x	x	-	-	23	0.45	2.00	0.72	3.20
x	x	x	-	23	0.48	2.14	0.76	3.38
x	x	-	x	23	0.63	2.80	0.91	4.05
x	-	-	-	43	0.17	0.76	0.33	1.47
x	x	-	-	43	0.53	2.36	0.69	3.07
x	x	x	-	43	0.55	2.45	0.71	3.16
x	x	-	x	43	0.66	2.94	0.81	3.60

[a] Represents maximum that would probably be paid for disposal site land.

[b] Values applicable to equivalent cost liners.

To convert from	to	Multiply by
sq yd	sq m	0.8361
mil	cm	0.00254
acres	sq m	4046.8
short tons	metric tons	0.9072

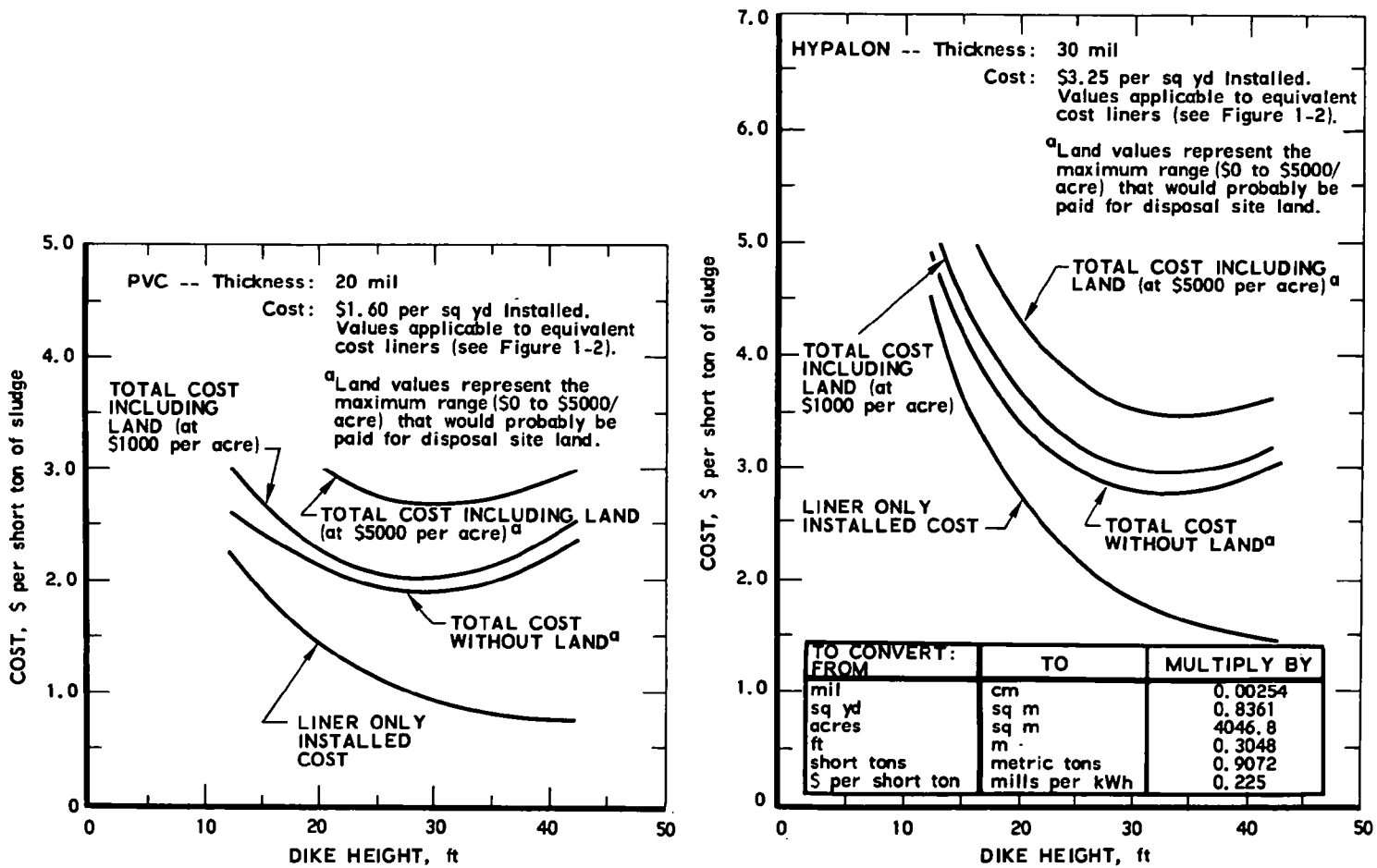


Figure 7-4. Sludge disposal costs--ponding (30-year average)

These disposal costs were calculated on the basis of an annual average cost of 18 percent of the initial investment being charged per year for interest, depreciation, replacement, maintenance, insurance, and taxes. The annual percentage that was used in this study was based on a generally accepted value by some power utilities and the EPA for estimating capital charges on operating equipment. Calculations were also made to determine an average cost per kWh to dispose of the sludge by ponding during the 30-year life of the power plant. Table 7-6 shows these values. The trends are the same as those indicated for the disposal costs as a function of the short tons of sludge produced.

Additional calculations were made to determine the disposal costs during the first year that the sludge disposal pond is in operation. The costs are in the range of $0.51 to $2.31/ton for a 3-year capacity pond, and $1.01 to $3.69 for a 10-year capacity pond. Table 7-7 presents the results of this study which was based on ponds with PVC or Hypalon liners, pond dike heights ranging from 13 to 43 ft, and land costs assumed to be $1000 and $5000/acre.

Data in Table 7-7 can be compared directly with the data in Table 7-6, which shows the average cost for the sludge disposal over a 30-year period. It can be seen that the first year costs are lower than the 30-year average value because of the larger quantity of sludge to be disposed of during the first year and a capital investment less than the 30-year average, although the capital charges are higher initially than the 30-year average. (For the quantities of sludge produced per year, refer to Section 7.1.1.)

7.2 SLUDGE CONDITIONING AND DISPOSAL COST ESTIMATES

The identification and technical descriptions of sludge fixation (conditioning) processes that have been studied thus far are

Table 7-7. SLUDGE DISPOSAL COST DURING FIRST YEAR ($/short ton of sludge)

Total land purchased for 30-year sludge capacity. Capital investment charges of 26.5 percent--first year only. The 6400 operating hours will give 1.438 million short tons of sludge per year. Sludge contains 50 percent solids and includes ash. Labor costs at $80,000/year. All costs based on 1973 dollars.

Material	Land cost, $/acre	3-year capacity			10-year capacity		
		Dike height, ft			Dike height, ft		
		13	23	43	13	23	43
PVC[b]							
20-mil thick; $1.60/sq yd installed	1000	0.74	0.52	0.51	1.46	1.01	1.04
	5000[a]	1.96	1.22	0.98	2.68	1.70	1.49
Hypalon[b]							
30-mil thick; $3.25/sq yd installed	1000	1.08	0.70	0.62	2.47	1.56	1.37
	5000[a]	2.31	1.40	1.09	3.69	2.25	1.82

[a] Represents maximum that would probably be paid for disposal site land.

[b] Values applicable to equivalent cost liners.

To convert from	to	Multiply by
sq yd	sq m	0.8361
acres	sq m	4046.8
ft	m	0.3048
mil	cm	0.00254
short tons	metric tons	0.9072
$/short ton	mills/kWh	0.225

given in Section 6.6. Cost estimates are discussed below for disposing of chemically fixed sludge based on relevant data available from these processes. Cost estimates vary considerably because of factors such as the fixation processing system and contractor operating efficiencies, sludge characteristics (e.g., water content, ash content, chemical constituents), disposal site location and characteristics, land costs, transportation, site monitoring, etc. Additionally, some power companies provide their own fixation process.

Since the fixation of power plant sludges is an emerging business, cost quotes quite often are related to the demonstration aspect of new developments and/or the public relations benefits that may accrue. Also, cost reductions that can be gained through process efficiency improvements may occur as an industry grows. Therefore, cost quotes are given as a range of values, and for the purpose of this report they are given in general terms related to what the fixation industry is experiencing. It is expected that within the following year industrial progress will have been made, and that direct charges resulting from actual disposal operations will be available.

Documents that quote fixation disposal costs have been reviewed. These are articles or brochures published by IUCS, Chemfix, and Commonwealth Edison, and portions of the proceedings of the National Power Plant Hearings in Washington, D.C., October and November, 1973. (See Refs. 7-24 through 7-32.) Additionally, costing data have been obtained through personal communications. The publication of fixation costs is somewhat vague, for reasons just mentioned and because of the varying conditions that exist in the sludge disposal operation. However, the values given tend to focus on the general region of the costs. Comments on each are given in the following paragraphs.

In Refs. 7-24 and 7-25, IUCS quotes the cost of conversion of the sludge to their conditioned material--"Sulf-O-Poz."

A range of $1.50 to $2.50/ton is given for new plants in the general size range of 1000 to 2000 MW using lime scrubbers. This may not include the cost of removing the Sulf-O-Poz from the plant site or all of the necessary handling required at the disposal site.

In Refs. 7-26 and 7-27, it is reported that Chemfix, which is currently treating industrial waste sludges, has quoted prices of 2 to 10 cents/gal of sludge processed, and that the average is about 4 cents/gal. These values do not include the cost of removing the material or handling it at the disposal site. Although Chemfix has not treated power plant sludges commercially, they have shown in their own laboratories that the Chemfix process is applicable. The cost information given in Ref. 7-27 is not directly convertible to applications to a power plant disposal program. Early indications made in this survey are that the Chemfix process could be used and that the cost could be less than $5.00/ton of sludge processed with the treated material deposited at a nearby disposal site. Furthermore, cost reductions may be realized through minimizing the water content of the sludge, minimizing the pumping distances, and accounting for large volume operations.

In Ref. 7-28, an estimate of sludge disposal costs at Commonwealth Edison's Will County Station is given as $7.00/ton on a dry basis. It is assumed, though not confirmed, that this would be approximately $3.50/ton on a 50 percent solids basis. However, contact with the author since that document was published indicates somewhat higher costs at this time. For example, recent costs of operation have varied from $5.25 to $10.00/ton of sludge (50 percent solids); the lower value is for a period in which conditions were trouble-free, whereas the higher value is for a period during which the operation experienced machinery breakdown and repair. In a more recent document, Ref. 7-29, a value of $17.10/ton on a dry basis ($8.55 wet) is given. These costs are for operations and maintenance only; they do

not include land acquisition, pond construction, or capital equipment. Unofficial estimates at Commonwealth Edison, considering improved processes and reliable operations, place the projected cost of disposal operations and maintenance at about $5.00/ton (50 percent solids).

The data from the references noted are difficult to relate to varying water content of the sludge, chemical constituents of the sludge, transportation and handling effects, and many other factors. Surveys of disposal processes have included contacts with the three companies noted and also with the Dravo Corporation in Pittsburgh, Pennsylvania, which offers its own fixation process using their Calcilox additive, and with the Duquesne Light Company, Pittsburgh, Pennsylvania, which is attempting its own disposal program using Calcilox purchased from the Dravo Corporation. A verbal report made recently by the Dravo Corporation (Ref. 7-32) identified a total disposal cost to the customer of $1.50 - $3.00/ton of wet sludge. This included pumping of the sludges as far as 10 miles from the plant site. These values have not been published by Dravo, and any related qualifications have not been identified. In Ref. 7-33, the Duquesne Light Company identified an estimated total disposal cost of their Phillips Station lime sludge of $14.00 - $15.00/ton on a dry basis (approximately $7.25 wet). This involves a fixation process, curing in a separate basin followed by excavation and hauling to a disposal site approximately 1 mile from the plant.

A summary of the cost data just discussed is given in Table 7-8. Continuing surveys of these processes will be directed toward refining these cost estimates and identifying conditions and qualifications attached to each quote so that the existing variations can be explained and possibly decreased, and to properly relate disposal requirements to technology, site, and operating conditions.

Table 7-8. SLUDGE FIXATION COST ESTIMATES

All values are condition and site dependent

Source	Quoted costs			1973, $/ton (50 percent solids)	Disposal conditions
	1973, $/ton	Percent solids	References		
Commonwealth Edison, Will County Station	11.82	Dry	7-29	5.91	On-site disposal--vendor quote
	17.10	Dry	7-29, -30	8.55	Current estimate[a]
	10.50	Dry	7-31	5.25	Best operating experience[a]
	20.00	Dry	7-31	10.00	Worst operating experience[a]
	5.00	50	7-31	5.00	Company target[a]
Duquesne Light Co., Phillips Station	14.00 - 15.00	Dry	7-33	7.25	Total disposal
IUCS, Inc.	1.50 - 2.50	30 - 50	7-24, -25	1.50 - 2.50	On-site disposal
Chemfix	~5.00	30 - 50	7-26	~5.00	On-site disposal
Dravo	1.50 - 3.00	30 - 50	7-32	1.50 - 3.00	Total cost to customer; includes pumping up to 10 mi

[a]On-site disposal; capital costs excluded

It should be noted that the technology being developed or offered by the chemical processors is or will be available to the power industry (see Section 6.6). Although the processors are willing to participate in a turnkey operation, they recommend providing a service to the power company such that for a price the processor will treat the material and remove it to a disposal site owned either by the power plant or by the processor. This service can also include the necessary monitoring of the disposal site for environmental impact.

Based on the preliminary estimates and referring to the numerous developments and applications for sludge fixation identified in Section 6.6, it appears that the cost of disposing of a sludge (50 percent solids) in this manner ranges from approximately $1.50 to $7.25/wet ton. Excluding unusual conditions it should be reasonable to narrow this general cost range to about $2.50 to $5.00/ton for typical operations.

The following example considers the cost of fixation/disposal of all sludge and ash produced at a 1000 MW station using a limestone scrubber. A total of 1.44 million tons of 50 percent solid sludge is produced and it is assumed that the output of the plant is 6.4 billion kWh/year, and that the coal has a 3 percent sulfur content and 12 percent ash. The annual cost of this form of disposal would be 0.56 to 1.12 mills/kWh, using a disposal cost of $2.50 and $5.00/ton, respectively. If a lime scrubber is used, the cost of disposal would be from 10 to 20 percent less, principally because the tonnage would be reduced. Also, reductions in disposal costs should be possible by: (a) reducing the tonnage by collecting the fly ash upstream of the scrubber and (b) reducing the water content of the sludge.

7.3 COST COMPARISONS--PONDING AND FIXATION

Based on information provided in Section 7.2, it is apparent that the cost of disposal of power plant sludge by fixation is indefinite at this time because that form of sludge disposal is in an emerging industry with little information based on actual practice

by the power utilities. Similarly, the cost of disposal by lined ponding (see Section 7.1) is indefinite but for different reasons. The art and technology of ponding are well established, but there is little experience with power plant sludge disposal through the use of lined ponds. There are many choices available that offer a wide range of costs with apparently small differences in net results. Therefore, at this time, comparisons are made by observing the ranges of values available and making rational comparisons in light of the variations in both the requirements and potential disposal methods.

It must be acknowledged that these two methods, which appear to be the best currently available or now in development, do not necessarily offer the same degree of environmentally sound disposal. For example, fixation, which may be the more expensive process of the two, appears to offer a permanent solution, but there is no proof that the environmental safeguards introduced by the fixation process will protect indefinitely. Whereas flexible liner ponding, which may be the less expensive of the two, may provide safeguards at a particular site for as long as approximately 25 years, and at that time some as yet undefined technology may have to be applied to provide environmental protection afterward. Whether nonflexible liners will be adequate for longer than 25 years is not known.

The power industry, therefore, is offered the following three general choices if environmental safety is to be achieved:

a. Fixation that may protect indefinitely and be suitable for land reclamation, but is unproven.

b. Flexible liners that may protect for up to 20 - 25 years but may require additional considerations for permanent environmental protection and land reclamation.

c. Nonflexible liners that may protect for periods greater than 25 years, but the systems are still unproven. Permanent environmental protection and land reclamation may require additional considerations.

Comparisons of fixation and lined ponding can not be made on an equal basis since the two methods do not always offer the same results. If the two could offer the same environmental protection indefinitely and if land reclamation is not of primary interest at a particular disposal site, then a reasonably equal comparison could be made.

Regardless of the many variations and differences that exist between the two processes, both are being considered throughout the power generating industry. Therefore, cost comparisons are in order at this time to assist in making the differentiation between the two, and in making the eventual determination of what the disposition should be toward a disposal site at the time it is filled to capacity.

Table 7-9 gives the sludge disposal cost ranges for both the fixation and the lined pond processes. Data on the fixation process are based upon current cost quotations from contractors and power companies undertaking this type of operation (see Section 7.2). The values given for the ponding process are estimates of first year costs based on ponds lined with PVC or Hypalon (see Section 7.1). The ponds have dikes varying from 13 to 43 ft in height, and a capacity for 10 years sludge production was selected. This is considered representative of a practical, initial design approach. The cost of land to accommodate the lined ponds that would be necessary to contain the full 30-year capacity was included in the capital investment.

A review of the values in Table 7-9 indicates that the disposal costs by the ponding process vary from $1.00 to $3.70/ton depending upon the dike height, liner material used, and cost of the land. The comparable numbers quoted for a typical fixation process as in Section 7.2 is $2.50 - $5.00/ton. Thus it appears that on a current cost basis, ponding is approximately half the cost of the fixation processes.

Table 7-9. DISPOSAL COST COMPARISONS--SLUDGE INCLUDING ASH; 50 PERCENT SOLIDS
($/short ton; 1973 dollars)

Disposal site suitable for reclamation. Soil cover not included. Current price quotes.

Fixation	
Cost, $	Remarks
1.50	Lowest quote Ideal conditions Disposal site adjacent to plant No land cost included
3.00	Maximum quote by two processors Fly ash supplied by plant Disposal site up to several miles distance Land cost included in one case
5.00	Quote by one processor Disposal site up to 1 mile distance Target cost for one processor No land cost included
7.25	Total disposal cost quote by one power company

[a] Values applicable to equivalent cost liners.

[b] Represents maximum that would probably be paid for disposal site land.

First year costs shown. Annual capital charge 26.5 percent first year. Ten-year sludge production capacity pond. Thirty-year land cost included - no residual value. Future effort may be required for permanent environmental protection or land reclamation.

Ponding	
Cost, $	Remarks
PVC liner, 20 mil thick[a]	
1.00 - 1.50	Land cost at $1000/acre
1.50 - 2.70	Land cost at $5000/acre[b]
Hypalon, 30 mil thick[a]	
1.40 - 2.50	Land cost at $1000/acre
1.80 - 3.70	Land cost at $5000/acre[b]

To convert from	to	Multiply by
short tons	metric tons	0.9072
acres	sq m	4046.8

The 30-year average ponding disposal costs are given in Table 7-6. Comparable values for fixation processes are not available at this time.

The many factors that affect the above disposal values are discussed in Sections 7.1 and 7.2, and in Appendix C. All costs are given in 1973 dollars, and fluctuations of the economy will impact the costs of both the fixation and ponding processes. Also, any costs associated with land reclamation or the effects of land values and whether the land is owned by the power company, the processor, or others, are economic considerations additional to the values shown above.

