To the Graduate Council:

I am submitting herewith a thesis written by Terry B. Allen entitled "Dewatering of Pulverized Coal-Conditioned Municipal Sewage Sludge and Heat Recovery of the Product." I recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Environmental Engineering.

Dennis Weeter, Major Professor

We have read this thesis
and recommend its acceptance:

Richard L. Church

Wayne T. Davis

Accepted for the Council:

L. Evans Roth

Vice Chancellor
Graduate Studies and Research

DEWATERING OF PULVERIZED COAL-CONDITIONED MUNICIPAL SEWAGE SLUDGE AND HEAT RECOVERY OF THE PRODUCT

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Terry B. Allen

March 1980

ACKNOWLEDGEMENTS

The author wishes to express his appreciation to his graduate committee: Dr. Dennis W. Weeter, Dr. Richard L. Church, and Dr. Wayne T. Davis; and to Dr. Roy O. Ball and Dr. Roger A. Minear for their contributions to his educational experience at The University of Tennessee. In addition, special thanks are given to Dr. George J. Hyfantis, Jr. for his assistance in the development of this project and to Mr. Julian Chu for his support throughout the study.

The author also wishes to thank his mother and father for enduring the times of disappointment and for their continued support and encouragement. Finally, special appreciation and thanks are given to his wife, Pam; without her total support and encouragement, this work would never have been done.

ABSTRACT

Advanced wastewater treatment requirements are resulting in the production of larger volumes of wastewater sludge which present problems for dewatering processes and final disposal. This study addresses these problems by investigating the use of pulverized coal as a conditioning agent in municipal sludge dewatering processes. The effects of variations in coal dosage and coal particle size fraction on the filter yield from vacuum filters and pressure filters were studied by utilizing laboratory scale filter-leaf and pressure filter apparatuses. In addition, calorimetric tests were conducted on the filter cake from several coal-sludge mixtures to examine the resulting heat content values. The objective of this process is to provide a product which can be effectively burned in a combustion process.

For the coal and sludge samples used in this study, both the total filter yield and the sludge filter yield were found to increase with increases in coal dosage. The coal dosage was also found to be indirectly dependent on coal particle size since the laboratory mixing apparatus was only able to maintain the smaller coal particles in suspension. When a coal dosage of greater than 1.0 gram of coal for each gram of sludge total solids is used, the heat content of the resulting filter cake was found to be at least 75 percent of the value for the pure coal.

The study indicates that the small increases in filter yield achieved by coal addition without other conditioning agents are not significant enough to warrant the use of coal for sludge conditioning prior to dewatering. However, coal additions will increase the heat content of the

filter cake and may help to minimize problems associated with wide variations in the heat content of boiler feed materials.

TABLE OF CONTENTS

CHAPTER PAGE

I. INTRODUCTION 1

II. REVIEW OF LITERATURE 4

III. STATEMENT OF THE OBJECTIVE 16

IV. EXPERIMENTAL DESIGN AND PROCEDURES 17

Vacuum Filtration Test 17
Pressure Filtration Test 19

V. RESULTS AND DISCUSSION 21

Filter-Leaf Test Laboratory Results 21
Calculated Vacuum Filter Yield Results 25
Heat Content Analysis Results 38
Results of Filtrate Quality Analyses 47
Results of Pressure Filtration Tests 49
Results of the Buchner Funnel Tests 52

VI. CONCLUSIONS 54

VII. RECOMMENDATIONS 57

LIST OF REFERENCES 59

VITA 62

LIST OF TABLES

TABLE		PAGE
I.	Particle Size Distribution of the Kingston Steam Plant Coal Sample	18
II.	Filter-Leaf Test Series I	22
III.	Filter-Leaf Test Series II	24
IV.	Filter-Leaf Test Series III	26
V.	Filter Yields for Coal Dosage Variations	27
VI.	Filter Yields for Coal Particle Size Variations	31
VII.	Calorimetric Test Data	39
VIII.	Calculated Heat Content Data	44
IX.	Filtrate Quality Analyses	48
X.	Pressure Filtration Data	50
XI.	Buchner Funnel Test Results	52

LIST OF FIGURES

FIGURE PAGE

1. Relationship between coal dosage and total filter yield from Filter-Leaf Test Series I and III 28

2. Relationship between coal dosage and sludge filter yield from Filter-Leaf Test Series I and III 30

3. Relationship between coal particle size and actual coal dosage 33

4. Relationship between the actual coal dosage as a function of particle size and total filter yield for Filter-Leaf Test Series II 34

5. Relationship between the actual coal dosage as a function of particle size and sludge filter yield for Filter-Leaf Test Series II 36

6. Relationship between unit sludge filter yield and coal particle size 37

7. Relationship between filter cake heat content and percent volatile solids 40

8. Relationship between filter cake heat content and percent coal in the mixture 40

9. Relationship between filter cake heat content and sludge filter yield 41

10. Relationship between filter cake heat content and total solids of the slurry 41

11. Relationship between filter cake percent total sulfur and percent coal in the mixture 42

12. Relationship between filter cake percent ash and percent coal in the mixture 42

13. Relationship between actual coal dosage and the calculated heat content of the corresponding coal-sludge mixture . . 46

CHAPTER I

INTRODUCTION

The volume of wastewater sludge requiring disposal is increasing because of advanced treatment requirements which result in higher sludge production. This situation is complicated by the diminishing number of environmentally and economically acceptable disposal techniques. Disposal techniques currently used include landfilling, land applications, incineration (or pyrolysis), and ocean disposal. Federal regulations eliminate ocean disposal as a future option, and the availability of suitable land will restrict the landfill and land application alternatives in many areas. Considering these constraints, it appears that sludge disposal by some combustion process will emerge as a major process alternative. Even this process, though, is not without drawbacks.

The advanced wastewater treatment processes, while substantially improving water quality, unfortunately produce a by-product which presents difficulties in preparation for combustion. It is most desirable to provide a sludge which can burn autogenously. This requires a sludge having a low moisture content, which is achieved by a dewatering process. Sludges from secondary and tertiary treatment processes are very wet and are more difficult to dewater than primary sludges. With these characteristics, it is extremely difficult and costly to obtain a dewatered sludge that does not require some auxiliary fuel to sustain combustion. The auxiliary fuels most typically used are fuel oil and natural gas, which are both increasing in cost and decreasing in availability. Along with difficult dewatering and the need for auxiliary fuel, the sludge from advanced treatment processes will contain higher contaminant concentrations. This fact will have an effect on the air emissions from the combustion process. These emissions are heavily regulated and subject to the sensitivities of public opinion.

Sludge dewatering has traditionally been accomplished by processing chemically conditioned sludge in various types of equipment. Examples of chemical conditioners would include ferric chloride and lime, aluminum sulfate, and organic polyelectrolytes. More recently, incinerator ash and fly ash have been successfully used to increase the solids content of dewatered sludge with the added advantage of decreasing the amounts of expensive conditioning chemicals needed. While the addition of ash improves dewatering equipment performance, it also reduces the energy content of the dewatered sludge because of the increased presence of inert material. In order to alleviate the problem of reduced energy content, pulverized coal has also been studied as a conditioner for wastewater sludge. These studies have focused on the magnitude of coal addition required to achieve autogenous combustion conditions. The pulverized coal increases the volatile content of the dewatered sludge along with providing improved yields from dewatering equipment. Since these studies were performed with the intent of using some type of incinerator, there was a desire to minimize excess heat generation from the process. With this constraint, relatively small pulverized coal additions were found to achieve autogenous combustion conditions in a multihearth furnace.[1] While enhancing the fuel value of the sludge tested, the final dewatered sludge solids were increased only marginally with these coal additions.

Because of the availability of large utility boilers at Tennessee Valley Authority steam plants, the potential for utilizing the heat value of dewatered wastewater sludge, and the potential for providing the service of sludge disposal to many communities within the Tennessee Valley, this study was initiated to further investigate the feasibility of using pulverized coal as a conditioner for wastewater sludge. The ultimate goal is to burn the optimum coal-sludge mixture in a steam plant boiler or in incinerators designed for waste heat recovery within the Tennessee Valley region.

CHAPTER II

REVIEW OF LITERATURE

Sewage sludge handling and disposal is a significant part of a total treatment process which may account for between 40 and 60 percent of the costs of treating sewage. A substantial portion of this cost is incurred in the preparation of the sludge for final disposal. This process often involves the conversion of a low solids liquid sludge into a filter cake which is suitable for incineration or landfilling. Sludges from advanced wastewater treatment processes, which are becoming more common, are generally difficult to dewater. This requires the addition of conditioning agents to enhance the dewatering process. Because of the expense of the polymeric conditioners and the decreasing effectiveness of inorganic chemical conditioners, other substances have been investigated to either replace or reduce needed quantities of these chemicals. Substances which have been given serious consideration over the past several years include incinerator ash, fly ash, and pulverized coal.

J. E. Smith, Jr., et al.[2] investigated the utility of ash from sludge incinerators for conditioning sludge. They also compared these results with those obtained from fly ash conditioning of the same sludge. The ash dosage, change in cake moisture content, and change in filtrate quality were the primary variables studied. This laboratory scale study was conducted utilizing a filter leaf apparatus to simulate vacuum filter operation. Considerable effort was expended to establish the various experimental operating parameters. Based on a review of current practice, a vacuum pressure of 15 inches of mercury was selected. Several experiments were conducted to establish the most suitable filter media and total cycle time. The results indicated that a nylon monofilament cloth with a nominal pore size of 0.033 inch and a cycle time of 2 minutes were the most suitable operating conditions.

Filtration experimentation indicated that addition of incinerator ash up to 2 lbs/lb sludge solids caused a linear increase in both yield and in sludge cake moisture content on an ash-free basis (lbs water/lb sludge solids). Higher dosages showed a departure from linearity attributed to a high initial solids content of the sludge (13.1 percent). Additions of 4 lbs ash/lb sludge solids converted the mixture into a paste rather than a fluid sludge.[2]

In order to provide a correlation between ash dosage and sludge yield, a "filtration improvement factor" was calculated. This factor is defined by the equation

$$FIF = Y_x/Y_o$$

where Y_x is the ash-free yield at ash dosage "x" and Y_o is the yield with no ash dosage. The linear relationships were found to hold best at ash dosages of greater than 0.5 lb ash/lb sludge solids.[2]

Experiments were also conducted to determine the effect of average ash particle size on conditioning. The ash was divided into three fractions: less than 8 mesh, less than 8 but greater than 50 mesh, and less than 50 mesh. Results indicated that the differences in the degree of improvement for these fractions was not significant. The general conclusion reached from these results is that it is unnecessary to provide grinding and screening operation to produce an "optimum" size range as long as the bulk of the material is below 8 mesh.[2]

A study of the filtrate characteristics from these dewatering experiments revealed that the total Kjeldahl nitrogen, total phosphorus, total organic carbon, and total suspended solids decreased with increasing ash dosages. Total dissolved solids were found to increase linearily with the amount of ash added to the sludge. Part of the filtrate improvements are related to the fact that the thicker cake derived from ash conditioning provides a better filtering medium than a thin cake.[2]

Study results indicate filtration improvement may be much poorer when conditioning with coal fly ash as opposed to sludge incinerator ash. There is some uncertainty in this conclusion, however, since only one fly ash sample was tested. An explanation offered for this result is that the "basicity" of the sludge ash is higher than the fly ash. Since it is known that lime is a good conditioning agent, the higher hydroxide content of the sludge ash may be responsible for the better performance.[2]

Because of the generally higher moisture content of ash-conditioned sludge, costs of incineration will increase since excess water must be evaporated. Capital costs of an incinerator should be effected only slightly, and the cost increase would be incurred in supplying additional auxiliary fuel. These added costs are more than offset by the cost savings realized by reducing the quantity of conditioning chemicals needed.[2]

A considerable amount of work has been done to investigate the use of fly ash from coal combustion as a conditioning agent for sludge dewatering. A patented process using ash as a filter aid and based on the premise that process effectiveness is dependent on providing ash with particle sizes below 0.1 mm was developed by Busse.[3] Laboratory scale studies have also been conducted with the Buchner Funnel test.[4,5] Suitable dosage levels for successful sludge conditioning have been reported by Tenney.[6] Dosages of fly ash of from 1 to 1.5 parts ash for each part sludge solids for digested sludge, and from 5 to 7 parts ash for dilute activated sludge were found to be appropriate. He also found that fly ash helps to improve filtrate quality by lowering the phosphorus and chemical oxygen demand (COD) content.

Nelson and Brattlof[7] have conducted laboratory and pilot scale pressure filtration tests using fly ash with ferric chloride and lime to condition a mixture of primary (33 percent by weight) and secondary waste activated (67 percent) sludges. By using the scanning electron microscope, the additional internal surface area provided by the particles was observed. The ability of ash to improve filterability is influenced by both particle size and surface area.[2,8] With the correct size and shape, a cake pore structure if formed by the feed mixture.[8] This structure prevents the migration of finely divided particles to or through the filter medium. This action improves cake porosity and prevents filter medium blinding. One of the problem areas anticipated in this study was metal solubilization from the fly ash to the filtrate. Atomic adsorption and emission spectrophotometric analyses showed that the fly ash would not contribute enough inorganics to exceed the toxic limits of the biological system receiving the filtrate. This conclusion was based on Federal Guidelines for Pretreatment of Pollutants Introduced Into Publicly Owned Treatment Works, published in October 1973. The study results indicate that fly ash additions at about 1.8 parts ash/part sludge solids replaced about 35 percent of the chemical conditioning requirements with no increase in filter size.

