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HYDRAULIC TRANSPORTATION AND SOLIDS SEPARATION OF EXCAVATED MATERIALS IN TUNNELS

Second Year Report
January 1977

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16. Abstract

Hydraulic transportation of tunnel muck can be safe and economical; however, it is not in wide use except in the Twin Cities area of Minnesota. There, it was developed along with hydraulic cutting for tunneling in the weak St. Peter sandstone. This combination has produced some of the lowest cost urban civil works tunnels in the United States. Most of the system used in the St. Peter sandstone could be used in soils and various soft rocks of other areas. It is the objective of this research project to increase the use of hydraulic transportation for tunnel muck by documenting the system which is now in use and by developing solids-water separation methods which will make the system compatible with the urban environment.

Systems for solids-water separation have been designed based on tests at the laboratory scale. Three basic systems are proposed: discharge into public waters, disposal into sanitary sewers or re-use in the tunneling operation. These systems would add about thirty dollars per lineal foot of tunnel (8ft ID) for a total cost of about $630. The system for re-use of the water will be tested in the field at full scale.

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INTRODUCTION

Approximately forty years ago, a method of hydraulic tunneling was developed for the weak St. Peter Sandstone underlying the Minneapolis - St. Paul area of Minnesota. The process, which consisted of cutting and disintegrating the sandstone with low pressure water jets and pumping the resulting slurry out of the tunnel, proved to be safe and economical. It has been so successful, in fact, that essentially the same technology is used today to construct some of the lowest cost urban tunnels in the nation. ($500 to $600 per lineal foot of tunnel based on an eighty-five square foot cross-sectional area and including the costs of hydraulic excavation, temporary ground support, and permanant lining.)

While the method is not extensively used outside of the Minneapolis - St. Paul area, it could be adapted for use in the tunneling of soils and some rock in other areas.

This research effort coincided with a renewed tunnel construction program in the Twin Cities area. The City of St. Paul initiated the excavation of about 12000 feet of storm sewer tunnel in May of 1974 and completed excavation in September of 1975. (This operation is documented in Report No. DOT-HTT-75-1.) A second project, undertaken by the City of Minneapolis and consisting of about 11000 feet of storm sewer tunnel, was begun in March of 1975 and is currently in progress. These operations provided for the firsthand study of the techniques and problems of hydraulic tunneling.

Scope

A major problem of hydraulic tunneling is the disposal of wastewater produced by the operation. In the past, this slurry was pumped into a small clarification tank where the coarse material settled out while the liquid and fine solids overflowed; the overflow was then discharged either into the Mississippi River or a sanitary sewer. However, today's stringent standards of discharge of effluents into public waters and the high costs of usage of the sanitary sewer provide incentive for the development of some alternate treatment system for hydraulic tunneling wastes. This report is directed toward that goal.

The body of the report is divided into two parts. The first part contains the following: a description of the present Minneapolis tunneling operation and its waste stream characteristics, a summary of relevant water quality standards, and design recommendations and economic analyses for several wastewater treatment systems. The second part deals with various liquid-solids separation processes, equipment components, and accessories, and evaluates them for possible utilization in a hydraulic tunneling wastewater treatment system. If the reader is unfamiliar with wastewater treatment process, he/she may find it advantageous to read Part II prior to the reading of Part I.

Conclusions

The results of this study indicate that the treatment of hydraulic tunneling wastewater is both technically and economically feasible. Three basic treatment systems are proposed:

1. Option 1 System - Produces effluent of a quality which is adequate for the discharge to public waters (suspended solids concentration less than thirty milligrams per liter and pH in the range of 6.5 to 8.5).
2. Option 2 System - Produces effluent of a quality which is adequate for disposal in sanitary sewers (removes material which could conceivably clog sewers and adjusts pH to within the range of 5.5 to 9.5).
3. Option 3 System - Produces effluent of a quality which is adequate for re-use in the tunneling operation (suspended solids concentration less than 180 milligrams per liter about ninety-five percent of the time).

Utilizing parameters of the Minneapolis tunneling operation and based on a hypothetical two mile long, eighty-five square foot cross-sectional area tunnel, each of the above systems was "costed out". Table I-1 briefly summarizes the costs of the various systems.

Table I-1
Costs for Treatment of
Hydraulic Tunneling Wastewater

Cost of Item	Option 1	Option 2	Option 3
Initial Investment	$157000-$213000	$272000	$126000-$181000
Total Cost*	$345000-$360000	$377000	$257000-$285000
Cost per Lineal Foot of Tunnel	$33-$34	$36	$24-$27
Cost per Cubic Yard of Excavation	$10-$11	$11	$8-$9

* Includes all foreseeable capital and operating costs minus salvage value.

The reader will note that treatment costs presented on a "per lineal foot" basis are about four to seven percent of the total construction costs cited above. Thus, the wastewater treatment processes should not impose an extreme economic burden on the entire hydraulic tunneling method.

PART I

EXAMINATION OF HYDRAULIC TUNNELING OPERATIONS IN THE ST. PETER SANDSTONE AND DESIGN AND ECONOMIC ANALYSIS OF TREATMENT PROCESSES FOR HYDRAULIC TUNNELING WASTEWATER

Chapter 1

HYDRAULIC TUNNELING OPERATIONS

Two major hydraulic tunneling operations have been undertaken in the Minneapolis-St. Paul metropolitan area during the past three years. The first was a storm sewer construction project (8000 feet of thirteen foot diameter tunnel and 4400 feet of eight foot diameter tunnel) sponsored by the City of St. Paul and constructed by Acton Construction Company of Hugo, Minnesota. The excavation phase of this project is essentially complete. Construction techniques employed on this project were discussed in an earlier report (1).

The second tunnel, also being constructed for use as a storm sewer, consists of about 5000 feet of eight foot finished "diameter" semi-elliptical tunnel and about 6000 feet of six foot "diameter" feeder tunnels. This project is sponsored by the City of Minneapolis and is being constructed by crews of the City of Minneapolis Sewer Construction Division. The portal, located on the Mississippi River near the University of Minnesota, and the proposed route are shown in Figure 1-1. Construction is currently in progress, and tunneling techniques utilized for this particular operation are discussed below; however, before beginning discussion of tunneling operations, a brief summary of relevant geology is presented.

Geology

Figure 1-2 represents the stratigraphic column of the Minneapolis-St. Paul area. Most tunnels in the metropolitan area, including the two mentioned earlier, have been constructed in the St. Peter Formation. The St. Peter is a rather weak, friable sandstone ranging in texture from medium- to fine-grained. Figure 1-3, a typical grain size distribution, illustrates that the St. Peter actually has two components: a sand-silt fraction, usually ninety-seven to ninety-nine percent by weight, and a clay fraction, usually one to three percent. (The sand and silt-size particles are nearly all frosted and well-rounded.) The sandstone's porosity is quite high (about thirty percent), but due

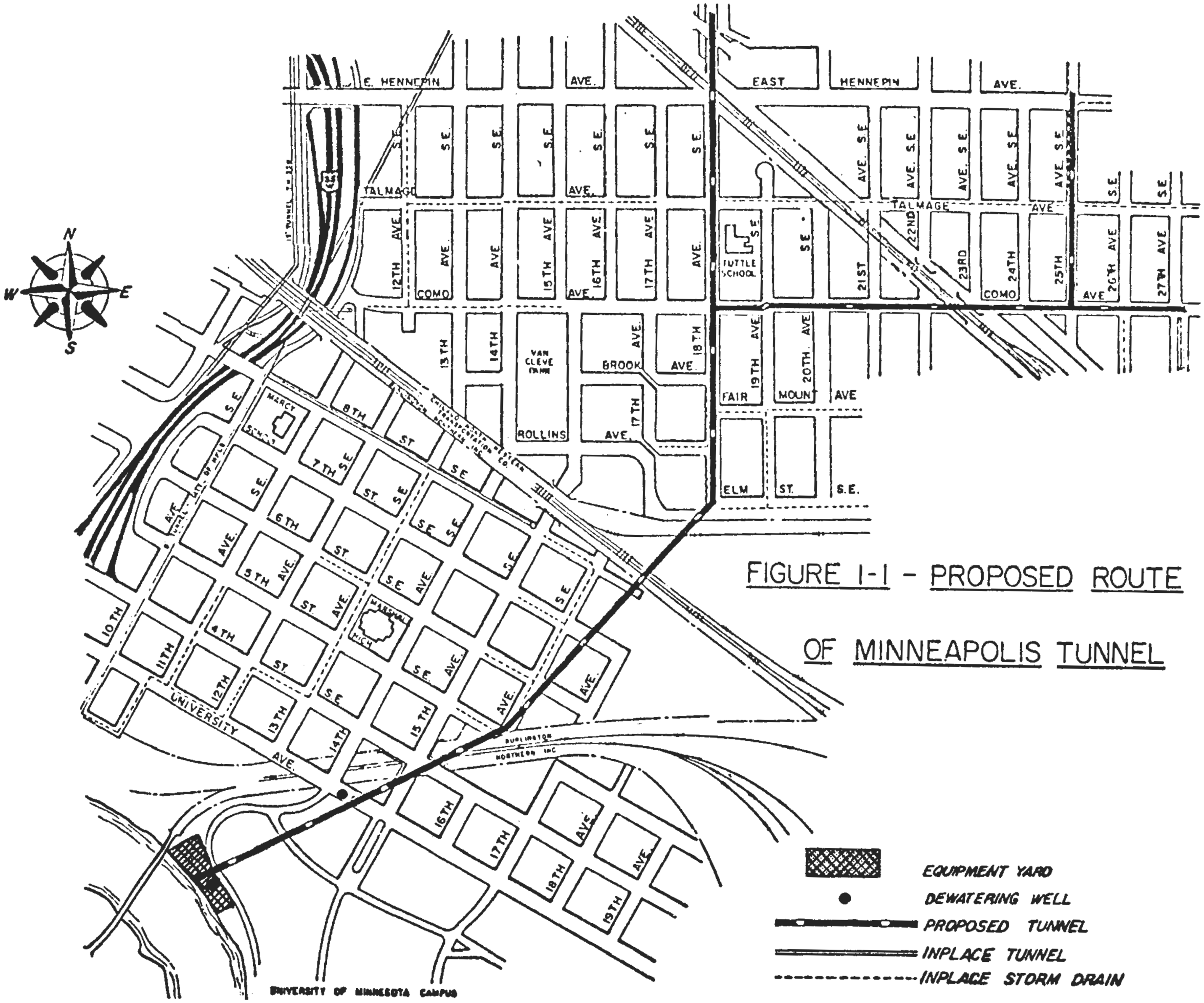


FIGURE 1-1 - PROPOSED ROUTE OF MINNEAPOLIS TUNNEL

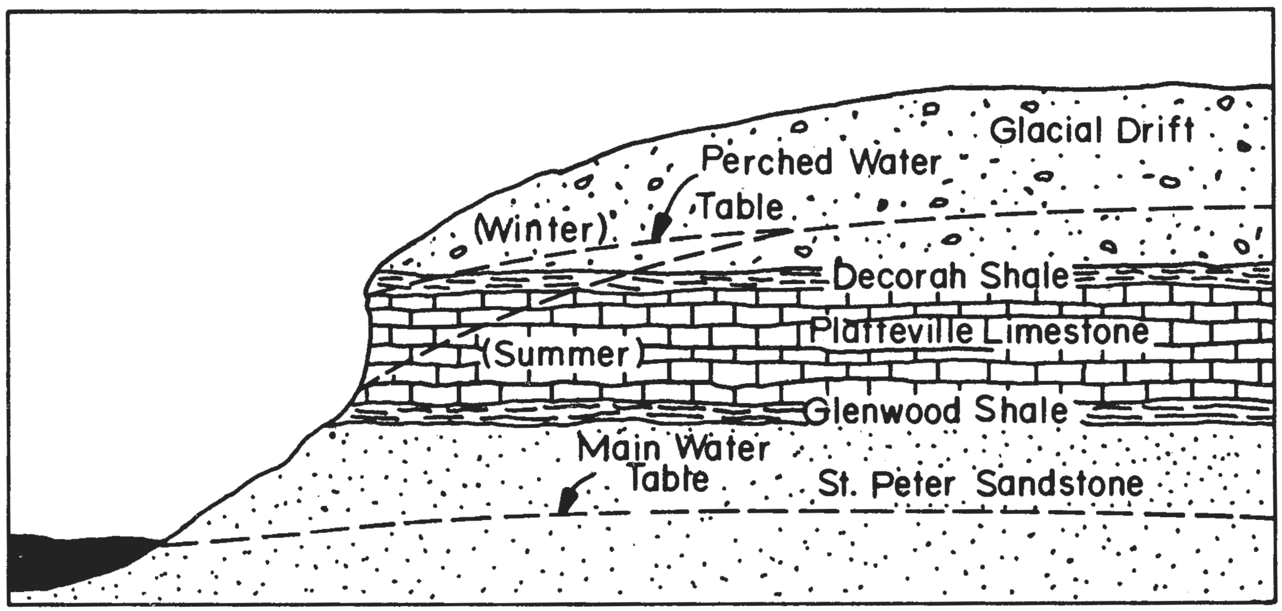


FIGURE 1-2 - STRATIGRAPHIC COLUMN OF MINNEAPOLIS - ST. PAUL AREA

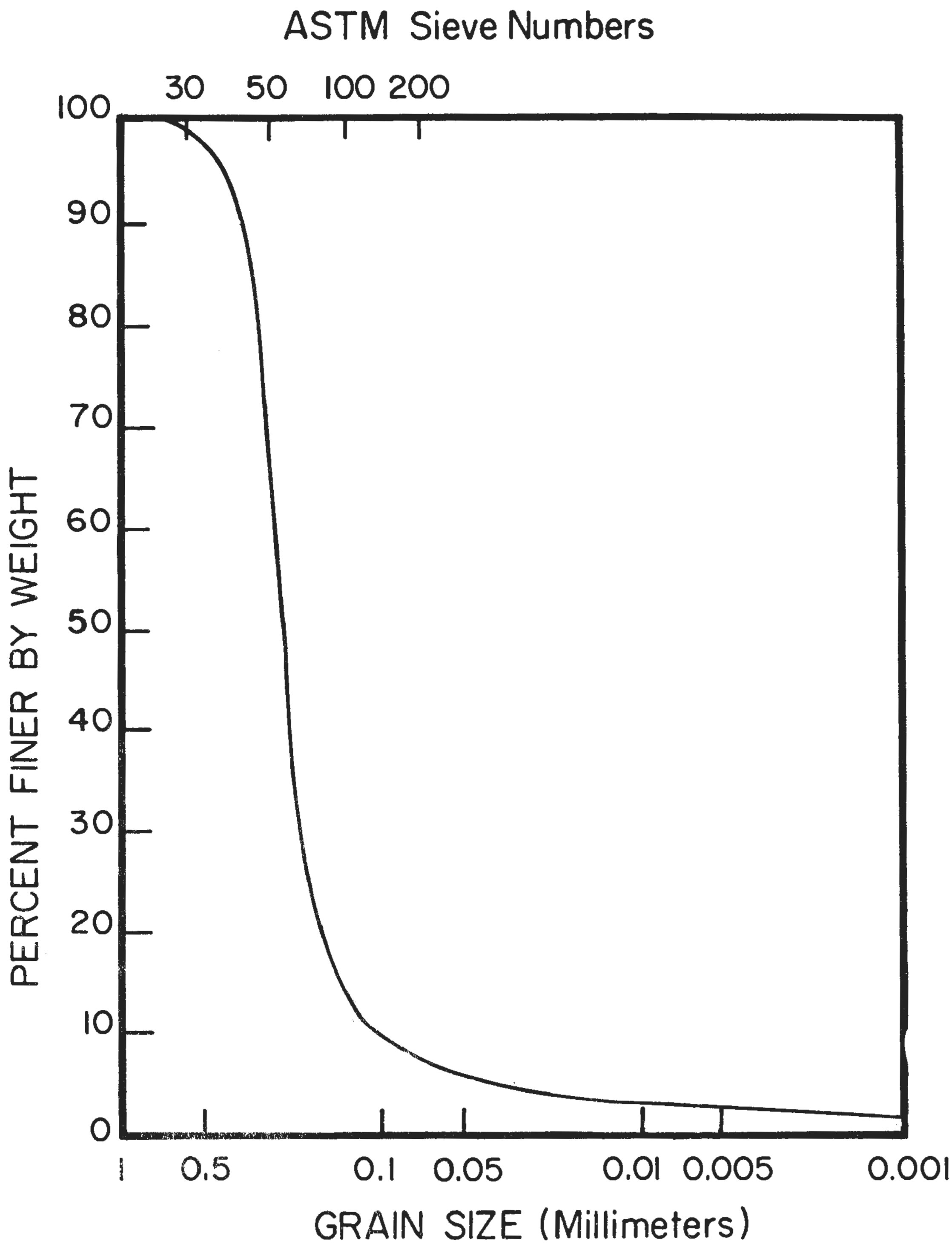


FIGURE 1-3 - TYPICAL GRAIN SIZE DISTRIBUTION to its fine texture, permeability is fairly low (about 3.5 x 10^{-3} centimeters per second). A fairly typical chemical composition is: SiO_2 (silica) - 97.6%, Al_2O_3-1.3%, Fe_2O_3-0.55%, CaO-0.41%, Na_2O-0.15%, and K_2O-0.02% (2).

As stated above, the St. Peter is a relatively weak sandstone; unconfined compressive strengths vary from zero to 2800 pounds per square inch for "fresh" samples and zero to 200 pounds per square inch for weathered samples. Compressive strengths are probably attributable to a combination of cementing by clay minerals and inter-particle friction and locking. Variations in sandstone strength may be due to changes in the mineralogy of the clay binder from point to point (3); the stronger sandstone seems to contain primarily illite and montmorillite, while the weaker material contains predominantly kaolinite. The presence of water can have a dramatic effect on the sandstone's strength and stability; immersing an unconfined sample in water can rapidly reduce the specimen to individual grains, probably by affecting the weak cementing clay and/or by decreasing the effective stress between particles.

Color of the St. Peter varies from almost pure white to a yellowish-tan. The white sandstone is essentially pure silica, while the yellow sandstone derives its color from interstitial iron oxide deposited by percolating ground water. The yellow sandstone is usually found in the upper twenty feet of the formation (particularly near river valleys) and adjacent to joints.

Although the St. Peter as a whole is quite homogeneous, several anomalies are found near the top of the formation. The upper fifteen feet is somewhat of a transition zone with a slightly coarser grain structure than that of the remainder of the formation. Contained in this transition is an eight inch thick "green layer" of sandstone containing a higher clay fraction than the rest of the St. Peter (2). Also present in the transition is an intermittent "nodule layer" containing hard sandstone concretions (up to fifteen inches long and five inches in diameter) embedded in a matrix of normal material.

Some jointing is present in the St. Peter. Most of the joints are steep to vertical, occur in sets, and are quite widely spaced.

The main water table elevation in the area varies from one location to another. Near the Mississippi River, the water surface is drawn down, as shown in Figure 1-2. Further from the river, the saturated zone may extend to the top of the St. Peter, and even join the perched water table present in the overlying limestone and glacial till.

Hydraulic Tunneling Operations

Methods of hydraulic tunneling utilized in the Minneapolis-St. Paul area have changed very little in the past forty years. Over the years, a workable tunneling procedure has developed that, in combination with local geological conditions, produces some of the lowest cost tunneling in the nation. As stated above, operations of the Minneapolis project will be discussed here, but variations of certain techniques will be mentioned where appropriate. Only those operations performed in day-to-day tunneling will be included; mobilization, set up, and similar activities will be omitted.

Route Dewatering Although the groundwater table in the metropolitan area has been drawn down to some extent, route dewatering has been necessary on both of the recent major tunneling projects. Presently, two dewatering wells have been installed on the Minneapolis project (see Figure 1-1). The dewatering pumps are standard 600 gallon per minute deep-well turbine types with surface-mounted motors and three stage impellers. Both wells have sixteen inch diameter casings and extend to about fifty feet below the tunnel invert.

Additional dewatering wells will be added as necessary, with spacings of about 1000 feet.

Water Supply Water for hydraulic tunneling operations is usually obtained from one of three possible sources: surface waters (usually the Mississippi River), municipal water supplies (fire hydrants, etc.), and groundwaters (dewatering wells). Water for the Minneapolis project is presently pumped from the Mississippi River. The St. Paul operation used all three supply sources at one time or another; originally water was pumped from the river, but later, a combination of municipal water and groundwater was used.

Water for the Minneapolis operation was originally supplied by one single stage centrifugal "river pump" (three inch suction and two inch discharge diameters) with a capacity of about 500 gallons per minute at a pressure of about 100 pounds per square inch. This arrangement performed satisfactorily until tunneling proceeded to a distance of about 1400 feet from the river (see Figure 1-1), at which time a booster pump, identical to the supply pump described above, was installed in the supply line. Additional booster pumps will be added as required.

Tunneling Train Figure 1-4 shows a typical cross section of excavated tunnel (Minneapolis project). The rails on the floor of the tunnel extend from the portal to the heading. Near the tunnel heading, a series of rail-mounted carts support the equipment used in the excavation process. This series of carts and equipment is known as the tunneling train, and its major components are discussed below.

Hydraulic Excavation Supply water is pumped from the source to the tunnel heading (in four inch PVC pipe used on Minneapolis project) where the supply line is tapped and the water supply distributed for various uses. One of the lines coupled to the water supply feeds the hydraulic cutting pump. This two-stage centifugal pump (2.5 inch suction and 1.5 inch discharge ports; 50 gallons per minute at 300 pounds per square inch) pressurizes water used for cutting and shaping operations. This pressurized water is discharged through two hydraulic lances. Lances consist of six foot long, three-fourths inch diameter conduits equipped with nozzles with three-sixteenths inch openings. They are fed by one inch diameter high pressure rubber hoses coupled to the discharge port of the cutting pump. Lances are hand-held, as shown in Figure 1-5, and emit narrow, well-defined streams which rapidly disintegrate the sandstone on contact. They are used to cut the outer shape of the tunnel and to dissect the cross section of material to be excavated into blocks which fall to the floor of the tunnel.

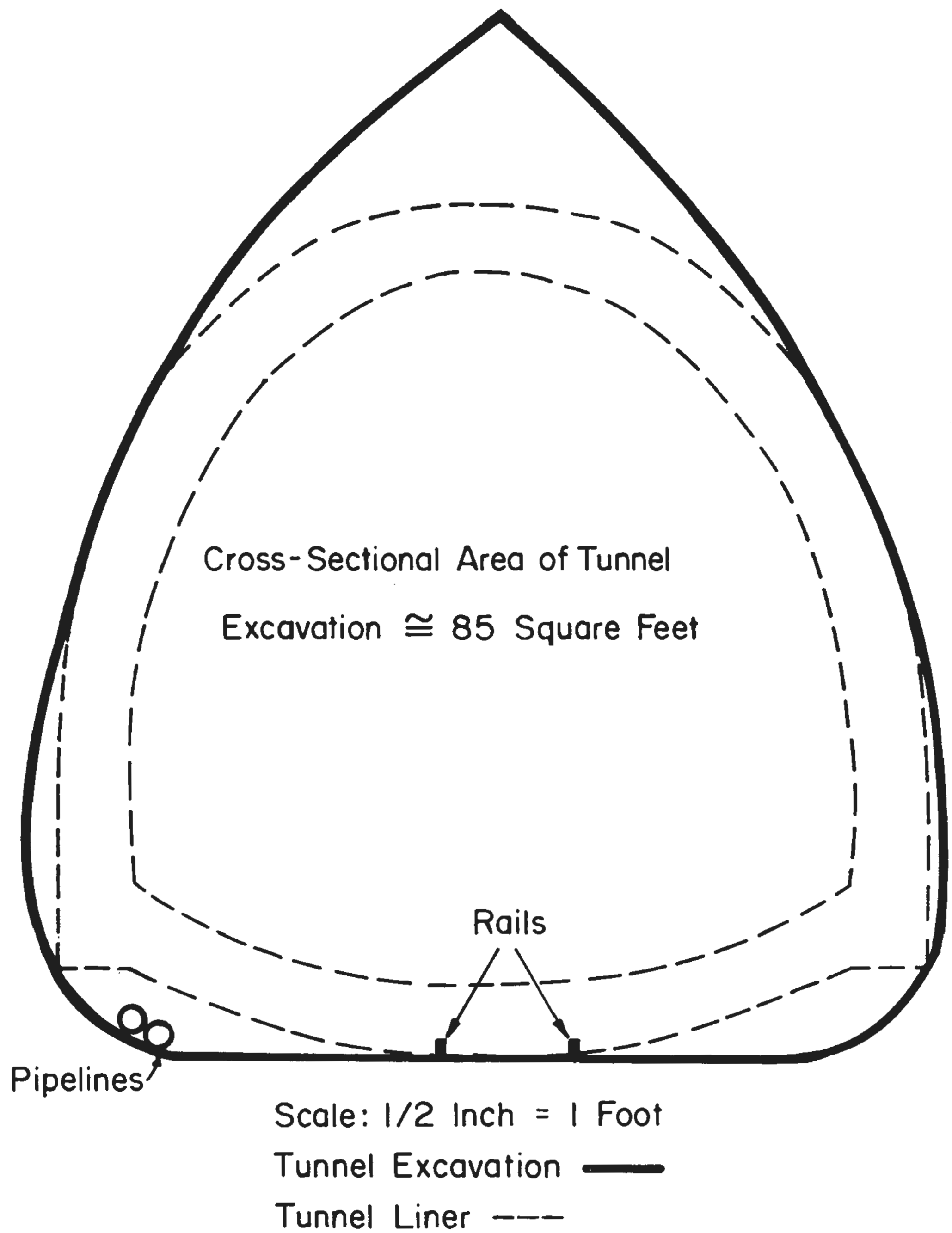


FIGURE 1-4 - TYPICAL TUNNEL CROSS SECTION

FIGURE 1-5 - SANDSTONE CUTTING WITH A HYDRAULIC LANCE

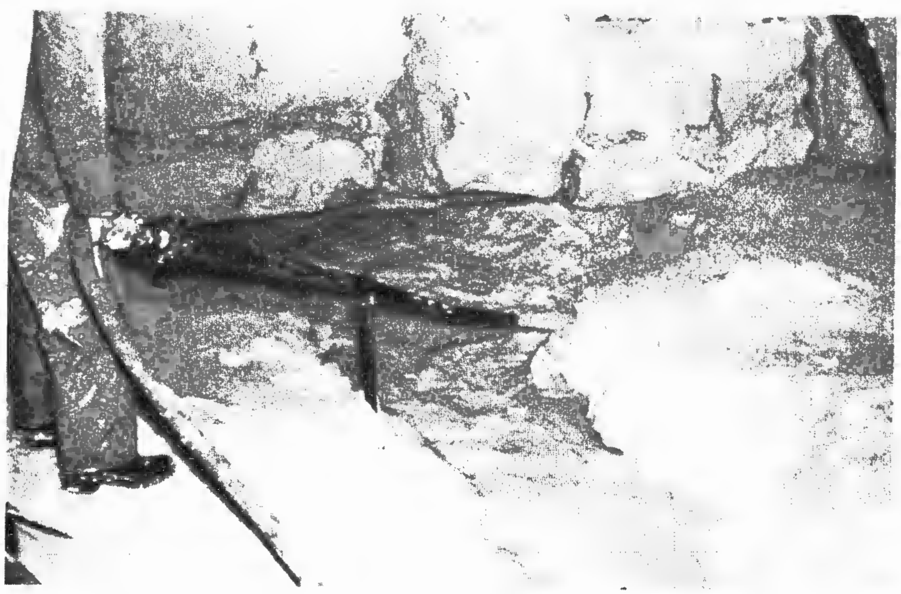


FIGURE 1-6 - SANDSTONE DISINTEGRATION WITH A WASH HOSE

While one or two miners are lance cutting the tunneling cross-section, a third utilizes a wash hose, as illustrated in Figure 1-6, to disintegrate the "blocks" of sandstone to individual grains, and generally fluidize the spoils for transport out of the tunnel. The wash hose nozzle is simply a straight, three foot section of 1.25 inch diameter steel pipe fed by a two inch rubber hose coupled directly to the supply line. Flow through the wash hose is regulated by a gate valve at the supply line.

Mucking Two methods of mucking (picking up of fluidized sand) have been observed on hydraulic tunneling operations in this area. They are the pump suction method and the jet pumping method.

The Minneapolis operation utilizes a pump suction system such as the one pictured in Figure 1-7. A heavy rubber hose is coupled with the suction eye of a single stage centrifugal pump (twenty-five horse-power, four inch suction and discharge diameters, 500 gallon per minute capacity). This pump is mounted on the cart nearest the heading. The suction hose is equipped with a screen to prevent the entrance of oversize sandstone nodules (plus 0.75 inch). The interior of the mucking pump is protected from abrasion by a replaceable rubber lining covering the volute and a bonded rubber lining covering the impeller. Also, a supply line from the main water supply injects water into the areas between impeller and volute to prevent the entrance of solids into these critical regions. (This water supply also maintains the pump prime.)

Before cutting operations begin, a sump is constructed by sand-bagging the tunnel floor several feet back from the heading. As material is excavated the resulting sand-water slurry is temporarily contained in the sump, and removed through the suction line of the mucking pump.