All values given are approximations and will be refined in succeeding efforts to include the effects of ash content and water content of the sludge, quantities of sludge produced per kilowatt hour based on the sulfur input and plant operating conditions, pond piping/pumping requirements, refined capital charges, etc.

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SECTION 8

WATER QUALITY AND SOLID WASTE DISPOSAL CRITERIA

8.1 SUMMARY

The measure of what conditions constitute the environmentally sound disposal of sludges is defined by authoritative water quality standards and solid waste disposal regulations,‡ or by the judgment of regulatory officials when standards are nonapplicable or nonexistent. The procedure, therefore, in the development of this task effort has been to gather the existing standards to determine what qualities or conditions must be prevented or controlled, and to compare the criteria specified therein with the characteristics of as many sludges as possible, including the effects of the method of disposal on the environment. Also, regulatory officials have been contacted for

‡Water Quality Standards consist of four major components: (a) use designations, (b) narrative and numerical criteria, (c) a plan of implementation and enforcement and solid waste regulations defining various types of waste materials with requirements for disposal, and (d) an antidegradation statement.

information on methods of standards application. The collection of standards has produced documents from all states for which water quality standards are available at this time (90 percent of all states). Accordingly, solid waste regulations have been obtained from 20 percent of the states. This collection of solid waste regulations is considered representative for an initial determination of status based on information provided by the EPA NERC, Cincinnati. All told, the water quality standards identify numerical criteria for the quality of receiving interstate waters. These criteria when considered in terms of regulations that may be applied to the qualities of sludges include items such as heavy metals, toxic materials, total dissolved solids, pH, and various compounds such as sulfates and chlorides.

Some excerpts from summaries of state water quality criteria, showing variations in the approaches taken by several states, are given in Table 8-1. Additionally, there are the U.S. Public Health Service (USPHS) - 1962 Drinking Water Standards (Ref. 8-1) that provide concentration limits for chemical substances in a water supply. This portion of the USPHS standards is reproduced in Table 8-2. Also, some states have regulations concerning the quality of ground water. For example, Illinois (Ref. 8-2) requires that underground waters that are a present or potential source of water for public or food processes supply shall meet the general and public and food processing water supply standards. In general, other states, which do not have a specific regulation concerning the quality of underground water, apply stream or drinking water standards to the underground water for lack of more definitive regulations. Finally, in all cases, according to EPA standards, stream dilution is not to be considered a substitute for or an extension of, a waste treatment facility.

As for the regulation of solid waste disposal, standards are much less specific than water quality criteria. Regulations ordinarily limit the disposal of toxic, hazardous, or harmful substances

Table 8-1. EXAMPLES OF VARIATIONS IN STATE WATER QUALITY STANDARDS

Illinois Public and Food Processing Water Supply

Constituents (selected)	Concentration (mg/ℓ)
Arsenic (total)	0.01
Barium	1.0
Cadmium (total)	0.01
Chlorides	250.0
Iron (total)	0.3
Lead (total)	0.05
Manganese (total)	0.05
Mercury	0.0005
Nitrates plus Nitrites as N	10.0
Selenium (total)	0.01
Sulfates	250.0
Total Dissolved Solids	500.0

After Conventional Treatment — USPHS Drinking Water Standards - 1962

Underground Waters

Present or potential sources of water for public or food processing limited to USPHS Drinking Water Standards - 1962; owner monitoring of ponds required.

Kansas Water Supplies

USPHS Drinking Water Standards - 1962

Nevada

General practice:

Quality of discharge to surface waters at least as good as receiving water

Ponding: Effluent treatment, or pond lining; owner monitoring required; quality of seepage as good as receiving water.

Criteria being developed

Table 8-2. EXCERPTS FROM UNITED STATES PUBLIC HEALTH SERVICE DRINKING WATER STANDARDS - 1962

The following chemical substances should not be present in a water supply in excess of the listed concentrations where, in the judgment of the Reporting Agency and the Certifying Authority, other more suitable supplies are or can be made available.

Substance	Concentration (mg/liter)
Alkyl Benzene Sulfonate (ABS)	0.5
Arsenic (As)	0.01
Chloride (Cl)	250.0
Copper (Cu)	1.0
Carbon Chloroform Extract (CCE)	0.2
Cyanide (CN)	0.01
Iron (Fe)	0.3
Manganese (Mn)	0.05
Nitrate (NO_3)	45.0
Phenols	0.001
Sulfate (SO_4)	250.0
Total Dissolved Solids	500.0
Zinc (Zn)	5.0

The presence of the following substances in excess of the concentrations listed shall constitute grounds for rejection of the supply.

Arsenic (As)	0.05
Barium (Ba)	1.0
Cadmium (Cd)	0.01
Chromium (Hexavalent) (Cr^{+6})	0.05
Cyanide (CN)	0.2
Lead (Pb)	0.05
Selenium (Se)	0.01
Silver (Ag)	0.05

by requiring that those materials not be disposed of on the ground, or underground without the express approval of a designated authority such as the State Department of Health, the State Health Commissioner, County Health Commissioner, or the State Department of Commerce. This survey to date indicates that those offices, when judging the disposal of sludges, base their judgment on sludge quality as related to PHS water quality criteria.

The limitations imposed on sludge disposal are further intensified by the recent passage of legislation and the potential passage of others. For example, the Federal Water Pollution Control Act Amendments of 1972 (Ref. 8-3) essentially require the revision and reapproval of all state water quality standards: to change applicability from interstate waters to all waters including ground waters, to specifically prohibit or limit direct discharges of pollutants to streams, to limit subsurface disposal, and to include Federal EPA-prescribed criteria for specific toxic elements. Additionally, the federal drinking water standards are being revised, and legislation is in process to develop new limitations for the land disposal of solid waste.

Chemical analyses conducted in this program have shown sludge properties that make those tested unsuitable for direct discharge into streams, and because of a lack of understanding of the attenuation of harmful or undesirable components into soil, it is believed that disposal on the earth or in an underground cavity will be disallowed because of the potential contamination of ground waters. The undesirable components in the sludge that have appeared in analytical tests are total dissolved solids, sulfates, chlorides, arsenic, mercury, lead, selenium, and other materials of lesser concentrations. A typical analysis of heavy metals is given in Table 8-3.

With current water quality standards and solid waste management regulations that prohibit sludge disposal in water and

Table 8-3. ANALYSIS OF SAMPLES TAKEN FROM LIMESTONE SCRUBBER AT TVA SHAWNEE STATION, PADUCAH, KENTUCKY, 11 JULY 1973
(parts/million)[a]

Element	Clarifier underflow liquor
Arsenic (As)	0.2[b]
Beryllium (Be)	0.01
Cadmium (Cd)	0.005
Calcium (Ca)	2500[c]
Chromium (Cr) (total)	0.05
Copper (Cu)	0.05
Lead (Pb)	0.1[b]
Magnesium (Mg)	600[c]
Mercury (Hg)	0.06[d]
Selenium (Se)	0.3[b]
Zinc (Zn)	0.5

[a]Equivalent to mg/liter

[b]Exceeds USPHS Standards - 1962 (see Table 1-6)

[c]Total dissolved solids exceed USPHS Standards - 1962 (see Table 1-6)

[d]Exceeds some state standards

that are being interpreted to prohibit its disposal on land without safeguards, and with new and pending legislation that is or will be more restrictive, it is apparent that the sludges must be disposed of in such a manner as to prevent direct discharge to streams. It also appears that it will be necessary to prevent leaching through the soil to ground or surface waters. There are EPA-sponsored programs in progress to verify effective means of impounding, chemically treating, or conditioning the sludges so that their disposal will be accomplished in an environmentally sound manner.

8.2 REGULATIONS

8.2.1 Water Quality Standards

In conformance with the requirements of the Water Quality Act of 1965 which amended the Federal Water Pollution Control Act of 1956, all of the states, the District of Columbia, and the territories of Guam, Puerto Rico, and Virgin Islands established or are establishing water quality standards** for interstate (including coastal) waters. In December 1970, the responsibility for administering the Water Quality Act of 1965 was transferred from the Secretary of the Interior to the Administrator of the EPA. Most of the state standards have now been written, and they have been accepted by the EPA. The state standards are, therefore, the major sources of criteria by which the power plant scrubber effluents are to be judged at this time, and they deal with the quality of the receiving surface waters before or after conventional treatment. Further, the state standards,

**Significant background information for the state standards can be found in "California Water Quality Criteria," McKee and Wolf (Ref. 8-4); "Federal Water Quality Criteria," FWPCA, Dept. of the Interior, (Ref. 8-5); "Public Health Drinking Water Standards - 1962," USPHS Publication 956 (Ref. 8-1); and "Water Quality Standards and International Development," Agency for International Development (Ref. 8-6).

when citing criteria for domestic water supplies or for food processing, generally repeat or refer to the USPHS Drinking Water Standards that apply to water distribution systems.

Other legislation [e.g., the Federal Water Pollution Control Act Amendments of 1972 (PL92-500), generally referred to as the "New Water Act"], has established a goal of zero pollution discharge by 1985. While calling for interim guidelines and standards to regulate pollution discharges, it establishes the applicability of two definitions of particular interest for future consideration in sludge studies. They are:

a. The act regulates pollution discharges to all waters of the United States including ground waters (previously, control was only for interstate waters including coastal waters).

b. The discharge of toxic elements is not allowed in toxic amounts.

These provisions are particularly important because of the inclusion of ground waters in the coverage, and the allowance of some toxic discharge even though the Act specifies a national goal of zero pollution discharge. Limitations, guidelines, and recommended criteria are to be published periodically by the EPA in response to the provisions of the Act.

Summaries of Water Quality Standards of 90 percent of the states have been obtained. Additionally, summaries of the State Standards have been compiled by the EPA and were issued in August 1972. The federal summaries are convenient for surveying requirements because they compile values for a particular category (e.g., "Mercury and Heavy Metals," "Acidity/Alkalinity," etc.) for all states in a single pamphlet. However, the status of water quality regulations is continually changing; therefore, variations will often occur between published summaries and the current state regulations whether in use

or in the process of being published. Additionally, "no degradation of the environment" is emphasized. A sample listing of the types of criteria that exist is given in Table 8-4.

In actual practice, and to a great extent because of the goals and expected limitations to be imposed in accordance with the New Water Act, the power industry generally has chosen to operate the scrubbers and to dispose of the sludge such that there will be no discharge to streams and no seepage to underground waters. This appears reasonable in light of the results of The Aerospace Corporation analyses of sludge samples to-date (see typical analysis in Table 8-3 and discussions of sludge quality in Section 2). Those data indicate concentrations of heavy metals in excess of the criteria defined in state standards and in the USPHS-1962 Drinking Water Standards. Additionally, those sludges contain excessive concentrations of total dissolved solids (TDS) or sulfates or chlorides. The consensus among our contacts is that raw sludges will not be acceptable for disposal without safeguards even if they do not have excessive concentrations of heavy metals because they will have excessive concentrations of TDS or the anions just mentioned.

Closed-loop operation of the scrubber prevents discharge to streams. To prevent leaching problems, plans for sludge disposal include chemical fixation or pond linings. The goal for both disposal approaches, fixation or lining, is zero pollution; however, the long-term effects of these approaches have not been determined. To verify the adequacy of the disposal, most regulatory agencies require the disposal site operator to monitor adjacent streams and the ground water, and they will make spot checks. If any leaching does occur, the USPHS drinking water standards will probably be used as the limiting criteria because the effects of soil attenuation are not well defined. Some exception to this may be taken since each disposal is

Table 8-4. SELECTED STATE WATER QUALITY CRITERIA (SHEET 1 of 3)

State	Material or condition	Applicability	Criteria (selected)
Illinois	Stream quality where water is withdrawn for treatment	Public and food processing water supply (PWS)	As 0.01 mg/liter Ba 1.0 Cd 0.01 Chlorides 250.0 Fe 0.3 Pb 0.05 Mn 0.05 Hg 0.0005 Nitrates plus Nitrites as N 10.0 Se 0.01 Sulfates 250.0 TDS 500.0
	After conventional treatment	PWS	USPHS Drinking Water Standards - 1962
Ohio	Stream quality where water is withdrawn for treatment	PWS	As 0.05 mg/liter Ba 0.800 Cd 0.005 Cr (Hex) 0.05 Pb 0.040 Se 0.005 Ag 0.001 Hg 0.0005
	After conventional treatment	PWS	USPHS - 1962

Table 8-4. SELECTED STATE WATER QUALITY CRITERIA (SHEET 2 of 3)

State	Material or condition	Applicability	Criteria (selected)
(Federal - Department of Interior, Ref. 8-5)	Toxicity	PWS	As 0.05 mg/liter Ba 1.0 B 1.0 Cd 0.01 Chlorides 250.0 Cr (Hex) 0.05 Cu 1.0 Fe 0.3 Pb 0.05 Mn 0.05 Se 0.01 Ag 0.05 Zn 5.0 Sulfates 250.0 TDS 500.0
Alabama	pH	Receiving waters	6.5 - 8.5
Maryland	pH	PWS	5.0 - 9.0
New Mexico	pH	Receiving waters	6.6 - 8.6
Arizona	Dissolved oxygen	[cold water fishery] - [warm water fishery]	6 mg/liter - 6 mg/liter
Kansas	Dissolved oxygen	[cold water fishery] - [warm water fishery]	-- - 5 mg/liter

Table 8-4. SELECTED STATE WATER QUALITY CRITERIA (SHEET 3 of 3)

State	Material or condition	Applicability	Criteria (selected)
Pennsylvania	Dissolved oxygen	[cold water fishery] - [warm water fishery]	6 mg/liter - 5 mg/liter daily avg; 5 mg/liter - 4 mg/liter minimum
Arizona	Turbidity	Warm water streams Cold water streams	50 Jackson Turbidity Units (JTU) 10 JTU
Indiana	Turbidity	All classes	No visible increase
Florida	Turbidity	All classes	50 JTU
(Federal - Department of Interior, Ref. 8-5)	Radiation		Gross Beta 1000 pc/liter Radium -226 3 pc/liter Strontium -90 10 pc/liter Tritium 3000 pc/liter

a distinct case usually different from all others, being affected by many parameters such as sludge quality, disposal techniques, weather, topography, soil conditions, and ground and surface water proximity and quality. The burden of proof for those exceptions, if any, will be on the operator of the disposal site.

8.2.2 Solid Waste Regulations

The principal controls for the disposal of solid waste are solid waste regulations prepared by the states. Additionally, there are literally thousands of state laws dealing with individual subjects related in one way or another to solid waste disposal; those are listed in Ref. 8-7. Also, there are "State Solid Waste Management Plans" which are prepared through federal grants provided by the 1965 Solid Waste Disposal Act (PL89-272) for the purpose of establishing policies and procedures, and to provide a base for improved solid waste legislation. And in response to the Resource Recovery Act of 1970 (PL91-512) which amended the Solid Waste Disposal Act of 1965, the EPA Office of Solid Waste Management Programs is in the process of issuing guidelines for land disposal and thermal processing operations.

Of all the documentation just mentioned, the state solid waste regulations and the proposed EPA guidelines for land disposal are the most appropriate for regulating sludge disposal, and then only remotely. For example, 20 State Regulations have been reviewed in addition to the proposed guidelines. None gives specific criteria for the disposal of sludge; the most relevant portion of each regulation appears to be in the definition of hazardous materials and the requirement of the approval of a regulatory official before dumping. A typical example is the definition of hazardous wastes given in "Regulations of the Virginia Department of Health Governing Disposal of Solid Waste," effective April 1, 1971 (Ref. 8-8): "Hazardous waste includes those materials which, because of their inherent nature and/or quantities,

require special handling during disposal to avoid creating environmental damage or hazards to public health or safety." The regulation goes on to say that "hazardous waste shall be disposed of in a manner approved by the Health Commissioner." The lack of numerical criteria apparently is due to the lack of sufficient information to define any limits on what material can be contained by the various soils upon which the sludges may be dumped. Contacts made with power plant personnel and solid waste regulatory officials all indicate that because of nonexistent criteria, the disposal of the sludge should be made in consideration of its potential hazard to water quality, and that it should be disposed of such that seepage should not occur to surface or ground waters. As noted in Paragraph 8.2.1, the general practice to prevent seepage is to provide either an impermeable liner in the disposal area, or a chemical fixation process. Some isolated cases, as in Kansas and Alabama, are considering the disposal of raw sludge in a pond or the disposal of dried and compacted sludge in a pond in hopes that continued monitoring of the local ground waters will show no appreciable degradation of the environment. The opinion of regulatory and power plant personnel of other states, without exception, is that the disposal of sludge in that manner will not be environmentally sound. The progress of those two cases will be followed during the second half of this study.

8.2.3 Status and Plans

In consideration of existing state water quality standards and solid waste regulations, of the Federal Water Pollution Control Act Amendments of 1972, and of the chemical characteristics of sludges analyzed so far in this program, it is believed that power plant sludges must be disposed of in a manner such that seepage to surface or ground waters will not occur. And, the prevention of seepage is considered mandatory in the absence of data necessary to determine the attenuation of leachates in soils. These statements are based on the analysis

of sludges from two sites only; therefore, they cannot be considered generally applicable at this time. Further efforts in this task will include considerations of the properties of sludges generated at other power plants, reviews of actions taken by regulatory agencies in the process of issuing permits for sludge disposal, and assessment of all processes available to minimize or eliminate the undesirable qualities of sulfur sludges.

REFERENCES

8-1. "A Guide to the Interstate Carrier Water Supply Certification Program," 1962 Drinking Water Standards, U. S. Public Health Service Publication 956.

8-2. Water Pollution Regulations of Illinois, State Department of Health, Springfield, Illinois.

8-3. "Federal Water Pollution Control Act Amendments of 1972, 92nd Congress - Second Session," United States Code Congressional and Administrative News, No. 10, West Publishing Company (1972).

8-4. McKee and Wolf, California Water Quality Criteria, Publication 3-A, State Water Resources Control Board, Sacramento, California (1971).

8-5. Federal Water Quality Criteria, Report of the National Technical Advisory Committee to the Secretary of the Interior, Federal Water Pollution Control Administration, Department of the Interior, Washington, D. C. (April 1968).

8-6. Water Quality Standards and International Development, Agency for International Development, U.S. Department of Commerce (October 1971).

8-7. Solid Waste Laws, Autocomp Incorporated, prepared for Environmental Protection Agency (1972).

8-8. "Regulations of the Virginia Department of Health Governing Disposal of Solid Waste," The Health Laws of Virginia, 1971 edition, Department of Health, Richmond, Virginia (1 April 1971).

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SECTION 9

PROGRAM STATUS AND PLANS

9.1 INTRODUCTION

This section presents brief summaries of the work that has been accomplished for each task in this study and identifies the work to be performed in the following year for each task. Most of these statements are included in various areas of each of the preceding sections; however, they are combined in this section for convenience.

