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Technical Report

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by

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ABSTRACT

This study investigated the impact of using coal in the design of sewage sludge dewatering beds when incineration is the means of final disposal. Bench scale experiments were conducted which evaluated the drainage of secondary waste activated sludge on fine and coarse granular coal. Experiments also evaluated sludge conditioning through the addition of coal. The study involved two types of economic analyses. One analysis compared the total annual costs of dewatering beds made of coal with those of sand. The second analysis evaluated the total construction and the annual operation and maintenance costs associated with sludge treatment options involving different dewatering and final disposal methods. All experiments were performed in the period from May 1982 to January 1983.

The experimental results indicated that faster secondary sludge drainage rates are possible with the use of fine granular coal rather than sand. The use of coarse granular coal achieved an improvement in drainage rates over the use of fine coal but was impractical with respect to the subsequent incineration. The experimental results also demonstrated that sludge conditioning occured when coal was added. The economic analyses showed that savings may be achieved from the operation of the dewatering beds utilizing coal rather than sand. They also indicated that savings from the use of coal rather than sand in the operation of dewatering beds may only be achieved with incineration as the method of final disposal.

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CHAPTER I

INTRODUCTION

An effect of the recent rise in the price of fuel is an increase in the cost of operation of existing wastewater treatment facilities, as well as in the cost of construction of new treatment works. Clough (6) suggests that energy alternatives to the fossil fuels are not likely to be used to any significant extent directly in sewage treatment; the emphasis in plant operations lies in the economical use of oil, natural gas, and coal. Research efforts need to investigate new cost-effective and energy efficient methods of operating existing unit treatment processes.

Although the volume of sludge produced in wastewater treatment is small in comparison to the volume of wastewater treated, it is this solids residue that poses considerable management problems. According to Holcomb (18) the cost of sludge treatment and disposal accounts for 25 to 50 percent of the total cost of waste management in this country. As a result, the development of the means to upgrade sludge handling operations is of considerable importance (9).

1.1 Sludge Treatment

Sludges resulting from conventional treatment processes are dilute suspensions. The solids concentration ranges from approximately 5 percent suspended solids content for primary sludge to .5 percent suspended solids content for secondary sludge. These suspensions usually need to be reduced in volume and weight to permit final disposal. The volume and weight reduction is achieved by operations such as thickening, conditioning, and dewatering.

The purpose of sludge conditioning is to facilitate the subsequent dewatering operations. It may involve a combination of a number of processes such as aerobic or anaerobic digestion, heat treatment, and addition of synthetic organic polymers, inorganic coagulants, or incinerator ash. Recently, the use of pulverized coal as a conditioning agent has also been attempted. Randall (25) points out that secondary waste activated sludge is particularly difficult to dewater and the conditioning processes are therefore important in its treatment.

Dewatering of the sludge from its liquid state to the suspended solids content in the range of 20 to 40 percent may be achieved by mechanical processes such as vacuum filters, filter presses, and centrifuges, as well as the less energy intensive and typically more economical use of sand drying beds and lagoons.

The sludge cake, at the high solids content, is ready for final disposal which may involve transport to a landfill or a land application site. Incineration of the sludge cake is often the means of final disposal when land disposal sites are locally unavailable, transportation costs are prohibitively high, or thermal conversion is required due to public health considerations (9). Incineration of the sludge involves the addition of supplementary fuel, either oil or natural gas, since the autonomous combustion of sludge at solids contents below 35 percent is rarely possible (27).

1.2 Use of Coal in Sludge Treatment

As a result of the increased interest in the energy efficient operation of treatment plants, the use of granular coal as a supplementary fuel in sludge incineration and as a sludge conditioning agent prior to filtration has been under investigation in recent years. Pilot and full-scale studies have been performed testing existing fluidized bed and multiple hearth incineration units with lump and pulverized coal used as a supplementary fuel, replacing conventional fuels such as oil and natural gas. Economic evaluations, performed in conjuction with these studies, indicate that the use of coal could realize a substantial savings without detrimental effects on process performance and without having to extensively retrofit existing equipment (2,15,17,24,27).

According to Swanson (27), coal costs roughly one-half as much as oil on a heating value basis and incineration using coal can be cost effective. Furthermore, it can conserve limited supplies of oil and assure continued operation of wastewater facilities.

The use of powdered and granular coal as a conditioning agent prior to filtration has also been investigated. The use of inorganic coagulants, such as ferrous sulfate, ferric chloride, aluminum sulfate and aluminum chloride requires high doses and an increase in the volume and weight of the resulting sludge cake. The use of polymers is advantageous since smaller doses are required. The advantages of the use of coal as a conditioner where incineration is the final disposal process are twofold: the introduction of a substance with high caloric content to the sludge and the reduction in the ash production when compared to the use of inorganic filter aids.

Pilot and full scale studies utilizing both vacuum filters and centrifuges have shown that the coal improved the performance of the dewatering units in a way comparable to the addition of incinerator ash; it increased filter yield, cake solids content, and cake separation from filter medium (2,4,15,24). Unlike ash however, coal represents a positive rather than a negative heat value in the incineration energy balance.

Investigations into the use of coal in sludge treatment also include studies of innovative processes. Continual sludge application and removal followed by the incineration of sludge cake and coal mixture can be performed on a granular coal filter. The collected filtrate is low in suspended solids and biological oxygen demand (17). A method of conditioning sludge with granular coal and aluminum or iron coagulant has been patented in Japan (26).

1.3 Purpose of the Study

The purpose of this study was to investigate the use of granular coal as a filter medium in the design of sludge dewatering beds. Since sludge dewatering beds are often the least energy intensive dewatering options, and because coal costs compare favorably with those of other fuels, it was believed possible that the use of coal in sludge bed design followed by incineration could provide a cost effective sludge treatment alternative.

It was also hypothesized that the use of coal as a support medium in dewatering beds could be beneficial to process performance. Finely crushed coal, rather than sand, might allow gravity drainage and simultaneous sludge conditioning. The use of coarse granular coal would permit the sludge solids to penetrate into the filter medium and result in faster and more complete drainage. In both of the above applications the dewatered sludge could be harvested together with some of the coal filter medium and incinerated. The incineration of a sludge-coal mixture could reduce or eliminate the need for supplemental fuels such as oil or natural gas.

Because of the importance of drainage in sludge dewatering bed performance the study evaluated drainage rates of secondary waste activated sludge which occur on coal and sand support media. Water is lost from the sludge on the dewatering beds through two mechanisms: drainage and evaporation. Dewatering begins by simultaneous drainage and drying, while a considerable amount of water is present in the sludge. At some time after sludge application, drainage stops and water is then removed by drying alone. In general, more time is required for evaporation than for drainage. Drainage alone will not remove enough water to make the sludge cake easily handleable; evaporation is necessary to dry the cake to a more solid form.

Several investigators stress the importance of the amount of water that can be removed by drainage. Walski (31) presents a model for the determination of sludge drying bed area which is very sensitive to the sludge solids content obtained at the end of drainage. Clark's (5) experimental data on sludge drying time likewise show dependence on the sludge moisture content at the onset of drying. This indicates that rapid drainage and drainage which results in a high sludge solids content will permit shorter drying time, smaller area requirements, and more efficient bed design.

The study investigated the drainage of biological sludges because these slurries, produced during secondary waste treatment, amplify sludge disposal difficulties. According to Caron (4) the secondary waste activated sludges are generated in quantities ranging from .5 to 1 kg dry solids per 1 kg of BOD removed. These solids represent 100 liters of sludge at 1 percent solids content per 1 kg of removed BOD. They may comprise 75 percent of the total sludge volume generated during primary and secondary treatment processes.

Biological sludges consist almost entirely of excess micro-organisms grown during biological treatment. The organisms contain water internally and flocculate into particles with a strong affinity for water. The waste activated sludges are in general more difficult to treat than primary sludges. Adverse effects on the dewatering of primary clarifier sludges have been observed as the consequence of secondary biological sludge additions (4).

Randall (25) suggests that the characteristics of activated sludge that affect both its drainage rates and its total drainable water are the sludge solids content and the microbial energy levels as measured by mixed liquor BOD and dehydrogenase activity. Sludge settleability, as measured by the sludge volume index, has been shown to be a poor indicator of the dewatering properties of waste activated sludges (25).

1.4 Objectives of the Study

This study was divided into three parts; each involved different bench scale experimental procedures. The study also addressed the economic feasibility of coal use in the design of sludge dewatering beds.

In Part One, finely crushed coal was used as the filter medium for cake filtration of secondary waste activated sludge. The use of coal was compared to the conventional use of sand as the filter medium. In Part Two, finely crushed coal was mixed with the secondary waste activated sludge and its conditioning effects were measured by the observation of the drainage rates resulting from cake filtration on sand filter medium, and by the evaluation of sludge properties important in filtration. In Part Three, the use of coarser granular coal in deep bed filtration of secondary waste activated sludge was investigated.

The economic evaluation of coal use in the design of sludge dewatering beds compared the performance and costs associated with the operation of the beds using coal and sand as filter media. The economic evaluation also compared the costs associated with sludge dewatering and final disposal options.

The overall objectives of the study were:

1. to determine the feasibility of coal use in the design of sludge dewatering beds; and
2. to evaluate the cost-effectiveness of coal use in sludge treatment involving the use of dewatering beds in conjunction with subsequent incineration.

Since bench scale experiments were performed as part of the study, the resulting recommendations are best suited for planning pilot scale experiments and to a limited extent for making full scale generalizations.

The specific objectives of the study were:

1. to quantitatively evaluate the drainage rates resulting from secondary waste activated sludge cake filtration on sand and coal media;
2. to quantitatively evaluate the extent of coal conditioning of secondary waste activated sludge by the measurement of cake filtration rates and by the measurement of sludge parameters important in filtration - specific resistance and coefficient of compressibility;
3. to qualitatively evaluate the feasibility of using the deep bed filtration process for sludge dewatering on granular coal beds;
4. to perform the economic analysis which compared the cost effectiveness of sludge dewatering beds constructed with coal and

with sand; and

5. to perform the economic analysis which compared the costs associated with sludge treatment utilizing coal dewatering beds and incineration and other methods of dewatering and final disposal.

CHAPTER II

BACKGROUND

Quantitative evaluation of the performance of sludge dewatering beds involves the use of models which take into account the two separate phenomena of drainage and drying. Drainage occurs at the beginning of the dewatering process. Drying occurs throughout the drainage process and for a considerable time after drainage has stopped until the sludge applied to the bed reaches the final, desired solids content.

2.1 Drainage - Cake Filtration

The conventional use of small diameter filter medium such as sand in the design of dewatering beds results in the formation of a sludge cake at the sludge-sand interface. The sludge cake results from the deposition of sludge solids during drainage. The forming sludge cake presents resistance to the subsequent fluid flow, contributes to most of the head loss through the dewatering bed and acts as the capture mechanism for sludge solids. The cake replaces the filter medium as the site of subsequent filtration. As drainage proceeds, the depth of the sludge overlying the cake decreases and so does the pressure head, the driving force in this type of filtration. Drainage occurs due to the falling head cake filtration process. Cake filtration occurs in the first 2 to 3 days after sludge application and yields sludges with approximately 15 to 20 percent solids content (21).

The falling head cake filtration process has been modeled by Nebiker (22). His study resulted in the formulation and the verification of an expression for the time of drainage as a function of the pressure head acting on the sludge, the depth from the sludge surface to the filtrate outlet elevation, H.

Eq.(1) $$Tdw = \frac{m}{3600}\left(\left(\frac{\mu\ So\ Rc}{100\sigma(\sigma+1)Hc^{\sigma}}\right)\left(Ho^{(\sigma+1)} + \sigma H^{(\sigma+1)} - (\sigma+1)HoH^{\sigma}\right)\right)$$

where:

Tdw = time of drainage in hrs

Rc = reference sludge specific resistance in sec2/gm

Hc = reference pressure head in cm of water

σ = coefficient of compressibility

μ = dynamic viscosity of filtrate in gm/cm-sec

So = initial sludge solids content in %

Ho = initial pressure head acting on the sludge in cm of water .

H = final pressure head acting on the sludge in cm of water

m = media factor

The model is limited in describing the drainage to the final time when the water present in the sludge no longer forms a supernatant layer at the sludge surface. The model makes use of design parameters such as the initial pressure head associated with the sludge application depth, Ho, and the initial sludge solids content, So.

The model is based on experimentally determined sludge filtration paramenters: the sludge specific resistance, Rc, at a given pressure head, Hc, and the coefficient of compressibility, σ. These sludge parameters are in common use in the modeling and design of the constant pressure vacuum filters (10). A more complete discussion of the specific resistance and the coefficient of compressibility and the derivation of Nebiker's dewatering model are included in Appendix A.

The dewatering model was experimentally verified by Nebiker only after the introduction of the dimensionless media factor, m, into Eq. (1). According to Nebiker (22) the factor must take into account the relationship between the sludge and the supporting medium, and can be considered a function of the ratio of a representative sludge floc diameter and an equivalent diameter of the supporting medium. The values of the media factor were observed to be larger for fine sands and smaller for coarse sands.

As the result of curve fitting the model to the experimental data, Nebiker obtained three different media factors while dewatering the same sludge on sands with three different effective sizes. The effective size, D10, of a granular medium corresponds to the maximum grain diameter of those particles which comprise 10 percent of the total sample weight. The effective size has been found to be a major factor in the effective pore diameter and is related empirically to drainage and seepage. The smaller the D10 of a sample the finer is the granular medium. Nebiker's media factor and effective diameter data is summarized in Table 1. The consideration of the media factors limits the usefulness of the dewatering model as a predictive tool. The model can still be used to compare the performance of various supporting media in the falling head cake filtration of sludge.

2.2 Sludge Specific Resistance

The sludge specific resistance and the coefficient of compressibility have been used as direct measures of the filterability of sludges treated with various conditioners. A decrease in the specific resistance is indicative of an increase in ease with which a particular sludge will dewater. Data are available on the changes in

Table 1. Summary of Effective Diameter and Media Factor Data - From Nebiker (22) and the Present Study

	D_{10}(mm)	Media Factor	D_{60}/D_{10}
Nebiker's Study			
Sand	.16	.75	1.25
Sand	.6	.6	1.23
Sand	.78	.45	1.41
Experiment No. 2			
Sand	.26	1.7	2.04
Coal	.14	1.3	7.06
Experiment No. 3			
Sand	.26	.4	2.04
Coal	.14	.2	7.06
Experiment No. 4			
Sand	.26	.9	2.04
Coal	.14	.7	7.06
Experiment No. 5			
Sand	.26	.6	2.04
Coal	.14	.5	7.06

sludge properties with varying dosages of conditioning agents such as polymers and ferric chloride.

Tabasaran (29) investigated the changes in specific resistance of digested sludges with the dosages of cationic polymers. His data indicate that the optimum conditioning occurs at a specific polymer dosage (see Figure 1). Coackley (8) in a seperate study showed that only one out of three cationic polymers used with digested sludge caused a marked reduction in specific resistance. The other two polymers produced sludge with worse filtration characteristics (see Table 2). The conflicting data from the two studies indicate that an increase or a decrease in the sludge specific resistance can occur as the result of conditioning by polymers. This may be a result of the great variations in sludge types and sludge properties.

Coackley (7,8) investigated the conditioning effects of ferric chloride on digested sludges in two seperate studies; in one using a pressure cell to determine specific resistance, in the other using the Buchner funnel test. The specific resistance reduction brought about by the trivalent iron was significant in both studies and is presented in Table 3. Data in Table 3 give a good indication of the large dosages of ferric chloride required to bring about the observed specific resistance reductions.

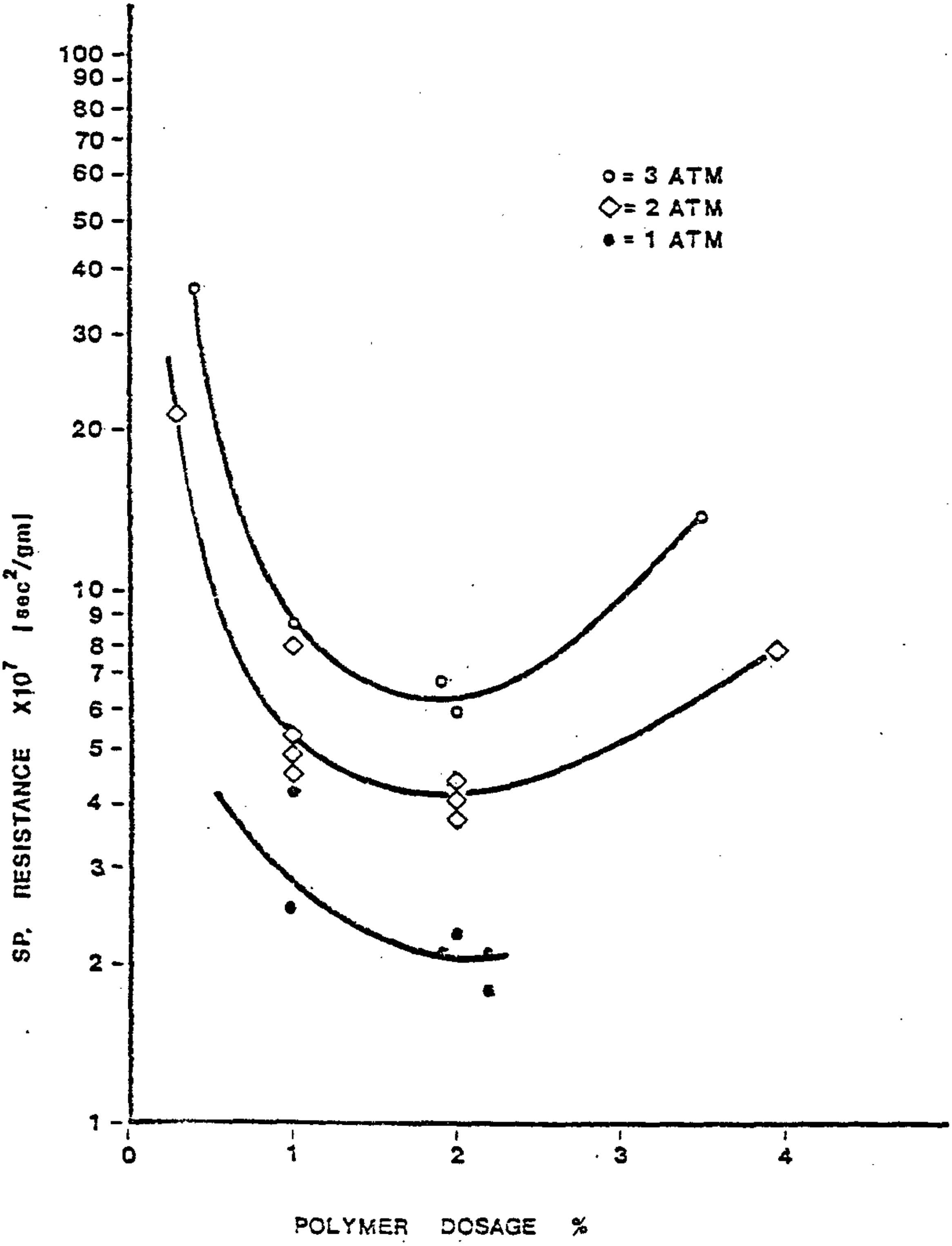

Figure 1. Effects of Polymer Dosage on Sludge Specific Resistance at Three Pressures from Study by Tabasaran (29).

Table 2. Effect of Cationic Polymer Addition on the Sludge Specific Resistance - From Study by Coackley (8)

	Polymer Concentration % Total Solids	Specific Resistance cm/g @ 21°C		Pressure, g/cm^2
	Untreated	5.62×10^9		500
Cationic Polymer 1	2.3	1.01		500
	5.7	.69		500
	9.7	.58		500
	25	1.32		500
	43.2	3.34		500
	69.5	10.6		500
Cationic Polymer 2	.8	7.1		500
	1.6	10.7		500
	4.0	4.5	13.2	500
	6.4	19.0	38.1	500
	8.0	16.1	29.1	500
Cationic Polymer 3	.8	7.4		500
	1.6	11.8		500
	4.0	12.4	26.8	500
	8.0	2.5	44.5	500

Table 3. Effect of Ferric Chloride Addition on the Sludge Specific Resistance - From Studies by Coackley (7, 8)

$FeCl_3$ % Total Solids	Specific Resistance cm/gm	Pressure, g/cm^2
Untreated	5.62×10^9	500
8.0	1.8	500
16.0	.69	500
32.0	.16	500
64.0	.22	500

$FeCl_3$ % Total Solids	Specific Resistance cm/gm	Pressure, g/cm^2
Untreated	1.6×10^{10}	2109
4.4	.16	2109
13.3	.0092	2109
22.2	.0047	2109
31.3	.0097	2109

Because of the variability encountered in sludge properties and the large variety of conditioning agents available, testing for specific resistance has been modified by fast laboratory procedures designed to measure the relative performance and the optimal dosages of different aids in the dewatering of sludges (16).

Although data on sludge specific resistance has accumulated, there is comparatively little interest in the coefficient of compressibility (10). This property is the measure of the degree of change that occurs in the sludge specific resistance as the filtration pressure varies.

2.3 Drainage - Deep Bed Filtration

Deep bed filtration is a process generally used in treating dilute suspensions. During filtration, suspension particles penetrate the filter medium and are captured within its pores. In some cases deep bed filtration may precede cake formation. The two types of filtration differ in degree of solids built up in the top sections of the filter medium.

Deep bed filtration is widely practiced in the water treatment industry. It has been studied as a form of treatment for wastewater (14). It has not been tried with wastewater sludges. With the use of coal as the filter medium, which can be harvested and co-incinerated with the applied wastewater sludge, deep bed filtration may be possible. If sludge particle removal is localized in the top section of the coal bed, only a small fraction of the coal bed may need to be harvested with each sludge application.

Swanson (27) presents data which shows the thermal deficit which needs to be offset by auxiliary fuel to maintain combustion in a multiple hearth incinerator under standard operating conditions (see Figure 2). From these data it is possible to calculate the required weight ratio of coal solids to dry sludge solids if coal with the heating value of 24,604 kJ/kg were used as the only auxiliary fuel. The values for coal solids to dry sludge solids ratios for some typical total solids contents of dewatered sludge are presented in Table 4. For a sludge with a 20 percent solids content no more than .27 coal solids to dry sludge solids may be required. The data indicate that the sludge penetration for a given sludge application depth on a deep bed filter should be shallow.

In a water filtration study Edzwald (12) used a dual media filter with anthracite, effective size D10=1.0-1.2 mm, and sand, effective size D10=.45-.55 mm, to filter humic, sub-micron particles. Particle removal in various portions of the filter bed was indirectly measured through the observation of the pressure head existing at different depths in the filter medium. The study documents that in the early stages of filtration head loss was equally distributed throughout the filter

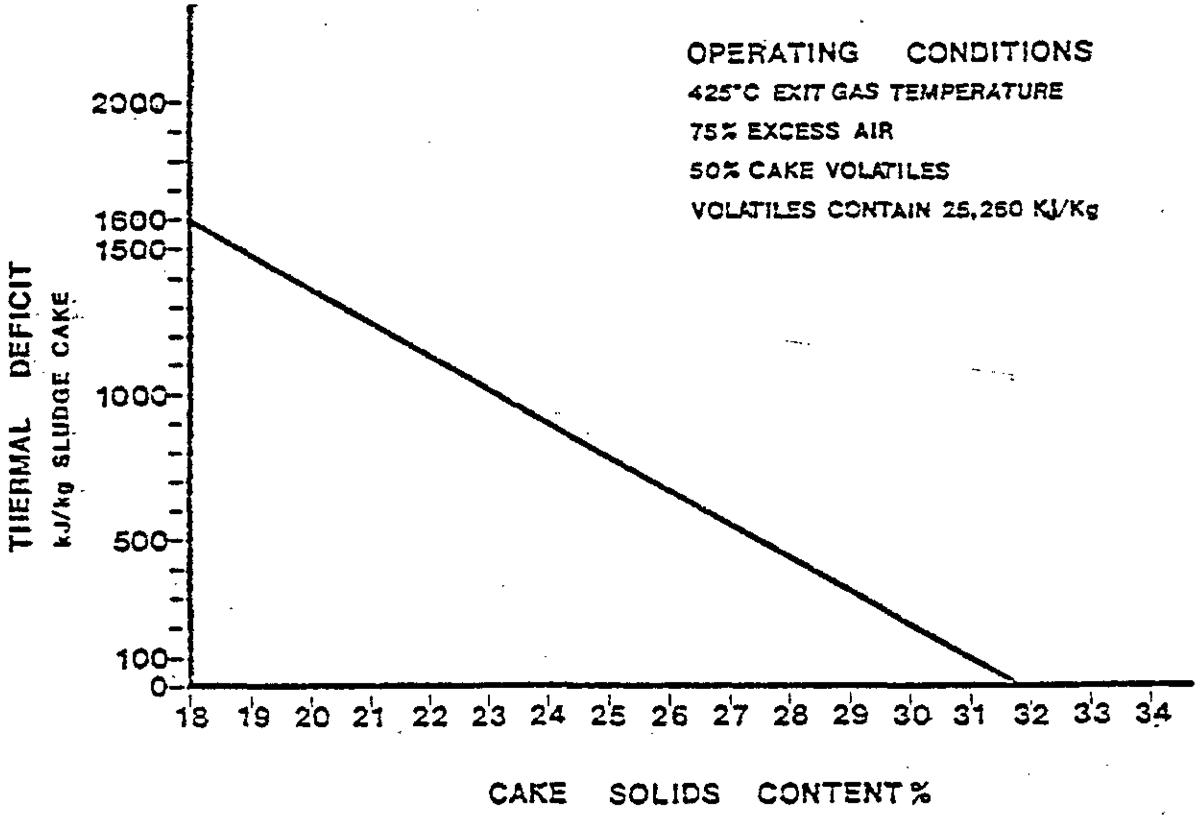

Figure 2. Effect of Sludge Cake Solids Content on Thermal Deficit of Multiple-Hearth Incinerators from Study by Swanson (27).