In a study of fly ash conditioning of industrial waste treatment sludge, Moehle[9] made several significant observations. His data showed that filtrate yield decreased linearly with increasing fly ash concentrations because of the absorption of moisture by the fly ash. As sludge temperature increased, an increased amount of organic sludge solubized causing a higher COD in the filtrate. Filtered sludge pH appeared to have little effect on the dewatering system. This was attributed to the fact that fly ash is not as highly chemically reactive or pH dependent as are many other sludge conditioners. As sludge solids concentration increases, a greater proportion of fly ash is required to provide equal dewatering.

To study the effect of vacuum pressure on dewatering, experiments were conducted by varying the pressure and observing the time required to break the vacuum with a given ash-sludge mixture. It was found that increasing the pressure shortened the vacuum break time. This holds true for pressures up to 20 inches of mercury, after which no appreciable reduction in break time was observed. The filtrate yield was also observed and found to increase with increasing vacuum until a pressure of 15 inches of mercury was reached. Any additional vacuum did not appreciably remove additional filtrate from the sludge. These facts would imply that a pressure range of from 15 to 20 inches of mercury would be optimum for vacuum filtration.[9]

Some of the early studies performed using pulverized coal for treatment of sewage sludge involved the preparation of a coal filter bed similar to a sand filter for water treatment.[1,10] All American coals above the rank of lignite were found to be suitable for use as a filter bed to remove suspended solid matter from sewage. In the filtration of raw or settled sewage the filter tended to block rapidly in a manner similar to any other type of filter used to separate solid matter from sewage. Periodic separation and removal of a thin layer of the filter surface along with the filter cake was required to attain continuous operation. This mode of operation illustrates a unique advantage of using coal in sewage treatment. Unlike other types of filter media, there is no requirement to separate the filter medium from the solid waste product or to preserve the integrity of the filter bed itself. These coal filters were capable of removing between 95 and 100 percent of suspended solid matter from sewage.[10] The dewatered sludges produced from the coal-bed system were reduced to approximately 70 percent moisture.[1]

Combustion tests using a fluidized bed incinerator indicated that the dewatered coal-sludge mixture would undergo sustained burning without the need for supplementary fuel. The organic matter content of the ash residue was on the order of 2 to 5 percent. From this it was concluded that almost complete burning of the mixture was achieved. Since sludge conditioned with ferric chloride has the potential of causing corrosion problems in the furnace, odor problems in the exhaust gases, and additional ash formation, it was suggested that polyelectrolyte conditioners were better suited for this operation.[1]

In the coal filter dewatering process, the phenomena of filtration and adsorption were found to occur simultaneously. All coals, regardless of rank, have been found to be able to adsorb dissolved organic matter from water solutions to various degrees. The extent of adsorption increases directly with concentration and inversely with particle size. There are indications that the maximum probable degree of adsorption of COD or biological oxygen demand (BOD) from sewage is on the order of 75 percent.[10]

Along with filtration and adsorption, there were tentative indications that the admixture of finely-divided coal to sewage enhanced the agglomeration of suspended solids in the manner of a flocculent, thereby increasing the degree of sedimentation. This admixture also appeared to increase the density of the sludge obtained in the sedimentation process, and aided in the separation and handling of scum. Floating layers of oil can be effectively agglomerated into discrete masses by the addition of dry pulverized coal to the surface of primary sedimentation tanks. This enhances the separation of oils from the liquid portion of the wastes.[10]

More recent studies have been conducted to investigate the use of crushed coal as a filter aid for vacuum filtration of sludge and as a supplemental fuel for sludge incineration. Pitzer[11] performed laboratory tests using the Buchner funnel to simulate a vacuum filter. He found that a ratio of 0.89 part of coal to 1.00 part of dry sludge solids would produce filter cakes of approximately 30 percent total solids. The main drawback to this coal-sludge ratio for incineration is that the thermal input from the coal would be almost four times that contributed by the fuel oil needed for sludge combustion. This excess thermal input results in a large quantity of waste heat and could be detrimental to the rabble arms and center shafts of the multiple-hearth incinerators. To alleviate these potential problems, realizing that crushed coal with a particle size distribution from 30 to 80 mesh exhibited similar conditioning characteristics to incinerator ash, combinations of the two materials were investigated. The best combination for this operation was found to be 0.27 part of coal to 0.81 part of ash to 1.00 part of dry sludge solids. This coal conditioning resulted in a 60 percent reduction in supplemental fuel costs for this process.

These laboratory tests were expanded to tests at a full scale facility where incinerator ash was already being used for conditioning. The replacement of a portion of the ash with crushed coal did not appear to either help or hinder full scale vacuum filtration. In general, coal was found to serve the same function in filtration as does the incinerator ash. The coal-conditioned sludge had the ability to burn without the use of fuel oil supplement, but this condition could not be maintained for extended periods. The coal-sludge mixture appeared to burn more uniformly than the sludge cake burned with fuel oil alone. This was attributed to the fact that the auxiliary fuel (coal) was a part of the sludge rather than being sprayed onto the sludge. The coal ash appeared to have no major effects on the composition of the incinerator ash.[11]

Pulverized coal conditioning of sludge has also been investigated in the laboratory by using filter-leaf tests to simulate vacuum filtration. The addition of coal in varying dosages, while increasing sludge solids concentrations in a linear fashion prior to filtration, did not show this linear increase in the sludge cake solids.[12] This is caused by the buildup of the cake on the filter media resulting in added resistance to filtration. Since sewage sludge is such a highly compressible substance, the system pressure causes the sludge particles to flatten out and expand. This action is detrimental to the separation of water from the solids because the filter medium porosity is decreased. The addition of an incompressible substance, such as pulverized coal, tends to reduce the original sludge compressibility.

Results of this study indicated that the addition of pulverized coal alone has little or no effect on the net yield of sludge solids (i.e., mass of coal in the cake is subtracted out).[12] Although the coal does provide the needed energy for autogenous combustion, additional conditioning chemicals will be required to provide suitable dewatering. Testing has indicated, however, that the interaction between the coal and the conditioning agent may result in a reduction in the quantities of conditioning chemicals required.

Pilot scale studies have also been conducted to study coal conditioning of sewage sludge. Hathaway and Olexsey[13] conducted vacuum filtration tests on various mixtures of pulverized coal and a blend of primary and waste activated sludges which had been preconditioned with 10 percent lime and 5 percent ferric chloride. Their findings indicated that the sequence of coal addition prior to incineration was significant. The addition of coal to the sludge before filtration not only increased the cake solids simply by the amount of coal solids added, but also aided the dewatering mechanism in the filtration operation itself.

Calculations were performed to determine the coal dosage required to produce autogenous combustion with this particular coal and sludge in a multiple-hearth incinerator. It was assumed that a stack gas temperature of 427°C was desired with excess air supplied at 75 percent. These calculations indicated that a coal dosage of 0.11 kg coal/kg dry sludge solids was required. This small coal dosage would provide only slight increases in filter yield, but no increase in plant filtration capacity would be required to accommodate the increased solids loading attributed to the presence of coal in the sludge feed.[13]

A brief investigation was conducted to determine the effect of the coal particle size distribution on dewatering. The coal fractions studied included 1.180 mm to 0.600 mm, 0.600 mm to 0.212 mm, and 0.212 mm to 0.150 mm. The 0.600 mm to 0.212 mm (28 to 65 mesh) fraction provided a slightly better filter yield than the other two fractions studied. The size of the coal, however, had no effect on the heat value of the conditioned sludge solids.[13]

Two other studies investigated the test-firing of wet coal, heavily contaminated by sewage solids, in a fluidized bed combustor.[14,15] The preliminary combustion efficiency tests indicated that sludge addition did not affect the combustion characteristics of the coal. The testing laboratory concluded that the coal-sludge combination could be effectively burned in any suitably designed, conventional combustion system.

Since coal-sludge mixtures have been successfully burned in other combustion processes, it has been suggested that this mixture could be utilized in coal-fired steam or electric power plants.[16] The high coal-to-sludge ratio should cause little modification to existing boiler operations with a co-combustion process similar to that used for coal and refuse. The amounts of trace constituents in coal are similar to those in sludge, so that air cleaning and ash removal should be increased insignificantly. Similarities in geographical distributions of coal-fired power plants and population (which is directly related to sludge generation) should minimize logistic costs. Power plants operate with combustion temperature profiles and retention times that are similar to those used for efficient sewage sludge incinerators. From this, it is assumed that complete combustion and odor control will be achieved.

There are several important factors which must be considered in a coal-sludge co-combustion process. Mass balance calculations conducted by Public Service Electric and Gas Company researchers indicate that the allowable percentage of sludge in the fuel mixture will depend on particulate-emission standards and the relative magnitude of sewage plant output and boiler fuel input.[17,18] These calculations were based on the assumption of a constant heat input since the boilers studied were combustion-air limited. The preliminary results indicate that a sludge cake containing 50 percent water could be fed into a grate-type boiler and burned in a manner similar to municipal solid wastes. Difficulties may arise, however, if the cake is to be burned in suspension in a utility boiler. Complete burnout would be prevented in this case because the evaporation of water would serve as a heat sink to keep the center of the particles relatively cool. Successful combustion would require that the sludge was dried and reduced to fine particles (similar in composition to refuse-derived fuel) prior to burning.

Depending on the sludge characteristics, which could cause increases in concentrations of toxic trace elements, problems with ash disposal and air emissions may be encountered. The fly ash and bottom ash may become unsuitable for certain commercial uses. The potential for leaching of trace metals from the ash ponds may require special pond construction considerations, and additional treatment of ash pond supernatent liquid may be required prior to discharge. There are currently no trace-element emission standards for utility boilers, but hazardous-emission standards have been developed by the Environmental Protection Agency (EPA) for sludge incinerators.[18] It is reasonable to expect that equally strict standards will be applied to boilers that burn sludge. These standards could ultimately limit the percentage of sludge that can be burned with the coal unless corrective measures are taken.[17]

CHAPTER III

STATEMENT OF THE OBJECTIVE

The major objective of this study is to provide additional insight into the effects of pulverized coal addition on the municipal sewage sludge dewatering process. Previous studies were concerned with determining the magnitude of pulverized coal addition required to achieve autogenous combustion of the sludge filter cake while minimizing excess heat generation. This approach resulted in a very low coal-sludge ratio that had little effect on the dewatering process.

This study will focus on determining if there is an optimum coal-sludge mixture that will maximize filter yield. In addition, various combustion parameters, including heat content, sulfur content, and ash content, will be studied for several coal-sludge mixtures. This information will provide background data for future examinations of the feasibility of burning a coal-sludge mixture filter cake with the coal in a steam plant boiler. This process will have the ability to provide a sludge disposal alternative that can utilize the heat energy available in the sludge solids.

It is also the intent of this study to provide more complete data on the effects of coal particle size on filter yield and to examine the variations in filtrate quality that may occur when pulverized coal is combined with sludge in the dewatering process. Filtrate parameters to be investigated include pH, conductivity, COD, total organic carbon (TOC), soluble organic carbon (SOC), dissolved solids, suspended solids, volatile suspended solids, copper, lead, zinc, nickel, and chromium.

CHAPTER IV

EXPERIMENTAL DESIGN AND PROCEDURES

Two types of sludge samples were obtained from the Moccasin Bend Wastewater Treatment Plant in Chattanooga, Tennessee. Primary sludge was obtained from the underflow of the primary clarifiers, and waste activated sludge was obtained from the final pass of the aeration basin. Prior to testing, the sludges were combined in a blend of 50 percent primary sludge and 50 percent waste-activated sludge by volume.

Pulverized coal samples were obtained from the Kingston Steam Plant and screened to determine the coal particle size distribution. Table I represents the results of the screening analysis as performed by the Central Laboratory, System Engineering Services Branch of the Tennessee Valley Authority. The total coal sample was thoroughly mixed and divided into two portions. One portion was used, as collected, for the tests involving investigations of the effects of total coal dosage variations on several system parameters. The remaining portion was screened, and the resulting quantities of the various particle sizes were separated. Portions of these individual particle size fractions were then combined into desired size distribution samples. These samples were prepared in the proper size proportions to simulate various selective screening options. Tests were then performed with these samples to determine the effects of coal particle size on the sludge dewatering process.

Vacuum Filtration Test

Vacuum filtration tests were conducted to determine the effects of various coal dosages and coal particle size fractions on the filtration

TABLE I

PARTICLE SIZE DISTRIBUTION OF THE KINGSTON STEAM PLANT COAL SAMPLE

Particle Size (Tyler Mesh)	Percent by Weight
+10	15.2
-10+20	39.5
-20+30	10.0
-30+40	9.0
-40+50	7.7
-50+60	3.2
-60+80	5.3
-80+100	1.7
-100+200	4.9
-200	3.4

yield and filterability of municipal sewage sludge. These tests were performed by using the filter-leaf apparatus and the Buchner funnel. Since the filter-leaf apparatus provides the best laboratory simulation of a full-scale vacuum filter, this apparatus was used as the primary device for data collection. After the optimum coal dosage and coal particle size fraction had been determined, the Buchner funnel was used in two tests to examine the effects of pressure variation on specific resistance.