9.2 STATUS AND PLANS

9.2.1 Chemical Analyses

Two sample sets from the TVA Shawnee Station and one from the Mohave Station have been analyzed by various chemical techniques. These analyses are not yet completed so that full chemical characterization is not now available; however, the data to date indicate that several toxic trace elements are or can be sufficiently soluble to cause environmental concern in the handling and disposal of power plant sludges.

Two additional sample sets from the Shawnee limestone scrubber will be obtained: a set from a lime eastern coal scrubber system and a set from a double alkali eastern coal burning system. Analyses will also be conducted on samples exposed to simulated and environmental conditions of high oxidation potential and low pH. In addition, analyses will be made of sludges chemically conditioned by several different processes.

9.2.2 Toxicity Determination

Arsenic, mercury, lead, and selenium have been identified in soluble constituents sufficient in quantity to be considered a potential toxicity problem. Therefore, attention will be addressed to a buildup in liquor concentrations of these elements in particular and to other elements in the recirculation system of the Shawnee limestone scrubber.

An explanation of the system's chemistry will be attempted with regard to the concentration of disposed elements relative to the variables of operation. Samples from other power plants will also be analyzed and compared with the analyses made on the Shawnee samples.

9.2.3 Physical Properties

All physical property measurements have been made on the Shawnee sludge and all except the completion of drainability measurements have been made on the Mohave sludge. The physical properties relating to sludge disposal technology will be determined for the sludges from a lime scrubbing system and the double alkali system.

9.2.4 Detoxification Potential

The most likely potentially toxic elements have been identified, and several alternative methods of detoxification have been considered in a cursory manner. Further definition of the detailed

chemistry of these elements will be determined, and the various alternative methods available for detoxification will also be further considered. In addition, detoxification techniques for other elements that appear to pose a toxic hazard will be assessed when the extent of their hazard has been identified.

9.2.5 Disposal Methods Determination

Surveys have been made of the technology related to potential or actual disposal methods using ponding techniques or chemical fixation of the sludges. Ponding data include the use of flexible and nonflexible liners. Fixation surveys have covered the available technology provided by three different processors. Tentative comparisons have been made between the use of ponding and chemical fixation.

Further surveys and assessments will be made of ponding techniques specifically to obtain more accurate data regarding the containment of sulfur sludges and the potential life of the liners. Contact will be continued with the three chemical processors already surveyed and others will be surveyed as appropriate.

9.2.6 Disposal Costs

Tentative costs have been determined for the disposal of power plant sludges by means of using lined ponds and chemical fixation processes. The costs are not firm and are currently given as a range rather than in specifics.

Studies will continue for the purpose of determining more accurate cost data for ponding and fixation. Additionally, the effects of all pertinent variables related to costs such as coal sulfur content, plant operating conditions, absorbent characteristics, scrubber operations, fly ash collection methods, etc., will be studied.

9.2.7 Water Quality and Solid Waste Criteria

A significant number of state water quality standards and solid waste management regulations have been obtained and reviewed. Sludges are generally judged against the limitations imposed by drinking water standards, and passage of the Federal Water Pollution Control Act Amendments of 1972 makes all waters of the United States subject to environmental control. Review of these regulations indicated that sludges must not be discharged directly into water courses and must be contained so that they cannot leach through the soil into ground water or surface waters.

Surveys of state water quality and solid waste regulations will continue and reviews will continually be made of new guidelines, limitations, or regulations resulting from requirements of the New Water Act (FWPCA - 1972). A final determination will be made relating sludge disposal to environmental quality regulations based on considerations of properties of sludges generated at other power plants, reviews of actions taken by regulatory agencies in the process of issuing permits for sludge disposal, and assessment of all processes available to minimize or eliminate the undesirable qualities of sulfur sludges.

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APPENDIX A

COMPANY/AGENCY VISITS OR COMMUNICATIONS

Company/agency	Personnel contacted
Allyn Transportation Company Los Angeles, California	M. Lucus, Sales Representative
Anti Pollution Liner, Inc. Odessa, Texas	G. H. Forehand, Manager
Argonaut Division of General Motors Detroit, Michigan	E. R. Harris, Supervisor
The Asphalt Institute Long Beach, California	D. C. Campbell, District Engineer
Bechtel Corporation San Francisco, California	Satish Almaula, Scientific Development Dewey A. Burbank Gene H. Dyer, Manager, Process Development Michael Epstein, Project Manager Abdul H. Saltar Robert M. Sherwin, Scientific Development Louis Sybert, Scientific Development

Company/agency	Personnel contacted
Black Hills Bentonite Company Mills, Wyoming	D. G. Grenier, Technical Sales
Black Top Materials Company Sun Valley, California	R. Donahue, Technical Representative
Buehler Tank and Welding Works Orange, California	J. Evans, Technical Representative
California Cement Company Los Angeles, California	J. A. Dobrowolski, Manager of Technical Services R. H. Covell, Civil Engineer
California Institute of Technology Pasadena, California	Jack E. McKee, Professor Environmental Engineering
Chemfix, Division of Environmental Sciences, Inc. Pittsburgh, Pennsylvania	Jesse R. Conner, President Donald Opacic, Vice President And General Manager Lawrence P. Gowman, Vice President Ronald J. Poloski, Technical Director Robert K. Salas, Manager Marketing Services
Coastal Engineering Company Bakersfield, California	K. Jones, Technical Representative
Combustion Engineering Company, Inc. Windsor, Connecticut	William C. Taylor, Kreisinger Development Laboratory
Combustion Equipment Associates, Inc. San Francisco, California	Irwin A. Raben, Vice President
Commonwealth Edison Company Chicago, Illinois	Donald C. Gifford, P.E. Eugene B. Smyk, Chemical Engineer

Company/agency	Personnel contacted
Commonwealth Edison Company (Continued)	Christine Kondrat Joseph Agosta
Control Specialists, Inc. El Monte, California	A. M. Beavens, Technical Representative
Dow Chemical USA Midland, Michigan	R. B. Cramer, Technical Representative, Olefin Plastics Department O. Davis, Technical Representative, Plaquemine, Louisiana
Dravo Corporation Pittsburgh, Pennsylvania	Mel Robinson, Vice President William H. Lord, Projects Director J. G. Selmeczi, Manager of Research
Duquesne Light Company Pittsburgh, Pennsylvania	C. N. Dunn, General Superintendent R. G. Knight, Superintendent of Technical Services Robert O'Hara Steve L. Pernick, Manager Environmental Affairs Department
E. I. du Pont de Nemours and Company Los Angeles, California	K. Rogers, Technical Sales Representative
Ebasco Services, Inc. New York, New York	John A. Rasile, P. E., Consulting Environmental Engineer
Ecodyne Corporation Graver Water Division Union, New Jersey	M. Fischer, Senior Engineer R. Parcelli, Technical Representative

Company/agency	Personnel contacted
Environmental Protection Agency	
NERC, Research Triangle Park North Carolina	
Control Systems Laboratory	Everett L. Plyler, Chief, Gas Cleaning and Metallurgical Processes Branch
	Frank T. Princiotta, Chief, Nonregenerable Processes, Section
	Richard D. Stern, Development Engineer (Chief, Regenerable Processes Section)
	Julian Jones, Development Engineer
	John Williams, EPA Representative, TVA Shawnee Power Station
Office of Air Quality, Planning and Standards	James Durham
NERC, Cincinnati, Ohio	
Solid Waste Research Lab	Norbert Schomaker, Branch Chief, Disposal Technology
	Henry Johnson, Project Manager, Hazardous Waste
Advanced Waste Treatment Research Laboratory	Ron Hill, Senior Engineer
NERC, Corvallis, Oregon	Alden G. Christianson, Research Sanitary Engineer
	Guy R. Nelson, Research Chemical Engineer
Region 5, Chicago, Illinois	Chris Potos, Chief, EPA Water Quality Standards
Regions 1 through 10	Offices of Water Quality and Solid Waste; Publications; Public Relations

Company/agency	Personnel contacted
Environmental Water Control, Inc. Denver, Colorado	B. Reetz, Technical Representative
General Concrete, Ltd. Hamilton, Ontario	J. F. Boux, Chief Product Engineer
General Motors Corporation Warren, Michigan	Thomas T. Dingo, Manufacturing Development James H. Frazier, Staff Engineer William R. Johnson, Administrator Robert J. Phillips, Staff Engineer
J. H. Glenn and Associates Vitla Park, California	J. Harlan Glenn
B. F. Goodrich, General Products Company Marietta, Ohio	D. T. Skowlund, Marketing Supervisor
Goodyear Tire and Rubber Company Akron, Ohio	D. Herchler G. E. Lewis, Southern California Technical Representative
Illinois State EPA Water Quality Standards Office Chicago, Illinois	Carl Blomgren
Industrial Resources, Inc. Chicago, Illinois	Jacques M. Dulin, President
IU Conversion Systems, Inc. Philadelphia, Pennsylvania	Leon V. Hirsch, President L. J. Minnick, Executive Vice President Gerald Kleiman, Vice President Richard D. Vaughan, Consultant William J. Minnick

Company/agency	Personnel contacted
Kern Rock Company Bakersfield, California	R. Jones, General Manager
Koch Engineering Company, Inc. Wichita, Kansas	Steve Smith, Senior Project Engineer
L. A. Liquid Handling Systems Los Angeles, California	H. Dewey, Sales Agent
Louisville Gas and Electric Louisville, Kentucky	Robert P. VanNess, Manager, Environmental Affairs
Maness Excavating and Grading, Inc. Paramount, California	M. Haberman, Technical Representative
McKittrick Mud Company, Inc. Bakersfield, California	W. A. Wheeler, President H. C. Ellingston, Jr., Vice President
National Ash Association, Inc. Washington, D. C.	John Faber, Executive Director
National Car Rental Mud Cat Division Minneapolis, Minnesota	D. Hallen, Western Sales Manager C. O'Brien, Design Engineer
National Lime Association Denver, Colorado	Clifford J. Lewis, Environmental Consultant
Northern States Power Company Minneapolis, Minnesota	J. A. Noer, Mechanical Engineer Gary C. Ashley, Senior Research Engineer Richard Krueger
Ohio Edison Company Akron, Ohio	Neil M. Bevere, Fuel Coordination Supervisor
Ontario Hydro Toronto, Ontario	Lew Hartman, Surplus Sales Engineer

Company/agency	Personnel contacted
Owl Rock Products Company Arcadia, California	J. Reece, Transportation Agency
Pacific Gas and Electric Company San Francisco, California	C. Roberts, Vice President, Rates and Evaluation
	S. M. Andrew, Manager, Economics and Statistics Department
	J. A. Jedlicka, Senior Civil Engineer
	C. Lee, Area Gas Superintendent, Hinkley Compressor Station, Barstow, California
	R. Plunkett, Superintendent, Moss Landing Facility
Walter W. Perkins Company Los Angeles, California	J. Langford, Technical Representative
Pennsylvania Department of Environmental Resources, Bureau of Water Quality Assessment Harrisburg, Pennsylvania	Gary Merritt
Phillips Asphalt Paving Glendale, California	B. Phillips, Owner
Phillips Petroleum Company Bartlesville, Oklahoma	R. J. Bennett, Technical Advisor
	F. Holland, Technical Advisor
Portland Cement Association Pacific Southwest Region Los Angeles, California	E. R. Koller, National Accounts Executive
Quelcor, Inc. Media, Pennsylvania	J. Watson Pedlow, President

Company/agency	Personnel contacted
Radian Corporation Austin, Texas	R. Murray Wells, Chemical Engineer Nancy Phillips, Chemical Engineer
Rheem Superior Division of Rheem Manufacturing Company Los Angeles, California	J. Lessing, Technical Representative
SAS Corporation Muscle Shoals, Alabama	A. V. Slack, President
Southern California Edison Company Rosemead, California	John Norris Alexander Wier, Jr., Principal Scientist for Air Quality
Stabilization Chemicals Newport Beach, California	W. C. Craghill, General Manager Soil Science Products J. Harlan Glenn, Professional Engineer, Consultant T. Selfridge, Manager, Technical Operations
Staff Industries, Inc. Upper Montclair, New Jersey	C. E. Staff, President
Superior Gunite North Hollywood, California	D. M. Gross, Technical Representative
T. E. Brown, Inc. San Leandro, California	T. E. Brown, Owner
Tennessee Valley Authority	James S. Morris J. B. Barkley James Crowe W. H. Elder Neal D. Moore Philip E. Stone

Company/agency	Personnel contacted
Tennessee Valley Authority (Continued)	Colby Ardis Gerald A. Hollinden Robert D. Mitchell Glendon L. Crow
Texasgulf, Inc. Moab Potash Operations Moab, Utah	R. L. Curfman, Manager A. K. Gentry, Operations Superintendent
Waterproofing Systems, Inc. Los Angeles, California	O. E. Hensgen, Vice President
Wisconsin Electric Power Company Milwaukee, Wisconsin	Merlin Abler, Sales Coordinator

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APPENDIX B

LABORATORY CHEMICAL ANALYSES
ANALYTICAL RESULTS

This appendix presents the analytical results of sludge samples taken at the Shawnee and Mohave power plants. The Shawnee (TVA) samples are from sludge produced by scrubbing flue gas from eastern coal with a limestone sorbent. The Mohave samples are from sludge produced by scrubbing flue gas from western coal with a limestone sorbent.

Suitable aliquots were taken for analysis. Methods used were emission spectroscopy (designated ES in tables of analytical results), spark source spectroscopy (SSMS), and atomic absorption (AA) spectrophotometry. Atomic absorption was the preferred method because its greater sensitivity gives more precision and higher accuracy. In most, if not all cases, when the AA analysis of some elements had low sensitivity, it was still greater than that obtained from the other analytical methods.

Power plant: Shawnee
Analysis, ppm: Process Water, Make-up

Date: 1 February 1973
pH: 7.40

Element	ES	SSMS	AA	Element	ES	SSMS	AA
Al			0.21	Mg			6
As			<0.02	Mn			
B				Mo			
Ba				N			
Be			<0.0005	Na			
Br				Ni			
C				P			
Ca			40	Pb			<0.005
Cd			<0.0005	Rb			
Cl				S			
Co				Se			<0.01
Cr			<0.001	Si			
Cs				Sn			
Cu			0.012	Sr			
F				Ti			
Fe				V			
Ga				Y			
Hg			0.007	Zn			<0.2
K				Zr			
Li							

Power plant: Shawnee
Analysis, ppm: Limestone

Date: 1 February 1973

Element	ES	SSMS	AA	Element	ES	SSMS	AA
Al	120	4,200		Mg	29,000	>10,000	
As			6	Mn	110	140	
B	<50	1.5		Mo			
Ba		10		N		4.5	
Be				Na	360	360	
Br				Ni	<10		
C				P		85	
Ca	350,000	>10,000		Pb	<100		2
Cd				Rb		1.7	
Cl		38		S		220	
Co	<10			Se			1
Cr	8.4	76	10	Si	6,500	>10,000	
Cs				Sn			
Cu	1.1		4	Sr	780	1,500	
F		12		Ti	<30	440	
Fe	1,000	2,500		V		15	
Ga	<20			Y			
Hg			2	Zn		59	
K	<2,000	580		Zr			
Li		1.8					

Power plant: Shawnee Date: 1 February 1973
Analysis, ppm: TCA Effluent, Separated,* Liquid Portion pH: 2.33

Element	ES	SSMS	AA	Element	ES	SSMS	AA
Al			1.7	Mg			100
As				Mn			
B				Mo			
Ba				N			
Be			0.006	Na			
Br				Ni			
C				P			
Ca			2800	Pb			0.030
Cd			0.0094	Rb			
Cl				S			
Co				Se			0.35
Cr			0.025	Si			
Cs				Sn			
Cu			0.041	Sr			
F				Ti			
Fe				V			
Ga				Y			
Hg				Zn			
K				Zr			
Li							

Power plant: Shawnee Date: 1 February 1973
Analysis, ppm: TCA Effluent, Separated,* Solids Portion

Element	ES	SSMS	AA	Element	ES	SSMS	AA
Al		>10,000		Mg		>10,000	
As		24	6	Mn		180	
B		28		Mo			
Ba		1,600		N		1	
Be				Na		2,800	
Br				Ni			
C		1,700		P		170	
Ca		>10,000		Pb		20	2
Cd			2	Rb		13	
Cl		47		S		>10,000	
Co				Se			2
Cr			15	Si		>10,000	
Cs		1		Sn			
Cu		33	14	Sr		750	
F		30		Ti		4,500	
Fe		>10,000		V		94	
Ga				Y		63	
Hg			2	Zn		330	
K		3,700		Zr			
Li		5.1					

*Liquor separated from effluent at power plant.

Power plant: Shawnee Date: 1 February 1973
Analysis, ppm: TCA Effluent, Retained,+ Liquid Portion pH: 7.80

Element	ES	SSMS	AA	Element	ES	SSMS	AA
Al			0.7	Mg			53
As			0.8	Mn			
B				Mo			
Ba				N			
Be			0.015	Na			
Br				Ni			
C				P			
Ca			1600	Pb			0.026
Cd			0.0014	Rb			
Cl				S			
Co				Se			0.15
Cr			0.006	Si			
Cs				Sn			
Cu			0.021	Sr			
F				Ti			
Fe				V			
Ga				Y			
Hg				Zn			
K				Zr			
Li							

Power plant: Shawnee Date: 1 February 1973
Analysis, ppm: TCA Effluent, Retained,+ Solids Portion

Element	ES	SSMS	AA	Element	ES	SSMS	AA
Al		>10,000		Mg		>10,000	
As		53	13	Mn		230	
B		42		Mo			
Ba		870		N		3	
Be				Na		290	
Br				Ni			
C		170		P		150	
Ca		>10,000		Pb		64	1
Cd			4	Rb		30	
Cl		79		S		2,100	
Co				Se			16
Cr		250		Si		>10,000	
Cs		1.2		Sn			
Cu		49		Sr		1,500	
F		16		Ti		5,300	
Fe		>10,000		V		150	
Ga				Y		45	
Hg				Zn		450	
K		760		Zr			
Li		7.9					

+Liquor separated from effluent after delivery at The Aerospace Corporation.

Power plant: Shawnee Date: 1 February 1973
Analysis, ppm: Clarifier Effluent, Retained,+ Liquid Portion pH: 7.15

Element	ES	SSMS	AA	Element	ES	SSMS	AA
Al	0.34		0.16	Mg	67		160
As				Mn	1.6		
B	11			Mo	0.56		
Ba				N			
Be			0.012	Na	7.5		
Br				Ni	<0.05		
C				P			
Ca	1100		1900	Pb			0.039
Cd			0.0039	Rb			
Cl				S			
Co				Se			0.54
Cr			0.015	Si	14		
Cs				Sn			
Cu	0.0017		0.051	Sr	2.1		
F	0.17			Ti			
Fe				V			
Ga				Y			
Hg				Zn			
K	19			Zr			
Li							

Power plant: Shawnee Date: 1 February 1973
Analysis, ppm: Clarifier Effluent, Retained,+ Solids Portion

Element	ES	SSMS	AA	Element	ES	SSMS	AA
Al	26,000	>10,000		Mg		>10,000	
As		16	33	Mn	130	190	
B	92	7.6		Mo			
Ba		520		N		3	
Be			6	Na	2,300	270	
Br				Ni	0.0017		
C		140		P		110	
Ca	270,000	>10,000		Pb	150		1
Cd			1	Rb		9	
Cl		42		S		330	
Co	<10			Se			2
Cr	25	66	14	Si	89,000	>10,000	
Cs				Sn			
Cu	5.3		9	Sr	990	1,100	
F		5.9		Ti	5,300	4,200	
Fe	2,500	>10,000		V		150	
Ga	27			Y		27	
Hg			1	Zn		90	
K	8,800	860		Zr			
Li			1.2				

+Liquor separated from effluent after delivery at The Aerospace Corporation.