Table 4. Coal to Sludge Solids Weight Ratios Required for Combustion - From Study by Swanson (27)

Sludge Solids Content (%)	Coal Dosage Required
20	.27
25	.13
30	.03

medium and became localized in the upper portion of the bed as filtration proceeded. If this phenomenon was observed in the filtration of secondary sludge, the use of deep bed filtration may have an application for sludge dewatering beds.

2.4 Drying of Wastewater Sludge

Sludge drying on sand beds has also been studied by Nebiker (21), who developed and experimentally verified sludge drying models for wastewater sludge.

The rate of drying for a typical sludge can be represented by the constant-rate period followed by the falling-rate period. During the constant-rate drying ample water is available in the sludge to keep the surface completely wet. During the falling-rate drying the surface layer of water begins to recede into the solid cake. The change in the drying rates occurs at the critical moisture content. The moisture content represents the weight fraction of water to dry solids present in the sludge. The critical moisture content can be represented by the empirical formula:

$$\text{Eq.(2)} \qquad Ucr = 500\sqrt{\left(\frac{Ic\ Ws}{X1}\right)}$$

where:

Ucr = moisture content, (wt. water/wt. dry sludge solids)x100, in %

Ws = mass of solids in kg

X1 = surface area in m2

Ic = constant drying rate in kg/m2-hr

The total drying duration of sludge for both constant and falling-rate periods is:

$$\text{Eq.(3)} \qquad Tdr = \frac{Ws}{100\ X1\ Ic}\left(Uo - Ucr + Ucr\ \ln\left(\frac{Ucr}{U}\right)\right)$$

where:

Tdr = time of drying in hrs

Uo = initial moisture content in %

U = final moisture content in %

and (U < Ucr < Uo)

If the sludge does not reach the critical moisture content before it is removed from a dewatering bed, evaporation from its surface will occur only through constant-rate drying. The drying in this case is represented by the following expression:

$$\text{Eq.(4)} \qquad Tdr = \frac{Ws}{100\ X1\ Ic}(Uo-U)$$

and $(Ucr < U < Uo)$

The derivation of the drying model is included in Appendix A.

2.5 Economic Evaluation - Cost Model

An economic evaluation of the optimal sludge bed design needs to consider total dewatering time. In order to evaluate the performance of a sludge drying bed, a drainage model as well as a drying model must be used.

Meier and Ray (19) developed an optimum design model for sludge dewatering beds. In this model the objective function to be minimized is:

$$\text{Eq.(5)} \qquad Z = C1\ X1 + C2\ X1\ X2$$

where:

Z = total annual cost in $

C1 = cost per unit land area in $

C2 = cost per application per unit land area in $

X1 = area of land required in m2

X2 = number of applications required

The number of necessary applications for a given year is represented by:

$$\text{Eq.(6)} \qquad X2 = \frac{365 \cdot 24}{Tdw+Tdr+48}$$

where:

Tdw = drainage time in hrs

Tdr = drying time in hrs

This model considers drainage and drying to occur sequentially even though some constant rate evaporation occurs during drainage. Nebiker's models for drainage and drying times, Equations (1), (3), and (4), are well suited for this type of economic evaluation.

The model does not take into account the effects of rainfall. It can be used, however, to compare the costs of sludge dewatering beds which require different drainage and drying times. These dewatering periods are in turn dependent on sludge filtration properties such as sludge specific resistance and the coefficient of compressibility as well as the media factor.

For a particular set of filtration parameters, the minimum cost of a sludge dewatering bed can be obtained by considering the optimum sludge application depth. The calculations necessary for obtaining the optimum application depth can be performed with the aid of a computer.

CHAPTER III

EXPERIMENTAL ANALYSIS

3.1 General Protocol

This bench scale study involved three experimental parts. A total of twelve experiments were performed: Part One consisted of 5 experiments, Part Two of 2 experiments, and Part Three of 5 experiments. In all twelve experiments, sludge was applied on top of various filter media and the drainage rates of the sludge were observed.

The experimental set-up for all three parts was the same. It was composed of six fiberglass columns. These were placed on a rack which also supported manometer boards on either end (see Figure 3). Columns 1 and 6 were equipped with manometers to measure head loss through the filter medium and the applied sludge during the dewatering periods.

Each column was provided with a filtrate outlet which prevented air from entering the medium from the bottom once drainage had begun and allowed the measurement of the total head in the columns through the observation of the cumulative filtrate volume (see Figure 4).

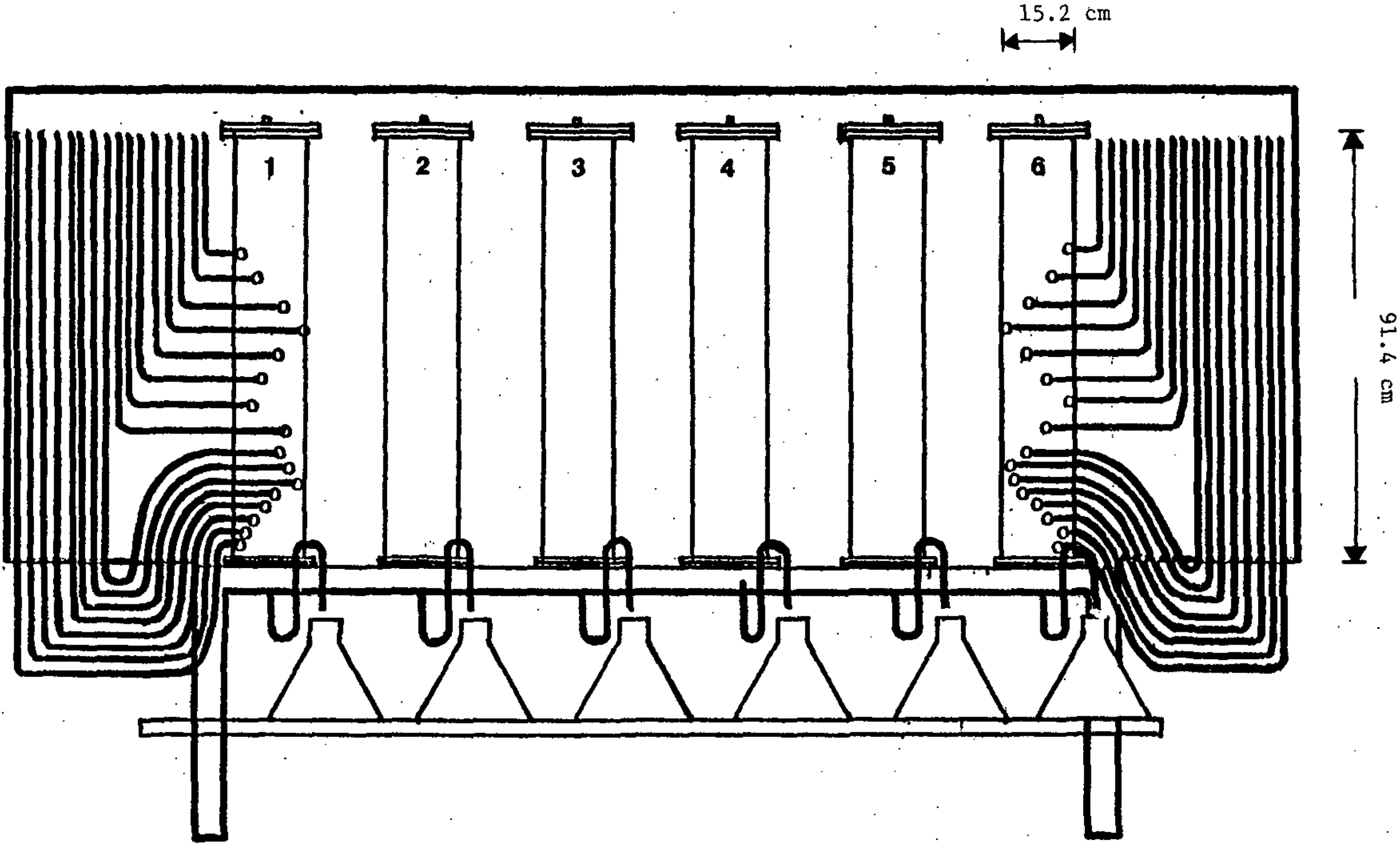

Figure 3. Experimental Drainage Set-Up Showing Columns, Manometer Boards, and Collection Vessels.

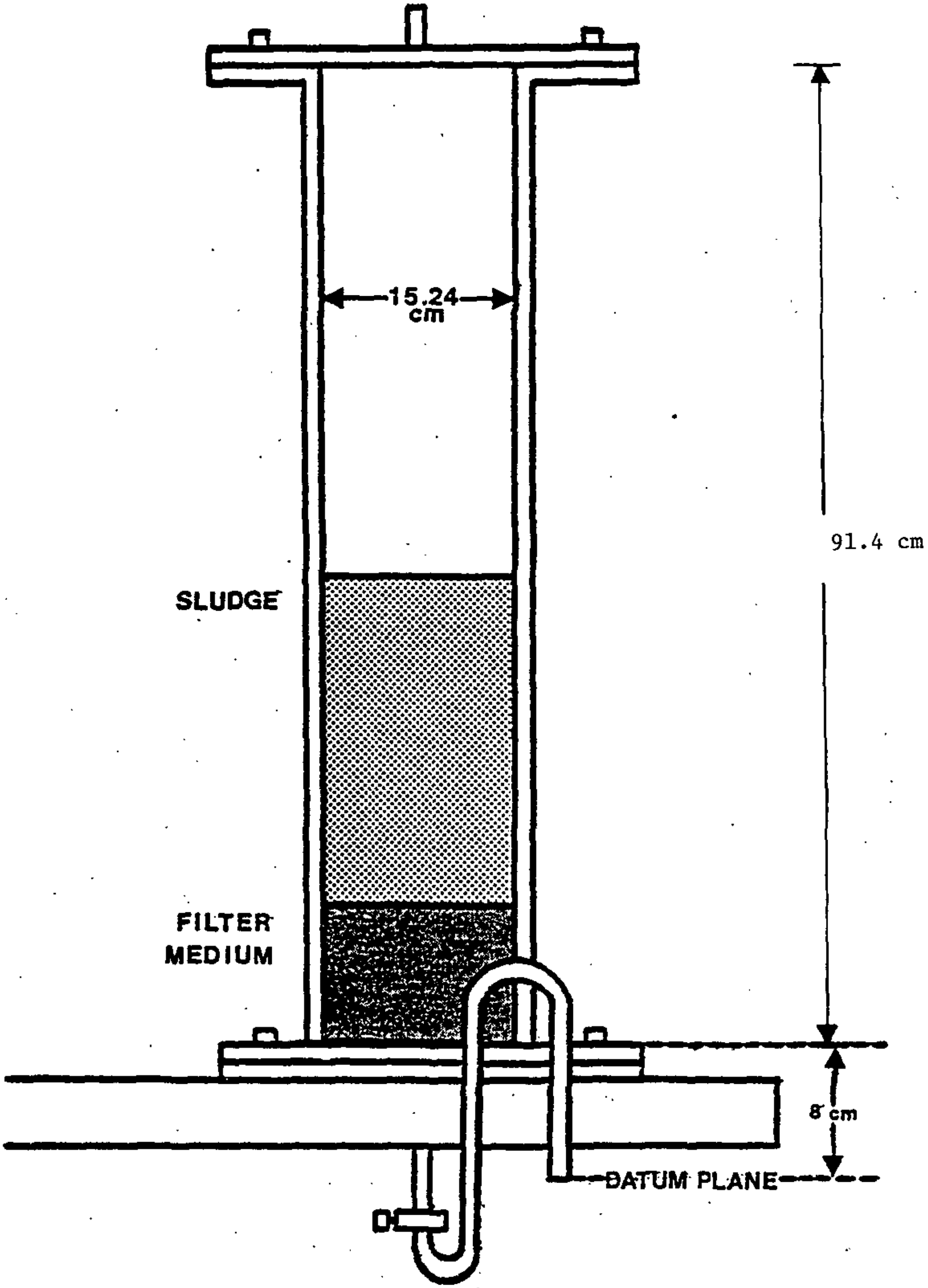

Figure 4. Drainage Column Diagram.

The tops of the columns were also provided with covers to minimize water loss through evaporation. Vent holes were made in the covers to prevent gas built up due to the biological activity of the sludge during the dewatering periods.

After each experiment the columns, the outlet openings and tubing, and the manometer tubes were thoroughly washed with tap water and without the use of detergents.

The sludge used in all the experiments, except experiment no. 10, was unaltered secondary waste activated sludge obtained one day in advance from the Amherst Wastewater Treatment Facility. In experiment no. 10 a mixture of secondary and primary sludge was used. Because the experiments were performed in the time span of one year the sludge properties varied from experiment to experiment. Sludge properties measured in this study for each experiment are presented in Table 5.

The sludges with solids content greater than 1 percent were mixtures of return waste activated sludge and thickened waste activated sludge obtained from the dissolved air floatation unit. During the annual turnover periods, polymers were added to the waste activated sludge by the treatment plant personnel. The polymers were always present in the thickened waste activated sludge. The approximate polymer dosage information is also included in Table 5. The usual polymer dosage required by the air floatation unit is .17 grams per

Table 5. Properties of Sludges Used in the Experimental Analysis

Experiment Number	Total Solids, %	Volatile Solids, %	pH	Specific Resistance, sec^2/gm	Coefficient of Compressibility	Polymer Dosage, g/ℓ	Type of Sludge
1	.32	85.1	6.5	1.35×10^9	1.09	.00725	Secondary-Waste Activated
2	.53	83.3	6.3	2.06×10^9	1.19	.00597	Secondary-Waste Activated
3	.68	80.1	6.5	1.94×10^9	.34	0	Secondary-Waste Activated
4	1.48	83.7	5.9	3.3×10^9	.58	.051	Secondary-Waste Activated and Thickened DAF
5	1.77	74.4	6.0	4.11×10^9	.56	.056	Secondary-Waste Activated and Thickened DAF
6	.52	83.5	6.5	7.26×10^9	1.18	0	Secondary-Waste Activated and Thickened DAF
7	1.2	78.8	6.2	2.17×10^{10}	1.5	0	Secondary-Waste Activated and Thickened DAF
9	.91	74.6	6.4	-	-	0	Secondary-Waste Activated
10	1.95	73.4	6.8	-	-	0	Secondary-Waste Activated and Primary-Raw
11	.88	79.1	6.6	-	-	0	Secondary-Waste Activated
12	.43	-	6.7	-	-	0	Secondary-Waste Activated and Secondary Effluent
12	1.45	-	6.3	-	-	.047	Secondary-Waste Activated and Thickened-DAF

liter of waste activated sludge.

The coal used in the experiments was a low sulfur bituminous coal obtained from the Power Plant at the University of Massachusetts. The sand used in the experiments was commercial Ottawa sand. Sieve analyses on the coal and sand were performed according to the procedure described in Appendix C. The procedure was designed to investigate if coal breakup occurred during sieving.

The sand and the coal effective size and uniformity coefficient data for experiments no. 1 through no. 7 are presented in Table 6. In experiments no. 8 through no. 12 specific particle size fractions of granular coal were used. This information is presented in Table 7. Tables 6 and 7 also provide information on the depth of the media and sludge investigated in the experiments and the resulting total initial pressure heads in the columns.

The filtrate volume was measured and collected at desired time intervals. The filtrate was stored at room temperature and analyzed at the end of the dewatering experiments. The sludge properties were analyzed during the filtration experiments.

The analyses of total solids, volatile solids, and total filterable solids were performed in accordance with Standard Methods (30). pH data were obtained with a combination electrode meter.

Table 6. Media Properties and Sludge and Media Depth Data for Conditioning and Cake Filtration Experiments

		Column 1	Column 2	Column 3	Column 4	Column 5	Column 6
Experiment Number	Medium Type	Coal	Coal	Coal	Sand	Sand	Sand
1-5	D_{10} (mm)	.14	.14	.14	.26	.26	.26
	D_{60}/D_{10}	7.02	7.02	7.02	2.04	2.04	2.04
	Sludge Depth (cm)	20	20	20	20	20	20
	Medium Depth (cm)	10	10	10	10	10	10
	Total Head (cm)	38	38	38	38	38	38
Experiment Number	Medium Type	Sand	Sand	Sand	Sand	-	-
6	D_{10} (mm)	.26	.26	.26	.26	-	-
	D_{60}/D_{10}	2.04	2.04	2.04	2.04	-	-
	Sludge Depth (cm)	20	20	20	20	-	-
	Medium Depth (cm)	10	10	10	10	-	-
	Total Head (cm)	38	38	38	38	-	-
Experiment Number	Medium Type	Sand	Sand	Sand	Sand	Sand	Sand
7	D_{10} (mm)	.26	.26	.26	.26	.26	.26
	D_{60}/D_{10}	2.04	2.04	2.04	2.04	2.04	2.04
	Sludge Depth (cm)	20	20	20	20	20	20
	Medium Depth (cm)	10	10	10	10	10	10
	Total Head (cm)	38	38	38	38	38	38

Table 7. Media Properties and Sludge and Media Depth Data for Deep Bed Filtration Experiments

Experiment Number		Column 1	Column 2	Column 3	Column 4	Column 5	Column 6
8	Medium Type	Washed Coal	-	-	-	-	Washed Coal
	Medium Size (mm)	1.18<D<4.75	-	-	-	-	4.75<D<12.5
	Water Depth (cm)	30	-	-	-	-	30
	Medium Depth (cm)	15	-	-	-	-	15
	Total Head (cm)	53	-	-	-	-	53
9	Medium Type	Washed Coal	Washed Coal	-	Washed Coal	Washed Coal	Washed Coal
	Medium Size (mm)	12.5<D	12.5<D	-	4.75<D<12.5	4.75<D<12.5	1.18<D<4.75
	Sludge Depth (cm)	20	20	-	20	20	20
	Medium Depth (cm)	27	27	-	27	27	27
	Total Head (cm)	55	55	-	55	55	55
10	Medium Type	Washed Coal	Washed Coal	Washed Coal	-	Unwashed Coal	Unwashed Coal
	Medium Size (mm)	1.18<D<4.75	1.18<D<4.75	4.75<D<12.5	-	D_{10}=.73 D_{60}/D_{10}=15.8	D_{10}=.73 D_{60}/D_{10}=15.8
	Sludge Depth (cm)	20	20	20	-	20	20
	Medium Depth (cm)	27	8	27	-	8	27
	Total Head (cm)	55	36	55	-	36	55

Table 7, Continued

Experiment Number		Column 1	Column 2	Column 3	Column 4	Column 5	Column 6
11	Medium Type	Washed Coal	Washed Coal	Washed Coal	-	-	-
	Medium Size (mm)	1.18<D<4.75	1.18<D<4.75	1.18<D<4.75	-	-	-
	Sludge Depth (cm)	30	45	15	-	-	-
	Medium Depth (cm)	15	15	15	-	-	-
	Total Head (cm)	53	68	38	-	-	-
12	Medium Type	Washed Coal	Washed Coal	-	-	Washed Coal	Washed Coal
	Medium Size (mm)	1.18<D<4.75	1.18<D<4.75	-	-	1.18<D<4.75	1.18<D<4.75
	Sludge Depth (cm)	45	30	-	-	30	15
	Medium Depth (cm)	15	15	-	-	15	15
	Total Head (cm)	68	53	-	-	53	38

Procedures for the determination of the sludge specific resistance and the coefficient of compressibility, although not standardized, have been described by many investigators (7,16,22,28,33). The procedure used by Nebiker (22) in the verification of the dewatering model was the Buchner funnel test performed in accordance to a method proposed and tested by Coackely (7). The same test was used in this study.

The reproducibility of the method was tested by performing triplicate determinations on a secondary sludge sample at the beginning of experimentation. Thereafter, all the specific resistance and the coefficient of compressibility determinations were performed once per sludge sample. The description of the procedure, the data obtained for all tested samples, and the error analysis performed on the triplicate sample are included in Appendix B.

3.2 Part One - Cake Filtration Experiments

Five experiments were performed in Part One of the study, which was designed to compare sludge drainage on coal and sand support media. In each experiment, a secondary waste activated sludge of different solids content was drained through sand and finely crushed coal filter media. Triplicate data for the drainage on the sand and the fine crushed coal were supplied by each experiment.

Prior to filling the columns with filter media and sludge, the columns were filled with tap water to the planned depth of sludge application. The manometers of columns 1 and 6 were allowed to fill with the water. The air bubbles trapped in the manometer tubes were eliminated and the top openings of the manometer tubes were clamped shut. The air bubbles were also eliminated from the outlet hoses. Each of the columns was then allowed to drain to the bottom and this drainage time was recorded. This was done to measure the effect of the outlet conditions on the drainage rates in the columns.

For each experiment three columns were filled with sand media which was supported by a 2 cm layer of larger gravel and placed on a fiberglass screen with mesh size of .508 mm. The other three columns were filled with the finely crushed coal which was supported by a 2 cm layer of coarser coal likewise placed on the fiberglass screen. The purpose of the gravel and the coarse coal was to prevent the movement of the fine sand and coal particles through the drain opening and to prevent the plugging of the filtrate passage.

The depth of the sand and the coal as well as support gravel in the columns was 12 cm. The distance from the bottom of the columns to the atmospheric outlet for the filtrate was 6 cm. When the columns were charged with a 20 cm depth of sludge, the total initial pressure head for each column was 38 cm of water.

Prior to charging the columns with sludge, the gravel and the coarse coal were saturated with known volumes of tap water. The sand and the fine coal were subsequently introduced to the columns and likewise saturated with known volumes of tap water. This was done by carefully stirring the filter media until no trapped air bubbles were visually evident. The sludge was then pumped into all of the columns. The top openings of the manometers were unclamped after the introduction of the sludge. Just before the unclamping of the outlet tubing, the start of the filtration, the sludge was gently stirred in all the columns and covers were placed over the tops of each column.

The filtrate from the columns was measured and collected at frequent intervals initially and at more lengthy intervals as drainage decreased. The time when there was no longer any observable layer of supernatant present over the sludge was noted and the experiment terminated shortly thereafter.

The sludge was tested for total solids content, volatile solids content, pH, specific resistance, and coefficient of compressibility. The filtrate was tested for total filterable solids content and pH.

3.3 Part Two - Conditioning Experiments

The experimental Part Two consisted of experiment no. 6 and experiment no. 7. These experiments were designed to evaluate the effect of coal addition to waste activated sludge on the drainage rates and the filtration parameters of the resulting sludge-coal mixtures.

In experiments no. 6 and no. 7 the filter medium in all the columns was sand. In both experiments, the secondary waste activated sludge was combined with certain amounts of finely crushed coal. The coal was of effective size, D10=.14 mm, and a uniformity coefficient, D60/D10=7.02.

The experimental set-up, the procedures for column charging, and the sludge and the filtrate analysis were the same as those in Part One. The desired coal dosages were calculated with total solids content determination performed on the day the sludge was obtained, one day prior the the beginning of the given experiment. In experiment no. 6, the unaltered sludge and each mixture was drained only once. In experiment no. 7 the unaltered sludge and the two coal mixtures were drained in duplicate.

3.4 Part Three - Deep Bed Filtration Experiments

Experiments no. 8 through no. 12 comprised Part Three of the study. In these experiments, filtration of secondary waste activated sludge with the use of coal composed of large particles was investigated. The use of the coarse coal permitted the sludge floc particles to penetrate the filter medium and deep bed filtration was possible.

The coal with effective size, D10=.73 mm, and the uniformity coefficient, D60/D10=15.75, was sieved and divided into fractions of different particle sizes in preparation for the experiments in Part Three.

To allow for the observation of the sludge floc particle penetration into the support media, more coal was used in the columns in Part Three than in Parts One and Two. For all experiments in Part Three, except for experiments no. 9 and no. 10, the depth of the coal in the columns was 15 cm. In experiments no. 9 and no. 10 the depth of the coal varied. The sludge application depths varied for each experiment and in each column.

The coal fractions were thoroughly rinsed with tap water prior to being used in the dewatering columns, with the exception of columns 5 and 6 in experiment no. 10. The fractions were placed on 2 cm of coal size fraction of 12.5<D mm which was supported by a fiberglass screen at

the bottom of the columns. The distance from the bottom of the column to the atmospheric outlet of the filtrate was 6 cm.

In all experiments in Part Three, before charging the columns with sludge, the coal in the columns was totally saturated with tap water. The air bubbles were excluded from the filtrate outlet tubing. The manometer tubes were filled with tap water, air bubbles eliminated, and the tops clamped off.

In experiment no. 8 only columns 1 and 6 were used with the smaller particle coal fractions. In this experiment tap water was allowed to drain to the top of the media. Periodic manometer readings were taken during the drainage to determine the amount of head loss which would result as a consequence of the fluid movement through the porous medium. Total drainage time was also recorded. Experiment no. 8 was run twice.

In experiment no. 9, three coal size fractions were used. Secondary waste activated sludge was applied to the columns and allowed to filter through the media. Periodic volumetric readings of the filtrate were taken and manometer readings from columns 1 and 6 recorded. In experiment no. 10 a mixture of primary and secondary sludges was applied to the columns. The sludge was analyzed for total solids content, volatile solids content, and pH. Filtrate was not analyzed in experiments no. 8 through no. 10.