The jet pumping system was used on the St. Paul project (1). Figure 1-8 illustrates the principle of the jet system. During cutting operations, the jet pump itself is submerged in a mining sump on the tunnel floor. It lifts slurry from this sump to a steel holding tank,

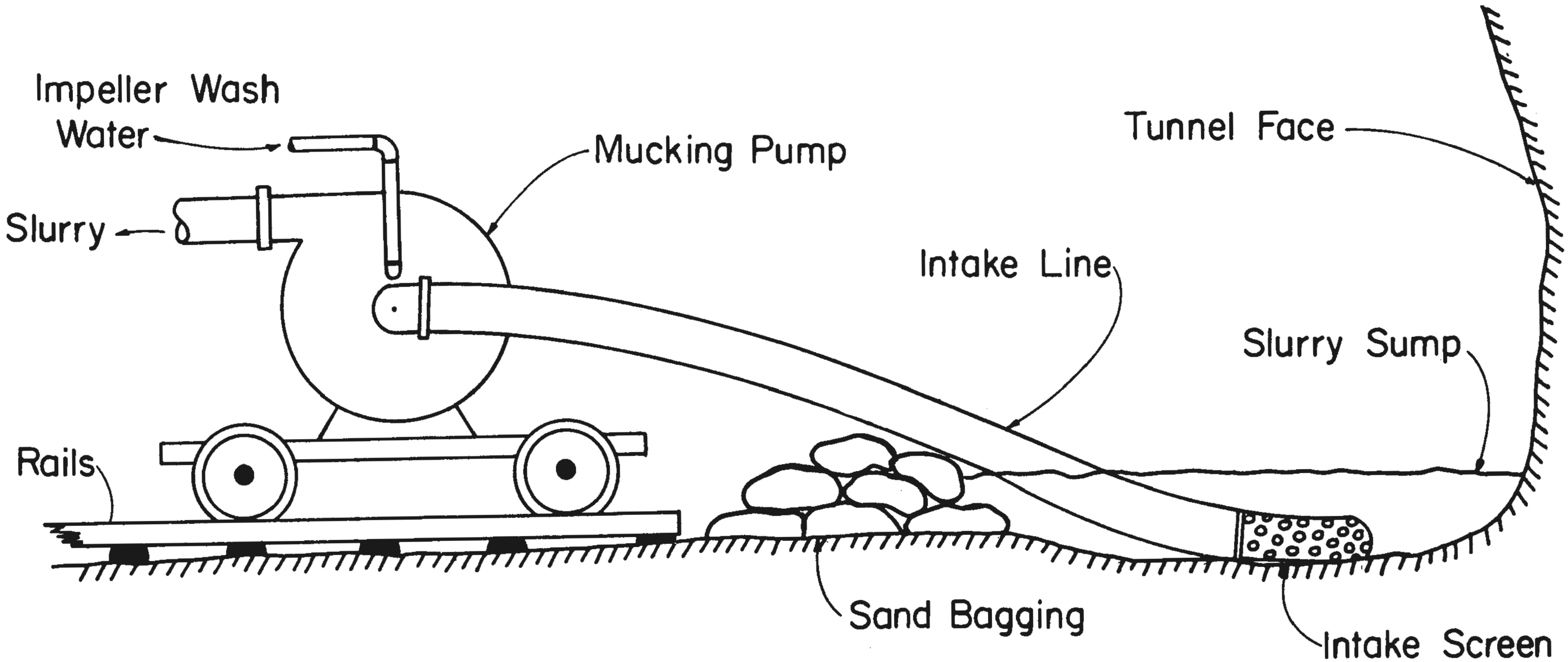
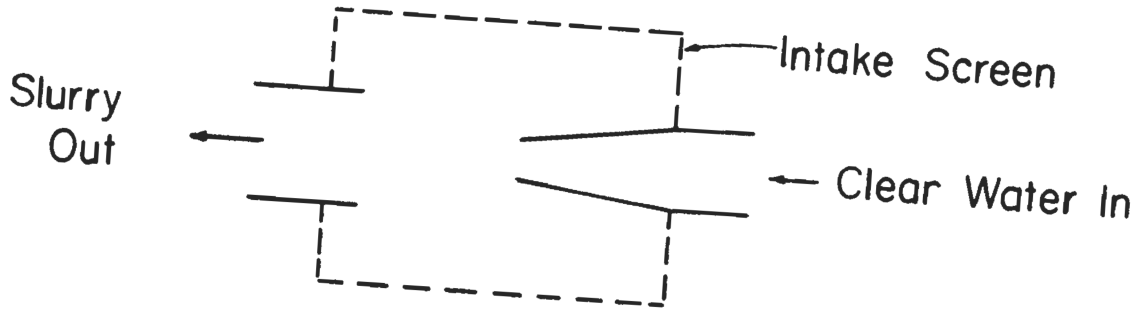


FIGURE I-7 - PUMP SUCTION MUCKING SYSTEM - MINNEAPOLIS PROJECT



Jet Pump Cross Section

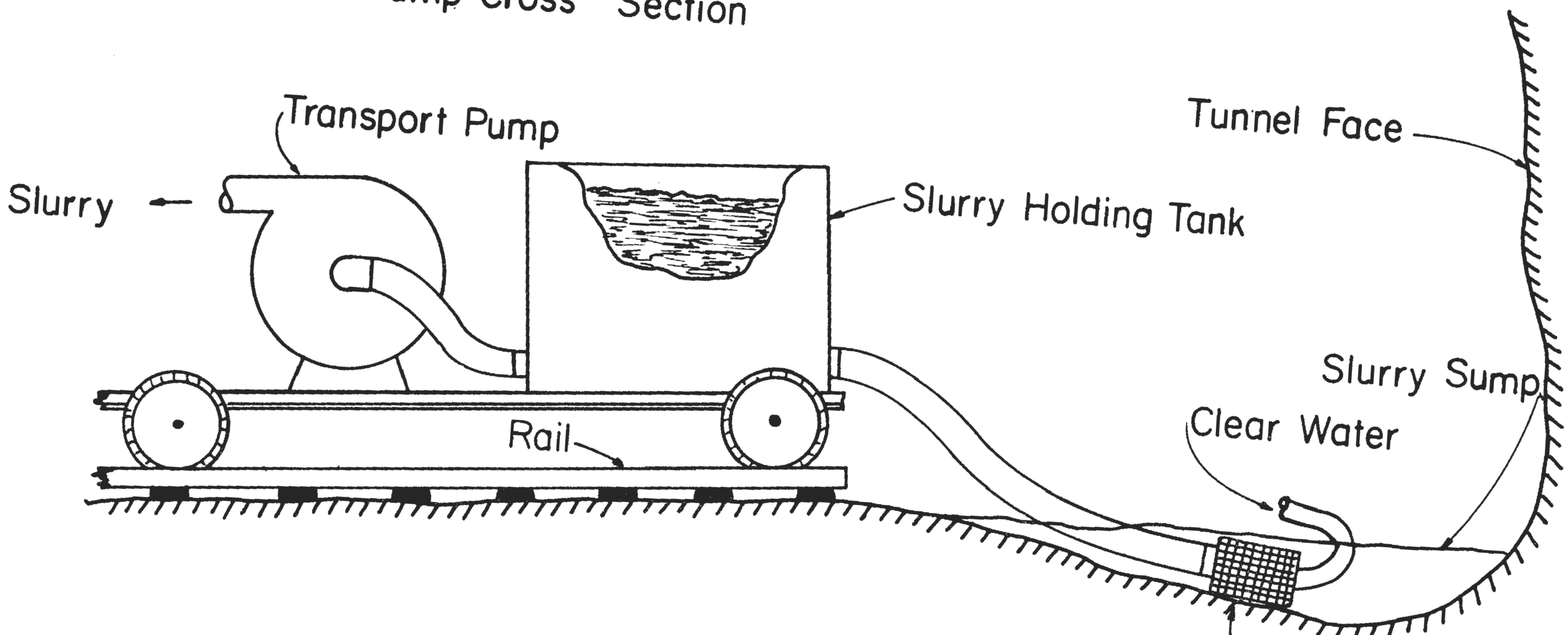


FIGURE 1-8 - TYPICAL JET PUMP MUCKING SYSTEM from which the slurry is pumped out of the tunnel.

Advancing the Tunneling Train After a certain advance of the tunnel face, the train must also be advanced. This process consists of moving the sandbagged wall of the sump ahead, placing another section of track, and pushing the pump carts ahead. The carts are coupled with the water supply and slurry transport lines by flexible rubber hoses which allow approximately forty-five feet of advance. However, when the hoses are fully extended, sections of pipe must be added to the supply and discharge lines to permit further advance of the train.

Spoils Transport After the slurry has been mucked, it is transported out of tunnel via a pipeline. On the Minneapolis project, the mucking pump supplies initial energy to transport slurry through a four inch diameter PVC pipeline. However, as the transport distance increases, booster pumps are placed in the line to maintain flow velocity necessary for solids transport. Experience has shown that booster pumps (identical to the mucker) are required about every 1200 feet of horizontal pipe (4). For a 100 foot vertical lift, an additional booster (again identical to the mucker) is required; a booster utilized for a 100 foot vertical lift is usually installed about 100 to 200 feet from the horizontal-to-vertical transition, thus utilizing the full capacity of the pump. Figure 1-9 schematically illustrates this set-up.

Transport energy on the St. Paul project was also supplied by centrifugal pumps. Two centrifugal pumps, connected in series, received slurry from a steel holding tank (mentioned in the previous section), and provided the initial transport energy. Booster pumps were installed as needed.

Sand-Water Separation On both recent tunneling operations, similar methods of sand-water separation have been used. Slurry is pumped into one of the twin compartments of a sedimentation hopper shown in Figure 1-10, while the other is being emptied. When slurry enters the sedimentation hopper, most of the coarse material (plus 325 mesh, see Figure 1-3) settles out of suspension while the clay fraction stays

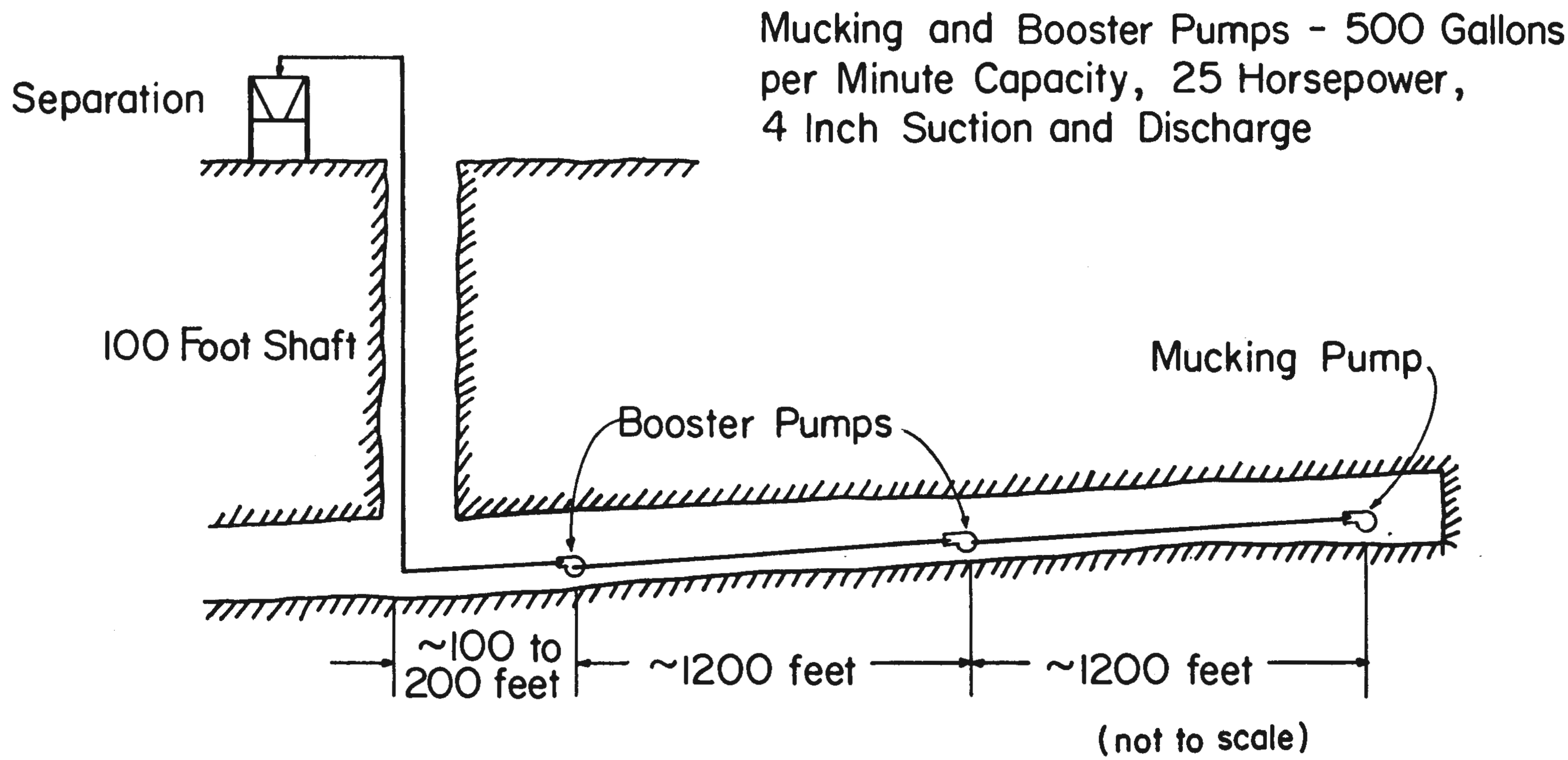


FIGURE 1-9 - TYPICAL SPOILS TRANSPORT SYSTEM

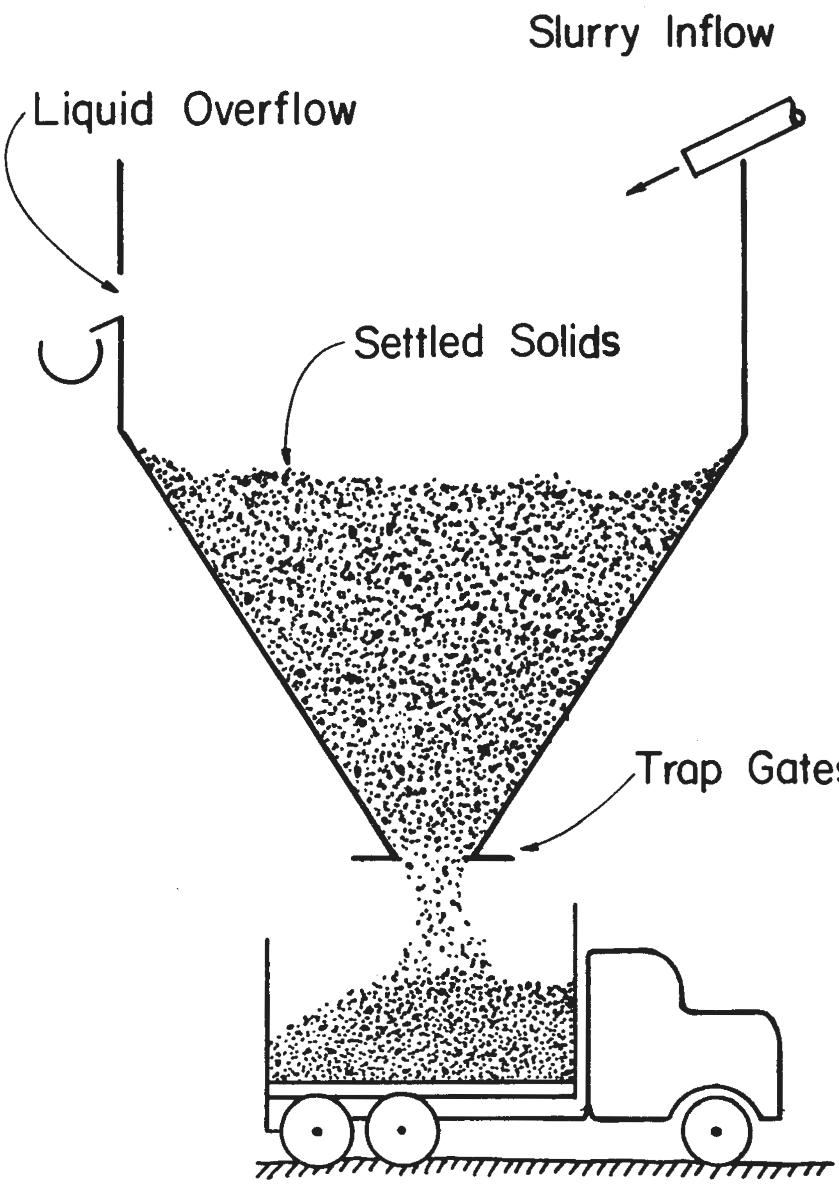


FIGURE 1-10 - SEDIMENTATION HOPPER

in suspension and overflows with the water.

The hopper overflow on the Minneapolis project is discharged into the sanitary sewer, while the overflow for the St. Paul project was discharged into a settling pond which, in turn, overflowed into the Mississippi River.

When a hopper fills with solids, any puddled water remaining on top of the solids is pumped off, and solids are removed via trap doors on the bottom of each hopper.

Miscellaneous Operations

All of the operations discussed to this point are integral parts of the hydraulic tunneling. However, two other operations, line, grade and cross section control, and temporary ground support are required for any method of tunneling. Thus, they are discussed below for continuity.

Line, Grade, and Cross Section Control Line and grade on the Minneapolis project is maintained by use of an electronic laser configuration similar to that shown in Figure 1-11. The wall-mounted laser is adjusted so that its beam passes through three wall-mounted targets and is parallel to the desired axis of tunnel line and grade. Brackets for the laser and targets are identical, so that when the laser is to be advanced, it is mounted on the bracket of the nearest target. The removed target is advanced to a new position near the face, thus "leap-frogging" others and becoming the leading target.

When changes in tunnel line and/or grade are required, a north-seeking gyroscopic theodolite is employed to turn required angles. The laser and targets must then be reset on the tunnel walls.

Tunnel cross section is controlled by use of a metal template, pictured in Figure 1-12. The template is placed against the face of the tunnel; a reference point on the template is placed at a fixed position relative to the laser beam. The horizontal member of the template is then leveled with a carpenter's level, thus completing the positioning of the template. The desired cross section may then be

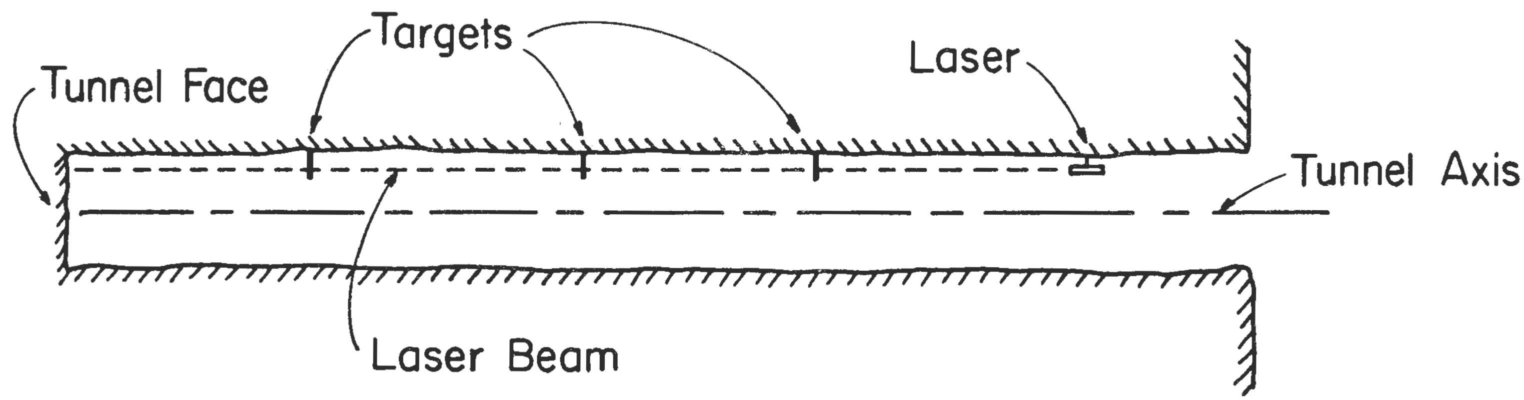
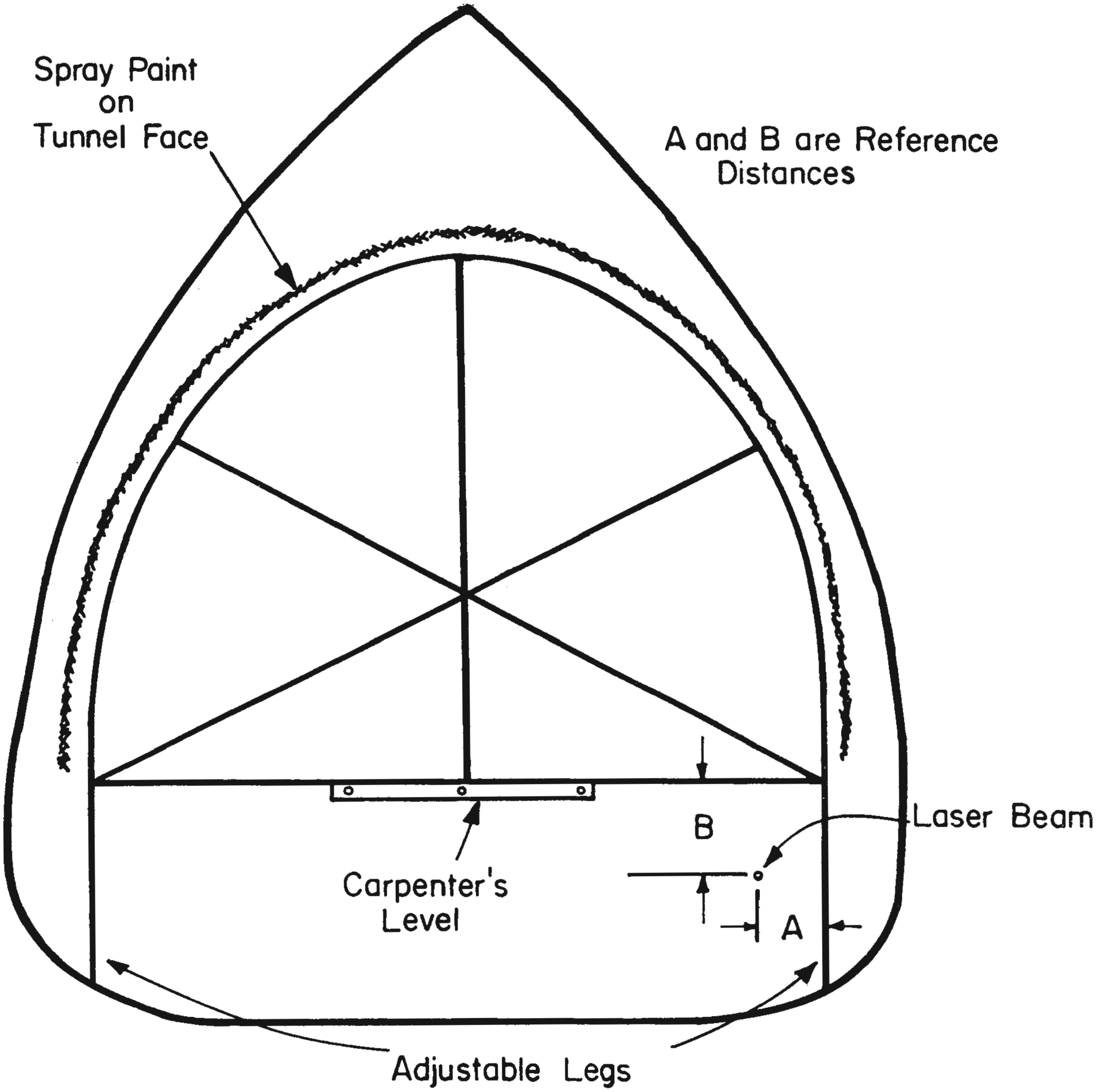


FIGURE 1-11 - PLAN VIEW OF TUNNEL SHOWING LASER AND TARGET LOCATIONS



Scale: 1 inch = 2 feet

FIGURE 1-12 - TUNNEL CROSS SECTION SHOWING CONTROL TEMPLATE spray-painted on the tunnel face.

Temporary Ground Support Many small tunnels (four feet or less in width) constructed in the St. Peter have served satisfactorily for decades with no artificial support whatsoever. However, the present Minneapolis project is of such a size that temporary ground support is necessary. Several support methods were considered, with the following technique being adopted at the time of this writing. The tunnel cross section is excavated to a slight peak (see Figure 1-12). The peak is then scaled to a relatively smooth surface and sprayed with a solution of sodium silicate and setting agent. This solution is drawn into the sandstone by capillary action (penetration up to six inches) and hardens shortly after application to form a true "skin-tight" shell around the tunnel. Unconfined compression tests show that the application of the sodium silicate solution can increase the strength of St. Peter sandstone from initial values in the range of 100 pounds per square inch to as much as 2000 pounds per square inch.

In critical sections in the tunnel, the crown and walls are shotcreted to increase structural stability. Shotcrete is very low slump concrete which is pneumatically sprayed on tunnel walls. The basic dry concrete mix is transported to the portal site in ready-mix trucks, where is it transferred to a pneumatic pipleine which in turn transports the mix to the tunnel heading. Water is then added, and the resulting concrete is sprayed on the walls. Experience showed that for shotcrete to effectively adhere to the sandstone, tunnel walls should first be sprayed with sodium silicate.

The St. Paul operation employed a more conventional method of ground support: steel ring beams and wood lagging. Figure 1-13 illustrates the installation of ring beams, which are actually two ribs which are lifted into place and bolted together at the crown. Wood lagging is then driven into place between the ring beams as shown in Figure 1-14.

FIGURE 1-13 - INSTALLATION OF STEEL RING BEAMS

FIGURE 1-14 - INSTALLATION OF TIMBER LAGGING

Summary

Figure 1-15 is a schematic of the entire water circuit for the current Minneapolis tunneling operation. As shown in the preceding paragraphs, several options are available for various phases of the operation, i.e., mucking. One significant improvement, in light of present environmental and waste treatment standards, would be the utilization of some system which could close the water loop.

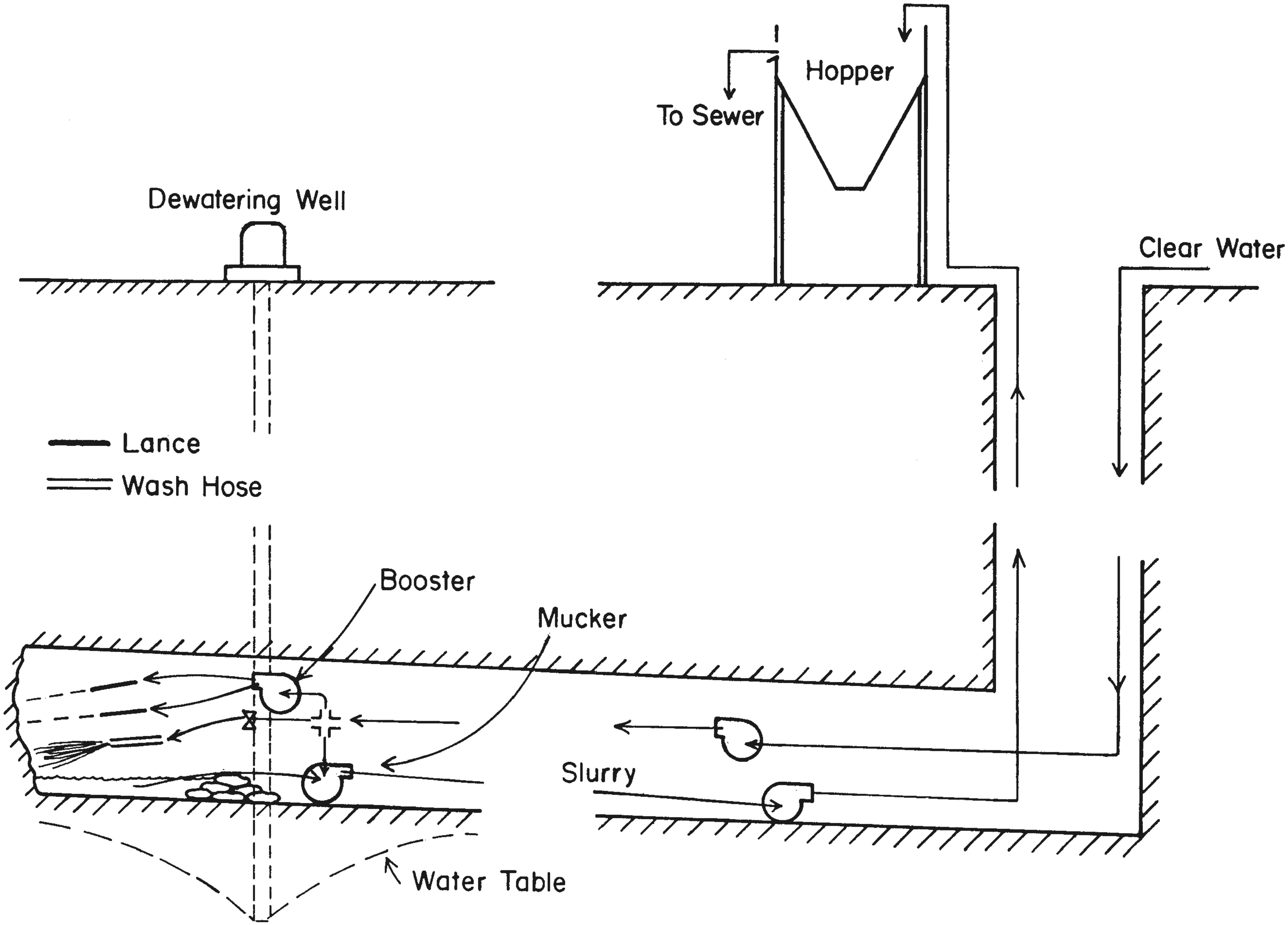


FIGURE 1-15 - TYPICAL HYDRAULIC TUNNELING WATER CIRCUIT

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Chapter 2

WASTE SURVEY, MINNEAPOLIS TUNNELING OPERATION

Before meaningful recommendations can be made for the design of an industrial wastewater treatment system, some characteristics of the particular waste stream must be determined. Consequently, a waste survey of the Minneapolis tunneling operation was carried out during August, September and October, 1975. (Eight separate tunneling periods, involving from 7.6 to 19.2 cubic yards of excavated sandstone, were monitored.) A spot check was made during April, 1976, to ascertain the validity of the data previously obtained in light of some changes in operating procedures.

Since relatively few processes are involved in a hydraulic tunneling operation, a waste survey may be carried out in a fairly straightforward manner. (For a complex industrial operation with numerous processes contributing to the waste stream, implementation and execution of a waste survey may be greatly complicated.) Parameters monitored during the Minneapolis tunneling waste survey include solids flow rates and wastewater flow rates, suspended solids concentrations, and pH values.

Data and Sample Collection

Measurement of Solids Flow Rates After each surveyed tunneling period, the dimensions of the "new" excavation were measured. The calculated volume of the excavation multiplied by the unit weight of the material yielded tonnage removed, and this value divided by excavation time yielded solids flow rate.

Measurement of Wastewater Flow Rates The liquid phase of the waste stream overflows the sedimentation hopper (see Chapter 1) into a trough of circular cross section, and from the trough into a conduit which carries it to the sanitary sewer. A Palmer-Bowlus flume (see Appendix F) was installed in the overflow trough to measure wastewater flow rates. Flow depths were measured just upstream of the flume by manually reading a staff gauge at time intervals of one minute. (The staff gauge was graduated in one-half inch increments, and readings were rounded to the nearest one-half inch.) The flume rating table was used to relate recorded depths to flow rates.

Measurement of Suspended Solids Concentrations During periods of wastewater flow rate monitoring, samples of overflow (500 milliliters) were taken at a well-mixed point in the waste stream at fifteen minute intervals. (Initially this sampling interval was arbitrarily selected, but later results showed it to be quite satisfactory.)

Wastewater samples were later analyzed in the laboratory by the following procedure. Each sample was poured through a 325 mesh soil sieve (0.044 millimeter diameter openings) to remove "coarse" particles, which were in turn collected, dried, and weighed. Duplicate twenty-five milliliter subsamples were then taken from the original "filtered" sample. These subsamples were evaporated in tared dishes to obtain the concentration of total solids in the filtered sample. The sum of "coarse" solids and "total" solids (from the filtered sample) minus the dissolved solids concentration of river water yielded suspended solids concentration.

Measurement of Wastewater pH Each of the 500 milliliter wastewater samples taken during the monitoring program was analyzed for pH using a standard laboratory pH meter.

Results of the Waste Survey

Solids Flow Rate Solids flow rate from the tunneling operation averaged about 8.7 tons per hour with high and low values of 14.2 and 4.8 tons per hour and a standard deviation of 3.5 tons per hour. High values of solids transport occurred on relatively "short", uninterrupted cutting periods while lower values occurred on longer cuts or where significant amounts of "heavy" rebounded shotcrete aggregate were mucked from the tunnel floor near the heading. (Some shotcrete aggregate rebounds from tunnel walls on impact and piles up on the floor in such quantities that it creates a nuisance condition and must be removed. At the present time, however, shotcrete is utilized only occasionally where extra support is required, and consequently, the amount of aggregate being mucked should be negligible.)