Power plant: Shawnee Date: 1 February 1973
Analysis, ppm: TCA Inlet Fly Ash

Element	ES	SSMS	AA	Element	ES	SSMS	AA
Al		>10,000		Mg		4,400	
As		22	32	Mn		180	
B		38		Mo			
Ba		1,000		N		5.1	
Be				Na		870	
Br		6.5		Ni			
C		2,000		P		140	
Ca		>10,000		Pb		27	3
Cd				Rb		11	
Cl		25		S		440	
Co				Se			8
Cr		440	15	Si		>10,000	
Cs		1.3		Sn			
Cu		25		Sr		440	
F		4.2		Ti		6,000	
Fe		>10,000		V		65	
Ga				Y		73	
Hg			6	Zn		290	
K		960		Zr			
Li		6.5					

Power plant: Shawnee Date: 1 February 1973
Analysis, ppm: TCA Outlet Fly Ash

Element	ES	SSMS	AA	Element	ES	SSMS	AA
Al		>10,000		Mg		5,700	
As		450	50	Mn		290	
B		220		Mo			
Ba		6,400		N		230	
Be				Na		2,800	
Br				Ni			
C		7,000		P		1,800	
Ca		>10,000		Pb		64	7
Cd				Rb		40	
Cl		58		S		1,200	
Co				Se			2
Cr		230	9	Si		>10,000	
Cs		1.4		Sn			
Cu		140	11	Sr		1,300	
F		30		Ti		>10,000	
Fe		>10,000		V		820	
Ga				Y		47	
Hg			7	Zn		1,600	
K		2,500		Zr			
Li		13					

Power plant: Shawnee Date: 1 February 1973
Analysis, ppm: Bottom Ash, Unit No. 10

Element	ES	SSMS	AA	Element	ES	SSMS	AA
Al		>10,000		Mg		9,700	
As		3	7	Mn		530	
B		220		Mo			
Ba		>10,000		N		3	
Be				Na		350	
Br				Ni			
C		2,500		P		680	
Ca		>10,000		Pb			
Cd				Rb		63	
Cl		17		S		200	
Co				Se			1
Cr		700	10	Si		>10,000	
Cs		6.0		Sn			
Cu		220	4	Sr		170	
F		4.1		Ti		>10,000	
Fe		>10,000		V		290	
Ga				Y		340	
Hg			2	Zn		640	
K		1,300		Zr			
Li		42					

Power plant: Shawnee Date: 1 February 1973
Analysis, ppm: Coal

Element	ES	SSMS	AA	Element	ES	SSMS	AA
Al		7,500		Mg		1,700	
As			4	Mn		350	
B		46		Mo			
Ba		1,800		N		<30	
Be			0.2	Na		1,700	
Br				Ni			
C		>10,000		P		40	
Ca		>10,000		Pb		30	0.5
Cd			1	Rb		24	
Cl		280		S		>10,000	
Co				Se			6
Cr		310	20	Si		>10,000	
Cs				Sn			
Cu			8	Sr		1,100	
F		7.9		Ti		5,900	
Fe		4,500		V		180	
Ga				Y		95	
Hg				Zn		180	
K		3,000		Zr			
Li		3.3					

Power plant: Shawnee Date: 11 July 1973
Analysis, ppm: Process Water, Make-up pH: 7.25

Element	ES	SSMS	AA	Element	ES	SSMS	AA
Al			0.02	Mg			5
As			<0.02	Mn			
B				Mo			
Ba				N			
Be			0.0012	Na			
Br				Ni			
C				P			
Ca			30	Pb			<0.005
Cd			<0.0005	Rb			
Cl				S			
Co				Se			<0.01
Cr			<0.001	Si			
Cs				Sn			
Cu			0.005	Sr			
F				Ti			
Fe				V			
Ga				Y			
Hg			<0.0001	Zn			<0.4
K				Zr			
Li							

Power plant: Shawnee Date: 11 July 1973
Analysis, ppm: Limestone

Element	ES	SSMS	AA	Element	ES	SSMS	AA
Al				Mg			
As			7	Mn			
B				Mo			
Ba				N			
Be				Na			
Br				Ni			
C				P			
Ca				Pb			2
Cd			0.6	Rb			
Cl				S			
Co				Se			2
Cr			9	Si			
Cs				Sn			
Cu			2	Sr			
F				Ti			
Fe				V			
Ga				Y			
Hg			1	Zn			
K				Zr			
Li							

Power plant: Shawnee Date: 11 July 1973
Analysis, ppm: TCA Effluent, Separated,* Liquid Portion pH: 2.44

Element	ES	SSMS	AA	Element	ES	SSMS	AA
Al			1.5	Mg			700
As				Mn			
B				Mo			
Ba				N			
Be			0.020	Na			
Br				Ni			
C				P			
Ca			2200	Pb			
Cd			0.0072	Rb			
Cl				S			
Co				Se			
Cr				Si			
Cs				Sn			
Cu			0.060	Sr			
F				Ti			
Fe				V			
Ga				Y			
Hg			0.11	Zn			0.25
K				Zr			
Li							

Power plant: Shawnee Date: 11 July 1973
Analysis, ppm: TCA Effluent, Separated,* Solids Portion

Element	ES	SSMS	AA	Element	ES	SSMS	AA
Al				Mg			
As				Mn			
B				Mo			
Ba				N			
Be				Na			
Br				Ni			
C				P			
Ca				Pb			
Cd			2.3	Rb			
Cl				S			
Co				Se			17
Cr			8	Si			
Cs				Sn			
Cu				Sr			
F				Ti			
Fe				V			
Ga				Y			
Hg				Zn			
K				Zr			
Li							

*Liquor separated from effluent at power plant.

Power plant: Shawnee Date: 11 July 1973
Analysis, ppm: TCA Effluent, Retained,+ Liquid Portion pH: 8.36

Element	ES	SSMS	AA	Element	ES	SSMS	AA
Al			0.45	Mg			950
As			2.0	Mn			
B				Mo			
Ba				N			
Be			0.028	Na			
Br				Ni			
C				P			
Ca			4,300	Pb			0.32
Cd			0.0092	Rb			
Cl				S			
Co				Se			3.1
Cr			0.17	Si			
Cs				Sn			
Cu			0.064	Sr			
F				Ti			
Fe				V			
Ga				Y			
Hg			8	Zn			38
K				Zr			
Li							

Power plant: Shawnee Date: 11 July 1973
Analysis, ppm: TCA Effluent, Retained,+ Solids Portion

Element	ES	SSMS	AA	Element	ES	SSMS	AA
Al				Mg			
As			7	Mn			
B				Mo			
Ba				N			
Be				Na			
Br				Ni			
C				P			
Ca				Pb			1
Cd			3	Rb			
Cl				S			
Co				Se			8
Cr			13	Si			
Cs				Sn			
Cu			20	Sr			
F				Ti			
Fe				V			
Ga				Y			
Hg			3	Zn			
K				Zr			
Li							

+Liquor separated from effluent after delivery at The Aerospace Corporation.

Power plant: Shawnee Date: 11 July 1973
Analysis, ppm: Clarifier Effluent, Retained,+ Liquid Portion pH: 9.01

Element	ES	SSMS	AA	Element	ES	SSMS	AA
Al			0.30	Mg			675
As				Mn			
B				Mo			
Ba				N			
Be			0.026	Na			
Br				Ni			
C				P			
Ca			2600	Pb			
Cd			0.0089	Rb			
Cl				S			
Co				Se			
Cr				Si			
Cs				Sn			
Cu			0.052	Sr			
F				Ti			
Fe				V			
Ga				Y			
Hg			0.07	Zn			
K				Zr			
Li							

Power plant: Shawnee Date: 11 July 1973
Analysis, ppm: Clarifier Effluent, Retained,+ Solids Portion

Element	ES	SSMS	AA	Element	ES	SSMS	AA
Al				Mg			
As			33	Mn			
B				Mo			
Ba				N			
Be				Na			
Br				Ni			
C				P			
Ca				Pb			1
Cd			3	Rb			
Cl				S			
Co				Se			4
Cr				Si			
Cs				Sn			
Cu			18	Sr			
F				Ti			
Fe				V			
Ga				Y			
Hg			1	Zn			
K				Zr			
Li							

+Liquor separated from effluent after delivery at The Aerospace Corporation.

Power plant: Shawnee
Analysis, ppm: TCA Inlet Fly Ash

Date: 11 July 1973

Element	ES	SSMS	AA	Element	ES	SSMS	AA
Al				Mg			
As			12	Mn			
B				Mo			
Ba				N			
Be			7	Na			
Br				Ni			
C				P			
Ca				Pb			4
Cd			4	Rb			
Cl				S			
Co				Se			7
Cr				Si			
Cs				Sn			
Cu			18	Sr			
F				Ti			
Fe				V			
Ga				Y			
Hg			2.6	Zn			
K				Zr			
Li							

Power plant: Shawnee
Analysis, ppm: Bottom Ash

Date: 11 July 1973

Element	ES	SSMS	AA	Element	ES	SSMS	AA
Al				Mg			
As			6	Mn			
B				Mo			
Ba				N			
Be				Na			
Br				Ni			
C				P			
Ca				Pb			1
Cd			0.4	Rb			
Cl				S			
Co				Se			7
Cr			17	Si			
Cs				Sn			
Cu			9	Sr			
F				Ti			
Fe				V			
Ga				Y			
Hg				Zn			
K				Zr			
Li							

Power plant: Shawnee

Date: 11 July 1973

Analysis, ppm: Coal

Element	ES	SSMS	AA	Element	ES	SSMS	AA
Al				Mg			
As			19	Mn			
B				Mo			
Ba				N			
Be				Na			
Br				Ni			
C				P			
Ca				Pb			0.3
Cd			5	Rb			
Cl				S			
Co				Se			6
Cr			10	Si			
Cs				Sn			
Cu			8	Sr			
F				Ti			
Fe				V			
Ga				Y			
Hg				Zn			
K				Zr			
Li							

Power plant: Mohave Date: 30 March 1973
Analysis, ppm: Scrubber Input from Hold Tank, Retained,+ Liquid Portion pH: 7.48

Element	ES	SSMS	AA	Element	ES	SSMS	AA
Al				Mg	300		2,400
As			0.038	Mn	3.0		
B	19			Mo			
Ba				N			
Be			<0.001	Na	29,000		
Br				Ni			
C				P			
Ca	300		300	Pb			<0.005
Cd			0.05	Rb			
Cl				S			
Co				Se			
Cr			0.23	Si	16		
Cs				Sn			
Cu	0.30		0.20	Sr	9.6		
F				Ti			
Fe				V			
Ga				Y			
Hg				Zn			0.18
K	<100			Zr			
Li							

Power plant: Mohave Date: 30 March 1973
Analysis, ppm: Scrubber Input from Hold Tank, Retained,+ Solids Portion

Element	ES	SSMS	AA	Element	ES	SSMS	AA
Al	34,000			Mg	5,300		
As			19	Mn	170		
B	< 50			Mo			
Ba				N			
Be			0.04	Na	24,000		
Br				Ni	24		
C				P			
Ca	250,000			Pb	< 200		0.4
Cd			0.4	Rb			
Cl				S			
Co				Se			7
Cr	71		11	Si	100,000		
Cs				Sn	80		
Cu	41		6	Sr	300		
F				Ti	1,000		
Fe	12,000			V	80		
Ga				Y			
Hg				Zn			
K	< 4,000			Zr			
Li							

+Liquor separated from effluent after delivery at The Aerospace Corporation.

Power plant: Mohave Date: 30 March 1973
Analysis, ppm: Scrubber Slurry Effluent, Retained,+ pH: 7.83
Liquid Portion

Element	ES	SSMS	AA	Element	ES	SSMS	AA
Al	1.2			Mg	310		2,400
As			0.03	Mn	3.1		
B	16			Mo			
Ba				N			
Be			<0.001	Na	30,000		
Br				Ni			
C				P			
Ca	200		400	Pb			0.01
Cd			0.1	Rb			
Cl				S			
Co				Se			
Cr			<0.005	Si	21		
Cs				Sn			
Cu	0.37		0.08	Sr			
F				Ti			
Fe				V			
Ga				Y			
Hg			0.0012	Zn			0.12
K				Zr			
Li							

Power plant: Mohave Date: 30 March 1973
Analysis, ppm: Scrubber Slurry Effluent, Retained,+ Solids Portion

Element	ES	SSMS	AA	Element	ES	SSMS	AA
Al				Mg		7400	
As		58	21	Mn		90	
B		28		Mo			
Ba		1400		N		72	
Be			0.07	Na			
Br				Ni			
C		920		P		1100	
Ca				Pb			0.1
Cd			0.6	Rb		22	
Cl		1600		S			
Co				Se			2
Cr		250	7	Si			
Cs		53		Sn			
Cu		1	10	Sr		1700	
F		190		Ti		1100	
Fe				V		42	
Ga				Y			
Hg			8	Zn		71	
K		1100		Zr			
Li		7.9					

+Liquor separated from effluent after delivery at The Aerospace Corporation.

Power plant: Mohave Date: 30 March 1973
Analysis, ppm: Centrifuge Discharge, Liquid Portion pH: 6.71

Element	ES	SSMS	AA	Element	ES	SSMS	AA
Al	4.0			Mg	390		2,800
As			0.028	Mn	3.0		
B	13			Mo			
Ba				N			
Be			<0.001	Na	29,000		
Br				Ni			
C				P			
Ca	180		480	Pb			<0.005
Cd			0.047	Rb			
Cl				S			
Co				Se			
Cr	< 2		0.25	Si	51		
Cs				Sn			
Cu	0.82		0.56	Sr			
F				Ti			
Fe				V			
Ga				Y			
Hg				Zn			
K				Zr			0.18
Li							

Power plant: Mohave Date: 30 March 1973
Analysis, ppm: Centrifuge Discharge, Solids Filtered from Liquid Portion

Element	ES	SSMS	AA	Element	ES	SSMS	AA
Al	150,000			Mg	13,000		
As			44	Mn	460		
B	160			Mo	88		
Ba	1,900			N			
Be			0.05	Na	52,000		
Br				Ni	140		
C				P	< 5,000		
Ca	42,000			Pb	640		3.2
Cd			2.5	Rb			
Cl				S			
Co	43			Se			8
Cr	720		10	Si	180,000		
Cs				Sn			
Cu	360		30	Sr	950		
F				Ti	9,400		
Fe	36,000			V	300		
Ga	240			Y			
Hg				Zn			
K	9,400			Zr			
Li							

Power plant: Mohave Date: 30 March 1973
Analysis, ppm: Centrifuge Discharge, Precipitate

Element	ES	SSMS	AA	Element	ES	SSMS	AA
Al				Mg		5600	
As		46	30	Mn		180	
B		35		Mo			
Ba		2000		N		41	
Be			0.05	Na			
Br				Ni			
C		5500		P		390	
Ca				Pb			18
Cd			0.4	Rb		7.3	
Cl		1400		S			
Co				Se			
Cr		290	17	Si			
Cs				Sn			
Cu		1	10	Sr		1600	
F		3500		Ti		3700	
Fe				V		59	
Ga				Y			
Hg			6	Zn		210	
K		2100		Zr			
Li		5.5					

Power plant: Mohave Date: 30 March 1973
Analysis, ppm: Process Water Make-up pH: 9.10

Element	ES	SSMS	AA	Element	ES	SSMS	AA
Al	< 0.04			Mg	230		590
As			0.21	Mn	< 0.05		
B	3.1			Mo			
Ba				N			
Be			0.009	Na	2700		
Br				Ni			
C				P			
Ca	610		200	Pb			0.0025
Cd			0.07	Rb			
Cl				S			
Co				Se			0.6
Cr	< 0.2		0.03	Si	41		
Cs				Sn			
Cu	0.91		0.2	Sr	3.7		
F				Ti			
Fe	0.34			V			
Ga				Y			
Hg				Zn			
K	130			Zr			0.20
Li	4.0						

Power plant: Mohave Date: 30 March 1973
Analysis, ppm: Process Water Make-up, Solids

Element	ES	SSMS	AA	Element	ES	SSMS	AA
Al	62,000			Mg	14,000		
As			10	Mn	1,300		
B	170			Mo	< 40		
Ba	< 2,000			N			
Be			0.06	Na	< 2,000		
Br				Ni	28		
C				P	26,000		
Ca	96,000			Pb	340		3.2
Cd			2.9	Rb			
Cl				S			
Co	< 20			Se			3
Cr	380			Si	220,000		
Cs				Sn	< 80		
Cu	3,800			Sr	1,600		
F				Ti	1,200		
Fe	42,000			V	< 80		
Ga	< 60			Y			
Hg			5.8	Zn	8,600		
K	< 4,000			Zr			
Li							

Power plant: Mohave Date: 30 March 1973
Analysis, ppm: Limestone

Element	ES	SSMS	AA	Element	ES	SSMS	AA
Al		3300		Mg		4000	
As		11	5	Mn		150	
B		0.80		Mo			
Ba				N		2.2	
Be			5	Na		1700	
Br				Ni			
C				P		50	
Ca				Pb			5
Cd			0.5	Rb		0.7	
Cl		4.3		S		30	
Co				Se			24
Cr		19	14	Si			
Cs				Sn			
Cu			8	Sr		220	
F		4.3		Ti		160	
Fe		900		V		5.3	
Ga				Y			
Hg			2	Zn		6.0	
K		330		Zr			
Li		0.31					

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APPENDIX C

POND LININGS AND POND CONSTRUCTION CHARACTERISTICS AND DESIGN FEATURES

C.1 INTRODUCTION

This appendix includes information on: (a) material properties and characteristics of flexible and nonflexible liners, (b) liner fabrication and installation, (c) pond design and construction, and (d) safety.

C.2 FLEXIBLE LINER CHARACTERISTICS

C.2.1 Polyvinyl Chloride

Table C-1 shows some typical properties of polyvinyl chloride (PVC) sheeting (without scrim) as used for pond lining. This material is used in thicknesses of 0.0254 - 0.0762 cm (10 - 30 mil) depending upon the designer's choice. The industry (Refs. C-1 through C-3) uses 0.0508-cm-thick (20-mil) liners because experience has indicated that: this thickness is sufficient to resist tearing, it is less expensive than the thicker sheetings, it is easy to handle during factory liner fabrication and field installation, and has sufficient elongation for expanding over hard points on the soil surface without tearing.