In experiments no. 11 and no. 12 only the smallest particle size fraction was used in the columns. Secondary waste activated sludges of three different solids contents were examined in these experiments at various application depths.

Prior to charging the columns with sludge, tap water was introduced to the columns to a depth of 30 cm above coal surface for experiment no. 11 and to a depth of 30 cm and 15 cm above coal surface for experiment no. 12. The water was allowed to drain to the bottom of each column. The drainage time for each column was recorded. The purpose of these tests was to measure the effect of column packing and outlet conditions on drainage rates.

In experiments no. 11 and no. 12 volumetric readings and manometer readings of columns 1 and 6 were taken periodically. The sludge was analyzed for total solids content, volatile solids content, and pH. Specific resistance and the coefficient of compressibility analyses were not performed in experimental Part Three. The filtrate was analyzed for total filterable solids content and pH.

CHAPTER IV

EXPERIMENTAL RESULTS

4.1 Part One - Cake Filtration Experiments

The experiments no. 1 through no. 5 were performed in order to compare the sludge drainage which occurs on sand and on coal support media. The drainage data from the experiments were compared with the use of Nebiker's cake filtration model.

Sludge types and the various sludge properties were different for each experiment. In all experiments, two filter media types were used, coal with D10=.14 mm and sand with D10=.26 mm. In each experiment, the sludge was drained simultaneously on three sand and three coal columns. The data for each column in experiment no. 3 is shown in Figure 5 and Figure 6. The close agreement of the triplicate data sets is characteristic of those obtained by other experiments in this part of the study. Data analyzed by Nebiker's drainage model was the average of the triplicate data sets for each experiment.

Nebiker (22) reported that the media factors, obtained by curve fitting his experimental data to the data predicted by the model, decreased with the increase in the supporting media effective size. His experimental drainage data for digested primary and waste activated

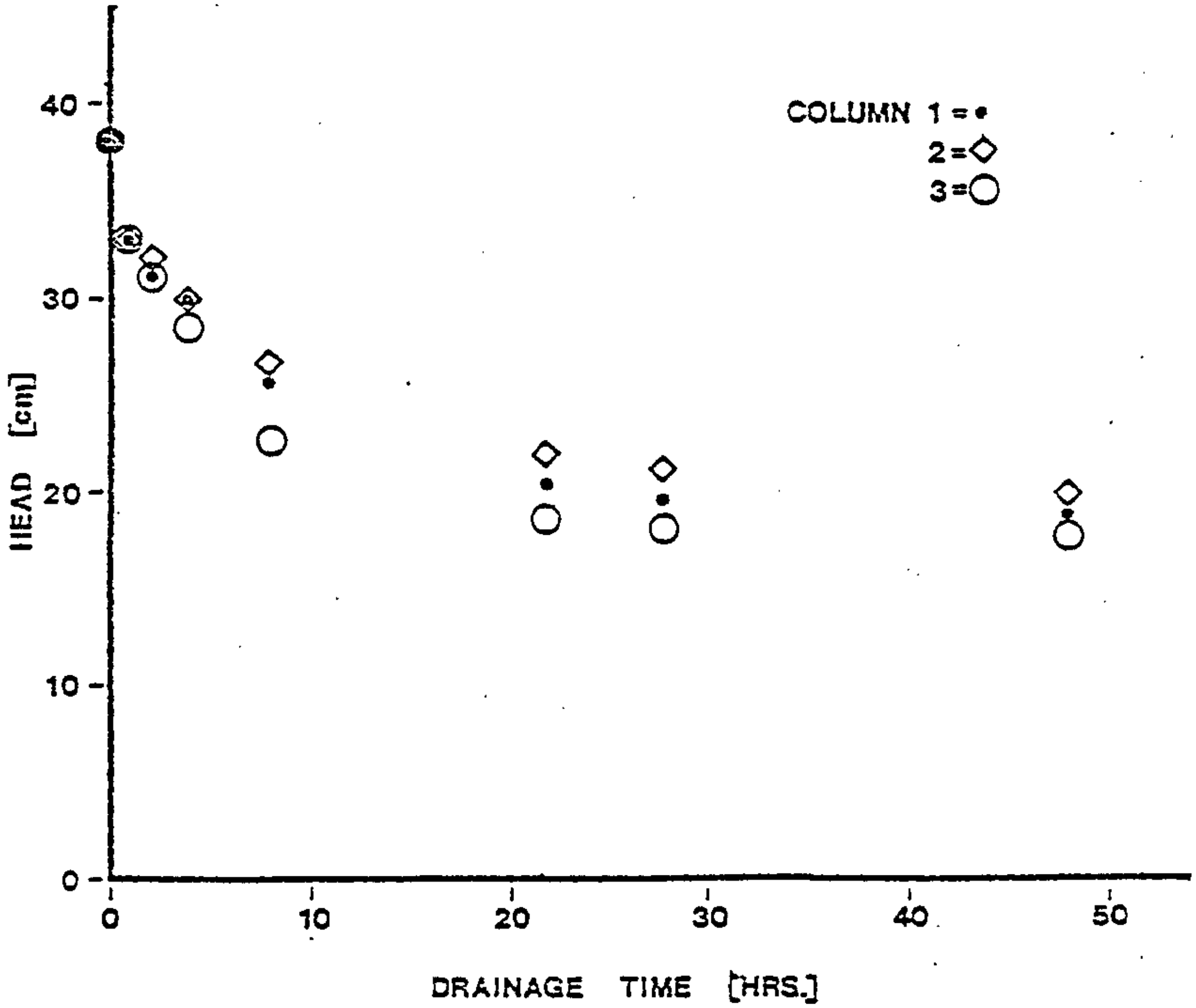

Figure 5. Drainage on Coal - Experiment No. 3.

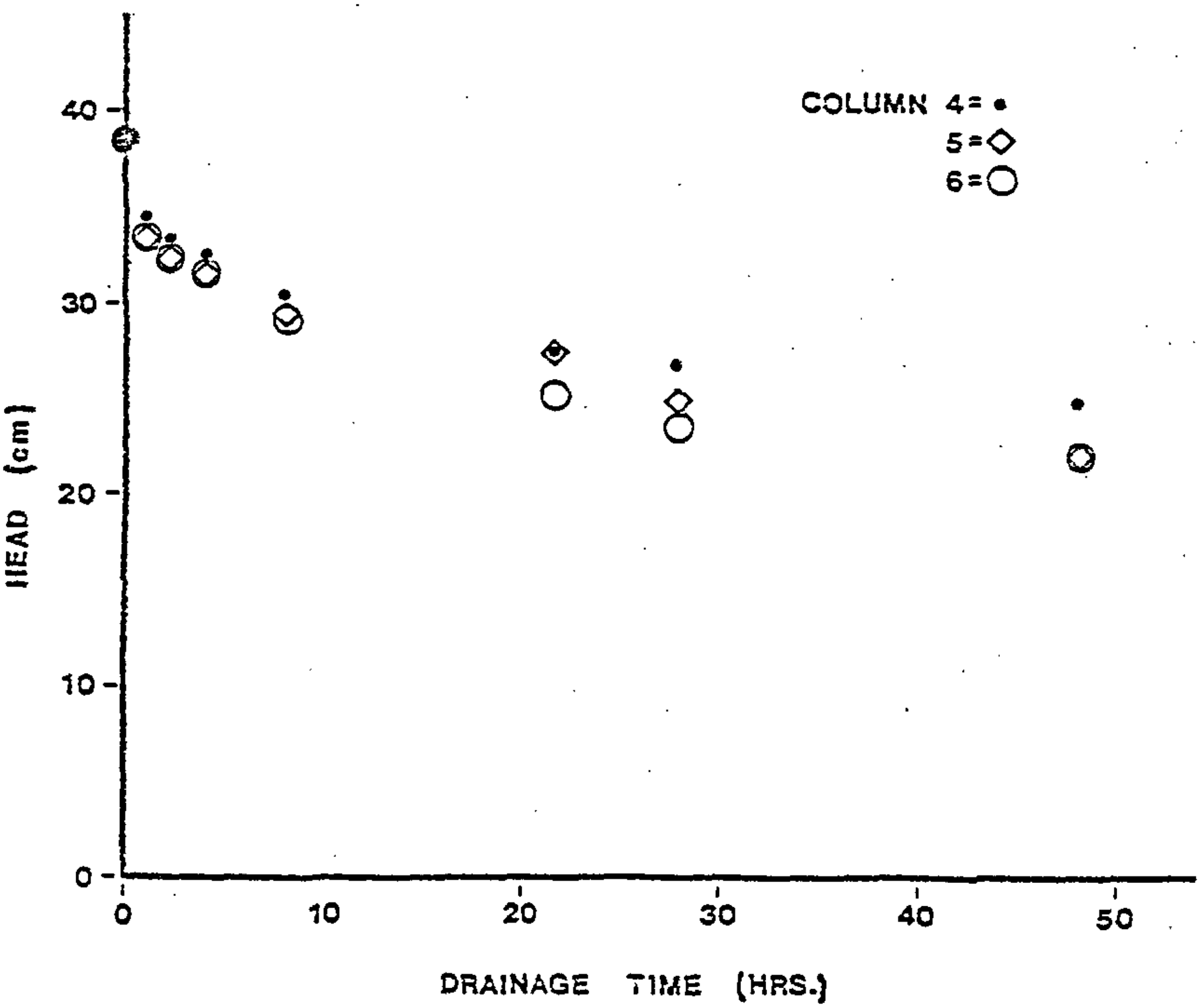

Figure 6. Drainage on Sand - Experiment No. 3.

sludge mixture at solids content of 2.8 percent are presented in Figure 7. Nebiker investigated sludges with different properties at different application depths and for each test the values for the media factor exhibited an increase with the corresponding decrease in the effective size of the sand.

Experiments no. 2 through no. 5 of this study showed, however, an opposite relationship. Experimental and predicted drainage data are presented in Figures 8 through 11. For each sludge type, a different media factor needed to be applied even though the filter media in each experiment were the same. It is evident, however, that the finer coal medium resulted in faster drainage rates for all four different sludges. The greatest variation in drainage between the coal and the sand columns occurred in experiments nos. 2 through 4 in which more dilute sludge was applied to the media. The experimental media factor data are summarized in Table 1 together with Nebiker's data for comparison.

The drainage data used for the determination of the media factor values was limited only to those readings where the sludge supernatant was visible in the columns. Once the liquid interface penetrates the sludge cake surface and the menisci in the sludge cake resist the suction of the underlying water, the drainage model does not apply. Because drainage occurred very rapidly in experiment no. 1, not enough data were collected to allow for the media factor determination. The drainage data for experiment no. 1 are included in Figure 12 and show

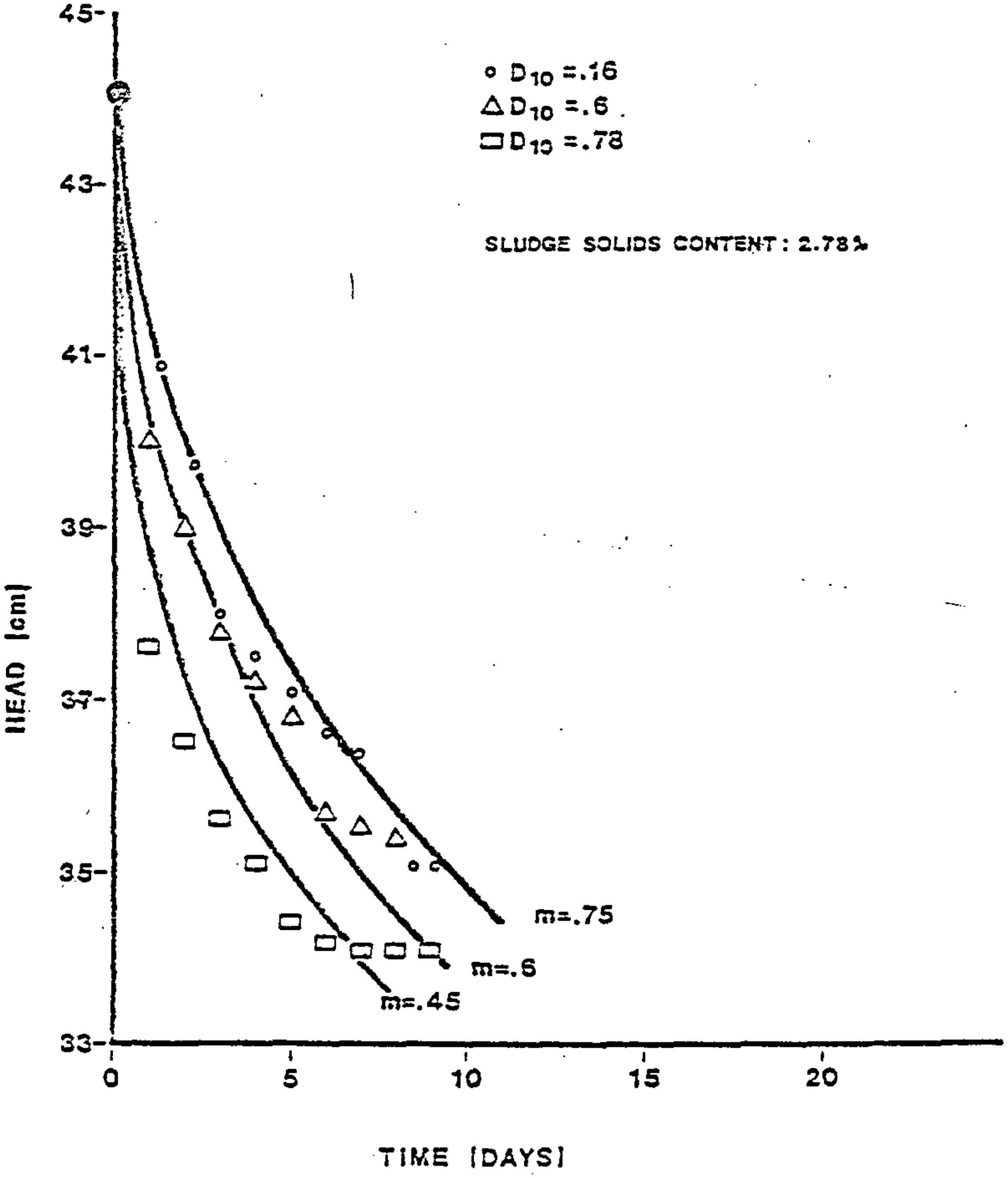

Figure 7. Experimental and Theoretical Drainage on Three Types of Sand from Study by Nebiker (22).

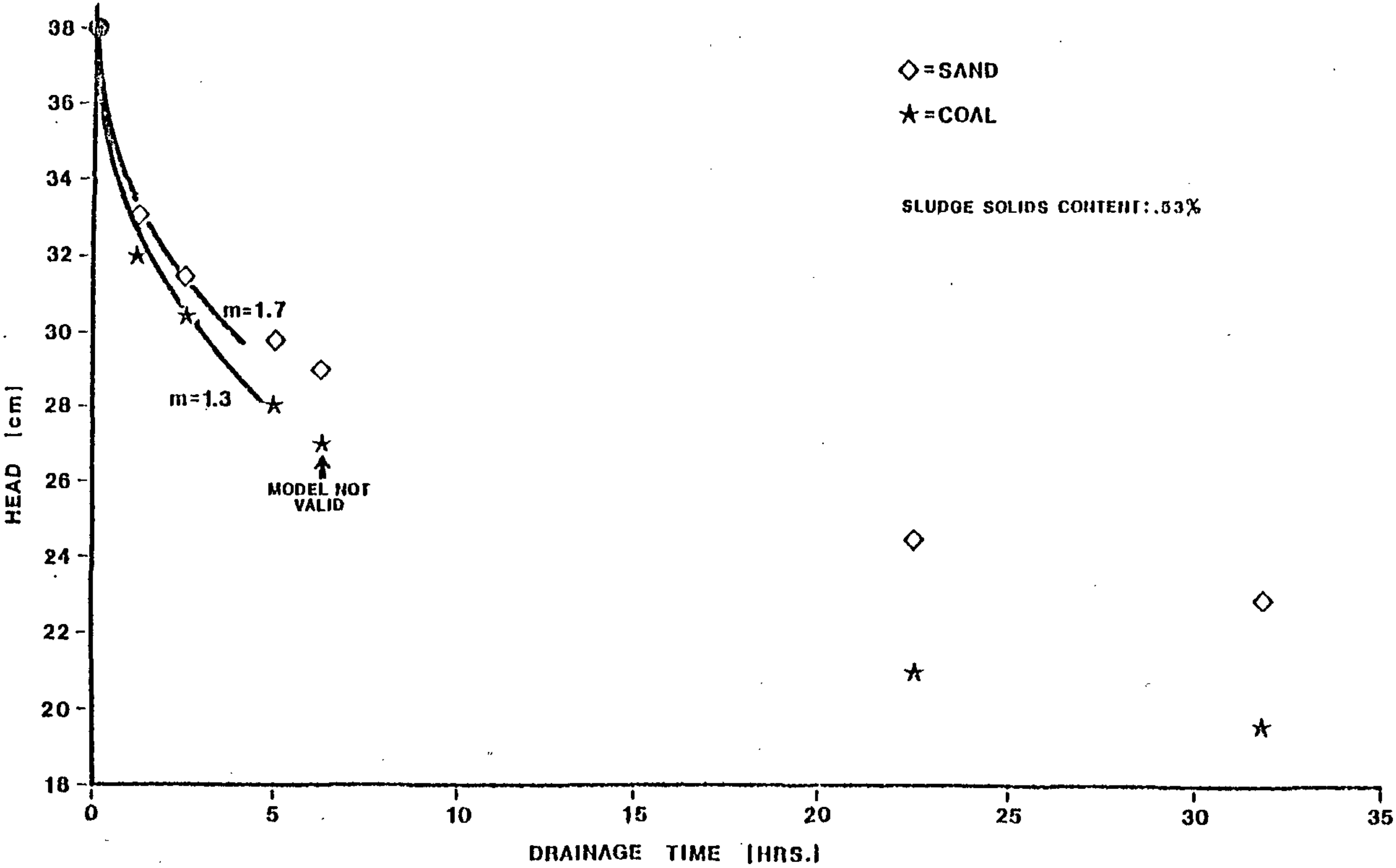

Figure 8. Experimental and Theoretical Drainage on Sand and Coal - Experiment No. 2.

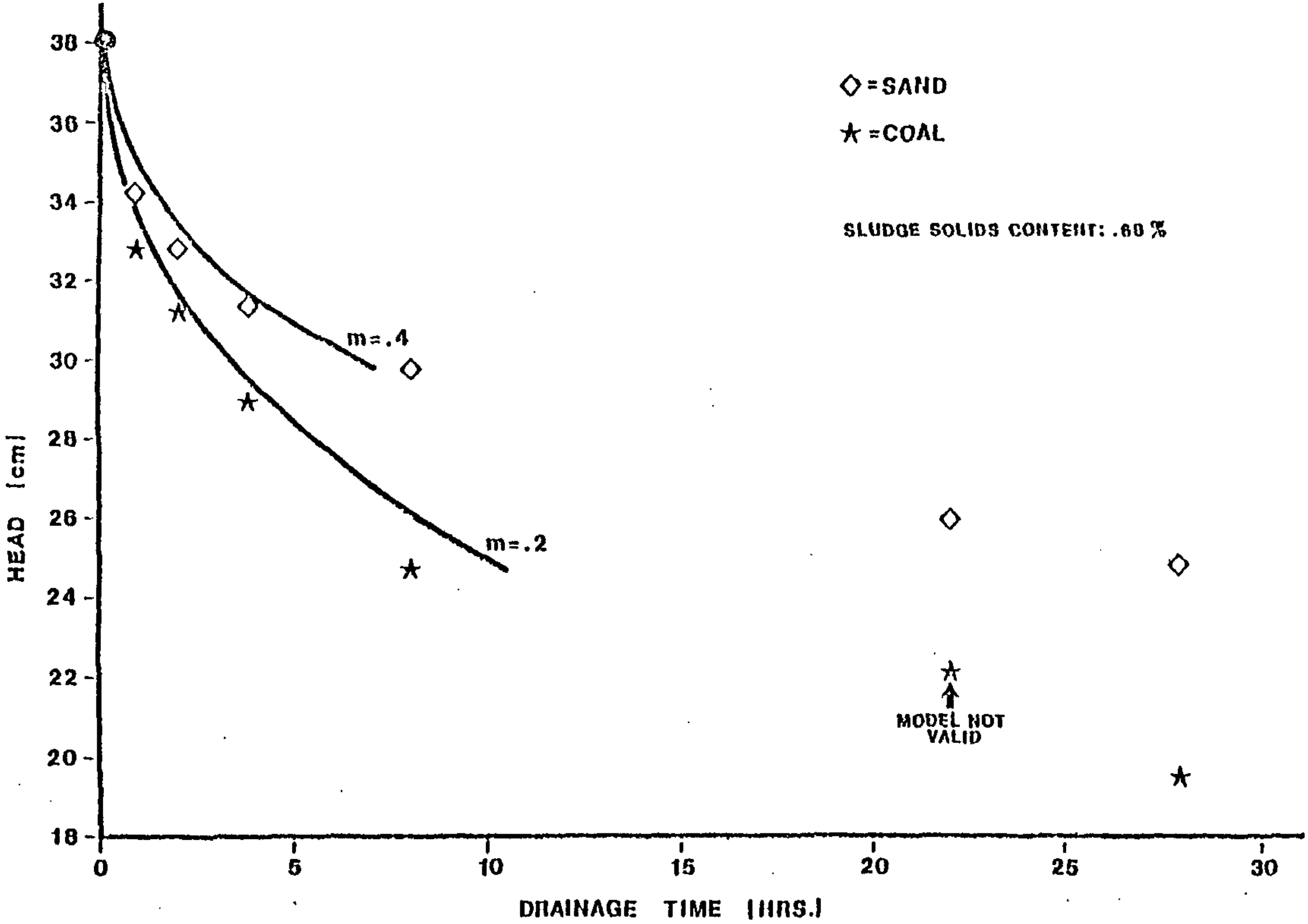

Figure 9. Experimental and Theoretical Drainage on Sand and Coal - Experiment No. 3.

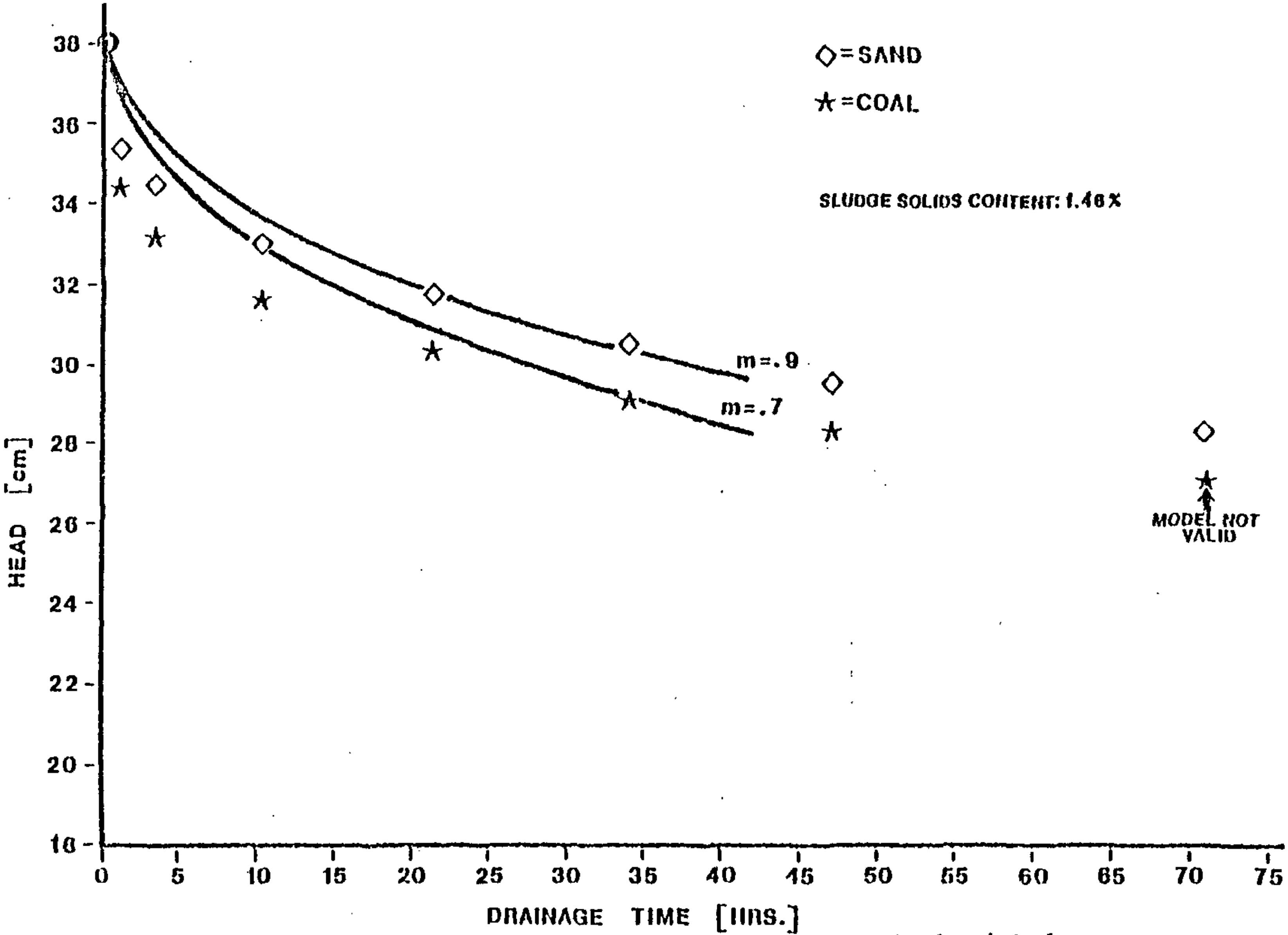

Figure 10. Experimental and Theoretical Drainage on Sand and Coal-Experiment No. 4.