The filter-leaf tests were conducted using a 0.1-sq-ft Eimco filter with a polypropylene filter media. (Eimco filter media, Media No. POPR-925F, Eimco BSP Division, Envirotech Corporation, Salt Lake City, Utah). A variety of media samples were tested with the sludge mixture to select the media which provided the best sludge cake yield. The decision for the selection of the media to be used for all of the filter-leaf tests was based on physical observation of the filter cake results of these tests. A system pressure of 15 inches of mercury was selected for all filter-leaf tests, and the general test procedures were obtained from "Treatment and Disposal of Wastewater Sludges."[19]

Two Buchner funnel tests were conducted with 80-ml samples of the optimum coal-sludge mixture. Pressure of both 10 and 20 inches of mercury were used. The funnel was 3 inches in diameter and 1.5 inches in depth. Number 5 Whatman filter paper with a diameter of 2.75 inches was used.

Pressure Filtration Test

A series of pressure filtration tests were conducted using a Millipore pressure filter apparatus (Millipore stainless, 142-mm diameter filter holder with 1.5-L stainless pressure vessel, Millipore Corporation, Bedford, Massachusetts). A 250-ml sample was poured into the pressure vessel and subjected to a pressure of 60 psi (122 inches of mercury) for a maximum time of 11 minutes or until the nitrogen gas used to create the pressure became evident in the filtrate discharge line. The 11-minute time limit was established by observing when the rate of filtrate discharge became negligible. This test procedure was repeated with various coal dosages and coal particle size fractions to determine the optimum conditions for these parameters. During each test, the volume of filtrate was recorded as filtration time progressed. This data was used to calculate the specific resistance and filter yield of the various mixtures.

CHAPTER V

RESULTS AND DISCUSSION

Filter-Leaf Test Laboratory Results

The initial filter-leaf tests were conducted to determine the effects of coal dosage on filter yield. Table II presents the data collected from this series of tests related to the solids content of each coal-sludge mixture and the moisture content of the filter cake. Using the values determined from the total solids of the various mixtures, the "actual" coal-sludge ratio for each mixture was calculated. This ratio was determined by assuming that the difference between the total solids of the coal-sludge mixture and the total solids of the unconditioned sludge sample for each series of tests was equivalent to the amount of coal available to the vacuum filtration apparatus. This difference was then divided by the value of the total solids of the unconditioned sludge to determine the "actual" ratio. The difference in this calculated ratio and the coal-sludge ratio of the original mixture indicates that some physical mechanism occurs in the mixing container to alter the relative quantities of coal and sludge solids that become involved in vacuum filtration. It is also possible that on this small scale, and particularly with the smaller coal dosages, the coal sample used for any individual test may not have been representative of the total coal sample with regard to particle size distribution.

The previous assumption implies that the coal does not significantly act to aid the settling of the sludge solids during the vacuum filtration

TABLE II

FILTER-LEAF TEST SERIES I

Original Mixture Coal Dosage (gm coal/gm sludge total solid)	Mixture Solids (mg/L) Dissolved	Suspended	Total	Volatile Suspended	Total Volatile	Percent Volatile	Actual Coal/Sludge Ratio[a]	Sludge Cake Percent Moisture	Percent Volatile
Sludge[b,c]	1,500	10,000	11,500	5,800	----	58.0	----	28.91	21.03
Sludge[b,d]	3,000	27,000	30,000	----	13,000	43.3	----	----	----
0.18:1	2,900	25,100	28,000	----	14,000	50.0	----	71.60	51.00
0.29:1[e]	1,400	22,000	23,400	12,000	----	54.5	1.03:1	30.29	23.83
0.58:1[e]	1,400	13,000	14,400	7,500	----	57.7	0.25:1	34.68	28.13
0.93:1	3,300	38,700	42,000	----	26,000	61.9	0.40:1	66.00	53.70
0.86:1[e]	2,200	22,000	24,200	12,000	----	54.5	1.10:1	29.28	22.32
1.48:1	2,900	45,100	48,000	----	30,000	62.5	0.60:1	62.40	55.00
1.44:1[e]	1,500	14,000	15,500	8,400	----	60.0	0.35:1	29.89	23.88
2.77:1	3,100	94,900	98,000	----	67,000	68.4	2.27:1	52.30	61.60

[a]Calculated from the difference in total solids of the unconditioned sludge sample and the total solids of the coal-sludge mixture.

[b]Unconditioned sludges--no coal addition.

[c]Sludge sample collected 2/14/79.

[d]Sludge sample collected 3/15/79.

[e]Values from mixtures of coal and sludge sample collected 2/14/79. Other values are from mixtures of coal and sludge sample collected 3/15/79.

process. When cleaning the container after each test, varying quantities of coal particles were observed in the bottom after the liquid had been removed. In each case, only very small amounts of sludge solids were present with the coal. This substantiates the assumption for the bench-scale apparatus in this case, but the literature indicates that this may not hold true for a larger scale process.[10] There are indications that the admixture of finely-divided coal to sewage enhances the agglomeration of suspended solids in the manner of a flocculent, thereby increasing the degree of sedimentation. This possibility must be considered in future process designs.

Efforts to prevent solids settling were undertaken by using a magnetic stirrer. The stirring had to be discontinued while the filter leaf was submerged because the stirring action scoured the filter media surface. The relatively short duration that the mixture was not being stirred (approximately one minute) would not allow significant settling to occur. The centrifugal force on the coal particles during stirring, however, may cause the larger coal particles to move to the perimeter of the container and away from the area where the filter leaf was submerged. This would leave only the smaller particle size fractions suspended in the mixture and available to affect dewatering.

In order to observe the effects of various coal particle size fractions on filter yield, a second series of filter-leaf tests was conducted. Results of these tests are summarized in Table III. In the first series of tests, the initial coal dosage of 1.6 gm of coal for each gm of sludge suspended solids (1.48 gm coal/gm sludge total solids) provided the best filter yield. An attempt to match this dosage resulted in the

TABLE III

FILTER-LEAF TEST SERIES II

Coal Particle Size[a] (Tyler mesh)	Mixture Solids (mg/L)					Actual Coal/Sludge Ratio[b]	Sludge Cake	
	Dissolved	Suspended	Total	Total Volatile	Percent Volatile		Percent Moisture	Percent Volatile
Unconditioned Sludge	1,000	22,000	23,000	12,000	52.2	----	71.69	51.12
+20	3,500	23,500	27,000	13,000	48.1	0.17:1	70.78	49.07
-20+40	3,000	29,000	32,000	18,000	56.3	0.39:1	58.72	63.32
-40+60	3,000	42,000	45,000	27,000	60.0	0.96:1	55.00	66.12
-60+80	3,200	47,800	51,000	33,000	64.7	1.22:1	50.89	65.76
-20	2,900	33,100	36,000	20,000	55.6	0.57:1	56.23	66.29
+80	2,900	29,100	32,000	17,000	53.1	0.39:1	60.52	57.59
-100	3,800	53,200	57,000	36,000	63.2	1.48:1	55.59	63.28
-20+80	3,300	38,700	42,000	25,000	59.5	0.83:1	58.99	62.86
-30+100	3,100	32,900	36,000	21,000	58.3	0.57:1	55.08	66.37
Total Mix	3,000	34,000	37,000	21,000	56.8	0.61:1	62.04	60.19

[a]Coal dosage of 1.69 gm coal/gm sludge total solids was added for each test.

[b]Calculated from the difference in total solids of the unconditioned sludge sample and the total solids of the coal-sludge mixture.

Note: Unconditioned sludge sample collected 5/8/79.

use of a constant initial coal dosage of 1.69 gm of coal for each gm of sludge total solids for all of the tests in this second series.

After determining the coal particle size fraction that provided the best filter yield for the laboratory tests, a third series of tests was conducted to verify the data gathered in the first filter-leaf test series. The laboratory results of this final series of filter-leaf tests are tabulated in Table IV. A constant coal particle size fraction of -60+100 mesh was used for each of these tests.

Calculated Vacuum Filter Yield Results

The results obtained from the laboratory filter-leaf tests were used to calculate the filter yields corresponding to each coal dosage and coal particle size fraction variation. The filter yields calculated for the various coal dosages are summarized in Table V. Values for the total filter yield were calculated by dividing the total dry solids of the filter cake by the cycle time (2 minutes) and the filter area (0.1 sq ft). Using the actual coal-sludge ratio, the yield of sludge solids was calculated by determining the percentage of total solids contributed by the sludge. The total dry solids in the filter cake was then multiplied by this percentage to determine the amount of sludge present, and then divided by the cycle time and filter area.

Figure 1 illustrates the relationship between actual coal dosage and total filter yield. The general trend for all data points, established by a linear regression analysis, indicates that as coal dosage is increased, the total filter yield increases. It is also shown that the same general trend occurs for each of the sludge total solids concentrations investigated. In addition, the dependence of filter yield on

TABLE IV

FILTER-LEAF TEST SERIES III

Original Mixture Coal Dosage	Mixture Solids (mg/L)					Actual Coal/Sludge Ratio*	Sludge Cake	
	Dissolved	Suspended	Total	Total Volatile	Percent Volatile		Percent Moisture	Percent Volatile
Unconditioned Sludge	1,500	24,500	26,000	11,000	42.3	----	----	----
0.35:1	1,300	49,700	51,000	37,000	72.5	0.96:1	67.9	59.2
0.70:1	1,400	40,600	42,000	26,000	61.9	0.62:1	56.6	68.5
1.05:1	1,700	41,300	43,000	38,000	88.4	0.65:1	55.0	63.8
1.75:1	1,800	71,200	73,000	52,000	71.2	1.81:1	51.7	73.4

*Calculated from the difference in total solids of the unconditioned sludge sample and the total solids of the coal-sludge mixture.

Note: Coal particle size fraction of -60+100 mesh was used for all tests. Unconditioned sludge sample collected 6/28/79.

TABLE V

FILTER YIELDS FOR COAL DOSAGE VARIATIONS

Coal Dosage (weight ratio--coal/sludge)		Filter Yield (lbs/hr/sq ft)		Slurry Total Solids (mg/L)
Original Mixture	Calculated Actual[a]	Total	Sludge Only	
Unconditioned[b]	----	1.00	1.00	11,500
Unconditioned[c]	----	----	----	30,000
Unconditioned[d]	----	1.06	1.06	23,000
Unconditioned[e]	----	----	----	26,000
0.18:1	----	0.71	----	28,000[c]
0.29:1	1.03:1	0.73	0.35	23,400[b]
0.58:1	0.25:1	0.29	0.24	14,400[b]
0.92:1	0.40:1	1.19	0.86	42,000[c]
0.86:1	1.10:1	1.04	0.50	24,200[b]
1.48:1	0.60:1	1.69	1.05	48,000[c]
1.44:1	0.35:1	0.51	0.38	15,500[b]
2.77:1	2.27:1	3.17	0.97	98,000[c]
0.35:1	0.96:1	0.68	0.35	51,000[e]
0.70:1	0.62:1	1.38	0.85	42,000[e]
1.05:1	0.65:1	1.88	1.15	43,000[e]
1.75:1	1.81:1	2.51	0.90	73,000[e]

[a]Calculated from the difference in total solids of the unconditioned sludge sample and the total solids of the coal-sludge mixture.

[b]Sample collected 2/14/79.

[c]Sample collected 3/15/79.

[d]Sample collected 5/8/79.

[e]Sample collected 6/28/79.