Table C-1. TYPICAL PROPERTIES OF PLASTIC LINERS WITHOUT SCRIM

Property	Test methods	Range of test results			
		PVC	Polyethylene	Chlorinated polyethylene	Hypalon
Specific gravity	ASTM-D-792	1.2-1.3	0.91-0.95	1.35-1.39	1.1-1.26
Thickness, mil	--	10-30	10-30	10-30	30
Tensile strength, psi	ASTM-D-882	2200-2800	2000-2500	1800-2000	1000-2000[a]
Elongation, % minimum	ASTM-D-882	300-400	500-600	350-600	250-400[b]
Graves tear, lb/in.	ASTM-D-1004	270-300	--	190-600	200
100% modulus, psi	ASTM-D-882	1000-1600	--	400-1000	--
Water extraction, % maximum	ASTM-D-1239	0.35	<0.01[c]	0.30	--
Volatility, %	ASTM-D-1203	0.7-0.85	--	0.30	--
Cold crack, °C	ASTM-D-746	-28.9	<-100	Pass -50	-45
Dimensional stability, % maximum (70°C)	ASTM-D-1204	2	--	3	--
Shore "A" durometer	ASTM-D-676	65-90	--	--	--
Pinholes per 10 sq m	--	<1	<1	<1	<1
Alkali resistance	CRD-572-61	Pass	--	--	--
Weatherability	--	Good	Poor	Good	Good
Resistance to burial	--	Good	Good	Good	Good
Color	--	Grey-black	Grey-black	Grey-black	White-black-grey
Vapor transmission rate[d]	ASTM-E-96-66	0.1-0.2	--	0.02	--

[a]Test method ASTM-D-412

[b]Elongation at break, % minimum, test method ASTM-D-412

[c]Test method ASTM-D-570

[d]gmH_2O/645.2 sq cm/24 hr/0.76 mm at 37.8°C

To convert from	to	Multiply by
mil	cm	0.00254
lb/in.	gm/cm	178.5
lb/sq in.	gm/sq cm	70.31

The PVC bonding process to be used (heat sealing or solvent/resin) depends upon the liner manufacturer's operating procedures; however, solvent/resin bonding is used exclusively for field installation. These joints are formed by overlapping the panel edges by about 2.54 - 5.08 cm (1-2 in.), and applying a solvent/resin mixture as the sealing agent. A three-man crew can field seam with the solvent/resin mixture at the rate of about 6.1 - 9.1 m/min (20 - 30 ft/min). A typical sealer for PVC is a mixture of basic PVC resin and tetrahydrofuran in the proper ratio to provide long shelf life and ease of application.

Since the PVC liner material will crack or craze if it is exposed to the ultraviolet rays of the sun for a long time, it must be protected by at least 6 in. of soil or by some other type of ultraviolet filter. The plastic liner material is fabricated both with and without scrim. The scrim increases the stability and strength of the liner and reduces its tendency to slump. Most scrims are nylon or Dacron threads of 210 or 420 denier and have more than 8 threads/in.

Many ponds and drainage canals have been constructed that use PVC liners. The ponds range in size from less than 2024 sq m (1/2 acre) for small sludge or water containment ponds to large facilities of 1,618,800 sq m (400 acres) such as the Texasgulf, Inc. plant at Moab, Utah. The Moab facility was constructed for the evaporation of water from the Texasgulf potash (KCl) extraction process. The process is used to extract KCl from the ground by dissolving the KCl and NaCl in hot water and pumping the salt solution into the evaporation ponds. The Texasgulf ponds were lined with 0.0508 cm (20 mil) PVC (Ref. C-4) and have been in continuous operation since they were constructed in 1970. At this facility, PVC is used in a single layer throughout the bottom and lower portion of the slopes. An extra layer is used on the upper area of the side slopes to protect the underneath sheeting; it is scheduled for replacement when visual

inspection reveals that it has become brittle through exposure to ultraviolet rays or is physically damaged. It is expected that the top layer on the side slopes will be replaced every 4 to 5 years and that the layer which is not exposed to the sunlight will last about 20 years. Since winds of 30.9 m/sec (60 knots) are common in the Moab area, special precautions are being taken to protect the liner, such as installing heavy chain link type fencing over the exposed liner material and weighing the fencing down with sandbags. Because of the high winds, a freeboard of at least 0.61 m (2 ft) is always maintained to keep any salt solution from washing over the berm.

C.2.2 Polyethylene

Table C-1 shows some typical physical properties of polyethylene (PE) liner material (without scrim). This material is used in thicknesses of 0.0254 - 0.0762 cm (10 - 30 mil); the thinner material is used most often because the thicker joints are difficult to work with. Polyethylene has been widely used for liners in water retention ponds for farms, golf courses, and recreational areas. It is less expensive than some of the other flexible liners and is readily available throughout the country. (Refs. C-1 and C-3.)

Polyethylene sheeting is purchased by the liner manufacturer in rolls of about 127 - 190.5 cm (50 - 75 in.) wide by 91.4 - 152.4 m (300 - 500 ft) long. It is processed by heat sealing or solvent/resin bonding in the factory to form the large 21.3 by 152.4 m (70 by 500 ft) panels.

Field installation of the PE panels is similar to other flexible liner material, except that some fabricators prefer to use a folded seam bond (Figure C-1) to provide a tighter seal. In addition, an adhesive-backed tape is sometimes placed over the seal to provide temporary added strength until the liner is covered with soil.

Polyethylene liners are normally covered with a minimum of 15.2 cm (6 in.) of soil primarily to protect the sheeting from

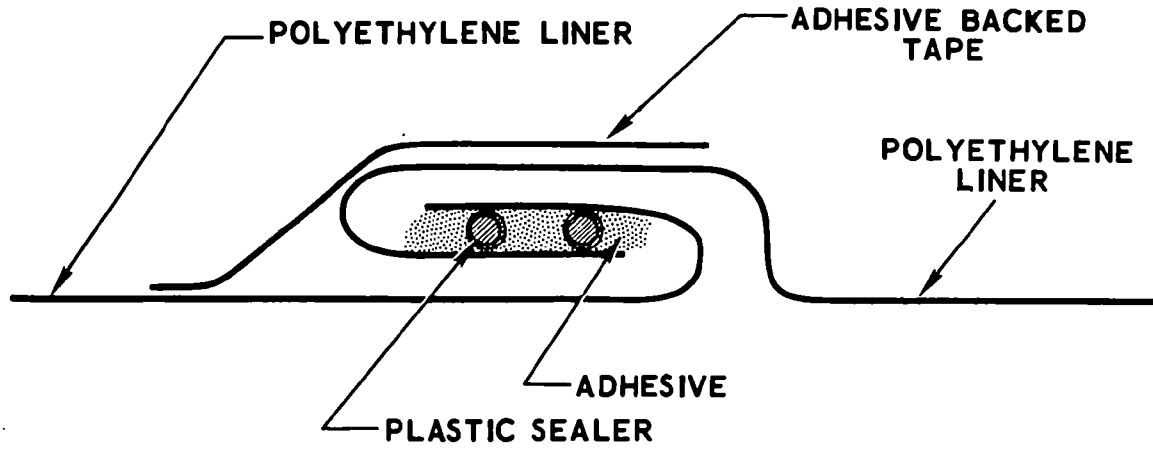

Figure C-1. Folded seam concept

ultraviolet rays, but also to help keep the liner from floating on the surface of the pond. The ultraviolet rays cause the film to crack or craze with age and subsequently result in leakage. The ray's detrimental effect on PE liners is a major disadvantage that must always be considered in any pond design. However, PE sheeting has been used successfully to line agricultural ponds because the soil, which in many cases was spread to protect the liner from farm animals that walk into the ponds, also protected the liner against ultraviolet rays. If the PE sheeting is protected from the ultraviolet rays, it should last about 20 years.

Polyethylene sheeting has been used successfully in a series of evaporation ponds of 830,000 sq m (205 acres) in Lindsay, California. At this facility, water is evaporated from the caustic waste of the olive processing industry. The 830,000 sq m (205 acres) of ponds are divided into eight individual ponds ranging in area from 64,800 - 206,000 sq m (16 - 50 acres).

Heat sealing sheets of chlorinated polyethylene (CPE) to the PE sheeting is a technique that was developed by the pond liner manufacturers to overcome the disadvantage of the ultraviolet attack. This approach incorporates an ultraviolet resistant material for use on the side slopes of the ponds (which are subjected to the sun's rays), while using the PE liner on the bottom surface of the pond. The bottom surface would be covered with liquid or sludge and not subjected to the direct ultraviolet rays. However, because the PE's specific gravity is less than 1, even if CPE is used for the side walls there should be some method of weighting down the PE to keep it from floating.

C.2.3 Chlorinated Polyethylene

The CPE is a flexible thermoplastic produced by the chemical reaction of chlorine and high-density polyethylene. Table C-1 summarizes some of the typical physical properties of CPE sheeting. Since CPE is a saturated polymer, it is reported to be relatively insensitive to ozone attack. Dow Chemical (Ref. C-5) reports that CPE samples exposed to the weather in the dry Arizona atmosphere for 7-1/2 years showed better than 90 percent retention of their original tensile and elongation properties. The pond lining industry has confirmed the information that CPE is weather resistant and is not affected by ultraviolet rays. Consequently CPE is now being widely considered in many applications where the side slopes of the ponds have prolonged exposure to the sun.

Although CPE is more expensive than PVC or PE, CPE is being used to line ponds requiring long life (at least 20 years) and resistance to certain toxic chemicals.

The CPE is fabricated into pond liners both with and without the incorporation of scrim. The sheet thickness varies from 0.0254 - 0.0762 cm (10 - 30 mil). Goodyear Rubber (Ref. C-6) reports that the 0.76 mm (30 mil) CPE liner with scrim is fabricated

from two plies of 0.0355 cm (14 mil) film with the scrim sandwiched between the films. This material is used on the side slopes of the ponds where the added stability provided by the scrim is used to prevent slumping of the plastic liner.

The large panels are fabricated in the factory by heat sealing or resin bonding procedures, the panels are accordion folded, brought into the field, and unfolded in place. The solvent used for sealing CPE is normally a mixture of about 50/50 parts of toluene and tetrahydrofuran that is mixed with CPE resin to form the bonding agent. Field sealing techniques are the same as those discussed for the PVC and PE liners.

C.2.4 Hypalon

Hypalon is a chlorosulfonated polyethylene polymer produced by DuPont and sold to film manufacturers for calendering into sheets about 0.0762 cm (30 mil) thick for use as pond lining. The calendered sheets are produced in rolls 1.22 - 1.823 m (4 - 6 ft) wide by several hundred feet long. In the liner manufacturer's factory the large panels are formed by heat sealing or adhesive bonding the narrower strips together. At the site, the accordion folded liner is unfolded and the sealing of the large panels is accomplished by overlapping 2.54 - 5.08 cm (1 - 2 in.) of the material and sealing the joint with adhesive. DuPont personnel (Ref. C-7) indicated that a hot-air, heat-welding process has also been developed for field sealing the panels. They further stated that a process has been developed for joining the panels together by a "zipper." The zipper is a 0.0762-cm-thick (30 mil) Hypalon extrusion that is installed along the panel edges when they are being fabricated. When the panels are to be connected in the field, adhesive is injected into the tracks and the zipper is rolled together. Trichloroethylene, which is used by many fabricators as the solvent for Hypalon, and a small amount of Hypalon resin are sometimes used as the adhesive bonding agent.

Table C-1 shows some of the physical properties of the Hypalon sheeting.

Hypalon is more expensive than the liners previously discussed, but it is being installed because of its reported good weathering characteristics, and resistance to ozone and the microorganisms in the soil. Hypalon liners are expected to have a serviceable life of about 20 years.

C.2.5 Butyl Rubber

Butyl rubber or isobutylene-isoprene resin that has been calendered into sheets is used for pond lining where there are specific requirements for resistance to highly acidic chemicals. The properties of butyl rubber are briefly summarized in Table C-2. The panels are joined at the site with adhesive cement or tape.

C.2.6 Ethylene-Propylene-Terpolymer Rubber

Ethylene-propylene-terpolymer (EPDM) rubber is a synthetic rubber proposed for pond linings because it has excellent weatherability and resistance to ozone and ultraviolet rays. Some physical properties of EPDM rubber are shown in Table C-2. At the present time not many ponds have been lined with this material as it is still more expensive than many other types of flexible liners and the annual U.S. production rate is lower. B.F. Goodrich is experimenting with EPDM rubber (Ref. C-8) and should be in full production for pond liners within the next year. Currently EPDM is used as a replacement for neoprene rubber products.

The procedures for preparing the pond site, fabricating the large panels, and installing the liner at the pond site are generally the same as for other types of flexible liners. In the factory, the panels are assembled by heat sealing or adhesive bonding together the strips of rubber sheeting. In the field, the panels are bonded

with an agent reported to be a mixture of halogenated hydrocarbons and EPDM rubber.

C.2.7 Fiberglass Mat Impregnated with Polyester Resin

Another type of liner material available for pond lining is fiberglass matting or fabric that has been impregnated with a polyester resin. This material is currently being manufactured in limited quantities by Anti Pollution Liner, Inc., Odessa, Texas, and has been installed in ponds up to 8094 sq m (2 acres) (Ref. C-9).

The pond construction is the same as that previously described for the flexible liners, except that the slopes are limited to 3:1 or less and the anchor design on the berm is limited to Method 1 as shown in Figure 6-1. The reason for these limitations is that this liner material is rather stiff and somewhat difficult to bend into a 90° angle without cracking the resin/fiberglass bond. However, because this liner material has a higher strength than the thin, flexible plastic liners, the need to remove all sharp rocks is not as imperative. The liner is manufactured in the factory by laying out fiberglass mats 1.52 by 15.2 m (5 by 50 ft) long and impregnating these mats with the polyester resin. The resin has been highly catalyzed for a rapid room temperature cure. After curing, the liner panel is rolled for delivery to the pond site. The liner is unrolled at the site, positioned to have about a 2.54 - 5.08 cm (1 - 2 in.) overlap and stapled to the adjoining panel. Next, a 10.2 - 15.2 cm (4 - 6 in.) mat strip is placed over the joint and catalyzed resin is applied to the matting to form a rigid seal. It is reported that a crew of three or four men can install 836 - 1255 sq m (1000 - 1500 sq yd) of liner per day. The liner can be repaired by applying a patch to the damaged area and impregnating it with resin.

Table C-2 shows some of the physical properties of this type of lining material.

Table C-2. TYPICAL PROPERTIES OF RUBBER AND FIBERGLASS LINERS

Property	Test methods	Range of test results		
		Butyl rubber	EPDM rubber	Fiberglass[a]
Specific gravity	ASTM-D-792	0.90-1.2	0.87-0.9	>2.5
Tensile strength, psi	ASTM-D-412	2,500-3,000	800-3,000	10,000-14,000
Elongation, % minimum	ASTM-D-412	650-850	200-600	--
Cold crack, °C	ASTM-D-746	-45	-50	--
Shore "A" Durometer	ASTM-D-676	40-90	20-95	--
Pinholes per 10 sq m	--	<1	<1	--
Weatherability	--	Good	Good	--
Flexural strength, psi at 25°C	--	--	--	27,000-38,000
Flexural modulus, psi at 25°C	--	--	--	1.3×10^6
Izod impact notched, ft lb/in.	--	--	--	12-14
Color	--	--	--	Marine blue
Thickness, mil	--	--	--	65

[a]Fiberglass mat impregnated with polyester resin; no ASTM test method specified

To convert from	to	Multiply by
lb/sq in.	gm/sq cm	70.31
ft lb/in.	gm-m/cm	54.5

C.2.8 Petromat

Petromat pond lining material is a nonwoven polypropylene fabric coated with an asbestos filled (0.254 cm size) asphalt emulsion. The liner material is fabricated by producing the lightweight fabric (169.5 gm/sq m) (5 oz/sq yd) in rolls 4.57 m (15 ft) wide by 91.4 m (300 ft) long, laying this fabric strip in the pond area, and then sewing the individual uncoated strips together. After covering the pond area with fabric, the asphalt emulsion is sprayed onto the fabric surface. The emulsion is sprayed warm to permit it to penetrate the fabric, but not hot so as to run down the slide slopes.

Phillips Petroleum Company makes Petromat and has been constructing ponds from this material for their own use since 1967 (Ref. C-10). About 242,000 sq m (60 acres) of ponding is now in operation. The largest single pond lined with Petromat is about 72,800 sq m (18 acres).

The pond configuration and construction techniques are the same as described previously for the plastic liners. The ground must be compacted, all roots and large stones removed (pea size gravel can be tolerated), and the slopes limited to 2:1 or less. If a large area of the liner needs to be repaired, the damaged section can easily be removed prior to sludge additions, a patch of uncoated polypropylene sewn in its place, and the patch sprayed with the warm asphalt emulsion. Small areas can be repaired with a roofing adhesive or mastic.

Petromat liners do not have to be covered with soil because the asphalt is unaffected by ultraviolet rays; however, the polypropylene is affected by the ultraviolet rays and must be coated with the asphalt within days after installation. If it becomes necessary to "dress" the liner on the side slopes, a spray coating of the asphalt emulsion can be applied to the surface. With proper maintenance and repair, Petromat liners should last over 20 years.

Table C-3 shows some of the physical characteristics of the Petromat fabric; the asphaltic emulsion is added to this fabric.

C.3 NONFLEXIBLE LINER CHARACTERISTICS

C.3.1 Chemical Soil Sealers

Treating the soil with an emulsion of oil soluable resinous polymers is another sealing technique used at the sludge disposal pond site. Chemical soil sealer is reported to be a mixture of sodium polyacrylates of molecular weight over 100,000 and cross-linked unsaturated fatty acids (such as linoleic acid) with a high degree of double bonds (Refs. C-11 and C-12). When the sealer is mixed with water in a ratio of 1 part sealer to 1000 parts water, the sealer penetrates the soil and fills in the pores thereby reducing the size of

Table C-3. TYPICAL PROPERTIES OF PETROMAT FABRIC

Property[a]	Range of test results
Tensile strength in either direction, minimum per inch of width, lb	50
Elongation, in. maximum	
Warp direction, 20-lb pull	0.5
Fill direction, 50-lb pull	1.1
Weight, oz/sq yd	3-5

[a]Material is nonwoven polypropylene fabric coated with an asbestos filled asphalt emulsion

To convert from	to	Multiply by
lb	gm	453.6
in.	cm	2.54
oz/sq yd	gm/sq m	33.9

openings among the soil particles. It is reported that by proper use of this type of material the seepage rate can be limited to 548 - 3280 liters/sq m (1.8 - 10.8 cu ft of water per sq ft) of wetted soil per year. Wet/dry cycles in some soils cause stress cracking that destroys the benefit of the chemical sealer, and a resealing process is necessary. This technique has been used in water control ponds, and has the advantage that it can be applied prior to filling the pond or used as a repair technique after the pond has been filled.

Since chemical soil sealers have been used primarily with drinking water and recreational ponds, information is not currently available about its reaction with the limestone sludge material.