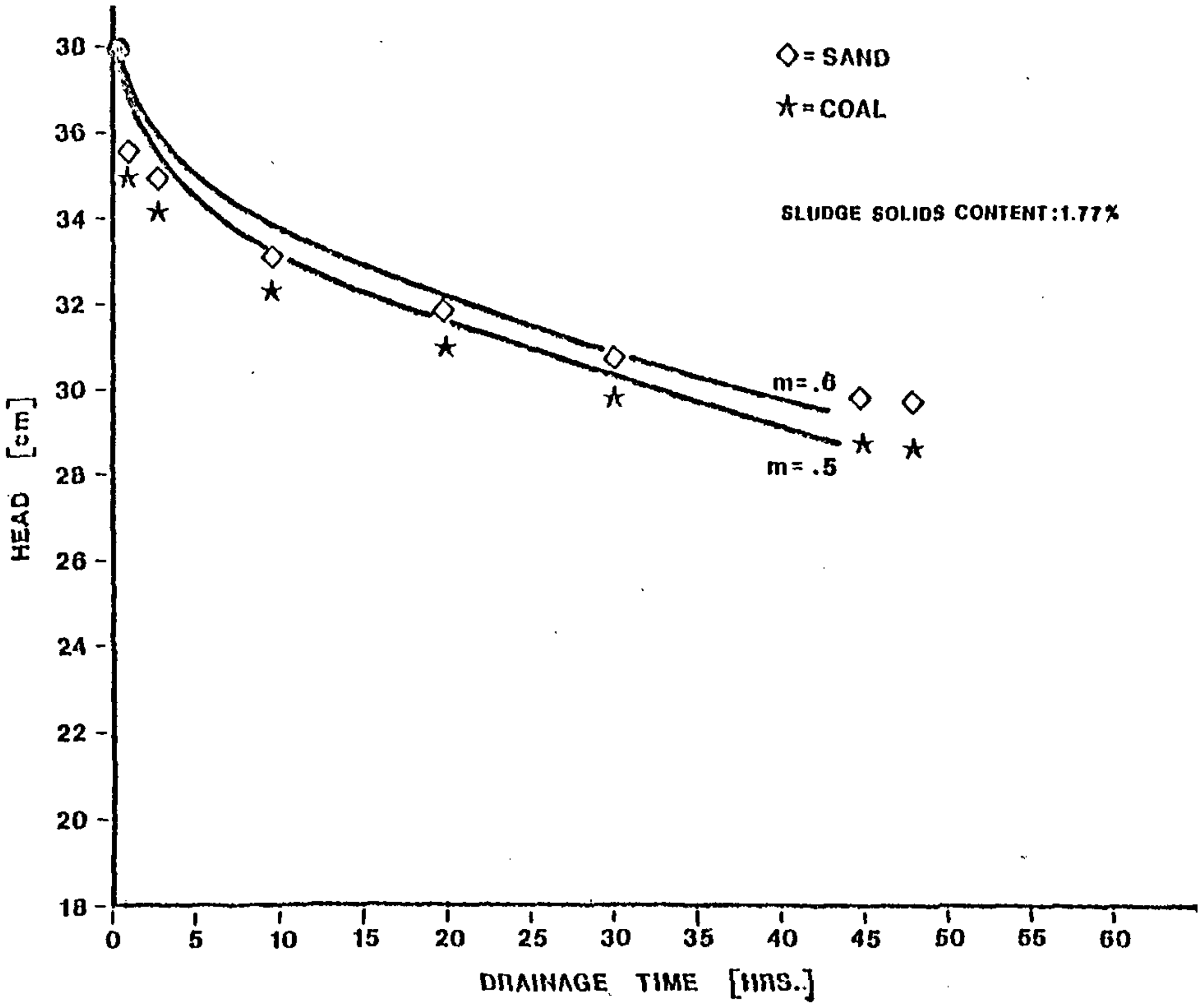

Figure 11. Experimental and Theoretical Drainage on Sand and Coal – Experiment No. 5.

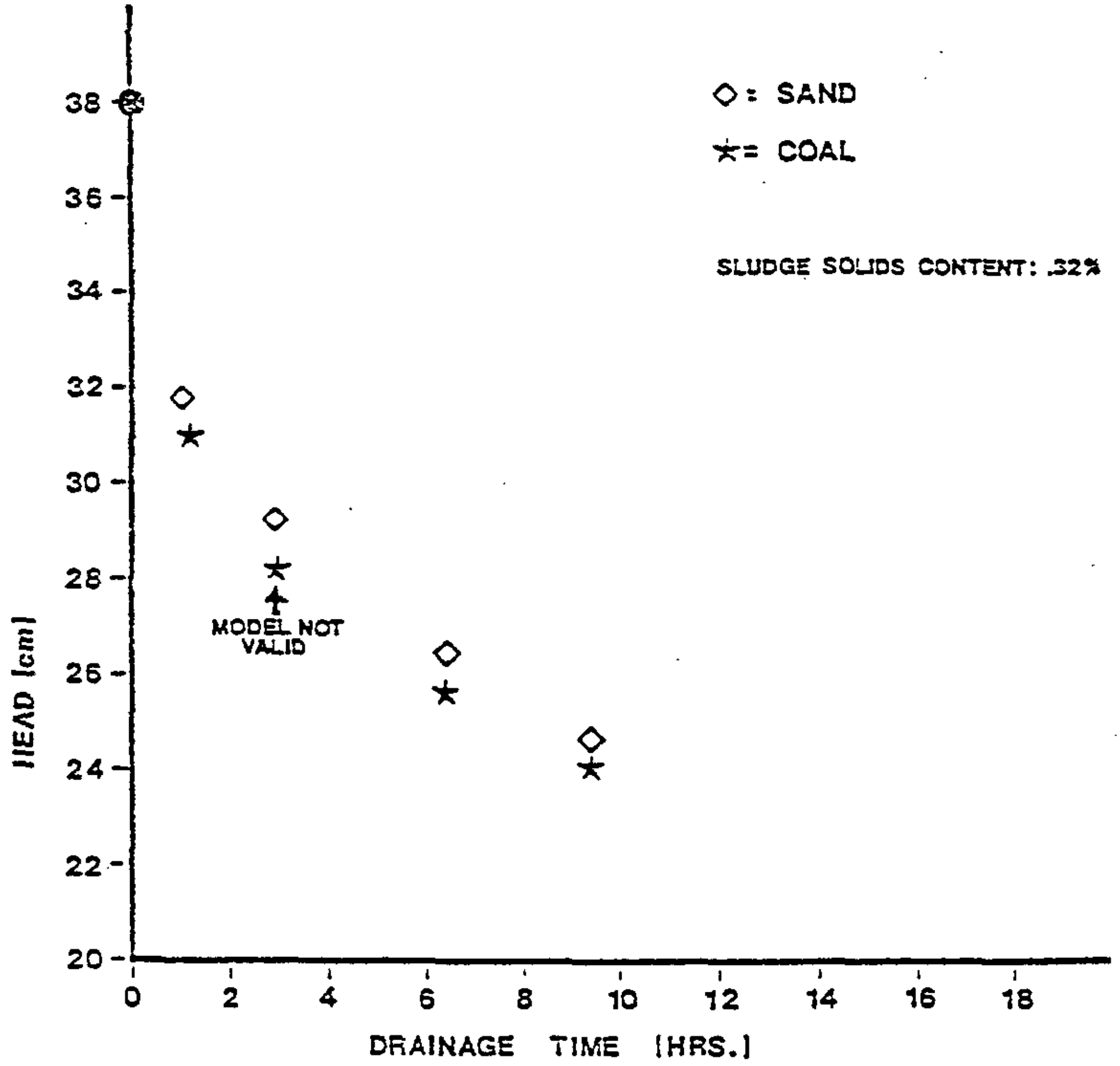

Figure 12. Experimental Drainage on Sand and Coal - Experiment No. 1.

faster filtration occurring on the coal rather than the sand medium.

In each of the experiments the head loss data were taken from columns 1 and 6. The head loss data from experiment no. 3 is shown in Figure 13 and are typical of those obtained in other experiments in this part of the study. From Figure 13 it can be seen that the sludge cake formation occurred during these filtration experiments, validating the use of Nebiker's model in the analysis. However, the head loss did not occur at the distance of 10 cm from the bottom of the filter media. This distance corresponds to the top edge of the filter media prior to charging the columns with sludge. During column charging, mixing of sludge with the filter media occurred or sludge particle penetration into the media took place during the dewatering. From the head loss data, it is evident that the top 5 cm of the filter media was part of the sludge filter cake.

Column drainage data, collected prior to column charging with coal, sand and sludge, are presented in Table 8. Drainage times did vary between columns but showed no correspondence with the subsequent sludge drainage rates of the six columns.

The filtrate from each experiment was analyzed for total filterable solids and pH. These data are presented in Table 9. The pH was not significantly affected by the filtration procedures and there was no difference in pH between the filtrate obtained from the coal and the

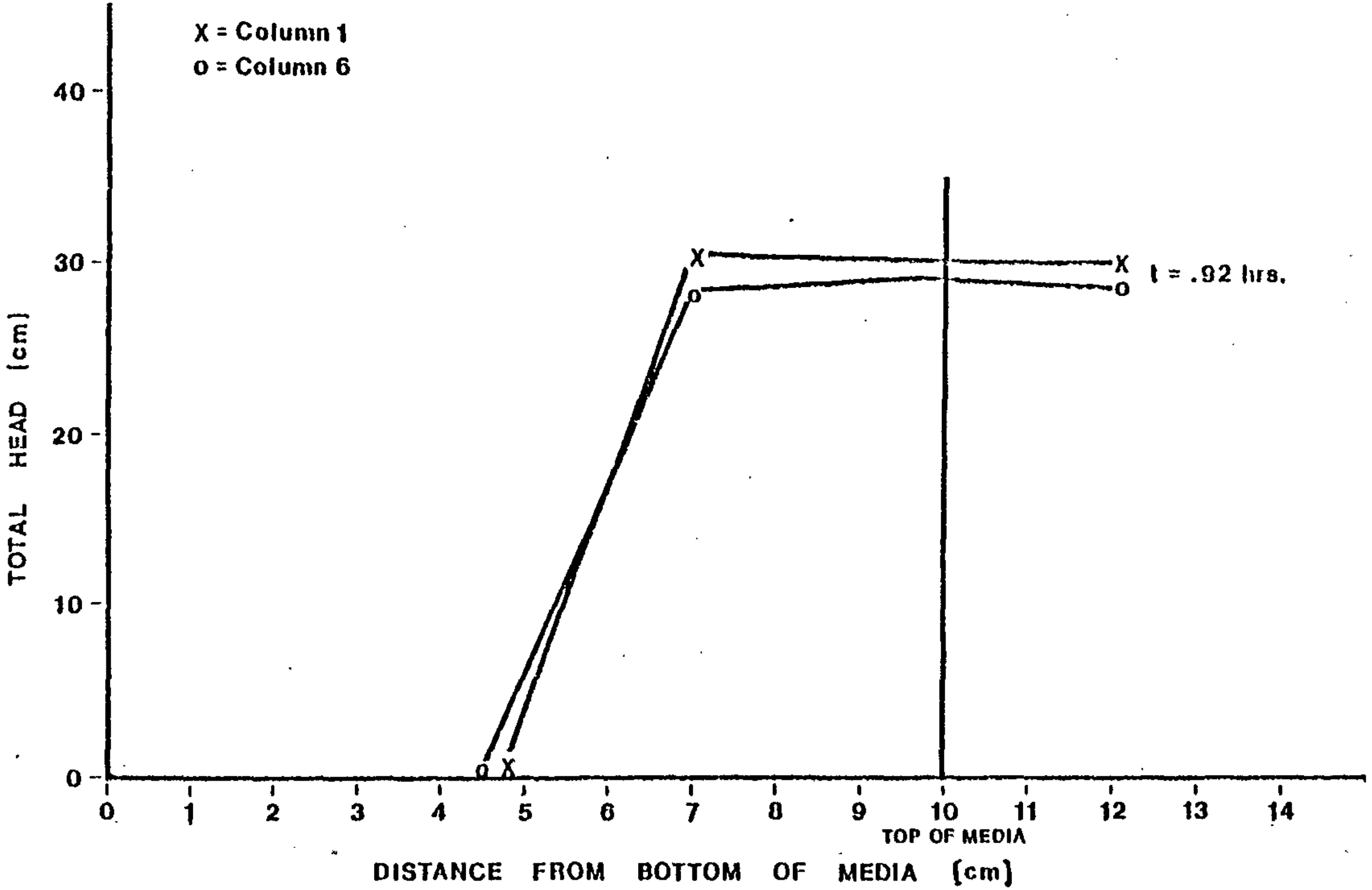

Figure 13. Head Loss Distributions in Drainage Columns - Experiment No. 3.

Table 8. Water Drainage Time in Minutes Prior to Column Charging with Sludge

Experiment Number	Column Number 1	2	3	4	5	6	Maximum Percent Difference
1	2.75	2.58	3.42	3.08	2.75	2.67	24.6
2	2.5	2.5	3.42	3.0	2.67	2.67	26.9
3	3.17	2.67	2.75	2.83	2.42	2.58	23.7
4	2.58	2.58	3.25	2.5	2.75	2.67	23.1
5	2.83	2.67	2.25	-	2.42	2.67	20.5
6	3.08	3.0	2.75	3.25	-	-	15.4
7	3.25	3.0	2.75	2.83	2.67	2.58	20.6
11	3.66 (30 cm)	3.75 (30 cm)	3.98 (30 cm)	-	-	-	8.0
12	4.22 (30 cm)	4.3 (30 cm)	-	-	-	-	1.9
	-	-	-	-	2.93 (15 cm)	2.58 (15 cm)	11.9

Table 9. Filtrate Properties

Experiment Number		Column Number					
		1	2	3	4	5	6
1	pH	7.1	7.0	7.1	7.0	7.0	6.9
	Total Filterable Solids (g/ℓ)	.245	.235	.147	.114	.121	.108
2	pH	6.8	6.8	6.8	6.8	6.8	6.8
	Total Filterable Solids (g/ℓ)	.159	.231	.172	.285	.262	.247
3	pH	6.5	6.5	6.6	6.7	6.7	6.6
	Total Filterable Solids (g/ℓ)	.126	.053	.114	.276	.243	.29
4	pH	6.5	6.5	6.5	6.5	6.5	6.5
	Total Filterable Solids (g/ℓ)	.157	.249	.167	.358	.226	.218
5	pH	6.7	6.65	6.6	-	6.65	6.6
	Total Filterable Solids (g/ℓ)	.221	.537	.323	-	.185	.205
6	pH	6.7	7.0	7.0	7.0	-	-
	Total Filterable Solids (g/ℓ)	-	-	-	-	-	-
7	pH	6.9	6.9	6.9	6.9	6.8	6.8
	Total Filterable Solids (g/ℓ)	.24	.26	.26	.24	.2	.22

sand columns. The filtrate clarity likewise showed no differences related to the type of medium used in filtration.

4.2 Part Two - Conditioning Experiments

Experiment no. 6 involved the addition of fine granular coal to a secondary sludge with a total solids content of .52 percent, and the observation of the conditioning aspects of the coal addition on the sludge. Specific resistances and coefficients of compressibility of the sludge-coal mixtures were measured. Drainage rates of the coal and the sludge mixtures on sand were also observed.

The effects of coal additions on the sludge specific resistance and the coefficient of compressibility are shown in Table 10. The coal dosages represent weight fractions of coal solids to dry sludge solids. The specific resistance is presented for all coal dosages at the same pressure of 250 cm of water (18.4 cm of mercury) for the purpose of comparison. At these low dosages, the sludge specific resistances and the coefficients of compressibility did not change appreciably.

The effect of adding the coal to the sludge is to increase the total solids content of the resulting sludge-coal mixture. Assuming that the density of the original sludge is equal to the density of water, the total solids content of each mixture can be calculated. The

Table 10. Properties of Sludges Observed in the Conditioning Experiments

Experiment Number	Coal Dosage $\frac{\text{Coal Solids}}{\text{Dry Sludge Solids}}$	Initial Total Solids Content, %	Specific Resistance sec^2/gm at 250 cm Water	Coefficient of Compressibility
6	0	.52	7.26×10^9	1.18
	.3	.67	8.02×10^9	.79
	.5	.78	8.07×10^9	.9
	.8	.94	5.58×10^9	1.07
7	0	1.2	2.17×10^{10}	.5
	3.3	4.57	8.913×10^9	.43
	6.6	7.8	4.95×10^9	.46

results of these initial solids content calculations are also presented in Table 10.

Drainage data for experiment no. 6 are represented in Figure 14. The amount of liquid initially present in each column was calculated assuming that the density of the original sludge did not change appreciably after the addition of the coal. The data indicate that the addition of coal slowed down the drainage through the sand. After 40 hours of dewatering, the fraction of the original filtrate remaining in the column filled with the sludge was .46. By contrast the fraction of original filtrate remaining in the column filled with the .8 ratio of coal solids to dry sludge solids was .67.

The drainage data of the empty columns before the addition of sand or sludge show no correspondence to the sludge drainage rates of the four columns. All four columns emptied at similar rates with 15.4 percent error between the fastest and the slowest drainage rates (see Table 8).

Experiment no. 7 involved the addition of greater amounts of coal to the sludge than those in experiment no. 6. The total solids content of the original sludge was 1.2 percent. Sludge properties as well as the drainage rates of the sludge-coal mixtures were observed. Two coal dosages were investigated and this permitted duplicate drainage of columns with the original sludge and the two mixtures.

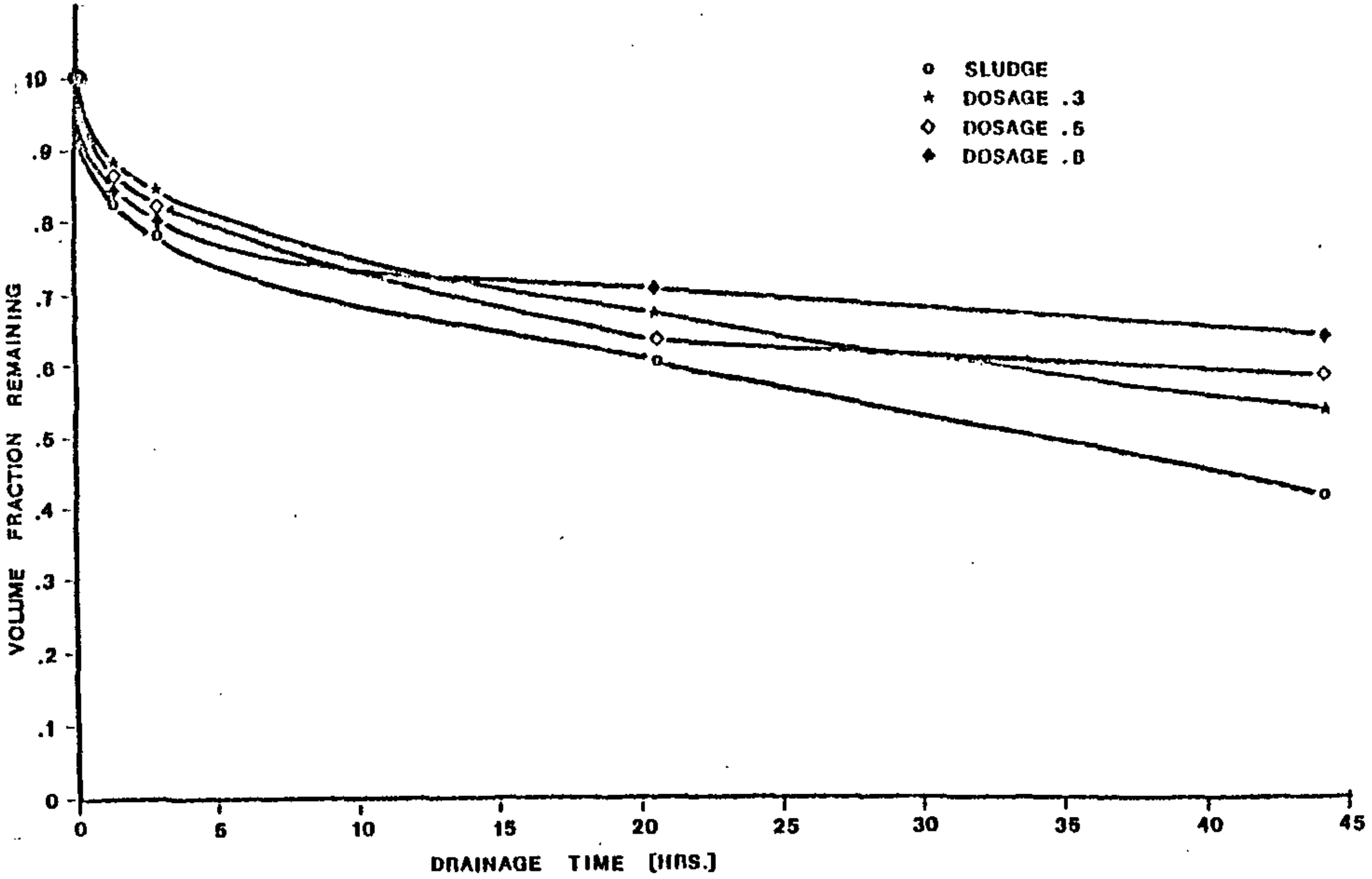

Figure 14. Drainage of Sludge-Coal Mixtures - Experiment No. 6.

The effects of coal additions on the sludge specific resistance and the coefficient of compressibility are presented in Table 10 and Figure 15. Table 10 also presents the initial solids content of the sludge coal mixtures. As in experiment no. 6, the coal dosages represent weight fractions of coal solids to dry sludge solids and the specific resistances are evaluated at the pressure of 250 cm of water.

At these higher coal dosages, appreciable reduction in the sludge specific resistance took place. The dosage effect on the coefficient of compressibility was not great.

The sludge drainage data for experiment no. 7 are presented in Figure 16. The initial liquid present in each column was calculated with the assumption that the sludge density did not change appreciably after the addition of the coal. The data indicate that some drainage improvement occurred as a result of the addition of coal to the sludge. However, the improvement is very slight. At 40 hours of drainage a fraction of .57 of the original liquid remained in the columns filled with the sludge; in comparison, a fraction of .50 of the original liquid remained in the columns filled with the mixture having a 6.6 coal solids to dry sludge solids ratio.

The fractions of the original filtrate remaining after 40 hours of drainage from both experiments are used to compare the effects of adding coal to the sludge prior to the drainage on sand beds and after the

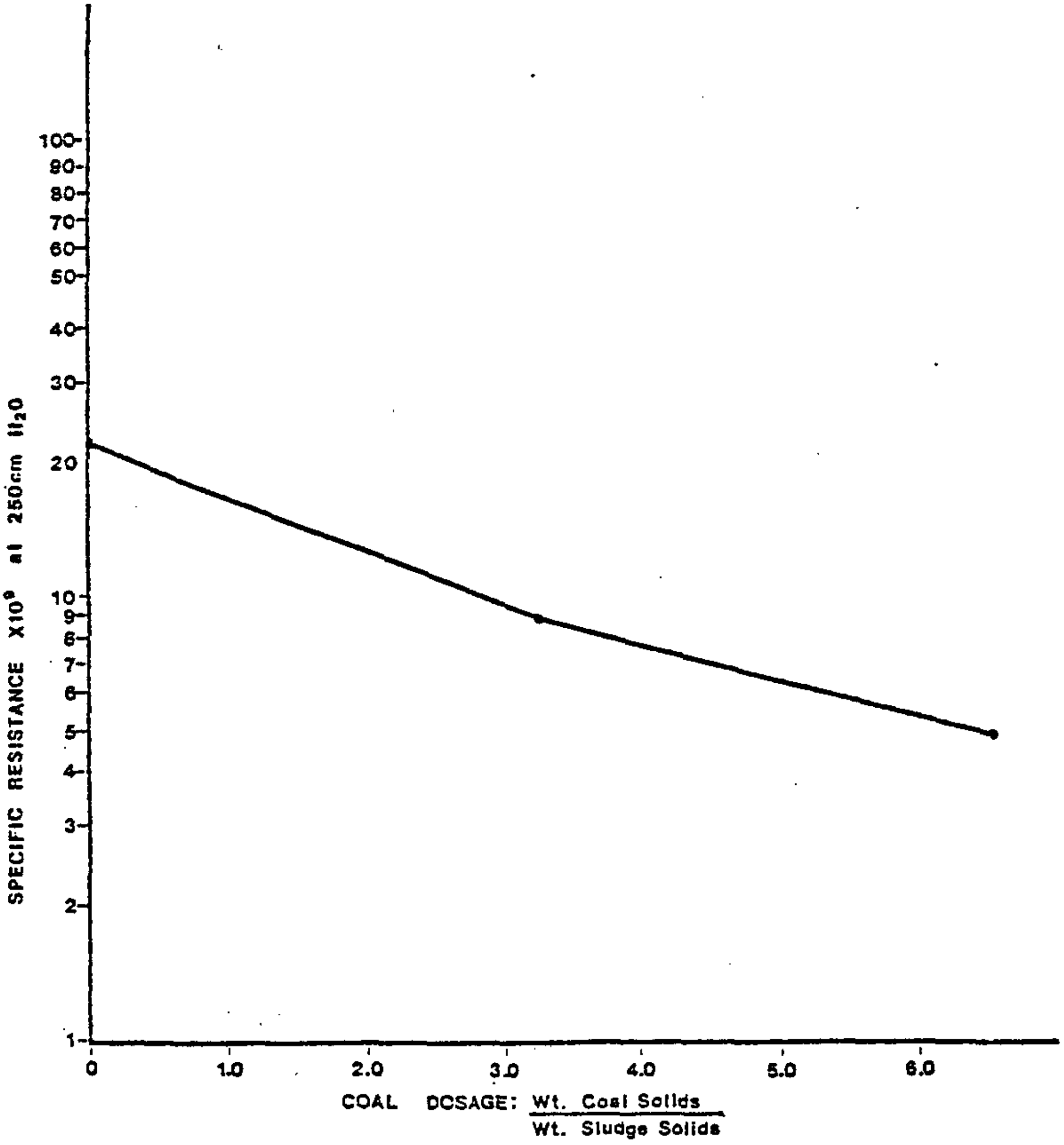

Figure 15. Effect of Coal Dosage on Sludge Specific Resistance-Experiment No. 7.

