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EVALUATION OF SELECTED SLUDGE DISPOSAL METHODS

BY

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A thesis submitted
in partial fulfillment of the requirements for the
degree Master of Science, Major in Engineering,
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1977

EVALUATION OF SELECTED SLUDGE DISPOSAL METHODS

This thesis is approved as a creditable and independent investigation by a candidate for the degree, Master of Science, and is acceptable as meeting the thesis requirements for the degree, but without implying that the conclusions reached by the candidate are necessarily the conclusions of the major department.

Major Adviser	Date
Thesis Adviser	Date
Head, Civil Engineering Department	Date

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INTRODUCTION

One of the primary functions of any wastewater treatment plant is the reduction of suspended solids in the wastewater flow. These solids, made up of particulates present in raw sewage as well as those generated through various biological and chemical treatment processes, are removed as sludge by means of settling tanks. Screenings or grit, which are handled separately, are not included with the sludge.

The sludge consists primarily of water. Thus, a relatively large volume of sludge results from the disposal of even small quantities of solids. Sludge composition depends on the raw wastewater characteristics and type of treatment processes employed.

In most cases, suspended solids are relatively easy to remove from the liquid flow. However, the disposal of sludge represents one of the more difficult problems facing sanitary engineers today. Wastewater sludges contain pathogenic organisms as well as other potentially harmful materials. A primary objective in sludge disposal is the protection of the public health (1). Prevention of pollution is also a concern.

The most frequently-used processes for sludge handling and disposal include: thickening, stabilization, conditioning, dewatering, heat drying, reduction, and final disposal. As shown in Figure 1, there are several alternatives available for each unit process. This research was confined to the dewatering and disposal processes.

Nature of the Project

The Sioux Falls Wastewater Treatment Plant presently consists of two phases of treatment as seen in Figure 2. These phases are referred to as the Industrial Plant and Domestic Plant. The Industrial Plant includes primary settling and two-stage trickling filtration of the waste flow from a meat packing company, stockyards company, rendering firm and a few domestic users. The influent to the Domestic Plant is almost entirely domestic in nature but does include some flow from miscellaneous small industries in the City. This influent also includes the effluent from the Industrial Plant. The Domestic Plant consists of primary settling, complete-mix activated sludge and final settling. A portion of the return activated sludge is wasted to the headworks of the Industrial Plant.

The existing sludge facilities for the Sioux Falls Treatment Plant are shown in Figure 3. After grit removal, the raw sludge flow from the industrial and domestic primary settling tank is thickened, heated and pumped into one of three anaerobic digesters. The digested sludge

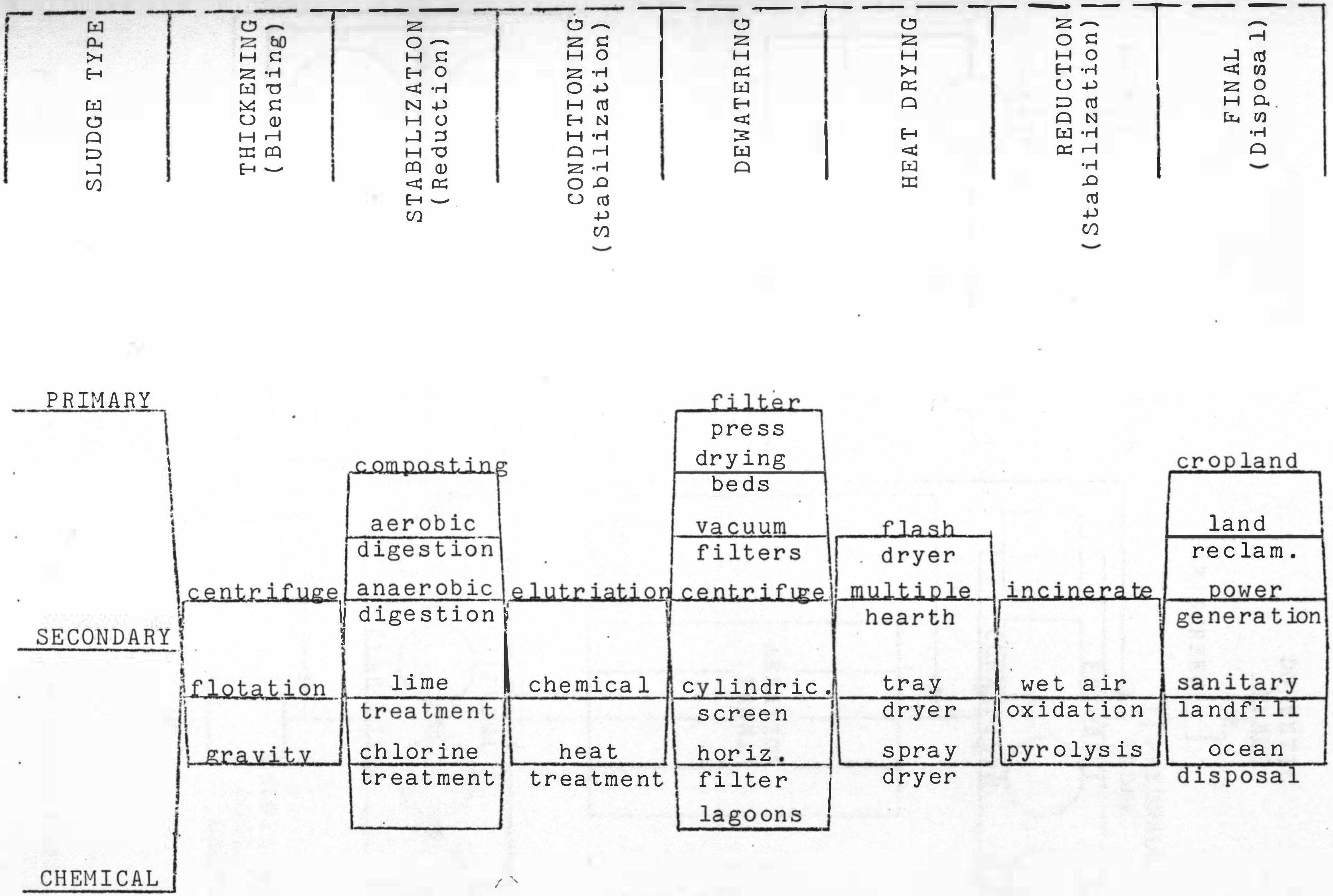

FIGURE 1

Unit Processes - Sludge Processing and Disposal

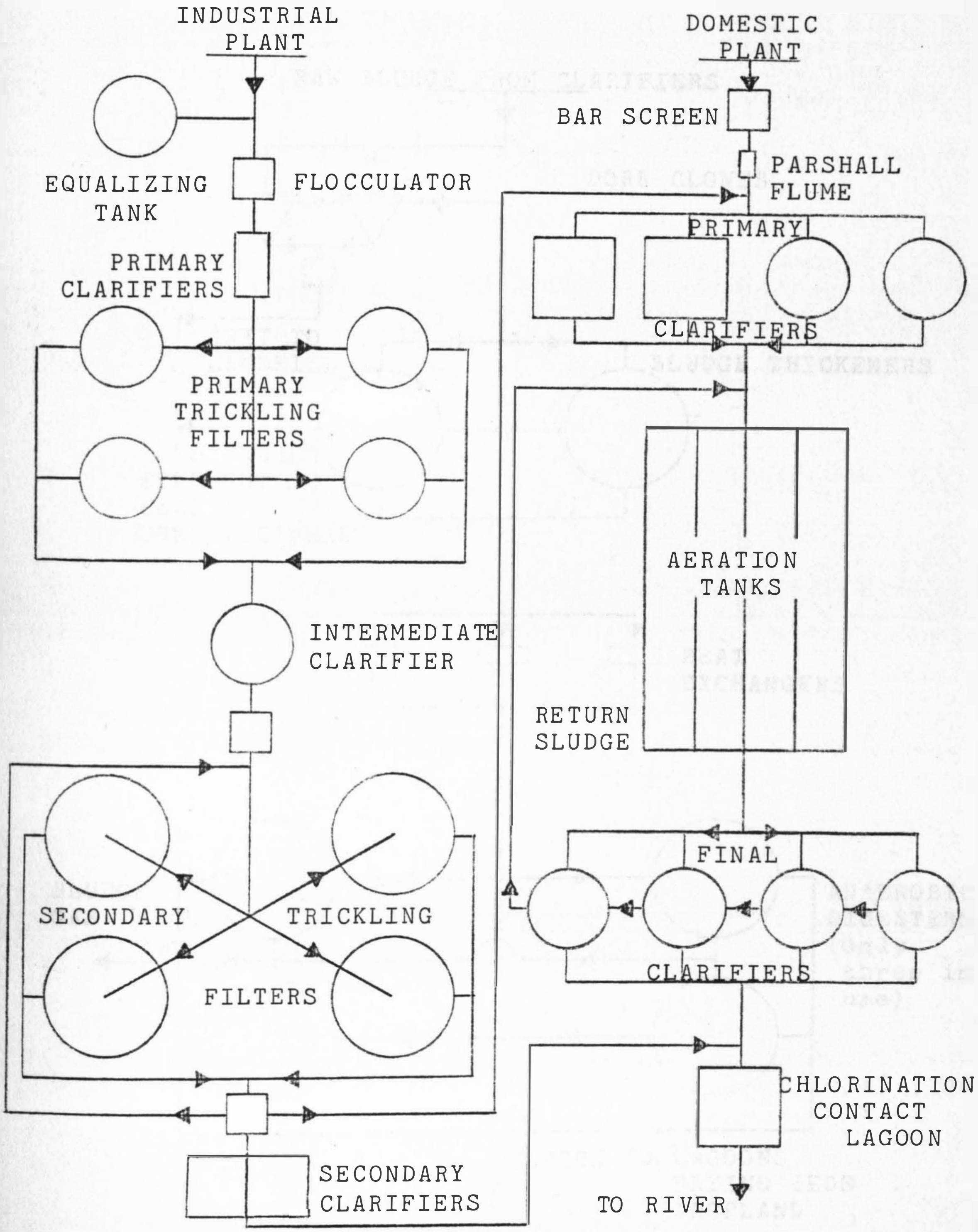

FIGURE 2

Flow Scheme - Sioux Falls Wastewater Treatment Plant

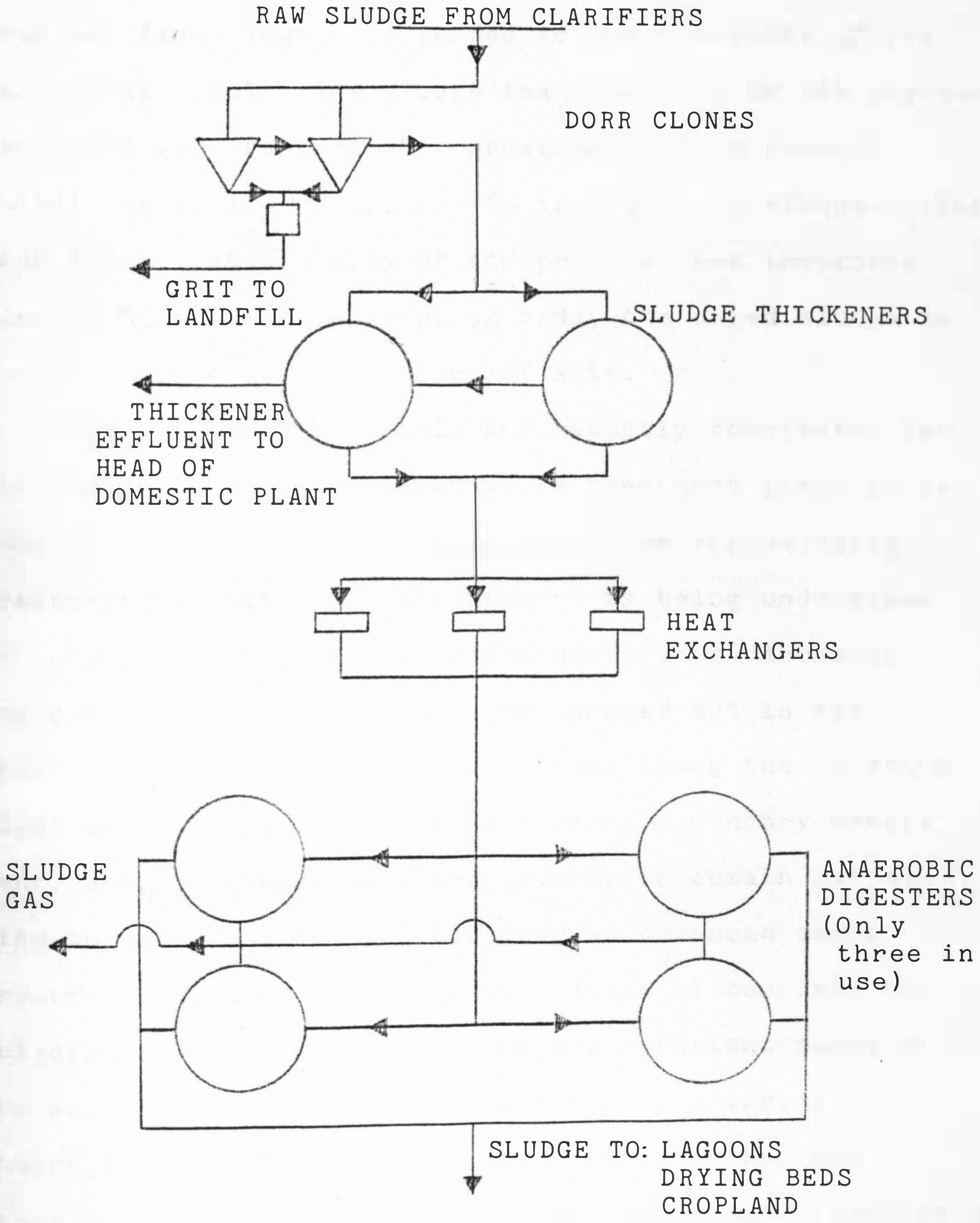

FIGURE 3
Sludge Flow Scheme
Sioux Falls Wastewater Treatment Plant

flows by gravity to a series of nine sludge-drying lagoons located adjacent to the treatment plant. The supernatant from the final lagoon is pumped to the headworks of the industrial plant. The sludge that collects in the lagoons is pumped into tankers at approximately four percent solids and is either applied to croplands or sludge-drying beds located at the site of the proposed new treatment plant. From the sludge-drying beds, the dried sludge is hauled to a solid waste disposal site.

The City of Sioux Falls has recently contracted for the design of a new advanced waste treatment plant to be located five river miles downstream from the existing treatment facilities. This project is being undertaken to comply with Federal and State wastewater discharge standards. Construction will be carried out in two phases. Phase I will consist of remodeling the existing plant which currently includes primary secondary treatment, constructing a combined gravity/forcemain outfall line to the new site, and building an advanced waste treatment plant at the new site. Phase II consists of building a new primary and secondary treatment plant at the new site and abandoning the old site entirely. The entire construction process, from initial plans and specifications for Phase I to completion of construction of Phase II will encompass ten years.

The consulting engineers designing the project have recommended abandonment of the present method of sludge handling and disposal and remodeling of the existing plant under Phase I to include installation of vacuum filters for sludge dewatering and disposal of the sludge in a landfill (2).

Scope of Data

This research was undertaken to determine the feasibility of dewatering digested sludge using vacuum filters or centrifuges followed by land spreading as opposed to the present method of sludge hauling and disposal. It was intended that this evaluation be accomplished by comparing the existing method of disposal to that of installing vacuum filters or centrifuges and providing land disposal facilities for an operating period of ten years. To obtain data for selection of filter or centrifuge equipment and chemical costs, it was necessary to conduct certain laboratory analyses such as suspended and total solids, Buchner funnel and centrifuge tests. Records from the Sioux Falls Wastewater Plant were used to determine existing costs of sludge disposal.