C.3.2 Soil Cement

Soil cement has been used for lining water storage reservoirs, irrigation and drainage channels, sewage lagoons, mill ponds, and as slope protection for earthen dams and other embankments (Ref. C-13). It consists of Portland cement, soil, and water; proportioned, mixed, placed, and compacted so that the complete soil cement in place forms a dense, uniform mass. Proportioning and mixing of the soil and cement are accomplished by either the mix-in-place or the central mixing plant method. In general, the central plant method is more economical, except for projects requiring very small quantities of soil cement.

Selection of soil materials and determination of cement content are prime factors in attaining the desirable soil cement characteristics (i.e., compressive strength, durability, and impermeability). In general the soil should be well graded, sandy, gravelly material. For example, in the application of soil cement for slope protection of earthen dams it is recommended that: the soil contain no material retained on a 5.08 cm (2 in.) sieve, at least 55 percent

of the material pass the No. 4 sieve, and between 5 and 35 percent pass the No. 200 sieve.

The average cement content, depending on the type of soil, may vary between 7 and 14 percent by weight. The most common type of cement used is the ASTM Type I. Water for mixing with soil cement can be raw, treated, or sea water. The only requirement is that the water be free from excessive amounts of alkalines, acids, or organic matter. Sandy soil cement mixtures need about 18.95 liters (5 gal) of water per 0.836 sq m (1 sq yd) for a 15.2 cm (6 in.) compacted thickness. Evaporation losses may require an additional 7.57 liters (2 gal) or more per 0.836 sq m (1 sq yd).

It was reported that the permeability of the average type of soil cement made with pure water is approximately 0.305 m (1 ft) per year [i.e., flow rate of 0.305 m (1 ft) per 0.0929 sq m (1 sq ft) per year through the material under a 0.305 m (1 ft) head]. This rate may be decreased to approximately 15.2 cm (0.5 ft) per year by increasing the cement content and adjusting the type of soil used.

On slopes of 4:1 or less, soil cement liners can be constructed with normal road construction equipment. Apparently with higher slopes a stair-step method is required. To move the equipment up and down these slopes it must be attached with a cable to additional equipment at the top of the slope. It has been estimated that about a 6-in.-thick soil cement liner would be satisfactory for sludge disposal ponds. Soil cement liner maintenance imposes no unique problems and can be accomplished by available techniques. Hairline shrinkage cracks will occur, but they will have a limited effect on the liner's permeability. These cracks will probably increase the normal seepage rate about 5 percent.

The advantage of soil cement is that no rodent or weed problems will be encountered. Also, with a soil cement liner, cleaning equipment can be operated within the sludge disposal ponds. The disadvantage is that the cement is subject to attack by sulfate compounds. Laboratory experimentation with specific sludges must be performed to determine the extent of this reaction. This reaction can be decreased or nullified by using ASTM Type V cement or a fly ash additive. Type V cement, which costs approximately 7 percent more than Type I, is used principally where soils or ground waters have a high sulfate content.

C.3.3 Concrete

Concrete, which is a controlled mix of cement, aggregate and water, has been used extensively in the construction of irrigation canals, dams, water and sewage treatment units, etc. The proportion of the three ingredients depends on the specific application. With a 15.2 cm (6 in.) liner of concrete and the proper water to cement ratio, it was reported that the rate of seepage could be reduced to approximately 0.304 cm (0.01 ft) per year as compared to soil cement at 15.2 cm (0.5 ft) per year. The application of a concrete liner on slopes of 2:1 imposes no unique problems and can be accomplished with existing equipment.

The problems and solutions to concrete being susceptible to attack by sulfate compounds within the sludge are similar to those of soil cement (see C.3.2). Some contractors suggested that several coats of linseed oil applied to the concrete surface might provide protection from the possible chemical reaction from the sludge. There should be no concrete damage by rodents or weeds.

C.3.4 Clay

Bentonite clay is a montmorillonite-based clay formed by the alteration of volcanic ash. Although montmorillonite is the

predominant constituent in bentonite, other clay minerals (e.g., illite and kaolinite) and variable amounts of nonargillaceous detrital minerals may be present. Certain bentonites appear relatively pure; however, the content of nonargillaceous minerals is very rarely below 10 percent. Moreover, cristobalite is frequently present in bentonites. The type of montmorillonite clay itself varies among bentonites, either in its lattice structure or in the nature of the exchangeable ions. Consequently, the characteristics of bentonite clays vary among products and a detailed knowledge of the properties of the specific clay to be used in the sludge pond is essential (Refs. C-14 through C-16).

The treatment of commercial bentonite is relatively simple and includes the following steps: mining, drying, and crushing to size. After it is mined, either in open pits or underground, the clay is transported to the treatment plant where it is crushed and dried in a rotary dryer to reduce the moisture content from its mined condition of about 40 percent moisture. This clay is next pulverized to the proper size for the specific application.

At the pond site common sand/gravel handling equipment can be used to apply the clay to the ground surface. Whether the clay is disked into the soil and then compacted or merely applied to the surface in the selected thickness depends on the local conditions at the pond site. The thickness required to prevent seepage of the leachate from the sludge is a function of the soil conditions at the pond site and type of clay used. It was reported that sludge ponds have used clay linings in thicknesses from a few inches to several feet.

Some of the disadvantages that must be considered when evaluating the possible use of clay as a seepage barrier are:

a. The clay will crack when exposed to wet/dry cycles and will not necessarily close again to form an effective seal when rewetted.

b. Small earth-burrowing animals have been reported to have burrowed many underground passageways

through the clay barrier and thus opened cracks for the flow of the leachate.

c. There may be a need to cover the pond slopes to protect the clay from erosion caused by the wave action.

C.3.5 Wood

California redwood, Douglas fir, and other weed species have been used extensively for liquid storage tanks for many years. Wood tanks made of 7.62-cm-thick (3 in.), clear, all-heart California redwood are readily available. A disadvantage is that these wooden free-standing tanks will dry out and become loose at the joints if left empty. If allowed to remain this way, the tanks will collapse. Ponds could be lined with creosote impregnated plywood panels nailed together and the joints could be sealed with a mastic. However, the cost is higher for these pond liners (Table C-4) than for other acceptable materials.

C.3.6 Steel

Welded steel tanks are used in the chemical processing industry; many of these tanks have inside coatings or liners to protect them from corrosion. A typical tank that might be used to contain the limestone sludge is one fabricated from 9.53-mm-thick (3/8 in.) low carbon sheet steel of ASTM A283, Grade C. However, because of the high cost of steel tanks (Table C-4) as compared to the cost of an open sludge pond, they were eliminated from evaluation in this study.

C.3.7 Asphalt

Asphalt linings have been used for many years in the construction of reservoirs, irrigation canals, and various types of waste ponds. Two of the major types of asphaltic materials (Ref. C-17) that could be considered for use as liners in sludge disposal ponds are: asphalt concrete, and hot sprayed asphalt membranes.

Table C-4. WOOD AND STEEL TANK COST ESTIMATES

Tanks (delivered and erected)	Diameter, ft	Height, ft	Cost, $
Redwood, 3-in.-thick material	42.5	20.0	22,500[a] 25,000[b]
	48.0	20.0	45,000[b]
Steel, ASTM A283, Grade C			
3/8-in.-thick	50.0	20.0	15,000[a] 25,000[b]
1/2-in.-thick	50.0	20.0	35,000[b]

[a]Without cover

[b]With cover

To convert from	to	Multiply by
in.	cm	2.45
ft	m	0.3048

Asphalt concrete is a mixture of asphalt cement and graded aggregate that is mixed, placed, and compacted under elevated temperatures. For canals and laterals the lining is normally constructed to thicknesses of at least 5.08 cm (2 in.), and for reservoirs thicknesses of over 7.62 cm (3 in.) are most generally used. The dense graded, hot-mix asphalt concrete that would be used for waste ponds is very similar to that used for highway surfaces. However, it would have a higher percentage of mineral filler and a higher percentage (6.5 - 9.5 percent) of asphalt cement of a low penetration

grade. A composition recommended by one of the contractors for a dense sludge disposal pond lining is as follows:

Sieve size	Percent passing by weight
9.52 mm (3/8 in.)	100
No. 4	65-85
No. 8	45-65
No. 30	20-36
No. 50	10-22
No. 200	3-9
Asphalt cement percent by weight of total mix	5.8-7.8

The asphalt mixes can be placed on side slopes of 2:1 and on flat planes with conventional paving equipment. Power winches and cables are generally used to maneuver the equipment on the side slopes. The maximum steepness of slope that should be permitted for various vertical heights of slope paving are as follows:

Vertical height of slope paving	Maximum Steepness	
	Horizontal	Vertical
up to 3 m (10 ft)	1-1/2	1
3 m to 6 m (20 ft)	1-3/4	1
6 m to 12 m (40 ft)	2	1
over 12 m	2-1/2	1

The hot sprayed asphalt membrane consists of a continuous layer of asphalt usually without filler or aggregate and is generally about 6.35 mm (1/4 in.) thick. The application temperature of the asphalt should be from 176.6° - 204.4°C (350° - 400°F); the hot asphalt can be applied under nearly any air or ground temperature from 37.8°C (100°F) to below -17.8°C (0°F). The heated asphalt is sprayed on in quantities of about 6.8 l/sq m (1-1/2 gal/sq yd) which

will produce a membrane of approximately 6.35 mm (1/4 in.) thick. The membrane should be covered or buried by approximately 0.254 m (10 in.) of earth to keep it from weathering and to protect it from mechanical damage. For the application of the membrane lining to the side slopes, the slopes should not be steeper than 2:1.

It was reported that the seepage rate for either of these two asphalt linings is "immeasurable" when properly applied; however, the exact amount of seepage is not known under field conditions. It was further reported that asphalt-lined ponds have experienced difficulties with liquid accumulating behind the liner and causing a crack to occur in the coating. Furthermore, liner selection is based primarily on the availability of material and equipment for a particular site and the specific characteristics of the site.

Subgrade preparation is generally the same for either type of asphalt lining to be used. It should be thoroughly cleaned of all organic and loose material and compacted sufficiently to attain stability (particularly the side slopes), and to sustain the traffic of any vehicles used to place and compact the lining. Subgrade soils that swell considerably when wetted can exert sufficient pressure to damage asphalt linings. Also trapped water, which cannot drain because of underlying impervious soil layers, can exert sufficient hydrostatic back pressure to break up large sections of the lining. When such conditions are likely to occur, it has been recommended that the faulty material be removed to a depth of at least 0.3 m (1 ft) and replaced with selected material. Application of a soil sterilant is recommended when favorable growth conditions exist.

The chemicals within the limestone sludge should have no effect on the asphalt, as asphalt is considered stable in the presence of inorganic chemicals except for high concentrations of sulfuric acid. The plasticity of asphalt concrete will allow for slight earth movements or settlements in the subgrade without damaging the liner structure.

C.3.8 Gunite

"Gunite" is a trade name of the Cement Gun Company of Allentown, Pennsylvania. Gunite is defined as a mixture of portland cement and sand thoroughly mixed dry, passed through a cement gun and conveyed by air through a flexible tube, hydrated at a nozzle at the end of the flexible tube, and then deposited where desired by air pressure. It has been reported (Ref. C-18) that this material has been successfully used to construct ponds for sewage treatment plants and for lining canals, flumes, and tanks. "Shotcrete" is similar to Gunite except that the cement, aggregate, and water are premixed and then passed through a cement gun. The recommended mix for Gunite is in the proportions of 1 part of cement to 4-1/2 parts of sand. The ASTM Types I or II cement are generally used, and the aggregate consists of washed sand. The limits of grading of the fine aggregates as specified by the Gunite Contractors Association are as follows:

Sieve size	Percent passing by weight
9.52 mm (3/8 in.)	100
No. 4	95-100
No. 8	65-90
No. 16	45-75
No. 30	30-50
No. 50	10-22
No. 100	2-8

Gunite is an extremely dense product that can be easily applied on 2:1 slopes. It has been recommended that at least a 7.6 cm (3 in.) Gunite lining with reinforcing of 15.2 cm (6 in.) No. 10 gauge welded wire mesh be used for sludge disposal ponds.

Gunite provides a good waterproof membrane; however, experimental testing should be accomplished to obtain actual test data.

Also, Gunite, like soil cement or concrete, require additives for protection against attack by the sulfate compounds within the sludge.

C.3.9 Pozzolan Stabilization

The use of fly ash as a pozzolan ingredient mixed with sand, lime, aggregate, and water to form a cementitious material is a well established process used to make road bases, airport runway bases, embankments, and reservoirs. This usage is particularly significant when watertightness and crack and sulfate resistance are required. It has been applied in various mixes by several users, with the more prevalent mix being Poz-O-Pac, originated and controlled by the G. and W. H. Carson Company of Philadelphia, Pennsylvania [now International Utilities Conversion Systems, Inc. (IUCS)]. This pozzolan stabilized material could be used as a pond base material superior to and cheaper than asphalt because it would be used at or near the fly ash supply (i.e., if the ash is collected and stored so that it can be used for this purpose).

The Poz-O-Tec process developed by IUCS uses sulfur sludges that include fly ash (or add fly ash separately) in a process similar to the Poz-O-Pac process. The new process reportedly achieves improved engineering properties and can be used without the addition of aggregate. Similar characteristics may be obtainable through the use of the Dravo Corporation's Calcilox additive. To date, the application of these pond linings for sludge disposal has not been reported; however, the possibility has been considered (e.g., at Commonwealth Edison Company's Will County Station in Joliet, Illinois).

The potential use of pozzolan stabilized materials as pond linings will be investigated further in the succeeding portion of this study.

C.4 PROCEDURE FOR FABRICATING FLEXIBLE LINER PANELS AND FIELD INSTALLATION

Flexible sheeting or film is purchased from the sheeting manufacturer in rolls about 127 - 191 cm (50 - 75 in.) wide by 152 m (500 ft) long. This sheeting is fabricated into large sections called panels in the liner manufacturer's factory heat sealing or solvent/resin bonding together strips of the narrower sheeting. The resultant pond liner panel is normally about 21.3 - 24.4 m (70 - 80 ft) wide by 106.7 - 137.2 m (350 - 450 ft) long. The panel size depends upon the size and shape of the pond to be lined, the capabilities of the factory, and the ability of the field personnel to handle the large sheets (Refs. C-1 through C-3).

The fabricated panels of the flexible liner are accordion folded in both the longitudinal and transverse directions, packaged for minimum handling in the field, and boxed at the factory for shipment. However, the pond lining contractor may elect to fabricate the large liner panels near the pond site rather than to ship from the factory area. Factories are located throughout the United States, and the decision as to factory versus on-site fabrication is essentially a matter of cost, construction feasibility, and the size and location of the pond to be lined.

At the pond site, the ground is graded and compacted to provide a reasonably smooth surface. Compaction of the soil to 90 - 95 percent is advisable to provide a firm base for the pond. The removal of sharp sticks, stones, and trash reduces the local stresses on the liner membrane and decreases the chances of developing holes in the liner. Roots and grasses have a tendency to grow through the membrane and should be destroyed before lining. The soil should be sterilized to preclude future growth.

Several methods of pond liner installation have been used, but the system that appears to be the easiest to perform is to:

a. Place the accordion folded panel on a flat-bed truck, a fork lift loader, or other suitable carrier and open the accordion fold to expose the panel lengthwise by holding one end of the panel and driving the vehicle forward. Each panel is positioned adjacent to the previously opened panel in the pond so that a field joint can be made.

b. Field seam the liner panels by using a solvent/resin sealer or taping technique (Figure C-1); other techniques (e.g., field heat sealing, zipper designs, or sewing in place) are used for specific applications. The quality control on the factory and field seams is by visual inspection of the seal which has been prepared based upon accepted company standard operating procedures.

c. The panel, which is opened lengthwise and bonded to the previously opened panel, is next opened to its full width by the construction crew pulling sideways on the liner.

d. The liners are positioned on the side slopes to fit into a perimeter trench located approximately 20.3 - 30.4 cm (8 - 12 in.) along the berm surface and still permit bonding to the adjacent panels.

e. Repair of a liner is accomplished by cutting out the damaged section and bonding in a new piece, or by installing a patch over a small hole.

C.5 POND DESIGN AND CONSTRUCTION PROCEDURE

In the design and construction of a sludge pond the following general procedures are normally employed:

a. The need for a pond has been established as the result of new manufacturing or operating processes being instituted, new or changed laws affecting the accepted disposal techniques, attempts to reduce costs, or many other equally urgent reasons.

b. An independent engineering firm or the Company's in-house engineering office will conduct field surveys

and experimentation to gather data for detailed technical and economic analyses to determine the best location, size, construction materials, special features, and other requirements for the pond(s).

c. If the project is large and costly, and special financing is required, arrangements are made through regular banking circles to obtain the capital for the initial investment.

d. Detailed construction drawings and plans are made after all preliminary investigations have been completed and details agreed upon. Normally, plans are prepared to solicit bids from the following:

- Contractors for dirt movement (e.g., building the roads, pond walls, covering the liners with soil)
- Pond lining contractors
- Building and fencing contractors
- Piping/steam fitting/pumping contractors
- Instrumentation and electrical contractors
- General contractor for more than one phase of the work

Construction and start-up schedules are established, and contracts are negotiated with the winning contractors. Construction times vary from a few weeks for small ponds like the Pacific Gas and Electric pond at Barstow, California, 2024 sq m (0.5 acres), to about a year for the 1,618,800 sq m (400 acres) at Texasgulf's Moab, Utah facility.

Construction is undertaken using local labor whenever possible with the job contractor providing the supervision. This philosophy applies to all the contractors including those who install the flexible pond linings. There are many local rules, regulations, and customs that influence how the pond is to be built. The preceding procedures are general in nature, but they provide an insight into some of the methods currently being employed.

C.6 POND SAFETY

Procedures must be made to protect the workers, the general public, animals, and in some cases, birds, from injuries associated with the sludge ponds. Some of the standard techniques that are used and should be evaluated in any sludge pond operation are summarized below:

a. Fencing - The pond area should be totally enclosed within a 1.83 - 2.44 m (6 - 8 ft) high sturdy fence (e.g., chainlink) to prevent intrusion from the general public and large animals. In some areas the fencing must be buried several feet deep in the ground to retard any intrusion from burrowing animals.

b. Netting - Polypropylene netting material is being used to prevent birds from landing on oil sump ponds (Ref. C-19). This netting material is lightweight (5 gm per 1000 sq m) and is currently being fabricated in panels 15.2 m (50 ft) wide by 60.96 m (200 ft) long. Guy wires attached at the berms are stretched across the ponds, the panels are laid over the wires, and each panel is laced to its adjoining panel with a Dacron cord. The polypropylene netting is usable to -45.6°C (-50°F), but its long-term weatherability is still unknown because the resin is affected by sunlight. However, Coastal Engineering Company reports a successful 5-year field installation test in New Mexico. A need for covering sludge ponds has not been shown.

c. Vehicle Travel on Berms - The size of the berms is a function of the depth and area of the sludge pond and the local terrain. To protect the employees, who have a need periodically to drive vehicles along the berm surface, from accidents during this phase of their work it is advisable to incorporate a specifically designed road surface into the design of any new large pond. By incorporating the road into the original design and engineering, sufficient planning can be given to the road bed, width of the road, and protective guard rails.

d. Security - Companies currently operating large evaporation or sludge ponds generally have a security guard to patrol the area on a periodic basis. This operation serves not only to discourage intruders, but acts as an emergency patrol if a person or animal should get past the protective barriers and should accidentally fall into the pond.