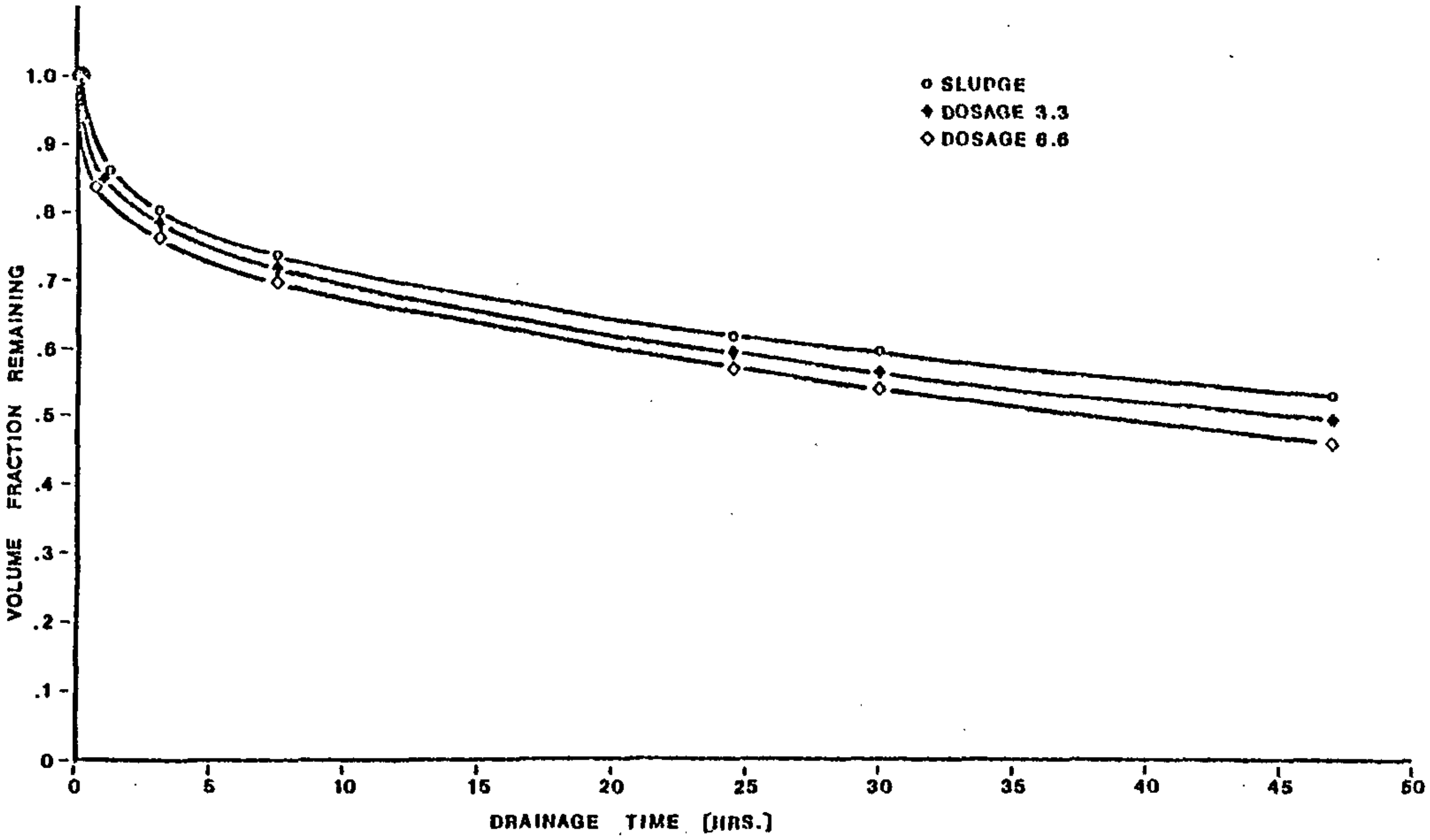

Figure 16. Drainage of Sludge-Coal Mixtures - Experiment No. 7.

drainage on the resulting total solids content of the sludge-coal mixtures. Table 11 shows that with the exception of the 6.6 coal dosage, the addition of coal to the sludge after drainage will result in higher total solids content of the mixture.

The drainage data of the empty columns, as in experiment no. 6, show no correspondence to the sludge dewatering rates of the six columns. The maximum difference between the fastest and the slowest drainage of the columns was 20.6 percent (see Table 8).

The total filterable solids and pH were analyzed with respect to the filtrate collected from the columns in the course of sludge drainage in both experiments no. 6 and no. 7. The data is presented in Table 9. Filtrate clarity and pH were not affected by the addition of coal to the sludge.

4.3 Part Three - Deep Bed Filtration Experiments

4.3.1 Experiment number 8

Experiment no. 8 involved the determination of the head loss due to fluid flow through the media used in experiments no. 9 through no. 12.

Table 11. Total Cake Solids Contents Resulting From Drainge of Sludge-Coal Mixtures and From Coal Addition to the Sludge Cake After Drainage

Experiment Number					
6	Coal Dosage	0	.3	.5	.8
	Total Solids Content % at 40 Hours of Drainage	1.12	1.15	1.27	1.4
	Total Solids Contents % Coal Addition After Drainage	1.12	1.45	1.67	2.0
7	Coal Dosage	0	3.3	6.6	
	Total Solids Contents % at 40 Hours of Drainage	2.24	8.9	15.2	
	Total Solids Content % Coal Addition After Drainage	2.24	8.97	14.8	

The drainage times observed in column 1, filled with a smaller particle medium, were slightly longer than those observed in column 6, filled with a larger particle medium, for both trials. The manometers, however, did not measure any head loss through the two filter media at any time during the drainage.

4.3.2 Experiment number 9

Experiment no. 9 involved the determination of the coal medium size which would result in the removal of secondary sludge solids but permit sludge particle penetration into the filter medium. Three different media sizes were tested (see Table 7).

Drainage occurred very rapidly in this experiment. In all five columns, more than 90 percent of the original water and sludge solids passed through the media in 21 hours (see Table 12).

The secondary sludge at total solids content of .91 percent passed through the media in columns 1, 2, 4, and 5 with minimal solids deposition taking place. No head loss was recorded as the result of observation of the manometers in column 1 at any time during the drainage. Head loss data were obtained for column 6 early in the filtration process at t=3 minutes, before the sludge surface entered the coal medium. The head loss data indicate that minimal sludge solids removal occurred with the use of the large size particle coal medium of

Table 12. Filtrate Volume Fractions Remaining in the Columns

Experiment Number	Column Number					
	1	2	3	4	5	6
9	.06	.06	-	.05	.06	.06
10	.36	.37	.35	-	.31	.31

column 1, however, sludge solids removal did occur in column 6.

From Figure 17, which represents the pressure head existing at various depths in the medium of column 6, it can be seen that sludge solids were deposited throughout the medium depth. The head loss was slightly localized at the top of the filter medium, 63 percent of it occurring in the top 28 percent of the medium depth.

4.3.3 Experiment number 10

Experiment no. 10 was performed to test the granular coal media sizes (see Table 7) with a primary and secondary sludge mixture at a total solids content of 1.95 percent. Drainage occurred at a much slower rate in this experiment than in experiment no. 9. The mixture of secondary and primary sludge was observed to form a cake at the sludge-coal interface in all the columns. In all the columns only 60 to 70 percent of the original filtrate was collected in 22.5 hours (see Table 12).

From Figure 18, which represents the head loss data of columns 1 and 6 at t=15 minutes, it can be seen that all of the measureable head loss occurred at the top 28 percent of the medium, where cake formation occurred.

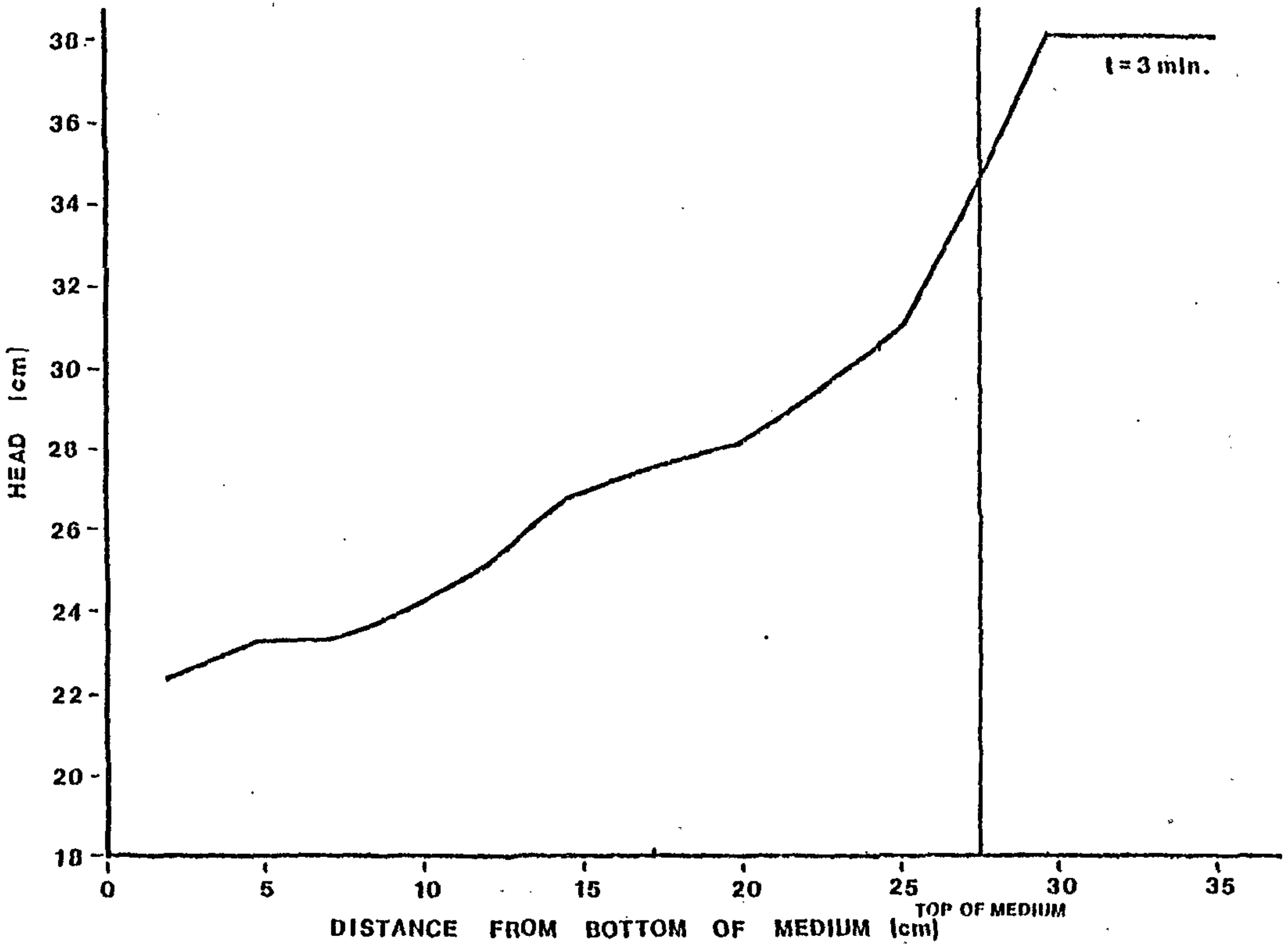

Figure 17. Head Loss Distribution in Drainage Column 6 - Experiment No. 9.

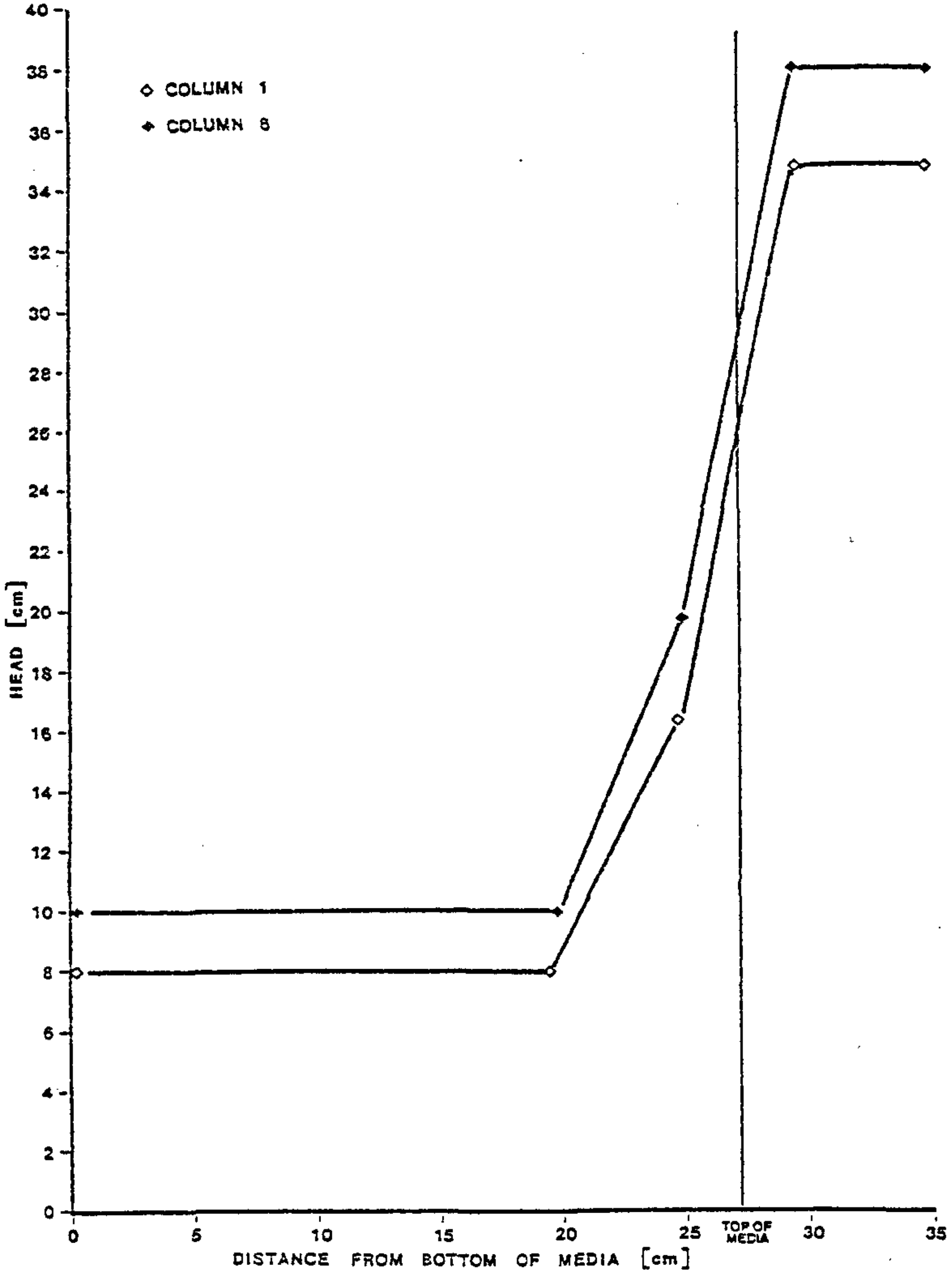

Figure 18. Head Loss Distributions in Drainage Columns - Experiment 10.

The effect of the cake formation, localization of the head loss at the top of the medium through the deposition of sludge solids, on the drainage rates can be seen in Figure 19. Figure 19 compares the drainage from columns 1 and 6 in experiments no. 10 and no. 9 respectively. In column 1, the mixture of primary and secondary sludge, with a solids content of 1.95 percent, formed a cake at the top of the coal of grain size 1.18<D<4.75 mm allowing only the filtrate to pass. Drainage was slow. In column 6, the secondary sludge, with a solids content of .91 percent, penetrated the same coal medium, resulting in a more even distribution of head loss and a more rapid drainage rate.

4.3.4 Experiments Numbers 11 and 12

Experiments no. 11 and no. 12 were designed to test the sensitivity of the coal with the particle size of 1.18<D<4.75 mm in the filtration of secondary sludges of different solids content at various application depths. Drainage rates, solids removal efficiency, and sludge particle bed penetration were observed. Drainage rates which occurred in all of the columns in both experiments are presented in Figures 20 through 22. Each figure indicates that, for a sludge with a given solids content, as the application depth increases drainage rate decreases. This effect is more pronounced for the sludges with higher solids contents.

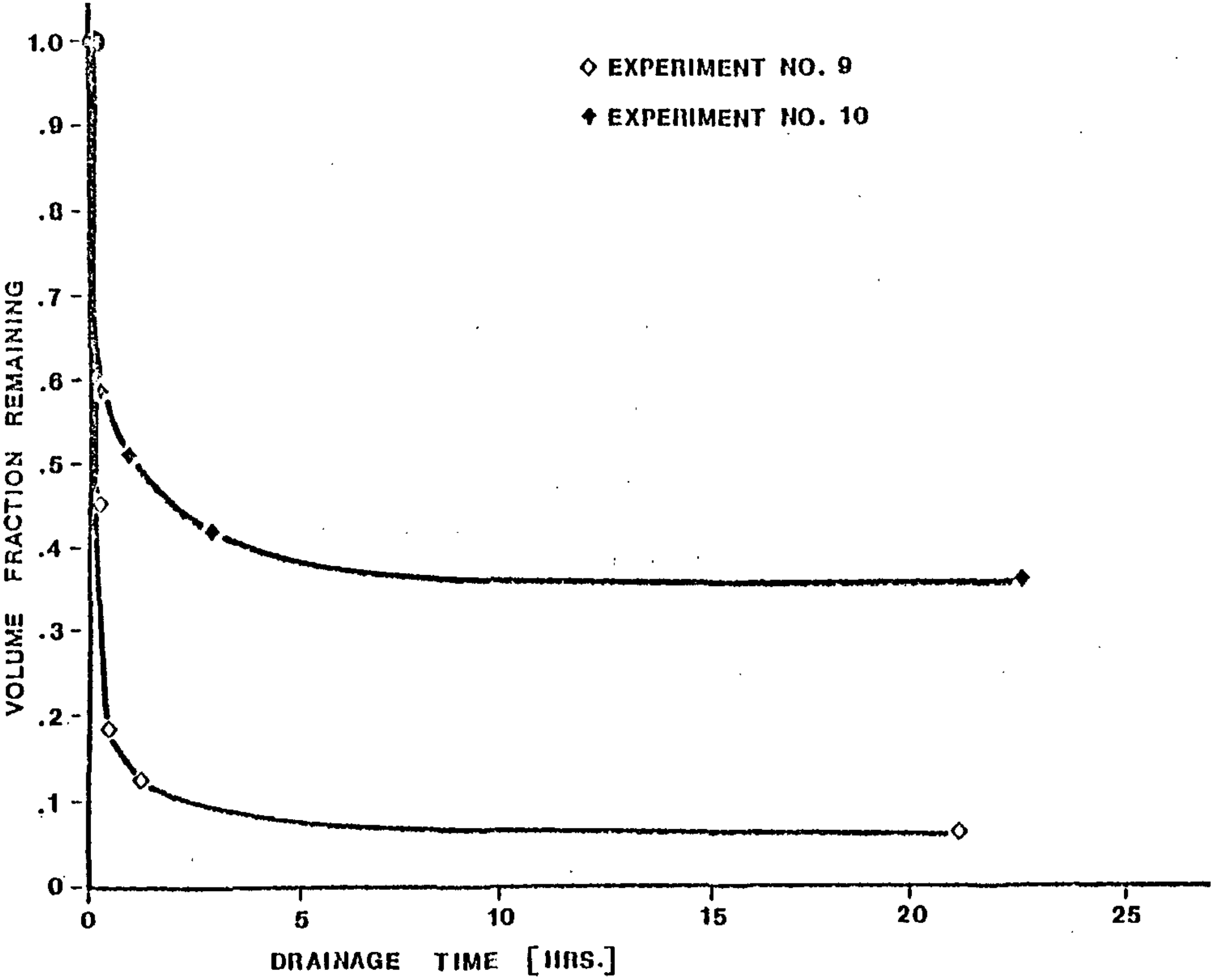

Figure 19. Effect of Sludge Cake Formation on Drainage on Coarse Coal.

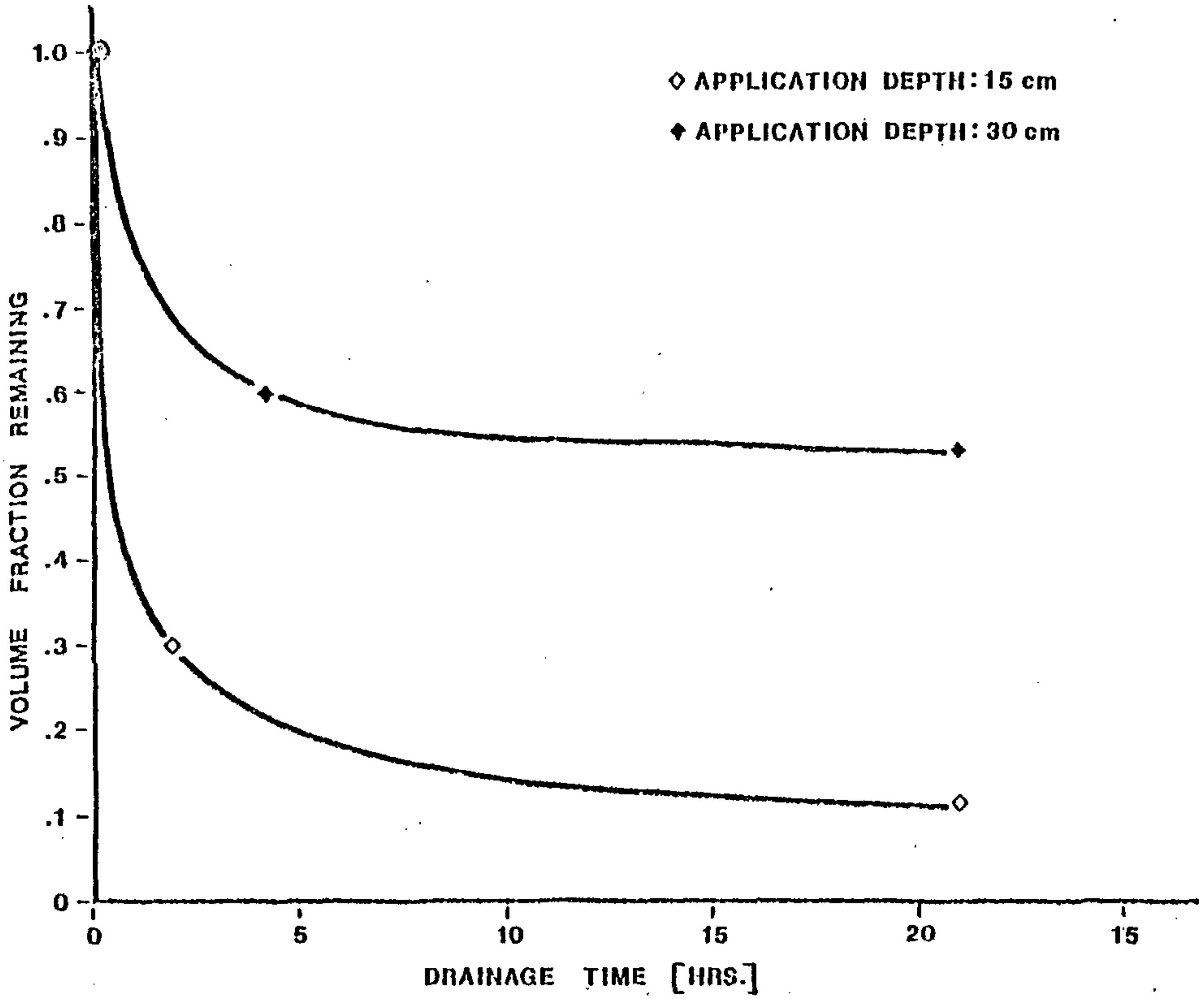

Figure 20. Drainage on Coarse Coal - Sludge Solids Content 1.45%.