Wastewater Flow Rates Figure 2-1 is a typical plot of rate of hopper overflow versus time. During normal operations, instantaneous flow rates may vary from about 430 gallons per minute to about 70 gallons per minute, often fluctuating by more than 100 gallons per minute from one reading to the next. Fluctuation is accounted for as follows: the mucking and transport system has greater flow capacity than the water supply system. Consequently, the mucking pump will pick up all available water in the mining sump, and, in the process, temporarily lose its prime. In a few seconds, the impeller flushing water reprimes the mucker which in turn begins to pump water from the sump again.

Figure 2-2 is a graph of instantaneous flow versus probability developed from analysis of all point readings taken during the flow monitoring program. The average instantaneous flow rate from Figure 2-2 is about 180 gallons per minute.

Another parameter of interest is the interval-averaged flow rate, which is simply the average flow rate over a portion of a tunneling period. Figure 2-3 tabulates accumulated flow volume against elapsed time for the "hydrograph" in Figure 2-1. The average flow rate for the entire hydrograph is found by dividing the total accumulated flow volume (8500 gallons) by the total elapsed time (50 minutes) to yield a value of about 170 gallons per minute. However, Figure 2-3 illustrates that for the first twenty-eight minutes, flow rate averaged about 210 gallons per minute, while for the remaining twenty-two minutes, flow averaged about 120 gallons per minute. The explanation for this phenomenon lies in the fact that interval-averaged flow rate from the tunneling operation must be approximately equal to clean water flow rate to

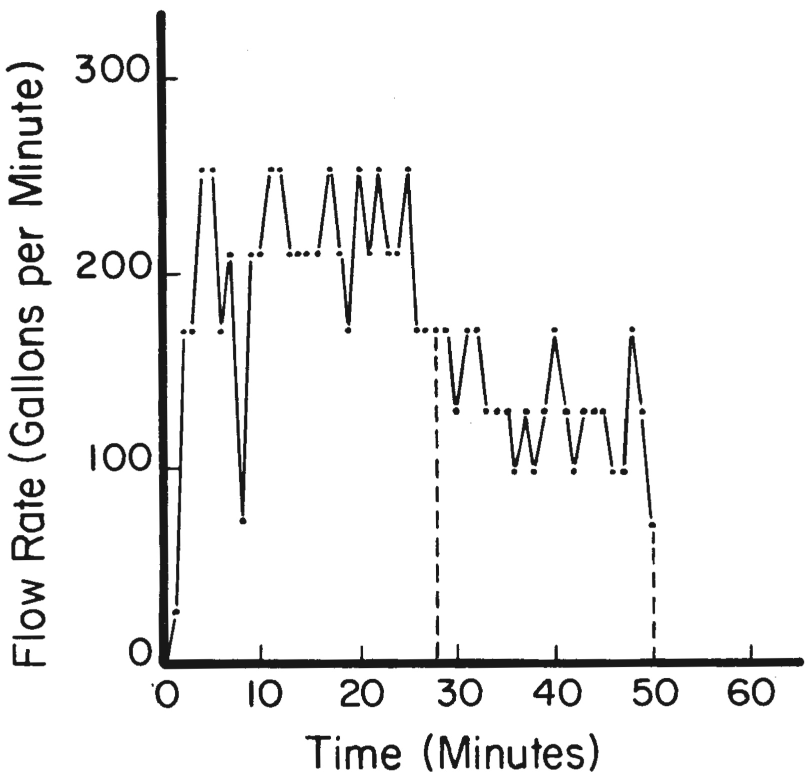

FIGURE 2-1 - POINT FLOW RATE VERSUS TIME

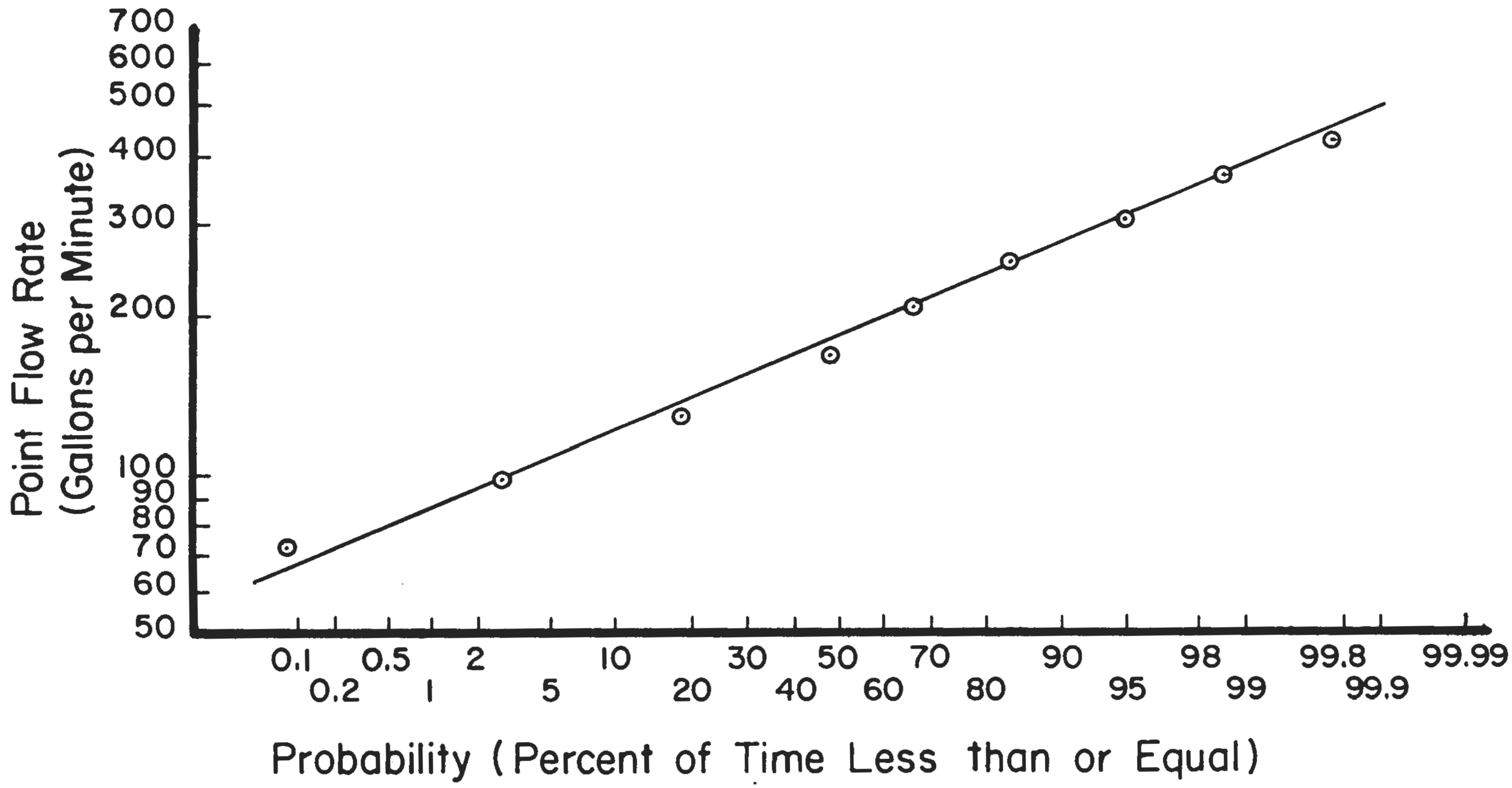

FIGURE 2-2 - POINT FLOW RATE VERSUS PROBABILITY

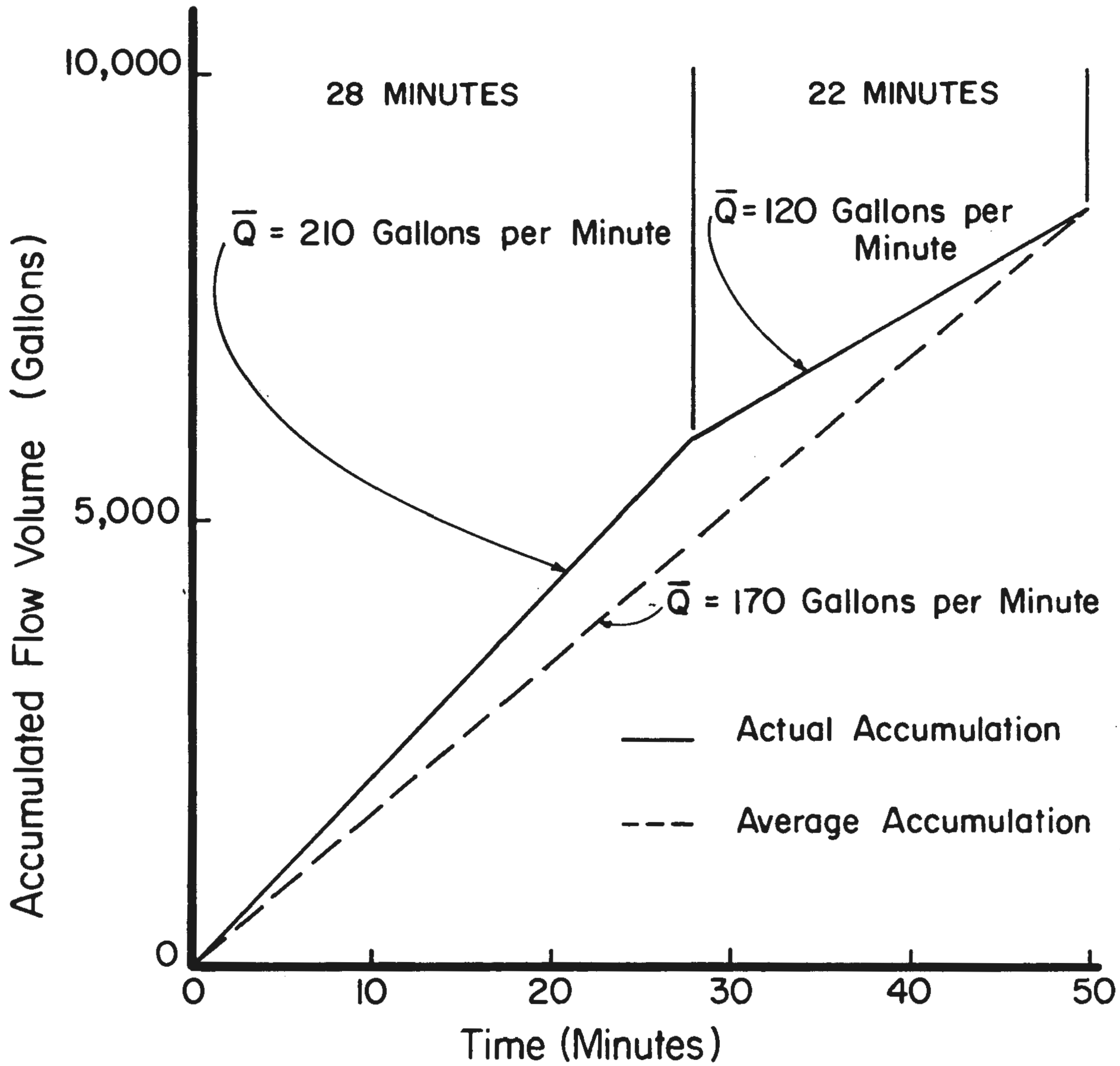

FIGURE 2-3 - ACCUMULATED WASTEWATER FLOW VOLUME FOR A TYPICAL OPERATING PERIOD the operation. Thus, at the beginning of the excavation phase of Figures 2-1 and 2-3, workmen adjusted the inflow rate to suit their immediate needs, and correspondingly, the interval-averaged outflow rate stabilized at a value of about 210 gallons per minute. Then, after about twenty-eight minutes of operation, the clean water inflow rate was reduced, and interval-averaged outflow rate re-stabilized at another value--120 gallons per minute. (The change in flow rate at twenty-eight minutes was probably the result of some change in operations at that time. For example, workmen may have initially been using both lances and the wash hose, and then, at twenty-eight minutes, terminated lance cutting and utilized only the wash hose.)

Figure 2-4 plots interval-averaged flow rate versus probability. This curve was developed by determining the total time that interval-averaged flow rate fell between each of the limits shown (100 to 110 gallons per minute, etc.). Each of these totals was then divided by the total monitoring time to yield the percent of time for each range. Percent values were then accumulated to determine the percent of time that flow rate fell in or below each of the ranges, and the results were then plotted to yield Figure 2-4.

Excavation Water Requirements From measurement of solids and wastewater flow rates, determination was made of the quantity of water required to excavate and transport a unit volume of sandstone. An average cut required approximately 2100 gallons per cubic yard, with high and low values of 3200 and 1000 gallons per cubic yard and a standard deviation of 700 gallons per cubic yard. Variations can be attributed to the same factors that caused fluctuations in solids flow rates with large required water volumes corresponding to low solids flow rates and vice versa.

Suspended Solids Concentrations Figure 2-5 is a plot of wastewater suspended solids concentration versus probability for the original waste survey and the spot check. The difference in the curves

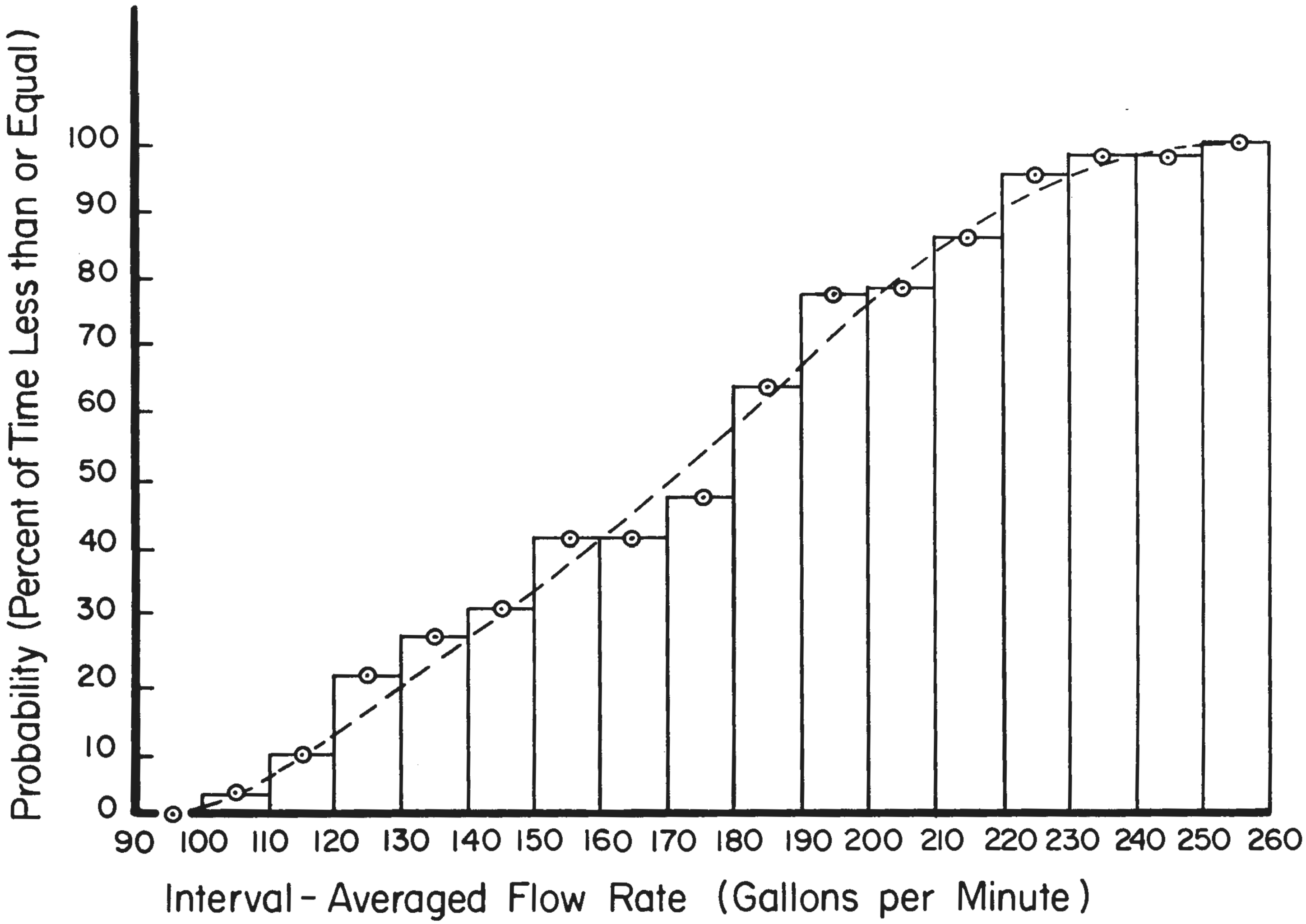

FIGURE 2-4 - INTERVAL - AVERAGED FLOW RATE VERSUS PROBABILITY

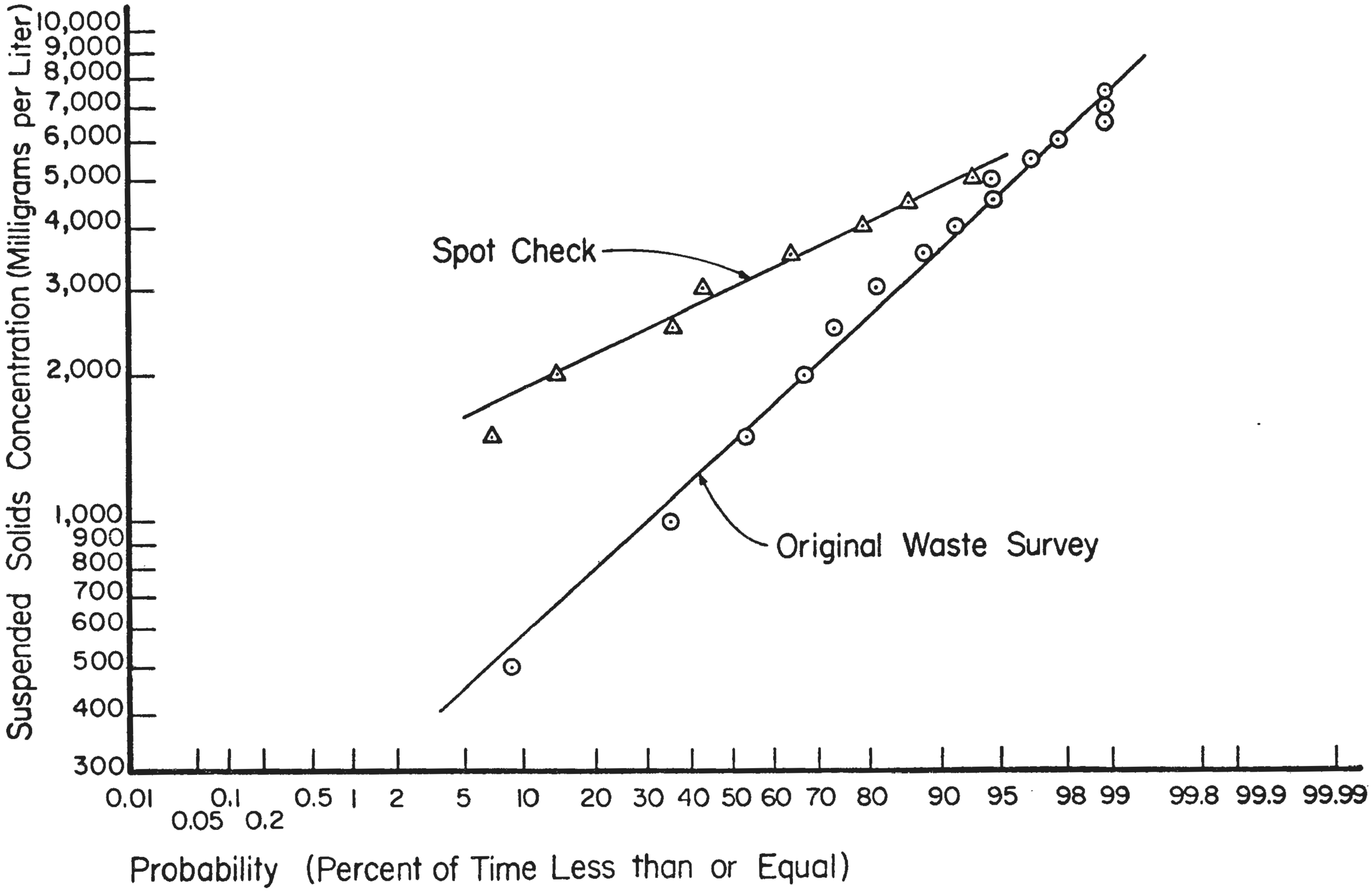

FIGURE 2-5 - SUSPENDED SOLIDS CONCENTRATION VERSUS PROBABILITY results from the manner in which the sedimentation hopper was operated. The hopper is very efficient at removing plus 325 mesh particles except when nearly full, in which case measurable amounts of coarse material are carried out by the overflowing liquid. During the original waste survey, the height of the solids level in the hopper varied from very low to nearly overflowing, and only when the level was high did coarse material appear in the overflow in any quantity. During the spot check, by contrast, the hopper was operated continuously at a nearly full condition (unintentionally) with sand occasionally drawn off through the trap gate, only to be replaced by sand flowing in from the excavation. Consequently, some amount of coarse material was found in nearly every spot check sample, resulting in higher solids concentrations then would normally be expected.

pH Figure 2-6 is a plot of waste stream pH versus probability for the original waste survey and the spot check. Since the pH of the supply source (the Mississippi River) averages about 7.9 (1), the tunneling operation has an obvious effect on waste stream pH. Figure 2-7 illustrates a phenomena observed frequently during the original waste survey--a sharp increase in wastewater pH shortly after initiation of sodium silicate spraying (see Chapter 1). (Sodium silicate is a product, containing SiO_2 and Na_2O, that forms alkaline solutions in which silicate anions form species ranging from monomeric to highly polymerized (2).) Initial runoff of silicate residue from tunnel walls caused sharp increases in waste stream pH with gradual decay to stable (although still quite high) values after spraying was terminated.

Figure 2-6 illustrates that the extremely high pH's which occurred during the original waste survey were no longer present during the spot check. The difference probably results from a modification of operating procedure which was enacted between the time of the original waste survey and the spot check. During the

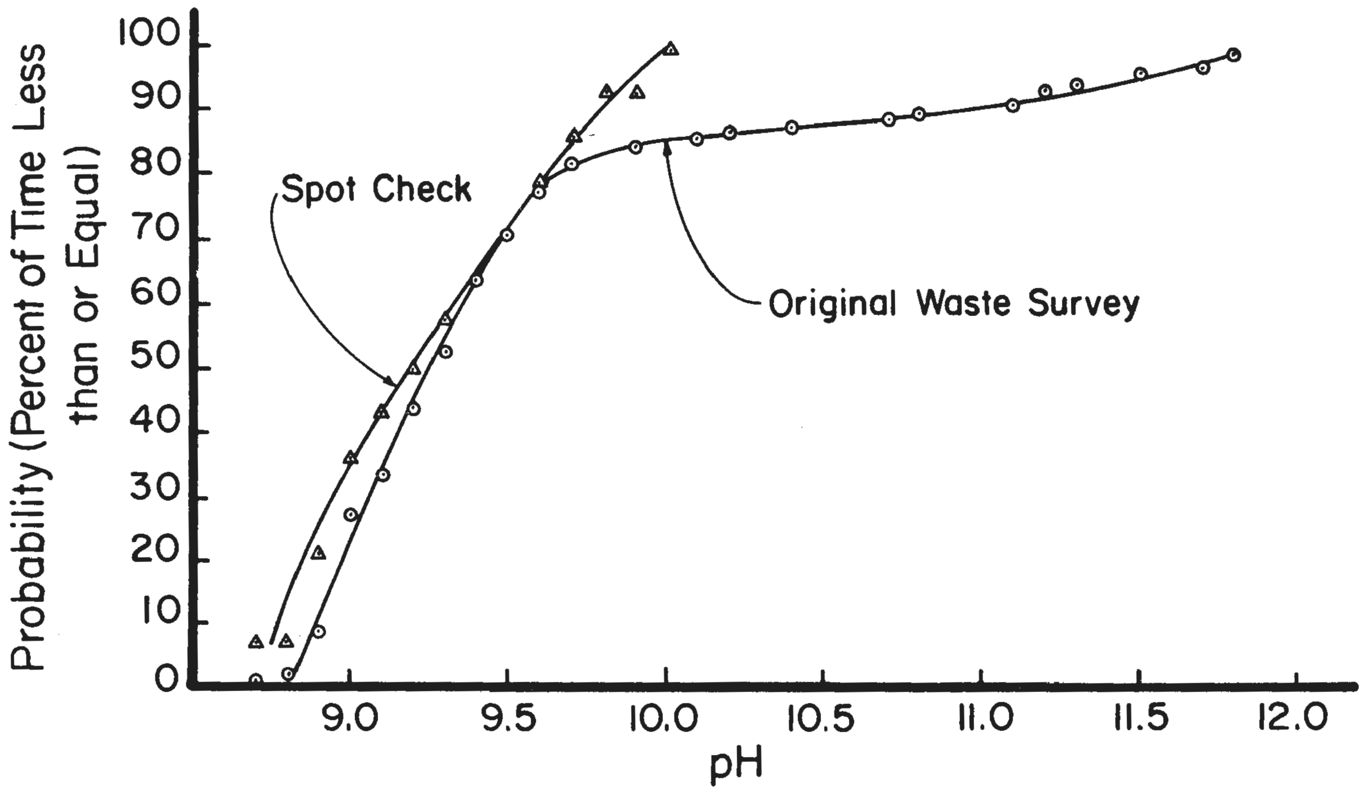

FIGURE 2-6 - WASTE STREAM pH VERSUS PROBABILITY

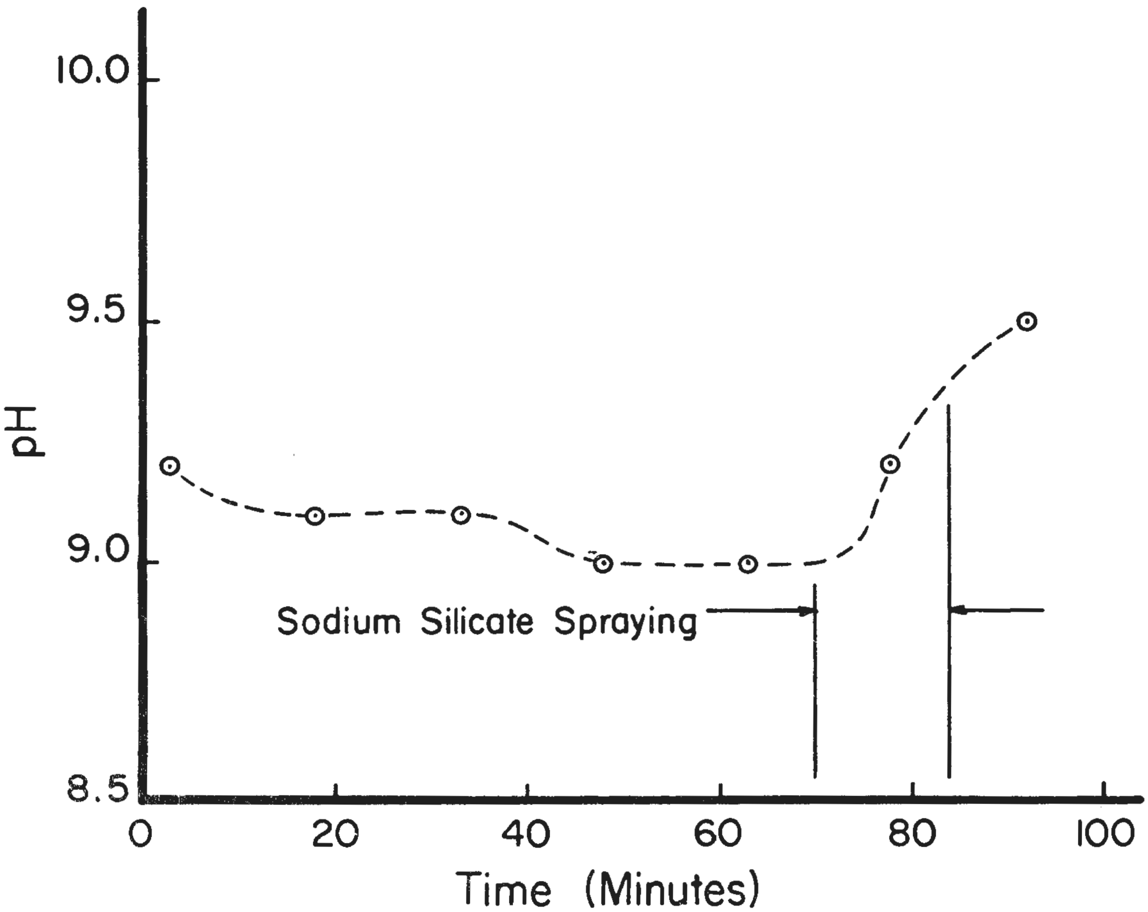

FIGURE 2-7 - WASTE STREAM pH FLUCTUATIONS FOR A TYPICAL OPERATING PERIOD original survey, the supply water-mucking system was operated continuously while spraying to "flush" silicate runoff and prevent "set-up" on the tunnel floor. During the spot check, by contrast, the supply-mucking system was shut off just prior to spraying and started shortly afterward. This revised procedure apparently had an attenuating affect on waste stream pH.

Summary

The data obtained in the Minneapolis tunneling waste survey is summarized below in Table 2-1

Table 2-1
Waste Survey Results

Parameter	Units	Average	Minimum	Maximum
Solids Flow	tons/hour	8.7	4.8	14.2
Wastewater Flow (instantaneous)	gpm	180	70	430
Wastewater Flow (interval averaged)	gpm	170-180	100-110	250-260
Suspended Solids	mg/l	1000-1500	0-500	7500-8000
pH	-	9.2	8.5	11.8

The above figures should be considered typical only for this particular operation. If similar information is desired for another hydraulic tunneling operation, another waste survey should be conducted.

References

1. Svanda, K., Personal Communication, Minnesota Pollution Control Agency, St. Paul, Minn., 1975.

2. DuPont Company, Sodium Silicates/Product Information (A-72721), DuPont Co., Wilmington, Del., 1975.

Chapter 3

WATER QUALITY REQUIREMENTS FOR HYDRAULIC TUNNELING OPERATIONS

The previous chapters have discussed the basic hydraulic tunneling operation and the characteristics of the waste stream it produces. The next step in the waste treatment discussion is to ascertain the quality of effluent to be produced by the treatment system. The required effluent quality is a function of the proposed final disposal or use of the effluent. Three potential disposal or re-use alternatives are available:

(1) Treatment and discharge of the waste stream to an existing body of water (if available).

(2) Pre-treatment and discharge of the waste stream into a sanitary sewer (if available).

(3) Treatment of the waste stream for direct re-use in the tunneling operation.

The following sections will discuss each of the options listed above.

Disposal in Public Waters

The method most frequently utilized in the past to dispose of hydraulic tunneling waste was to simply remove the coarse material from the waste stream and discharge the fines-bearing liquid into some public body of water. However, strict quality standards now protect the public waters of Minnesota, making such discharges unacceptable.