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APPENDIX D

POTENTIAL COMMERICAL UTILIZATION OF SULFUR DIOXIDE SLUDGES

D.1. OVERVIEW

As a result of the extensive research that has been performed to determine the technical properties and characteristics of the potential commercial products to which sludge may be applied numerous products and applications have been developed. Some of the products and applications would require the consumption of a major portion of the available sludge if used nationally on a large scale. However, these new products would have to compete successfully (both technically and economically) on the open market with well established manufactured or natural products. Since sludge is a relatively new material that is not yet available in large quantities throughout the nation, a true market test has not been made. However, indications are that potential sludge products will not be competitive enough in the near term to consume an appreciable portion of the projected supply and that the principal concern for sludge will be "disposal" and not "utilization."

This appendix discusses that situation and provides the rationale for the conclusion just made.

D.2. TECHNICAL STATE OF THE ART

D.2.1 Potential Utilization

Research, development, and investigative activities have been conducted or sponsored by numerous government and private organizations to determine the potential utilization of power plant desulfurization sludges. Some of the more significant organizations include: the EPA (Refs. D-1 through D-3), the Bureau of Mines (Ref. D-4), the Federal Highway Administration (Ref. D-5), West Virginia University's Coal Research Bureau (Refs. D-1, D-2, and D-6), the TVA (Ref. D-7), The Aerospace Corporation (Ref. D-3), Combustion Engineering, Inc. (Ref. D-8), International Utilities Conversion Systems, Inc. (Refs. D-9, D-10, D-11, and D-12), the National Ash Association, the Dravo Corporation (Ref. D-13), and the Chicago Fly Ash Company. These efforts have identified desulfurization sludge as a unique raw material that has some potential use in the manufacture of products now using fly ash as an additive, or in new products or applications.

An inspection of the products listed for which fly ash is used as an additive, and the applicability of sludges to these products, provides an insight into the great difficulty attached to the possible utilization of the throwaway sludge. For example, an annual survey conducted by the Edison Electric Institute (EEI) (Ref. D-14) presents a breakdown (Table D-1) of ash collection and utilization in the United States for 1972. Three significant factors regarding sludge have been derived from this table and previous EEI surveys (Ref. D-3), namely: the low percentage of available fly ash that is actually used; some technical capability, but an economic inability to apply sludge in most uses of fly ash; and the economic inability to apply sludge in the major uses of bottom ash and boiler slag.

Table D-1. ASH COLLECTION AND UTILIZATION YEAR 1972 AS REPORTED IN REFERENCE D-14 (tons)

Ash utilization	Fly ash	Bottom ash	Boiler slag (if separated from bottom ash)
1. Ash sold or used internally (This includes ash sold by a utility or its sales agent and/or ash used by a utility)			
a. Mixed with raw material before forming cement clinker	116,178	30,248	110,000
b. Mixed with cement clinker or mixed with cement (pozzolan cement)	72,201	-	-
c. Partial replacement of cement in:			
Concrete products (blocks, bricks, pipe, etc.)	143,112	22,678	-
Concrete	301,689	-	-
Dams and/or other mass concrete	67,880	-	-
d. Lightweight aggregate	133,901	23,521	-
e. Fill material for roads, construction sites, land reclamation, etc.	584,860	750,660	477,293
f. Stabilizer for road bases, parking areas, etc.	153,629	24,648	4,683
g. Filler in asphalt mix	139,937	14,634	43,431
h. Miscellaneous	426,737	921,193	701,663
Total Item No. 1	2,140,124	1,787,582	1,337,070
2. Ash removed from plant sites at no cost to utility, but not covered in categories listed under Item No. 1	1,495,156	814,336	1,235
3. Total ash utilized (Item Nos. 1 and 2)	3,635,280	2,601,918	1,338,305
4. Total ash produced	31,808,065	10,672,860	3,781,660

Table D-1 shows that 7 percent of all fly ash produced was utilized in the products noted, and that another 4.8 percent was removed from plant sites at no cost to the utility (some was used and the remainder was probably stored). In addition, there is the utilization of bottom ash and boiler slag, principally as a constructional fill material with which the sludges cannot compete economically because the bottom ash and slag are used as aggregate without appreciable processing. When all these applications for power plant ash are considered, the maximum utilization of the total produced is about 16 percent. Of these applications, the "stabilizer for road bases, parking areas, etc." category is the only current use in which the sludge should be able to compete technically and economically on a national basis in the ash market. As an artificial aggregate, it can also enter some local markets depending on the supply of natural aggregate. However, the current ash-usage categories of road bases and aggregate account for a usage of less than 1 percent of the total ash produced. Also, it has been shown (Ref. D-3) that for a given power plant, an alkali scrubber system will produce up to three times as much sludge as the amount of ash produced without scrubbing. Therefore, with the by-product production increased as much as three times at a given plant and the potential utilization in the near term being inconsequential on a national basis, the disposal of the by-product appears to be the principal method for handling these materials.

D.2.2 Material Properties

A theoretical chemical analysis of the sludge reveals the wide range of values attached to the chemical constituents depending on the sulfur and ash content of the coal burned. Physical phases vary widely in the same manner. Table D-2 shows the values for 10 and 20 percent ash content coal and for a sulfur content of 1 and 4 percent in

Table D-2. LIMESTONE SLUDGE -- THEORETICAL VARIATIONS IN CHEMICAL AND PHASE COMPOSITION WITH VARIATIONS IN SULFUR AND ASH CONTENT OF COAL BURNED AS REPORTED IN REFERENCE D-3

The following conditions were used in this theoretical analysis: the sulfur collection system was assumed to be 95 percent efficient, limestone was added at 110 percent stoichiometric and was assumed to be 100 percent $CaCO_3$, and the only ash collection device was a wet scrubber.

	Composition	Typical fly ash (unmodified)	10 percent ash in coal		20 percent ash in coal	
			Sulfur content of coal			
			1 percent	4 percent	1 percent	4 percent
		Weight percent				
Constituents	SiO_2	45	30.6	16.2	36.8	23.9
	Al_2O_3	23	15.7	8.3	18.8	12.2
	Fe_2O_3	19	12.9	6.8	15.5	10.1
	TiO_2	1	0.7	0.4	0.8	0.5
	CaO	2	14.4	28.5	9.5	21.5
	MgO	1	0.7	0.4	0.8	0.5
	SO_2, SO_3	0.7	17.5	36.2	10.8	26.9
	Other	2.3	1.6	0.8	1.9	1.2
	LOI[a]	6	4.1	2.2	4.9	3.2
	Relative Quantity	1.00	1.47	2.77	1.22	1.88
Major Phases	Gypsum[b]	0	28.3	60.1	17.5	43.5
	Free Lime	2.0	2.8	4.5	2.3	3.7
	Fly Ash	97.3	66.3	35.1	79.5	51.6

[a]Loss on ignition.

[b]Values given for gypsum include both sulfates and sulfites, but exclude combined water.

each case. The variations in properties are large, and the differences are considerable when compared to fly ash. The principal problems that face the utilization of the sludge are, therefore, centered in several areas:

a. The sludge quality is affected appreciably by the sulfur content of the coal burned and by the efficiency of the combustion and scrubbing process.

b. The sludge contains sulfur that creates additional problems of sulfur gas collection for manufacturing processes requiring high temperatures.

c. The pozzolanic (concreting) properties of the sludge are weak when compared to those of fly ash.

d. The volume of sludge produced will be much greater than that of the ash produced without the scrubbing process.

On the positive side, as appropriate, the sludge contains: some pozzolanic properties, nominal amounts of unreacted lime, and appreciable amounts of gypsum.

The sludge qualities shown in Table D-2 consider the collection of fly ash in the scrubber. At power plants where efficient fly ash collection systems exist, the fly ash will be collected upstream of the scrubber, and very little fly ash will exist in the sludge. Therefore, for essentially all developments for sludge usage (other than gypsum production and processing for one claimed landfill method) fly ash will have to be added to provide the pozzolanic properties necessary for structural qualities.

D.2.3 Potential Product Applications

Technical developments for the potential usage of the sludge have been made for the most part by: the Coal Research Bureau at the University of West Virginia under the sponsorship of the EPA; The G. and W. H. Corson Company (now International Utilities Conversion Systems, Inc.), Philadelphia, Pennsylvania; Combustion Engineering, Inc., Windsor, Connecticut; and Michigan Technological

University, Houghton, Michigan. Uses being studied or considered include those for which fly ash is being used or could be used, plus new developments. Table D-3 summarizes those considerations and includes uses that may be possible regardless of how slight their potential is.

Table D-3. POTENTIAL PRODUCT APPLICATIONS

Uses same as or similar to those for fly ash	Potential new uses
Concrete admixture (structure and products)	Autoclaved products - gas concrete, bricks, mineral aggregate
Manufacture of portland cement	Hot press sintering - pipes, metal coatings
Fired brick	Gypsum products - wallboard, plaster
Filler in bituminous concrete	Mineral recovery
Road base course, parking lots, etc.	Sulfur or sulfuric acid production
Structural fill	Artificial aggregate
Soil amendment	
Mine void fill	
Neutralization of acid mine drainage	

D.2.4 Use Inhibitions

The difficulty associated with the small usage of fly ash in the United States and the weak projections for the potential use of sludge products are best seen by examining the inhibitions to the use of fly ash and by comparing fly ash properties with those of sludge. It has been determined that the major inhibitions to the use of fly ash, which generally apply to the inhibitions to the use of sludge, are:

a. Highly variable chemical and physical properties

b. Lack of control or availability of usable supply when needed

c. Necessity for appreciable capital expenditures to classify, handle, store, or process materials

d. High transportation costs

e. Inability to compete economically with other materials

Thus it has been shown (Ref. D-3) that although there are many uses for the fly ash considering already developed technologies, and that these potential products are in many ways equal to or superior to existing materials, its actual utilization is particularly limited. The situation is worse for sludge as an additive in the production of commercial products as described in the following discussion.

When the potential technical uses of the sludge are related to the basic properties and qualities mentioned in Paragraphs D.2.2 and D.2.3, various factors are applicable to the potential utilization of large tonnages of sludge on a national basis. These factors identify reasons where: (a) the sludge product is expected to be technically or economically inferior to a fly ash product (which is already in a weak marketing position as shown in Table D-1, (b) its production or use may create a pollution problem, or (c) it may be technically

sound, but not economically competitive on a wide scale. These factors are:

a. The sludge is produced in a wet state and will have to be dewatered or dried for many uses to prevent agglomeration due to the interaction of the pozzolan with self-contained lime in the presence of water. Agglomeration can require a grinding operation depending on the fineness required for structured concrete qualities.

b. Its pozzolanic properties for concrete product applications are reduced because the sum of the SiO_2, Al_2O_3, and Fe_2O_3 content and consequently, the glassy phase is reduced (see Table D-2).

c. Sludge properties can be highly variable (see Table D-2); therefore, blending may be required for many applications.

d. The use of sludge in the manufacture of sintered products has three distinct disadvantages:

- Sulfur is released and would have to be collected.
- Decomposition of sulfates (or sulfites) takes place at temperatures below sintering and results in the physical destruction of the "green formed" product.
- The fusion temperature is such that a short range exists between sintering and melting, thereby requiring a sophisticated temperature control system for the sintering process.

e. The soluble salt content of the sludge presents a problem of leaching heavy metals to ground waters for certain applications (e.g., soil amendment and acid mine drainage neutralization).

f. There is the problem of nondeveloped or high-cost technology for mineral recovery to obtain aluminum (Ref D-1), iron, titanium, silicon, and lime.

g. Severe competition from a saturated current market for products such as gypsum‡, mineral wool (Ref. D-3) sulfur, and sulfuric acid (Refs. D-3 and D-8).

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‡Gypsum is the only sludge product sold overseas; it is marketed in Japan where the material is competitive (Refs. D-4 and D-15). In Reference 4, it is projected that in Japan in the mid-1970s, the sludge-gypsum supply will exceed demand.

h. High capital investments are required to produce autoclaved products.

In consideration of the factors noted, it should be recognized that of all the potential large-scale uses for the sludge, the most promising are: (a) road base materials (Refs. D-5, D-6, D-10, and D-12). and artificial aggregate (Ref D-9) and (b) landfill or land reclamation when appropriately conditioned to prevent leaching (Refs. D-8, D-9, D-11, and D-13). The former are considered commerical utilizations of the sludge while the latter is generally considered a disposal process. As a road building material, the sludge has a potential for large tonnage utilization; however, it must compete with existing materials such as crushed rock and bituminous concrete (Ref. D-3). Although the sludge-produced road base materials are believed to be superior in regards to strength, stability, water-tightness, and crack resistance when compared to competing products, a comparatively thin layer of crushed rock in particular is accepted by most specifications and agencies and is generally used because it is cheaper. Only in local areas where crushed rock is unavailable or not allowed would sludge-produced materials be considered. Artificial aggregate could also consume large masses of sludge, but its demand is only local where natural aggregate is not available. In the near term, this is not expected to be a widespread condition.

D.3 POTENTIAL UTILIZATION CONCLUSIONS

Because the sludge is not expected to find large-scale commercial outlets in the near term, it is concluded that its potential utilization as an ingredient in a commercial product is low and that the major consideration for its disposition must be disposal. The principal applications then would be: landfill, artificial aggregate to be used in a landfill and possibly to be reclaimed later, and possibly for both the filling of mine voids and the neutralization of acid mine

drainage. All of these applications will require the appropriate determination of environmental impact on the earth and water supplies, and the appropriate treatment or conditioning necessary for the environmentally sound disposal of the material.

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APPENDIX E

COMMENTS ON SELECTED POWER PLANT SLUDGE DISPOSAL PROGRAMS

This Appendix contains comments on four different approaches to sludge disposal, each being investigated by one of four different power companies. Progress is being made by each of these; however, none has reached the point of steady-state operation and it is expected that all of these programs will undergo change either within themselves or in succeeding applications as the technology improves. These approaches and others will be investigated during the remainder of this program to form as complete a survey of all industrial progress as is possible.

E.1 COMMONWEALTH EDISON, WILL COUNTY STATION, JOLIET, ILLINOIS

The sludge at this station is produced by a full-scale scrubber on a 175 MW boiler. The disposal problem is compounded by the unavailability of sufficient acreage to contain the sludge, the immediate proximity to the Illinois River, and a high water table. Since Commonwealth Edison operates in high-density population areas, considerations given to disposal techniques at the Will County Station

can be reasonably extended throughout the company's power system. In this regard, the company has addressed sludge disposal with consideration given to the following priorities: (a) Economic Land Use - pit disposal or landfill areas within short haul distance of power plants are not considered for thixotropic sludge because they may not allow subsequent economic development of the land after filling, (b) Environmentally Safe - the sludge must not contaminate by leaching to ground water or nearby water courses, (c) Disposal Costs - the disposal technique must minimize transportation and eliminate excessive handling, thereby reducing disposal costs. Commonwealth Edison has decided, therefore, that the sludge must be conditioned so that it will not leach to the ground water and that it must serve adequately as a landfill material because the final disposal is planned on land that is not owned by the power company.

Commonwealth Edison has consulted with several commercial sludge processors, but because of the economics involved they are attempting to develop their own fixation process with the aid of the Chicago Fly Ash Company who, in turn, has employed the Civil Engineering Department of the University of Illinois for assistance. Their plans are to extract thickener underflow to which lime and fly ash and one wet additive will be intermixed with the sludge in a pug mill and loaded in a dump truck. The truck will transport these ingredients to one of two 10-ft-deep clay basins that total about 7 acres. An arbitrary lining thickness of 1 foot was chosen for these basins. The clay has a permeability coefficient of about 10^{-6} cm/sec whereas the cured material is expected to have a coefficient in the range of 10^{-7} to 10^{-9} cm/sec. The material cures for approximately 1 month and is inspected by local authorities to obtain permission for each site disposal. It will be dredged from this basin and hauled to a nearby land fill area while the second basin is being filled.

The present additives are reported to be approximately 10 percent lime and 20 percent fly ash on a dry basis. A development program is planned to reduce costs by increasing fly ash and reducing lime contents. Their present philosophy is an acknowledged over-kill to avoid possible variability in sludge chemistry. Subsequently they hope to optimize for steady-state operation, but they realize they must plan for scrubber downtime such that boiler operation is unaffected. Tests are still being conducted to improve the final product by the elimination of cracks during curing and to verify impermeability in the field. They have not yet determined whether their leachate contains trace heavy metals. They have determined that with enough lime, a concrete-like product with 3000 psi strength can be obtained. For landfill disposal purposes, a product with a strength far less than this is desired because of the subsequent need to dredge it from the cure pond.

In the present operation, sludge is being dredged from an interim pond, loaded in a Redi-mix truck to which the fixation ingredients are added. The truck mixes these materials enroute to one of the cure ponds where the materials are unloaded. The cost has varied between $5.25 to $10.00 per ton of sludge (50 percent solids); the higher value results from specific case operations that include machinery breakdown and repair. These costs are only operating and maintenance costs and do not include pond costs or $600,000 of capitalization. Unofficial estimates for disposal including all costs after optimization for steady-state operation are placed at $5.00 per ton. Besides the inclusion of a pug mill and the replacement of the Redi-mix truck with a dump truck, it is believed that a vacuum filter must be installed between the clarifier and pug mill to reduce the water content of the waste. Their present estimate for flue gas scrubbing at Will County has been placed at $100/kW capacity.

Commonwealth Edison does not know whether their sludge may pose an environmental hazard. Liquors are saturated in sulfate, and present chloride content has been measured at 800 ppm. At this concentration, evidence of corrosion-assisted erosion is apparent. The recirculation system has been installed or replaced with rubber lined piping and pumps, and no further problems have been experienced.

Commonwealth Edison is under way in a disposal development program designed to satisfy their particular disposal requirements. All data collected represent present status and are not firm. It is expected that firm values regarding the technical quality of the fixed materials and attendant costs will not be adequately determined for at least another year.

E.2 NORTHERN STATES POWER COMPANY, SHERBOURNE COUNTY STATION, MINNEAPOLIS, MINNESOTA

This new station will have a total capacity of 1360 MW and will be on-line in 1975/76. The plant will use western coal having a sulfur content of 0.8 percent and will guarantee a 50 percent sulfur removal using a limestone scrubber. The sludge will be sluiced to clay-lined ponds (with 18-in.-thick linings) and excess water will be returned to the scrubber system. An initial (10-year) pond will be approximately 65 acres with 40 ft dikes. A second basin will be added later bringing the total capacity to 160 acres for an expected 35- to 40-year plant life. This site is located on bluffs above the Mississippi River at an elevation of 965 ft; the normal river water elevation is 920 ft. Pond costs are in excess of $30,000 per acre.