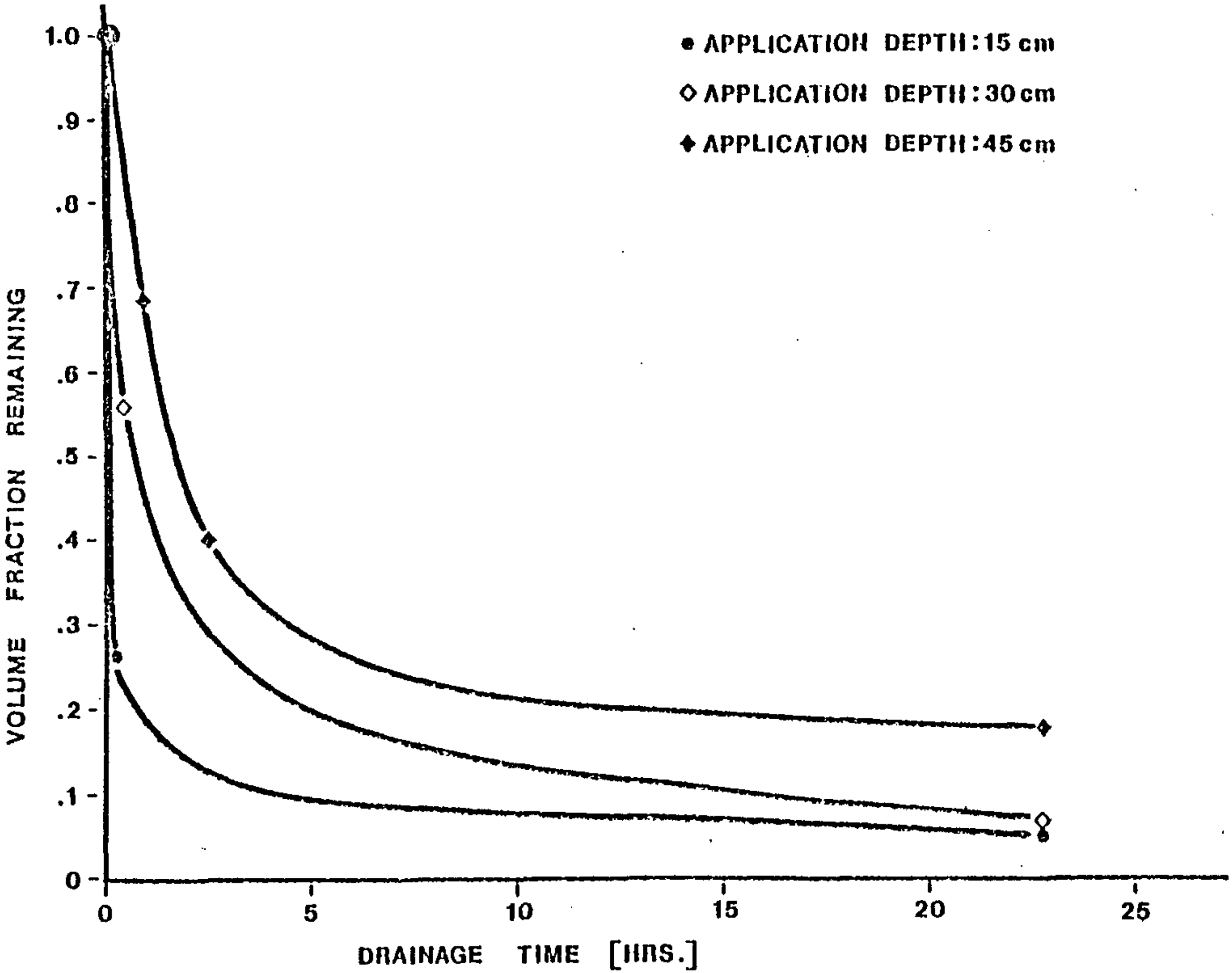

Figure 21. Drainage on Coarse Coal - Sludge Solids Content.88%.

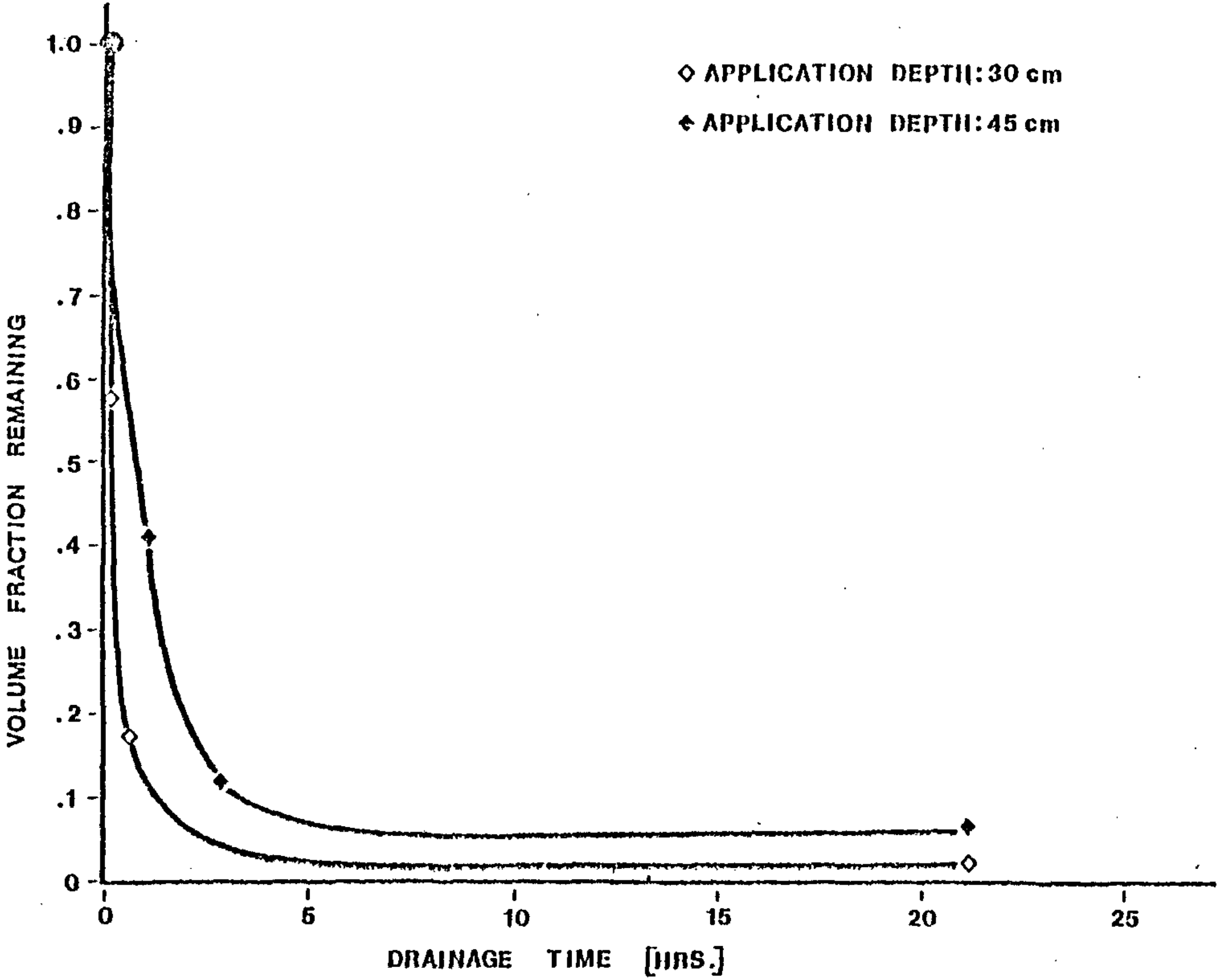

Figure 22. Drainage on Coarse Coal - Sludge Solids Content 43%.

Volume fractions of filtrate remaining and percent solids removed in the columns at 20 hours of drainage are listed in Table 13. The data show that as the solids content of the sludge is increased at a particular application depth the drainage rate decreases. From Table 13 it can also be seen that, for each application depth, as the sludge solids content increases so does the percent solids removal.

The head loss data collected in experiments 11 and 12 are presented in Figures 23 through 25. Figure 23 is applicable to a 15 cm application depth of sludge with a solids content of 1.45 percent. At the time when 64 percent of the filtrate was collected from the sludge, t=1.75 hours, all of the head loss occurred in the top 20 percent of the coal medium depth and above the sludge-coal interface.

Figure 24, which represents a 30 cm application of sludge with the solids content of .88 percent, shows that all of the head loss occurs in the top 35 percent of the coal medium depth. This head loss reading corresponds to a time when 71 percent of the liquid was collected from the sludge, t=2.95 hours.

Figure 25, which represents a 45 cm application of sludge with a solids content of .43 percent, shows that all of the head loss occurs in the top 71 percent of the medium. The head loss reading corresponds to the time when 86 percent of the filtrate was removed from the sludge, t=2.82 hours.

Table 13. The Effects of Application Depth and Initial Sludge Solids Contents on Drainage Rates and Filtrate Quality in Deep Bed Filtration Experiments Numbers 11 and 12

Application Depth (cm)		Initial Sludge Solids (%)		
		1.45	.88	.43
15	Filtrate Volume Fraction Remaining	.115	.07	-
30		.53	.08	.02
45		-	.18	.07
15	Solids Removal (%)	95	91	-
30		99	96	88
45		-	90	90

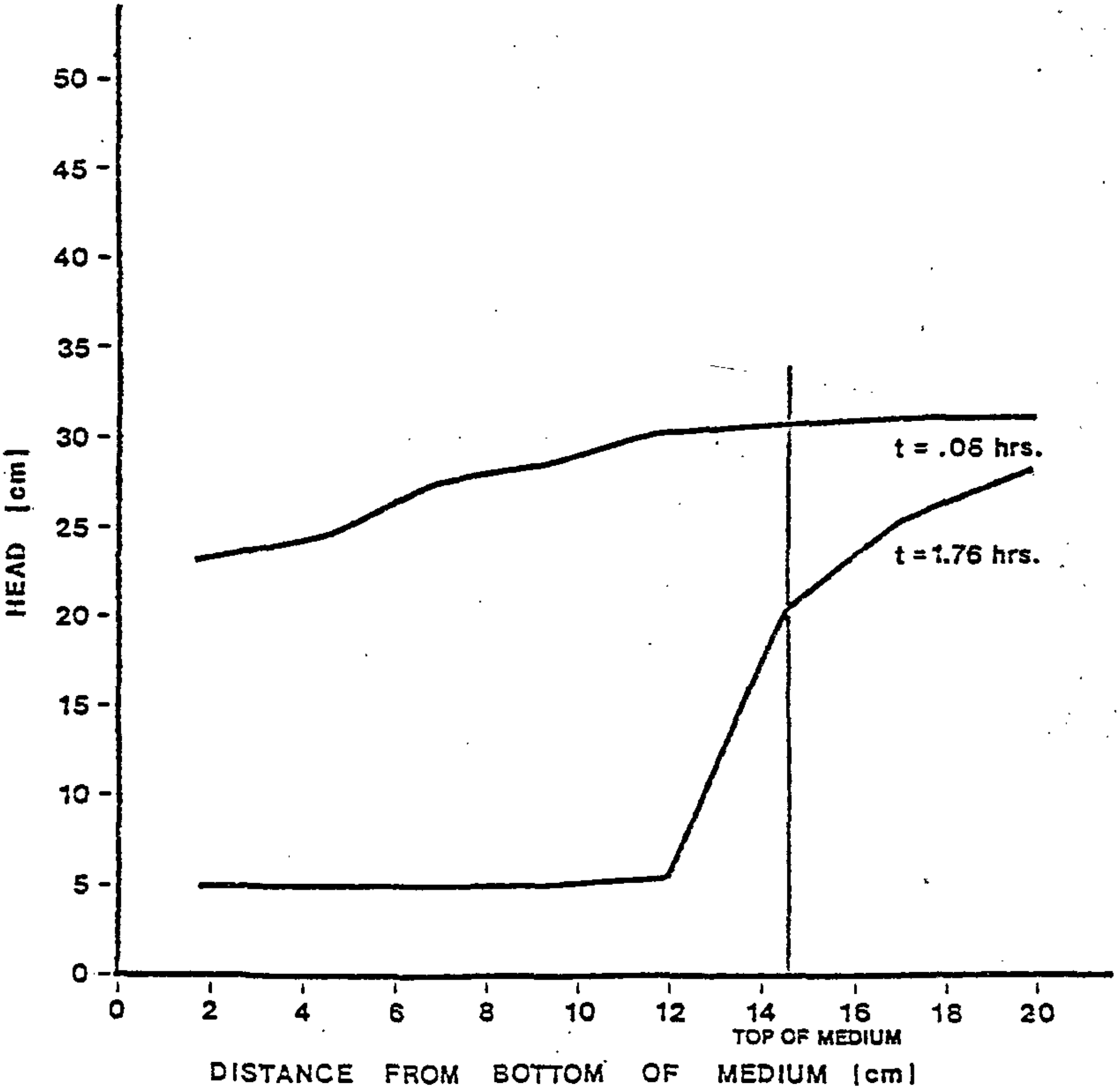

Figure 23. Head Loss Distributions in Drainage Column
Sludge Solids Content 1.45%.

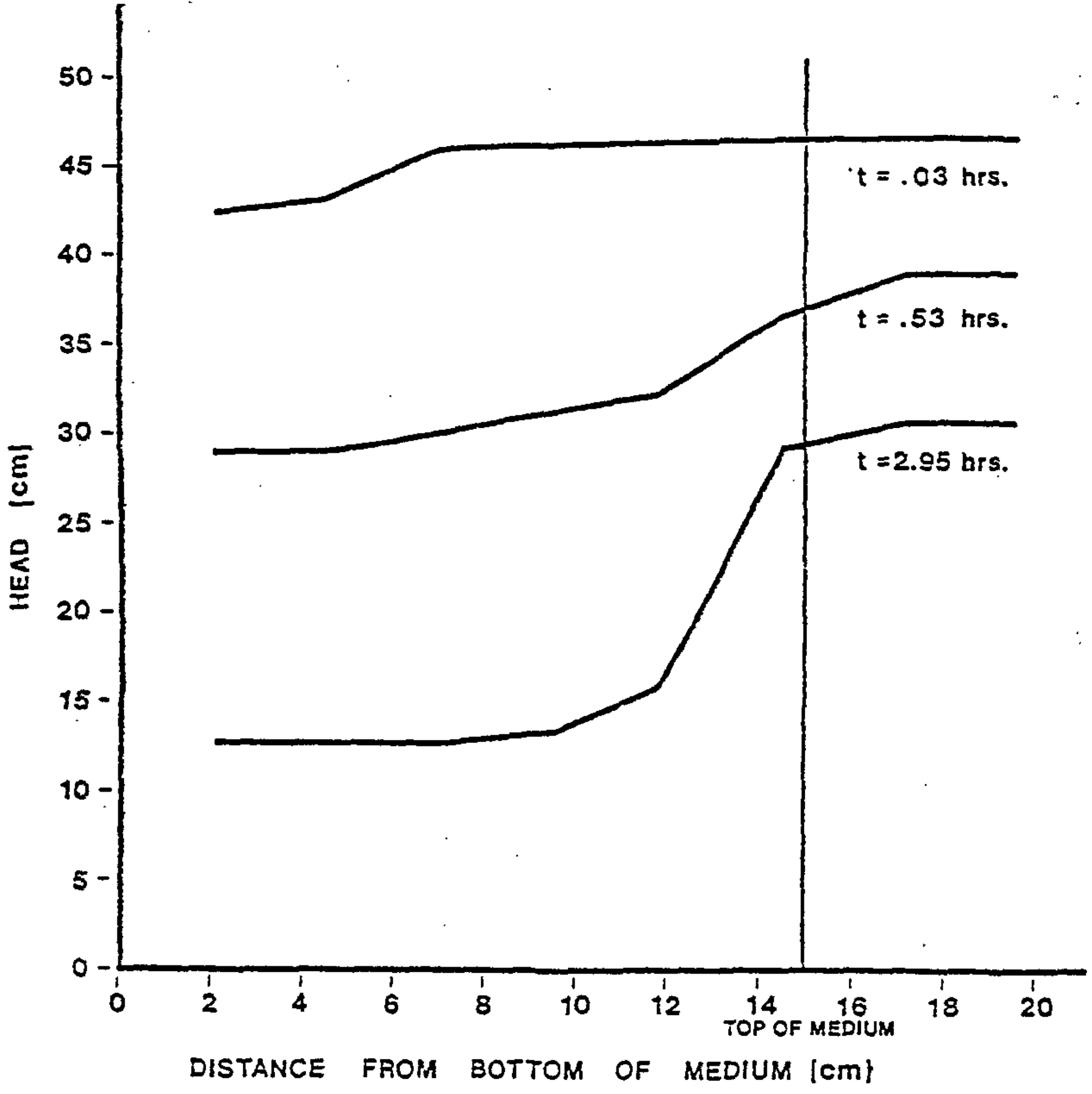

Figure 24. Head Loss Distributions in Drainage Column
Sludge Solids Content .88%

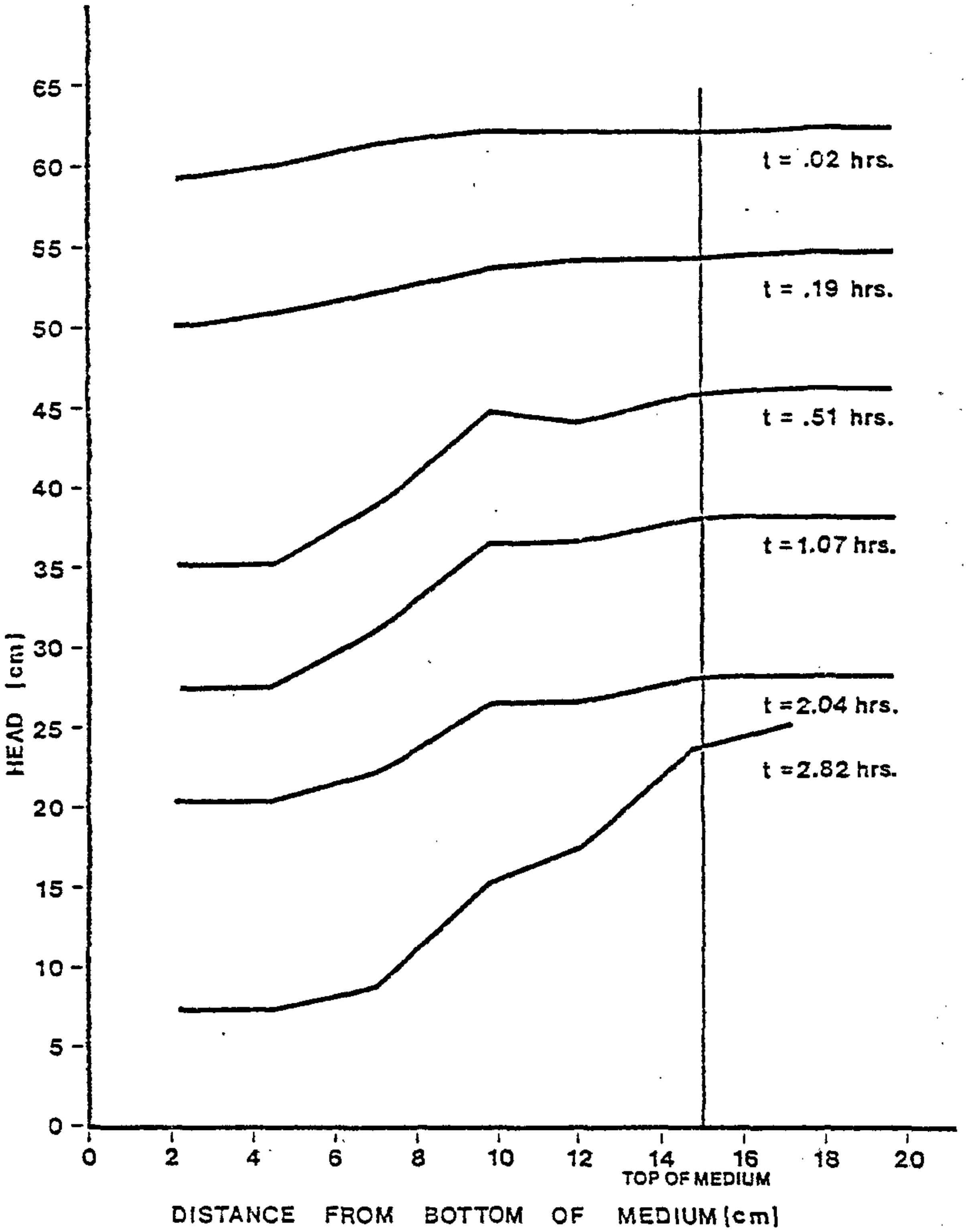

Figure 25. Head Loss Distributions in Drainage Column Soludge Solids Content .43%.

From Figures 23 through 25, it can be concluded that as the sludge solids content increases the head loss and sludge solids deposition occurs in the upper sections of the filter medium. Also, each of the figures representing the head loss data shows that as the filtration proceeds the head loss becomes localized at the top sections of the filter media. This may be happening because, as solids are deposited in the medium in the course of filtration, progressively smaller pores are available for the subsequent sludge flow, and the top section of the medium acts as a more effective filter.

The data on the drainage of tap water through the media prior to charging the columns with sludge are shown in Table 8. The rapid drainage of the water was not significantly affected by the column packing and did not seem to influence the filtrate drainage observed as the result of sludge application. These data also indicate that column plugging due to the coal media particles did not occur.

CHAPTER V

ECONOMIC ANALYSIS

5.1 Part One - Cost Comparison of Sludge Dewatering on Sand and on Coal Beds

5.1.1 Introduction

The purpose of this analysis is to compare the costs associated with sludge dewatering on sand and on coal beds. Wastewater drainage and drying models developed by Nebiker (21,22) are used in conjunction with a cost analysis model developed by Meier and Ray (19). The cost model determines the optimum application depth, which results in the lowest cost for a sludge with particular properties and a dewatering bed with given operational parameters.

The objective function to be minimized is:

Eq.(5) $Z = C1\ X1 + C2\ X1\ X2$

where:

Z = total annual cost in \$

C1 = cost per unit land area in \$/m2

C2 = cost per unit land area per application in \$/m2-application

X1 = area of land required in m2

X2 = number of applications required

The analysis is performed on the basis of a one year period.

If the total annual volume of sludge to be dewatered is VT in m3, then:

Eq.(7) $$h = \frac{VT}{X1\ X2}$$

where:

h = sludge application depth in m

The objective function can be rewritten:

Eq.(8) $$Z = C1\frac{VT}{h\ X2} + C2\frac{VT}{h}$$

The number of applications per year will depend on the drainage and drying times of the particular sludge under the given design conditions. With the assumption that a two day resting period elapses between successive applications, the number of applications per year can be expressed by:

$$\text{Eq.(6)} \qquad X2 = \frac{365\ 24}{Tdw+Tdr+48}$$

where:

Tdw = drainage time in hrs

Tdr = drying time in hrs

It should be noted that a maximum number of applications will yield lowest dewatering cost.

Nebiker's sludge drainage and drying models can be used to estimate drainage and drying times.

Drainage is represented by:

$$\text{Eq.(1)} \qquad Tdw = \frac{m}{3600}\left(\left(\frac{\mu\ So\ Rc}{100\sigma(\sigma+1)Hc^{\sigma}}\right)\left(Ho^{(\sigma+1)} + \sigma H^{(\sigma+1)} - (\sigma+1)HoH^{\sigma}\right)\right)$$

The initial total pressure head acting on the sludge can be expressed as:

Eq.(9) $H_o = h/100+s$

where:

H_o = initial total pressure head acting on the sludge in cm

s = depth of the coal or sand filter media in cm

The final pressure head acting on the sludge, assuming that the density of the sludge before and after drainage is the same as the density of the filtrate, can be expressed as:

Eq.(10) $$H = \frac{h\ S_o}{100\ S_f} + s$$

where:

S_o = total sludge solids content at the beginning of drainage in %

S_f = total sludge solids content at the end of drainage in %

The drainage time depends on sludge properties: Rc, σ, and So. It also depends on the design parameters: h, s, and Sf. The media factor, m, can also be considered a design parameter, although it is not easily determined and controlled.

The drying time can be evaluated for evaporation occurring under constant-rate conditions as well as for constant-rate followed by falling-rate conditions.

If the sludge were removed before the critical moisture content is reached only constant-rate evaporation occurs and drying time is represented by:

Eq.(4) $$Tdr = \frac{Ws}{100\ X1\ Ic}(Uo-U)$$

and for $X1 = \frac{VT}{h}$, Eq. (4) can be rewritten:

Eq.(11) $$Tdr=\frac{Ws\ h}{100\ Ic\ VT}(Uo-U)$$

If the sludge must remain on the dewatering bed after the critical moisture content is reached then the falling-rate evaporation must also be considered and Eq.(3) rewritten for $X1 = \frac{VT}{h}$, gives:

$$\text{Eq.(12)} \qquad Tdr = \frac{Ws\ h}{100\ VT\ Ic}\left(Uo-Ucr+Ucr\left(\ln\frac{Ucr}{U}\right)\right)$$

The drying time is dependent on the design parameters such as U and h; and variables such as Uo, Ucr, Ws, VT, and Ic.

Because many simplifying assumptions are made, the model in this analysis is used not as a design tool but as a method to compare the costs associated with the use of coal and sand dewatering beds. The reduction in cost through the use of coal instead of sand may be approximated by considering the four parameters which can change due to the use of coal: the media factor, the sludge specific resistance, the sludge initial solids content, and the sludge cake final solids content.

The experimental part of this study has shown that a media factor reduction is possible with the use of coal. It also suggested that the conditioning of sludge with coal can bring about a reduction in the specific resistance as well as an increase in the initial sludge solids content. Changes in both of these factors may lead to significant changes in the costs of sludge dewatering beds.

The additional design parameter which can be changed when a coal support medium is used is the final solids content. Dried sludge is removed from the conventional sludge dewatering beds generally when cake cracking occurs at a solids content of about 35 to 40 percent (13). This final solids content depends on the method of removal as well as upon the disposal method for the dried sludge.