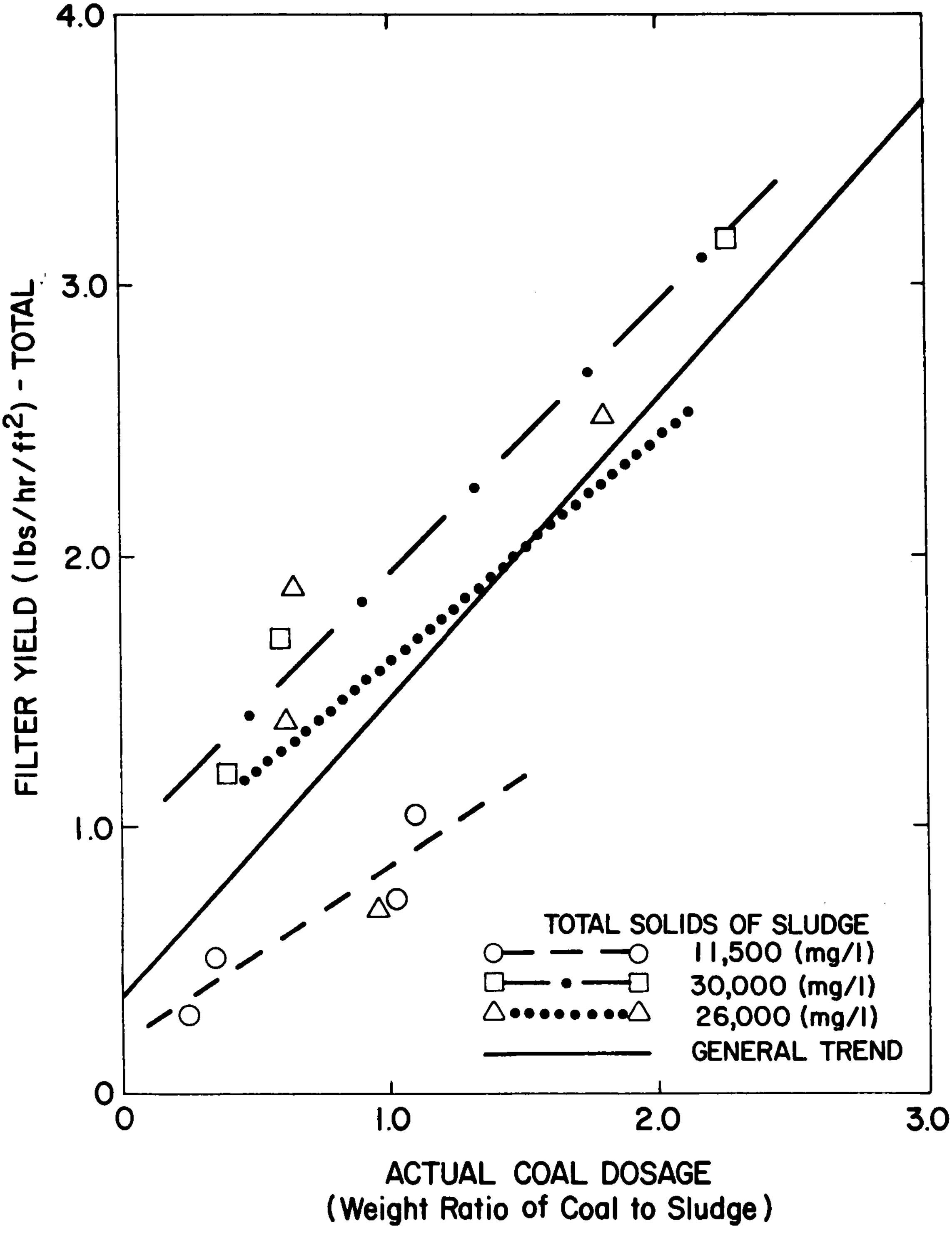


Figure 1. Relationship between coal dosage and total filter yield from Filter-Leaf Test Series I and III.

sludge total solids concentration is demonstrated by the higher filter yields that result with the higher initial sludge total solids concentrations at any given coal dosage.

The relationship between coal dosage and sludge filter yield is illustrated in Figure 2. The general trend of increasing filter yield with increasing coal dosage is again demonstrated. The best sludge filter yields of 1.05 and 1.15 lbs/hr/sq ft were obtained with actual coal dosages of 0.6 and 0.65 gm of coal for each gm of sludge total solids, respectively. Of particular significance is the fact that the original coal dosages for these two tests were 1.48 and 1.05, respectively. This indicates that only approximately 40 to 60 percent of the coal originally added to the sludge container in these two tests became available to effect the filtration process. It is possible that the means of mixing the coal and sludge (magnetic stirrer), the limited power input into the mixing process, or coal particle settling that may occur in the mixing container may individually or collectively be responsible for the difference between the original and actual coal dosage. Also of significance is the fact that the filter yield of the unconditioned sludge is greater than the yields from many of the coal-sludge mixtures (Table V). This would indicate that when no other conditioning agents are used, certain coal dosages may have a detrimental effect on vacuum filter yield.

The filter yields calculated for the tests with various coal particle size fractions are summarized in Table VI. An initial coal dosage of 1.69 gm of coal for each gm of sludge total solids was used for each test. Using the procedure described previously, the actual coal dosage associated with each particle size fraction was calculated. The

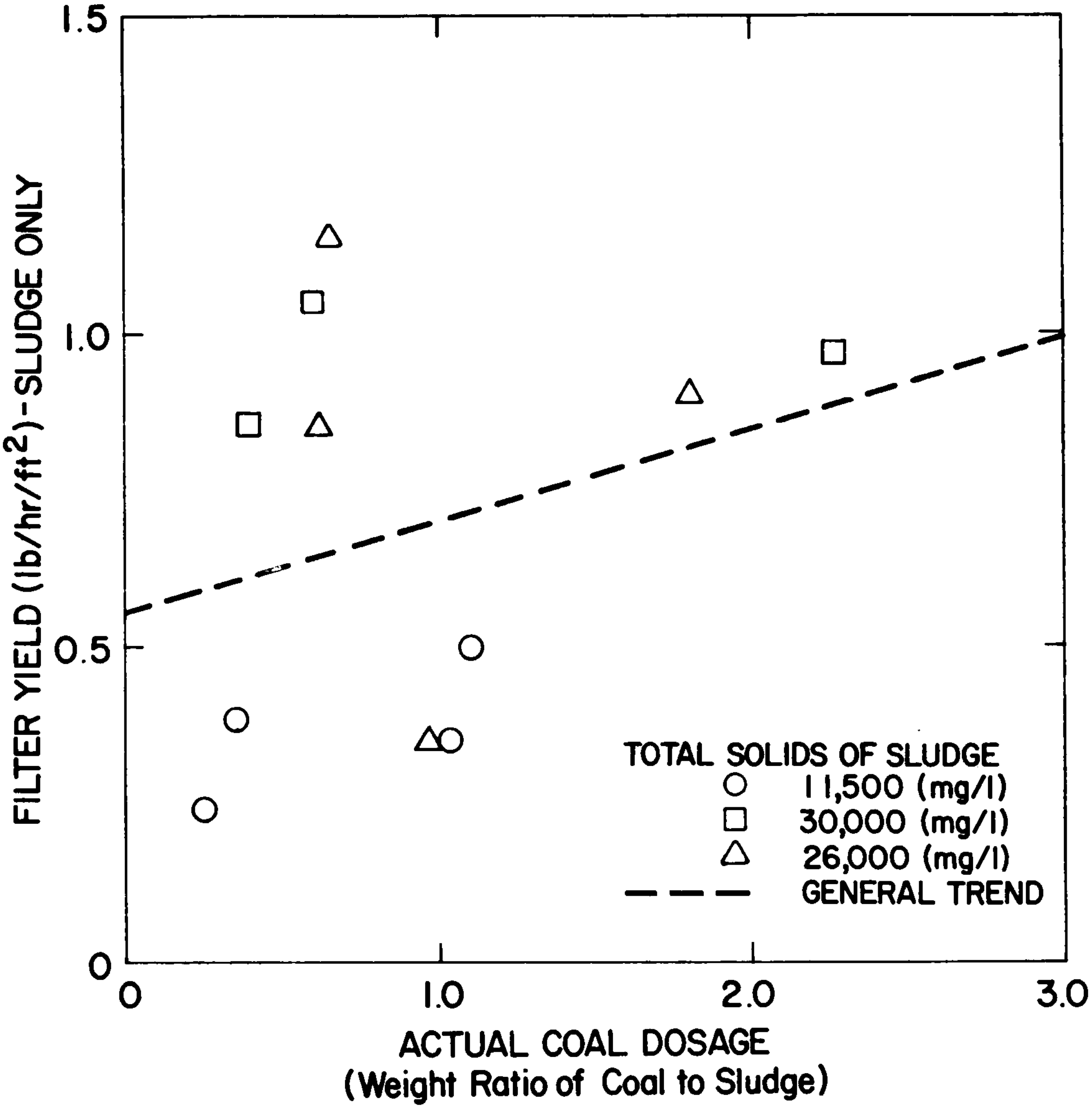


Figure 2. Relationship between coal dosage and sludge filter yield from Filter-Leaf Test Series I and III.

TABLE VI

FILTER YIELDS FOR COAL PARTICLE SIZE VARIATIONS

Coal Particle Size (Tyler mesh)	Actual Coal/Sludge Ratio*	Filter Yield (lbs/hr/sq ft)		Unit Sludge Filter Yield (lbs/hr/sq ft/lbs coal)
		Total	Sludge Only	
Unconditioned Sludge	----	1.06	1.06	----
+20	0.17:1	0.71	0.62	3.65
-20+40	0.39:1	1.55	1.12	2.87
-40+60	0.96:1	3.45	1.76	1.83
-60+80	1.22:1	6.42	2.89	2.37
-20	0.57:1	3.75	2.39	4.19
+80	0.39:1	1.41	1.01	2.59
-100	1.48:1	6.77	2.73	1.84
-20+80	0.83:1	2.24	1.23	1.48
-30+100	0.57:1	3.61	2.29	4.02
Total Mix	0.61:1	1.73	1.08	1.77

*Calculated from the difference in total solids of the unconditioned sludge sample and the total solids of the coal-sludge mixture.

Note: An original coal-sludge ratio of 1.69:1 was used for all tests. Unconditioned sludge sample collected 5/8/79. Unit sludge filter yield calculated by dividing the sludge filter yield by the actual coal dosage.

relationship between coal particle size fractions and actual coal dosage is presented in Figure 3. Even though the initial coal dosage was the same in each case, a larger amount of the original coal sample remained suspended in the mixture when the smaller particle sizes were present. This would indicate that to obtain a desired coal dosage, provisions will be required for providing coal in the smaller particle size fractions unless a mechanism can be applied to maintain all of the coal particle sizes in suspension. This will consequently require the determination of the economic trade-off between the costs for the development of a process with adequate power to maintain all of the coal in suspension and the costs for pulverizing and screening equipment required to achieve the desired coal particle size fraction that can minimize power input.

Because of limitations of the laboratory equipment used for the vacuum filtration studies, the effects of coal particle size on filter yield from the standpoint of achieving a filter cake structure that will optimize the removal of the filtrate could not be pursued. Further insight into this mechanism is found in the pressure filtration studies described in a subsequent section of this chapter.

The data obtained from this series of tests (Table VI) provided another opportunity to investigate the relationship between actual coal dosage and filter yield. Each of the coal dosages represented in these data are known to be dependent on coal particle size. The relationship between the actual coal dosage and total filter yield is shown in Figure 4. The same general trend of increasing total filter yield with increasing coal dosage found in the previous tests (Figure 1) is also evident with this data. Similarly, the relationship between actual coal dosage and

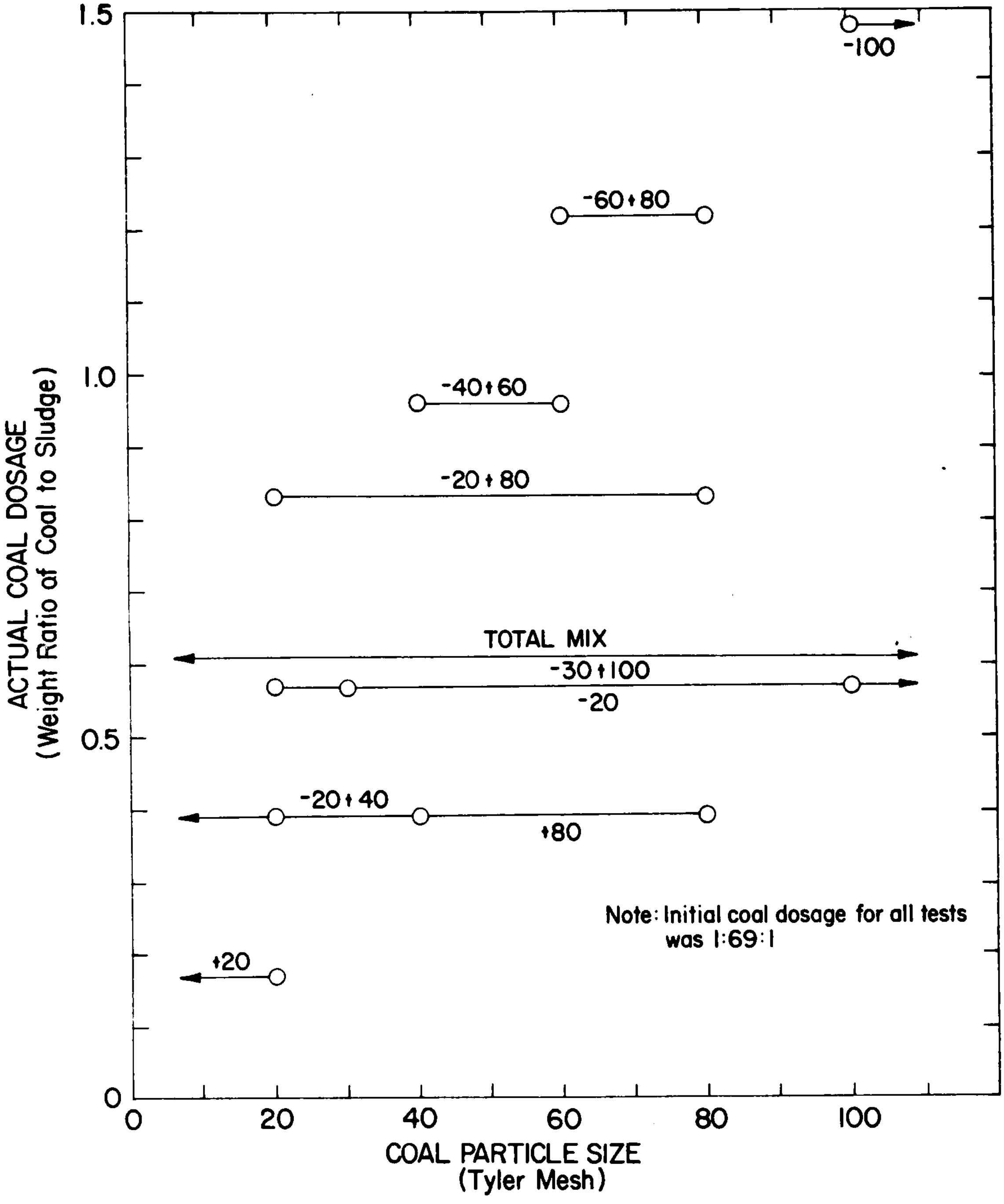


Figure 3. Relationship between coal particle size and actual coal dosage.