<u>Effluent Quality Standards</u> The Minnesota Pollution Control Agency (MPCA) has categorized Minnesota's public waters into five major use groups (1):

(1) <u>Domestic Consumption</u> ("waters which are or may be used as sources of supply for drinking, culinary, or food processing use or other domestic purposes...")

(2) <u>Fisheries and Recreation</u> ("waters which are or may be used for fishing, fish culture, bathing, or any other recreational purposes...")

(3) Industrial Consumption ("waters which are or may be used as sources of supply for industrial process or cooling water, or any other industrial or commercial purposes....")

(4) Agriculture and Wildlife ("waters which are or may be used for any agricultural purposes including stock watering and irrigation, or by water-fowl or wildlife....")

(5) Navigation and Waste Disposal ("waters which are or may be used for any form of water transportation or navigation, disposal of sewage, industrial waste or other waste effluents, or fire prevention...")

For each of the above use groups, water quality criteria (including limits on various substances or characteristics such as suspended solids, turbidity, pH, and oil) have been developed (1). From these criteria, the assimilative capacity of a particular use group may be estimated and suitable effluent standards may be developed. In addition, the MPCA has established minimum quality standards for any effluent discharged into Minnesota waters; a partial list of these standards is found in Table 3-1.

Table 3-1 (1)
Effluent Quality Standards

Substance or Characteristic	Limiting Concentration or Range
Total Suspended Solids	30 milligrams per liter
Turbidity	25 Jackson Turbidity Units
pH	6.5 - 8.5
Oil	Essentially free of visible oil
Unspecified Toxic or Corrosive Substances	None at levels acutely toxic to humans or other animals or plant life, or directly damaging to real property

In the event that the thirty milligram per liter suspended solids concentration appears insufficient in preventing pollution, the MPCA reserves the option to reduce the suspended solids limit to as little as five milligrams per liter.

Nearly all of the State's public waters have been assigned one or more of the use group categories listed above. A list of the various bodies of water and their corresponding use groups is found in reference 1.

Discharge Permit Any party desiring to discharge industrial waste treatment effluent into a public body of water must obtain a permit from the MPCA specifying effluent standards and monitoring requirements. The following paragraphs are excerpts from an actual discharge permit issued by the MPCA for a hydraulic tunneling operation discharging effluent into the Mississippi River in St. Paul. (Extraneous information has been deleted.) The permit was issued in 1974 and remains valid through 1979 under stipulations contained within.

* *

PART I

A. EFFLUENT LIMITATIONS AND MONITORING REQUIREMENTS

1. During the period beginning on the effective date of this permit, and lasting until June 30, 1979, the permittee is authorized to discharge from outfall serial number. . .

   Such discharges shall be limited and monitored by the permittee as specified below:

EFFLUENT CHARACTERISTIC	DISCHARGE LIMITATIONS		MONITORING REQUIREMENTS	
	Daily Avg	Daily Max	Measurement Frequency	Sample Type
Flow-M^3/Day (MGD)	-	-	Weekly	Daily Average Flow Estimate
Total Suspended Solids	20 mg/l	30 mg/l	Weekly	8 Hr. Composite
Turbidity	-	25 JTU	Weekly	Grab

The pH shall not be less than 6.5 nor greater than 8.5.
There shall be no discharge of floating solids or visible foam in other than trace amounts.
Samples taken in compliance with the monitoring requirements specified above shall be taken at the following location: at a point representative of the discharge to the river.

B. MONITORING AND REPORTING

1. Representative Sampling

   Samples and measurements taken as required herein shall be representative, of the volume and nature of the monitored discharge.

2. Reporting

Monitoring results obtained during the previous month shall be summarized and reported on a Discharge Monitoring Report Form (EPA No. 3320-1), postmarked no later than the 15th day of the month following the completed reporting period. The first report shall be submitted within ninety (90) days of the date of issuance of this permit. Signed copies of these, and all other reports required herein, shall be submitted to the Minnesota Pollution Control Agency. . .

3. Definitions

   a. "Daily Average" Discharge

      1. Weight Basis - The "daily average" discharge means the total discharge by weight during a calendar month divided by the number of days in the month that the production or commercial facility was operating. Where less than daily sampling is required by this permit, the daily average discharge shall be determined by the summation of the measured daily discharges by weight divided by the number of days during the calendar month when the measurements were made.

      2. Concentration Basis - The "daily average" concentration means the arithmetic average (weighted by flow value) of all the daily determinations of concentration made during a calendar month. Daily determinations of concentration made using a composite sample shall be the concentration of the composite sample. When grab samples are used, the daily determination of concentration shall be the arithmetic average (weighted by

flow value) of all the samples collected during the calendar day.

b. "Daily Maximum" Discharge

   1. Weight Basis - the "daily maximum" discharge means the total discharge by weight during any calendar day.

   2. Concentration Basis - the "daily maximum" concentration means the daily determination of concentration for any calendar day.

4. Test Procedures

Test procedures for the analysis of pollutants shall conform to regulations published pursuant to Section 304(q) of the Act. and Minnesota Statute Chapter 115.03 Subd. 1 (3) (7), under which procedures may be required.

5. Recording of Results

For each measurement or sample taken pursuant to the requirements of this permit, the permittee shall record the following information:

a. The exact place, date, and time of sampling;
b. The dates the analyses were performed;
c. The person(s) who performed the analyses;
d. The analytical techniques or methods used; and
e. The results of all required analyses.

6. Additional Monitoring by Permittee

If the permittee monitors any pollutant at the location(s) designated herein more frequently than required by this permit, using approved analytical methods as specified above, the results of such monitoring shall be included in the calculation and reporting of the values required in the Discharge Monitoring Report Form (EPA No. 3320-1). Such increased frequency shall also be indicated.

7. Records Retention

All records and information resulting from the monitoring activities required by this permit including all records of analyses performed and calibration and maintenance of instrumentation and recordings from continuous monitoring instrumentation shall be retained for a minimum of three (3) years, or longer if requested by the Regional Administrator of the Minnesota Pollution Control Agency.

PART II

A. MANAGEMENT REQUIREMENTS

1. Change in Discharge

All discharges authorized herein shall be consistent with the terms and conditions of this permit. The discharge of any pollutant identified in this permit more frequently than or at a level in excess of that authorized shall constitute a violation of the permit. Any anticipated facility expansions, production increases, or process modifications which will result in new, different, or increased discharges of pollutants must be reported by submission of a new NPDES application or, if such changes will not violate the effluent limitations specified in this permit, by notice to the permit issuing authority of such changes. Following such notice, the permit may be modified to specify and limit any pollutants not previously limited.

2. Noncompliance Notification

If, for any reason, the permittee does not comply with or will be unable to comply with any daily maximum effluent limitation specified in this permit, the permittee shall provide the Regional Administrator and the State with the following information, in writing, within five (5) days of becoming aware of such condition:

a. A description of the discharge and cause of noncompliance; and

b. The period of noncompliance, including exact dates and times; or, if not corrected, the anticipated time the noncompliance is expected to continue, and steps being taken to reduce, eliminate and prevent recurrence of the noncomplying discharge.

3. Facilities Operation

The permittee shall at all times maintain in good working order and operate as efficiently as possible all treatment or control facilities or systems installed or used by the permittee to achieve compliance with the terms and conditions of this permit.

4. Adverse Impact

The permittee shall take all reasonable steps to minimize any adverse impact to navigable waters resulting from noncompliance with any effluent limitations specified in this permit, including such accelerated or additional monitoring as necessary to determine the nature and impact of the noncomplying discharge.

5. Bypassing

Any diversion from or bypass of facilities necessary to maintain compliance with the terms and conditions of this permit is prohibited, except (i) where unavoidable to prevent loss of life or severe property damage, or (ii) where excessive storm drainage or runoff would damage any facilities necessary for compliance with the effluent limitations and prohibitions of this permit. The permittee shall promptly notify the Minnesota Pollution Control Agency, Attn: Compliance and Enforcement Section in writing of each such diversion or bypass.

6. Removed Substances

Solids, sludges, filter backwash, or other pollutants removed from or resulting from treatment or control of wastewaters shall be disposed of in a manner such as to prevent any pollutant from such materials from entering waters of the State.

7. Power Failures

In order to maintain compliance with the effluent limitations and prohibitions of this permit, the permittee shall either:

a. In accordance with the Schedule of Compliance contained in Part I, provide an alternative power source sufficient to operate the wastewater control facilities;

or, if no date for implementation appears in Part I,

b. Halt, reduce or otherwise control production and/or all discharges upon the reduction, loss, or failure of one or more of the primary sources of power to the wastewater control facilities.

B. RESPONSIBILITIES

1. Right of Entry

The permittee shall allow the head of the State Water Pollution Control Agency, the Regional Administrator, and/or their authorized representatives, upon the presentation of credentials:

a. To enter upon the permittee's premises where an effluent source is located or in which any records are required to be kept under the terms and conditions of this permit; and

b. At reasonable times to have access to and copy any records required to be kept under the terms and conditions of this permit; to inspect any monitoring equipment or monitoring method required in this permit; and to sample any discharge of pollutants.

2. Transfer of Ownership or Control

In the event of any changes in control or ownership of facilities from which the authorized discharges emanate, the permittee shall notify the succeeding owner or controller of the existence of this permit by letter, a copy of which shall be forwarded to the Regional Administrator and the State Water Pollution Control Agency.

3. Availability of Reports

Except for data determined to be confidential under Section 308 of the Act, and Minnesota Statute Chapter 116.075 Subd. 2, all reports prepared in accordance with the terms of this permit shall be available for public inspection at the offices of the Minnesota Pollution Control Agency and the Regional Administrator. Procedures for submitting such confidential material shall be pursuant to Minnesota Regulation WPC 36, J (2). As required by the Act, effluent data shall not be considered confidential. Knowingly making any false statement on any such report may result in the imposition of criminal penalties as provided for in Section 309 of the Act and Minnesota Statute Section 115.072 Subd. 3.

4. Permit Modification

After notice and opportunity for a hearing, this permit may be modified, suspended, or revoked in whole or in part during its term for cause including, but not limited to, the following:

a. Violation of any terms of conditions of this permit;
b. Obtaining this permit by misrepresentation or failure to disclose fully all relevant facts; or
c. A change in any condition that requires either a temporary or permanent reduction or elimination of the authorized discharge.

5. Toxic Pollutants

Notwithstanding Part II, B-4 above, if a toxic effluent standard or prohibition (including any schedule of compliance specified in such effluent standard or prohibition) is established under Section 307(a) of the Act and Minnesota Chapters 115 and 116 as amended, for a toxic pollutant which is present in the discharge and such standard or prohibition is more stringent than any limitation for such pollutant in this permit, this permit shall be revised or modified in accordance with the toxic effluent standard or prohibition and the permittee so notified.

6. Civil and Criminal Liability
Except as provided in permit conditions on "Bypassing" (Part II, A-5) and "Power Failures" (Part II, A-7), nothing in this permit shall be construed to relieve the permittee from civil or criminal penalties for noncompliance.

7. Oil and Hazardous Substance Liability
Nothing in this permit shall be construed to preclude the institution of any legal action or relieve the permittee from any responsibilities, liabilities, or penalties to which the permittee is or may be subject under Section 311 of the Act, and Minnesota Chapters 115 and 116 as amended.

8. State Laws
Nothing in this permit shall be construed to preclude the institution of any legal action or relieve the permittee from any responsibilities, liabilities, or penalties established pursuant to any applicable State law or regulation under authority preserved by Section 510 of the Act.

9. Property Rights
The issuance of this permit does not convey any property rights in either real or personal property, or any exclusive privileges, nor does it authorize any injury to private property or any invasion of personal rights, nor any infringe-

ment of Federal, State or local laws or regulations.

10. Severability

The provisions of this permit are severable, and if any provision of this permit, or the application of any provision of this permit to any circumstance, is held invalid, the application of such provision to other circumstances, and the remainder of this permit, shall not be affected thereby.

PART III

A. DESCRIPTION

The proposed disposal system will consist of a classifier followed by a settling pond. This system will discharge clarified water at a maximum rate of 720,000 gallons per day. The principal activity at this facility is the cutting of sandstone with high pressure water.

B. OTHER REQUIREMENTS

1. Any variation from the above description shall be done only in accordance with WPC-36.

2. The Permittee shall submit a monitoring plan to the Minnesota Pollution Control Agency within forty-five (45) days after date of issuance of this permit to the Agency for its approval and thereafter submit a written report to the Minnesota Pollution Control Agency each month in compliance with the plan. The monitoring plan shall describe the monitoring equipment and the monitoring methods, including where appropriate biological monitoring methods, type of samples, sampling procedure or manner, location and interval of sampling and such other information as the Minnesota Pollution Control Agency may reasonably require of the Permittee.

3. The Permittee shall report the results of the monitoring requirements in the units specified in this permit. A report

or written statement is to be submitted even if no discharge occurred during the reporting period. The monthly report shall include (a) a description of any modifications in the waste collection, treatment and disposal facilities; (b) any changes in operational procedures; (c) any other significant activities which alter the nature or frequency of the discharge; (d) any other material factors regarding the conditions of this permit.

* *

Any discharge permit (for hydraulic tunneling) issued by the MPCA in the near future would probably resemble the above example in form and content. However, the reader should be aware that pollution control requirements are in a period of rapid change and revision. Thus, a contractor contemplating discharge of effluent to public waters, should contact the appropriate local or State agency, as well as the U.S. Environmental Protection Agency concerning latest standards and regulations.

Sewer Disposal

A simple option to "on-site" slurry treatment is to discharge the waste stream into a sanitary sewer. Some of the aspects of sewer disposal, including pretreatment requirements, service connection, and costs of waste treatment, will be discussed in the following paragraphs.

Pretreatment Requirements The federal government, through the Environmental Protection Agency (EPA), has established guidelines on the minimum quality of waste that may be admitted to the sanitary sewer. These guidelines require that the industrial discharger pretreat his waste stream if it is of such a character that it could damage or impair the sewer or treatment system, or pass through the system to create a toxic or nuisance condition at the outfall. Prohibited wastes or conditions most likely to be encountered in hydraulic tunneling operations are (2):

"waste waters containing pollutants which will cause corrosive structural damage to treatment works, but in no case wastes with pH lower than 5.0, unless the works designed to accommodate such wastes",

"waste waters containing solid or viscous wastes in amounts which would cause obstruction to the flow in sewers, or other interference with the proper operation of the publicly owned treatment works",

"waste waters at a flow rate which is excessive relative to the capacity of the publicly owned treatment works and which would cause a treatment process upset and subsequent loss of treatment efficiency",

"waste waters containing such concentrations or quantities or pollutants that their introduction into a publicly owned treatment works over a relatively short time period (sometimes referred to as slug discharges), would cause a treatment process upset and subsequent loss of treatment efficiency".

EPA guidelines are generally aimed at "major contributing industries", defined as industrial users contributing more than 50000 gallons per day or five percent of the total flow to the treatment facility, whichever is greater (2). (The EPA plans to release more specific pretreatment guidelines for individual industries, but at present, none are available.)

Most individual waste treatment facilities specify their own pretreatment standards and prohibited wastes. In some cases, these regulations may simply rephrase EPA guidelines, while in other cases they are significantly stricter. The Metropolitan Waste Control Commission (MWCC), a unified sewage collection and treatment system for the Minneapolis-St. Paul metropolitan area, has established pretreatment guidelines that may be considered typical. Most of the EPA guidelines cited above are found in nearly identical form in MWCC regulations, with one exception: the MWCC requires stricter pH limits

(5.5 - 9.5) (3).

Service Connections Requirements for actual connection to a sanitary sewer vary from one system to another. For discussion purposes, MWCC requirements are considered here.

Any party desiring to make a connection to a sanitary sewer in the MWCC system must file an application for connection with the appropriate agency of the city where connection is to be made (4). The application must contain information such as location of the connection, expected flow volumes, and a qualitative description of the waste stream. If approved by the city, the application is forwarded to the MWCC for final consideration. It is then returned to the city agency, which notifies the applicant of approval or rejection.

For direct connection to an MWCC interceptor (a large trunk sewer), the application is submitted directly to the MWCC (4). If the application is approved, the MWCC will issue a direct connection permit to the potential user.

Capital Recovery Charges An urban wastewater collection and treatment system is usually designed with a capacity sufficient to handle projected industrial as well as domestic sewage flows. Consequently, the EPA, when administering wastewater facility construction grants, stipulates that local agencies (such as the MWCC) implement programs to recover, from contributing industries, the costs of increased system capacities required to meet industrial demands. Cost recovery programs may specify that cost recovery charges be prorated over the life of facilities or assessed on a "lump sum" basis.

The MWCC has not as yet instituted a cost recovery program for federal funds, but intends to do so by 1977. The cost recovery program, when implemented, will probably consist of yearly payments prorated according to the projected life of the wastewater collection and treatment system (4).

The MWCC has incorporated a program for recovery of local funds used for collection and treatment system construction. The program consists of charging each industrial user with a lump sum assessment at the time of connection to the sewer. This "Service Availability Charge" (SAC Charge) is computed by the following formula (4):

SAC Charge = (Q day/274 gallons) x $350

where: Q day = total volume of wastewater discharged to the sewer per day (gallons)

Although no provisions are presently available for prorating the SAC Charge for a temporary user, such arrangements could probably be made.

Treatment Charges Charges for treatment of wastewater may be assessed on two bases: volumetric flow rate and concentration of pollutants in the waste stream. The MWCC has incorporated both alternatives in its treatment charge plan.

Contributing municipalities are charged a constant rate (about $350 per million gallons) for treatment of normal-strength wastewater. Each municipality in turn bills its industrial users at a rate not less than that imposed by the MWCC. (For direct connection to an interceptor, the MWCC would bill the user directly.) Thus, the industrial user is responsible for metering his own waste flow, subject to verification by municipality or MWCC representatives.

A surcharge may be imposed for treatment of wastewater with exceptionally high suspended solids concentration and/or chemical oxygen demand. (The reader should note that although the rationale for surcharging of high-strength wastewater has been developed, the program has not as yet been implemented. The MWCC hopes to initiate it by January, 1977, however.) The surcharge formula is presently under revision, but the proposed form is given below (5):

$$SCF = 0.60 \left(\frac{0.50(SS-317)}{317} + \frac{0.50(COD-684)}{684}\right)$$

where:

SCF = strength charge factor (dimensionless multiplier)

SS = suspended solids concentration (if solids concentration is less than 317 milligrams per liter, use 317; if solids concentration is greater, use actual value)

COD = chemical oxygen demand (if chemical oxygen demand is less than 684 milligrams per liter, use 684; if chemical oxygen demand is greater, use actual value)

For a relatively inorganic waste stream such as that produced by a hydraulic tunneling operation, the chemical oxygen demand should be negligible, and consequently, the COD term of the above equation could probably be ignored.

The actual surcharge imposed on a quantity of high-strength wastewater is computed as follows (5):

$$\text{Surcharge} = Q_{HS} \times \text{SCF} \times (\$140.60/1000000 \text{ gallons})$$

where:

Q_{HS} = volume of high-strength wastewater (gallons)

SCF = average strength charge factor for the volume of high-strength wastewater (dimensionless)

As with volumetric flow rate, the discharger is responsible for monitoring the suspended solids concentration and chemical oxygen demand of his own waste stream.

Re-use

The previous sections of this chapter have discussed systems in which water is cycled once through the tunneling operation and then discarded. Although these systems were adequate in the past, more stringent controls on industrial discharges to public waters and sanitary sewers seem to indicate that other alternatives should at least be considered. The most obvious possible option seems to be the re-use of tunneling water (after some treatment). An earlier report discussed the potential effects of re-use on the tunneling system (6). This discussion considers actual water quality standards for re-use and the phenomena of solids buildup which may occur in recycled liquid.

Water Quality Standards for Re-use Standards for re-use of hydraulic tunneling water would result from a balance of treatment costs and costs associated with use of "dirtier" water. However, compilation of quantitative water quality standards requires empirical testing to determine the "dirtiest" water which may be economically used with the particular system. To the author's knowledge, no such testing program has been undertaken for the hydraulic tunneling industry.

Some insight on required water quality may be gained by examining the quality of Mississippi River in Minneapolis-St. Paul. Water from the Mississippi has been used successfully on numerous hydraulic tunneling operations in the area. The average suspended solids content for Mississippi River water in this reach is approximately eighteen milligrams per liter. (Suspended solids concentrations have been sampled at the Minneapolis Waterworks, located on the Mississippi River, since 1953. Of the sixty-nine samples analyzed for suspended solids in this period, the average is 18.4 milligrams per liter, the maximum is 120 milligrams per liter, the minimum is 0.5 milligrams per liter, and the standard deviation is 17.4 milligrams per liter (7). The above average provides at least an order of magnitude for allowable suspended solids content.

Conversations with personnel associated with hydraulic tunneling operations lead the author to believe that much dirtier water (than the 18.4 milligram per liter value) could be used economically (8). Figure 3-1 shows turbid effluent from a hydraulic tunneling operation discharging into the Mississippi River. (Conceivably, this water could have contained as much as 1000 milligrams per liter suspended solids at times.) For a time, supply water for this tunneling operation was withdrawn from the river at the point of effluent discharge, creating, in effect, a "semi-recycling" system. In an attempt to reduce tunneling systems maintenance, construction personnel moved the supply point upstream to a point where clean river water was taken in. However, the mechanical problems were not significantly reduced by the change, seeming to indicate that other factors, such as normal wear-and-tear and poor maintenance, may have been more critical. (The

FIGURE 3-1 - DISCOLORATION OF THE MISSISSIPPI RIVER FROM DISCHARGE OF UNTREATED HYDRAULIC TUNNELING WATER preceding statement does not infer that the presence of solids has no effect on system deterioration; clean water should be used for pump seal water and any other critical applications, if possible.) Thus, for normal operations such as hydraulic cutting and washing, water containing moderate concentrations of suspended solids (above the eighteen milligram per liter figure cited above) should be acceptable.

Before closing the discussion of water quality standards for re-use, a final point should be noted: the treatment system must be designed so that all particles which could cause immediate damage or impairment to tunneling equipment are completely removed (such as particle sizes that are too large for pump clearances).

Solids Build-up in Recycled Water A treatment system for suspended solids separation is normally designed to remove essentially all particles above a certain size, with only partial removal of particles below that size. For discussion purposes, the sedimentation hopper described in Chapter 1 may be considered; the hopper removes nearly all the coarse material (plus 325 mesh - see Figure 1-3) from the waste stream, while most of the fine material overflows with the liquid phase as effluent. If effluent was cycled through the tunneling and treatment processes numerous times, a fines build-up would obviously occur. However, this solids build-up should approach a finite limit.

The phenomenon of limiting concentration would occur because the fine material would form a homogeneous mixture with the liquid phase, and the resulting fluid would be lost at various points in the system (by pipeline leakage, insufficient dewatering of coarse materials, etc.), only to be replaced by "clean" make-up water. Thus, solids concentration increases from essentially zero at start-up to an equilibrium point where rate of solids removal due to water loss equals the rate of solids overflow from the hopper. To determine the magnitude of the equilibrium solids concentration, a sample calculation is presented.

For this example, the following assumptions are made:

(1) Rate of overflow from the hopper averages about 170 gallons per minute (see Figure 2-4).

(2) Solids content of hopper overflow averages about 1500 milligrams per liter or 0.0125 pounds per gallon (see Figure 2-5).

(3) Water loss from leakage, etc., throughout the system averages about twenty gallons per minute.

Thus, if hopper overflow is cycled directly into the feed line for the tunneling operation, solids are admitted back to the system at a rate of about 2.125 pounds per minute. (170 gallons per minute times 0.0125 pounds per gallon equals 2.125 pounds per minute.) At equilibrium conditions, this solids gain must be balanced by the solids loss due to leakage. Consequently, the average solids concentration of the system liquid must attain a value of 0.106 pounds per gallon or 12700 milligrams per liter for equilibrium. (20.0 gallons per minute times 0.106 pounds per gallon equals 2.125 pounds per minute.)

Although the author cannot definitely state that such direct recycling of hopper overflow is impractical or uneconomical, the resulting buildup of fine solid material (to more than one percent by weight) would very likely result in significant increases in required system maintenance. However, with a more efficient treatment system, the equilibrium solids concentration would be proportionately lower.

Summary

Up to this point, three major disposal options have been discussed:

(1) Disposal of effluent in public water.

(2) Disposal of effluent in sanitary sewer.

(3) Re-use of effluent.

The discussion of effluent discharge in public waters cited a suspended solids limit of thirty milligrams per liter and a pH range of 6.5 to 8.5 (see Table 3-1). Requirements for sanitary sewer disposal, while not directly specifying a limit on solids content, impose a surcharge for treatment of wastewater containing more than 317 milligrams per liter suspended solids, and limit pH to a range of 5.5 to 9.5. Although no definite effluent limits were specified for re-use, experience has shown that water approaching that of mean river quality may satisfactorily be used (suspended solids concentration about eighteen milligrams per liter and pH of about 7.9), although water of significantly poorer quality could probably also be tolerated.

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3. Metropolitan Sewer Board, Sewage and Waste Control Rules and Regulations for the Metropolitan Disposal System, Metropolitan Sewer Board, St. Paul, Minn., 1971.

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Chapter 4

TREATMENT SYSTEM DESIGN

The previous chapter discussed water quality criteria for three possible wastewater disposal or re-use alternatives. This chapter will deal with design of basic treatment systems capable of producing effluent of quality adequate for each of these options. For discussion purposes, the following terms will be used:

(1) Class A Liquid Processing Option - Treatment system producing effluent of quality adequate for discharge to public waters.

(2) Class B Liquid Processing Option - Treatment system producing effluent of quality adequate for disposal in a sanitary sewer.

(3) Class C Liquid Processing Option - Treatment system producing effluent of quality adequate for re-use in the tunneling system.

(The class designations above should not be construed as relating to effluent quality - see Chapter 3.) In addition to liquid processing systems, the chapter will also deal with design of a sludge treatment system. However, before entering the actual treatment system design discussion, several other points will be considered.

Design Methods

Three primary methods are utilized for the design of liquid and sludge processing systems:

(1) Design based on laboratory test results, e.g., various polyelectrolytes were tested to determine the type(s) which most satisfactorily coagulates hydraulic tunneling wastes.

(2) Design based on manufacturers' recommendations, e.g., because of a manufacturer's wide experience, he can recommend a pump to fulfill the particular application without extensive testing.

(3) Design based on typical design parameters, e.g., a reference cites a typical hydraulic loading value for a particular filter type, so the unit is sized so as to have a similar hydraulic loading.

Obviously, none of the above methods is independent or mutually exclusive of another, and each has its own shortcomings. However, the third method should be viewed with more "suspicion" than the first two, particularly when designing a system for new applications, i.e., hydraulic tunneling wastewater treatment.

Selection of Design Parameters

The discussion below will assume that St. Peter sandstone is the material being excavated, and the design calculations will utilize data obtained in the Minneapolis tunneling waste survey (see Chapters 1 and 2).

The required quality of a treatment system effluent is generally constrained by external factors such as discharge standards of maximum tolerable suspended solids concentrations, etc. (see Chapter 3). Consequently, a high quality of effluent must be consistently maintained, and the processes relating to effluent quality are designed on the basis of waste stream maximums (maximum flow rate, suspended solids concentration, etc.). By contrast, sludge treatment processes are much less constrained by outside factors, and the primary focus is placed on the most economical method of sludge treatment. Therefore, more fluctuation in sludge quality is acceptable, and sludge processes are designed on the basis of waste stream averages. (The reader should note that while some sludge treatment design parameters (such as wastewater flow rates and solids concentrations) may vary widely over short periods of time (such as a few hours), the same quantities would be much more constant when averaged on a day-to-day basis.)

Equipment Component Descriptions

Appendices A through D contain descriptions of various liquid/solids separation processes and equipment components. Appendix E evaluates these processes and separation devices according to a set of desirable criteria for a hydraulic tunneling wastewater treatment system and makes qualitative recommendations. Appendix F discusses controlling and monitoring devices which could be used in a treatment system. Thus, the reader who is unfamiliar with processes and equipment utilized in wastewater treatment should refer to Appendices A through F, and the references cited therein for further information.

System Design: Class A Liquid Processing Option

Figure 4-1 schematically illustrates processes required to obtain Class A effluent. A brief description of the various processes is presented below:

(1) Coarse Fraction Removal (process A-1 in Figure 4-1) - Removal of coarse particles from the waste stream. Coarse material, as considered here, is any particle of diameter greater than about 0.044 millimeters or 325 mesh (see Figure 1-3). Particles of this size and larger constitute the major portion of waste stream solids concentrations.

(2) Flow Equalization (A-2) - Volumetric flow rate from a tunneling operation fluctuates widely and frequently. Utilization of an equalization system can reduce fluctuation amplitude and frequency.

(3) Initial Chemical Destabilization (A-3 and A-4) - The waste stream typically contains a portion of fine material (minus 325 mesh) which is not removed by the coarse fraction removal process. If the material is sufficiently fine and present in significant quantities, chemical coagulation may be required to promote grain growth and accelerate removal.

(4) Clarification (A-5) - After the fines-bearing waste stream has been chemically treated, some process must be utilized to remove suspended agglomerations.

(5) Secondary Chemical Treatment (A-6, A-7, and A-8) - A small concentration of fine suspended solids is usually present in clarification effluent. These solids may again be chemically treated to aid in their removal.

(6) Filtration (A-9) - This step would be used for final removal of suspended solids from the hydraulic tunneling waste stream.