If the dried sludge can be incinerated at a solids content of 20 percent rather than transported to a landfill at 40 percent solids content, a cost reduction in the construction and operation of the dewatering beds could be achieved. The reduction in the necessary final solids content results in a considerable increase in final moisture content, U. A shorter drying time and lower costs can be expected.

Three analyses quantitatively evaluate the cost reductions possible by considering the changes in the media factor, the specific resistance, and the initial sludge solids content, and the final solids content. A computer program was written to evaluate the costs associated with an optimal application depth for each analysis. The documented version of the program used in Analysis One is included in Appendix D.

5.1.2 Cost information

The costs used in the analysis are obtained from the EPA Design Manual (13). The costs corresponding to the second quarter of 1982 were used in the analyses.

The annual cost of the dewatering beds associated with the construction and purchase of the land comprises the cost per unit area (C1) in the model.

The following are assumed:

life span - 30 yrs

interest rate - 10%

land salvage value ≐ 50% of original price

The total costs are:

total construction cost - $ 40.36 /m2 ($ 163,350 /acre)

total land cost - $ 4.94 /m2 ($ 20,000 /acre)

After the application of the discounting formulas, the annual cost for the dewatering beds is:

C1 = $ 4.79 /m2 ($ 19,389 /acre)

The annual cost of the dewatering beds associated with the application and removal of sludge comprises the cost per unit area per application (C2) in the model.

The costs are listed below.

Diesel Fuel - based on:

3 hrs/371.6 m2 (3 hrs/4000 ft2)

15.14 l/hr (4 gal/hr)

$ .30 /l ($ 1.15 /gal)

$ .037 /m2-application ($ 150.28 /acre-application)

Labor - based on:

3 hrs/371.6 m2 (3 hrs/4000 ft2)

$ 12.00 /hr

$ .097 /m2-application ($ 392.04 /acre-application)

Maintenance Material - replacement of .635 cm (.25 inch) of sand lost during cleaning:

$ .015 /m2-application ($ 60.00 /acre-application)

The maintenance material cost comprises 11% of the diesel and labor costs and it is ignored in the analysis. This is done for the purpose of conservative comparison since the additional costs associated with coal but not sand are not included in the analysis.

Combining diesel and labor costs yields:

C2 = $ .134 /m2-application ($ 542.32 /acre-application)

5.1.3 Analysis one - media factor reduction.

This analysis compares the costs of the dewatering beds associated with the reduction of the drainage model media factor. The analysis is performed for a plant treating a flow of 3.79x104 m3/day (10 mgd) with the following constant process parameters:

sludge initial solids content in % - 2.0
sludge solids content at the end of drainage in % - 15.0
dynamic viscosity of sludge filtrate in gm/cm-sec - .01
depth of the filter medium in cm - 45
annual sludge volume in m3 - 2.76x104
annual weight of applied solids in kg - 5.53x105
drying intensity in kg/m2-hr - .02
moisture content at the end of drainage in % - 567.0
final moisture content in % - 150.0

The final moisture content of 150 percent corresponds to a final sludge total solids content of 40 percent.

Sludge with the following properties was evaluated:

specific resistance at 150 cm of water in sec2/gm = 1x109

coefficient of compressibility = 1.0

The results are presented in Table 14. The maximum cost reduction obtained with a media factor of .1 results in 10 percent annual savings.

5.1.4 Analysis two - specific resistance reduction

This analysis evaluates the costs of dewatering beds associated with the conditioning of sludge through the addition of coal prior to its application on the beds. The analysis assumes that a reduction of an order of magnitude in the specific resistance occurs as a consequence of the addition of coal solids equal to the total solids in the sludge, or coal solids to sludge dry solids weight ratio of 1. The coal is assumed to have no effect on the coefficient of compressibility of the sludge.

The analysis is performed with the same process parameters as those in Analysis One. The annual weight of applied solids and the initial sludge solids content are adjusted as a result of the hypothetical coal addition.

initial sludge solids content in % = 3.92

annual weight of applied solids in kg = 1.106x106

Table 14. Effect of Media Factor Reduction on Total Annual Cost of Sludge Dewatering Beds

Media Factor	Optimum Application Depth, m	Bed Area m^2	Number of Applications	Total Annual Cost, $	% Cost Reduction
1	.37	.1537 x 10^5	4.9	.836 x 10^5	-
.7	.41	.1505 x 10^5	4.5	.8112 x 10^5	2.97
.4	.46	.1468 x 10^5	4.1	.7839 x 10^5	9.3
.1	.53	.1426 x 10^5	3.7	.753 x 10^5	9.93

The results are presented in Table 15. The result of conditioning sludge with an original specific resistance of 1x109 sec2/gm at 150 cm of water to obtain a specific resistance of 1x108 sec2/gm at 150 cm of water is a 79 percent increase in annual costs. The increase is 26 percent when the original sludge with a specific resistance of 1x1010 sec2/gm is conditioned by the addition of coal to obtain a specific resistance value of 1x109.

5.1.5 Analysis three - final solids content reduction

This analysis determines the costs of sludge dewatering beds which vary as a consequence of changing the required final solids content of the sludge cake. Three final solids contents are evaluated; 40, 25, and 20 percent. These final solids contents correspond to final moisture contents of 150, 300, and 400 percent, respectively.

The analysis is performed with the process parameters defined in Analysis One. The results are presented in Table 16. For sludge with a specific resistance value of 1x1010 sec2/gm at 150 cm of water, the reduction in the final solids content from 40 to 20 percent results in a 31 percent reduction of total cost.

By examining the costs of construction and land purchase separately from the costs associated with the operation of the beds, it is noted that all of the savings are associated with the construction and land

Table 15. Effect of Conditioning Sludge with Coal on Total Annual Cost of Sludge Dewatering Beds

	Optimum Application Depth, m	Bed Area m^2	Number of Applications	Total Annual Cost, $	% Cost (Increases)
Original Specific Resistance 1×10^9, sec^2/gm	.37	$.1537 \times 10^5$	4.9	$.836 \times 10^5$	–
Specific Resistance After Coal Addition 1×10^8, sec^2/gm	.27	$.2828 \times 10^5$	3.6	$.1492 \times 10^6$	78.5
Original Specific Resistance 1×10^{10}, sec^2/gm	.15	$.2074 \times 10^5$	8.9	$.124 \times 10^6$	–
Specific Resistance After Coal Addition 1×10^9, sec^2/gm	.23	$.2919 \times 10^5$	4.1	$.1559 \times 10^6$	25.7

Table 16. Effect of Increasing the Final Moisture Content on Total Annual Cost of Dewatering Beds (in dollars)

Final Moisture Content, %	Specific Resistance, sec^2/gm		
	1×10^9	1×10^{10}	1×10^{11}
150	$.836 \times 10^5$	$.124 \times 10^6$	$.256 \times 10^6$
300	$.596 \times 10^5$	$.1013 \times 10^6$	$.234 \times 10^6$
400	$.445 \times 10^5$	$.862 \times 10^5$	$.219 \times 10^6$

purchase of the dewatering beds. The 31% cost reduction will be considered in Part Two of the Economic Analysis.

5.2 Part Two - Comparison of Costs for Sludge Treatment Options

5.2.1 Introduction

In recent design manuals, dewatering beds are not considered compatible with subsequent treatment by incineration. The ultimate disposal techniques used most frequently with sludge cakes collected from sand dewatering beds include application on agricultural land and disposal in landfills. The design guidelines, however, are general and location specific considerations have a large influence on the design of dewatering processes (13). In this analysis, the use of coal in the design of dewatering beds with incineration as the means of final disposal is investigated.

Dewatering beds require energy only for pumping the sludge to the beds and for the mechanical equipment used to remove the dewatered sludge from the beds. The energy requirements for this process are low in comparison with processes such as centrifuges and vacuum filters (13). In addition, Hathaway (15) points out that although the costs of all fuels vary geographically in the U.S., coal is generally the most economical fuel. The independent researchers, who performed the evaluations of coal use in incineration, report that coal prices may range from .3 to .5 times the price of fuel oil on a heating value basis (2,15,24,27). According to this information the complete replacement of oil by coal in incineration can result in a 50 to 70 percent reduction of fuel costs.

Swanson has shown that, by adding granular coal to an already dewatered sludge cake, a 50 percent replacement of supplemental oil was possible with no major changes in the operating methods of multiple-hearth incinerators (27). An estimated 70 to 80 percent reduction in oil use was possible with closer control. One hundred percent substitution of oil with coal was not practical unless heat was wasted at times due to variations in the sludge cake total and the volatile solids contents.

Pitzer (24), by adding crushed coal and ash mixture to the sludge prior to dewatering on a vacuum filter, could achieve a 93 percent replacement of oil by coal in the multiple-hearth incinerators.

Dick (11) reports that incineration is at present being successfully used in plants treating small (7.57x103 m3/day, 2 mgd) as well as large (7.57x104 m3/day, 20 mgd) municipal flows. It may, therefore, be used in conjunction with dewatering beds which are usually limited by area requirements to treating low flows.

If transport costs associated with final disposal are considerable, or if thermal conversion through incineration is required, the use of coal as support media in dewatering beds could be considered.

The purpose of this analysis is to compare costs associated with construction and operation and maintenance of dewatering processes followed by final disposal. Costs associated with flows of 1.9x104 m3/day (5 mgd) and 7.57x103 m3/day (2 mgd) are examined for four sludge treatment options:

1. conventional dewatering beds followed by landfilling with 32.2 km (20 mile) one-way truck transport;
2. coal dewatering beds followed by incineration with the use of supplemental coal;
3. conventional dewatering beds followed by incineration with the use of no. 2 fuel oil; and
4. vacuum filtration followed by incineration with use of no. 2 fuel oil.

5.2.2 Analysis

The cost information is obtained from a Weston (Environmental Consultants-Designers) publication (32). The total construction, and the operation and maintenance costs in the Weston publication are based on the third quarter of 1976. With the use of the EPA cost index the data are updated to represent the costs corresponding to the third quarter of 1982.

The costs of the conventional sludge dewatering beds are based on the treatment of a mixture of primary and secondary undigested sludge produced at the rate of .228 kg/m3 (1,900 lb/mg) with the bed loading of 97.64 kg/m2-yr (20 lb/ft2-yr).

The analysis assumes that coal dewatering bed design is an accepted and tested method of treatment which achieves cost reduction described in Part One of the Economic Analysis. The total construction costs for the coal dewatering beds are therefore 70 percent of those for the conventional dewatering beds. The operation and maintenance costs for both types of beds are assumed to be the same.

The costs for vacuum filtration are based on the treatment of a mixture of primary and secondary sludge produced at the rate of .228 kg/m3 with a filter yield of 24.41 kg/m2-hr (5 lb/ft2-hr). The filter is in operation 6.8 hrs/day for a 7.57x103 m3/day plant and 8.8 hrs/day for a 1.9x104 m3/day plant.

The multiple hearth incineration costs are based on the combustion of the mixture of undigested, dewatered primary and secondary sludge produced at a rate of .228 kg/m3 with a 20 percent total solids content and a 75 percent volatile solids content. The use of no. 2 fuel oil and 7 day/week operation are considered.

The operation and maintenance costs for the multiple hearth incinerator supplemented with coal are considered to be lower than those for the oil burning incinerator. The analysis assumes that 50 percent of the necessary fuel oil can be replaced by crushed coal in the multiple hearth incinerators. The price of coal is considered to be one-half the price of no. 2 fuel oil on the heating value basis. It is assumed that the total construction cost for both types of incinerators is the same, and that no additional pollution control equipment is needed as the result of coal use as supplemental fuel.

The landfill costs are based on the treatment of dewatered biological sludge at 40 percent solids content being produced at the rate of .228 kg/m3. As a consequence of the Resource Conservation and Recovery Act (RCRA) landfill construction and the operation and maintenance costs have increased due to the following requirements:

1. a liner for leachate collection;
2. a venting system for methane; and
3. a groundwater monitoring program.

According to the cost estimate study performed by Metcalf and Eddy Engineers (20) for the Town of Amherst, Massachusetts, the recent RCRA requirements result in the following approximate increases in landfill development costs:

1. an increase in total construction cost of 31%; and
2. an increase in annual operation and maintenance costs of 10%.

The landfill cost figures used in this analysis are the landfill costs published by Weston (32) and adjusted to reflect the recent cost increases.

The truck transport costs are based on the transport of dewatered sludge at 40 percent total solids content. A one-way travel distance of 32.2 km is considered.

The costs associated with the pertinent sludge treatment processes of dewatering, incineration, landfill disposal, and transport are presented in Table 17.

5.2.3 Results

The results of the analysis of the four options at the design flows of 1.9x104 m3/day and 7.57x103 m3/day are presented in Table 18.

The use of conventional dewatering beds followed by transport of the sludge cake to a landfill, option 1, is the most cost effective option for both flows. Option 2, involving coal dewatering beds and subsequent incineration is less economical, despite the hypothetical savings possible through the use of coal in incineration and the decrease in the final solids content requirement with the use of the

Table 17. Costs of Sludge Treatment Processes (in million dollars)

SLUDGE TREATMENT PROCESS Cost Type	Design Flow 1.9×10^4 m^3/day	Design Flow 7.6×10^3 m^3/day
CONVENTIONAL SLUDGE DEWATERING BEDS		
Total Construction	.52	.26
Annual Operation and Maintenance	.082	.036
COAL SLUDGE DEWATERING BEDS		
Total Construction	.364	.182
Annual Operation and Maintenance	.082	.036
VACUUM FILTRATION		
Total Construction	.80	.51
Annual Operation and Maintenance	.113	.062
INCINERATION-MULTIPLE HEARTH NO. 2 FUEL OIL		
Total Construction	1.34	.98
Annual Operation and Maintenance	.173	.088
INCINERATION-MULTIPLE HEARTH COAL AND OIL		
Total Construction	1.34	.98
Annual Operation and Maintenance	.149	.078
LANDFILLING		
Total Construction	.238	.141
Annual Operation and Maintenance	.0417	.027
TRUCK TRANSPORT		
Total Construction	.147	.147
Annual Operation and Maintenance	.033	.025

Table 18. Costs of Sludge Treatment Options
(in million dollars)

SLUDGE TREATMENT OPTION Cost Type	Design Flow 1.9×10^4 m^3/day	Design Flow 7.6×10^3 m^3/day
OPTION 1: DEWATERING BEDS - LANDFILLING WITH TRANSPORT		
Total Construction	.905	.548
Annual Operation and Maintenance	.157	.088
OPTION 2: DEWATERING BEDS - INCINERATION WITH COAL AND OIL		
Total Construction	1.704	1.162
Annual Operation and Maintenance	.231	.114
OPTION 3: DEWATERING BEDS - INCINERATION WITH OIL		
Total Construction	1.86	1.24
Annual Operation and Maintenance	.255	.124
OPTION 4: VACCUM FILTER - INCINERATION WITH OIL		
Total Construction	2.14	1.49
Annual Operation and Maintenance	.286	.15

dewatering beds. Option 3, involving the use of conventional sand dewatering beds and subsequent incineration requiring the use of only no. 2 fuel oil, compared less favorably with option 2. The increase in the total construction cost was the result of more expensive dewatering bed construction and the increase in the annual operation and maintenance costs was due to the price difference between coal and oil as supplemental fuels. The least cost effective alternative involved vacuum filtration followed by incineration.

CHAPTER VI

DISCUSSION

6.1 Experimental Analysis

6.1.1 Part one - cake filtration experiments

The results of the cake filtration experiments on coal and sand indicate that increased drainage is obtained when the sludge is applied on top of the coal rather than on top of the sand. By examining the drainage rates with a model developed by Nebiker (22), it was determined that the increased drainage rates could not be explained by the differences in the effective size of the granular coal and sand media. The sand with the larger effective size was draining the sludge samples at slower rates than the coal with the smaller effective size. The opposite effect was reported by Nebiker, who performed similar sludge drainage experiments on sand granular media of different effective sizes.

By examining the head loss data for this experimental part of the study, it was observed that the mixing of sludge and coal and of sludge and sand occured at the sludge-medium interface in the columns. This mixing may have been caused by the pumping of sludge into the columns or could have resulted from the shallow penetration of sludge solids into the support media at the onset of drainage.

The variations in the drainage rates observed for all the sludge samples in Part One between the coal and sand media were possibly caused by sludge conditioning. The sludge conditioning process may have occured at the sludge-medium interface where mixing of the sludge and the support medium occured. It is possible that the sand increased the sludge specific resistance or that the coal decreased the resistance. Both media could also have caused a change in the coefficient of compressibility of the sludge samples.

6.1.2 Part two - conditioning experiments

Part Two of the experimental analysis was designed to test the extent of conditioning which occurs as a consequence of mixing sludge and the fine crushed coal used in Part One.

The results of the experiments indicate that considerable reduction in sludge specific resistance occurs at high coal dosages. Insignificant reduction occurs at low coal dosages. The coefficient of compressibility is insignificantly effected by the addition of the low as well as the high amounts of coal to the sludge.

The drainage of the sludge-coal mixtures was either slightly improved with high coal dosages or actually impaired with low coal dosages. The sludge drainage process on granular materials is effected by the sludge total solids content. Sludges with a high initial solids content drain slower than sludges with a low initial solids content. This can be verified by inspecting the theoretical expression for the drainage time, by considering the experimental results of Part One where sludges with similar properties but higher solids content dewatered at slower rates, or by considering the experimental results of other studies (25).

The minimal modification of drainage rates after sludge conditioning with coal observed in Part Two is due to the simultaneous increase in the sludge total solids content and the changes in sludge specific resistance.

6.1.3 Part three - deep bed filtration experiments

The data from experiments no. 9 and no. 10 indicate that a considerable increase in the drainage rates may be achieved if sludge penetration into the filter medium is possible as compared to the drainage resulting when a sludge cake formation takes place. The experiments also indicate that deep bed filtration of secondary sludge can be performed with a filter medium of a small particle size, $1.18<D<4.75$ mm.

Experiments no. 11 and no. 12 show that the performance of the particular medium with respect to drainage rates, solids removal efficiency, and sludge solids penetration of the filter bed is dependent upon the sludge solids content and the depth of sludge application.

In order to harvest the sludge together with a small amount of coal for the purpose of final incineration, the sludge solids penetration should be localized at the top of the filter bed. The minimal sludge penetration of 3 cm occured in experiment no. 12 with the application of 15 cm of sludge with initial solids content of 1.45 percent. On a unit area basis such an application and harvest would result in a sludge-coal mixture of 10.29 coal solids to dry sludge solids weight ratio. This ratio is greatly in excess of the coal required to combust the dewatered sludge.

It is apparent that two conflicting constraints exist with the use of the deep bed filtration of sludge on coal. More rapid drainage occurs as the result of the penetration of the sludge solids into the filter bed. This penetration, however, needs to be minimized in order to make the process practical and economically feasible.

As the result of the experiments in this part of the study, it can also be concluded that variations in sludge type and slight variations in the sludge total solids content determine if deep bed filtration or cake formation occurs with sludge drainage on granular coal.

6.2 Economic Analysis

6.2.1 Part one - cost comparison of sludge dewatering on sand and on coal beds

This part of the economic evaluation of the sludge dewatering bed design allowed the determination of the savings associated with the possible modification of the drainage, and the bed operation with the use of coal.

The reduction of the media factor in the drainage model which may result with the use of coal rather than sand as cake filtration medium corresponds to minimal savings in total annual dewatering bed cost. The analysis showed that the reduction in drainage time to one tenth of the original resulted only in a 10 percent decrease in the total annual dewatering bed cost.

The addition of coal to the sludge prior to dewatering on beds was simulated by considering a sludge specific resistance reduction accompanied by an increase in the sludge initial total solids content. Since the increase in solids content adversely effects drainage and drying rates, a cost increase was observed in the total annual dewatering bed budget.

Considerable savings in cost could be achieved by decreasing the required final solids content of the dewatered sludge cake. This decrease in the final solids content could be made possible by the use of coal as a filter medium since the harvested sludge-coal mixture may be incinerated at a lower total solids content than that usually associated with the sludge cake which is harvested from conventional dewatering beds and subsequently placed in a landfill. This considerable reduction in cost resulted from a decrease in the drying time of the sludge.

6.2.2 Part two - comparison of cost for sludge treatment options

This part of the economic analysis compares the costs of four methods of sludge treatment involving dewatering and ultimate disposal. From the results it is evident that the most economical sludge treatment option evaluated involves sludge dewatering beds followed by disposal in a landfill.

The savings which result from the use of coal as the filter medium for the dewatering beds and as supplemental fuel in incineration are offset by the high construction and operation and maintenance costs of the incinerators. Landfills are a considerably cheaper final disposal method in comparison with incinerators even when the requirements of the Resource Conservation and Recovery Act are met.

The use of coal in the construction of sludge dewatering beds compared favorably with the use of sand in the design of the beds when both processes are followed by incineration of the dewatered sludge cake. The use of coal dewatering beds and incineration presented considerable savings in comparison with vacuum filtration and incineration.

CHAPTER VII

CONCLUSIONS

The use of coal as the support medium resulted in a more rapid drainage of the secondary waste activated sludge when conventional cake filtration was performed on a fine granular medium. The cake filtration experiments together with the conditioning experiments of the study indicated that the improved drainage took place because sludge cake conditioning occured at the sludge-coal interface. The mixing of the sludge and the coal at high coal to sludge solids ratios caused marked reductions in the sludge specific resistance to filtration.

The mixing of sludge and coal and the subsequent drainage of the mixtures on sand did not result in marked increases in drainage rates. This result is attributable to the increase in the total solids content of the sludge-coal mixtures over the original sludge.

The use of coarse granular coal as a support medium allowed the penetration of the sludge particles into the filter bed. The deep bed filtration in the study was successful since very rapid drainage rates resulted. However, the resulting sludge-coal mixtures were of very high coal to sludge solids ratios, far in excess of those required for incineration.

The drainage rates and the penetration of the sludge solids into the filter bed may be controlled by choosing appropriate media grain size or by adjusting the sludge application depths. Such control measures would be of use since the drainage rates and the extent of sludge penetration into the coal filter bed showed marked sensitivity to variables such as the sludge total solids content and the sludge type.

The study indicated a potential for improving sludge dewatering bed operation through the use of coal. Considerable reduction in dewatering bed costs can take place as a consequence of the early harvest of the sludge cake. A lesser reduction in cost may be brought about through cake filtration of the sludge on beds of fine crushed coal. Savings can not be brought about as a result of conditioning by mixing sludge and coal prior to filtration.

When the sludge dewatering on beds is followed by incineration, however, the improved dewatering bed performance and the resulting savings are offset by the high costs of incinerator construction, operation, and maintenance. Due to the high costs of incineration, this method of sludge disposal is usually undertaken where land for landfills is unavailable. Since dewatering beds are constructed in areas were land is available, the use of landfills is most often the method of final sludge cake disposal.

The sludge treatment option which combines the use of dewatering beds and incineration may be considered either where sludge incineration is required or where for unusual reasons sludge landfilling is impossible or prohibitively expensive. Under such circumstances, the use of coal in conjunction with the dewatering beds and incineration should be considered, rather than the use of conventional sand dewatering beds and incineration.

CHAPTER VIII

RECOMMENDATIONS

Because this study involves bench scale experiments and the use of sludge with site specific properties the results should be used to plan succeeding investigations and pilot scale experiments of coal use in treatment plant processes. The results are useful to a limited extent for making generalizations to full scale applications.

As a consequence of the economic analyses performed in this study, it is necessary to assess the practicality of coal use in sludge bed design before proceeding with additional pilot scale or bench scale experimentation. This could be achieved by performing surveys of existing industrial and municipal treatment facilities. Since sludge bed dewatering followed by incineration is an unconventional sludge treatment scheme, the surveys should focus on the final disposal options available to wastewater treatment facilities with existing dewatering beds and especially on the dewatering options available to plants with existing incinerators. Costs associated with on-site handling of coal should also be carefully evaluated.

The pilot scale experiments should focus on both drainage and drying of the wastewater sludges. The reduction in drying time results in marked reduction of dewatering costs. The decrease in the relatively more rapid drainage rates does not result in a high decrease in costs. Since drying is the longer process, the effects of different types of filtration with the use of coal should be evaluated with respect to reducing its duration. Investigations of drainage on coal beds should focus more on the total drainable water rather than on drainage rates. If more water were released from the sludge as drainage, less remains to be removed by evaporation.

Because of the use of drainage models and the observation of head loss during the filtration experiments of this study, the coal used as filter medium was thoroughly saturated with water prior to sludge application. Pilot scale experiments should evaluate the use of initially dry coal as the filter medium since this type of material would be used in full scale applications.

Finally the use of coal in treatment plant operations other than those associated with dewatering should also be investigated. The addition of coal earlier in the treatment process may result in performance improvements in more than one process. A series of processes may benefit from a single coal addition.