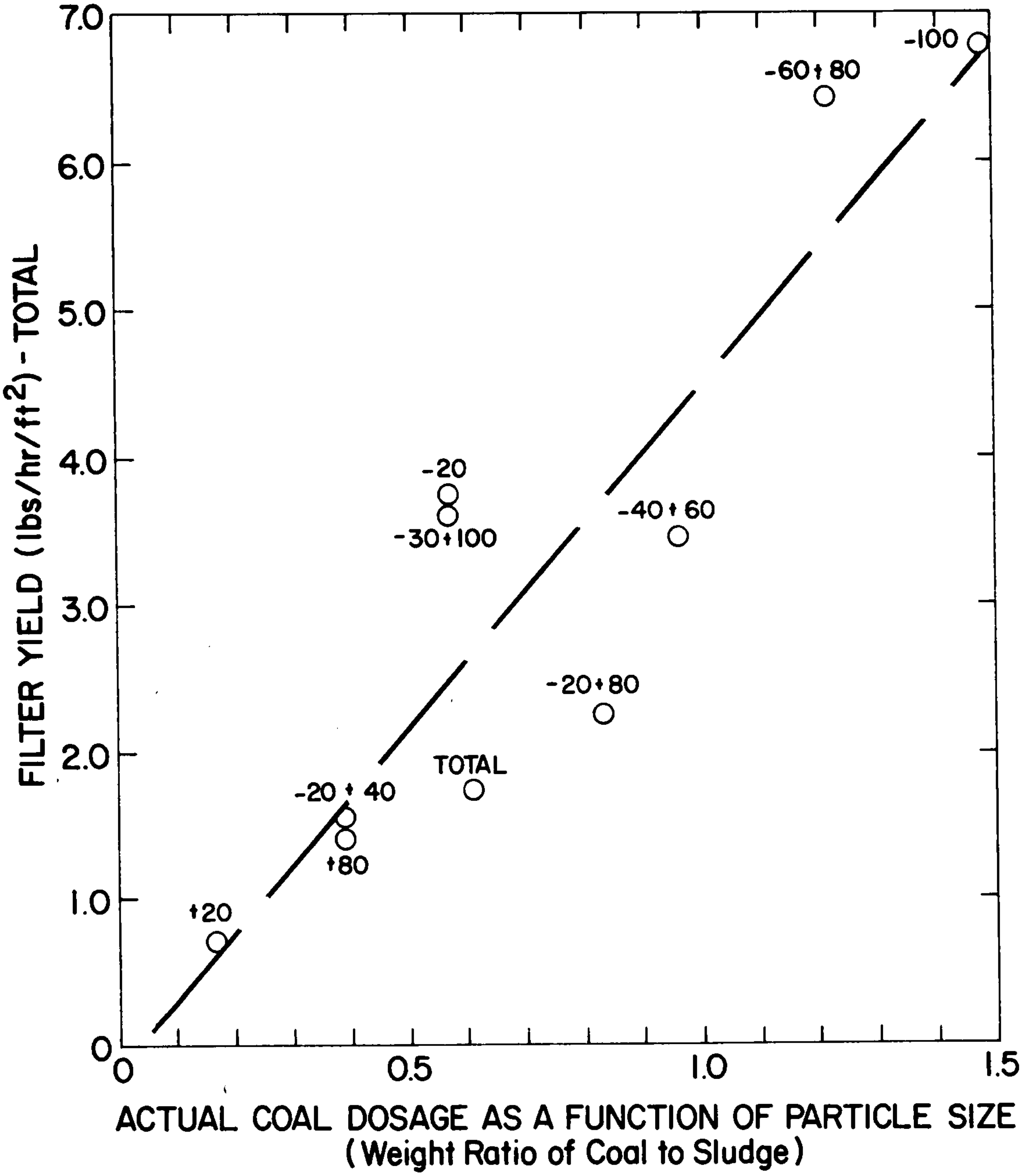


Figure 4. Relationship between the actual coal dosage as a function of particle size and total filter yield for Filter-Leaf Test Series II.

sludge filter yield shown in Figure 5 demonstrates a similar trend to the data presented in Figure 2. When analyzing Figures 3, 4, and 5 together, there is an indication that the filter yield is primarily dependent on the coal dosage and dependent on coal particle size only because more of the smaller coal particles remain suspended in the mixture when using the available laboratory apparatus.

To further investigate the effects of coal particle size on filter yield, a unit sludge filter yield was calculated by dividing the sludge filter yield by the actual coal dosage. This provided a means of normalizing the sludge filter yield values with respect to coal dosage. The relationship between the unit sludge filter yield and coal particle size is shown in Figure 6. Even though the best sludge filter yield was achieved with the -60+80 mesh coal particle size sample (Figure 5), the -20 mesh sample provided the best unit sludge filter yield (Figure 6).

It is important to note that the -20 mesh coal sample was produced by adding the proper porportions of the various size fractions to simulate a coal sample from which the particles greater than 20 mesh had been screened. Since it was previously concluded that the actual coal dosage is indirectly dependent on the coal particle size because of the laboratory apparatus used, the actual dosage represented by the -20 mesh coal sample may in actuality be representing only a smaller dosage of the -60+80 mesh coal samples.

These data (Table VI) indicate that the sludge yield obtained with the -60+80 mesh coal sample represented a 21-percent improvement over the sludge yield obtained with the -20 mesh coal sample. However, the -60+80 mesh coal sample provided an actual coal dosage equivalent to 114 percent

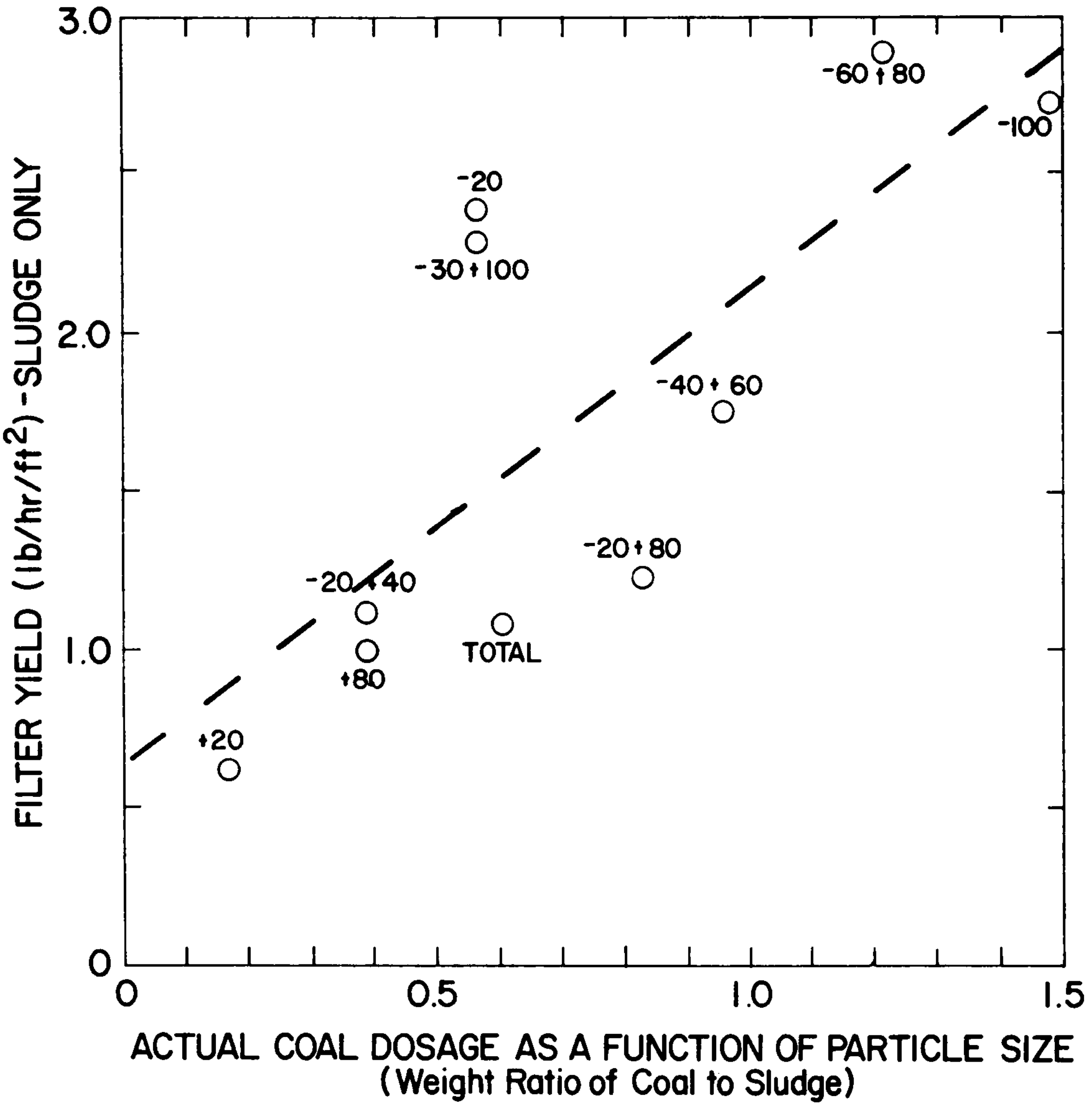
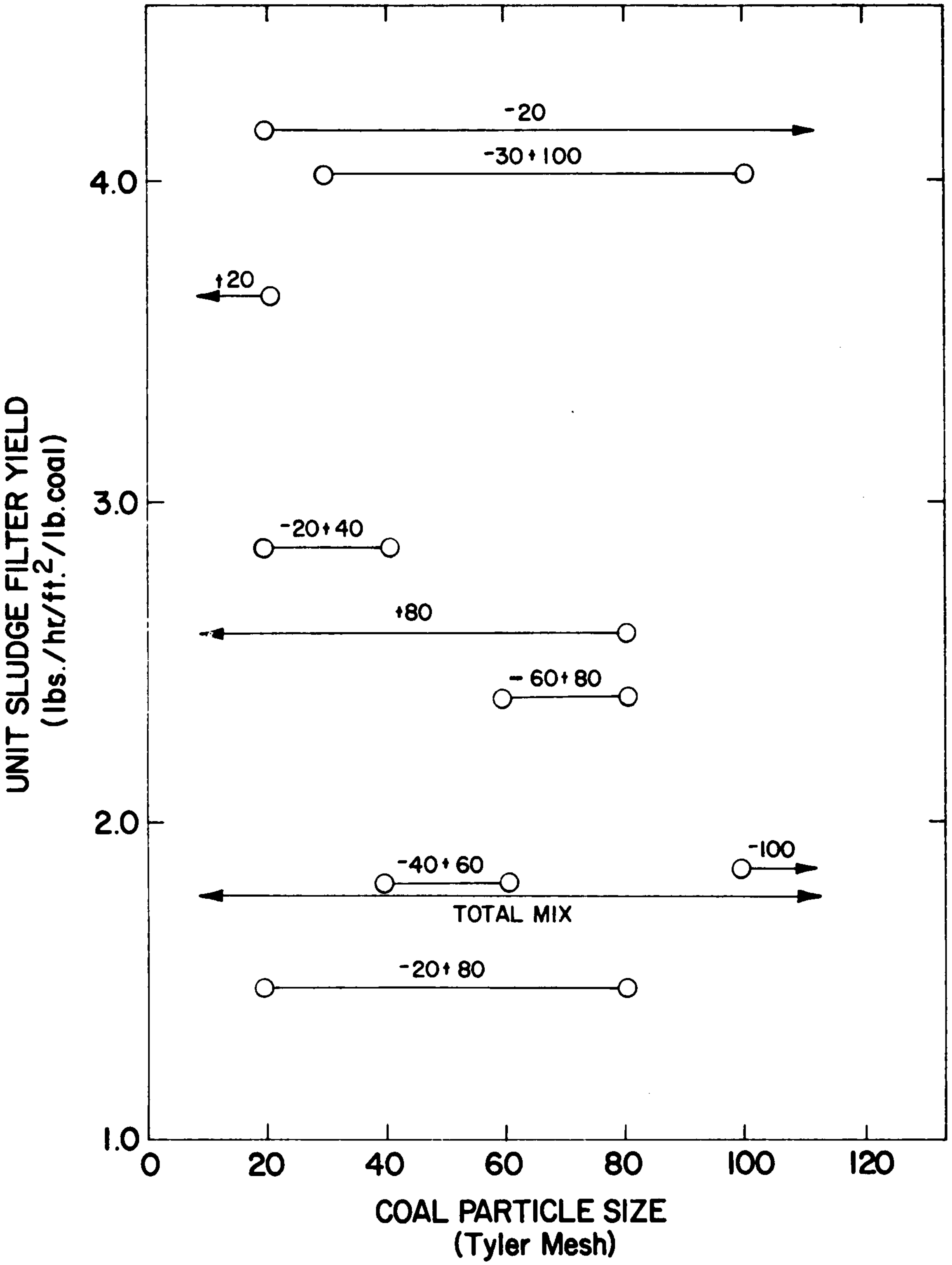


Figure 5. Relationship between the actual coal dosage as a function of particle size and sludge filter yield for Filter-Leaf Test Series II.