The objectives of these experiments were to:

1. Determine whether the sludge from the Sioux Falls Wastewater Treatment Plant with the addition of a selected polymer could be dewatered by means of a vacuum filter.

2. Determine whether the sludge from the Sioux Falls Wastewater Treatment Plant with the addition of a selected polymer could be dewatered by means of a solid bowl centrifuge.
3. Establish capital costs for sludge dewatering and disposal by means of vacuum filtration, centrifugation and the existing method of lagoons and drying beds with land application.
4. Establish operation and maintenance costs for sludge dewatering and disposal by means of vacuum filtration, centrifugation and the existing method of lagoons and drying beds with land application.
5. Compare the average annual costs of the three mentioned dewatering and disposal methods.

REVIEW OF LITERATURE

Introduction

Sludge disposal is one of the most costly and controversial phases of wastewater treatment. In the past, sanitary engineers have been mainly concerned with the removal of solids from the main flow stream of sewage and have not shown much concern for the solids after removal.

According to Shea and Stockton (4), a secondary treatment plant will generate 1,000 pounds of dry solids per day per million gallons of sewage assuming the sludge from the primary clarifiers contains five percent solids. A secondary clarifier can be expected to generate 500 pounds per day per million gallons at two percent solids. This sludge has the texture of buttermilk. A total solids of three to four percent will average one percent of the total wastewater inflow or 10,000 gallons per million gallons of wastewater (1).

This research is concerned with the costs involved in dewatering and disposal of the digested sludge. On the average, sludge handling is responsible for about 30 to 40 percent of the capital costs of a treatment plant, and about 50 percent of the operating costs (5). Wastewater treatment personnel, however, contend that sludge facilities require 80 to 90 percent of the operation and maintenance time of a treatment plant if problems in operation and control are included.

Vacuum Filtration

Vacuum filters have many advantages in handling sludge. Among the principal advantages are (6):

1. Plant area requirements are greatly reduced when a small sludge dewatering building is substituted for drying beds or lagoons.
2. Mechanical dewatering can be placed on a routine schedule, coordinated with the rest of the plant, and unaffected by weather conditions.
3. Improved plant operation is permitted and a greater degree of flexibility in operation is afforded.
4. Digester requirements may be reduced since capacity need not be designed into them for winter storage, or it is possible that digesters may be eliminated entirely with the dewatering of fresh sludge.

In addition to these, the Battelle Memorial Institute (7) lists the additional advantages of, 1) an increase in the various types of sludges that can be dewatered and, 2) the percent of solids capture is high. The ability to dewater different kinds of sludges is a necessity because any treatment plant will produce a variety of sludges due to variations in influent quality.

Objectives. In the operation of a vacuum filter, it is desirable to maximize the solids capture, filter cake yield, and filter cake solids content thereby reducing operational costs to a minimum (2),(6). The relative importance of these objectives will vary depending on the method of filter cake disposal. Usually, it is not possible to simultaneously accomplish all three of the objectives. If the sludge cake is to be incinerated, then a sludge cake with the lowest possible moisture content is desirable. If ultimate disposal of the sludge cake is a landfill, then the objective would be to obtain the highest possible cake solids content. Maximum solids capture is of prime importance in minimizing the amount of filtrate solids returned to the headworks of the plant. To reduce operating costs to a minimum, each of the previously-mentioned objectives would have to be compromised to some degree. Furthermore, for successful performance, operation of the vacuum filters must be adjusted to the characteristics of the sludge to be filtered.

Description of a Vacuum Filter. A sectional view of a rotary filter consisting of a cylindrical drum rotating partially submerged in a vat or tray of conditioned sludge can be seen in Figure 4. The drum is divided into a number of sections connected by internal piping to the valve plate at the hub. This plate rotates in contact with a fixed valve plate which is connected to a vacuum supply, a compressed air supply, and an atmospheric vent.

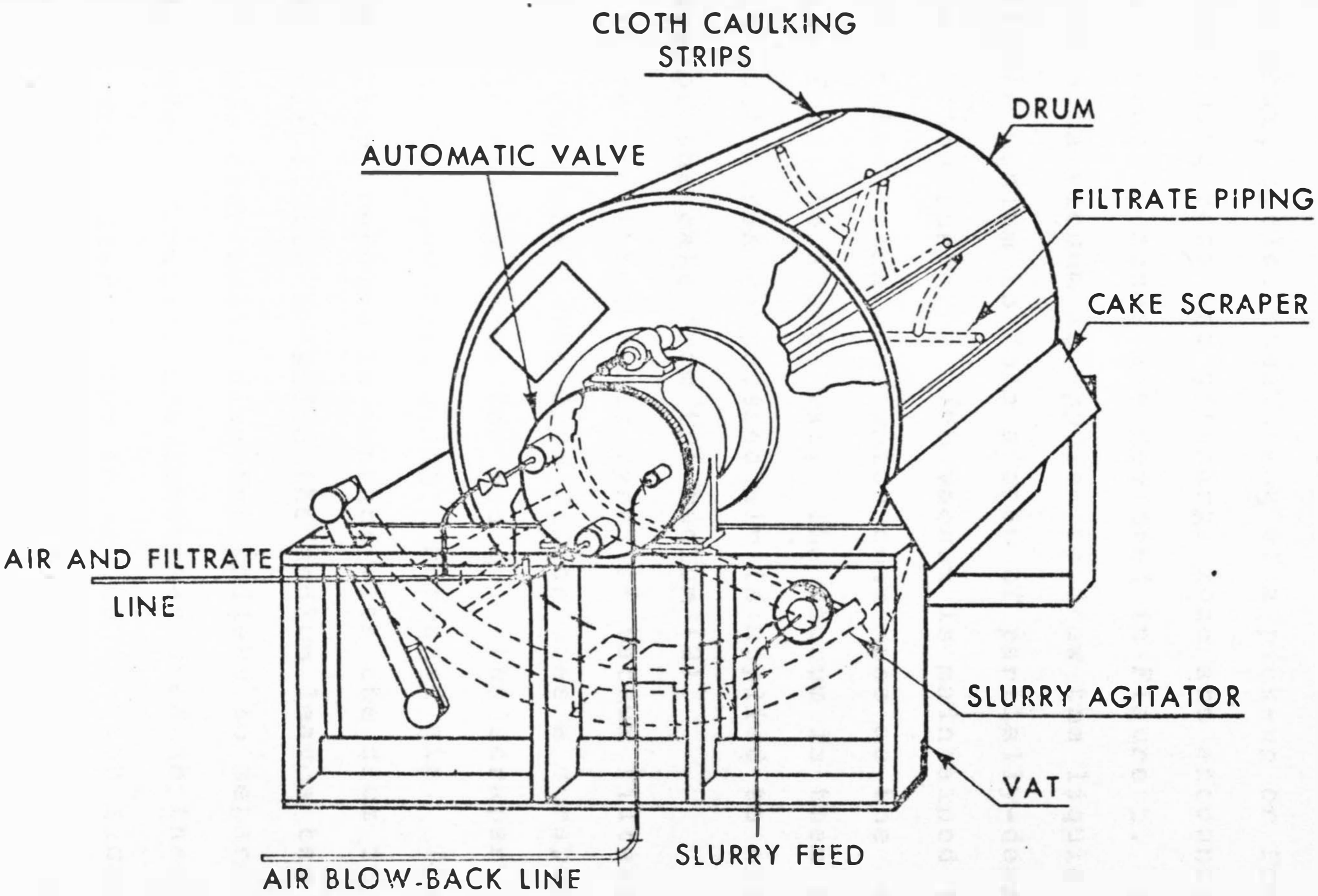

FIGURE 4

Cutaway view of a rotary drum vacuum filter (2).

As the drum rotates, each section becomes aligned with the appropriate service so that during a complete revolution of the drum, cycles consisting of a pick-up or form zone, a cake-drying zone and discharge zone are encountered. These operating zones are depicted in Figure 5. In the form zone, a vacuum is applied to draw the liquid through the filter medium to form a cake of partially-dewatered sludge on the surface. The vacuum is maintained throughout the cake-drying zone which commences as the cake emerges from the sludge vat. The vacuum is then broken and in most cases compressed air is applied to aid in the release of the cake from the medium (2).

There are three basic types of vacuum filters: drum, belt and coil (8). The drum filter uses a scraper to remove sludge cake from the medium. The scraper is aided by a pressure blow-back using compressed air. The filter medium always remains in contact with the drum in contrast to the belt filter in which the medium leaves the drum and travels over small diameter rollers to separate the sludge cake. Scrapers are sometimes used in the latter type and the filter medium is washed on both sides before returning to the drum.

A corduroy arrangement of stainless steel coil springs is used on the coil type filter in place of the medium. Here again, the springs leave the drum for cake

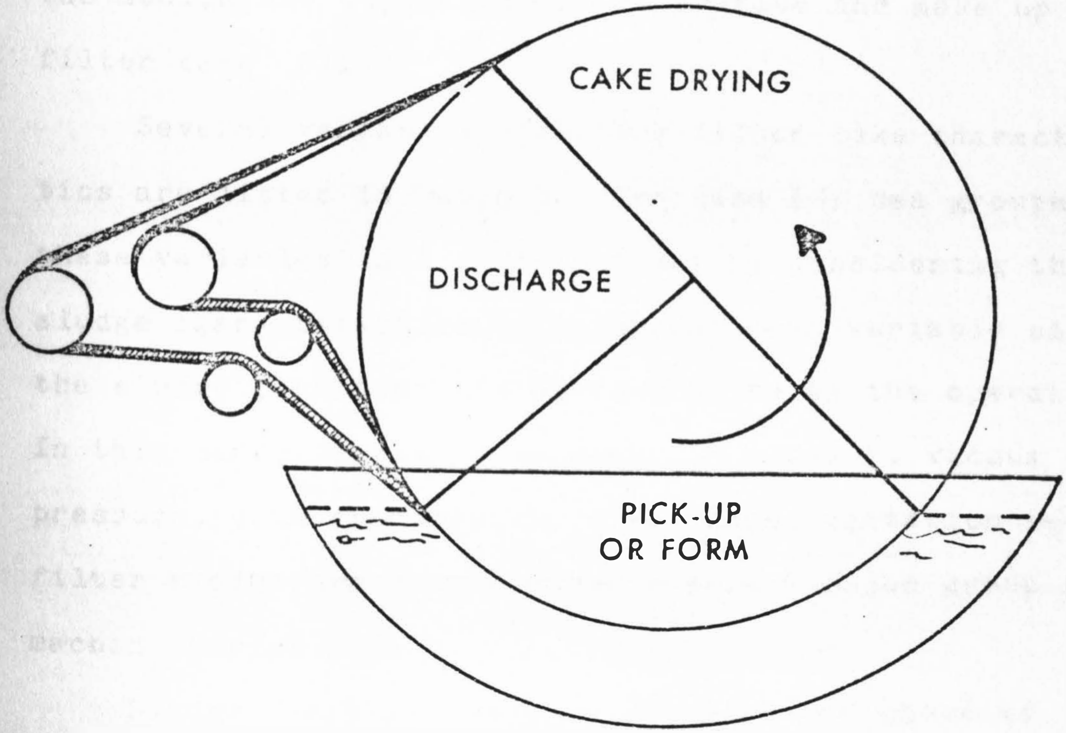

FIGURE 5

Operating zones of a vacuum filter (2).

discharge and are washed thoroughly before returning to the drum (8).

Operation of a Vacuum Filter. The chemicals used to condition the sludge and make it easier to filter, are combined with the feed sludge prior to discharge into the sludge vat. The vacuum inside the drum draws filtrate from the sludge through the medium. The filtrate is pumped from the drum. The solids that cannot pass through the medium are deposited on the surface and make up the filter cake (5).

Several variables affecting filter cake characteristics are listed in Table 1. Vesiland (5) has grouped these variables in a different way by considering the sludge characteristics as an operational variable since the sludge condition can be controlled by the operator. In this classification, as shown in Table 2, vacuum pressure, drum submergence, drum speed, agitation and filter medium are listed under a second major group as machine variables.

Sludge Characteristics. The size and shape of the solids particles in the feed sludge will affect the operation of the filter. By achieving a high solids capture, the accumulation of recycled fines can be minimized. When the level of fine particles becomes excessive, filter blinding (plugging of the holes in the filter

TABLE 1

Variables Affecting Filter Cake Characteristics (9)

Sludge Characteristics

1. Size and shape of solid particles
2. Concentration of suspended solids in the filter feed
3. Compressibility of the sludge particles
4. Chemical composition & particle charge within the sludge solids
5. Sludge age and temperature
6. Sludge and filtrate viscosity
7. Origin of the sludge as to primary, secondary or digested

Major Operational Variables

1. Vacuum levels during the form and drying cycle
2. Form and drying times
3. Amount of drum submergence
4. Drum speed
5. Characteristics of the filter media
6. Degree of agitation during the after chemical addition

TABLE 2

Vacuum Filter Variables (5)

Machine Variables	Operational Variables
Vacuum pressure	Type and condition of sludge chemical conditioners
Drum submergence	Sludge characteristics
Drum speed	
Agitation	
Filter medium	

medium) occurs. High levels of fines will also upset other processing units in the treatment plant including clarification and BOD removal (8).

The concentration of solids in the feed sludge has a significant influence on the filter yield. An increase in the feed sludge solids concentration usually results in a substantial increase in filter yield; in fact, the filter yield, in pounds per square foot per hour, is often numerically equal to the percent solids in the feed sludge (5). It is also noted that more concentrated sludges will filter and release more easily than thin sludges (8).

Compressibility of a sludge will directly affect the vacuum that can be imposed on sludge. Vesiland reported that the vacuum that can be applied to a sludge has a maximum practical limit of 15 inches Hg (5). Others have reported vacuum filters normally operate with as much vacuum as can be obtained (8). It has been recommended that a vacuum of 20 to 25 inches be maintained (10). Parkhurst, et al., reportedly used a vacuum 20 to 25 inches Hg in pilot studies (11).

The chemical composition, particle charge and origin of the sludge (primary, secondary or digested) affect vacuum filtration. Broad experience indicates that properly conditioned raw primary sludge is generally the most readily dewaterable, with conditioned, digested, and activated sludges increasingly more difficult to filter (2),(7). The charge of the sludge particles will affect the type and amount of conditioner to be used.

Filterability appears to decrease with increases in the time between sludge draw-off and subsequent filtering (5). Also, digested sludge that has been allowed to cool does not seem to filter as well as sludge taken directly out of the digester. The viscosity of sludge is as difficult to control as its temperature, and both significantly affect sludge filterability (5).

Machine Variables. Machine variables important in the operation of vacuum filters are listed in Table 2 (5). Increases in drum submergence provide more time for pickup of solids. This results in thicker, wetter sludge cakes. Increasing the drum speed reduces the contact time between the sludge and the filter. This also results in wetter cakes. A reduction in drum speed will produce a drier cake but lower filter yield.

Operational problems can occur if solids are allowed to settle in the trough. Agitation prevents this from occurring. However, excessive agitation will cause the floc to break up and result in poor filtration.

One of the most important machine variables is the selection of the proper filter medium. Either open or tight-weaved media are available. The tighter the weave the fewer the fines that pass through with the filtrate, but the greater the potential for filter binding. Available media range from rayon acrylic, polyolefins, and polyesters, to wire screens and stainless steel coils (12). Figure 6 is a chart showing an array of textile fibers from which various woven or non-woven filter media can be made.

Centrifugation

Increased operational control and use of new organic polyelectrolytes for sludge conditioning have enhanced the feasibility of centrifugation as an alternative to vacuum filtration. According to Barlow (1), the use of centrifuges instead of vacuum filters is growing.