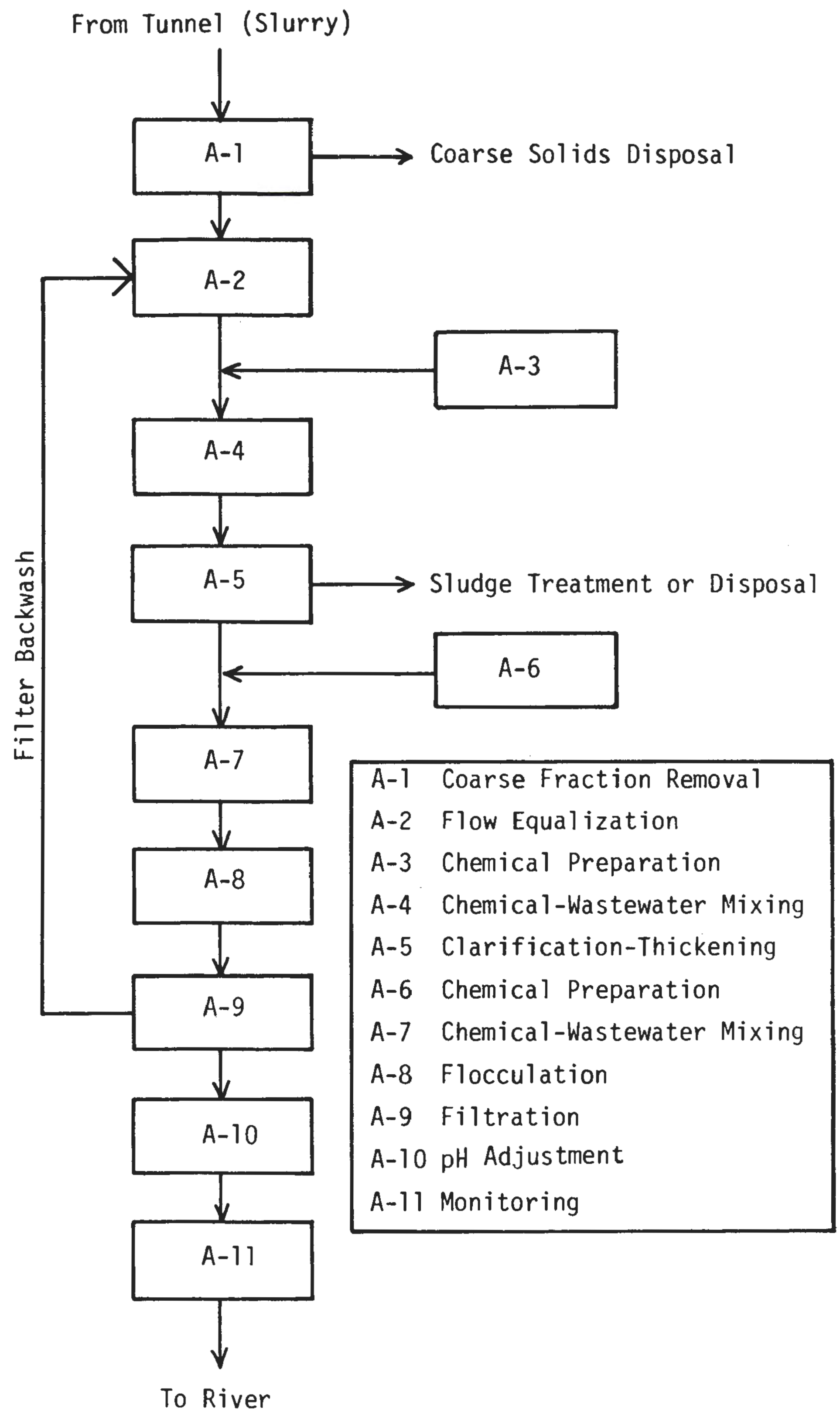


FIGURE 4-1 - SCHEMATIC OF CLASS A EFFLUENT SYSTEM

(7) pH Adjustment (A-10) - If the waste stream pH fluctuates outside of acceptable limits, a system must be provided to control the fluctuations.

(8) Discharge Monitoring (A-11) - Effluent discharge permits stipulate that various waste stream parameters, such as flow rate, suspended solids concentration, turbidity, and pH, must be monitored.

The following discussion will make quantitative recommendations for the design of subsystems to perform each of the processes described above.

Coarse Fraction Removal (A-1) - Any coarse fraction removal device has three primary functions: to remove coarse material from the waste stream, to dewater separated material, and to transmit separated material to trucks for final disposal. The sedimentation hopper is well suited for these processes (see Appendix E), and the unit presently in use on the Minneapolis project will be analyzed below. However, some general discussion of suspended particle removal will be presented first.

Suspended Particle Removal Discussion - The coarse solids in a hydraulic tunneling waste stream (plus 325 mesh) settle as discrete particles independent of the actions of one another (see Appendix C). In discrete particle settling, wastewater flow rate and horizontally projected area of the settling basin interact with particle settling velocity distribution to determine the portion of waste stream solids removed by a gravity sedimentation process.

Settling velocity distribution is related to particle size distribution of waste stream solids. Figure 1-3 is a typical grain size distribution for St. Peter sandstone determined from sieve and hydrometer analysis of several disintegrated samples from various locations throughout the metropolitan area. (Procedures for sieve and hydrometer analysis are discussed in reference 1.) Settling velocities for the various grain sizes may be determined by use of Stokes' Law (2); Figure 4-2 is a plot of settling velocity versus particle diameter. (Data for Figure 4-2 was obtained by utilizing Stokes' Law for a number of particle sizes, assuming

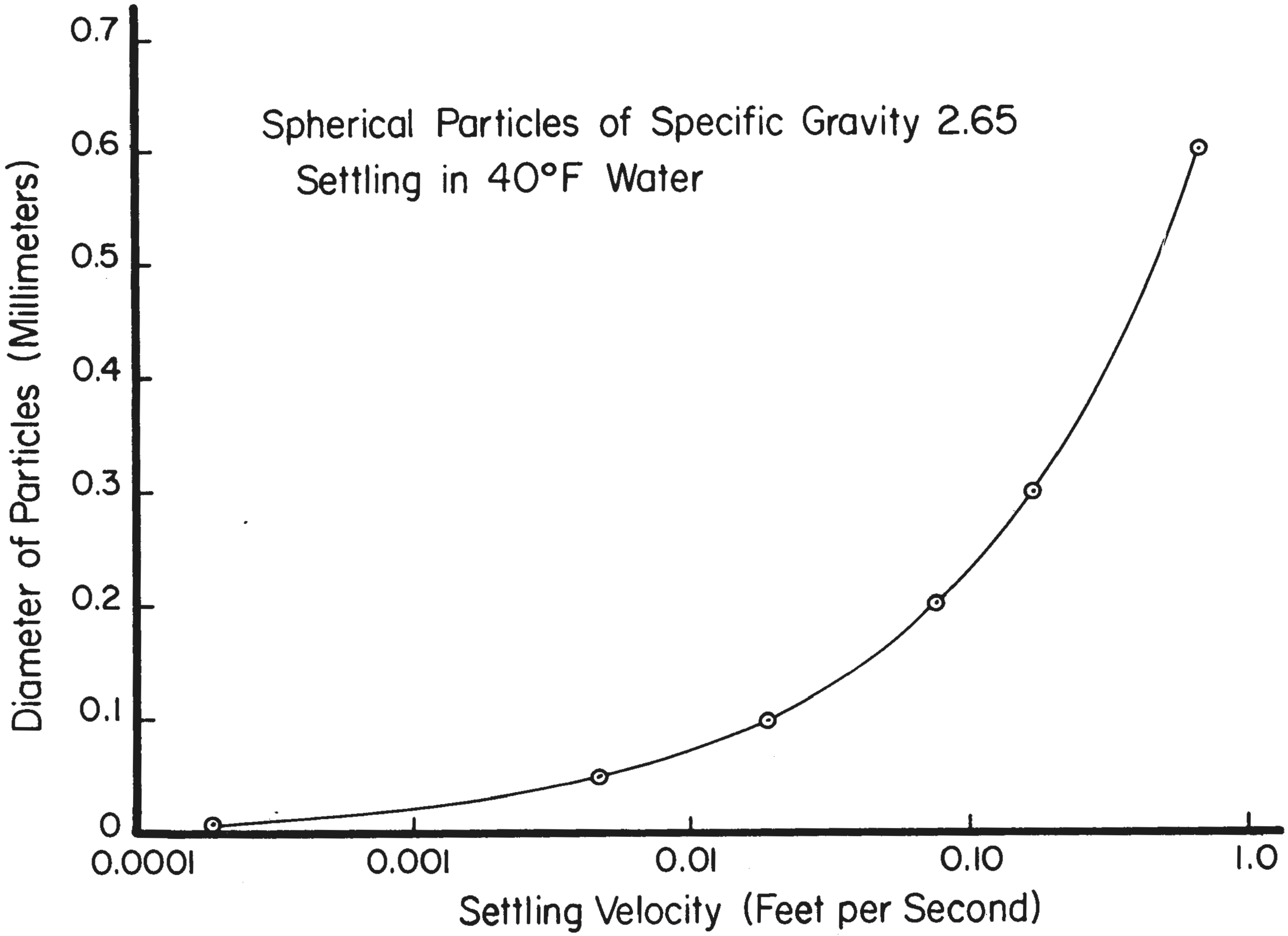


FIGURE 4-2 - PARTICLE DIAMETER VERSUS SETTLING VELOCITY a particle specific gravity of 2.65 and a water temperature of 40 degrees Farenheit. This indirect method of determining particle settling velocity distribution was utilized because coarse particles settled too rapidly for direct determination of settling velocity distribution.

Sedimentation Hopper Solids Removal Analysis - Instantaneous wastewater flow rates for the Minneapolis operation are less than or equal to 300 gallons per minute about ninety-five percent of the time (see Figure 2-2). Consequently, this value will be used to analyze hopper separation performance. Settling area of a hopper compartment is about 169 square feet (see Figure 4-3). These values for flow rate and settling area may be used to determine the hopper's overflow rate--a parameter indicative of the removal efficiency of the basin. Overflow rate is calculated by the following equation (2):

$$V_s = Q/A$$

where: V_s = overflow rate (gallons per minute per square foot <u>or</u> feet per second)

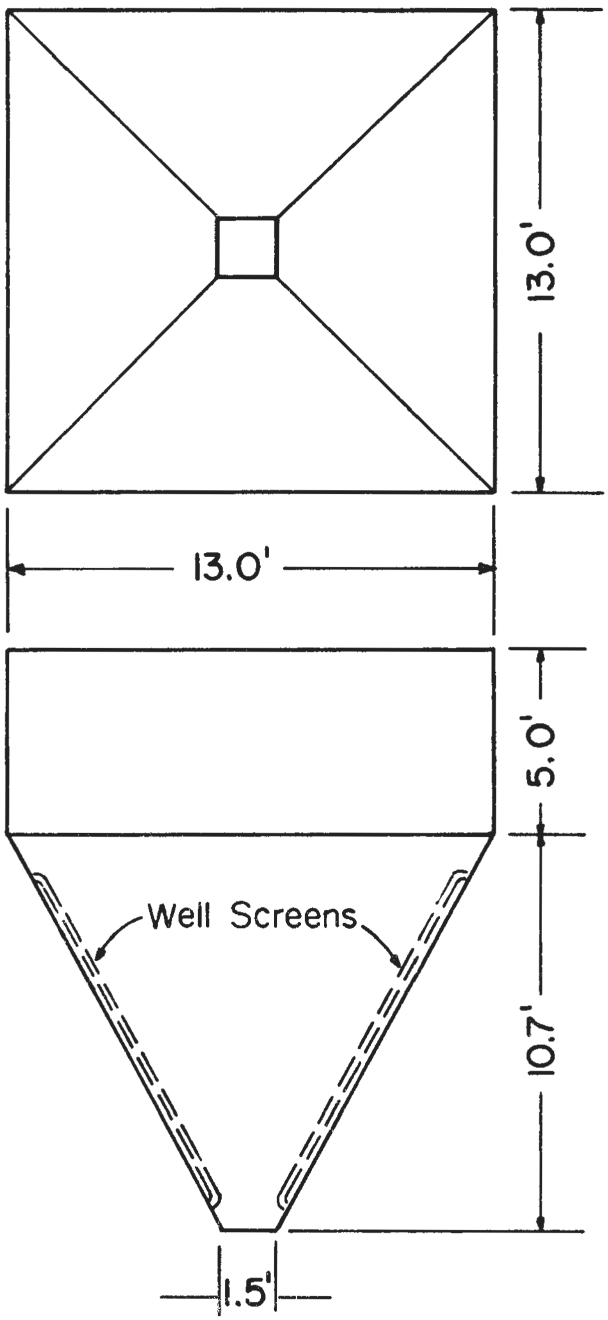
Q = wastewater flow rate (gallons per minute <u>or</u> cubic feet per second)

A = settling area of hopper (square feet)

Thus, the overflow rate for the Minneapolis hopper is about 1.78 gallons per minute per square foot, or 0.0039 feet per second. The latter value theoretically represents the settling velocity of the smallest particle completely removed by the hopper.

The portion of the total waste stream solids load removed by the hopper may be determined as follows. Figure 4-2 illustrates that, under the given conditions of particle specific gravity and water temperature, a settling velocity of 0.0039 feet per second corresponds to a particle diameter of about 0.045 millimeters for forty-five microns. Therefore, the hopper will remove from the waste stream essentially all material of diameter greater than forty-five microns. This conclusion was verified by the waste survey (see Chapter 2).

(The reader should note that the discrete particle settling model used to analyze hopper performance is not completely accurate. At times,



Compartment Settling Area = 169 Square Feet

Compartment Storage Volume = 42 Cubic Yards

FIGURE 4-3 - DIMENSIONS OF A SEDIMENTATION HOPPER COMPARTMENT waste stream solids concentrations may reach forty or fifty percent. At these concentrations, settling particles do interact with one another. However, the majority of the suspended waste stream solids are so "heavy" that, in spite of the fact that they interact and retard the settling of one another, they still settle out very rapidly. Consequently, the solids concentration of the suspension phase is rapidly reduced, and the finer fraction of the coarse solids may settle discretely.)

Solids Dewatering - The Minneapolis hopper performance is quite poor in the category of solids dewatering. Typically, when a hopper compartment is filled with solids, flow is transferred to the other compartment. Excess surface water is then pumped out of the first compartment and wet sand is withdrawn through the trap gate. Thus, water constitutes a large portion of the first few truckloads withdrawn from the hopper. A possible solution would be to place a well-point apparatus in each hopper compartment to remove excess water; such a device was used successfully on the St. Paul project. One possible configuration for well screen installation is shown in Figure 4-3; four such well screens could be placed in one hopper and piped so as to feed a single dewatering pump.

Solids Transmittal - The basic requirement for solids transmittal by the sedimentation hopper is that an individual compartment has sufficient volume to store incoming solids while the other compartment is being emptied. To examine the adequacy of the present Minneapolis hopper set up (forty-two cubic yards of storage volume per compartment), the following example is presented. A hypothetical eight hour tunneling shift is considered, for which a total of six hours are spent in actual excavation. During this time, solids flow rate averages 8.7 tons per hour (see Chapter 2). Thus, a total of about 52.2 tons is excavated, transported, and separated during the shift. Assuming a unit weight of sandstone in the hopper of about 110 pounds per cubic foot or 1.5 tons per cubic yard, the total volume of excavated material for the shift is about 34.8 cubic yards. In most cases, a single medium-sized dump truck should be able to haul this amount in one shift (depending on haul distance). Consequently, the forty-two yards of storage are adequate.

Flow Equalization (A-2) - Chapter 2 discussed volumetric flow rates and illustrated that in spite of gross short-term fluctuations, flow rates which were averaged over longer periods of time proved fairly constant. (They were, however, subject to changes in water demand at the tunnel heading - see Chapter 2.) Consequently, a system designed to dampen minute-to-minute flow variations could have the following beneficial effects (3):

(1) Treatment facilities could be designed for peak interval-average flow rates rather than peak instantaneous flow rates.
(2) Occurrences of hydraulic upset caused by fluctuating flow rates would be drastically reduced.
(3) If mixing were provided in the equalization system, the blending of wastewater would result in more uniform solids loadings and more efficient treatment downstream.

A flow equalization system for a hydraulic tunneling operation would have two essential components: a storage reservoir immediately below the coarse fraction removal process and a positive displacement pump to supply a "constant", controlled flow from the storage reservoir to downstream processes.

Flow Reservoir - Figure 4-4 is a plot of accumulated flow volume versus time for a selected monitoring period. A line drawn from the origin to the end point represents average flow for the period. Parallel lines constructed at 500 gallon increments above and below the average line envelope all data points. Similar plots for other monitoring periods yield essentially the same results; thus, a 1000 gallon capacity reservoir should have sufficient capacity to dampen fluctuations. (The 1000 gallon value recommended above is quite conservative; the vertical distance between enveloping curves tangent to the actual accumulation line represents the minimum required storage volume - see Figure 4-4. However, the additional volume is recommended as added protection against over-

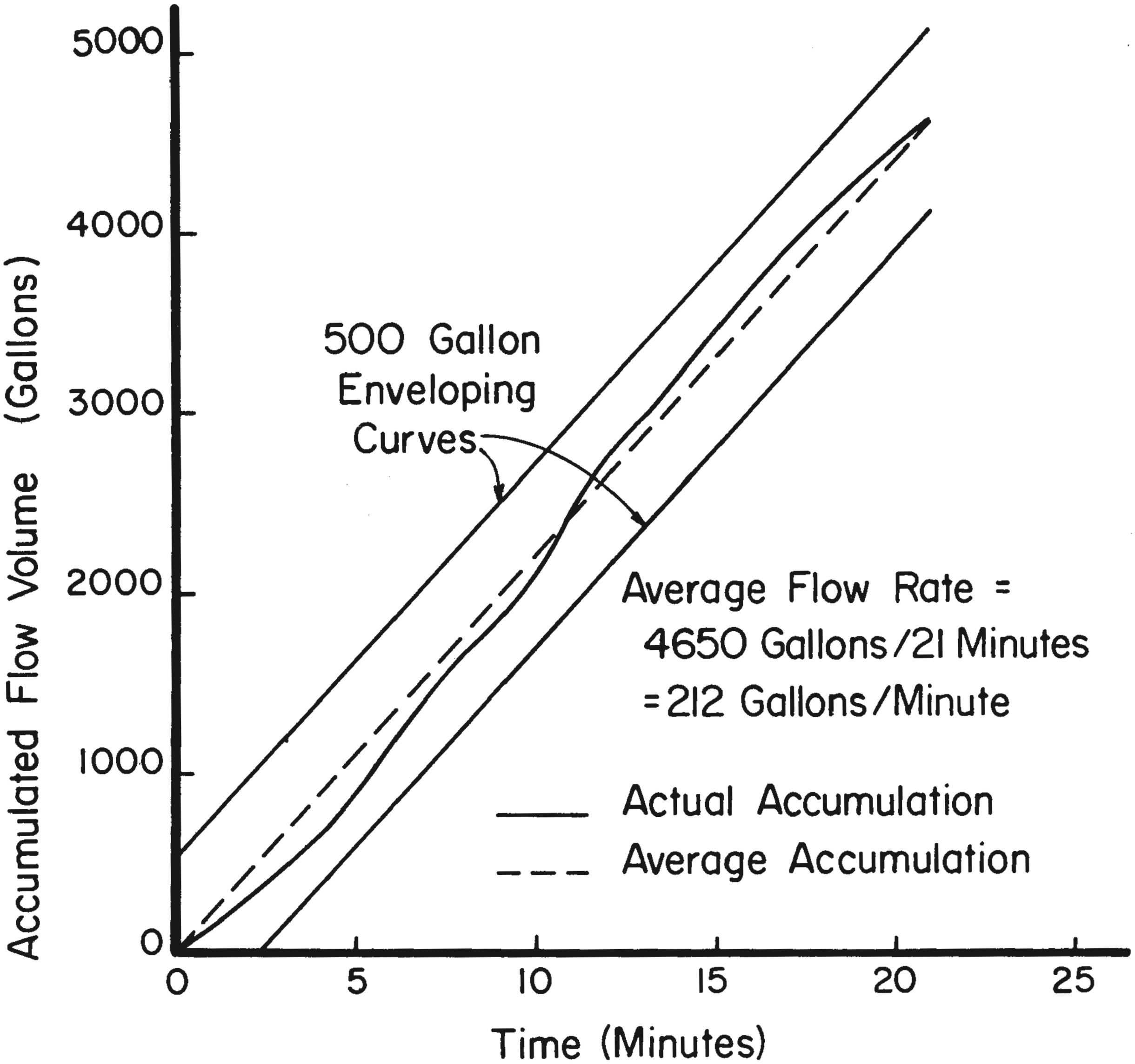
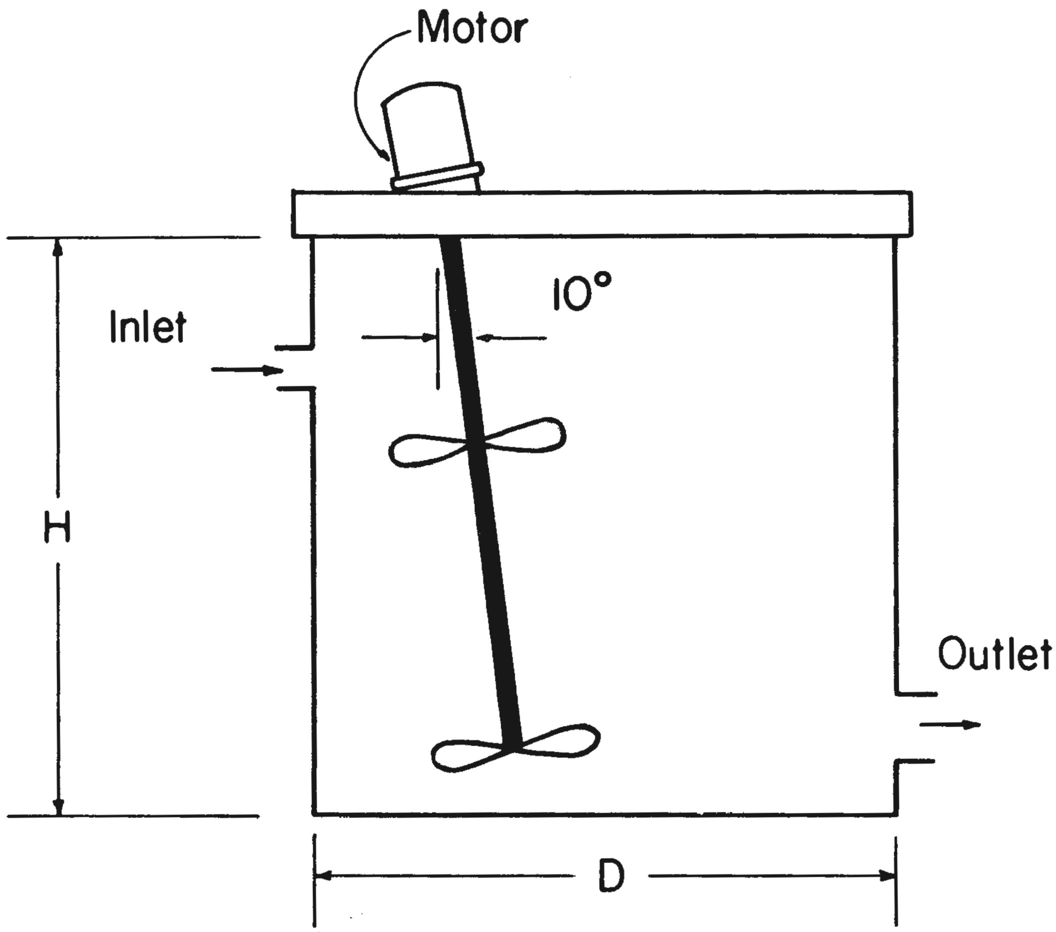


FIGURE 4-4 - ACCUMULATED WASTEWATER FLOW VOLUME FOR A TYPICAL OPERATING PERIOD flowing or completely draining the tank.)

The reservoir should be equipped with a mixer to maintain particles in suspension and blend the wastewater. (The vast majority of particles entering the reservoir should be below the 325 mesh size.) Mixing should be provided as near as possible to the point of entrance of wastewater. Power requirements for mixing depend on basin and wastewater characteristics and are usually determined by experience and/or by manufacturers' recommendations; a two-horsepower propeller mixer is recommended for this application (4). Figure 4-5 illustrates one possible flow reservoir configuration which should be adequate for equalization of flows and blending of the wastewater for the Minneapolis tunneling waste stream.

Pumping Requirements - The flow equalization pump actually has two functions: to provide a controlled rate of flow from the reservoir and to provide hydraulic head for downstream processes. Measured interval-averaged flow rates varied from 100 to about 250 gallons per minute (see Figure 2-4), and consequently, the equalization pump should have a somewhat larger range; possibly 50 to 300 gallons per minute. The pump could be of the diaphragm or progressive cavity type (see Appendix F), or other suitable positive displacement type.

Flow Equalization Controls - Since changes in interval-averaged flow rate out of the tunnel are caused by changes in water demand at the tunnel heading, the obvious base parameter for flow equalization control is the flow rate of clean water into the tunneling operation. Clean water flow rate could be monitored by a vortex shedding flow meter equipped with a visual read-out device. Information on inflow rate could be used to adjust the pumping rate from the equalization reservoir. The equalization pump should be adjustable and volumetrically calibrated, or if not calibrated, equipped with an electromagnetic flow meter immediately downstream. Thus, the equalization system pumping rate could be manually adjusted to equal clean water inflow rate. The frequency of required pumping rate adjustments would probably vary from as little as once every fifteen minutes to as much as once every several hours, with a mean



Tank Volume = 1100 Gallons

H:D Ratio should be from 0.75 to 1.5

Mixer Motor - 2.0 Horsepower, 1150 Revolutions per Second

Motor Shaft Speed = 233 Revolutions per Second

Propeller Diameter = 16.4 Inches

FIGURE 4-5 - SUGGESTED DESIGN FOR FLOW EQUALIZATION RESERVOIR frequency on the order of once per hour. (Occasionally, inflow rate would not equal interval-averaged outflow rate because outflow would not respond instantaneously to a change in inflow rate. However, the short time lag between adjustment of inflow and restabilization of interval-averaged outflow should not cause serious operational problems.)

The reservoir should be equipped with a float gauge or similar level detecting device which provides for continuous, remote observation of water level. The level detecting device should be provided with high- and low-stage alarms and a low-stage pump shutoff.

Initial Chemical Destabilization (A-3 and A-4) - This section will discuss some of the factors involved in initial chemical treatment, including: selection of a polyelectrolyte, determination of optimum chemical dosage, preparation, mixing and flocculation requirements, and system controls.

Selection of Polyelectrolytes - Various polyelectrolytes, ranging in charge characteristic from anionic to cationic, were tested to determine their performance over a range of possible waste stream characteristics, including: sandstone type (heavily iron-stained to essentially pure white - see Chapter 1), suspension water source (river and municipal supplies), and suspension pH (2.75 to 8.5).

Testing was performed utilizing the standard jar test procedure (5). Suspension samples were obtained by placing measured amounts of sandstone in water, stirring the mixture to "leach out" fine material, and straining the mixture through a 200 mesh sieve (0.074 millimeter diameter openings) to remove the coarse fraction. One liter "filtered" suspension samples were placed in beakers and dosed with different polymer types. The samples were then placed in a jar test mixer similar to the one pictured in Figure 4-6 and agitated with the following mix cycle: three minutes at 100 revolutions per minute, five minutes at 50 revolutions per minute, and seven minutes at 35 revolutions per minute. After a five minute settling period, turbidity samples were withdrawn, tested, and compared. Of the polyelectrolytes tested, a cationic (Calgon Cat-Floc T) seemed to provide the best performance at the lowest cost.

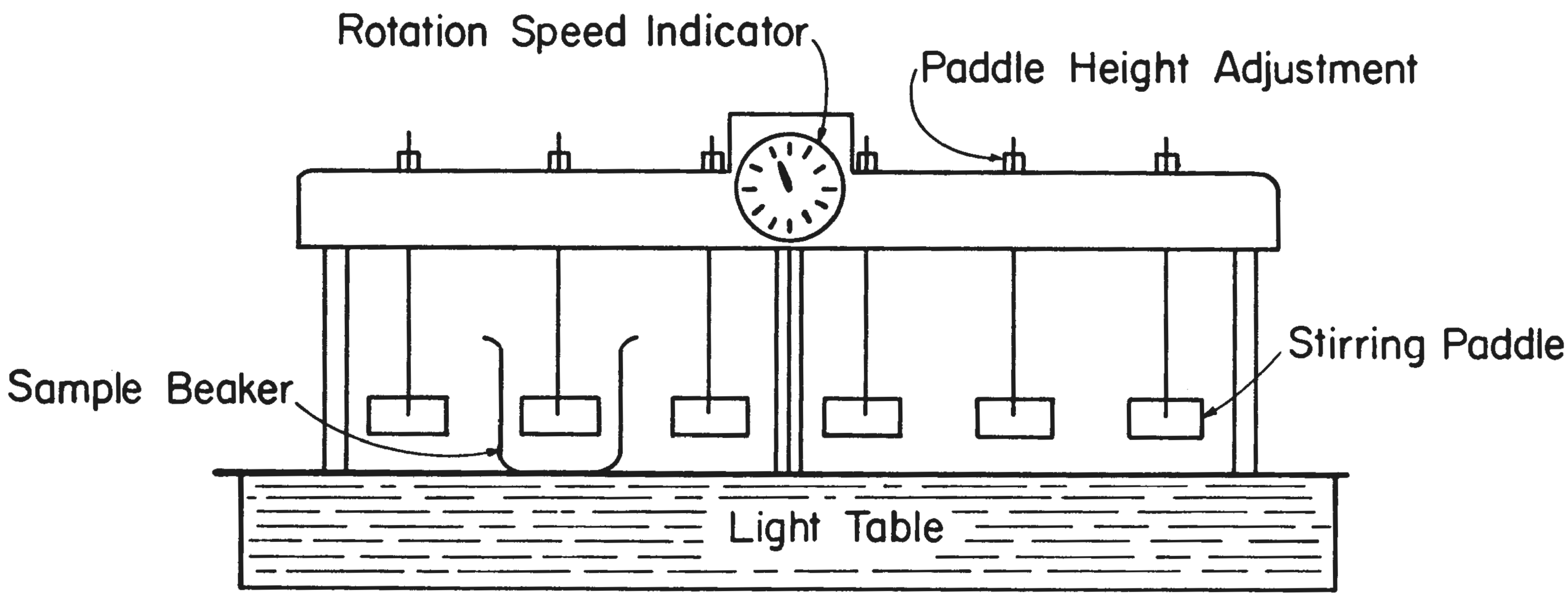


FIGURE 4-6 - JAR TEST STIRRER

The reader should note that although the recommended cationic polymer performed acceptably over the pH range tested, it may behave differently at higher pH ranges such as those encountered by the waste survey (see Figure 2-6). If the polymer's performance is not acceptable at higher pH's, additional testing would be required to find an alternative polymer.

Optimum Dosage Determination - A series of jar tests was performed to determine the range of polyelectrolyte dosages (of Calgon Cat-Floc) required to reduce suspension turbidities and solids contents to acceptable levels, and to ascertain the effects of chemical overdosage. Basic test procedure was similar to that described above for initial coagulant selection, except that polymer dosage was varied rather than polymer type. Five separate test runs were made on suspensions ranging from 810 to 12240 milligrams per liter suspended solids. For each solids concentration, supernatant turbidity was measured as a function of dosage; the results were plotted as shown in Figure 4-7. (The term "supernatant turbidity" refers to the light-scattering properties of the clarified effluent of a chemically treated laboratory solids suspension sample. Although no definite relationship exists between turbidity and solids concentration, turbidity values may be used for quick, qualitative comparisons of the solids contents of various suspension samples. Turbidity measurement is discussed in Appendix F.)