The scrubbing system will use two stages, a variable throat venturi and a marble bed scrubber. Fly ash will be collected simultaneously with the sulfur sludge. The Sherbourne County permit

requires 50 percent sulfur removal and 99 percent particulate removal. The venturi removes 55 percent of the total 70 percent sulfur removed and 90 percent of the particulates. The second scrubbing stage is required for particulate removal. It was speculated that newer plants would use precipitators for fly ash removal predominantly because it would increase operating flexibility, reduce erosion, provide for the sale of dry ash, and allow single-stage scrubbing.

The Sherbourne County Station scrubbing unit design was based on experiments presently being conducted at the Black Dog Station on a pilot scrubber. The coal ash contains 17 percent CaO, and it was found that only a 20 percent stoichiometric addition of limestone produces satisfactory scrubbing efficiencies. The use of fly ash as a sorbent predicated the collection of particulates in the scrubbing unit. The company's Black Dog Power Station operation is a research effort for determining scrubber parameters; however, this research philosophy was not extended to considerations regarding waste disposal.

Trace metal analyses on sludge and fly ash were not known. The possibility exists that the Sherbourne County Station disposal pond will undergo environmental monitoring by the analysis of leachate from wells placed around the pond.

E.3 LOUISVILLE GAS AND ELECTRIC COMPANY, PADDY'S RUN STATION, LOUISVILLE, KENTUCKY

This full-size scrubber is operating on a 70 MW 25-year-old boiler that has an 18 percent operating efficiency factor and runs approximately 40 percent of the time. The deep mine southern Kentucky coal used at this station has a sulfur content of approximately 3-1/2 percent and an ash content of 15 percent. The scrubber operates on a fully closed-loop cycle and attains an 85 percent sulfur removal efficiency. The disposal process includes extracting underflow from the thickener,

vacuum filtering the underflow to approximately 55 percent solids, and trucking it 1 mile to a state borrow pit. No environmental control is applied. Disposal costs are not well defined; however, it is believed that the hauling cost is approximately $0.50/ton at this particular site. The company uses its own 12-ton capacity dump trucks.

Disposal of this material is not considered representative of company policy. Louisville Gas and Electric Company has committed itself to $165M over 10 years for scrubbing equipment. Disposal plans are now considering chemical fixation and possible use of fixed wastes in land salvage of strip mined areas or as a support material for recovery of the 30 to 60 percent of the coal remaining in deep mines. No estimation of disposal costs has been made, but it is assumed that $70/kW capacity is a representative figure for scrubbing; however, this does not include disposal (disposal is a coal cost and is directly transferred to customers).

The Paddy's Run Station is unique in that it uses a waste carbide sludge (calcium hydroxide) as the sorbent. The system operates in a transient between pH 5 and 11 by the reaction of bisulfite with the calcium hydroxide. The resulting sludge is about 95 percent sulfite; oxidation of the liquors is retarded such that the sulfate in the liquors is about 400 ppm.

All sludge is collected independently of fly ash. Precipitators now exist on all stacks and are planned for all future plants. A primary consideration for upstream fly ash removal is the control of erosion and the elimination of boiler downtime during periods of scrubber maintenance. Their evaluation shows that savings by boiler downtime avoidance more than offsets the precipitator costs. Alternative disposal schemes consider collection of thickener underflow at 20 to 30 percent solids to which dry collected fly ash might increase solids content to 50 to 60 percent, or to pass the underflow through a filter to get 50 percent solids to which fly ash might be added.

Louisville Gas and Electric Company has a well run, full-scale scrubber demonstrating the capability of this technique for SO_2 control. Although plans for environmentally sound disposal techniques were discussed, no implementation of such plans was observed.

E.4 DUQUESNE LIGHT COMPANY, PHILLIPS STATION, PITTSBURGH, PENNSYLVANIA

This is an operational scrubber system. The sludge disposal system consists of removing the underflow from the clarifier, treating it with Calcilox (a Dravo material), and allowing it to set for 30 days in one of three curing basins. A disposal development program will be conducted at this station. The cured sludge will be removed from the curing basin and hauled about 1 mile to the disposal demonstration site. This site includes one unlined pond and two ponds lined with Hypalon. Each pond will have underdrainage and overdrainage piping to collect water for testing. No definitive costing data are available; however, Duquesne notes that their present fly ash disposal system consists of dredging fly ash from a lagoon and hauling it about 1 mile to a landfill site, compacting it, and seeding it. The fly ash contains approximately 18 - 20 percent water and costs between $2.50 and $3.00/ton for disposal. They equate this to approximately $0.40/ton of coal burned. By comparison, they equate the cost of sludge disposal--on a dry basis--to approximately $3.00/ton of coal. Those values include capital cost and, in the case of the sludge, the material will be eventually covered with top soil and seeded. Also, they are not to be considered firm rates. Other cost estimates are given in Section 7.2.

This plant uses eastern coal containing 20 percent ash and 2 percent sulfur. The scrubber sulfur collection efficiency is approximately 90 percent. In the combustion process 80 percent of the ash produced is fly ash and the remainder is bottom ash. A

primary consideration in their design for sludge disposal is land reuse possibly as a consequence of strong state regulations with regard to waste disposal. In addition, the sludge must not contaminate the environment. Both the Federal EPA and State Agencies have stated their satisfaction with the leachate from their fixed sludge. Duquesne Light Company is conducting one of the more comprehensive research and development programs with respect to disposal technology but, as with other companies, their efforts are constrained by their own equipment and restricted to their unique condition.

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APPENDIX F

TOXIC EFFECTS OF TRACE ELEMENTS

F.1 INTRODUCTION

The determination of heavy element toxicity is dependent upon observed physiological effects resulting from either carefully controlled experiments or from an environmental catastrophe of epidemic proportions. Clinical experiments rarely if ever precede the observed consequence of illness and death that often results from acute exposure to specific element intoxication. Moreover, health hazards from clinical testing preclude these experiments so that the relationship between exposure and the effects on humans is most often evaluated from the effect on animals. Thus, the resulting threshold or exposure limits for humans are not always established with the certainty that may be desired. The role of trace elements in man's biological processes is only now beginning to be understood: many elements toxic to man in relatively high concentrations are essential to his health in trace quantities.

Nine elements found in nature in trace quantities (chromium, cobalt, copper, iodine, iron, manganese, molybdenum, selenium, and zinc) are essential to man's life or health. They are

probably important catalysts for differing biological functions. In addition, vanadium, nickel, fluorine, and arsenic are suspected of having useful biological functions. Other elements, which are now considered inert, are found in human tissue and may perform useful roles in the body, but the study of their biological activity has not been undertaken. Cadmium, mercury, and lead have no known biological function and can act synergistically with other substances to increase toxicity. Once in the human system, their toxic effects are cumulative and are harmful to the degree that the dosages and resultant concentrations approach a lethal threshold. Even those trace elements having proven biological functions, when ingested at high concentrations, can produce disease either by their accumulative effect or by inhibition of natural functions.

From the two known accumulative diseases, hepatolenticular degeneration from copper and idiopathic hemochromatosis from iron, accumulative diseases are suspected for other essential cations--chromium, manganese, cobalt, and possibly zinc and vanadium. The medical profession has long recognized that all essential trace elements are toxic in excess. If it were not for homeostatic mechanisms that reject excesses and conserve deficiencies, man would have to regulate his intake voluntarily. For elements such as cadmium, lead, and mercury to which man has experienced only recent exposure, it is unlikely that adequate homeostatic mechanisms have developed. In these cases trace elements are absorbed, accumulated, and eventually lead to the development of disease. Cadmium represents one of the more serious toxic elements because it not only causes kidney and liver dysfunction, but also interferes with the natural function of zinc leading to arterial hypertension and toxemia of pregnancy.

In making an assessment of the toxicity created by stack-gas scrubber sludge, a literature search was conducted to determine the toxic limits of the trace elements present in fossil fuels

and limestone. The following discussions provide a short review for some of these elements.

F.2 LITERATURE SURVEY

F.2.1 Beryllium

Beryllium and its compounds (Ref. F-1) are capable of including acute or chronic pathologic changes in a number of human tissues. Fulminating and fatal cases of pneumonitis, with pulmonary edema, have developed after exposure to massive concentrations of beryllium compounds. Lesions of the skin and mucous membrane of the eyes and respiratory tract have been evoked by soluble beryllium salts, but these pathologic processes are not serious even in acute cases.

Chronic beryllium disease including berylliosis and pulmonary granulomatosis have occurred among individuals with known industrial exposure to beryllium and also among those with no known accountable beryllium exposure. In the latter cases there exist uncertainties as to whether the degree of exposure has been grossly underestimated and whether there exist individual susceptibilities to the disease. As a consequence of these uncertainties, standards have been set for beryllium that are among the most stringent of any recognized toxic material. The in-plant concentration of beryllium is limited to 2 $\mu g/m^3$ as an average daily concentration with a maximum concentration limit of 25 $\mu g/m^3$ for any short-time exposure. An average monthly concentration in a plant's neighborhood is limited to 0.01 $\mu g/m^3$ with a maximum discharge of 10 g/day not to be exceeded on any day for each beryllium facility. The relationship has never been established between exposure and acute or chronic beryllium disease.

Since the discovery of the disease in the early 1940's and the establishment of standards in 1948, beryllium ore refineries and processing plants have taken the necessary precautions that have nearly

eliminated the occurrence of beryllium diseases in industrial situations. Air sample data collected during the time between the recognition of the disease and the implementation of safety measures in plants processing beryllium and its alloys have indicated that the air quality standards had been exceeded manyfold, continuously and probably for several years, without apparently producing the chronic disease. The uncertainties, concerning the quantitative relationships between the severity and duration of the exposure and the occurrence of the chronic disease, raise questions as to the need for limits as low as those promulgated. The paucity of evidence on which to establish alternative limits has rendered these standards not as precise criteria for human safety, but rather as guides to acceptable industrial and technological practice in the matter of hygiene.

The hazard of severe toxicity from beryllium is experienced exclusively through the inhalation of fumes and vapors of beryllium and its compounds. The primary sources of these materials in the atmosphere are beryllium processing plants and electric power generating plants. Since the imposition of standards, neighborhood exposure levels have been well under 0.01 $\mu g/m^3$. Although insufficient data exist, urban atmospheres typically contain far less than 0.001 $\mu g/m^3$ of beryllium, and its source has been credited to ultrafine particulates, presumably fly ash originating from the combustion of coal.

F.2.2 Cadmium

Cadmium (Ref. F-2) has no known function in the human body and is accumulated in the kidneys and liver causing dysfunction in both organs at high body concentrations. Its toxicity is further aggravated by a long biological half-life, possibly as long as 1 year. Cadmium can enter the human body from natural sources by both inhalation and ingestion. Brief inhalations of high concentrations of cadmium compounds can give rise to severe, often fatal, pulmonary edema. Exposure for longer periods at lower concentrations of cadmium

compounds can give rise to chronic pulmonary disorders characterized as emphysematous changes.

Serious illness and death have occurred by acute poisoning from ingesting foods containing cadmium. Long-term exposure to cadmium from ingestion will develop renal tubular dysfunction, principally proteinuria, glucosuria and amino-aciduria, and changes in the metabolism of calcium and phosphorus. In addition, osteomalacia, hypertension, anemia, liver dysfunction, and testicular changes have been noted from long-term exposure to cadmium.

The absorption of cadmium has been determined to be about 5 percent from ingested and as much as 25 percent from inhaled cadmium. The kidneys and liver concentrates cadmium and will constitute one-half of the body burden of a normal adult. Whereas a normal adult may accumulate a total body burden of about 30 mg from exposure to natural levels, an accumulation of 60 mg within the kidney alone would be required to initiate renal dysfunction. However, an increase in cadmium accumulation by a factor of ten differentiates "normal" adult levels from the level necessary to give rise to kidney disorders in a 50-year life span. (A decrease in cadmium levels accumulated within the body has been observed in individuals 50-60 years of age.)

Humans are exposed to cadmium through food, water, and air: ingestion is the most important route of accumulation typically constitutuing 90 percent (2.5 μg) of the daily contribution to the body burden. In uncontaminated areas, most foodstuff will contain less than 0.05 ppm of cadmium and the daily intake probably will be about 50 μg. Liver and kidney from animals, shellfish, and certain contaminated grains are primary sources of cadmium at concentrations greater than 0.05 ppm. In water the normal concentration of cadmium is less than 1 ppb and becomes significant relative to total body burden only when the concentration in drinking water exceeds 10 ppb.

The normal concentration of cadmium in urban air is about 0.05 g/m^3 and will not contribute significantly to the daily intake. However, since a considerably larger percentage of inhaled cadmium compared with ingested cadmium will be expected to be absorbed, an increase in air concentration to 0.5 g/m^3 would contribute equally to body burden from ingested sources.

F.2.3 Mercury

Mercury (Ref. F-3) enters the human body by both ingestion and inhalation in both inorganic and organic forms. Only about 2 percent of ingested inorganic mercury is absorbed by the body whereas alkylmercurial absorption has been estimated at more than 90 percent. After exposure to mercury vapor, mercury accumulates in the brain in quantities far in excess of that which would result from an equivalent amount of ingested mercury. Metallic mercury and inorganic mercury compounds attack the liver and kidney preferentially, but in ordinary exposure they are excreted before serious injury is incurred. Organic mercury compounds are more dangerous because they preferentially attack the central nervous system, primarily the motor and sensory system. In cases of acute alkylmercurial intoxication these symptoms are not reversible, indicating that permanent brain damage has occurred. In cases of chronic intoxication by alkylmercurial compounds, the symptoms are similar to those for acute alkylmercurial intoxication and because of the relatively long half-life (70 days), continued exposure could lead to progressive and sometimes complete loss of muscular control and finally death. While elemental or inorganic mercury poses no real threat to man or the environment directly, the ability of any form of mercury entering the aquatic environment to be converted to methylmercury subjects all forms of mercury to a common biological threat.

There is still some uncertainty as to the level of mercury concentrations that are required for lethal doses to man. For elemental or inorganic mercury, lethal doses are likely to be encountered only in acute or seriously chronic exposure from industrial, mining, and refining operations. However, methylmercury intoxication can occur by the consumption of fish and shellfish and other heavily contaminated foods. An average daily intake of methylmercury from all sources for persons on a varied diet has been estimated at 0.02 mg/day, whereas an intake of 0.3 mg/day has been estimated as a maximum chronic dose required before primary symptoms of mercury intoxication are apparent. At 0.5 mg/day intake, overt symptoms occur. An intake of 0.3 mg/day represents consumption of 2 lb of food a day contaminated with 0.5 ppm methylmercury. Thus a daily mercury intake 15 to 25 times that normally experienced by the average consumer would be required before signs of mercury intoxication would appear.

The sources of mercury contamination in our environment are many and varied. Discharges from industrial plants into rivers, incineration of mercury bearing trash, exhausts from metal smelters, and crop applications put mercury into the air, soil, and waterways. These sources are credited for an estimated one-third of the yearly contribution, an additional one-third originates from combustion of fossil fuels, and the remaining fraction originates from natural sources. In soils, a reasonable background mercury concentration would be between 10 and 150 ppb. The lakes, rivers, and oceans are the primary method of transport for mercury in the environment with background levels of mercury in these waters typically ranging from 0.02 to 0.7 ppb. Background atmospheric mercury concentrations vary between 0.1 and 50 $\mu g/m^3$ depending on urbanization. Rainwater has been reported to contain 0.05 to 0.5 ppb mercury that

results from scrubbing the atmosphere and is credited to man-generated sources.

The hazard of mercury to man is primarily through the methylation of inorganic mercury to organic mercury that takes place principally in aquatic environments. Man's contribution to the total accumulated environmental mercury pollution is less than 1 percent except for local area concentrations. Although the contribution to the worldwide mercury pollution has been little affected by man, over-exposure to man-generated sources is the principal health hazard.

F.2.4 Other Elements

Additionally, adverse health effects have been observed for the following elements (Ref. F-4). A short description of these effects is given in the following listing:

a. Antimony - Toxic primarily as soluble compounds causing injury to the heart, an increase in red blood cells accompanied by a decrease in white cells, and possible nervous system injury.

b. Arsenic - Arsenic toxicity is aggravated by its accumulation within the body. Arsenic hazards are disputed, but most evidence confirms its carcinogenic potential, primarily to the skin.

c. Boron - Boron toxicity has been observed only as the gaseous boranes or ingested as borates in heavy doses. Primary symptom is nausea; very heavy doses are required before boron compounds are lethal. Boron, however, is toxic to a large variety of plant life, many of which are included in man's diet.

d. Lead - Accumulates within the body as the result of inhalation and ingestion. Lead poisoning is known to cause brain damage, convulsions, behavior disorders, and death. It has been most prevalent among children as a consequence of their consumption of lead-bearing paint chips.

e. Nickel - There is no evidence of nickel toxicity as an element; however, as nickel carbonyl some evidence exists that lung cancer can develop from inhalation.

f. Selenium - Toxicity similar to arsenic; as hydrogen selenide there exists some evidence for carcinogenic reactions in test animals; when ingested in high doses (significantly above natural mean background) evidence exists for high incidence of dental caries.

g. Vanadium - Evidence exists for beneficial effects from ingesting low concentrations of vanadium. Toxicity effects are uncertain.

h. Zinc - Zinc is required as a nutrient in humans. Objection to zinc as a "toxic" material is based primarily on taste and appearance of drinking water containing low concentrations.

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GLOSSARY

AA	atomic absorption spectrophotometry
CPE	chlorinated polyethylene
EPDM	ethylene-propylene-terpolymer rubber
ES	emission spectroscopy
IUCS	International Utilities Conversion Systems, Inc.
JTU	Jackson Turbidity Units
NERC	National Environmental Research Center
PE	polyethylene
ppb	parts per billion
ppm	parts per million
PVC	polyvinyl chloride
SSMS	spark source mass spectroscopy
TCA	Turbulent Contact Absorber
TDS	total dissolved solids
TVA	Tennessee Valley Authority
USPHS	United States Public Health Service

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16. ABSTRACT

The report describes the initial phase of a study: to identify potential environmental problems that may be associated with sludge disposal from non-regenerable power plant flue gas desulfurization systems; to assess potential methods for sludge disposal; to assess technologies and attendant economics for eliminating or minimizing potential environmental problems related to sludge disposal; and to make recommendations for sludge disposal. It includes the following results: laboratory chemical and physical analyses of limestone sludges from two plants, one burning eastern coal and the other, western; a review of power plant sludge production and disposal plans; a survey of pond lining techniques and economics; technical and economic surveys of sludge chemical fixation processes which treat the sludge to produce a suitable landfill material; and a review of water quality and solid waste management regulations.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Air Pollution	Physical Tests	Air Pollution Control	13B, 14B
Sludge	Limestone	Stationary Sources	7A
Sludge Disposal	Coal	Pond Lining	21D
Flue Gases	Ponds	Chemical Fixation	21B, 8H
Desulfurization	Lining Processes		7D, 13H
Economic Analysis	Earth Fills		5C, 13C
Chemical Analysis	Water Quality		

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