Some of the advantages of centrifugation are as follows (7):

1. small area requirements
2. rapid start-up and shut-down capabilities
3. easy adaption to changing feed conditions
4. potential of low maintenance costs when proper grit protection is provided
5. independence from climatic conditions

In addition to these, Nielsen, *et al.*, (13) also included:

1. greater flexibility of operation with a wide range of cake solids
2. low initial capital investment and annual costs
3. operation requires a minimum amount of surveillance

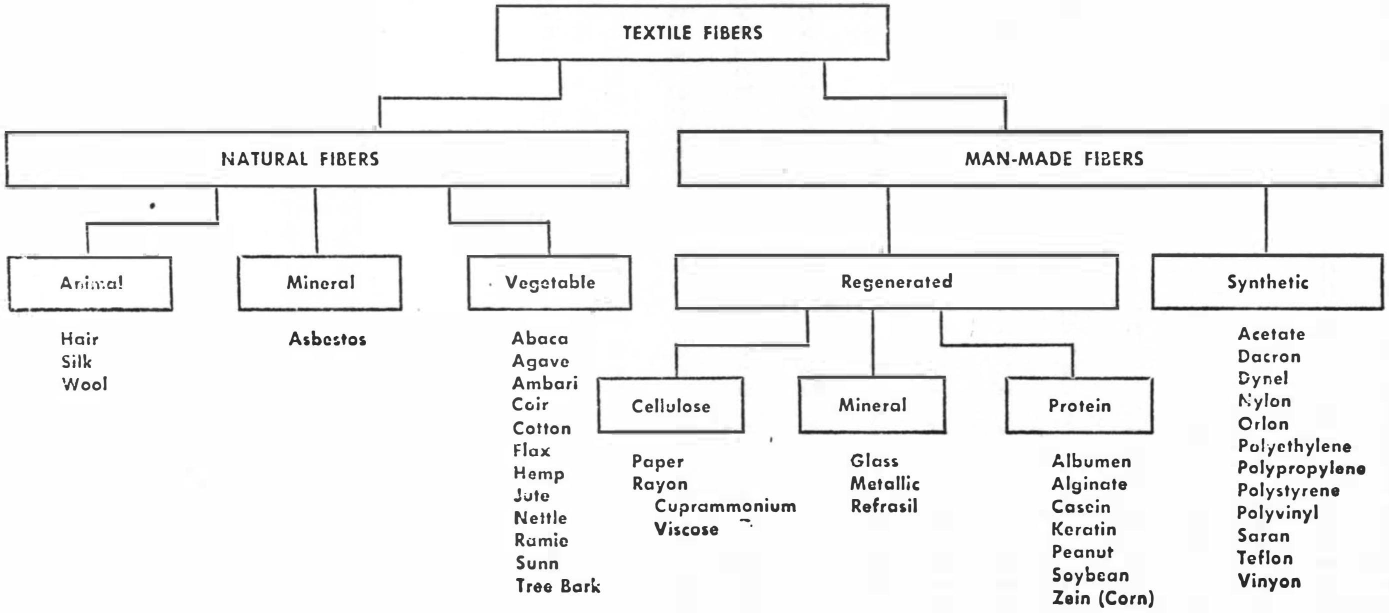

FIGURE 6

Textile Fiber Classification (12).

Description of a Centrifuge. The solid bowl or decanter type centrifuge is the machine used in wastewater treatment. This machine has the ability to separate any solids from any liquid as long as the solids are heavier (5). There are three major components of the solid bowl machine. These components include a rotating solid bowl having the shape of a truncated cone, an inner screw conveyor, and a gear reducing unit. Minor components include the steel base plate, pillow block bearings, motor, etc. These parts can be seen in Figures 7 and 8.

The cylindrical bowl has a conical section at one end from which the solids are discharged. This bowl rotates at a speed sufficient to generate enough centrifugal force to cause a separation of solids from the liquid. The liquid is retained in the bowl by weirs at the large end and the slope of the conical section at the other end.

The screw conveyor is mounted on the inside of the bowl and rotates at a slightly lower speed than the bowl. This differential speed causes the settled solids to be pushed toward the small end of the bowl. Thus, the solids are moved up the incline, out of the liquid and discharged from the machine. The third major component is the gear unit located at the end of the bowl used to drive the screw conveyor (15).

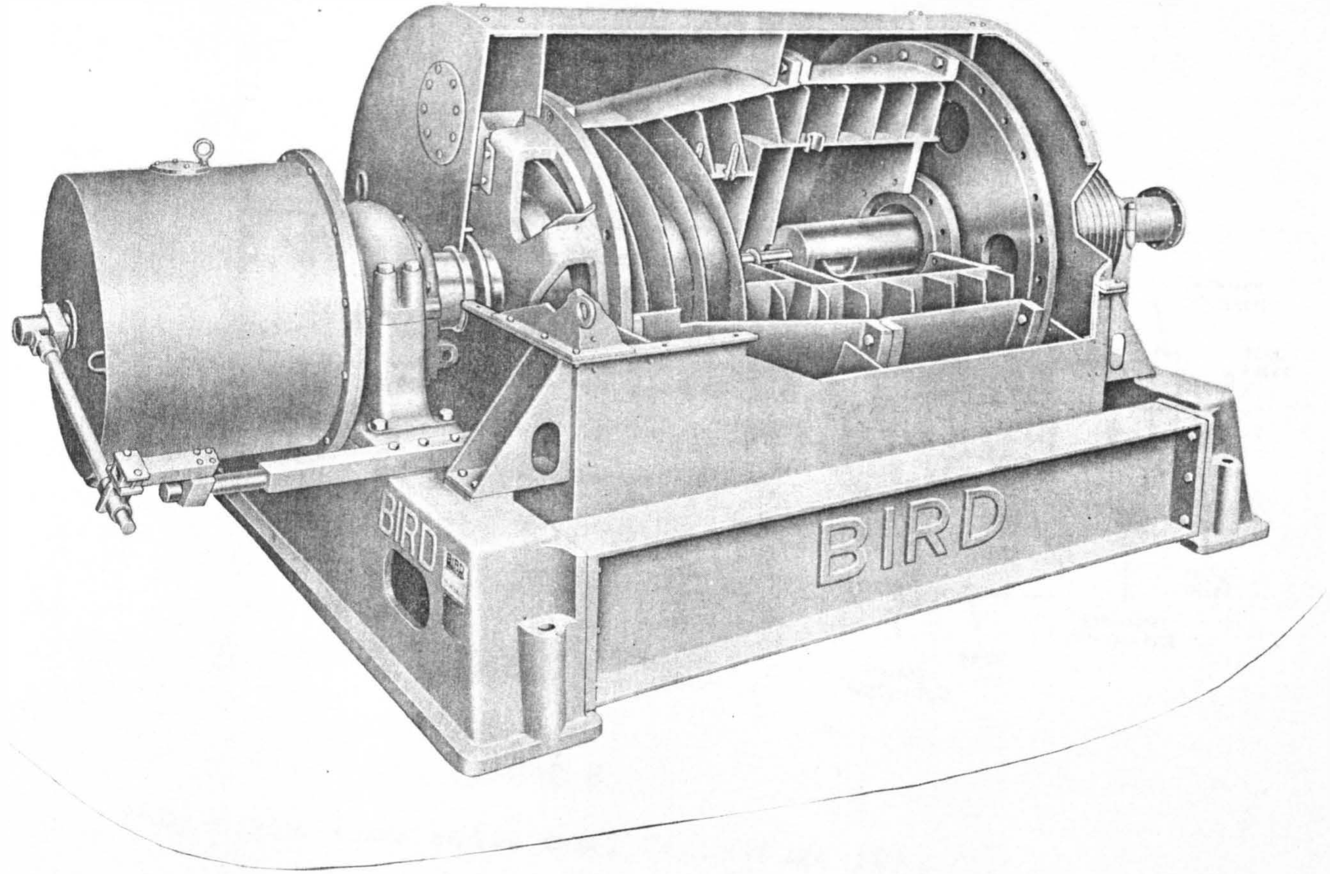

FIGURE 7

Cutaway View of a Solid Bowl Centrifuge (14).

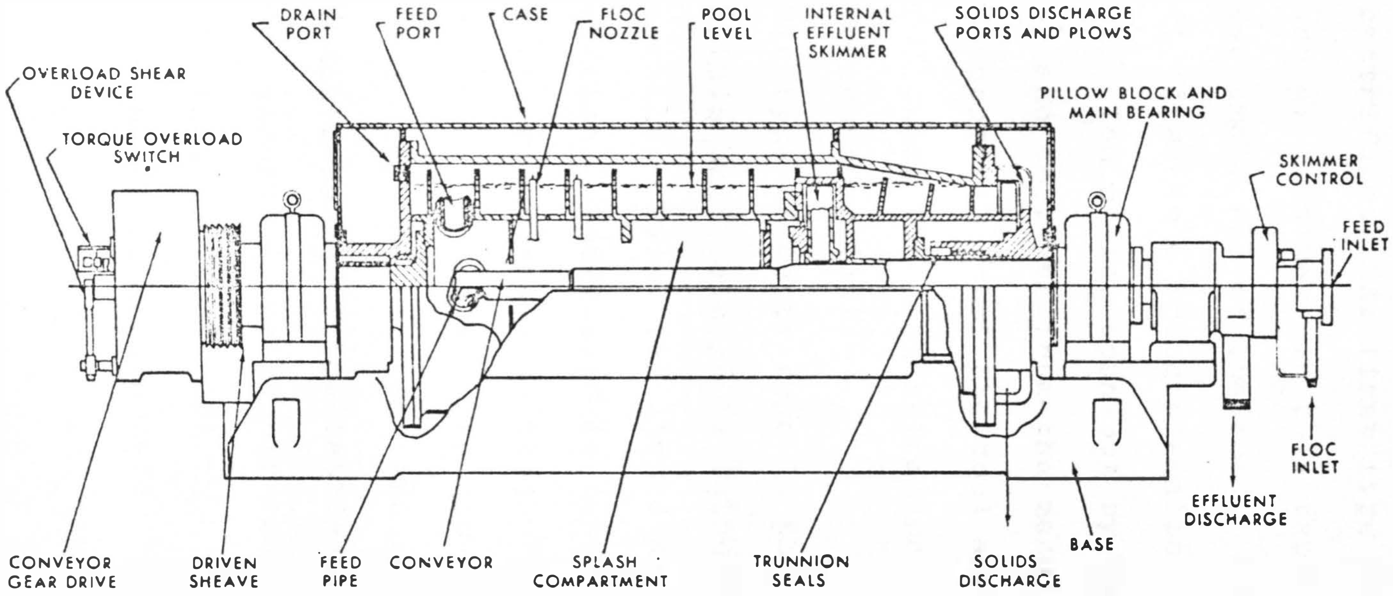

FIGURE 8

Concurrent Flow Solid Bowl Centrifuge (2).

There are two basic types of flow schemes in the solid bowl centrifuge. The first type is the conventional or countercurrent machine. In this type, feed is introduced near the small end of the bowl. After leaving the feed pipe, it flows to a preacceleration chamber and then into the bowl. The solids spun out by centrifugal force are picked up and conveyed from the machine. The liquid flows to the opposite end of the bowl and out of the machine by following the long spiral path created by the blades of the conveyor (15).

The other type of centrifuge is the concurrent flow machine. In this unit, sludge is introduced at the large end of the machine. Here, the liquid and solids flow in the same direction. The liquid is intercepted and flows into an effluent chamber and is skimmed off for discharge. The solids continue onward and are conveyed out of the small end. This type of flow pattern reduces turbulence and prevents disturbance of the settled sludge. Also, the weirs for removal of the liquid can be adjusted while the machine is in operation. (15).

Solid bowl machines accommodate typical inlet flows up to 300 gallons per minute. They can accommodate particle sizes up to one-half inch in diameter. Solids concentrations in the output, range between 20 and 45 percent, with solids recovery usually in the 60 to 95 percent range. Coagulants are required to obtain the higher levels (16).

Operation of a Centrifuge. Sludge is pumped into the conventional solid bowl centrifuge through a central pipe and hugs the inside walls of the outer bowl due to the centrifugal force generated by rotation of the bowl. As rotation continues, the heavier solids sink to the bottom and the lighter liquid remains pooled on top. Basically, the bowl centrifuge acts as a highly effective settling tank. The solids removal process is accomplished by the scroll which rotates at a slightly different speed than the bowl so that the solids are conveyed up the incline end of the bowl (called the beach) and out the narrow coned end. The clear liquid, or centrate, flows out the other end via the weir ports (17). The operation principle is the same for the concurrent solid bowl except that the solids and liquid move in the same direction.

Factors affecting centrifugal dewatering can be divided into two categories similar to those for vacuum filtration. A list of these variables is shown in Table 3 (5).

Residence Time. Residence time is controlled by adjusting the flow rate of sludge to the centrifuge. Increases in residence time result in increased solids recovery at the expense of cake dryness (5).

TABLE 3

Variables Affecting Centrifuge Performance (5)

Machine Variables	Operational Variables
Bowl diameter	Residence time
Bowl length	Sludge characteristics (including sludge conditioning)
Bowl rotational speed	
Beach angle	
Beach length	
Pool depth	
Scroll rotational speed	
Scroll pitch	
Feed point of sludge	
Feed point of chemicals	
Condition of scroll blades	

Sludge Characteristics. In general, the fresher the sludge, the more easily it can be dewatered (2). The dewatering characteristics of mixed digested sludges depend on the type of secondary sludge produced. Secondary sludges with high sludge volume indexes are more difficult to dewater than sludges with low indexes.

Machine Variables. Settling time and surface area can be increased for a given diameter bowl by increasing the length/diameter ratio. Increasing the bowl diameter and maintaining the same centrifugal force will result in a longer retention time within the machine. This will result in higher solids recoveries but wetter sludge cakes. Changing the length of the bowl will also increase the retention time but the cake dryness then becomes unstable. Customarily, length/diameter ratios of 2.5 to 3.5 are employed (2).

Bowl speed is established by selection of the proper gear ratio. Increasing the bowl speed will increase the solids recovery and possibly the cake solids as well. The newer centrifuges, however, are coming out with lower rotating speeds to extend conveyor life (18).

The pool depth can be changed in some machines during operation while in others the machine must be stopped. Increasing the pool depth increases the retention time which, in turn, enhances solids recovery but produces a wetter cake. Increasing the rotational speed of the screw conveyor (scroll) will increase the solids concentration in the cake but decrease the solids recovery because only the larger, heavier solids will be removed. Similarly, increasing the scroll pitch will result in the removal of only the larger and heavier solids.

If the feed point of the sludge is changed so that it is nearer the beach, solids recovery will increase at the expense of a wetter cake. This is due to the longer travel time required for the sludge (5).

Chemical conditioners can either be added before the sludge enters the centrifuge or fed directly into the machine. Parkhurst, et al. (11), found that higher solids recoveries were achieved when polymers were injected directly into the bowl rather than the sludge stream entering the bowl.

The scroll blades are subject to severe wear and tear from constant grinding against sand and gritty materials in the sludge. When the conveyor wears down, solids recovery decreases since many fines are not picked up (5).

Conditioning Sludge Prior to Dewatering

Conditioning sludge prior to dewatering can be accomplished a number of ways. Table 4 lists five of the usual conditioning methods and their functions (2). The

TABLE 4

Conditioning Methods and Purposes (2)

Conditioning Method	Unit Process	Function
Polymer Addition	Dewatering	Improve production rate, cake solids content, and solids capture.
Inorganic Chemical	Dewatering	Improve production rate, cake solids content, and solids capture.
Elutriation	Dewatering	Decrease acidic chemical conditioner demand and increase degree of concentration.
Heat Treatment	Dewatering	Eliminate or decrease chemical use, improve production rate, cake solids content, and stabilization. Some conversion may also occur.
Ash Addition	Dewatering	Provide improved cake release from belt type vacuum filters and facilitate filter pressing. It can also result in higher filter yields and reduced chemical requirements.

first two methods involve chemical conditioning. These methods do not materially change the nature of the sludge. Although in the past, ferric chloride and lime have been the principal conditioning chemicals used prior to dewatering, polymer conditioning is becoming much more widespread. Elutriation was originally developed to decrease the alkalinity of anaerobically-digested sludges to reduce the demand for acidic metal salts. Heat treatment facilitates dewatering and will be employed in a number of plants currently under design in the United States (2).