From each suspended solids concentration, the approximate chemical dosage required to reduce suspension turbidity to twenty-five Formazin Turbidity Units (FTU) was estimated. Figure 4-8 plots initial solids concentrations versus chemical dosages required to obtain twenty-five FTU supernatant. (Theoretically, chemical dosage should attain a nearly constant value above a certain solids concentration; this is because the close proximity of individual particles should allow the chain-like polymer molecules to perform more efficiently. Here, however, the opposite trend is observed; the polymer seems to perform more efficiently at lower solids concentrations. This phenomenon probably results from less uniform

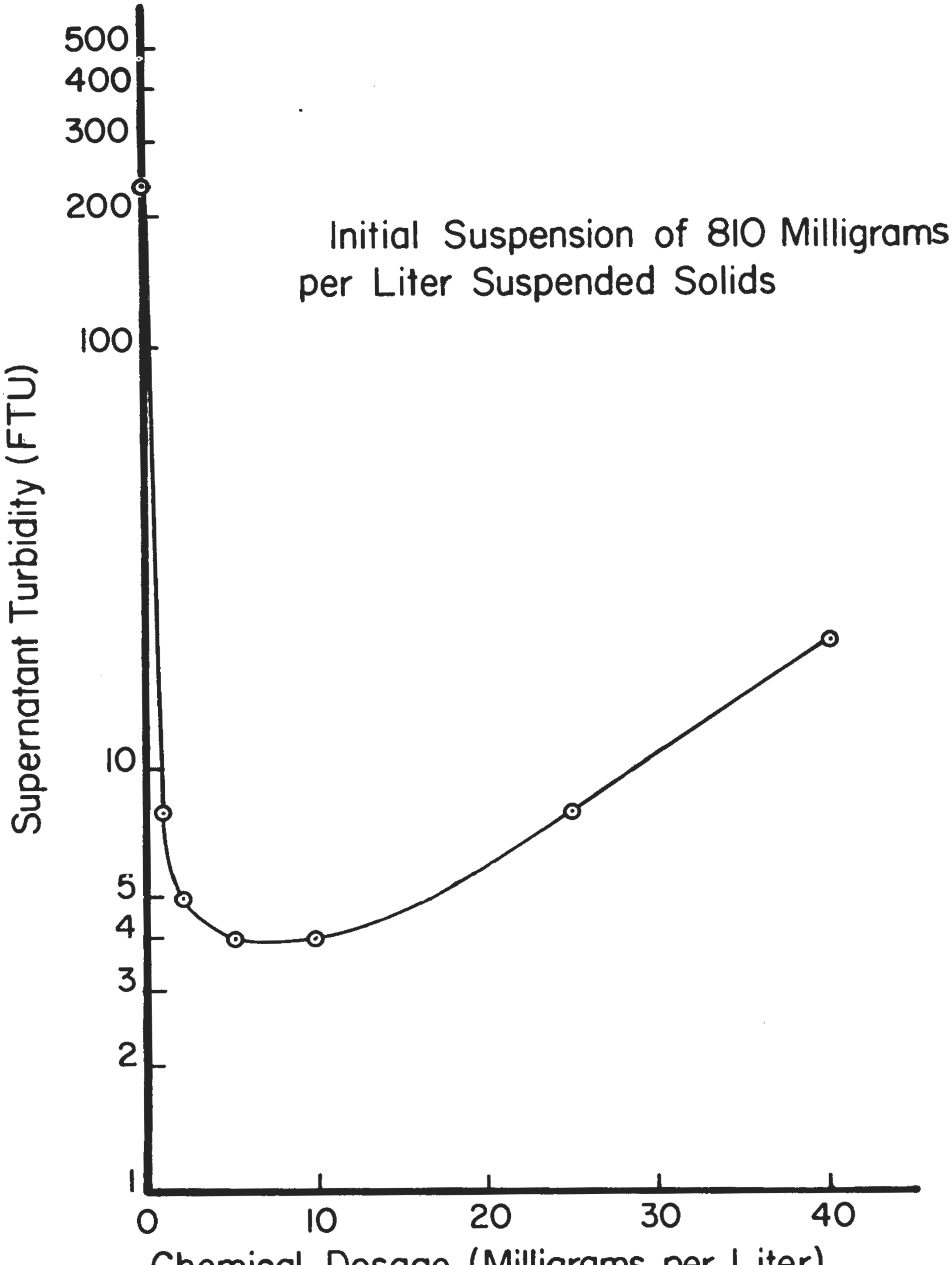


FIGURE 4-7 - SUPERNATANT TURBIDITY VERSUS CHEMICAL DOSAGE

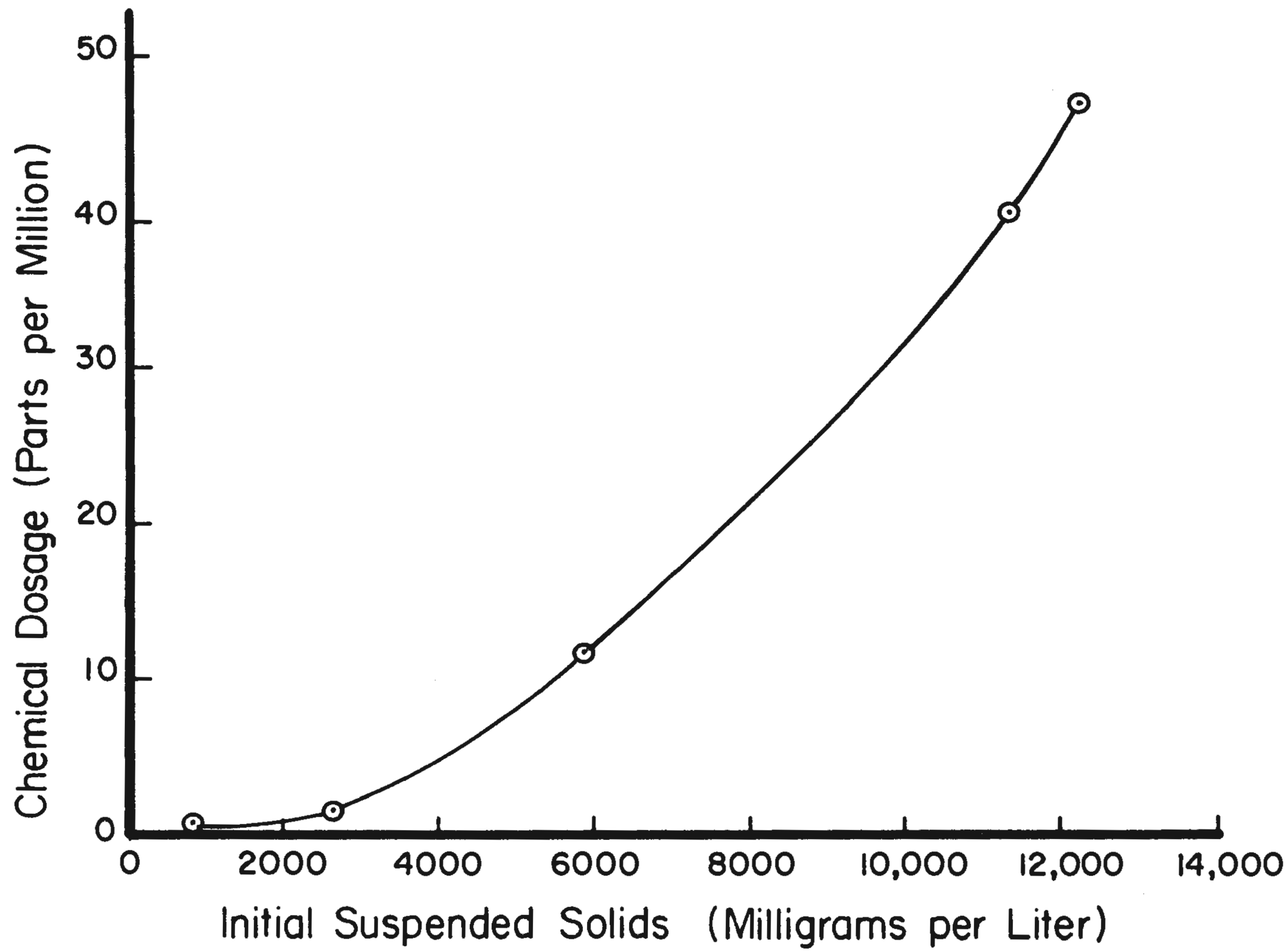


FIGURE 4-8 - CHEMICAL DOSAGES REQUIRED TO REDUCE SUSPENSION TURBIDITIES TO 25 FTU chemical-particle contact at high solids concentrations.)

Test results indicated that suspension restabilization due to chemical overdosing should not be a problem. Figure 4-8 illustrates that, for the particular solids concentration, a chemical dosage of five parts per million resulted in a supernatant turbidity of four FTU, while a dosage of forty parts per million resulted in a turbidity of twenty FTU. Thus, although some restabilization did occur, the results were not cause for alarm; effluent for the suspension dosed with forty parts per million of polymer was of relatively good quality when compared with the initial suspension turbidity of 230 FTU.

Determination of Chemical Feed Rate - Coagulant feed rate may be controlled on the combined basis of wastewater flow rate and solids concentration or simply on the basis of flow rate. (Due to the equalization system, flow rate should be fairly constant, varying only with changes in water demand at the tunnel heading.) Experience has shown, however, that when chemical dosage is varied to "chase" suspended solids concentration, the resultant effluent is of poorer quality than that which would be obtained if the chemical was proportioned on the basis of flow rate only (6). Therefore, a flow rate proportioned feed system is recommended.

Figure 2-5 illustrates that the waste stream solids concentration is less than or equal to 4500 milligrams per liter about ninety-five percent of the time. (Figure 2-5 represents hopper overflow solids concentration. However, the presence of an equalization system should tend to attenuate solids concentration fluctuations. Thus, the 4500 milligram per liter value should be a conservative assumption.) Figure 4-8 indicates that a coagulant dosage of about seven parts per million should reduce the turbidity of a 4500 milligram per liter suspension to a value of about twenty-five FTU. Since overdosing of a suspension does not appear to cause gross restabilization (see above), feeding the chemical into the waste stream at a rate of seven parts per million should result in effluent of turbidity less than or equal to twenty-five FTU about ninety-five percent of the time. A chemical feed rate of ten parts per million, or ten gallons per million gallons of wastewater would probably be a more realistic value because the higher dosage compensates for various imperfections in the chemical treatment process such as non-uniform mixing, etc. (Normally, the polymer feed rate is expressed as pounds of chemical per ton of dry waste solids; however, for the system discussed above, such a unit is meaningless because the chemical-solids ratio is constantly changing. Thus, the unit of gallons of chemical per million gallons of wastewater is used.)

Chemical Preparation and Feeding - When the chemical type and dosage have been determined, a preparation and feeding system must be selected. Since the selected polymer, Calgon Cat-Floc T, is a liquid in product form, a liquid polyelectrolyte preparation unit, such as that illustrated in Figure A-2, could be utilized. Although the packaged preparation unit usually includes a feeding pump, any of those illustrated in Figure A-3 could be used, depending on chemical characteristics.

Another point to be considered in chemical preparation and feeding processes is dilution (see Appendix A). Most wet chemical feeders are equipped for two separate dilutions of coagulant. Chemical manufacturers should be consulted to determine suggested chemical-to-dilution water ratios.

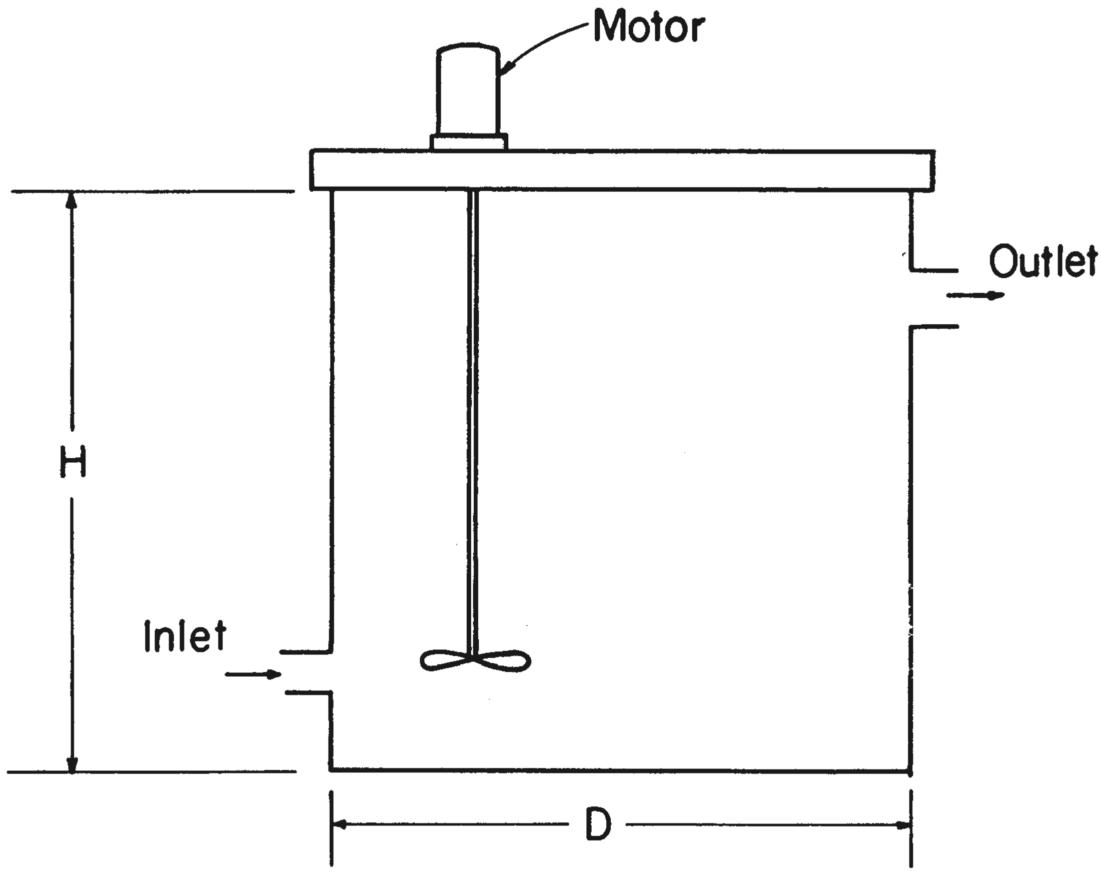
Determination of Mixing-Flocculation Cycle - The coagulant-suspension mixing and flocculation cycle was determined by a trial-and-error procedure. Test suspension samples were made by placing measured amounts of sandstone in water, stirring the mixture to "leach out" fine material, and straining the mixture through a 325 mesh sieve (0.044 millimeter diameter openings) to remove coarse material. Twenty liter batches of this suspension were placed in a fifty liter tank equipped with an eccentrically mounted, one-eighth horsepower, variable speed, turbine mixer. These suspensions were then dosed, mixed, and allowed to settle. Various mix cycles were tested until one capable of consistently producing good suspension settling was discovered. This cycle consisted of one to two minutes of moderately intense agitation, followed by zero to five minutes of mild agitation. The following result was frequently observed: the settling rate of the suspension seemed relatively insensitive to the amount of agitation, provided good initial chemical-solids contact was made. For example, a suspension allowed to settle immediately after the initial, moderate agitation period was found to have supernatant quality similar to that of suspensions subjected to additional periods of mild agitation (flocculation). Thus, sufficient particle collisions were apparently induced by residual turbulence from mixing and differential settling velocities so as to promote the necessary grain growth and render a separate flocculation process unnecessary. These results were verified by an independently conducted study (7).

Mix Tank Design - Since flow to the rapid mix process would be equalized, the device may be designed for maximum interval-averaged flow rate rather than maximum point flow rate. Figure 2-4 indicates that interval-averaged flow rate is less than or equal to 230 gallons per minute about ninety-five percent of the time. To compensate for possible short-circuiting, the mix tank will be designed for a flow rate of 250 gallons per minute. So, for a detention time of at least one minute, the tank should have a volume of 250 gallons. The mixing device should be a low shear single propeller type with a one-third horsepower, variable speed motor (4). Figure 4-9 illustrates the tank and mixer unit.

In some cases, the rapid mix unit may be an integral part of the particular clarification device (as with the Lamella settler). General design requirements are the same as those presented above, however.

System Control - Since coagulant feed rate is based on wastewater flow rate, some means of regulating chemical and dilution water feeds must be provided. Figure A-2 illustrates one possible means of control; polymer is fed by a calibrated, variable discharge feed pump, and dilution water is controlled by a rotometer and valve assembly. Information on wastewater flow rates could be obtained from the flow equalization metering system, and chemical and dilution water feed rates could be manually adjusted in accordance with the former.

Clarification (A-5) - Clarification is the process of removing suspended solids from the waste stream in order to produce a relatively clear



Tank Volume = 250 Gallons

H:D Ratio should be from 0.75 to 1.5

Mixer Motor - 1/3 Horsepower

Mixer Shaft Speed - 20 to 350 Revolutions per Minute

Propeller Diameter - 10.0 Inches

FIGURE 4-9 - SUGGESTED DESIGN FOR RAPID MIX TANK effluent. A packaged gravity clarifier; the Model 740/45 Lamella settler (see Appendices C and E), will be analyzed to determine its suitability for clarification of the waste stream. The effects of chemical treatment on clarification performance will also be examined.

Clarification Data - The discrete particle settling model is assumed for gravity clarification. Consequently, removal efficiency of the clarification basin is defined by wastewater flow rate, effective settling area, and particle settling velocity distribution.

Determination of the first two parameters is very straightforward. Interval-averaged flow rate data is found in Figure 2-4; the ninety-five percent value of 230 gallons per minute will be used to analyze clarification performance. Effective settling area depends on the particular equipment component and will be discussed later.

Particle settling velocity distribution for an untreated suspension was determined directly by the laboratory procedures discussed below. Test suspensions were produced by the method described in the previous section. (Plus 325 mesh material was removed.) Suspensions were then placed in an open container, similar to that shown in Figure 4-10, and thoroughly agitated. During the agitation period, suspension samples were taken and were later analyzed for solids content. (Initial suspended solids concentrations averaged about 6500 milligrams per liter.) Agitation was then terminated, and the suspension was allowed to settle. Samples were withdrawn at a constant depth (four inches below the surface) at various times (up to as much as forty-eight hours after initiation of settling). Each of these samples was also analyzed for suspended solids concentration. By dividing each of the latter sample solids concentrations by the initial solids content, the percent of solids in suspension at the sampling depth was determined as a function of time. By dividing the sampling depth (four inches) by the various sampling times, a series of settling velocities was also calculated. In Figure 4-11, each of these settling velocities is plotted against the percent of solids in suspension at that particular time. The resulting curve represents the settling

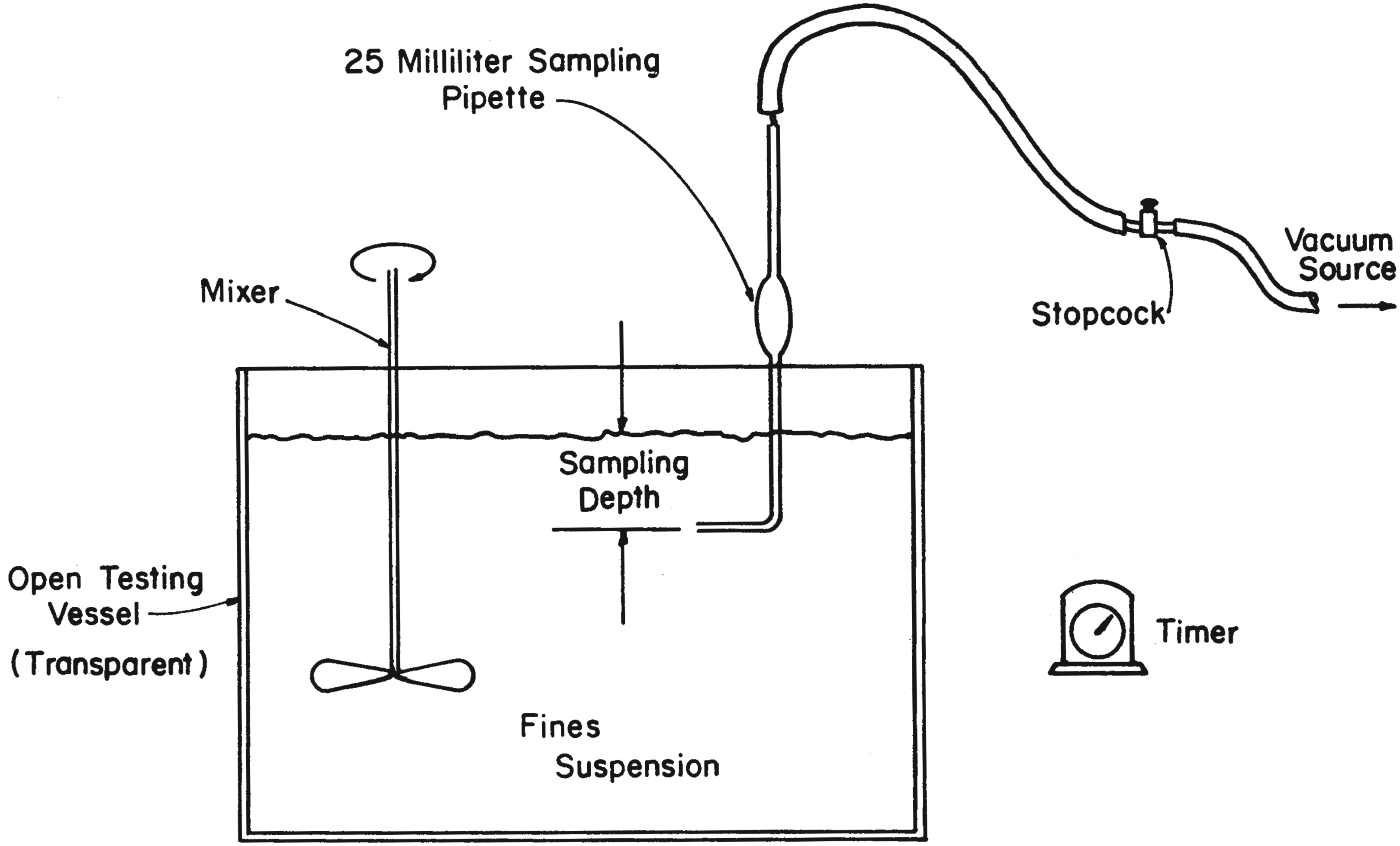


FIGURE 4-10 - APPARATUS FOR SUSPENSION SETTLING ANALYSIS

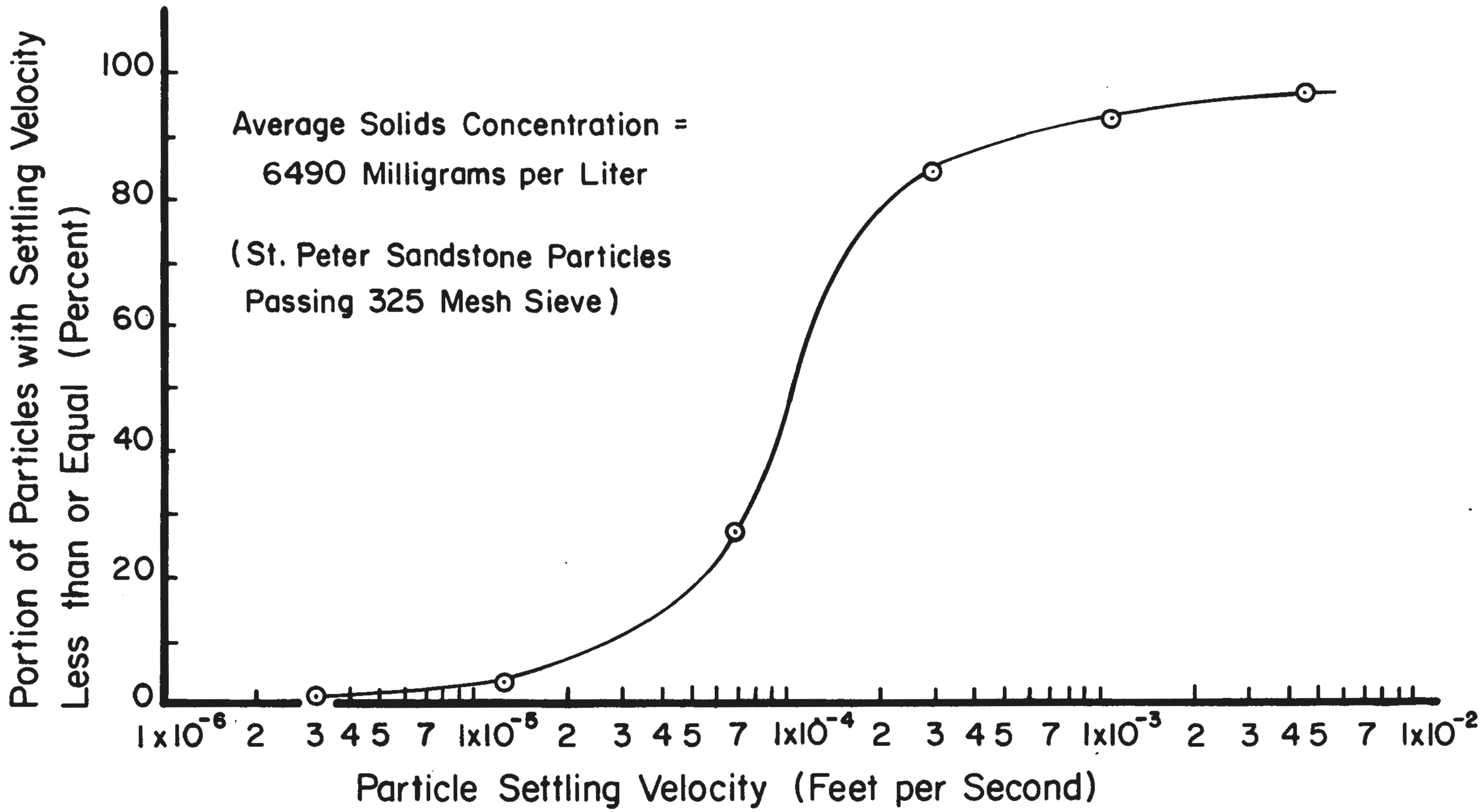


FIGURE 4-11 - SETTLING VELOCITY DISTRIBUTION FOR UNTREATED FINES SUSPENSION velocity distribution of the untreated minus 325 mesh fines suspension.

The settling velocity distribution of the treated fines suspension was determined in essentially the same manner with the following difference. After the initial solids concentrations were taken, the suspension was dosed with polyelectrolyte, mixed, and then allowed to settle. (Initial suspended solids concentrations averaged 3900 milligrams per liter, and coagulant dosages of fifty parts per million of Calgon Cat-Floc T were used.) Figure 4-12 illustrates the settling velocity distribution for the treated fines suspension.

Before leaving the discussion of settling velocity distribution, a final point should be discussed. Comparison of Figures 4-11 and 4-12 illustrates the profound effect of chemical coagulation on particle settling velocity distribution. However, the settling velocity distribution illustrated in Figure 4-12 was obtained under laboratory conditions. Under actual field conditions, "faster" or "slower" settling suspensions may be obtained. However, chemical treatment technology is sufficiently advanced that duplication, if not improvement, of laboratory results should be possible in prototype operations.

Analysis of Model 740/45 Lamella Settler - This component has an effective settling area of about 496 square feet (7). Thus, for a design flow rate of 230 gallons per minute, the tank overflow rate is about 0.47 gallons per minute per square foot or 1.0×10^{-3} feet per second. Figures 4-11 and 4-12 indicate that, for the above overflow rate, eight and ninety-six percent removal may be expected for the untreated and treated suspensions. Thus, assuming a feed suspended solids concentration of 4500 milligrams per liter (ninety-five percent value - see Figure 2-5), removal of 360 and 4320 milligrams per liter may be anticipated which corresponds to effluent qualities of approximately 4140 and 180 milligrams per liter suspended solids for untreated and treated suspensions respectively.

Examination of the effluent quality values quoted above illustrates the necessity of good chemical treatment to obtain clarification. Ineffective chemical treatment could shift the treated suspension settling velocity distribution toward that of the untreated suspension, thus rendering the Lamella settler almost completely incapable of removing solids.

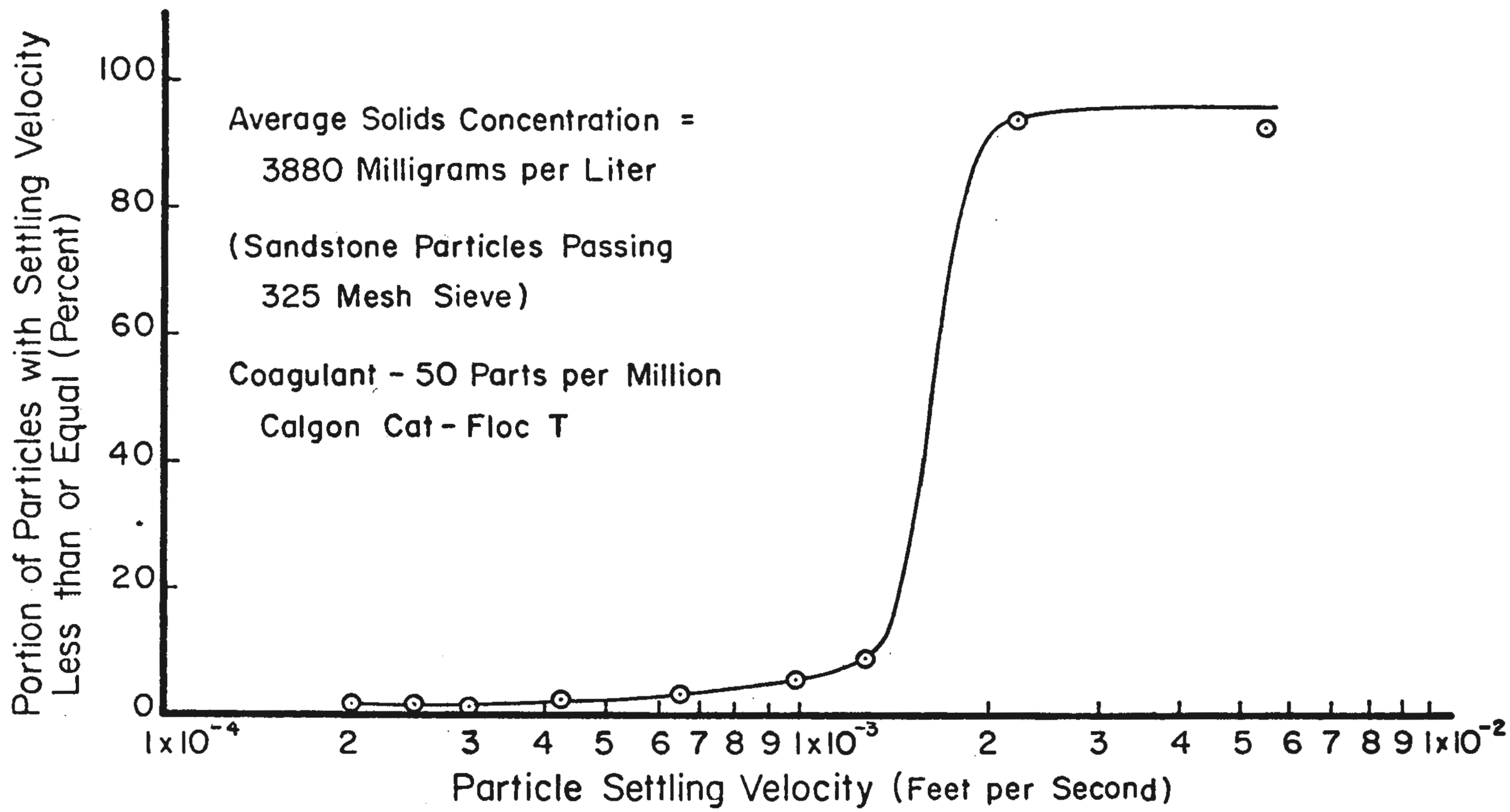


FIGURE 4-12 - SETTLING VELOCITY DISTRIBUTION FOR CHEMICALLY TREATED FINES SUSPENSION

Clarification Monitoring - Continuous monitoring of clarification effluent is highly desirable as it provides a means of evaluating treatment system performance up to and through the clarification process. Probably the simplest method of monitoring would be utilization of a "surface-scatter" type turbidimeter (see Appendix F) receiving its sample from the clarification effluent discharge line. Data from the turbidimeter would provide a continuous check-point for waste stream quality.