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APPENDIX A

Specific Resistance and Coefficient of Compressibility Theory

The concept of specific resistance is developed by starting with the Darcy-Weisbach equation for the head loss, hf (L), of a fluid in laminar flow in a non-circular conduit:

$$\text{Eq.(A1.0)} \qquad hf = \frac{2 \mu L v^{2}}{v Rh^{2} \rho g}$$

μ = dynamic viscosity ($M L^{-1} T^{-1}$)

v = mean velocity ($L T^{-1}$)

L = length of conduit (L)

Rh = hydraulic radius (L)

ρ = fluid density ($M L^{-3}$)

g = acceleration due to gravity ($L T^{-2}$)

For flow through incompressible, porous material it is assumed that all particles are identical and the hydraulic radius can be redefined as:

Eq.(A1.1) $$Rh = \frac{\varepsilon\, Vp}{(1-\varepsilon)\, Sp}$$

ε = porosity (M0 L0 T0)

Sp = surface of each particle (L2)

Vp = volume of each particle (L3)

The superficial velocity is defined in terms of the mean velocity as:

Eq.(A1.2) $$vs = v\,\varepsilon$$

vs = superficial velocity (L T-1)

Combining Eq.(A1.1) and Eq.(A1.2) with Eq.(A1.0) results in the following expression for head loss:

Eq.(A1.3) $$hf = \frac{2\,(1-\varepsilon)^2\, vs\, \mu\, L\, Sp^2}{\varepsilon^3\, g\, Vp^3\, \rho} = \frac{\Delta P}{\rho\, g}$$

ΔP = pressure drop across sludge cake ($M L^{-1} T^{-2}$)

Media resistance, R (L^{-2}), can be defined as:

Eq.(A1.4)
$$R = \frac{2\,(1-\varepsilon)^2\,Sp^2}{\varepsilon^3\,Vp^2}$$

and Eq.(A1.3) can be rewritten:

Eq.(A1.5)
$$\frac{hf\,\rho\,g}{L} = \frac{\Delta P}{L} = \mu\,vs\,R$$

Since

Eq.(A1.6)
$$vs = \frac{1}{A}\,\frac{dV}{dt}$$

A = cross sectional area (L^2)

dV/dt = volumetric flow rate ($L^3 T^{-1}$)

Eq.(A1.5) and Eq.(A1.6) can be combined to result in an expression for fluid flow through incompressible filter medium:

Eq.(A1.7) $$\frac{dV}{dt} = \frac{A \Delta P}{\mu L R}$$

If the filter consists of two strata of different lengths and resistances the equation for flow through the filter media can be written as:

Eq.(A1.8) $$\frac{dV}{dt} = \frac{A \Delta P}{(L_1 R_1 + L_2 R_2)}$$

To describe the flow in a cake filtration process with the use of the resistance parameter, the length of the accumulating filter cake must be defined as:

Eq.(A1.9) $$L = \frac{vc\ V}{A}$$

vc = volume of cake per unit volume of filtrate (MO LO TO)

V = volume of filtrate (L3)

The accumulation of sludge particles may be more easily expressed and determined if vc is replaced by fc, weight of cake solids deposited per unit volume of filtrate $(M\ L^{-2}\ T^{-2})$, and Eq.(A1.8) can be rewritten as:

Eq.(A1.10)
$$\frac{dV}{dt} = \frac{A\,\Delta P}{\mu(fc\ V\ R/A + l\ r)}$$

The resistance of the cake, R, is referred to as the specific resistance and has units of $(M^{-1}\ T^{2})$. The parameters l and r refer to the support medium length and resistance. Rearranging Eq.(A1.10) and integrating from t=0 and V=0 yields:

Eq.(A1.11)
$$t = \frac{\mu\ fc\ R}{2\ A^{2}\ \Delta P}V^{2} + \frac{\mu\ r\ l}{A\ \Delta P}V$$

The experimental data plotted as t/V versus V will yield a straight line on arithmetic paper. The slope of the line allows the calculation of the specific resistance R since:

Eq.(A1.12)
$$R = \frac{2\ A^{2}\ \Delta P\ b}{\mu\ fc}$$

b = slope of the t/V versus V plot

The specific resistance of a compressible material depends on the pressure. This pressure dependency offers no problem if the test pressure is constant. However, to enable the calculation of specific resistance at different vacuums, the relationship of specific resistance to pressure is described by an empirical equation:

Eq.(A1.13) $$R = Rc\left(\frac{\Delta P^{\sigma}}{\Delta Pc}\right)$$

σ = coefficient of compressibility ($M^0 L^0 T^0$)

Rc = reference specific resistance ($M^{-1} T^{2}$)

ΔPc = reference pressure ($M L^{-1} T^{-2}$)

A plot of the log of specific resistance versus the log of its corresponding pressure will yield a straight line with a slope equal to the coefficient of compressibility.

Dewatering Model Derivation

The development of the model for gravity drainage starts with the flow rate equation for compressible cake filtration:

Eq.(A1.10)
$$\frac{dV}{dt} = \frac{A\,\Delta P}{\mu(fc\ V\ R/A + l\ r)}$$

Since $P = \rho g H$ and

Eq.(A2.0)
$$R = Rc\left(\frac{\Delta P}{\Delta Pc}\right)^{\sigma} = Rc\left(\frac{H}{Hc}\right)^{\sigma}$$

H = head acting on the cake (L)

Hc = reference head corresponding to ΔPc (L)

it is possible to describe the flow through a dewatering cake as:

Eq.(A2.1)
$$\frac{dV}{dt} = \frac{A^{2}\,\rho\ H\ g}{\mu(fc\ V\ Rc\ (H/Hc)^{\sigma} + A\ r\ l)}$$

Because the specific resistance is much greater than the resistance of the supporting media, r << Rc, Eq.(A2.1) can be rewritten as:

Eq.(A2.2) $$\frac{dV}{dt} = \frac{A^2 \rho H g}{\mu (fc\ V\ Rc\ (H/Hc)^{\sigma})}$$

Since, dV/dt=−A(dH/dt), and V=A(Ho − H), Eq.(A2.2) can be rewritten as:

Eq.(A2.3) $$\frac{dH}{dt} = -\frac{\rho\ g\ H\ (Hc/H)^{\sigma}}{\mu\ fc\ Rc\ (Ho - H)}$$

Reorganizing and integrating Eq.(A2.3) from t=0 and H=Ho yields:

Eq.(A2.4) $$t = \frac{\mu\ Rc\ fc}{\rho\ g\ Hc^{\sigma}\ (\sigma+1)} \left(H^{(\sigma+1)} - \frac{\sigma+1}{\sigma} HoH^{\sigma} - Ho^{(\sigma+1)} + \frac{\sigma+1}{\sigma} Ho^{(\sigma+1)}\right)$$

The value of fc, solids deposited per volume of filtrate, requires analysis to simplify Eq.(A2.4). The volume of filtrate at any time during drainage, if no solids are present in the filtrate, is:

Eq.(A2.5) $$V = 100 \frac{Wts}{\rho\ g} \left(\frac{1}{So} - \frac{1}{S}\right)$$

Wts = weight of solids in filtered cake ($M\ L\ T^{-2}$)

So = solids content of sludge at beginning of test (%)

S = solids content of sludge cake during drainage (%)

Since fc=Wts/V, then by substitution into Eq.(A2.5):

Eq.(A2.6) $$fc = \frac{\rho\ g}{100/So - 100/S}$$

The value of So will be much smaller than the value of S since dewatering will increase the solids content of a dilute sludge 10 to 15 times, therefore the term 100/S is neglected and upon substitution of the simplified Eq.(A2.6) into Eq.(A2.4), the final expression is obtained:

Eq.(A2.7) $$t = \frac{\mu\ Rc\ So}{100\ Hc^{\sigma}(\sigma+1)}\left(H^{(\sigma+1)} - \frac{\sigma+1}{\sigma} Ho H^{\sigma} + Ho^{(\sigma+1)} + \frac{\sigma+1}{\sigma} Ho^{(\sigma+1)}\right)$$

Drying Model Derivation

The initial stages of sludge drying occur at two distinctly different rates. The first stage involves constant-rate drying and after the critical moisture content of the sludge is reached the subsequent drying occurs at a linearly decreasing rate, falling-rate drying.

The critical moisture content for wastewater sludges can be represented by an empirical equation:

$$\text{Eq.(A3.0)} \qquad Ucr = 500\sqrt{\left(\frac{Ic\ Ws}{A}\right)}$$

Ucr = moisture content at critical point in %

Ws/A = mass of solids per surface area in kg/m2

Ic = constant drying rate in kg/m2-hr

The rate of weight loss by drying maybe expressed as:

$$\text{Eq.(A3.1)} \qquad -\frac{dWw}{dt} = A\ I$$

Ww = weight of water in sludge in kg

t = time in hrs

A = surface area in m2

I = drying intensity in kg/m2-hr

The expression for moisture content is:

Eq.(A3.2) $$U = 100\frac{Ww}{Ws}$$

Eq.(A3.2) maybe substituted into Eq.(A3.1) yielding:

Eq.(A3.3) $$dt = -\frac{Ws}{100\ A\ I}dU$$

If drying occurs solely in the constant rate period, I=Ic, and for constant Ic and Ws the solution to Eq.(A3.3) is:

Eq.(A3.4) $$t = \frac{Ws}{100\ A\ Ic}(Uo-U)$$

Uo = initial moisture content in %

U = moisture content at time t

where (Ucr < U)

Experiments have shown that the rate of drying is related linearly with the moisture content during the falling-rate drying period and:

Eq.(A3.5) $$If = Ic\left(\frac{U-Up}{Ucr-Up}\right)$$

If = drying rate during the falling-rate period in kg/m2-hr

Up = equilibrium moisture content in %

Because the equilibrium moisture content is negligible in comparison with the critical moisture content Eq.(A3.5) simplifies to the following expression:

Eq.(A3.6) $$If = Ic\frac{U}{Ucr}$$

Substitution of Eq.(A3.6) into Eq.(A3.3) yields:

Eq.(A3.7) $$dt = -\frac{Ws\ Ucr}{100\ A\ Ic}\frac{dU}{U}$$

which can be integrated with the result:

Eq.(A3.8) $$t = \frac{Ws\ Ucr}{100\ A\ Ic}\ln(Uo/U)$$

where (Uo < Uc)

A sludge sample drying in both constant and falling rate periods will have a total drying duration of:

Eq.(A3.9) $$dt = -\frac{Ws}{100\ A\ Ic}\left(dU + \frac{Ucr}{U}dU\right)$$

which when integrated yields:

Eq.(A3.10) $$t = \frac{Ws}{100\ A\ Ic}(Uo-Ucr+Ucr\ln(Ucr/U))$$

where (U < Ucr < Uo)

APPENDIX B

Specific Resistance and Coefficient of Compressibility

Experimental Methods

It was determined that a simple set-up of a vacuum pump, a mercury manometer, a 250 ml burette, a vacuum reservoir, and a porcelain Buchner funnel gave consistent results in the determinations of the specific resistance and the coefficient of compressibility (see Figure 26).

The procedure used to obtain data for the determination of specific resistance involved the following sequence of steps.

1. Place one Whatman No. 5 filter paper on the bottom of the Buchner funnel.
2. Wet paper with distilled water.
3. Apply vacuum of 15 cm of mercury for approximately ten seconds to remove excess water.
4. Measure out 100 ml of sludge of predetermined solids content and pour into Buchner funnel.
5. Apply desired vacuum and record filtrate volume every 30 seconds.
6. Repeat steps 1-5 for two other vacuums in the range of 5 to 40 cm of mercury.

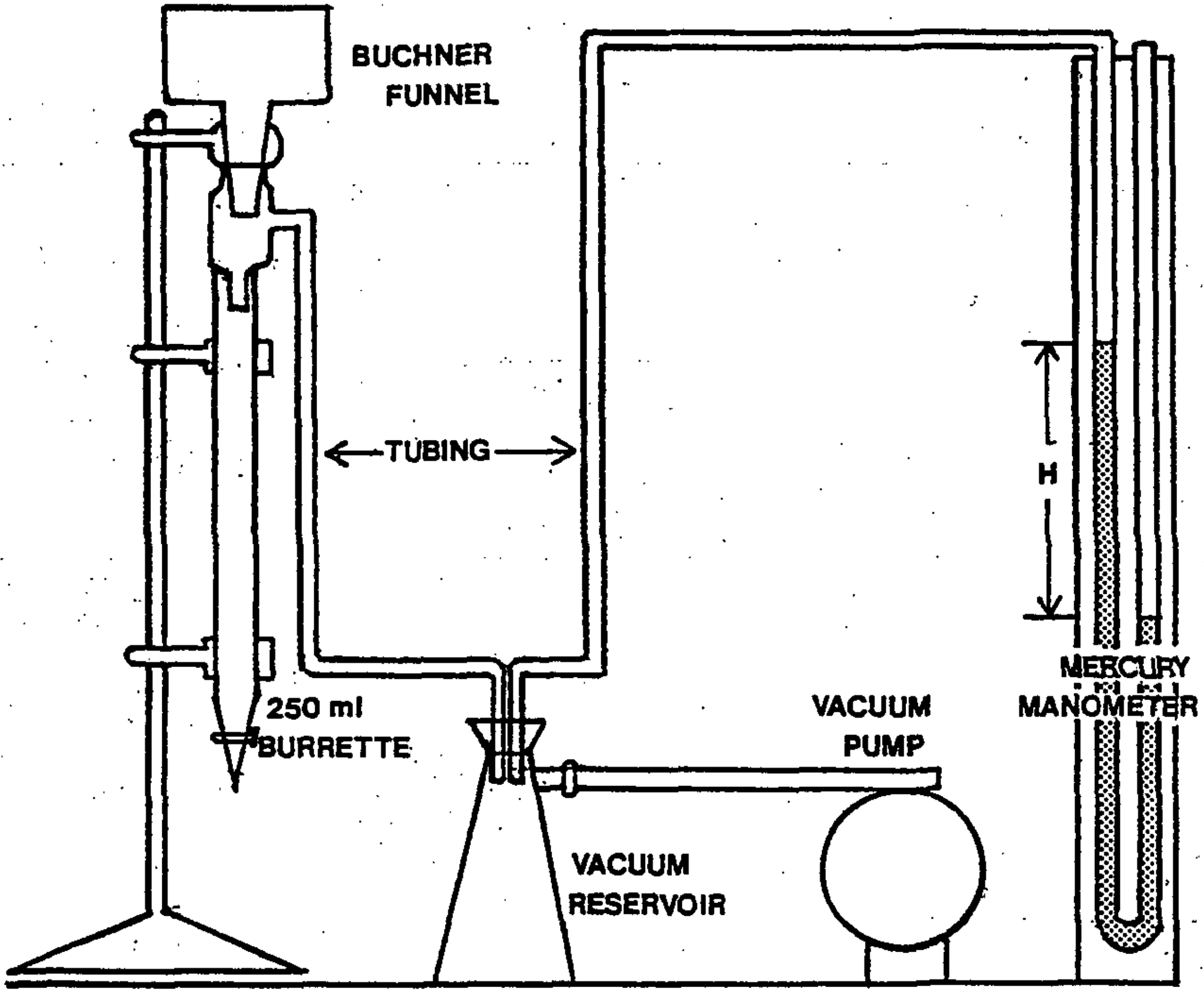

Figure 26. Experimental Set-Up for Specific Resistance and Coefficient of Compressibility Determinations. (Not drawn to scale.)

The plot of time/volume versus volume of filtrate was made for each sludge sample and pressure investigated. For the linear part of the curve the slope was set equal to:

Eq.(B1.0) $$b = \frac{R\ fc\ \mu}{2\ A\ \Delta P} = \frac{R\ fc\ \mu}{2\ A\ \rho\ g\ H}$$

A = area of filter paper in cm2

ρ = density of filtrate in g/cm3

g = acceleration due to gravity in cm/sec2

μ = dynamic viscosity in g/cm-sec

H = pressure head in cm of water

fc = weight of solids per unit volume of filtrate

= ρ g So/100

where So is the initial solids content of the sludge in %

The viscosity of the filtrate was evaluated at the room temperature. The vacuum across the cake, constant throughout each run, was measured by the mercury manometer. The solids content analysis was performed by Standard Methods (30).

The slope of the time/volume versus volume curve was calculated by linear regression analysis.

Once the specific resistances of a particular wastewater sludge were calculated at three vacuums, the coefficient of compressibility could be determined by considering the empirical relationship:

Eq.(B1.1) $$R = Rc\left(\frac{H}{Hc}\right)^{\sigma}$$

A bi-logarithmic plot of the specific resistances versus their respective vacuums yields a straight line with a slope equal to the coefficient of compressibility. The slope was calculated by linear regression analysis.

Specific Resistance and Coefficient of Compressibility Experimental Results

Triplicate Test

In the triplicate specific resistance test secondary sludge with the total solids content of .62 percent was used. The determinations were performed three times and the summarized results are the following:

Analysis 1

R = 8.57x109 at 250 cm of water, σ = .925

Analysis 2

R = 8.43x109 at 250 cm of water, σ = .852

Analysis 3

R = 8.85x109 at 250 cm of water, σ = 1.045

The largest error in the specific resistance analysis is 4.7 percent.

The largest error in the coefficient of compressibility analysis is 18.5 percent.

The experimental method of the determination of the specific resistance produced a smaller variability then the resulting analyses for the coefficient of compressibility.

Specific Resistance Data

Based on the results from the triplicate test the specific resistance differences observed in experiment no. 6 and no. 7 were significant. In experiment no. 6 the smallest difference between the specific resistance of the original sludge and the sludge conditioned with coal was 10.5 percent. In experiment no. 7 the smallest difference between the specific resistance of the original sludge and sludge conditioned with coal was 59 percent.

The coefficient of compressibility results of experiment no. 6 and no. 7 do not, however, show a significant variation.

The results of all the specific resistance and the coefficient of compressibility evaluations performed in the study are presented in Table 19. The variance and the correlation coefficient data resulting from the linear regression procedures are included.

Table 19. Summary of Specific Resistance and Coefficient of Compressibility Determination Data

Experiment Number	Specific Resistance sec^2/cm	Correlation	Variance	Coefficient of Compressibility	Correlation	Variance
1	3.35×10^8	.99	.03			
	9.09×10^8	.99	.03	1.09	1.0	.001
	2.53×10^9	.98	.03			
2	4.72×10^8	.996	.02			
	1.49×10^9	.997	.02	1.19	.998	.04
	1.72×10^9	.998	.02			
3	1.40×10^9	.995	.04			
	1.92×10^9	.97	.09	.34	.98	.06
	2.42×10^9	.85	.13			
4	2.12×10^9	.98	.24			
	4.08×10^9	.997	.09	.58	.77	.29
	4.69×10^9	.96	.14			
5	2.15×10^9	.99	.17			
	3.62×10^9	.99	.14	.56	.997	.04
	5.86×10^9	.99	.13			
6	3.98×10^9	.99	.11			
	1.04×10^{10}	.99	.08	1.18	.97	.14
Dosage 0	1.28×10^{10}	.92	.18			
	5.48×10^9	.99	.13			
	9.65×10^9	.97	.19	.79	.999	.02
Dosage .3	1.21×10^{10}	.99	.12			

Table 19, Continued

Experiment Number	Specific Resistance sec^2/gm	Correlation	Variance	Coefficient of Compressibility	Correlation	Variance
6, Continued						
	5.15×10^9	.98	.17			
	9.68×10^9	.99	.11	.9	1.0	.02
Dosage .5	1.26×10^{10}	.99	.08			
	3.17×10^9	.97	.2			
	7.21×10^9	.99	.13	1.07	.99	.07
Dosage .8	9.09×10^9	.997	.07			
7	1.09×10^{10}	.98	.63			
	2.27×10^{10}	.96	.67	.5	.96	.13
Dosage 0	2.61×10^{10}	.99	.28			
	6.03×10^9	.97	.89			
	8.08×10^9	.99	.31	.43	.99	.05
Dosage 3.3	1.19×10^{10}	.99	.35			
	3.15×10^9	.98	.47			
	4.64×10^9	.96	.72	.46	1.0	.007
Dosage 6.6	6.82×10^9	.99	.32			
Triplicate Test	7.39×10^9	.95	.15			
	9.01×10^9	.98	.12	.93	.998	.04
	2.12×10^{10}	.99	.07			

Table 19, Continued

Experiment Number	Specific Resistance sec^2/gm	Correlation	Variance	Coefficient of Compressibility	Correlation	Variance
Triplicate Test, Cont.						
	7.7×10^8	.92	.24			
	8.38×10^9	.99	.12	.85	.98	.10
	1.9×10^{10}	.97	.13			
	7.23×10^9	.95	.21			
	9.94×10^9	.98	.18	1.05	.99	.07
	2.46×10^{10}	.99	.16			

APPENDIX C

Sieve Analysis

The coal and sand used in the experimental Part One and Part Two of the study were analyzed twice. The coal and sand sample were dried at 110°C oven prior to sieving. In both trials the sand and the coal samples of similar weight were shaken for different periods of time. The results are presented in Table 20.

Little variability was observed in the effective size and the uniformity coefficient values and it is concluded that there was minimal coal breakup occurring during the sieve analysis.

The average D10 and D60/D10 values are as follows:

Coal - D10 = .14 mm; D60/D10 = 7.02.

Sand - D10 = .26 mm; D60/D10 = 2.04.

The granular coal used in the experimental Part Three of the study was sieved once. It was not dried prior to sieving.

Coal - D10 = .73 mm; D60/D10 = 15.75.

Table 20. Summary of Sieve Analysis Data

	Sand		Coal		
Shaking Time (min)	8	4	8	6	4
Sample Weight (g)	307	309	301	263	267
D_{10} (mm)	.27	.28	.14	.15	.15
D_{60}/D_{10}	1.88	1.86	6.86	6.93	6.93
Sample Weight (g)	423	312	353	253	330
D_{10} (mm)	.25	.23	.106	.135	.135
D_{60}/D_{10}	2.2	2.2	7.92	6.8	6.7

The density of the coal fraction, 4.75<D<1.18 mm, was: 0.746 gm/ml.

APPENDIX D

Economic Analysis Program

```
      PROGRAM COSTM
C
C     CONSTANT CONSTRAINTS
C
C     SO  INITIAL SLUDGE SOLIDS CONTENT - %
C     U   DYNAMIC VICOSITY OF WATER - MEAN - G/CM-SEC
C     HS  DEPTH OF SAND OR COAL FILTER MEDIA - CM
C     VT  VOLUME OF SECONDARY SLUDGE PRODUCED PER YEAR - M3/YR
C     WS  TOTAL WEIGHT OF SOLIDS PRODUCED PER YEAR - KG/YR
C     DI  DRYING INTENSITY - KG/M2-HR
C     MF  FINAL MOISTURE CONTENT - %
C     MO  INITIAL MOISTURE CONTENT - %
C     C1  COST PER UNIT LAND AREA - $/M2
C     C2  COST PER APPLICATION PER UNIT LAND AREA - $/M2-APPL.
C     R   REFERENCE SPECIFIC RESISTANCE - SEC2/G
C     HC  REFERENCE HEAD - CM H2O
C     C   COEFFICIENT OF COMPRESSIBILITY
C
C     VARIABLE CONSTRAINTS
```

```
C
C     M   MEDIA FACTOR
C
C     VARIABLE DECLERATIONS
C
      REAL M,MF,MO,MX,MC
      CHARACTER*20 DATAFILE,RESULTFILE
      DIMENSION M(4),H(30)
C
C     FUNCTION SPECIFICATIONS
C
      T1(B1,HX,HS,C,HF,MX)=MX*((B1*(HX+HS)**(C+1)+B1*C*
     + (HF+HS)**(C+1)-B1*(C+1)*(HX+HS)*(HF+HS)**C)/3600.)
      T2(B2,B3,HX,MO,MF)=B3*HX*(MO-B2*HX**.5+B2*HX**.5*
     + LOG((B2*HX**.5)/MF))
      Z(C1,C2X,VT,HX,AZ)=(C1*VT)/(HX*AZ)+(C2X*VT)/HX
      A(A1,A2)=(365*24)/(A1+A2+48)
C
C     DATA INPUT
C
      WRITE(6,40)
      WRITE(6,50)
      READ(5,55) DATAFILE
      READ(5,55) RESULTFILE
```

```
        OPEN (UNIT=2,FILE=DATAFILE,STATUS='OLD')
        OPEN (UNIT=8,FILE=RESULTFILE,STATUS='NEW')
        DO 10 I=1,4
        READ(2,*) M(I)
10      CONTINUE
        READ(2,*) R,HC,C
        CLOSE (UNIT=2)
C
C       CONSTANT CONSTRAINTS SPECIFICATION
C
        SO=2.
        SF=15.
        U=.01
        HS=45.
        VT=2.76E4
        WS=5.53E5
        DI=.02
        MO=567
        MF=150
        C1=4.79
        C2=.134
C
C       START OF COST MODEL ROUTINE
C
```

```
      B2=500*((DI*(WS/VT))**.5)
      B3=WS/(100*VT*DI)
      B1=(U*R*SO)/(100*C*(C+1)*HC**C)
      DO 20 N=1,4
      H(1)=1.
      WRITE(8,60)
      WRITE(8,70) M(N)
      WRITE(8,80)
      DO 30 I=1,30
      HF=(H(I)*SO)/SF
      A1=T1(B1,H(I),HS,C,HF,M(N))
      H(I)=H(I)/100.
      MC=B2*(H(I)**.5)
      IF (MF.GE.MC) GO TO 5
      A2=T2(B2,B3,H(I),MO,MF)
      GO TO 15
5     A2=(WS*H(I)*(MO-MF))/(VT*100*DI)
15    AZ=A(A1,A2)
      TC=Z(C1,C2,VT,H(I),AZ)
      AREA=VT/(H(I)*AZ)
      H(I+1)=H(I)*100+2
      WRITE(8,90) H(I),TC,AREA,AZ
30    CONTINUE
20    CONTINUE
```

```
      CLOSE (UNIT=8)
C
C     OUTPUT FORMATTING
C
40    FORMAT (' DATAFILE=?')
50    FORMAT (' RESULTFILE=?')
55    FORMAT (A)
60    FORMAT ('  M')
70    FORMAT (E10.4)
80    FORMAT ('  APL    T COST    AREA    NO.APPL.')
90    FORMAT (4(2X,E10.4))
C
      STOP
      END
```