Lime and Iron Salts. Hydrated limes including both calcium lime ($Ca(OH)_2$) and dolomitic lime ($Ca(OH)_2 \cdot 8MgO$) have application as conditioners either alone or in conjunction with other conditioning agents. The active agent in sludge conditioning is the strong alkaline calcium fraction of the lime. The calcium ion released by dissolution of lime is effective in the precipitation of carbonates, phosphates and soaps as seen below.

$$Ca(OH)_2 + H_2CO_3 \longrightarrow \underline{CaCO}_3 + 2H_2O \qquad (1)$$

$$Ca(OH)_2 + Ca(HCO_3)_2 \longrightarrow \underline{2CaCO}_3 + 2H_2O \qquad (2)$$

The moderate effectiveness of lime as a sludge conditioner has been attributed to the dehydrating and colloid-shrinking effects of the calcium hydroxide.

Ferric salts such as $FeCl_3$ and $Fe_2(SO_4)_3$ are salts that release trivalent ferric ions when dissolved in water. These ferric ions are highly reactive and form slightly soluble precipitates with hydroxides, carbonates, phosphates, and soaps as seen below.

$$\mathrm{2FeCl_3 + 3Ca(HCO_3)_2 \longrightarrow}$$
$$\mathrm{\underline{2Fe(OH)}_3 + 3CaCl_2 + 6CO_2} \qquad (3)$$

$$\mathrm{Fe_2(SO_4)_3 + 3Ca(HCO_3)_2 \longrightarrow}$$
$$\mathrm{\underline{2Fe(OH)}_3 + 3CaSO_4 + 6CO_2} \qquad (4)$$

Ferrous salts release divalent ferrous ions which tend to be less active than ferric ions and tend to form compounds of greater solubility.

$$\mathrm{FeSO_4 \cdot 7H_2O + Ca(HCO_3)_2 \longrightarrow}$$
$$\mathrm{Fe(HCO_3)_2 + CaSO_4 + 7H_2O} \qquad (5)$$

$$\mathrm{Fe(HCO_3)_2 + 2Ca(OH)_2 \longrightarrow}$$
$$\mathrm{\underline{Fe(OH)}_2 + \underline{2CaCO}_3 + 2H_2O} \qquad (6)$$

Ferrous precipitates may promote aggregation of sludge particulates (10).

Polymers. Polymers are long-chain, water soluble, organic molecules with high molecular weights that abound with active functional groups along the entire length of the chain. Organic polymers can serve as primary coagulants and/or coagulant aids. Furthermore, polymers minimize dependence on the common inorganic coagulants such as alum and iron salts (19).

There are three basic types of polymers used: anionic, cationic and nonionic (11). Nonionic polymers do not ionize in solution. However, they do contain active surface sites along the chain that assist in cross-link binding of sludge particles into aggregates. Nonionic polymers are generally used in conjunction with other sludge conditioning agents. Anionic polymers become negatively charged on the organic portions of molecules after ionization of functional groups has released cations to the solution. This reaction results in long, fibrous, polyvalent organic ions which are effective in collecting and binding positively charged particles. The particles in wastewater are generally negatively charged. Cationic polymers possess a positive charge on the organic portion of the molecule after ionization (10).

Specific Resistance as a Measure of Sludge Filterability

This test involves filtration of a given volume of sludge using a Buchner funnel. The time at which the vacuum breaks due to cracking of the cake is measured along with the volume of filtrate. These values are used to determine the specific resistance of the sludge. The time until the vacuum breaks depends upon a number of variables.

These variables include the (20):

1. initial solids content of the sludge
2. volume of sludge filtered
3. area of filtering surface
4. pressure at which filtration is carried out

The analysis of filtration of sludges based on the liquid flow through porous media was first reported by Darcy. Carman adapted Darcy's equation to filtration and Coackley and Jones (20) adapted Carman's analysis to the operation of a vacuum filter.

The basic filtration equation is:

$$\frac{dV}{d\Theta} = \frac{PA^2}{u(wrV + R_f A)} \qquad (7)$$

where: V = volume of filtrate, ml
Θ = time each filtrate volume is measured, seconds
$\frac{dV}{d\Theta}$ = rate of flow, volume per unit time
P = applied vacuum, N/cm^2
A = filter area, m^2
u = viscosity of filtrate, N-sec/m^2
r = specific resistance, sec^2/gr.
w = weight of dry cake solids per unit volume of filtrate
R_f = resistance of filter medium

If Equation (7) is integrated assuming pressure is constant during the filtration time, the following expression is obtained (2):

$$\frac{\Theta}{V} = \frac{rwV}{2PA^2} + \frac{R_f}{PA} \qquad (8)$$

This expression is in the form of a straight line when Θ/V is plotted versus V obtained by measuring the volume of the filtrate, V, at various times, Θ. The slope of this line, b, is:

$$b = \frac{urw}{2PA^2} \tag{9}$$

By rearranging Equation (9), an expression is obtained from which the specific resistance, r, which is a measure of sludge filterability, can be calculated:

$$r = \frac{2PA^2b}{uw} \tag{10}$$

Typical specific resistance values for various biological sludges are presented in Table 5 (21). Also shown in this table are specific resistance values from Sisk (22) and Miller (23).

The sludge cake, reported as dry solids per unit volume of filtrate, w, can be approximated by the feed solids concentration in kg/m^3. Equation (11) also can be used to accurately calculate w (5):

$$w = \frac{C_kC_o}{100(C_k-C_o)} \tag{11}$$

where: C_k = cake solids concentration, percent
C_o = feed solids concentration, percent

For reliable results it is necessary that (20): 1) the filter area be accurately known, 2) the pressure

TABLE 5

Typical Specific Resistance Values For Various Sludges

Sludge Type	Specific Resistance, r (sec^2/g)	Reference
Primary	$1.5 - 5.0 \times 10^{10}$	(21)
Activated	$1 - 10 \times 10^{9}$	(21)
Digested	$1 - 6 \times 10^{10}$	(21)
Digested + elutriated with lime sludge	$3 - 33 \times 10^{8}$	(22)
Digested + elutriated with lime sludge + polymer	$1 - 14 \times 10^{8}$	(22)
Digested + elutriated with tap water + lime sludge + polymer	$0.7 - 5 \times 10^{8}$	(22)
Digested + elutriated with lime sludge + ferric chloride	$0.25 - 4 \times 10^{8}$	(23)
Digested + elutriated with tap water + ferric chloride and lime	$0.7 - 0.84 \times 10^{8}$	(23)

at which the filtration is carried out be known, 3) the volume of filtrate be measured at various time increments starting at the commencement of the filtration test, 4) the ratio 'w' be determined, and 5) the viscosity of the filtrate be known (this may, except in the case of very accurate work, be taken as that of water at the same temperature).

After a vacuum break has occurred or after 20 minutes elapsed time, the volume of filtrate can be determined directly. The volume of sludge cake can also be determined directly. The solids in the sludge cake can be determined as mentioned earlier or by using a standard total solids test.

Lab Centrifuge as a Measure of Sludge Centrifuge Performance

Solids retention time (flow rate to the machine) and centrifugal force are two of the most important influences on centrifuge performance. A bench-scale method for evaluating these parameters has been devised using a laboratory centrifuge (24).

It is possible to define the efficiency of centrifugation as (5):

$$\text{Percent Recovery} = \frac{C_o - C_c}{C_o} \times 100 \qquad (12)$$

where: C_c = solids concentration of the centrate
C_o = feed solids concentration

This equation is not a proper measure of centrifuge performance since it does not measure the amount of solids deposited as cake. However, the equation does yield results that are very similar. Letting C_c' designate the centrate solids concentration obtained with the laboratory centrifuge, the efficiency for a laboratory analysis becomes $(C_o - C_c')/C_o$ and would represent a quanitative estimate of the sludge settling characteristics in the laboratory centrifuge. The feed solids concentration C_o, would be identical for both the laboratory analysis and the prototype. The laboratory centrifuge term C_o', is evaluated by centrifuging a sample of sludge at the same acceleration and residence time contemplated for the prototype. Centrifugal acceleration (C.A.) is calculated as follows (5):

$$\text{C.A.(x gravity)} = \frac{r_1 + r_2}{2} \; \frac{w^2}{g} \qquad (13)$$

where: r_1 = radial distance from the center of the centrifuge to the top of the sludge, cm
r_2 = radial distance to the bottom of the centrifuge tube or inner wall of the bowl, cm
w = radial velocity, radians per second
g = gravitational constant

The residence time for the laboratory centrifuge can be estimated by the 'power on' time if the starting and stopping times are approximately equal and it is assumed that the loss in centrifugation during start-up is compensated by the time required to stop the machine (24). After spinning, the volume of centrate, solids concentration in the centrate, and volume of solids can be determined directly. The cake solids can be determined as previously mentioned or by running a standard total solids test.

EXPERIMENTAL METHODS AND TEST PROCEDURES

This study was conducted to determine whether the cost of vacuum filtration or centrifugation would be less expensive than the existing sludge disposal methods used at the Sioux Falls Water Reclamation Plant. Laboratory-scale experiments were used to simulate vacuum filter and centrifuge operations. The sludge was conditioned with polymers prior to dewatering. Well-defined methods of sampling and analyzing the sludge as recommended in _Standard Methods for the Examination of Water and Wastewater_ and as indicated in the following sections, were established to obtain reproducible and comparable data.

Sludge Sampling and Conditioning

Digested sludge samples were collected directly from the digester overflow. Testing was initiated as soon as possible after sampling. Each sample was continually stirred while the tests were conducted. The sludge-mixing apparatus is shown in Figure 9.

The polymers were obtained from the Nalco Chemical Company, Sioux Falls. Preliminary studies were conducted by personnel at the Water Reclamation Plant Laboratory and Nalco to identify the polymers most likely to successfully and economically condition the sludge. Ultimately, four polymers were selected for use in these

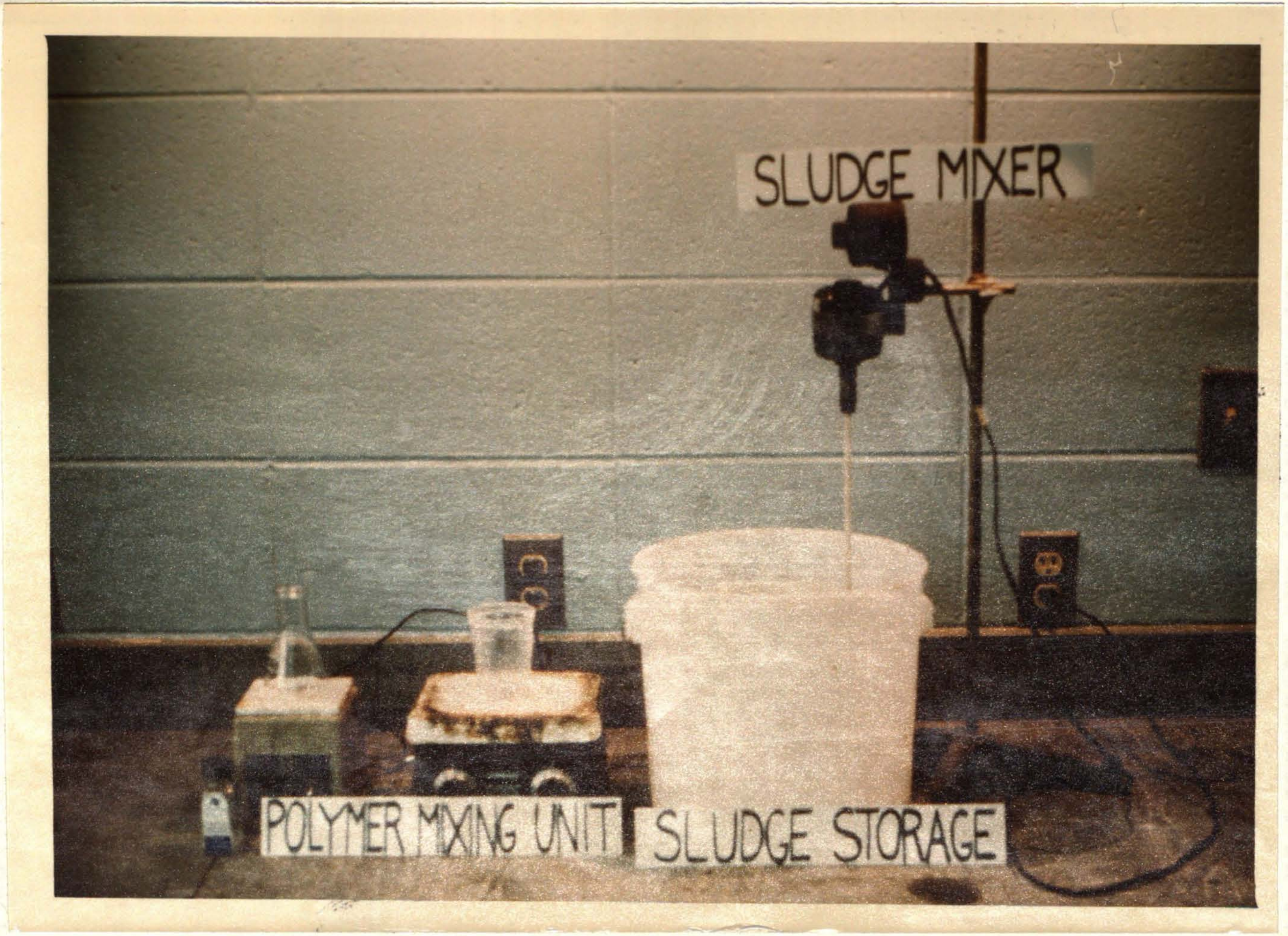

FIGURE 9

Sludge and Polymer Mixing Units

studies. Polymer 7120 was recommended as the polymer that would be the most successful and economical in conditioning the sludge. The results of these preliminary studies may be found in Appendix I.

Even with the recommendation of polymer 7120, it was decided that all four polymers would be initially tested to verify that polymer 7120 was the best choice for Sioux Falls. The four selected polymers were diluted to concentrations recommended for use at the time of sludge addition. The diluted polymer solutions were allowed to mix for one to two hours before adding to the sludge sample. The samples were continuously mixed during polymer addition. After 20 to 30 seconds of mixing, the conditioned sludge was tested. The apparatus used for diluting the polymer and mixing the polymer with the sludge can be seen in Figure 9.

Laboratory Centrifuge Test Procedure

The laboratory centrifuge apparatus used in determining the dewatering characteristics of centrifuged sludge and optimum polymer dosage is shown in Figure 10. This apparatus includes a desk-top centrifuge with heads to hold a minimum tube size of 15 ml., metal tube holders, 15 ml. spin tubes, timer, and accessory equipment for determination of centrate and cake solids. The procedure

FIGURE 10

Laboratory Centrifuge Apparatus

for this test is a modification of the procedure outlined by Vesiland (5) described as follows:

1. Calibrate the centrifuge at a speed producing about 500-1,000 times the acceleration of gravity.
2. Place 12.5 ml. of digested sludge in each of the six 15 ml. tubes.
3. Start the spin.
4. Turn off spin after allotted residence time.
5. Read the sludge-liquid level and record as percent of total (i.e. 12.5 ml. corresponds to 100 percent).
6. Pour off and measure centrate volume.
7. Determine solids content of centrate.
8. Slide sludge into tared aluminum dish to determine dry weight of cake.
9. Repeat steps 2-8 for varying dosages of each polymer used.

A spin (residence) time of two minutes was used. The centrifuge was operated at 2,400 r.p.m. (500 G). This relatively low centrifugal force was used to prevent disruption of the sludge floc formed by the polymer addition. Also, higher centrifugal speeds are normally associated with higher maintenance and repair costs (16).

The solids contents of the feed sludge, centrate and sludge cake were determined by the procedures outlined in Standard Methods (25).