Secondary Chemical Treatment (A-6, A-7, and A-8) - Removal of suspended solids from clarification effluent would probably dictate the use of another chemical treatment phase. A constant chemical feed rate of one gallon of polymer per million gallons of wastewater would probably be sufficient for secondary chemical treatment although no laboratory tests were performed to support this assumption. (A series of jar tests would probably be required to ascertain the optimum coagulant type as well as the dosage.) The actual chemical preparation and feeding systems and the rapid mixing unit would probably be identical to those suggested for initial chemical destabilization. A final requirement of the secondary system would be the utilization of a flocculation unit to induce inter-particle collisions and grain growth in the dilute wastewater. Since flocculation is largely an empirical procedure, no attempt is made here to cite design requirements, other than to refer the reader to Appendix A.

Filtration (A-9) - Two filtration types, the rotary microstrainer and the plate-and-frame pressure filter, show promise for the filtration of clarification effluent. Both units are sized below on the basis of typical loading rates.

Microstrainer - The microstrainer typically has a hydraulic loading of five to ten gallons per minute per square foot of submerged screen area (8). Utilizing the lower value and a design flow rate of 230 gallons per minute, a filtering area of about forty-six square feet would be required. Since the submerged area of a microstrainer normally includes about two-thirds of the total screen area, a unit possessing about sixty-nine square feet of total screen area would be required.

Filtering media for the microstrainer is generally some sort of metal fabric. Opening size in the fabric generally varies from one product to the next, but the finest weave available has openings on the order of twenty microns (0.020 millimeter) (8). Such a media would probably be desired for this application because of the fineness of the suspended solids.

The microstrainer operates with very little hydraulic headloss. Filtrate flows by gravity through the media, and normally, a three to six inch head drop occurs across the mesh (depending on backwashing efficiency). Total headloss for the entire unit (including inlet valves, etc.) is usually twelve to eighteen inches (9).

The microstrainer backwashing apparatus utilizes strainer effluent for wash water. The rate of backwash flow varies from two percent of the total effluent flow at fifty pounds per square inch pressure to five percent at fifteen pounds per square inch (8). The suspension of backwash water and solids would probably be returned to the head of the treatment plant. However, this procedure would increase both volumetric and solids concentration loadings on the various other processes. Therefore, if backwash recycling should be seriously considered, the effects on the other processes should be thoroughly examined.

The effluent from the clarification process should normally contain less than or equal to 180 milligrams per liter suspended solids (see above). However, solids concentrations approaching or exceeding this value may cause clogging of the microstrainer media. (Reference 8 cites average feed solids concentrations for eighteen prototype microstrainer installations. Of these, the highest average influent concentration is about sixty-five milligrams per liter of biological suspended solids (specific gravity of 1.25). On a volumetric basis, this value compares to a concentration of about 140 milligrams per liter of sandstone solids (specific gravity of 2.65).) Thus, the ability of the microstrainer to provide good, <u>continuous</u> performance must be questioned if not doubted.

Pressure Filter - Like the microstrainer, this device is sized on the basis of hydraulic loading. Typical values range from 60 to 120 gallons per hour per square foot, or one to two gallons per minute per square foot (10). Again, using the lower value and a flow rate of 230 gallons per minute, an area of 230 square feet of filtering surface would be required. Pressure filter media is normally some type of woven cloth. If a tighter media is desired, some type of pre-coat may be utilized.

The pressure filter system would consist of three basic components: a holding tank, a pressure pump, and the filtering unit. The tank would receive and temporarily hold wastewater from the flocculation process; a 600 gallon tank capacity seems appropriate. Wastewater would then be withdrawn and pressurized by a centrifugal pump. (Unlike the microstrainer which consumes less than two feet of hydraulic head, the pressure filtration system commonly utilizes operating pressures on the order of 100 pounds per square inch or 230 feet of water (10) necessitating the use of a pressure pump.) The pump could discharge to the filter at some constant rate (probably on the order of 230 gallons per minute) and could be controlled by appropriate level sensing devices.

The pressure filtration system, unlike the highly automated microstrainer system, requires manual labor for solids removal and media cleaning. The plate-and-frame assembly must be dismantled, and solids jarred or scrapped from the individual plates. Plates and frames are then reassembled and filtration is resumed.

Filtration Monitoring - Probably the most satisfactory means of filtrate monitoring is continuous turbidity analysis. This could be accomplished by utilization of the "surface-scatter" type turbidimeter receiving its sample from the filtrate discharge line.

In the pressure filtration system, required operating pressure indicates the degree of solids build-up on the filtering media; an excessively high pressure is usually synonymous with a heavily caked media in need of cleaning. Thus, the pressure filter should be equipped with some means for remote sensing of internal pressure so as to provide information on solids cake build-up.

pH Adjustment (A-10) - The pH control system for Class A effluent would consist of four basic components: a retention reservoir, a mixing unit, a pH sensing system, and a reagent feed system.

For adequate control, the reservoir should have a retention time of about five minutes (11). Thus, for a design flow rate of 230 gallons per minute, a tank volume of 1150 gallons would be required. The tank should be approximately cubical or cylindrical in shape. The volume required for pH control is only slightly larger than that suggested earlier for flow equalization. Therefore, a two-horsepower mixer, identical to the ones recommended for the equalization system, should be adequate for the pH adjustment process.

Control for the pH adjustment system would consist of a sensing probe located near the tank outflow and an electronic monitor to receive data from the probe, and in turn, transmit the appropriate information to the reagent feed system. Two types of monitoring devices could be used: the first would merely start and stop a constant discharge pump as required, and the second would actually control pump discharge so as to proportion reagent feed. The latter generally provides much closer pH control (11), and would probably be desirable for a Class A system with its relatively narrow pH range (see Chapter 3). The monitoring device could also be set up to drive a graphic recorder, which would provide a permanent record of effluent pH values.

The feed system would consist of a reagent storage tank and a metering pump to supply acid to the alkaline waste stream. The pump would feed concentrated sulfuric acid at a rate of not greater than 1.6 gallons per hour (11). (This reagent feed value is merely an estimate. A series of waste stream titrations would be required to determine the actual feed rates.)

Discharge Monitoring (A-11) - Monitoring requirements for discharge of hydraulic tunneling effluent into public waters stipulate that the following waste stream characteristics should be periodically measured: flow rate, suspended solids concentration, turbidity, and pH (see Discharge Permit - Chapter 3). Of these, all but suspended solids could be effectively monitored by the various process control systems. Flow rates would be metered by the flow equalization system, and pH values could be recorded in the titration system.

Requirements for suspended solids sampling would probably specify something like one eight hour composite per week (see Chapter 3). Such a sample could be manually obtained and analyzed by a commercial wastewater testing laboratory.

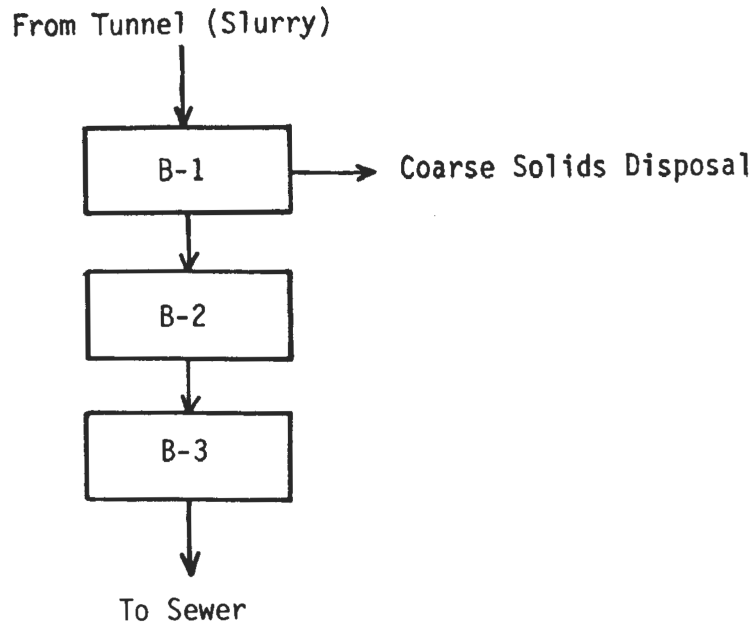
System Design: Class B Liquid Processing Option

A hydraulic tunneling waste stream would, with few exceptions, require some basic pretreatment so as to meet minimum requirements for disposal in sanitary sewers. Federal (EPA) and local (MWCC) pretreatment guidelines were briefly discussed in Chapter 3. The EPA guideline most relevant to hydraulic tunneling operations is the prohibition of discharge of wastes containing solids which could obstruct the flow in the sewer. Other EPA guidelines which prohibit the discharge of low pH wastes and wastes which could cause hydraulic and/or concentration-type overloadings on the treatment system are not applicable to the present situation (Minneapolis operation discharging to MWCC sewer). Of the local guidelines, the most significant is the pH range limitation (5.5 to 9.5).

From the characteristics of the hydraulic tunneling waste stream (see Chapters 1 and 2) and the pretreatment guidelines above, the reader may conclude that a Class B liquid processing system should consist of the following processes: coarse fraction removal, flow equalization, pH adjustment, and discharge monitoring. Such a system is schematically illustrated in Figure 4-13.

The reader should note that a variance of the pH requirement could possibly be obtained provided the range of fluctuation was not too great (see spot check data - Figure 2-6). However, the pH adjustment process is included in the Class B system in the event that such a variance could not be obtained.

<u>Treatment Process Design</u> - The coarse fraction removal, flow equalization,



B-1	Coarse Fraction Removal
B-2	pH Adjustment
B-3	Discharge Monitoring

FIGURE 4-13 - SCHEMATIC OF CLASS B EFFLUENT SYSTEM and pH titration processes for the Class B system (processes B-1, B-2, and B-3) would be identical to those designed for the Class A system (processes A-1, A-2, and A-10) with one minor difference: the control unit for the Class B pH adjustment system could be of the "on-off" type rather than the proportioning type because of the wider pH range allowed for sewer disposal (see above).

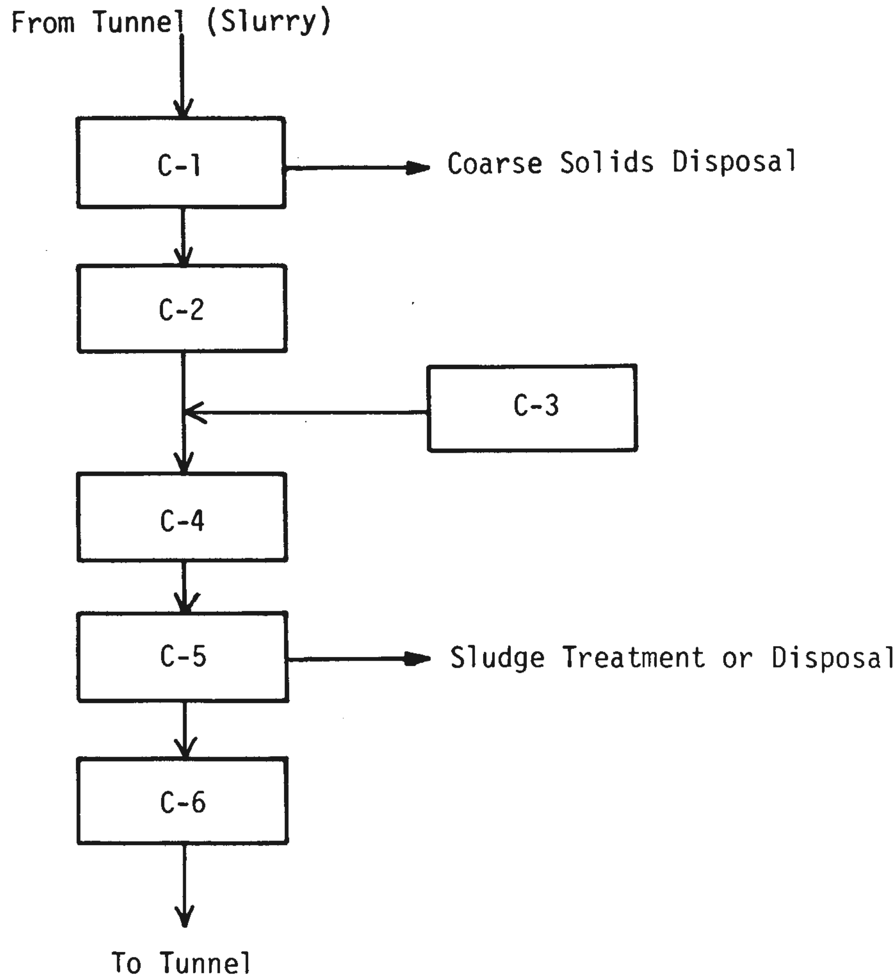
Discharge Monitoring (B-4) - The MWCC requires periodic monitoring of waste discharge into its sewer system. Required parameters are flow rate and suspended solids concentration. Flow rates would be metered by the flow equalization system, so that no separate system would be required for flow measurement. Although no specific procedures are cited for suspended solids sampling and analysis, the program could probably be executed similarly to that for public water discharge monitoring (12).

System Design: Class C Liquid Processing Option

This section discusses the design of a system that produces effluent of a quality which is adequate for the direct re-use in the tunneling system. The assumption is made that clarification process effluent would be of a quality sufficient for re-use.

Treatment System Design - Figure 4-14 illustrates the proposed Class C liquid processing system. Coarse fraction removal, flow equalization, chemical preparation, feeding and mixing, and clarification processes (C-1, C-2, C-3, C-4, and C-5) would be identical to those of the Class A section (A-1, A-2, A-3, A-4, and A-5). Clarification effluent would flow to a secondary flow equalization system from which it would be pumped back to the tunneling system.

The secondary equalization system (process C-6 in Figure 4-14) would consist of a storage reservoir and a make-up water pump. (In some cases, such as when a fire hydrant would be utilized for water supply, a solenoid valve could take the place of the make-up pump.) Figure 4-15 illustrates the general configuration of the secondary flow equalization system.



C-1	Coarse Fraction Removal
C-2	Flow Equalization
C-3	Chemical Preparation
C-4	Chemical-Wastewater Mixing
C-5	Clarification
C-6	Secondary Flow Equalization

FIGURE 4-14 - SCHEMATIC OF CLASS C EFFLUENT SYSTEM

A point was made earlier that inflow rate (to the tunneling operation) does not necessarily equal interval-averaged outflow rate; transient conditions associated with flow adjustment (at the tunnel heading) may cause brief periods for which the flow rates are unequal. The difference in flow rates may be as much as 150 gallons per minute (see Figure 2-4), i.e., a situation may temporarily occur for which inflow rate may equal 250 gallons per minute while interval-averaged outflow rate equals 100 gallons per minute.

Reservoir levels A and B in Figure 4-15 represent the water surface heights at which the make-up pump starts and stops operating; if the water surface reaches level A, the pump begins operating and continues until water level B is reached. The following volumes are assumed: tank bottom to level A - 150 gallons, level A to level B - 150 gallons, level B to overflow - 300 gallons, total storage capacity - 600 gallons. (These volumes were somewhat arbitrarily selected and should be subject to change in a prototype unit.)

Since inflow to the tunneling operation may exceed interval-averaged outflow by as much as 150 gallons per minute, the make-up pump should likewise have a capacity of 150 gallons per minute. Level sensors, located at levels A and B, could be utilized to start and stop the pump, as required. The pump should be self-priming, or have a flooded suction intake, as it may start and stop several times per hour. When operating, it should supply make-up water at a constant rate. Plumbing for the Class C system should include a line from just below the equalization system to the head of the treatment plant. Thus, plant effluent could be directly recycled back through the treatment system if desired, thus simplifying shutdown procedures.

<u>Effects of Water Re-use</u> - The Class C alternative should be examined with a greater degree of uncertainty than the previously discussed systems. Continuous recirculation of tunneling water could conceivably lead to the build-up of extremely high pH's or solids concentrations, or have other unforeseen effects. Thus, a substantial "shake-down" period should be

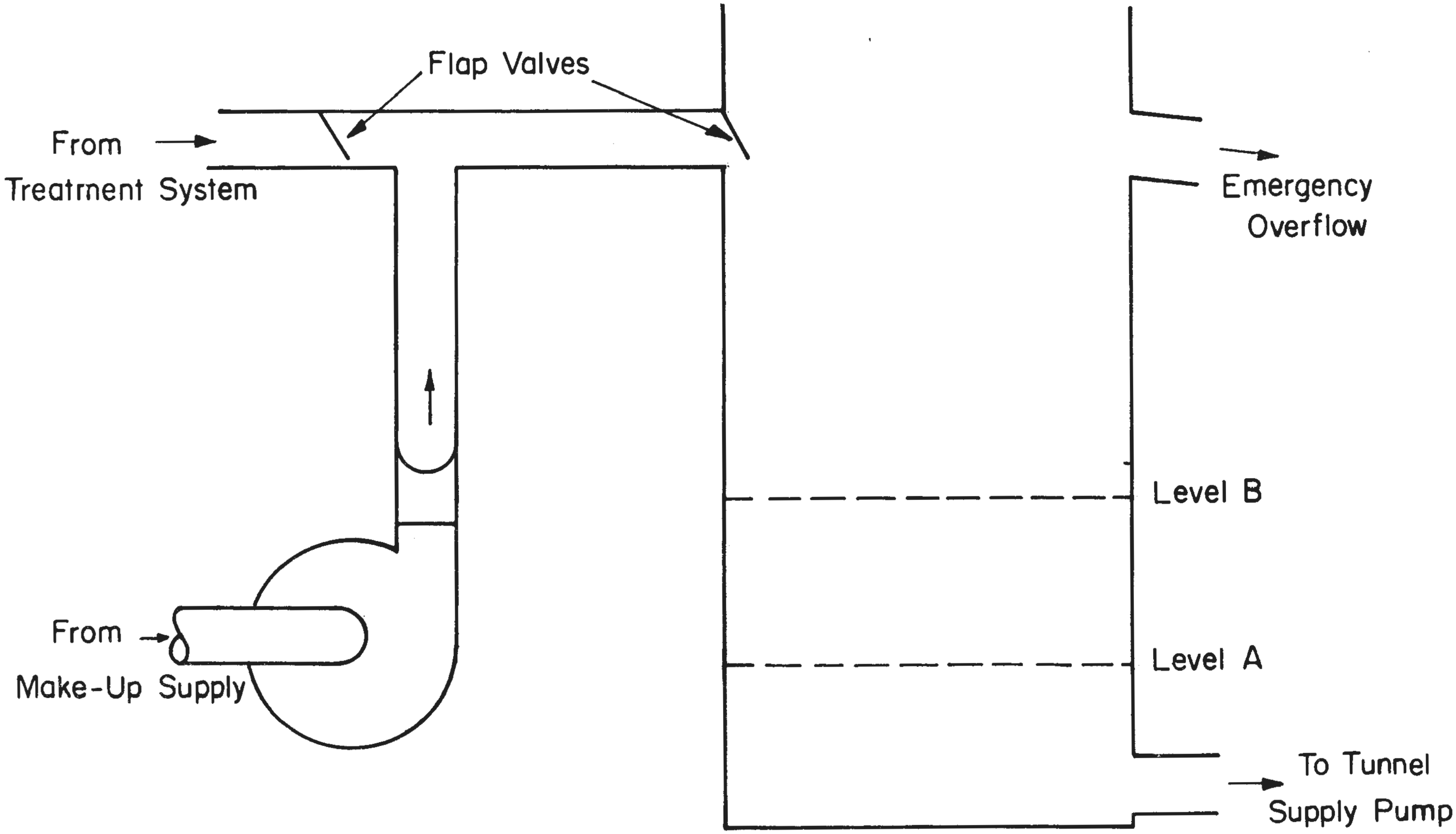


FIGURE 4-15 - SECONDARY FLOW EQUALIZATION SYSTEM anticipated for the Class C alternative.

System Design: Sludge Handling and Treatment

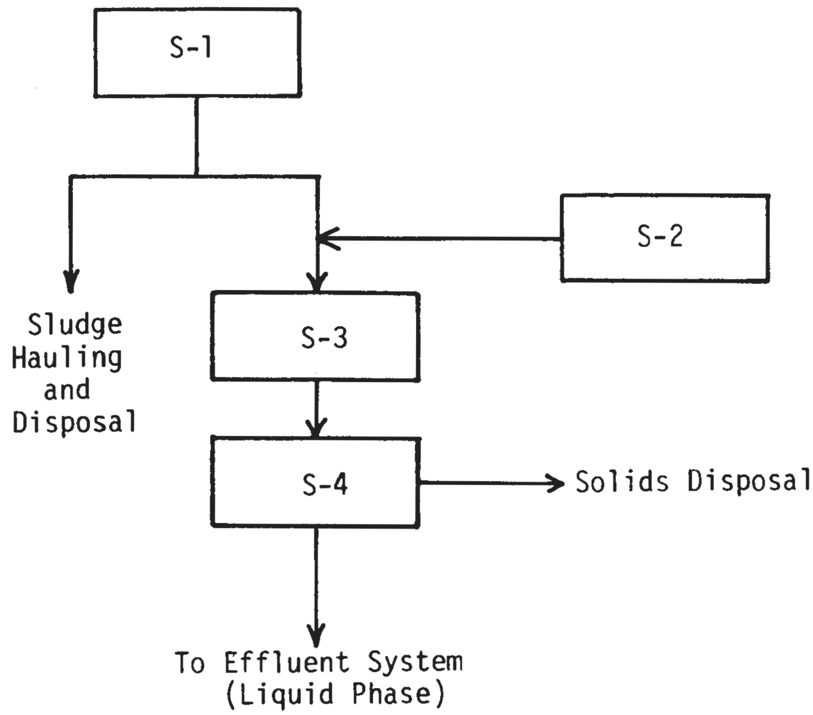
The clarification processes described above generally produces a watery muck usually referred to as "sludge". Various alternatives are available for sludge handling and treatment: the sludge may be trucked away after basic treatment, or it may be extensively dewatered before disposal. Figure 4-16 schematically illustrates options and processes for sludge handling and treatment.

The discussion below will first consider the most basic sludge treatment process--gravity thickening (S-1 in Figure 4-16). This process simply allows the separated solids to subside under the force of gravity, thus forming a denser and less volumous solids mass. (Gravity thickening may occur in the lower regions of a sedimentation tank while clarification is simultaneously occurring "higher" in the tank.) Thickening would be required if the sludge was merely trucked away immediately afterwards, or if it was extensively treated.

The second topic considered below concerns the basic requirements of a system for hauling the thickened sludge to the sanitary land-fill or other suitable site.

Finally, extensive treatment processes which may be utilized in lieu of sludge hauling are discussed. These processes, termed sludge conditioning and mechanical dewatering (S-2 and S-3 in Figure 4-16), reduce the volume and tonnage of material to be hauled to the final disposal site. Sludge conditioning, as considered here, is the treatment of thickened sludge with coagulant chemicals so as to produce a more readily dewaterable product. Mechanical dewatering, as the name implies, is the utilization of physical processes to produce a solids product which can be handled and disposed of as a solid rather than a liquid.

Thickening (S-1) - Clarification performance of a Model 740/45 Lamella settler was analyzed earlier. This section discusses laboratory tests on and analyses of sludge produced by simulation of the clarification



S-1	Clarification-Thickening
S-2	Chemical Preparation
S-3	Chemical-Sludge Mixing
S-4	Sludge Dewatering

FIGURE 4-16 - SCHEMATIC OF SLUDGE TREATMENT SYSTEM process and utilizes this information to predict the thickening performance of the Lamella settler.

Laboratory Testing - Sludge samples were produced in the fifty liter mixing tank apparatus described earlier in this Chapter (see Determination of Mixing - Flocculation Cycle). Twenty liter batches of fines suspension (average solids content about 7000 milligrams per liter) were placed in the tank, dosed (fifty parts per million Cat-Floc T), mixed, and allowed to settle. Supernatant liquid was siphoned off, and the sludge was collected.

Two phases of testing were utilized to determine the gravity thickening characteristics of the hydraulic tunneling sludge. In the first phase, sludge samples of various known solids concentrations were placed in a two-liter graduated cylinder and thoroughly agitated. Each sample was then allowed to settle. Shortly after the initiation of settling, a water-sludge interface would form just below the liquid surface. This interface gradually progressed downward as the sludge compressed, and measurements of interface height versus time were recorded.

The second phase of testing was conducted similarily to the first, except that a thirty liter, transparent column was used in place of the graduated cylinder (see Figure 4-17). This column was equipped with a stirring apparatus consisting of four rigid eighth-inch diameter wires mounted vertically in the column; the stirring assembly turned at a rate of about one revolution per minute. Samples for this phase of testing varied from 1.0 to 6.1 percent solids. Figure 4-18 is a typical plotting of interface height versus time for a large column settling test.

Although the test procedure just described is very simple, numerous factors can affect the results. For a discussion of potential error sources, the reader is referred to reference 13.

Analysis of Data - The slope of the linear portion of the curve illustrated in Figure 4-18 represents the settling velocity of the sludge at that

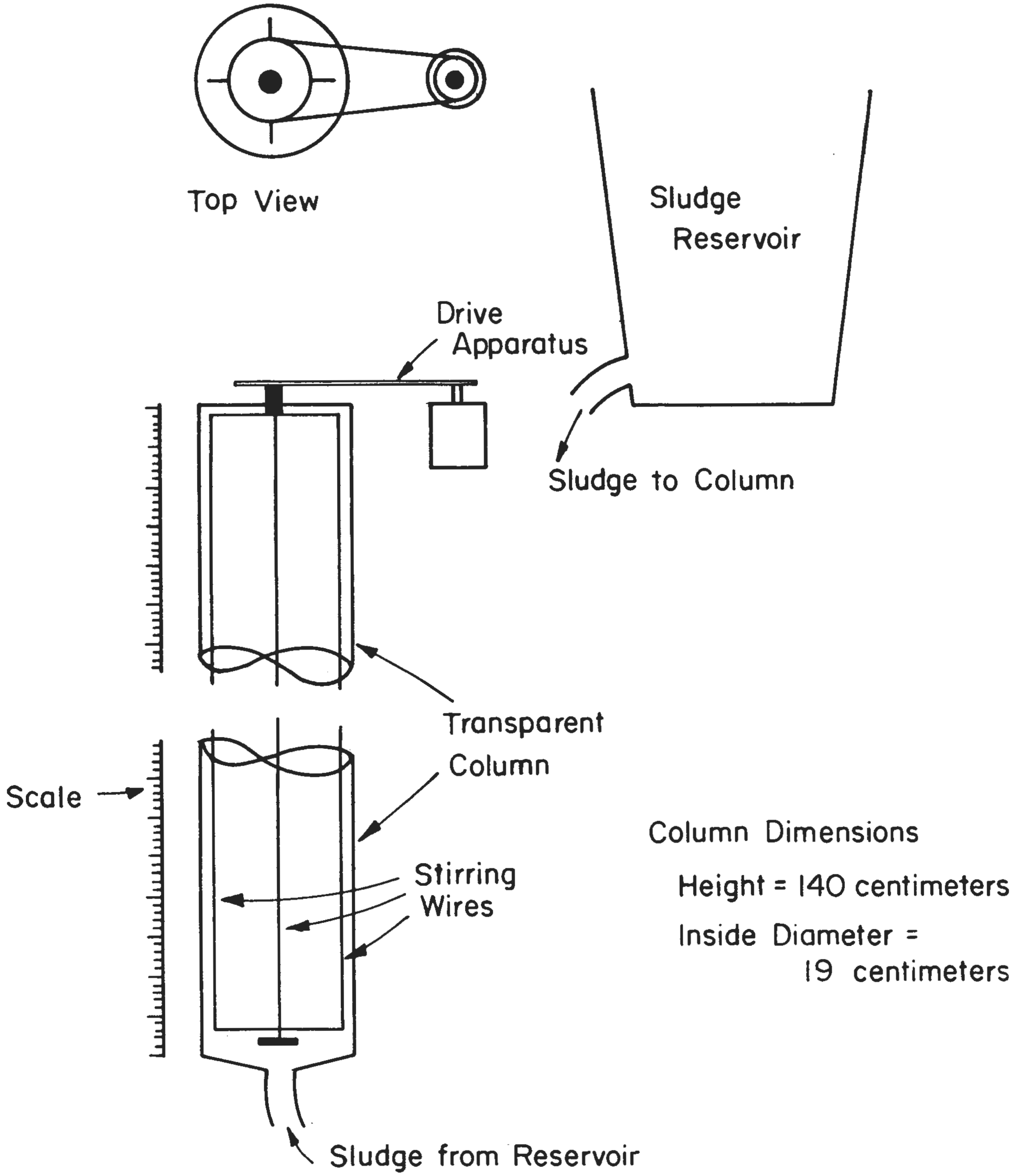


FIGURE 4-17 - LARGE SLUDGE THICKENING COLUMN

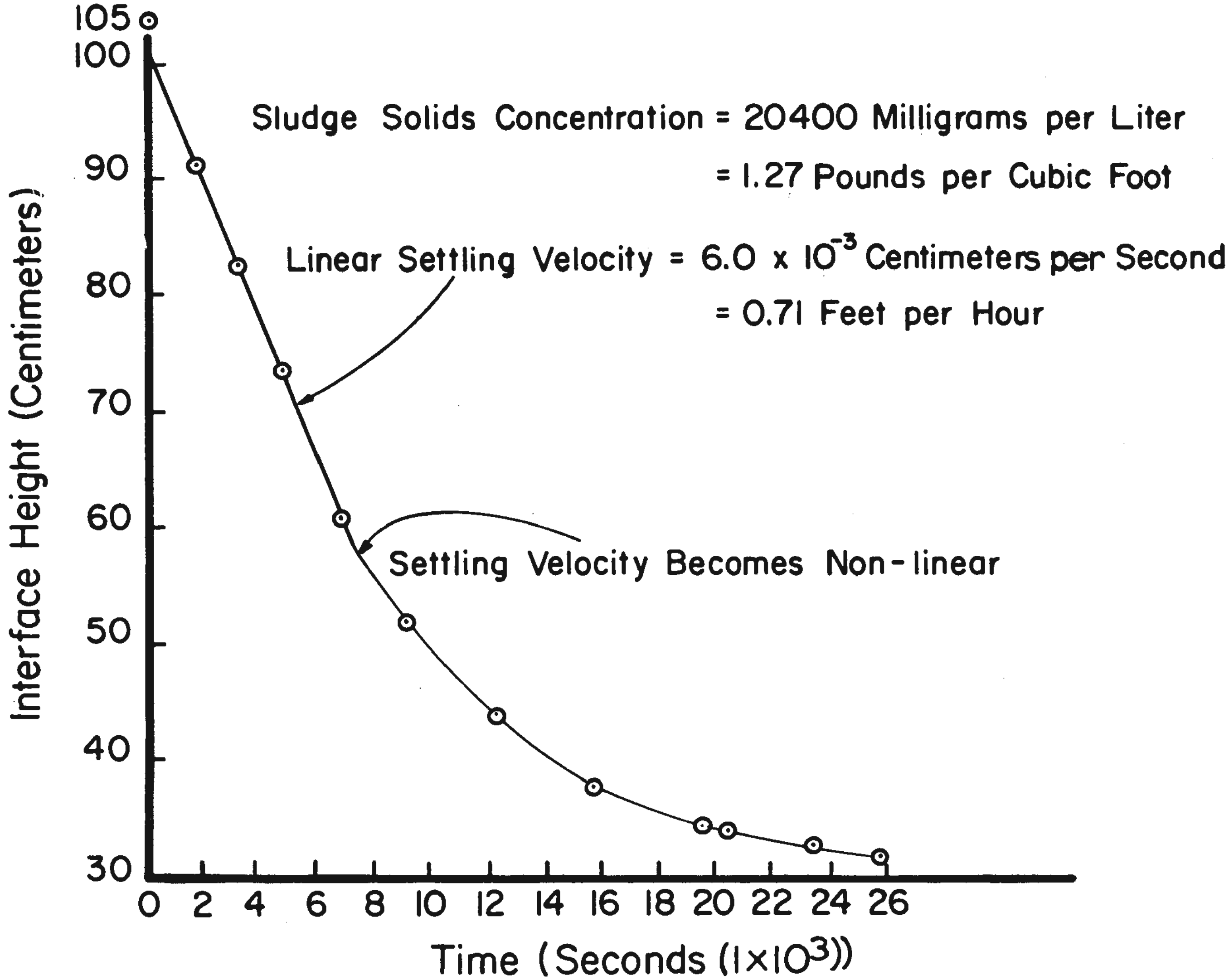


FIGURE 4-18 - SLUDGE INTERFACE HEIGHT VERSUS TIME particular solids concentration. When the settling velocity of a sample is multiplied by its corresponding solids concentration, the product is termed "flux" and has the units of mass (or force) per unit area per unit time. Table 4-1 tabulates flux rates for thickening tests made in the large column (discussed above), and Figure 4-19 plots these flux rates versus their various solids concentrations.