Filter 6. Relationship between unit sludge filter yield and coal particle size.

of the actual coal dosage provided by the -20 mesh sample. The benefits of sludge filter yield improvements are more than offset by the high coal dosages required to achieve the improvements. It is also significant that the addition of the +20 mesh coal results in a unit sludge filter yield which is higher than that achieved by the -60+80 mesh coal sample. These facts lead to the conclusion that when no other conditioning agent is added, the small increases in sludge filter yield realized by adding pulverized coal to the laboratory filter-leaf apparatus does not warrant the use of coal as a conditioner for municipal sewage sludge prior to dewatering.

Heat Content Analysis Results

A representative sample of the coal, unconditioned sludge filter cake, and the filter cake from three different coal-sludge mixtures were fired in a calorimeter to determine the heat content of the various samples. The data obtained from this analysis are summarized in Table VII. The various general relationships of system parameters determined by linear regression analyses have been plotted in Figures 7 through 12. Examination of these relationships provides a verification of the expected effects of several variables on heat content. Figure 7 illustrates the relationship between percent volatile solids in the filter cake and heat content. This data indicates that heat content will increase as the percent volatile solids increases. The relationship between percent coal in the mixture and heat content is shown in Figure 8 and indicates that the heat content increases as the amount of coal in the mixture increases. Heat content is also shown to increase with increases in sludge filter

TABLE VII

CALORIMETRIC TEST DATA

Sample Description[a]	Heat Content[b] (Btu/lb)	Percent Moisture	Volatile Solids (percent)	Percent Coal in the Mixture	Sludge Filter Yield (lbs/hr/sq ft)	Total Solids of Slurry (mg/L)	Percent Ash[b]	Percent Sulfur[b]
Pure Coal[c]	11,430	3.10	----	100.0	----	----	19.9	2.3
2.27:1[c,d]	8,440	52.30	61.60	69.4	0.97	98,000	38.6	0.6
Unconditioned Sludge[e]	5,610	71.69	51.12	0.0	1.06	23,000	48.3	0.3
1.22:1[f] (-60+80 mesh)	9,030	50.89	65.76	55.0	2.89	51,000	33.6	1.2

[a]Ratios presented represent the actual weight ratio of coal to sludge in the sample.

[b]Dry basis.

[c]Coal sample used represented total particle size mixture.

[d]Sludge collected 3/15/79--initial sludge total solids = 30,000 mg/L.

[e]Unconditioned sludge sample collected 5/8/79.

[f]Sludge collected 5/8/79--initial sludge total solids = 23,000 mg/L.

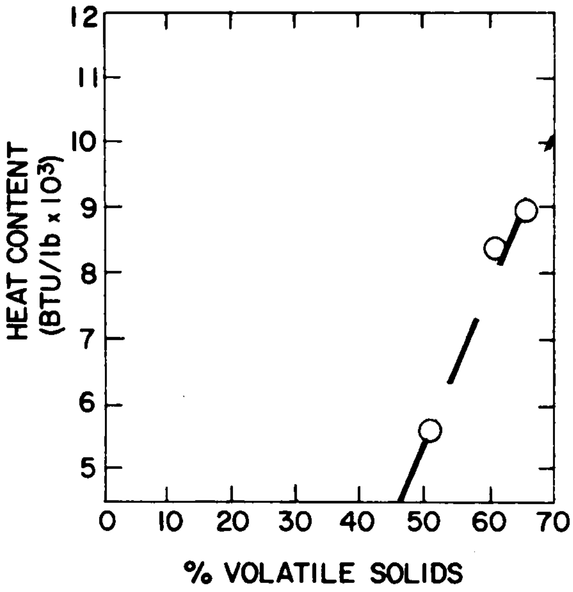


Figure 7. Relationship between filter cake heat content and percent volatile solids.

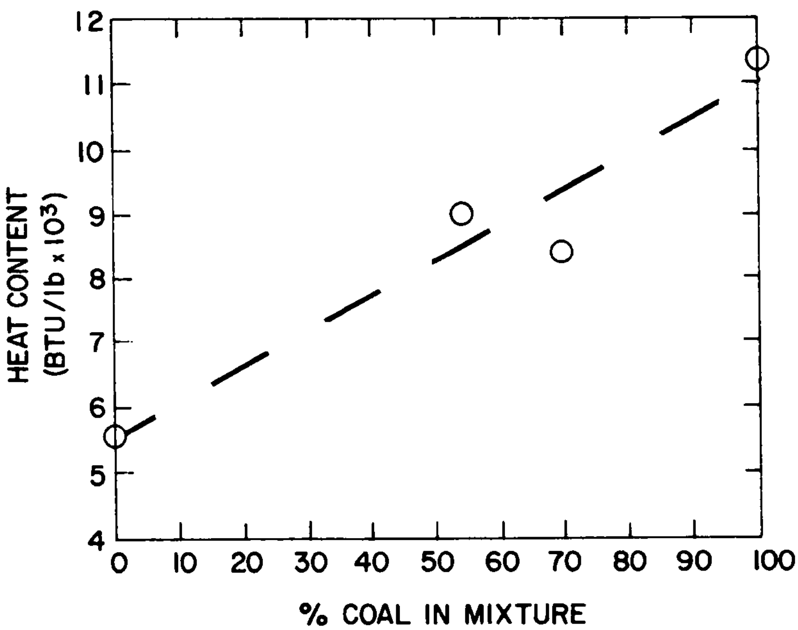


Figure 8. Relationship between filter cake heat content and percent coal in the mixture.

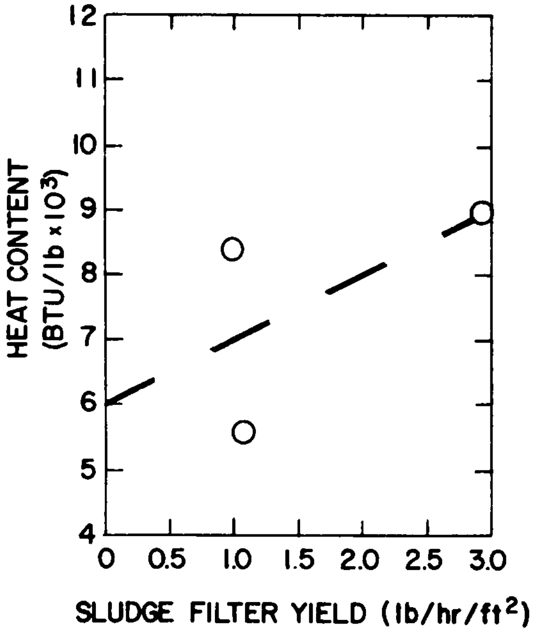
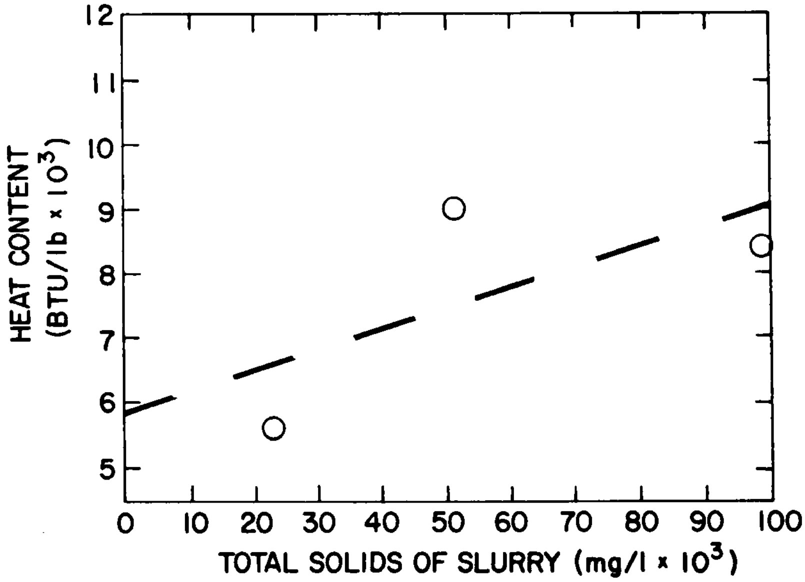
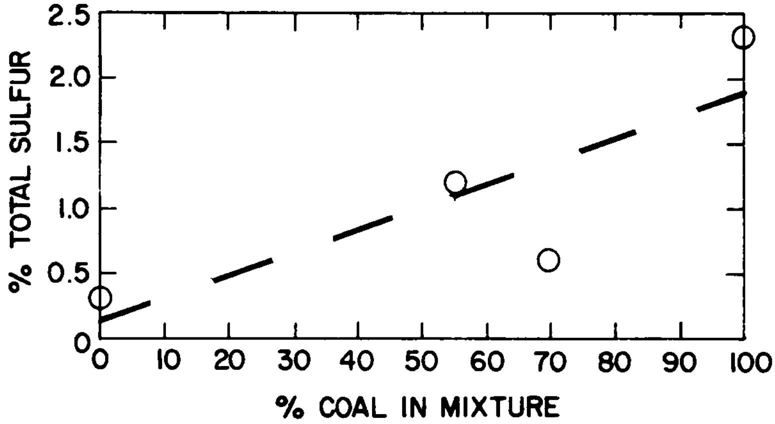


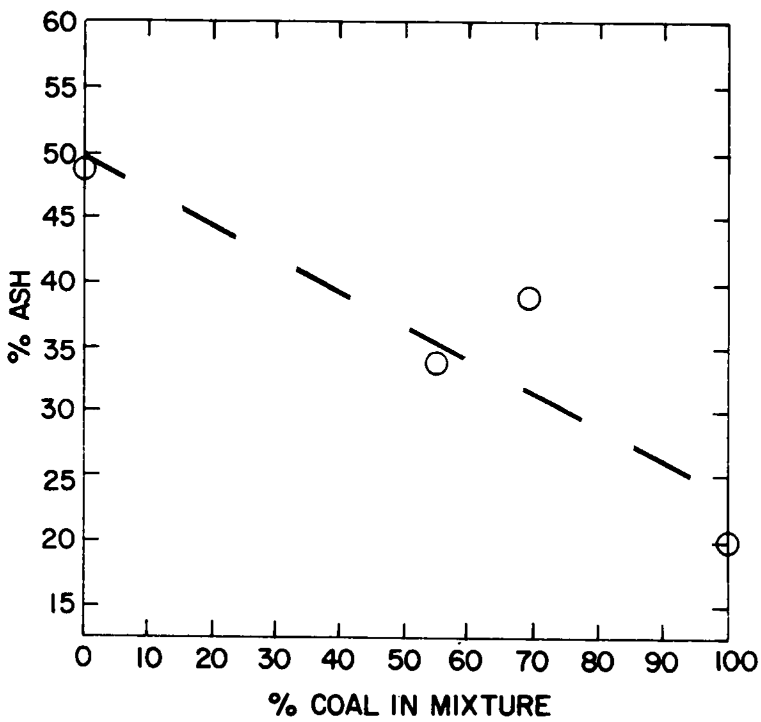
Figure 9. Relationship between filter cake heat content and sludge filter yield.



Filter 10. Relationship between filter cake heat content and total solids of the slurry.



Filter 11. Relationship between filter cake percent total sulfur and percent coal in the mixture.



Filter 12. Relationship between filter cake percent ash and percent coal in the mixture.

yield (Figure 9). This indicates that not only the quantity of coal present, but also the quantity of sludge solids will affect the heat content of the filter cake. Figure 10 presents the relationship between heat content and the total solids of the original coal-sludge slurry prior to dewatering. These data indicate that increases in total solids of the slurry may be caused by either increases in coal addition or increases in the sludge solids concentration.

In addition to the heat content, the percent ash and percent total sulfur will also be affected by changes in the percentage of coal in each mixture, as illustrated in Figures 11 and 12. These data indicate that the percent total sulfur will increase with increases in the percentage of coal (Figure 11), and the percent ash will decrease with increases in the percentage of coal (Figure 12). This would imply that in a combustion process such as a utility boiler, where a coal-sludge mixture is being burned, the air emissions of sulfur compounds should not be affected by the presence of the sludge, but ash-handling facilities may require alterations to provide the capacity for the additional sludge ash.