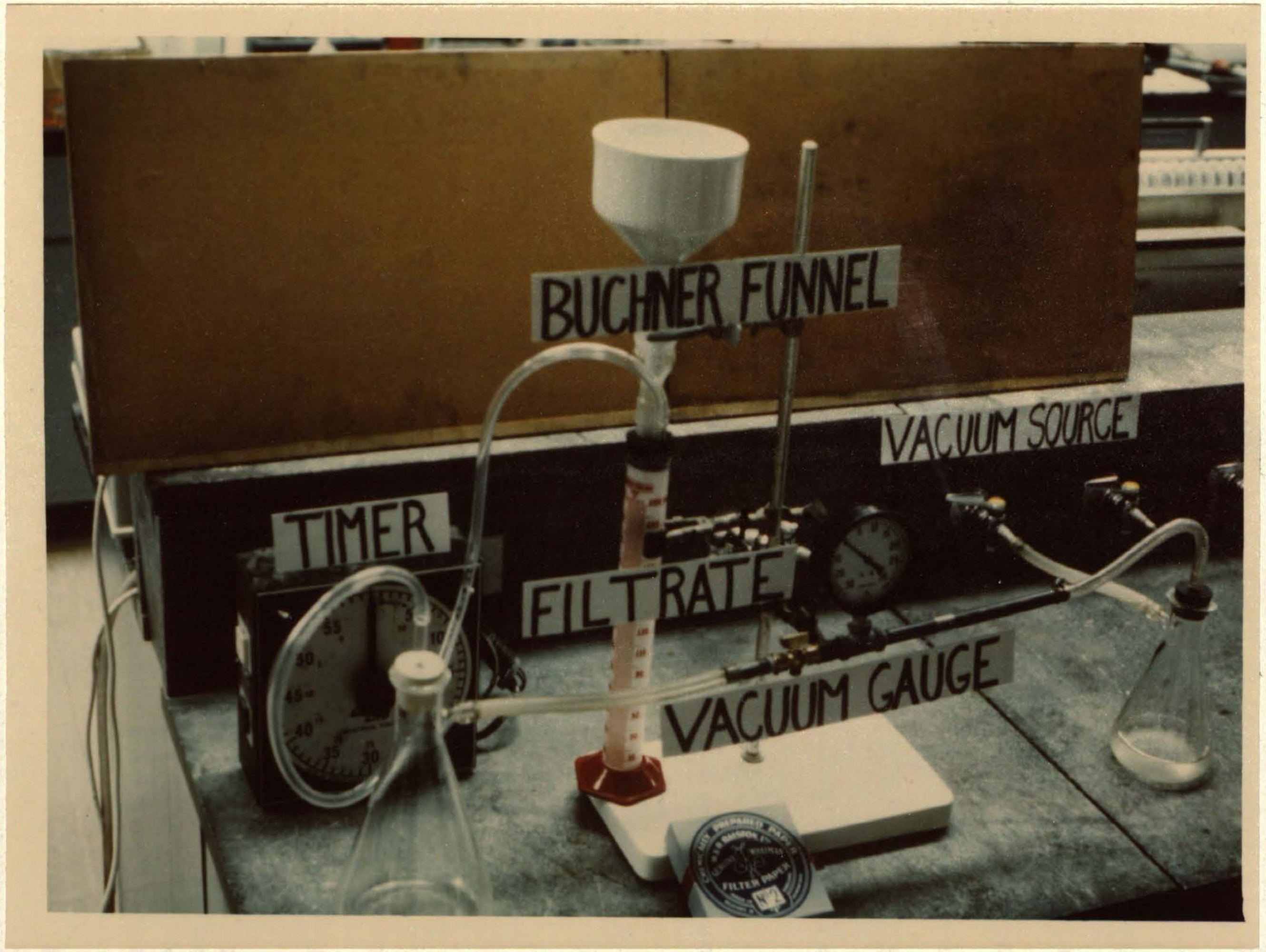

FIGURE 11

Buchner Funnel Apparatus

Buchner Funnel Test Procedures

The Buchner funnel apparatus used in determining the dewatering characteristics of vacuum filtered sludge and optimum polymer dosage for best dewatering is shown in Figure 11. This apparatus includes a Buchner funnel, vacuum source, vacuum gauge, timer, 250 ml. graduated cylinder and miscellaneous tubing and valves for pressure regulation. Whatman No. 2 filter paper, eleven centimeters in diameter, was used in the Buchner funnel.

The procedure for this test is similar to that followed by Sisk (22) and Miller (23) with slight modifications taken from Vesiland (5). The modified procedures were as follows:

1. The solids content and temperature of the feed sludge were determined.
2. A vacuum was applied to a moistened filter paper to obtain a seal.
3. The vacuum was turned off and a 100 ml. sludge sample was poured into the funnel.
4. The vacuum was left off for one minute to allow for cake formation.
5. After one minute, recorded as time zero, the liquid level in the graduated cylinder was read and recorded and a vacuum of 22 inches of mercury (10.8 psi) was applied.
6. The filtrate volume was recorded at frequent intervals until the cake cracked and a vacuum break occurred or until twenty minutes had elapsed.

7. The solids content of the final cake was determined.
8. Steps 3-7 were repeated for sludge samples treated with varying dosages of polymer.

The volume of filtrate was recorded at 30-second intervals for the first three minutes, 60-second intervals for the next five minutes, 2-minute intervals for the next four minutes and 4-minute intervals until the vacuum break occurred or until 20 minutes had elapsed. The solids contents of the initial sludge sample and final filter cake were determined according to methods described in Standard Methods (25). These results were used in determining the specific resistance of the sludge. Sample calculations for the determination of specific resistance are included in Appendix II.

Evaluating Costs of Existing Sludge Dewatering Methods

As previously mentioned, the existing sludge-dewatering and disposal method consists of lagoons and drying beds. The liquid is spread over crop land while the cake from the drying beds is hauled to a landfill for disposal. Figure 12 shows an overall view of the sludge lagoons. Cleaning of a portion of the sludge-drying beds is depicted in Figure 13. A major portion of the maintenance costs are incurred in the upkeep of the lagoons (27 acres) and drying beds (33 acres). Tankers with a liquid capacity of 8,000 gallons are used for transporting liquid sludge

FIGURE 12

Sludge Lagoons - Sioux Falls Wastewater Treatment Plant

FIGURE 13

Sludge Drying Beds - Sioux Falls Wastewater Treatment Plant from the lagoons to the drying beds and/or crop lands. Open box dump trucks are used for transporting dried sludge to the sanitary landfill.

Operational costs include 1) electricity for pumping the liquid sludge into the tankers, 2) fuel for the tankers, dump trucks and additional loading equipment at the drying beds (i.e. road grader, bulldozer, front-end loader, etc.), 3) equipment rental when necessitated, 4) wages for the operational personnel, 5) miscellaneous items not covered above. Maintenance items include 1) upkeep of the lagoons and drying beds including weed control, cleaning overflow pipes, etc., 2) repair of the sludge pumps, tankers, dump trucks and accessory equipment, 3) wages for maintenance personnel, 4) miscellaneous repairs and maintenance.

It should be noted that the amount and quality of supernatant transferred from the sludge lagoons to the headworks of the treatment plant depends on the amount of liquid sludge pumped to the lagoons along with the weather conditions during the time the sludge is in the lagoons. For example, the dry summer of 1976 resulted in virtually no supernatant return to the head of the plant. In a wet year the return of supernatant has sometimes been continuous. Another major point that had to be considered was the revenue aspect. Liquid sludge that is transported to crop land is purchased by the farmer at twenty cents per mile round trip from the lagoons to the disposal field and back in Sioux Falls. At the present time there is no market for the dried sludge in the Sioux Falls area.

PRESENTATION OF RESULTS

Preliminary Tests

The digested sludge from the Sioux Falls Wastewater Plant was originally sampled and analyzed for total and volatile solids content. The daily sludge flow was estimated based on flow records from April and May of 1976. Sampling was carried out for fourteen consecutive days in June of 1976 and two days in August of 1977. These data are presented in Table 6.

TABLE 6

Composition of Digested Sludge
from Sioux Falls Wastewater Treatment Plant

	Mean	Standard Deviation
Flow	175,000 (662 cu. m/day)	83,000
Solids concentration	1.9% by wt.	0.1
Wet sludge concentration	8.47 lb/gal (1013 gm/l)	0.78
Dry sludge concentration	0.16 lb/gal (19 gm/l)	0.01
Volatile solids concentration	0.10 lb/gal (12 gm/l)	0.004
Volatile solids in cake	64.0%	1.06

The flow range was normally 100,000 to 250,000 gallons per day. Flow was measured on the basis of sludge pump operation time. Using the average flow value of 175,000 gallons per day, 14 tons of dry solids were produced each day.

Estimated Chemical Costs for Sludge Centrifugation

Digested sludge with and without polymer addition was subjected to the centrifuge test to determine the most cost-effective polymer and approximate cost of dewatering and disposal for sludge using centrifugation. The results of these tests for the digested sludge are summarized in Appendix III, Table III-1 and depicted graphically for conditioned sludge in Appendix III, Figures III-1 through III-4. Calculations to determine the amount of polymer added to each sample are shown in Appendix IV. The dosage range for each of the four pre-selected polymers was recommended by the manufacturer as noted in Appendix I.

To determine the most cost-effective polymers, the cost of each polymer per ton of dry solids conditioned was calculated using the optimum dosage along with the unit costs obtained from the Nalco Company (Appendix V). The costs are based on the least expensive shipping quantity which is 3,000 gallons for liquid and 12-ton truckloads for pulverized. The resultant polymer costs ranged from $1.48 per ton up to $18.96 per ton with polymer 7132 the most expensive and 7763 the least expensive. However, polymer 7763 demonstrated the highest centrate solids and lowest cake solids concentration. Further inspection of Figure III-4 reveals that although polymer 7120 and 7132 were quite similar in their influences on centrifugation, polymer 7132 was three times more expensive. Also, in comparing the effects of varying dosages for the four polymers under consideration (Appendix III), it can be seen that polymer 7120 generally exhibited less sensitivity to changes in dosages near the optimum.

Estimated Chemical Costs for Vacuum Filtration

Specific resistance determinations were run on the digested sludge with and without polymers to determine the effect of polymer conditioning and the optimum polymer and its dosage should chemical conditioning appear to be worthwhile. The unconditioned sludge became so compact after 20 minutes of applied vacuum that virtually no filtration occurred. In all tests run on the unconditioned sludge, less than one-half the initial 100 ml. sample volume passed through the filter during the test period.

On the basis of recommendations from the Nalco Company and the polymer evaluation for conditioning sludge prior to centrifugation, polymer 7120 was used for the vacuum filtration studies. To determine the optimum dosage, specific resistances were determined on five digested sludge samples conditioned at several different polymer dosages. The result of these tests have been plotted in Figure 14. It can be seen from this figure that specific resistance increases with an increase in polymer dosage. At approximately the three percent dosage,

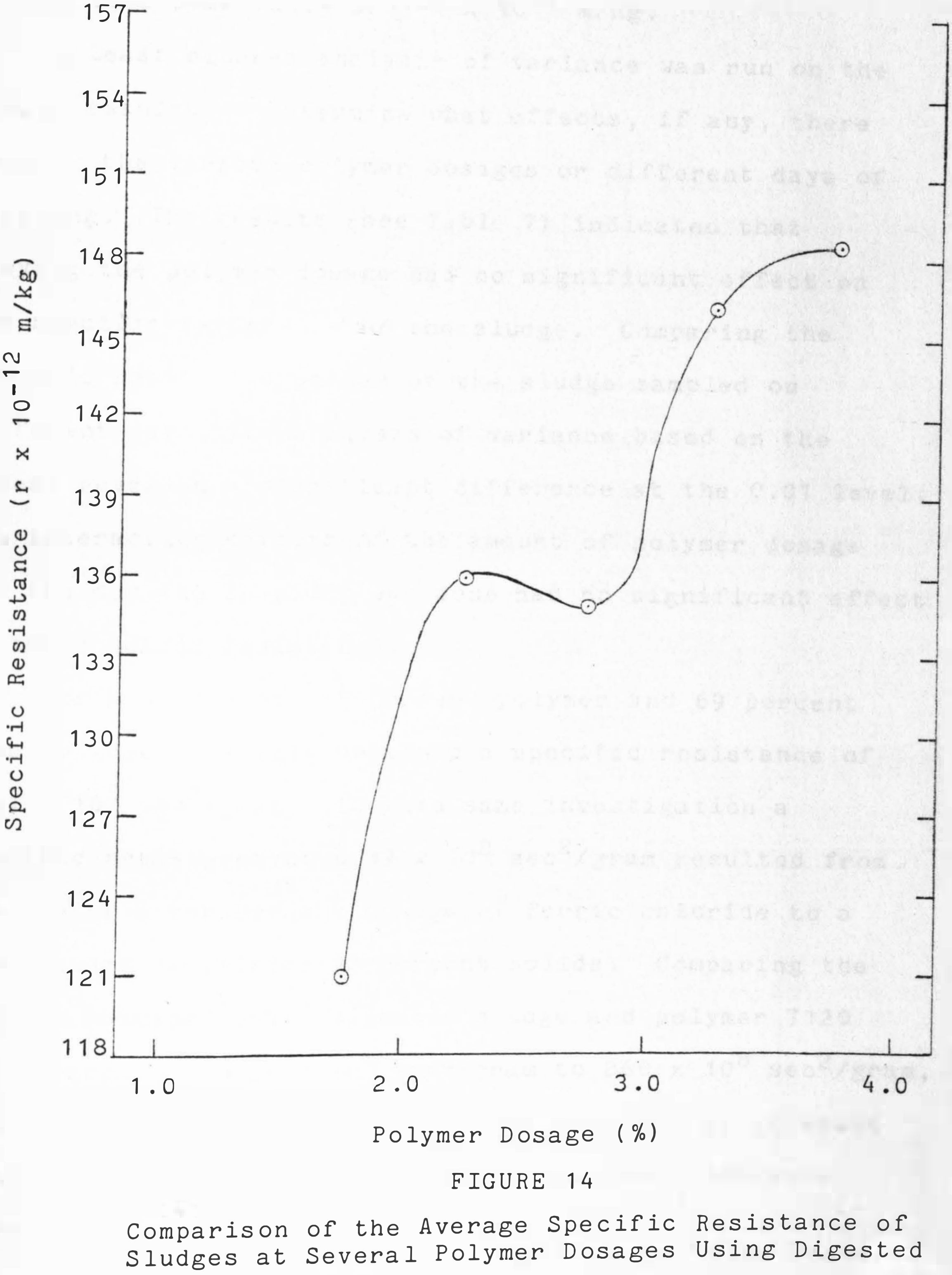

FIGURE 14

Comparison of the Average Specific Resistance of Sludges at Several Polymer Dosages Using Digested Sludge the specific resistance showed a slight decline before rising to a peak value of 149×10^{12} m/kg.

A least squares analysis of variance was run on the sample results to determine what effects, if any, there were by the various polymer dosages or different days of sampling. The results (see Table 7) indicated that varying the polymer dosage had no significant effect on the specific resistance of the sludge. Comparing the specific resistance values of the sludge sampled on different days, the analysis of variance based on the F-test revealed a significant difference at the 0.01 level. The interaction effects of the amount of polymer dosage and the day the sampling was done had no significant effect on the specific resistance.

For a dosage of six percent polymer and 69 percent lime solids, Sisk (21) obtained a specific resistance of 0.71×10^{8} sec^2/gram. In this same investigation a specific resistance of 0.69×10^{8} sec^2/gram resulted from the use of a ten percent dosage of ferric chloride to a lime sludge containing 73 percent solids. Comparing the results obtained using digested sludge and polymer 7120 which ranged from 94×10^{8} sec^2/gram to 260×10^{8} sec^2/gram, with the values reported by Sisk and in Table 5, it would appear that the values obtained with polymer 7120 were substantially higher.