After obtaining measured heat content values for the coal and the unconditioned sludge filter cake, values for the heat content of various coal-sludge mixtures were calculated. A summary of the coal-sludge mixtures with corresponding filter yields and calculated heat content values is presented in Table VIII. The theoretical heat content values were calculated from the coal-sludge ratios in the original mixtures. These values represent the heat content that should be derived if all of the coal originally added to the sludge was captured by the vacuum filtration process. The actual heat content values were calculated from the corrected

TABLE VIII

CALCULATED HEAT CONTENT DATA

Coal Dosage		Filter Yield (lbs/hr/sq ft)		Heat Content (Btu/lb)	
Original Mixture	Calculated Actual[a]	Total	Sludge Only	Theoretical[b]	Actual[c]
Unconditioned[d]	Unconditioned	1.00	1.00	----	----
Unconditioned[e]	Unconditioned	1.06	1.06	----	----
0.18:1	----	0.71	----	6,500	----[f]
0.29:1	1.03:1	0.73	0.35	6,920	8,560[d]
0.58:1	0.25:1	0.29	0.24	7,750	6,770[d]
0.92:1	0.40:1	1.19	0.86	8,400	7,270[f]
0.86:1	1.10:1	1.04	0.50	8,300	8,660[d]
1.48:1	0.60:1	1.69	1.05	9,080	7,790[f]
1.44:1	0.35:1	0.51	0.38	9,040	7,120[d]
2.77:1	2.27:1	3.17	0.97	9,890	9,650[f]
0.35:1	0.96:1	0.68	0.35	7,120	8,460[g]
0.70:1	0.62:1	1.38	0.85	8,010	7,840[g]
1.05:1	0.65:1	1.88	1.15	8,590	7,900[g]
1.75:1	1.81:1	2.51	0.90	9,310	9,360[g]

[a]Calculated from the difference in total solids of the unconditioned sludge sample and the total solids of the coal-sludge mixture.

[b]Calculated from the coal-to-sludge ratio of the original mixture.

[c]Calculated from the coal-to-sludge ratio of the calculated actual mixture.

[d]Sludge sample collected 2/14/79--original sludge total solids = 11,500 mg/L.

[e]Sludge sample collected 5/8/79--original sludge total solids = 23,000 mg/L.

[f]Sludge sample collected 3/15/79--original sludge total solids = 30,000 mg/L.

[g]Sludge sample collected 6/28/79--original sludge total solids = 26,000 mg/L.

Note: Heat content values were calculated on a dry-weight basis.

coal-sludge ratios determined by previously described assumptions and calculations.

The relationship between the actual coal dosage and the calculated heat content of the corresponding coal-sludge mixture is shown in Figure 13. These data indicate that for coal dosages greater than 1 gm of coal for each gm of sludge total solids, the heat content of the mixture will have a value of at least 75 percent of the heat content of pure coal. This should aid in minimizing any detrimental effects of wide variations in the heat content of boiler feed material. The relationship for the measured heat content values shown in Figure 13 indicates generally lower values than those obtained by calculations. Additional measured values in the lower dosage range will be required before a valid comparison can be made.

There are indications that on a national level the annual rate of coal consumption in 1980 will reach 480 million tons/year, whereas the quantity of sludge that will be generated is approximately 8 million dry tons/year.[16] The total amount of sludge available for this disposal alternative would be very small in proportion to total coal consumption, not only nationally, but at individual plants as well. The actual coal-sludge mixture introduced into a utility boiler would be on the order of at least 60 tons of coal for each ton of dry sludge solids. One of the disadvantages of sludge addition to utility boiler feed pointed out by this study, caused by the excess ash production from sludge combustion, would be de-emphasized because of the relatively small amount of sludge to be added. It is important to realize, however, that reliability and availability problems, derating, and increased maintenance costs have been

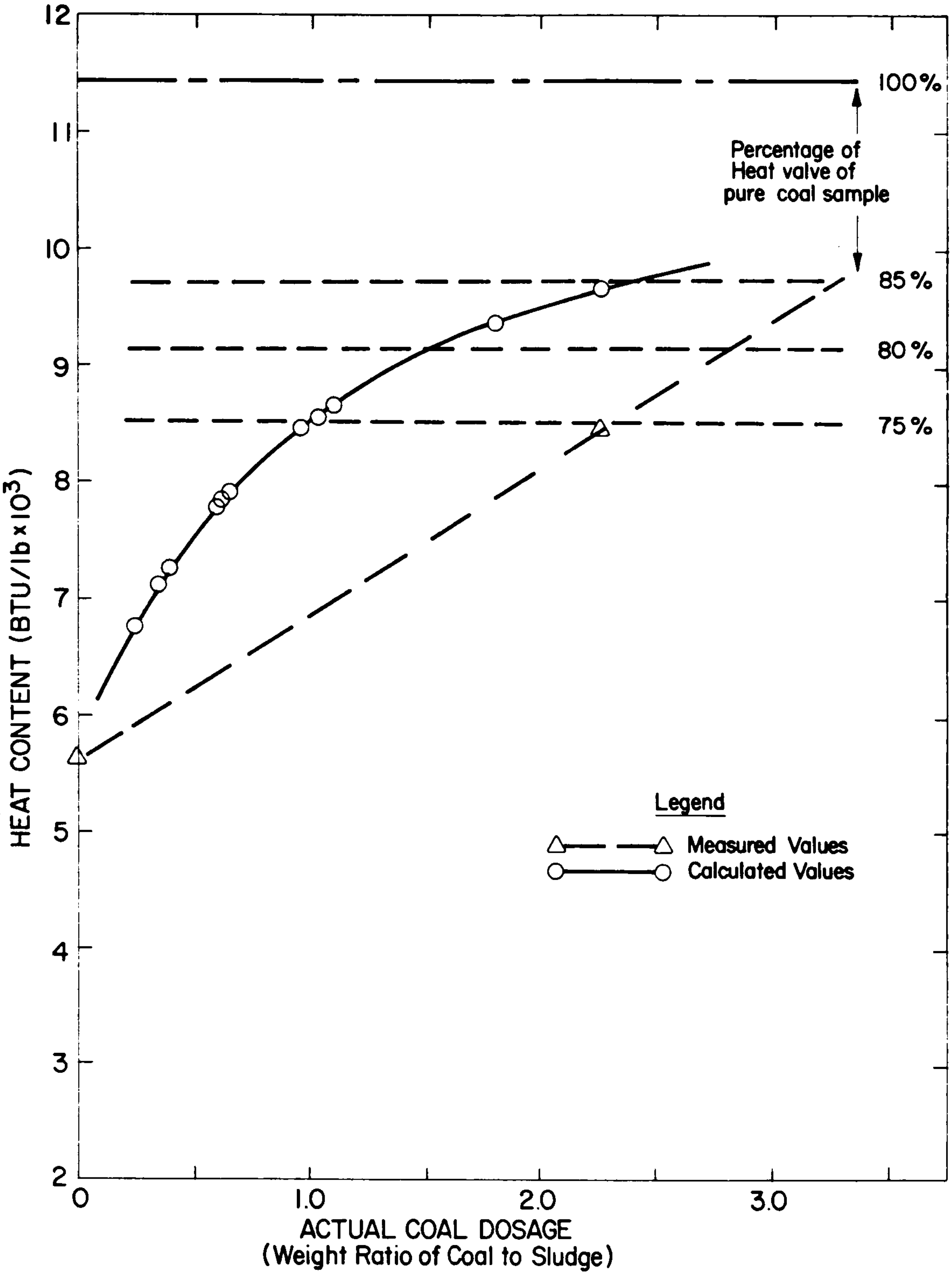


Figure 13. Relationship between actual coal dosage and the calculated heat content of the corresponding coal-sludge mixture.

attributed to the poor quality of the coal being burned. High ash content of coal is considered to be primarily responsible for the problems being experienced at steam plants. In addition, high moisture content and low Btu content results in a loss of generating capacity and a loss in generating efficiency.

Results of Filtrate Quality Analyses

While conducting the filter-leaf tests, several filtrate samples were collected and analyzed for a series of parameters. A summary of these analyses is provided in Table IX. This data set must be evaluated in three distinct segments since the sludges used in the various mixtures were collected at three different times and would be subject to many variables associated with the treatment plant influent characteristics and plant operations. The determination of any relationships between these treatment variables and the resulting sludge characteristics is beyond the scope of this study.

The independent variable in each series of tests was the coal dosage. (Even when the coal particle size fraction was varied, the ultimate result was a variation in coal dosage.) By studying various coal dosages in each series of tests, an attempt was made to determine if changes in the parameters listed in Table IX could be attributed to the amount of coal present in each mixture.

Only two of these parameters show a definite and consistent dependence on changes in coal dosage. Both the dissolved solids and the conductivity of the filtrate were found to increase with increases in coal dosage. Since previous portions of this study have shown that sludge filter yield increases with increasing coal dosage, increases in

TABLE IX

FILTRATE QUALITY ANALYSES

Coal Dosage Actual (original mixture)	Filtrates					Filtrate Metals (µg/L)					Filtrate Solids (mg/L)		
	pH	Conductivity (µmhos/cm)	COD (mg/L)	TOC (mg/L)	SOC (mg/L)	Cu	Zn	Ni	Pb	Cr	Dissolved	Suspended	Volatile Suspended
Test Data 2/14/79:[a]													
Unconditioned	7.0	2,100	480	1,600	1,500	90	540	80	86	50	1,100	300	220
0.25:1 (0.58:1)	7.0	2,200	1,000	1,600	1,500	90	380	120	63	94	1,200	270	220
0.35:1 (1.44:1)	7.1	2,200	1,100	1,500	1,500	80	470	130	60	43	1,300	270	220
1.03:1 (0.29:1)	7.2	2,200	1,500	1,900	1,800	100	480	130	61	11	1,300	420	310
1.10:1 (0.86:1)	7.3	2,200	980	2,000	1,400	100	480	110	46	24	1,300	360	320
Test Date 3/15/79:[b]													
(0.18:1)	6.9	1,900	1,500	2,100	1,600	120	670	220	53	41	920	570	470
0.40:1 (0.92:1)	7.1	2,400	1,500	2,200	2,000	70	240	150	27	18	1,500	600	470
0.60:1 (1.48:1)	6.8	2,400	960	2,100	2,000	60	450	150	40	25	1,600	400	330
2.27:1 (2.77:1)	6.0	3,000	1,100	2,900	2,000	110	960	390	25	23	2,200	300	170
Test Date 6/28/79:[c]													
Unconditioned	7.1	1,700	630	1,200	1,000	150	580	50	71	89	1,000	240	150
-20+40 Mesh 0.39:1 (1.69:1)	7.0	2,400	910	1,200	1,100	130	350	100	29	26	1,500	340	200
-60+80 Mesh 1.22:1 (1.69:1)	6.4	2,900	890	1,200	1,000	630	160	160	23	<5	2,400	360	180
-100 Mesh 1.48:1 (1.69:1)	6.4	3,300	1,030	2,400	1,800	50	340	300	<10	<5	3,100	470	200
Coal[d]						26.2	45.5	22.3	13.6	25.2			
Sludge[b,d]						4.8	10.3	3.4	4.8	6.9			

[a] Sludge total solids = 11,500 mg/L. [b] Sludge total solids = 30,000 mg/L. [c] Sludge total solids = 26,000 mg/L.

[d] These values are from individual samples of coal and sludge prior to dewatering (values in ppm).

dissolved solids, and therefore conductivity, could be attributed to increases in the amount of sludge found in the filter cakes formed with the higher coal dosages. This implies that changes in filtrate dissolved solids and conductivity are indirectly dependent on coal dosage and directly dependent on the concentration of the sludge solids in the filter cake.

Some general trends were also observed with other parameters, but the variability of the data diminishes the confidence in predicting relationships between these parameters and changes in coal dosage. A general trend interpretation would indicate that filtrate TOC, SOC, and nickel concentrations will increase with increases in coal dosage, whereas lead and chromium concentrations seem to decrease with increases in coal dosage. The other parameters investigated showed no consistent trend that would imply a dependence on coal dosage.

For each of these parameters, the magnitude of the changes in concentration over the range of coal dosages studied is very small. This fact would indicate that the addition of pulverized coal to sewage sludge would have neither a significant positive nor detrimental effect on the quality of filtrate from a vacuum filtration dewatering process.

Results of Pressure Filtration Tests

A summary of the results of the pressure filtration tests is tabulated in Table X. The tests were conducted in two phases similar to the vacuum filtration tests. The first phase involved the variation of coal dosage while the coal particle size fraction remained constant. In the second phase, the coal dosage was held constant, and the coal particle size fraction was varied.