TABLE 7

Summary Table for Analysis of Variance on Specific Resistance and Filter Yield

Specific Resistance

Source	D.F.	Sum of Squares	Mean Squares	F
Date	1	22,538.78	22,538.78	25.91*
Treatment	4	3,675.56	918.89	1.06
Date x treatment	4	4,628.66	1,157.17	1.33
Remainder	15	13,049.41	869.96	

Filter Yield

Source	D.F.	Sum of Squares	Mean Squares	F
Date	1	0.00877	0.008771	74.21*
Treatment	4	0.00032	0.000080	0.68
Date x treatment	4	0.00026	0.000065	0.55
Remainder	15	0.00177	0.000118	

	α	
	0.05	0.01
F_{α} (1,15)	4.54	8.68
F_{α} (4,15)	3.06	4.89

*Significant at the 0.01 level

In Figure 15, filter yield is plotted versus polymer dosage. From these plots it is evident that the maximum yields were obtained at polymer dosages of about one and three-fourths percent or 30 pounds of polymer per ton of dry solids.

Again, an analysis of variance was run to determine what effect if any the date of sampling, the amount of polymer or both parameters combined had on the resultant filter yield analysis. These results are shown in Table 7. The analysis of variance based on the F-test indicated that the amount of polymer and the interaction effects of the combined variables of polymer dosage and sampling dates had no significant effect on the filter yield. The effects of the sampling date on the filter yield was, however, quite significant at the 0.05 level.

The values for filter yield shown in Figure 15 (0.10 to 0.15 pounds per square foot per hour) appear to be about the same as those obtained by Sisk (21) using various polymer dosages with lime sludge (0.05 to 0.15 pounds dry solids/ft^2/hour at the lower lime dosages up to 0.5 lbs/ft^2/hour at the higher lime dosages). Miller (22) reported higher filter yields (as high as 2.4 pounds per square foot per hour) with lime sludge conditioned with ferric chloride. Even though the sludge conditioning showed an improvement in filter yields over unconditioned sludge, the Battelle

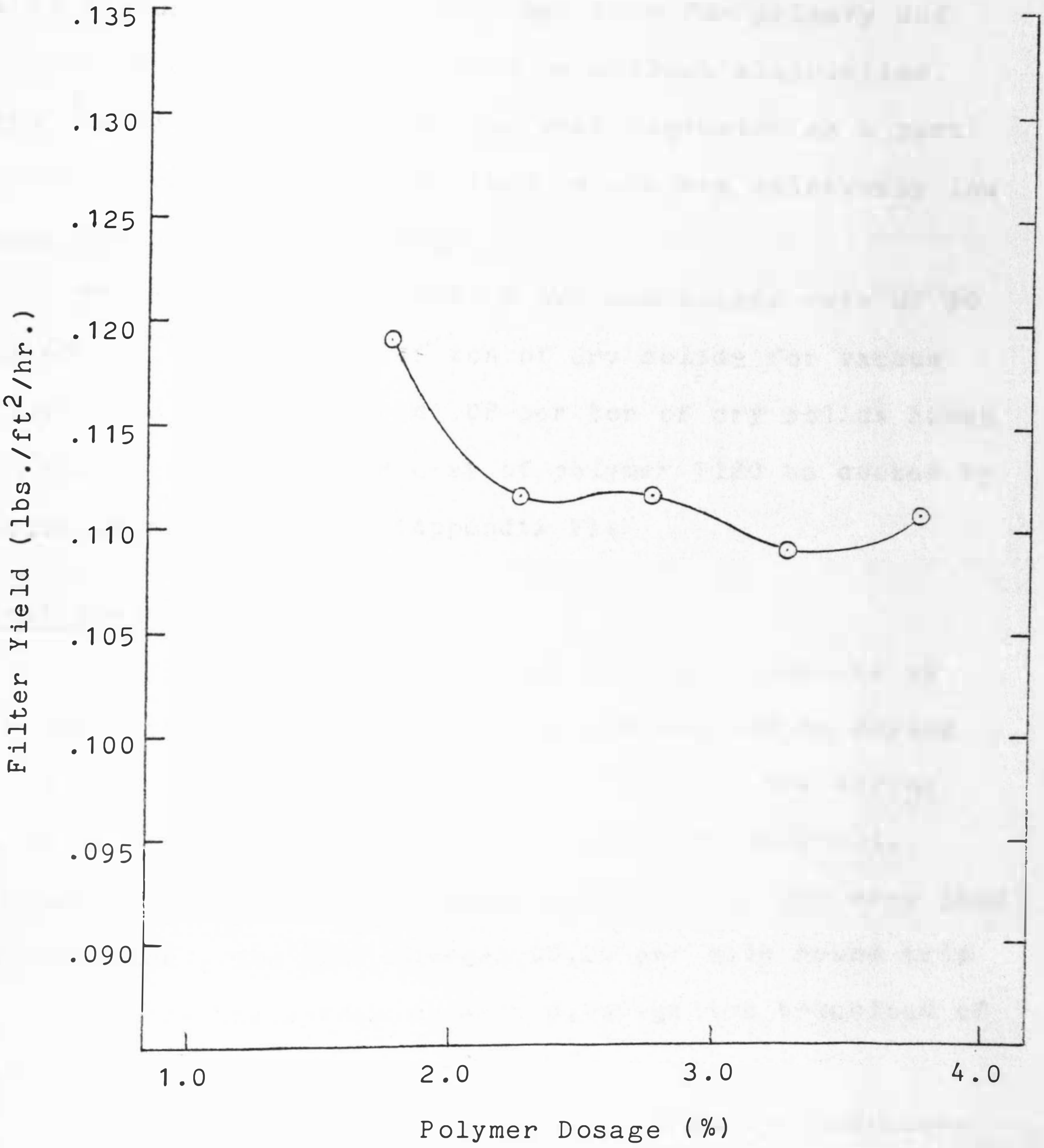

FIGURE 15

Comparison of Average Filter Yields at Several Polymer Dosages Using Digested Sludges

Institute (6) advocated typical vacuum filter yields of 4 to 5 pounds per square foot per hour for primary and activated digested sludge with or without elutriation. The yields obtained in the analyses conducted as a part of the investigations described herein are relatively low when compared to this range.

The chemical costs for an optimum dosage rate of 30 to 60 lbs. of polymer per ton of dry solids for vacuum filtration was $3.45 to $7.08 per ton of dry solids based on the $0.118 per pound cost of polymer 7120 as quoted by Nalco Chemical Company (Appendix V).

Cost Evaluation

The present method of sludge disposal consists of trucking the digested sludge from the lagoons to drying beds and/or agricultural land. Sludge from the drying beds is utilized for cover at the sanitary landfill. Farmers purchase liquid sludge from the City for crop land application. The City charges $0.20 per mile round trip for delivery and spreading each 8,000-gallon truckload of sludge.

Consequently, as long as this arrangement continues it will be unnecessary for the City to purchase any land for this method of disposal. Also, a capital outlay is not required for a landfill since the existing sanitary landfill is owned and operated by the City and adequate room is available for handling the sludge from the drying beds. Additionally, the existing drying beds and lagoons used in the land disposal scheme are also owned by the City of Sioux Falls. Since heavy equipment and dump trucks for disposal of the dried sludge will only be needed once or twice a year (the drying beds need cleaning semi-annually at the most), they can be rented from the private sector or borrowed from other City departments. Another possibility would be to purchase the equipment through a joint venture program with other City departments. However, capital expenditures will be required to purchase additional sludge hauling equipment.

Sludge hauling equipment, used sludge tankers and tractors, have been purchased from a low bidder at a cost of approximately $10,000 to $12,000 per tanker and tractor unit. In 1975 the Sioux Falls Treatment Plant averaged 2.3 tankers on the road per day over 225 working days per year. This resulted in approximately 2,268 loads or 46,000 gallons per day based on 365 days of sludge flow being hauled out of the lagoons. Of the total amount hauled, approximately 25 percent was spread on crop land and 75 percent went into the drying beds. The sludge was hauled at 4% solids with limited supernatant flow to the headworks of the Industrial Plant.

Since the treatment plant owned five tankers and maintained 2.3 on the road during working days, it can be assumed that eight tankers equivalent to existing equipment would be needed to maintain approximately five tankers on the road. The total down time of the tankers was not just maintenance problems, but included lack of operators and weather conditions. Using five tankers under the conditions of 7,500 gallons per load and five loads per day per tanker, approximately 187,500 gallons per working day could be hauled. This 187,500 gallons per working day, using 225 working days, averages out to 115,600 gallons per calendar day for the year. This figure is also based on the following assumptions:

1. The round trip haul distance from the treatment plant to the drying beds is ten miles.
2. The average round trip haul distance from the treatment plant to the crop land disposal areas is 30 miles.
3. Disposal of sludge on crop lands would be more efficient since these data were collected before a regular routine had been developed.

The annual evaporation in the Sioux Falls area exceeds the annual precipitation by eleven inches per year (26). Adding to this any seepage that may occur at one inch per year, total liquid loss in the 27 acres of lagoons amounts to over eight million gallons per year. This averages out to 24,000 gallons per calendar day. Adding this to the

115,600 gallons tanked out per calendar day, slightly more sludge is being removed than would be entering. The capital cost for an additional three units to add to the existing five tanker units would be $36,000 or $12,000 per unit. The average life for these used units will be estimated to be five years. Therefore, assuming the existing five tanker units will be supplemented with three additional units and all units will be replaced in five years, the capital cost for the existing method of disposal would be $132,000 plus $5,000 per year for miscellaneous equipment.

As mentioned earlier, operational costs include electricity, fuel, oil, maintenance and repair, wages and miscellaneous items. Based on past records at the treatment plant, these can be broken down as shown in Table 8.

TABLE 8

Operation and Maintenance Costs for Sludge Disposal at the Wastewater Treatment Plant Sioux Falls, South Dakota

		Annual Cost ($)
Lagoon maintenance		6,000
Tank truck: driver wages		40,000
fuel, oil, maintenance and repairs		25,000
Drying bed maintenance		3,000
Wages		8,000
Truck operation and maintenance		25,000
Miscellaneous		7,000
	SUBTOTAL	$114,000
Less revenue from sludge sales		8,500
	TOTAL	$105,500

The costs in Table 8 were based on actual 1975 operation and maintenance costs and increased according to the additional amount of equipment needed. It is possible that dump trucks would need to be rented at the rate of $20 per hour at a maximum of sixty days. If conditions warrant that City dump trucks were not available for hauling the dried sludge to the solid waste disposal site, then the dried sludge could be stockpiled at the drying beds until the sludge could be transported. This would result in removing the sludge from the drying beds with a minimum of cost in rental equipment.

To reconstruct the existing facilities to adapt either vacuum filtration or centrifugation will involve capital improvements on almost the same order. The sludge quantities, thickeners and anaerobic digesters would remain the same for any of the three methods under study (vacuum filtration, centrifugation or the existing method of lagooning and land spreading with drying beds). This would mean that the digester overflow would be pumped directly into the mechanical dewatering device to be used. The building used to house the dewatering equipment, the trucks for hauling the sludge cake, the sludge pumping station and miscellaneous piping and equipment would be nearly identical capital expenditures for either of the mechanical dewatering devices. The major difference in capital expenditure for either mechanical dewatering device would be the dewatering mechanism itself. Assuming these dewatering devices would not vary considerably in cost, the cost evaluation done in the 201 Wastewater Facilities Plan for Sioux Falls, South Dakota (2) which is shown in Table 9 would be appropriate.

TABLE 9

Capital Cost Summary for Sludge Dewatering Facilities at Sioux Falls, South Dakota (2)

Vacuum filters	$ 607,500
Building	400,500
Sludge hauling trucks	100,000
Sludge pumping station with miscellaneous equipment	122,000
TOTAL	$1,230,000

It has been assumed that three vacuum filters were to be installed and operate approximately 36 hours per week. Other assumptions include the following:

1. 138,000 gallons per day at four percent solids underflow from the thickeners.
2. Total suspended solids feed to the digesters of 46,280 pounds per day at four percent solids and 39,705 pounds per day of volatile solids.
3. Sludge feed to filters of four percent solids.
4. Filter yield of four pounds per hour per square foot with a cake solids of 20 percent.

It should be noted again that these numbers are only preliminary values used to determine estimated capital, operational and maintenance costs.

Since earlier tests have indicated that the flow from the digesters is actually 1.9 percent solids and not four percent, some type of thickening device would be needed. It has been assumed that the fourth digester (only three are presently being used) can be used as a secondary digester at a capital cost of $150,000. Increasing the solids in the feed sludge to the filter will increase the filter yield to the projected four pounds per hour per square foot.

The Facilities Plan also evaluated probable operational and maintenance costs that would be involved in the operation previously described. These estimated operation and maintenance costs can be seen in Table 10. All costs are based on one year's operation under the previously-mentioned conditions.

TABLE 10

Operation and Maintenance Costs
For Proposed Sludge Dewatering Facilities
At Sioux Falls, South Dakota (2)

Sludge Dewatering	
Power costs	$ 4,000
Labor	15,000
Chemical	118,000
Repair and miscellaneous	11,100
Hauling and Landfilling	
Labor	44,600
Truck operation and maintenance	23,200
TOTAL	$215,900

The landfill charges have been left off this list as compared to the Facilities Plan from which the list was made. Since the City owns the landfill, it is assumed that, as is presently done, dewatered sludge is used as a final cover at the landfill and, therefore, is not charged as the solid waste. Other assumptions include sludge truck capacities of six cubic yards, 40-mile round trips and 15 cents per mile for fuel, oil and truck maintenance and repair.

The major expenditure in Table 10 was for the chemicals. Previously in this report it was shown that chemical costs were $6.50 per ton of dry solids with a centrifuge and up to $7.10 per ton of dry solids with a vacuum filter. These values were based on a digested sludge flow of 175,000 gallons per day at 1.9 percent solids concentration. At 14 tons of dry solids per day, chemical costs would be in the range of $35,000 per year and not $118,000. Therefore, the total operation and maintenance costs would be nearer $132,900 per year.

TABLE 11

Summary of Costs for Sludge Dewatering and Disposal at Sioux Falls, South Dakota

Sludge lagoons and drying beds	
Operation and maintenance	$ 105,500
Capital	182,000
Vacuum filters	
Operation and maintenance	132,900
Capital	1,230,000
Centrifuges	
Operation and maintenance	132,900
Capital	1,230,000

As indicated in Table 11, the existing method of sludge dewatering and disposal by lagooning is slightly less than the proposed methods of vacuum filtration and centrifugation. This alone would not be a major influence upon the choice. However, when comparing the capital costs of the various methods, expanding the scope of the existing dewatering scheme is considerably less expensive than changing over to vacuum filtration or centrifugation.

CONCLUSIONS

The following conclusions were drawn from the laboratory results used to evaluate the feasibility and costs of mechanical dewatering of digested sludge with disposal as opposed to the existing methods of disposal:

1. The combined primary and secondary anaerobically digested sludge produced at the Sioux Falls Wastewater Treatment Plant requires conditioning before dewatering with a vacuum filter or centrifuge.
2. The addition of a cationic polymer to the wastewater sludge was beneficial in the dewatering process.
3. The addition of a cationic polymer did not aid the dewatering process for vacuum filtering as much as it did for the centrifuge.
4. The operation and maintenance and capital costs for dewatering by mechanical means is highly dependent on the concentration of solids in the feed sludge and the sludge yields desired.
5. The estimated capital costs for continuing with the present method of sludge dewatering and disposal is considerably less than the capital costs required for a vacuum filtration or centrifugation type process.

6. The operation and maintenance costs for continuing with the present method of sludge disposal as compared to vacuum filtration or centrifugation is slightly less.

FUTURE STUDY

During these studies to evaluate the comparative costs of possible dewatering schemes as opposed to the present method, several alternatives were noted that may warrant future investigations:

1. A pilot plant could be set up utilizing a vacuum filter and a centrifuge to more accurately evaluate their operation and maintenance costs as well as their efficiency.
2. Future sludge studies should be completed to determine the effect of continued application of sludge to agricultural land.
3. Future studies could be done to determine the effect of varying the feed sludge solids concentration before mechanical dewatering.
4. Future studies could be done to determine the effect of varying the temperature of the sludge before mechanical dewatering.

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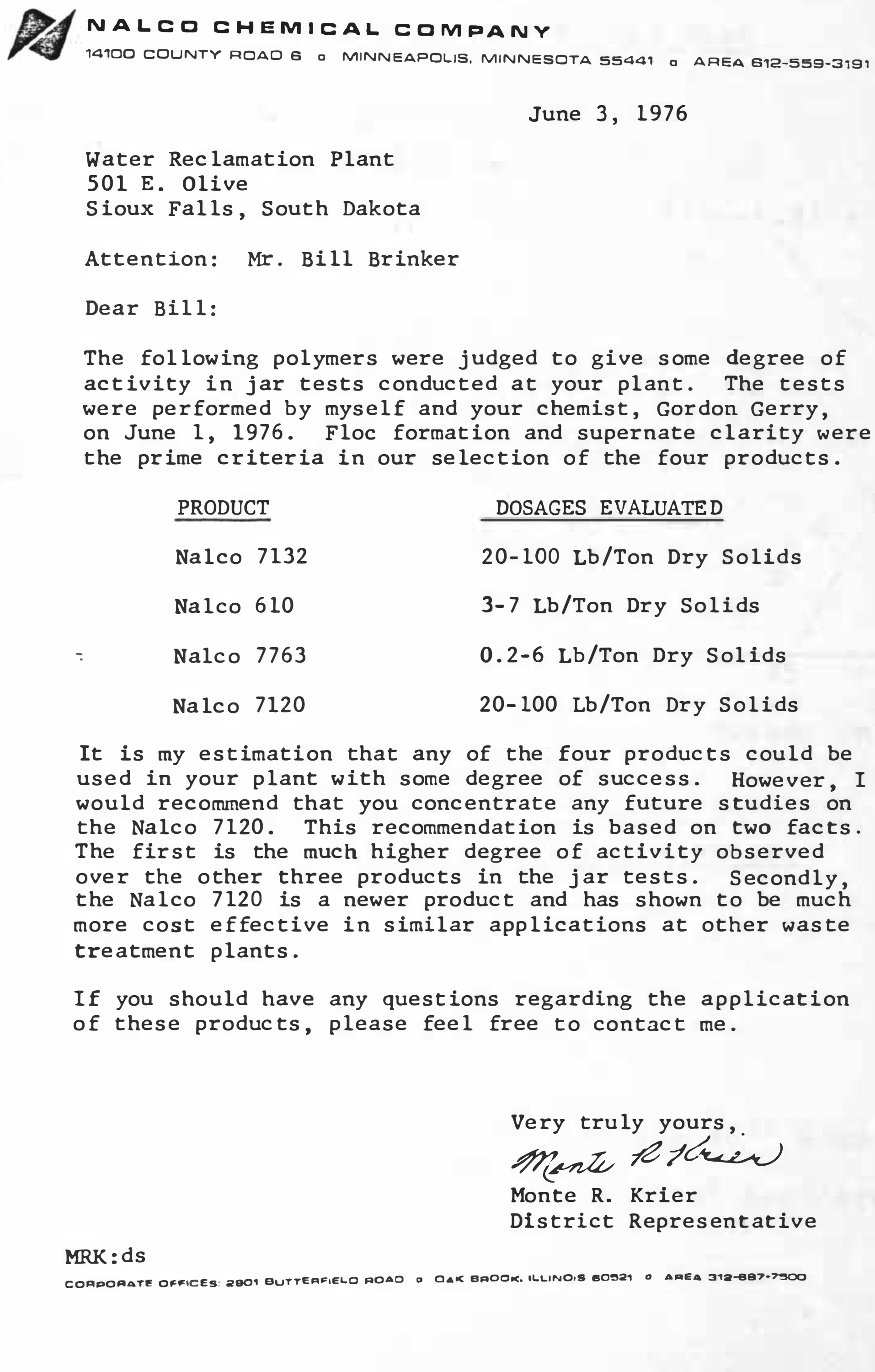
APPENDIX I
Letter of Recommendation from the Nalco Chemical Company on the Type and Amount of Polymer to Use



NALCO CHEMICAL COMPANY
14100 COUNTY ROAD 6 ▫ MINNEAPOLIS, MINNESOTA 55441 ▫ AREA 612-559-3191

June 3, 1976

Water Reclamation Plant
501 E. Olive
Sioux Falls, South Dakota

Attention: Mr. Bill Brinker

Dear Bill:

The following polymers were judged to give some degree of activity in jar tests conducted at your plant. The tests were performed by myself and your chemist, Gordon Gerry, on June 1, 1976. Floc formation and supernate clarity were the prime criteria in our selection of the four products.

PRODUCT	DOSAGES EVALUATED
Nalco 7132	20-100 Lb/Ton Dry Solids
Nalco 610	3-7 Lb/Ton Dry Solids
Nalco 7763	0.2-6 Lb/Ton Dry Solids
Nalco 7120	20-100 Lb/Ton Dry Solids

It is my estimation that any of the four products could be used in your plant with some degree of success. However, I would recommend that you concentrate any future studies on the Nalco 7120. This recommendation is based on two facts. The first is the much higher degree of activity observed over the other three products in the jar tests. Secondly, the Nalco 7120 is a newer product and has shown to be much more cost effective in similar applications at other waste treatment plants.

If you should have any questions regarding the application of these products, please feel free to contact me.

Very truly yours,
Monte R Krier
Monte R. Krier
District Representative

MRK:ds

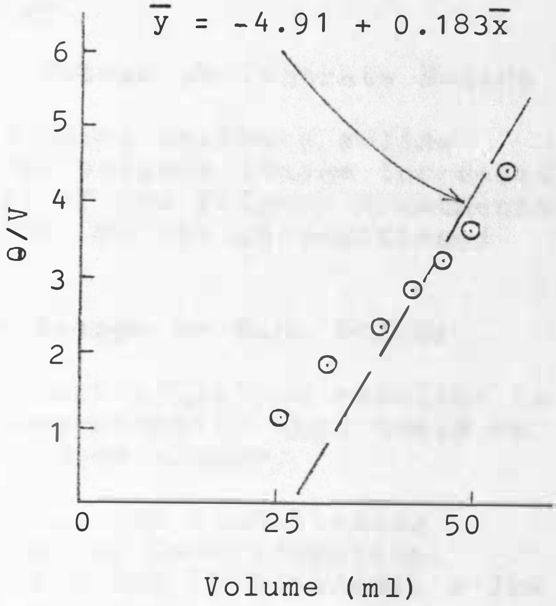
CORPORATE OFFICES: 2901 BUTTERFIELD ROAD ▫ OAK BROOK, ILLINOIS 60521 ▫ AREA 312-887-7500

APPENDIX II
Sample Calculation for the Determination of Specific Resistance

Conditioning Agent - Nalco polymer 7120
Dosage - 1.75%

Results of Buchner Funnel Test

sec	V ml	V(corr) ml	θ/V corr sec/ml
-60	12	-	-
0	13	0	-
30	39	26	1.15
60	46	33	1.82
90	51	38	2.37
120	55	42	2.86
.	.	.	.
.	.	.	.
.	.	.	.
1200	101	88	13.64



slope by least squares method - n=15

$$\text{slope } b = \frac{SSxy}{SSx} = 0.183$$

$$\text{intercept } a = \bar{y} - b\bar{x} = -4.91$$

best fit line

$$\bar{y} = -4.91 + 0.183\bar{x}$$

Determination of Specific Resistance

$P = 10.8 \text{ psi} = 7.46 \times 10^4 \text{ N/m}^2$
$A = 95 \text{ cm}^2 = 0.0095 \text{ m}^2$
$u = 0.011 \text{ poise} = 0.0011 \text{ Ns/m}^2$
$b = 0.183 \times 10^{12} \text{ sec/m}^6$
$W = \frac{1.75 \text{ gr dry solids in cake}}{88 \text{ ml of filtrate}}$
$w = 0.01975 \text{ g/ml} = 19.75 \text{ kg/m}^3$

$$\text{Specific Resistance} = r = \frac{2bPA^2}{uw} = 113.4 \times 10^{12} \text{ m/kg or}$$
$$115 \times 10^8 \text{ sec}^2\text{/gram}$$

APPENDIX III

Verification of Polymer Recommendation by the Nalco Chemical Company

TABLE III-1. Results of the centrifuge tests on the digested sludge without polymer addition.

FIGURE III-1. Effect of Polymer Dosage on Cake Volume. With the exception of polymer 7763, the cake volume decreased as the polymer dosage increased. It should be noted that the polymer tested sludge-cake volumes were all less than that of untreated sludge.

FIGURE III-2. Effect of Polymer Dosage on Centrate Solids Concentration.
Polymer 7132 was the only one in which centrate solids concentrations were reduced as the polymer dosage increased. Also, the centrate solids for all of the polymer treatments were less than the centrate solids for the unconditioned sludge.

FIGURE III-3. Effect of Polymer Dosage on Cake Solids Concentration.
Conditioning the sludge prior to centrifugation resulted in a sludge cake higher in solids concentration than could be obtained by centrifuging unconditioned sludge.

TABLE III-2. Optimum Polymer Dosage for Conditioning Digested Sludge Prior to Centrifugation.
Selection was made on the basis of a low cake volume, a low centrate solids concentration, and a high cake solids concentration. To minimize chemical costs, the lowest effective dosage of each polymer was chosen as the optimum.

FIGURE III-4. Comparison of Optimum Polymer Dosages.
It is evident that the cake volumes and solids concentrations are generally of the same magnitude whereas considerable differences are apparent in centrate solids.

TABLE III-1

Centrifuge Test on Digested Sludge

	Mean	Standard Deviation
Centrate		
Volume	8.3 ml	0.3
Solids concentration	475 mg/l	190
Cake		
Volume	4.2 ml	0.3
Solids concentration	45.8 gm solids/liter of cake	4.3
% by volume after spin	35	0.6