TABLE X

PRESSURE FILTRATION DATA

Description		Filtrate		Filtrate Solids (mg/L)				Sludge Cake		Sludge	Specific
		pH	Conductivity	Dissolved	Suspended	Total	Volatile Suspended	Percent Moisture	Percent Volatile	Filter Yield (lbs/hr/sq ft)	Resistance (m/kg x 10^{13})
Unconditioned*		7.2	1,800	1,100	39	1,139	34	75.1	44.4	0.76	4.87
0.4:1	-60+100	7.2	1,900	1,200	120	1,320	98	59.0	50.5	0.78	4.46
0.8:1	-60+100	7.0	1,900	1,200	92	1,292	87	49.0	47.0	0.84	3.88
1.2:1	-60+100	7.3	1,900	1,200	67	1,267	60	45.4	55.4	0.96	3.04
1.6:1	-60+100	7.1	2,000	1,200	52	1,252	50	44.9	46.7	1.42	1.41
2.0:1	-60+100	7.2	2,000	1,300	50	1,350	49	44.2	51.4	2.58	0.43
1.6:1	+30 mesh	7.0	1,900	1,200	88	1,288	74	56.5	42.1	0.72	5.76
1.6:1	-30+60	7.2	2,000	1,200	48	1,248	39	53.7	49.5	0.78	4.82
1.6:1	-60+100	7.1	2,000	1,200	52	1,252	50	44.9	46.7	1.42	1.41
1.6:1	-100	7.2	2,200	1,500	66	1,566	56	34.6	49.0	1.23	1.85

*Unconditioned sludge sample collected 6/28/79--sludge total solids = 26,000 mg/L.

The same general trend of increasing sludge filter yield with increases in coal dosage noted in the vacuum filtration tests (Figures 2 and 5) is evidenced in these pressure filtration tests. There is no indication of an optimum coal dosage within the dosage range investigated in the pressure filtration tests.

In the vacuum filtration tests when the coal particle size was varied, the best sludge filter yield was obtained with the -60+80 mesh coal (Figure 5). Since the laboratory apparatus did not permit all of the coal in each size range tested to remain in suspension, the results obtained only indicate that for the mixing mechanism provided, this particle size range provided a larger coal dosage than most other size ranges. When examining the particle size variations with the pressure filtration apparatus, it was possible to ensure that the total coal sample for each size range tested became involved in the filtration process. In these tests, the -60+100 mesh coal provided the best sludge filter yield for the constant coal dosage used. These results seem to indicate that the -60+100 mesh coal particles will combine with this sludge to form the best cake structure on the filter media to allow passage of the filtrate while aiding in the formation of the filter cake. This may explain the results obtained in the vacuum filtration tests which indicated that the best sludge yield was achieved with the -60+80 mesh coal even though the -100 mesh coal sample provided a larger actual coal dosage to the filtration process.

A comparison of the results of the sludge filter cake analysis for vacuum filtration (Tables III and IV) and pressure filtration (Table X) reveals that pressure filtration will provide a dryer filter cake. This is in agreement with the literature[19] but may be misleading since the filter media used in the two types of tests were very different in porosity. This difference in media porosity also explains the order-of-magnitude difference in the filtrate suspended solids from vacuum filtration (Table IX) and pressure filtration (Table X). The general trends for filtrate pH, conductivity, and dissolved solids are similar for both types of filtration, but increases in dissolved solids and conductivity with increases in coal dosage seem to be more pronounced for vacuum filtration. The larger quantities of coal and sludge and the longer test period for vacuum filtration may account for these differences.

Results of the Buchner Funnel Tests

Using a coal dosage of 1.6 gm coal/gm of sludge solids and a coal particle size range of -60+100 mesh, two Buchner funnel tests were conducted to observe the effect of pressure variation on filter yield. The calculated specific resistance and filter yield are summarized in Table XI.

TABLE XI

BUCHNER FUNNEL TEST RESULTS

Pressure (inches of mercury)	Specific Resistance (m/kg)	Filter Yield (lbs/hr/sq ft)
10	4.18×10^{13}	0.22
20	4.70×10^{13}	0.29

The data indicate that there is an increase in filter yield with increased pressure, but in this case the increase is insignificant and the filter yield values are poor. The poor yield is partially due to the lack of conditioning agents, such as ferric chloride and lime or organic polymers. Primarily, though, the poor yield may be caused by blinding of the filter media by the small coal particles.

A further comparison of these data with the data from the pressure filtration test using the same coal dosage and particle size fraction gives a further insight into this relationship. The pressure filtration test was conducted at a pressure of 122 inches of mercury, resulting in a filter yield of 1.42 lbs/hr/sq ft. Again, the increase in filter yield is evident but insignificant in relation to the large pressure change.

CHAPTER VI

CONCLUSIONS

Based on the results of the foregoing studies of the use of pulverized coal to enhance dewatering and improve the heat content of municipal sewage sludge, the following conclusions can be made:

1. Both total filter yield and sludge filter yield will increase as the coal dosage is increased. No absolute optimum coal dosage was observed for the coal dosage range studied.
2. At a given coal dosage, the total filter yield will increase as the initial sludge total solids concentration increases.
3. The means of mixing the coal and sludge in the laboratory tests (magnetic stirrer), the limited power input into the mixing container, and the coal particle settling that may occur in the mixing container may individually or collectively be responsible for differences in the initial coal dosage and the actual coal dosage that becomes involved in the filtration process.
4. At a constant power input (mixing speed) and initial coal dosage, the smaller coal particles will provide a higher actual coal dosage than the larger coal particles and consequently a higher filter yield.

5. When no other conditioning agents are used, certain coal dosages may have a detrimental effect on vacuum filter yield. This was not as evident with the pressure filtration process.
6. When no other conditioning agents are used for sludge dewatering, the increases in filter yield achieved by the additions of pulverized coal does not seem significant enough to warrant coal addition as an aid for dewatering prior to sludge combustion. Coal addition prior to dewatering, however, will increase the heat content of the filter cake and may help to minimize problems associated with wide variations in boiler feed materials.
7. For coal dosages greater than 1.0 gm of coal for each gm of sludge total solids, the heat content of the mixture will have a value of at least 75 percent of the heat content of pure coal.
8. The combustion of a coal-sludge mixture should have no detrimental effect on the SO_2 emissions from a steam plant, but the high ash content of the sludge may require alterations to the ash handling process.
9. The heat content of the filter cake will increase with increases in percent volatile solids, percent of coal in each mixture, sludge filter yield, and total solids of the slurry.

10. The addition of pulverized coal to sewage sludge has no significant impact on the quality of the filtrate from the vacuum filtration process.
11. No significant improvement in filter yield can be achieved by increasing system pressure when pulverized coal is used as the conditioning agent for dewatering sewage sludge.
12. The filter yield values obtained from this study should only be used for relative comparisons with the other values from similar tests in this report. Filter yields obtained from actual operations would require further improvement by the addition of other conditioning agents. No additional conditioning was used in these tests to aid in minimizing process variables.

CHAPTER VII

RECOMMENDATIONS

The following recommendations are made for future studies to further develop this process for municipal sludge dewatering and disposal:

1. Determine the effects of coal addition on the quantity of conditioning chemicals required for dewatering. Both inorganic and organic conditioners should be investigated along with the effects of these chemicals on moisture content, ash content, sulfur content, and Btu content. The effects of coal addition on the settling of sludge solids should also be investigated.
2. The relative economics of the combustion of a coal-conditioned dewatered sludge and the combustion of chemically dewatered sludge in a steam plant utility boiler must be studied. This should include any benefits from reduced quantities of chemical conditioners that may be realized by pulverized coal addition prior to dewatering. In addition, the benefits of increased filter cake heat content must be considered. These benefits must be weighed against the costs of transportation and storage of the coal at the treatment facility along with the costs for a system to provide the desired coal dosage. System alternatives include the development of a process with adequate power to maintain all

particle sizes of the desired pulverized coal dosage in suspension or the additional pulverizing and screening equipment required to achieve the desired coal particle size fraction that can minimize power input.

3. The burning of sludge filter cake in a utility boiler should be studied to develop boiler feed processes to ensure efficient combustion. The study should include a comparison of the results of using a dewatered coal-sludge mixture added to the steam plant coal and the addition of dewatered chemically conditioned sludge to the plant coal without prior coal addition. A determination should also be made as to whether the dewatered sludge or coal-sludge mixture can be combined with the steam plant coal prior to boiler feed, or whether the filter cake and plant coal must be introduced into the boiler in separate feed lines.
4. The effects of sludge addition to utility boiler feed on air emissions should be investigated.
5. Additional ash handling requirements related to sludge additions and the potential problems associated with filter cake transportation and storage must also be studied.

LIST OF REFERENCES

LIST OF REFERENCES

1. Hirota, Moriyuki, Hiroo Okada, Yasunao Misaka, and Kenji Kato, "Dewatering of Organic Sludge by Pulverized Coal," Journal Water Pollution Control Federation, 47(12), pp. 2774-2782, December 1975.

2. Smith, J. E., Jr., S. W. Hathaway, J. B. Farrell, and R. B. Dean, "Sludge Conditioning with Incinerator Ash," Proceedings of the 27th Industrial Waste Conference, Purdue University, Lafayette, Indiana, 1972.

3. Busse, Osward, "Sewage Disposal Involving Filtration of the Sewage," U.S. Patent Number 3,279,603. Patented October 18, 1966.

4. Tenney, M. W. and T. G. Cole, "The Use of Fly Ash in Conditioning Biological Sludges for Vacuum Filtration," Journal Water Pollution Control Federation, 40, R281-R302, 1968.

5. Eye, J. D. and T. K. Basu, "The Use of Fly Ash in Wastewater Treatment and Sludge Conditioning," Journal Water Pollution Control Federation, 42, R125, 1970.

6. Tenney, M. W. and W. F. Echelberger, Jr., "Fly Ash Utilization in the Treatment of Polluted Waters," Presented at the Second Ash Utilization Symposium, Pittsburgh, Pennsylvania, March 10-11, 1970.

7. Nelson, R. F. and B. D. Brattlof, "Sludge Pressure Filtration with Fly Ash Addition," Journal Water Pollution Control Federation, 51(5), pp. 1024-1031, May 1979.

8. Gerlich, J. W. "Pressure Filtration of Wastewater Sludge with Ash Filter Aid," Environmental Protection Agency Service, EPA-R2-231 (1973).

9. Moehle, Fred W., "Fly Ash Aids in Sludge Disposal," Environmental Science and Technology, 1(5), pp. 374-379, May 1967.

10. Carlton, S. S., C. M. Marr, Jr., C. W. Foye, C. K. Owens, R. A. Chiancone, and B. C. Raynes, "Investigation of the Use of Coal for Treatment of Sewage and Waste Waters," Prepared for the Office of Coal Research, Department of the Interior, Washington, D.C., 1965.

11. Pitzer, Ronald L., Ronald F. Wukasch, and Dennis B. Wells, "The Vacuum Filtration and Incineration of Sewage Sludge Using Crushed Coal as a Conditioning Agent," Proceedings of the 32nd Industrial Waste Conference, Purdue University, Lafayette, Indiana, May 1977.

12. Hathaway, S. W. and R. A. Olexsey, "Improving the Fuel Value of Sewage Sludge," News of Environmental Research in Cincinnati, U.S. Environmental Protection Agency, October 31, 1975.

13. Hathaway, Steven W. and Robert A. Olexsey, "Improving Sludge Incineration and Vacuum Filtration With Pulverized Coal," Journal Water Pollution Control Federation, 49(12), pp. 2419-2430, December 1977.

14. Rand Development Corp. 1971. "Development of a Coal-Based Sewage Treatment Process," U.S. Department of the Interior, Office of Coal Research, OCR 55F. NTIS PB-124 786. November 1976.

15. Sverdrup and Parcel Associates, Inc. 1971. "Evaluation of a Coal-Sewage Treatment Pilot Plant," U.S. Department of the Interior, Office of Coal Research, OCR 63F. NTIS PB-235 785. November 1971.

16. Bernard, Hal, "Disposal of Municipal Wastewater Treatment Plant Sludges by Utilization in Coal Burning Steam and Power Plants," Proceedings of the Fifth National Conference on Acceptable Sludge Disposal Techniques, Orlando, Florida, February 1978.

17. Zwillenberg, M. L. and C. R. Guerra, "Sewage Sludge: A Fuel Alternative?" Power, p. 107, March 1979.

18. Guerra, C. R. and M. L. Zwillenberg, "Co-disposal of Municipal Sludges in Oil and Coal-Fired Power Plants," Proceedings of the Eighth National Conference on Municipal Sludge Management, Miami Beach, Florida, March 19-21, 1979.

19. Vesilind, P. Aarne, Treatment and Disposal of Wastewater Sludges, Ann Arbor Science, p. 109, 1974.

VITA

Terry Brooks Allen was born in Chattanooga, Tennessee on August 17, 1948. He attended elementary school in that city and was graduated from Brainerd High School in June 1966. The following September he entered The University of Tennessee, and in August 1971 he received a Bachelor of Science degree in Chemical Engineering. In March of 1972 he joined Hensley-Schmidt, Inc. consulting engineers and began study toward a Master's degree on a part-time basis in 1974. In 1978 Mr. Allen joined the Tennessee Valley Authority as an Environmental Engineer.

The author is a registered Professional Engineer in the State of Tennessee and is a member of the Water Pollution Control Association. Mr. Allen will continue full-time employment with the Tennessee Valley Authority after graduation.

He is married to the former Pamela Cloyd of Oak Ridge, Tennessee.