TABLE III-2

Optimum Polymer Dosage for Conditioning Digested Sludge Prior to Centrifugation

Polymer	Dosage(lb/dry ton)
7132	40
7120	55
7763	2
610	5

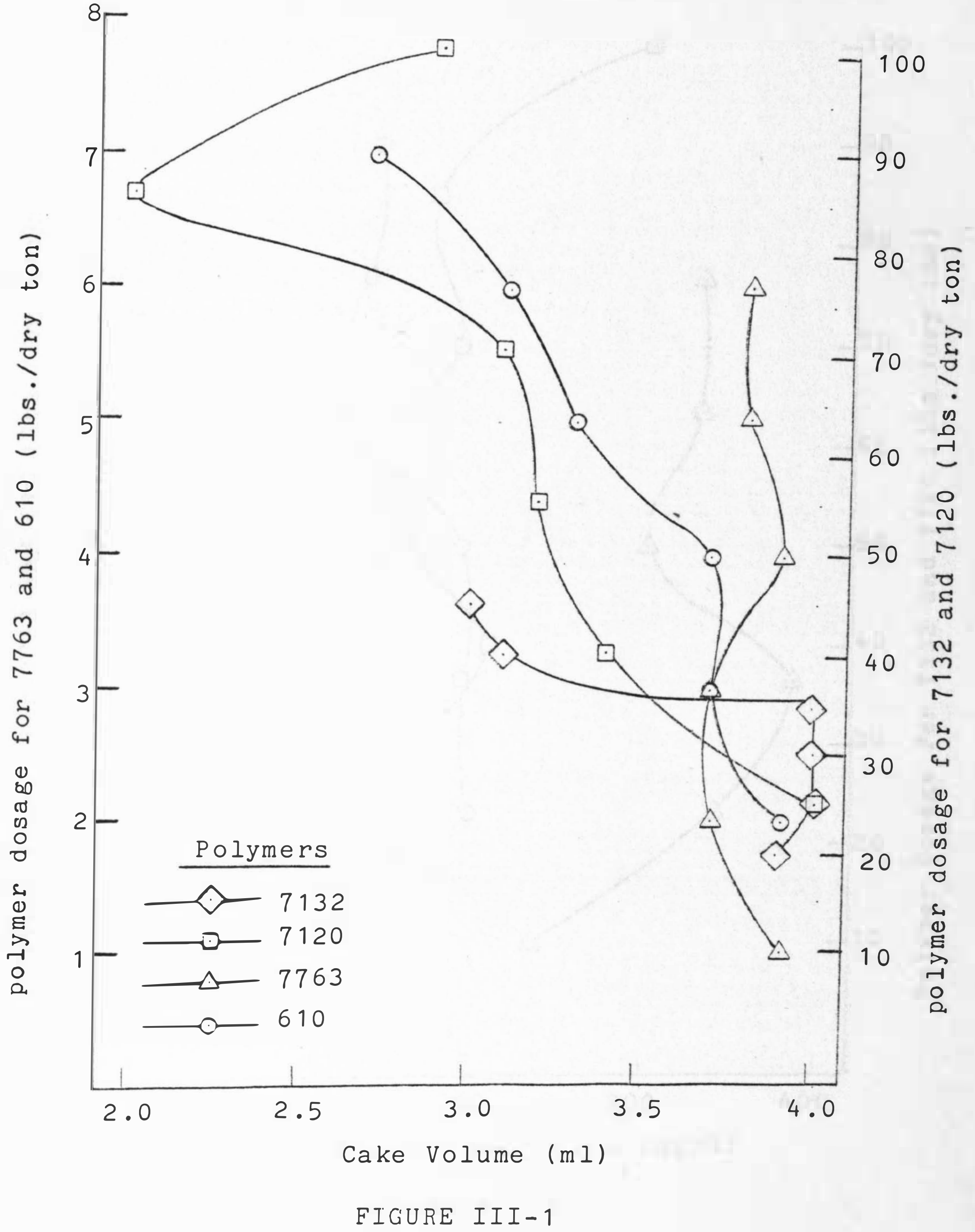


FIGURE III-1

Effect of Polymer Dosage on Cake Volume

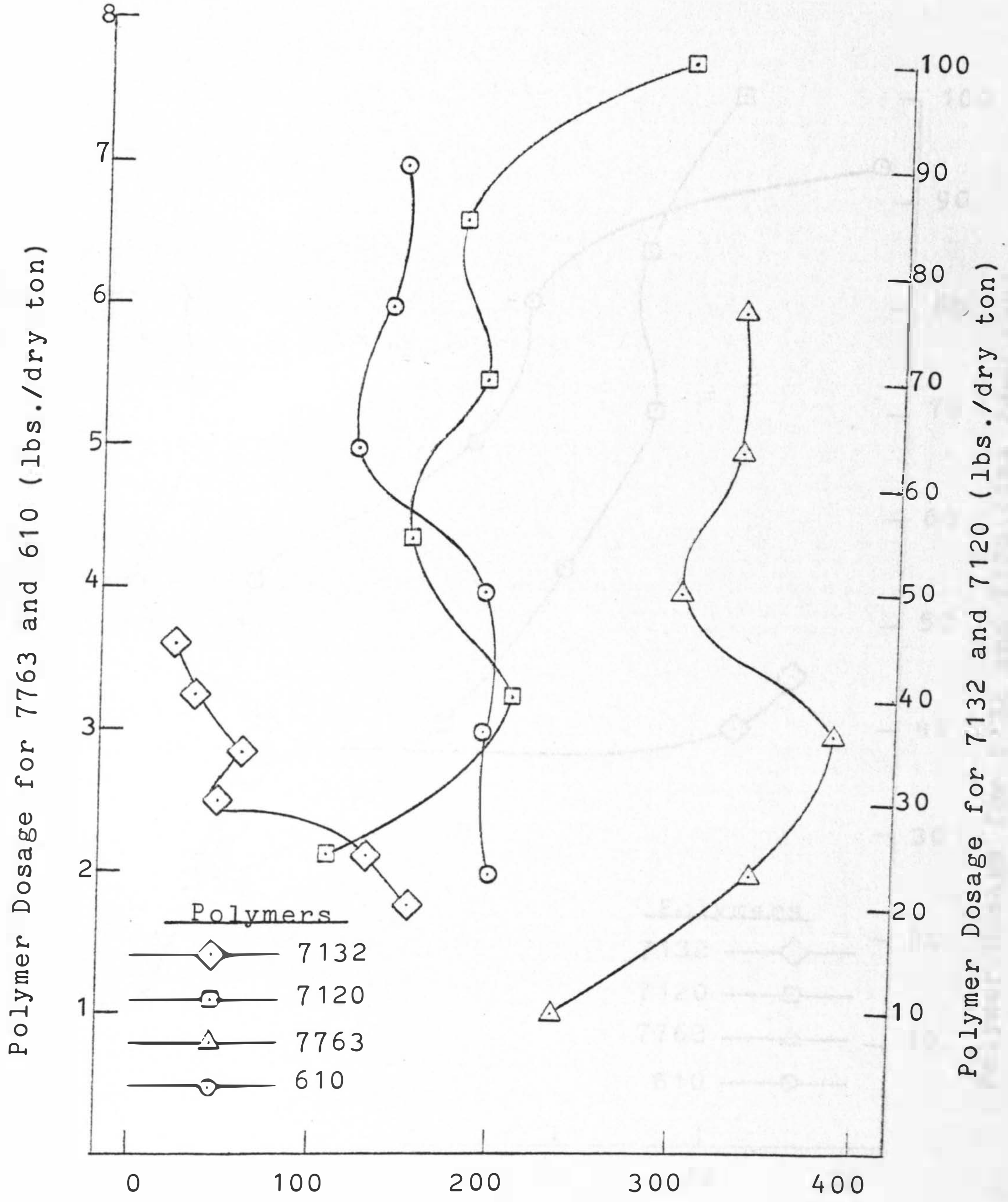


FIGURE III-2

Effect of Polymer Dosage
on Centrate Solids Concentration

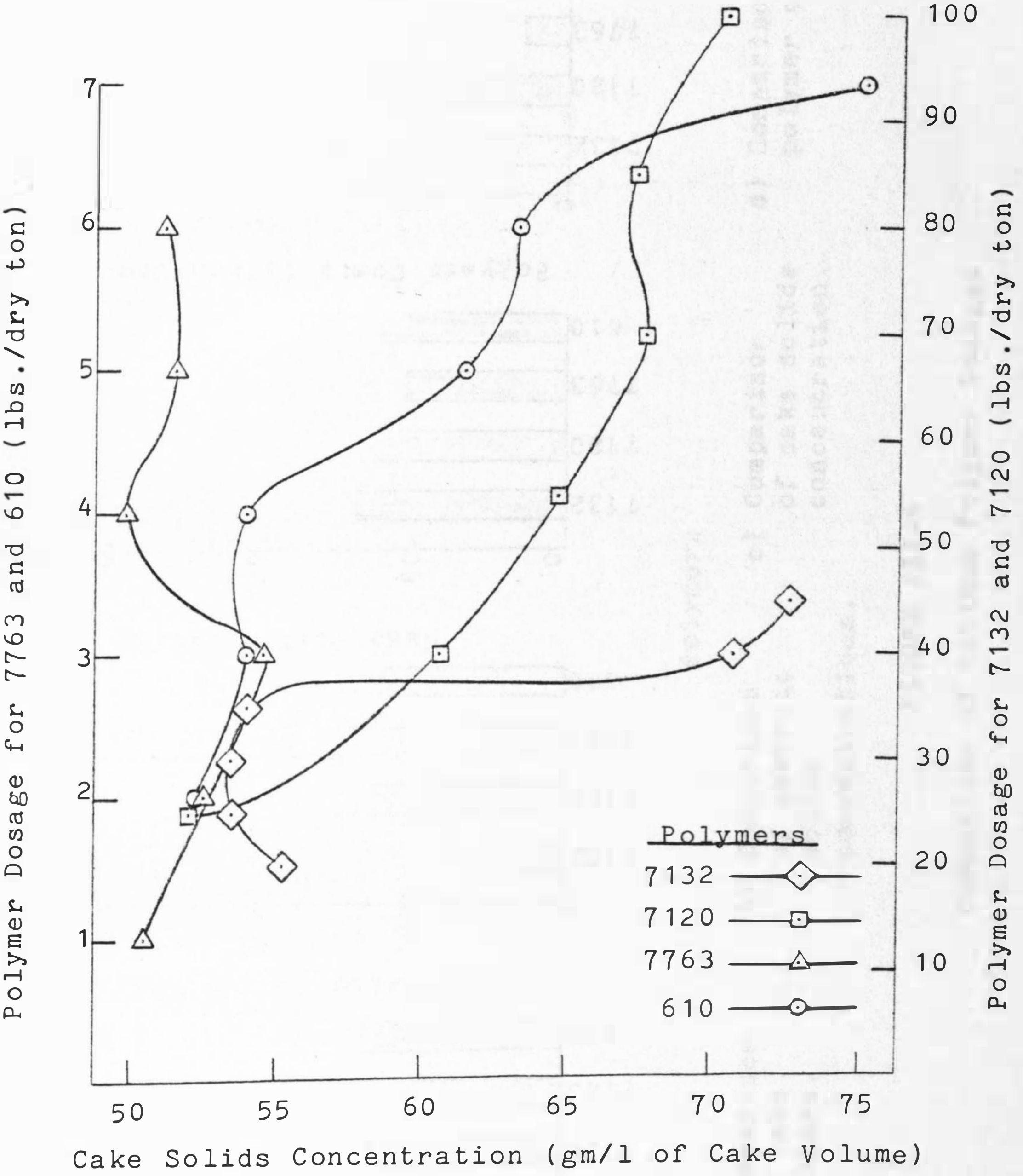
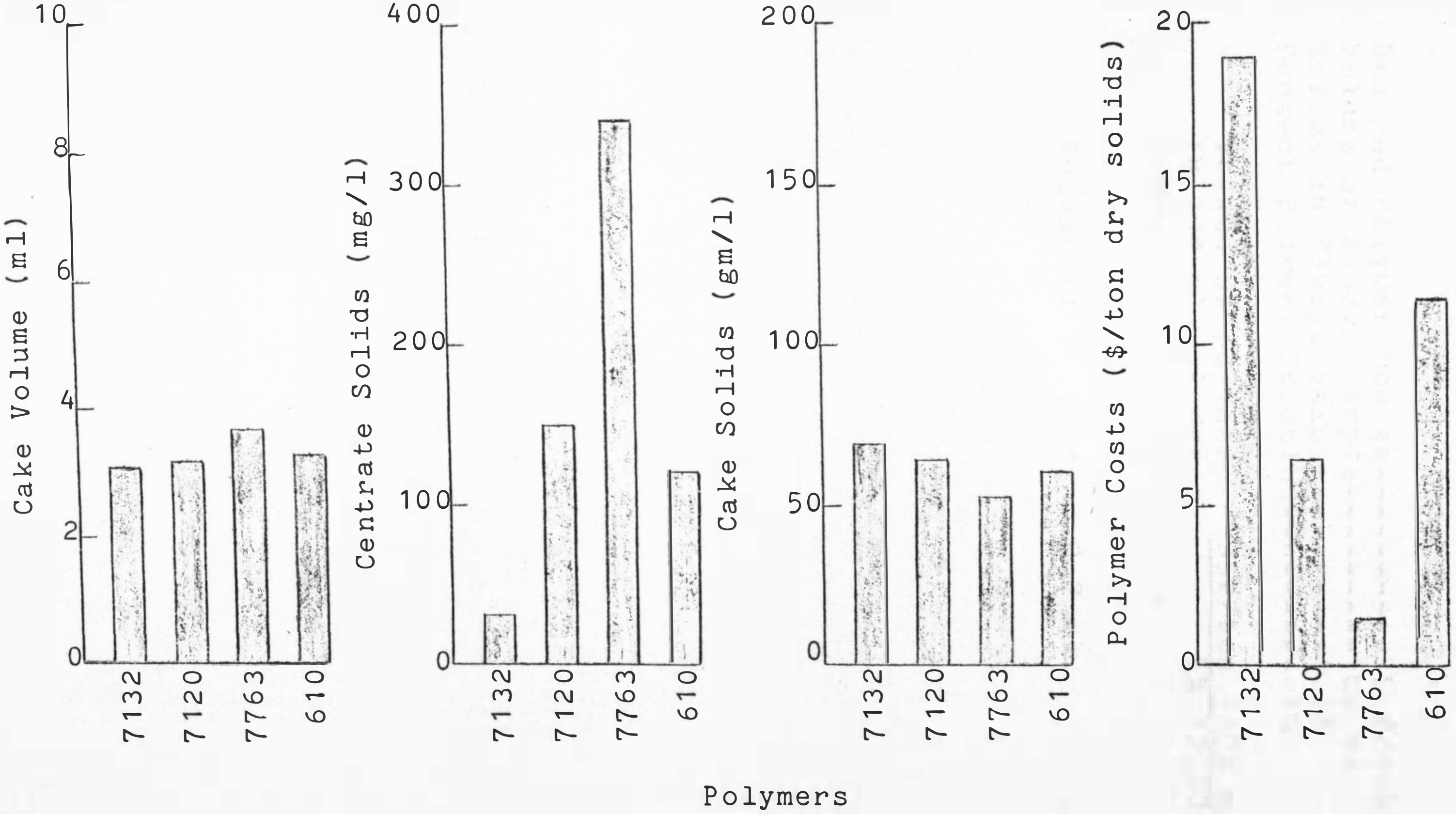


FIGURE III-3

Effect of Polymer Dosage
on Cake Solids Concentration



a) Comparison of cake volumes.

b) Comparison of centrate solids concentrations.

c) Comparison of cake solids concentration.

d) Comparison of polymer costs.

FIGURE III-4

Comparison of Optimum Polymer Dosages

APPENDIX IV

Sample Calculation of Polymer Dosage in mls. to 100 mls. of Test Sample of Sludge

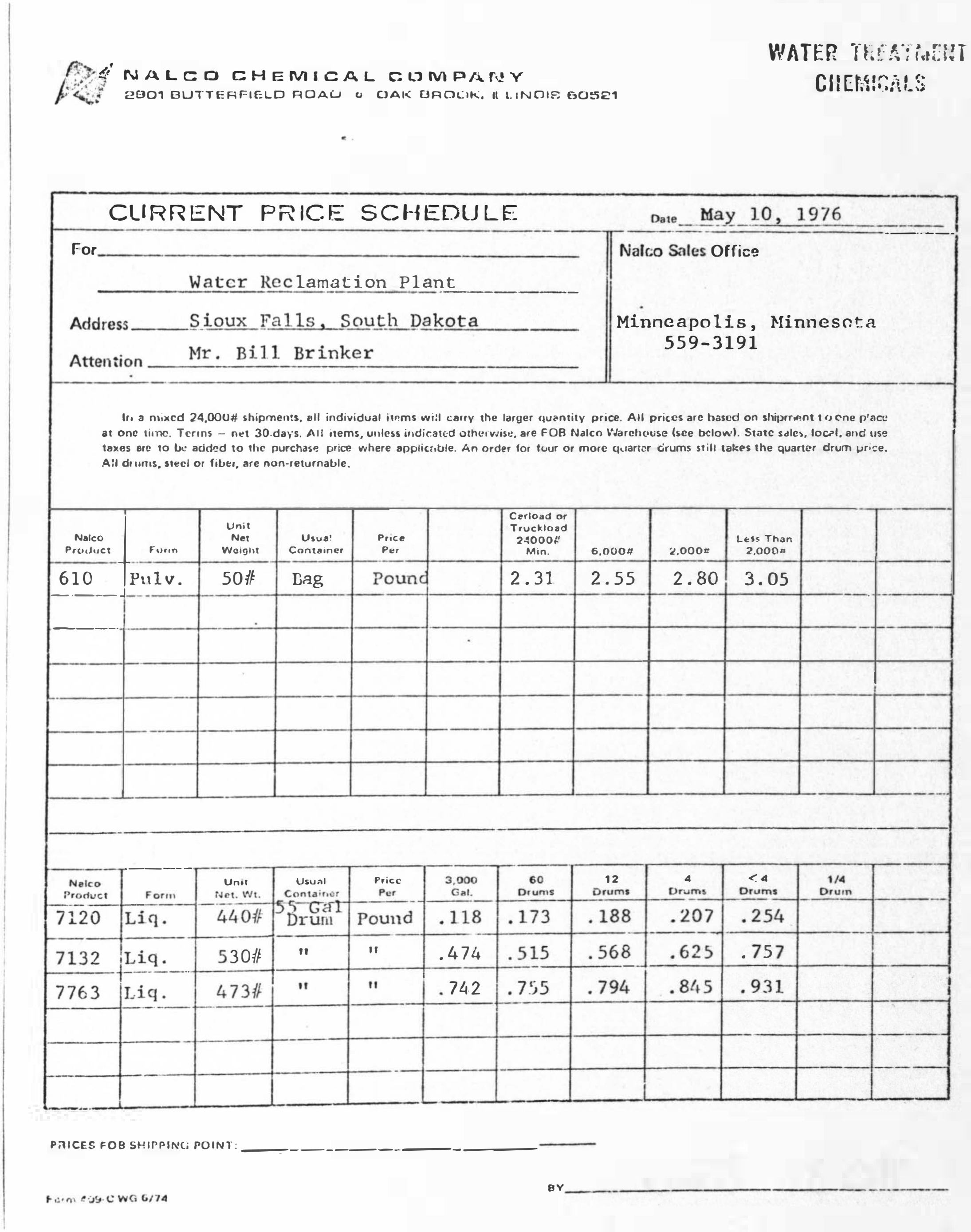
Desired Polymer Dosage----------35 #/ton dry solids (1.75%)
Volume of Sludge Sample---------100 ml.
Solids in Sludge Sample---------1.9%
Percent Polymer Solution----------5%

Volume of polymer in 100 ml. sludge sample =

$$\frac{35\#/\text{ton}\ (100\ \text{ml.})\ 1.9\%}{5\%\ (2{,}000)}$$

Volume of polymer = 0.7 ml.

APPENDIX V
The Current Price Schedule for the Polymers Under Study from the Nalco Chemical Company



NALCO CHEMICAL COMPANY
2901 BUTTERFIELD ROAD • OAK BROOK, ILLINOIS 60521

WATER TREATMENT CHEMICALS

CURRENT PRICE SCHEDULE

Date May 10, 1976

For

Water Reclamation Plant

Address Sioux Falls, South Dakota

Attention Mr. Bill Brinker

Nalco Sales Office

Minneapolis, Minnesota
559-3191

In a mixed 24,000# shipments, all individual items will carry the larger quantity price. All prices are based on shipment to one place at one time. Terms – net 30-days. All items, unless indicated otherwise, are FOB Nalco Warehouse (see below). State sales, local, and use taxes are to be added to the purchase price where applicable. An order for four or more quarter drums still takes the quarter drum price. All drums, steel or fiber, are non-returnable.

Nalco Product	Form	Unit Net Weight	Usual Container	Price Per		Carload or Truckload 24000# Min.	6,000#	2,000#	Less Than 2,000#		
610	Pulv.	50#	Bag	Pound		2.31	2.55	2.80	3.05		

Nalco Product	Form	Unit Net. Wt.	Usual Container	Price Per	3,000 Gal.	60 Drums	12 Drums	4 Drums	< 4 Drums	1/4 Drum	
7120	Liq.	440#	55 Gal Drum	Pound	.118	.173	.188	.207	.254		
7132	Liq.	530#	"	"	.474	.515	.568	.625	.757		
7763	Liq.	473#	"	"	.742	.755	.794	.845	.931		

PRICES FOB SHIPPING POINT: ____________

BY ____________

Form 409-C WG 6/74