Table 4-1

Flux Rates for Sludge Tests in Large Settling Column

Test Number	Settling Velocity (ft./hr.)	Solids Concentration (lb./ft.^{3})	Flux Rate (lb./ft.^{2}-hr.)
1	4.63	0.60	2.78
2	0.71	1.27	0.90
3	0.45	1.86	0.83
4	0.18	2.47	0.45
5	0.07	3.77	0.26

Interpretation of the Batch Flux Curve - Figure 4-19 is known as the batch flux curve and may be interpreted as follows. When a sludge sample is initially placed in a column and thoroughly dispersed, the solids concentration is uniform throughout. As the interface forms and begins to settle, an infinitesimally thin zone of slightly heavier sludge forms at the bottom of the column and begins to propagate upward, followed immediately by another infinitesimally thin zone of still heavier sludge, and so on. When the first "zone of increasing concentration" propagates upward far enough to contact the settling interface, settling velocity ceases to be constant and interface height begins to approach to a constant value (see Figure 4-18). As time passes, the solids concentration eventually becomes uniform again (below the interface). However, between the initiation and completion of settling, a range of solids concentrations occur simultaneously from top to bottom of the settling mass. Figure 4-19 represents the rate of the gravity settling of the solids (in pounds per hour) per unit settling area for a portion of the range of concentrations which may occur in the settling column.

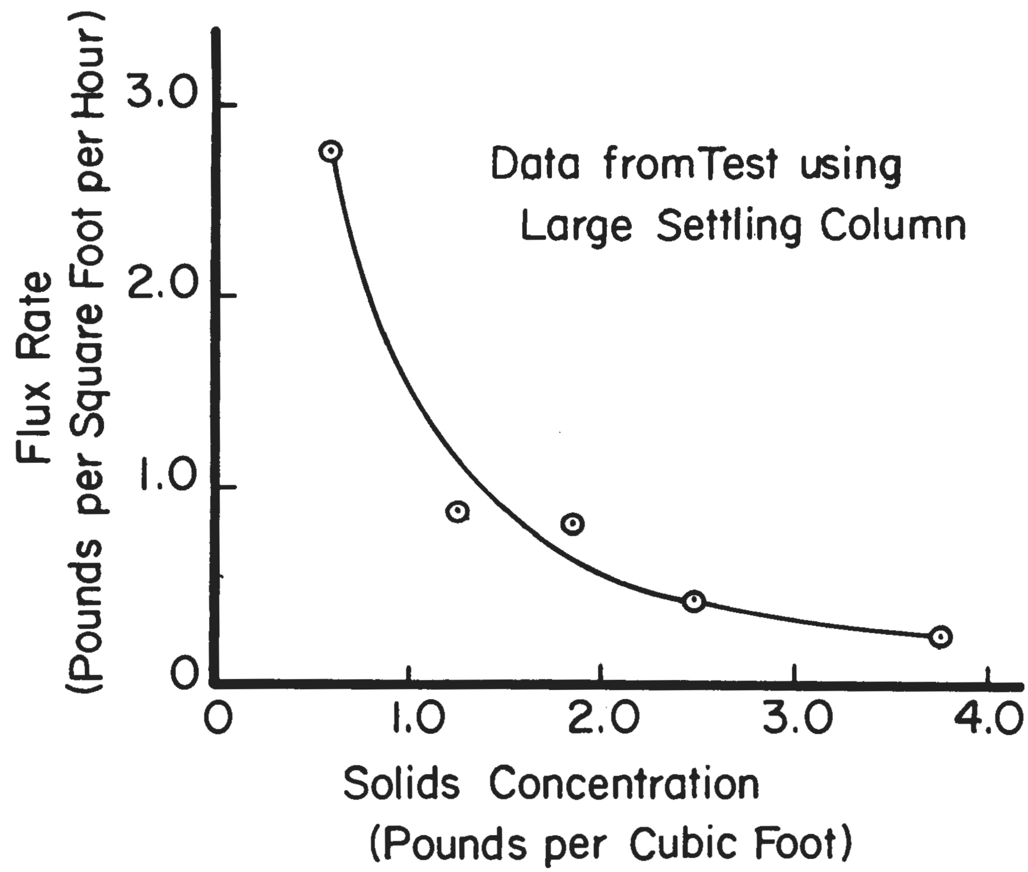


FIGURE 4-19 - BATCH FLUX SETTLING CURVE,
HYDRAULIC TUNNELING SLUDGE

Thickening Performance-Lamella Settler - The batch flux curve of Figure 4-19 may be used to analyze the thickening performance of the Model 740/45 Lamella settler (13). The flux and concentration axes of the curve respectively represent the range of solids loadings on the Lamella settler and underflow concentrations from it. Underflow concentration for a given solids loading may be determined by constructing a straight line through the appropriate loading value and tangent to the batch flux curve. The intersection of this line with the concentration axis represents the corresponding underflow concentration, and the slope of the tangent is the required draw down or pumping rate.

The solids loading rate on the Lamella settler is determined as follows. The average wastewater flow rate, 170 gallons per minute, is multiplied by the average solids concentration, 1500 milligrams per liter or 0.0125 pounds per gallon, to yield a solids flow rate of 2.12 pounds per minute or 128 pounds per hour (see Chapter 2). This value is divided by the total thickening area of the Lamella settler, 244 square feet (area of the sludge hopper plus a portion of the total plate area), to yield a solids loading of 0.52 pounds per square foot per hour.

Figure 4-20 illustrates the tangent for a solids loading of 0.52 pounds per square foot per hour. The corresponding underflow concentration is about 6.5 pounds per cubic foot, or 10.4 percent. The draw down rate for this situation is about 0.08 feet per hour, which, for a thickening area of 244 square feet, corresponds to a pumping rate of 19.5 cubic feet per hour or 2.4 gallons per minute.

The above analysis must be viewed with caution because the batch flux curve of Figures 4-19 and 4-20 may not be representative of sludge subsidence in the Lamella settler. The height of the laboratory sludge sample used for batch flux curve construction has been shown to affect the settling rate in some cases (14); usually, in these cases, increasing sample height results in increased settling rate. Since the thickness of sludge on a Lamella settler plate would probably be on the order of one to three centimeters, as opposed to an average sample height of about 100 centimeters for development of Figure 4-19, utilization of that batch flux curve may

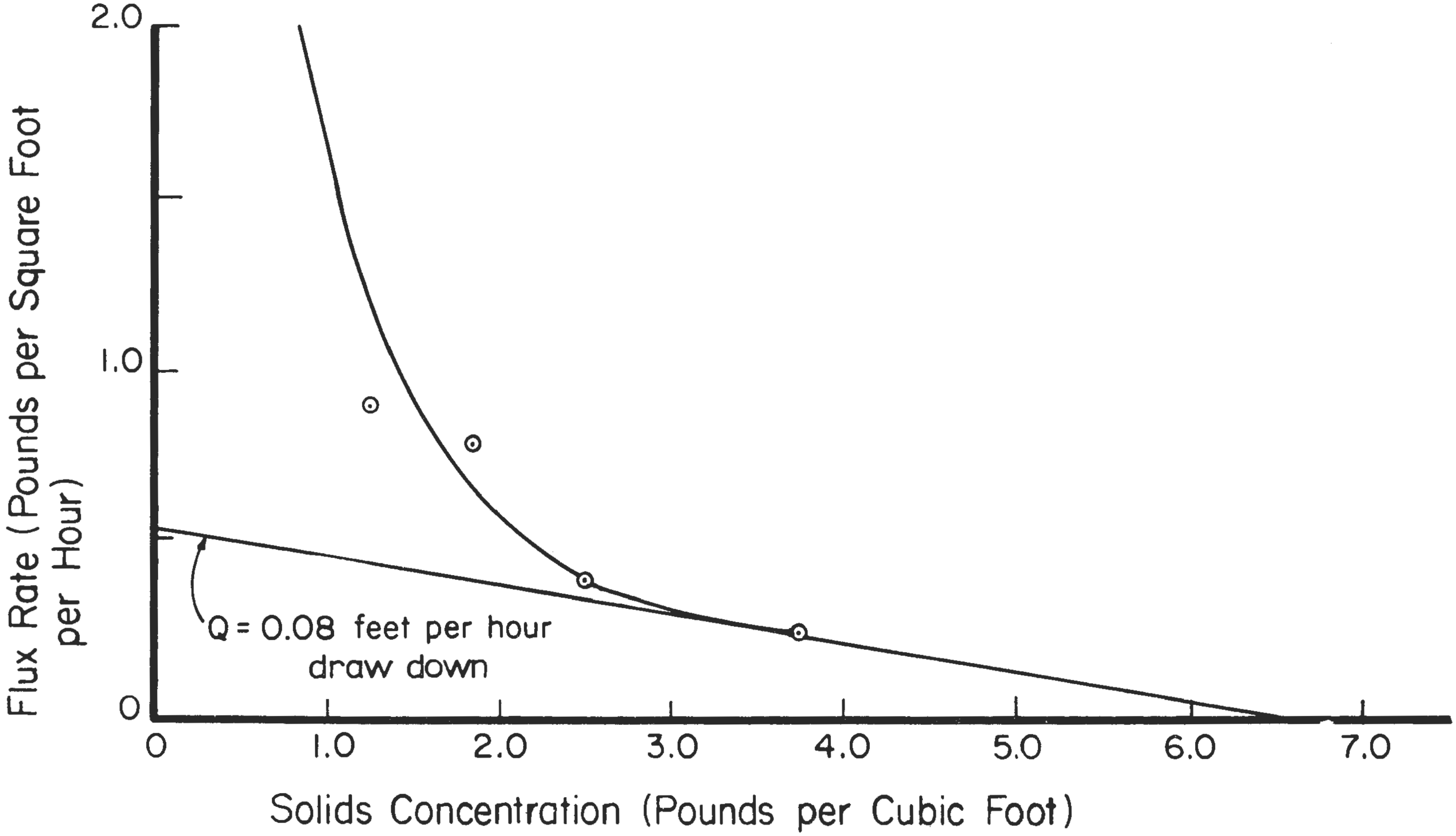


FIGURE 4-20 - BATCH FLUX CURVE FOR ANALYSIS OF LAMELLA SETTLER THICKENING PERFORMANCE be overly optimistic.

On the positive side, results of another study of Lamella settler thickening of hydraulic tunneling sludge indicated that underflow concentrations of fifteen percent solids should be attainable (7).

Sludge Pump - The above discussion specifies a sludge pumping rate of 2.4 gallons per minute. However, the pumping rate is a key factor in the thickening process, and consequently, the sludge pump should be adjustable over a range of flow rates (possibly up to ten gallons per minute). The pump should be a calibrated diaphragm or progressive cavity type.

Thickening Control - The ultrasonic sludge density controller, described in Appendix F, could be utilized as a means of monitoring thickening performance. The device could be installed in the underflow line just "above" the sludge pump, and if sludge density should fall below some arbitrary value, the controller could shut off the sludge pump and/or activate an alarm. This would prevent the pumping of thin, watery sludge.

Another useful control device would be the reflection type interface level sensor. The device would be useful as a means of monitoring sludge height in the hopper. Thus, settled sludge could be prevented from reaching settling plates--a condition which could lead to the re-entrainment of settled solids in incoming wastewater.

Sludge Hauling System - A sludge hauling system would basically consist of a tank truck or trailer suitable for hauling the heavy fluid, and a storage reservoir to hold sludge produced while the hauling vehicle was "on the road." Sludge could be pumped directly from the Lamella settler to the hauling vehicle, which could be sized to transport an entire day's production in a single load. Thus, required storage volume would be about 480 cubic feet (2.5 gallons of sludge per minute multiplied by sixty minutes per hour multiplied by six hours per shift multiplied by three shifts per day multiplied by an extra capacity factor of 1.33 divided by 7.5 gallons per cubic foot).

Since the sludge hauling vehicle would transport only one load per day, use of a specialized truck would be impractical from an economical standpoint. Therefore, the obvious solution would be to use some sort of sealed trailer; a trailer with adequate capacity would undoubtedly be of the "fifth wheel" type. The sludge storage tank should have capacity for at least four hours of production or 600 gallons. The system should also be equipped with an abrasion-protected centrifugal pump to transfer stored sludge to the hauling vehicle.

Sludge Conditioning (S-2) - Sludge conditioning, as considered here, consists of the treatment of sludge with coagulant chemicals so as to produce a more readily dewaterable product. Conditioning aids the dewatering process primarily by increasing the effective size of agglomerated particles. Associated with the increased particle size is an increase in sludge permeability which allows the liquid phase to escape more rapidly. Also, the larger particles are more easily trapped by the actual dewatering process.

Conditioner Selection - The initial problem in conditioner selection is simply to find several polymers which satisfactorily coagulate the sludge. When this primary screening process has been completed, the selected chemicals can be tested further to determine the most economical conditioning coagulant.

Initial screening was performed by treating samples of sludge with equal dosages of polymer and visually comparing the floc particles produced by each. (This procedure obviously requires experience; a technical representative from a coagulant manufacturing company performed the screening process discussed here (15)). Six polymer types were tested ranging in charge characteristic from strong anionic to strong cationic. Of these chemicals, the strongest anionic and two intermediate cationics performed well enough to merit further study. Interestingly, Calgon Cat-Floc T, the coagulant which was so successful in destablizing the original fines suspension, appeared unsuitable for sludge conditioning.

During the second phase of conditioner screening, sludge samples were placed in 100 milliliter graduated cylinders and treated with equal "cost dosages" of the selected coagulants. The amount of interface settling was measured at one, three, and five minutes. The sample treated with the strong anionic, Calgon WT-3000, settled most rapidly, and on this basis, WT-3000 was selected as a likely sludge conditioner.

Dosage and Mix Cycle Testing - After a chemical conditioner was selected, dosage and mixing parameters were studied. Sludge samples (solids concentration of about 3.4 percent) were treated in the jar test apparatus (see Appendix A) at dosages of five, ten, fifteen, twenty, fifty, and one hundred milligrams per liter of coagulant. Samples were mixed at a speed of 100 revolutions per minute, and small test samples (twenty to forty milliliters) were withdrawn at one-half, one, two, three, four, and five minutes.

Test samples were analyzed by the capillary suction time (CST) unit illustrated in Figure 4-21. The specimens were placed in the cylindrical reservoir, and the device measured the time required for the liquid phase of the sludge to flow through one centimeter of blotter paper. (The CST can be used as an index of a sludge's resistance to dewatering. However, CST is dependent upon sludge solids concentration, and consequently, solids concentrations should be equal if CST's of different sludge samples are compared.) Results of the CST analysis indicated that the effects of mixing time are negligible. Figure 4-22 plots CST versus coagulant dosage.

Specific Resistance Testing - Sludge samples for this stage of testing were treated with the same procedure utilized for treating CST samples. Sludge solids concentrations averaged 7.6 percent solids and coagulant dosages from 0 to 130 parts per million were utilized.

Procedure for specific resistance testing is described in reference 5 and the standard testing apparatus is shown in Figure 4-23. Briefly, testing was performed as follows: a single Whatman Number 1 filter paper (diameter of 9.0 centimeters) was placed in the Buchner funnel and sealed, the test sample (150 milliliters) was poured into the Buchner funnel, and vacuum was applied (fifteen inches of mercury). The rate of filtrate accumulation was recorded, and when the filtrate

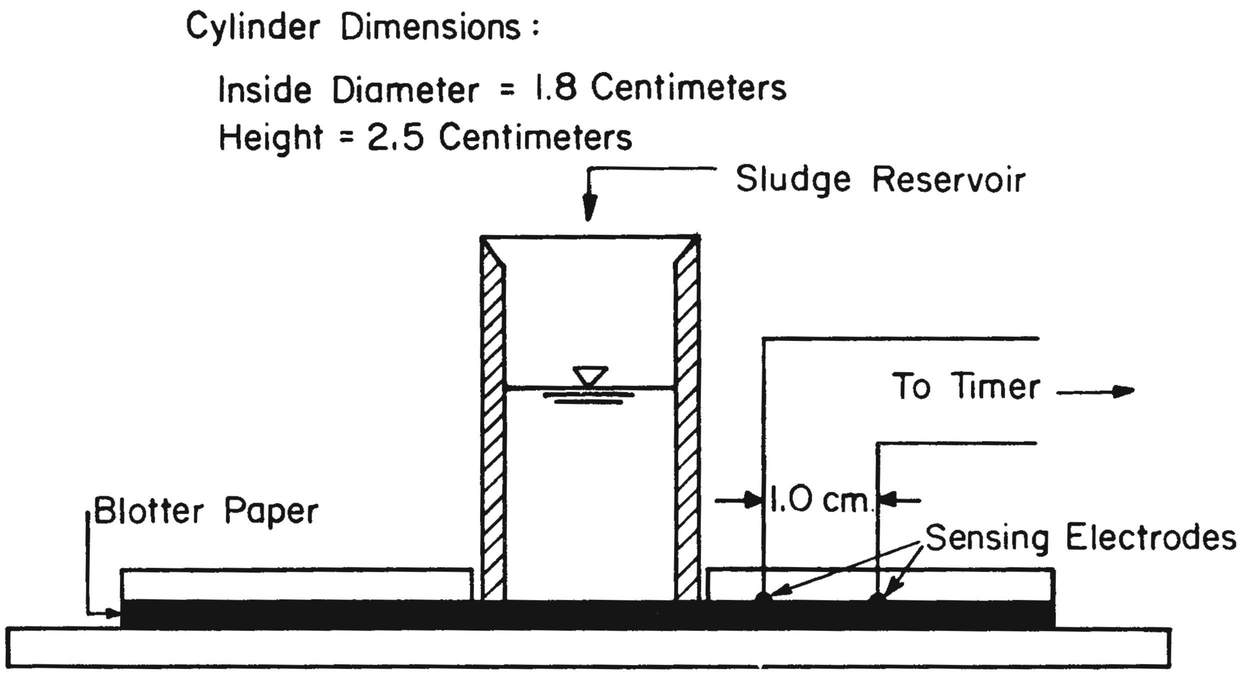


FIGURE 4-21 - CAPILLARY SUCTION TIME (CST) UNIT

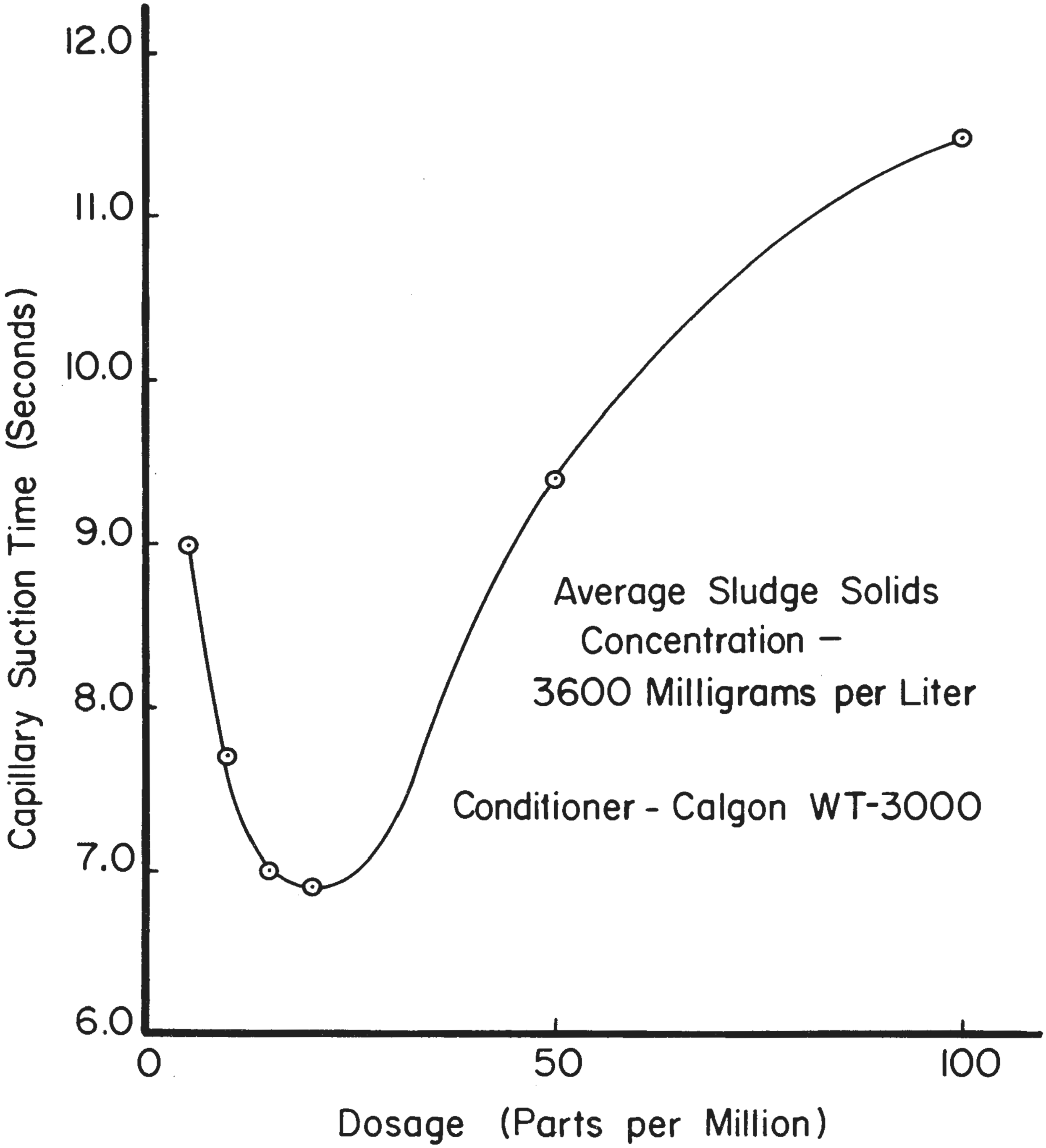


FIGURE 4-22 - CAPILLARY SUCTION TIME VERSUS CONDITIONER DOSAGE

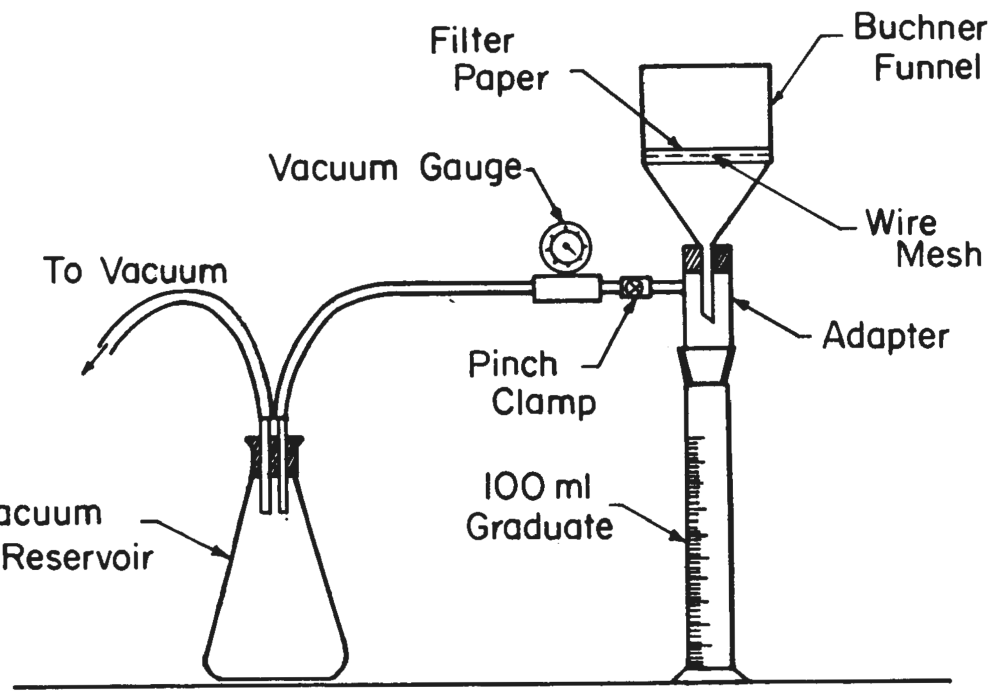


FIGURE 4-23 - SPECIFIC RESISTANCE APPARATUS flow had essentially ceased, the vacuum was terminated. Final filtrate volume and temperature were recorded, and the solids cake was removed, dried, and weighed. This procedure was repeated for each of coagulant dosages tested.

Analysis of Specific Resistance Data - Specific resistance of a sludge may be calculated by the following equation (13):

$$r = \frac{2 \cdot b \cdot P \cdot A^2}{u \cdot w}$$

where:

r = specific resistance (cm/gm)

b = slope of the plot of filtrate volume versus the quantity of time divided by volume (sec/cm^6)

P = vacuum pressure ($dynes/cm^2$)

A = filtering area (cm^2)

u = filtrate viscosity (gm/cm-sec)

w = mass of dry solid cake divided by final volume of filtrate (gm/cm^3)

Most of the above parameters may be readily evaluated from data taken during the experimental phase. However, the slope, "b", is determined as follows. Each time value from the time-volume tabulation is divided by its corresponding filtrate volume and this quantity is plotted against the filtrate volume. A typical plotting is shown in Figure 4-24. The slope of the linear portion of this curve is the "b" value.

Specific resistance values were calculated for each of the sludge samples tested; the results are illustrated in Figure 4-25. Dosages of fifty to one hundred parts per million of Calgon WT-3000 appeared to produce optimum conditioning at the test solids concentration (7.6 percent solids or 76000 milligrams per liter). This dosage range may be equivalently expressed as 1.3 to 2.6 pounds of chemical per ton of dry waste solids. (Here, as opposed to earlier sections on chemical treatment, chemical dosage is expressed as "pounds of chemical per ton of dry solids" because the conditioning operation would receive solids at a relatively constant rate from the thickener.) An average value of 2.0 pounds of WT-3000 per ton of dry solids will be used for design purposes.

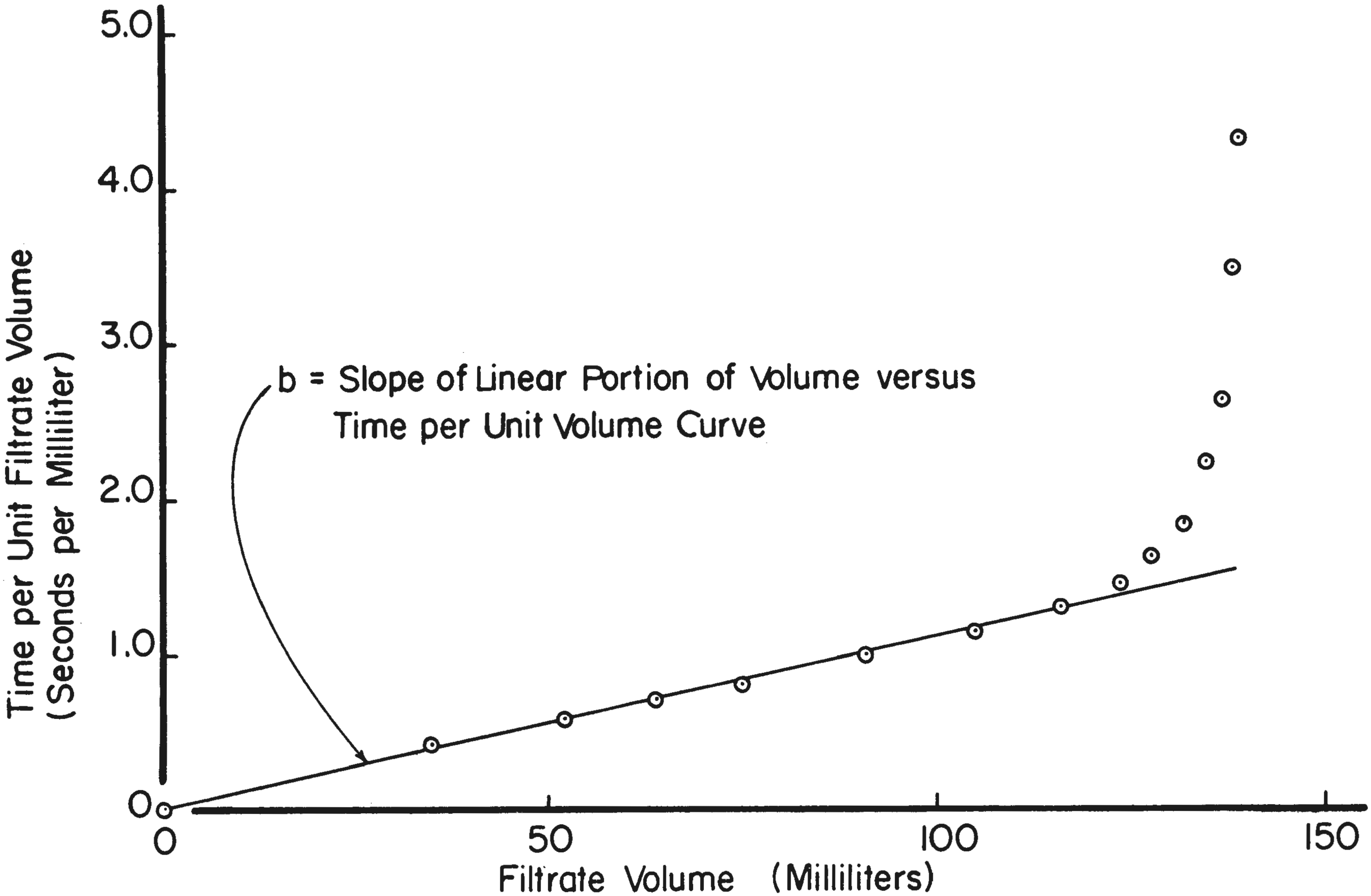


FIGURE 4-24 - TYPICAL PLOT OF THE QUANTITY TIME OVER FILTRATE VOLUME VERSUS FILTRATE VOLUME

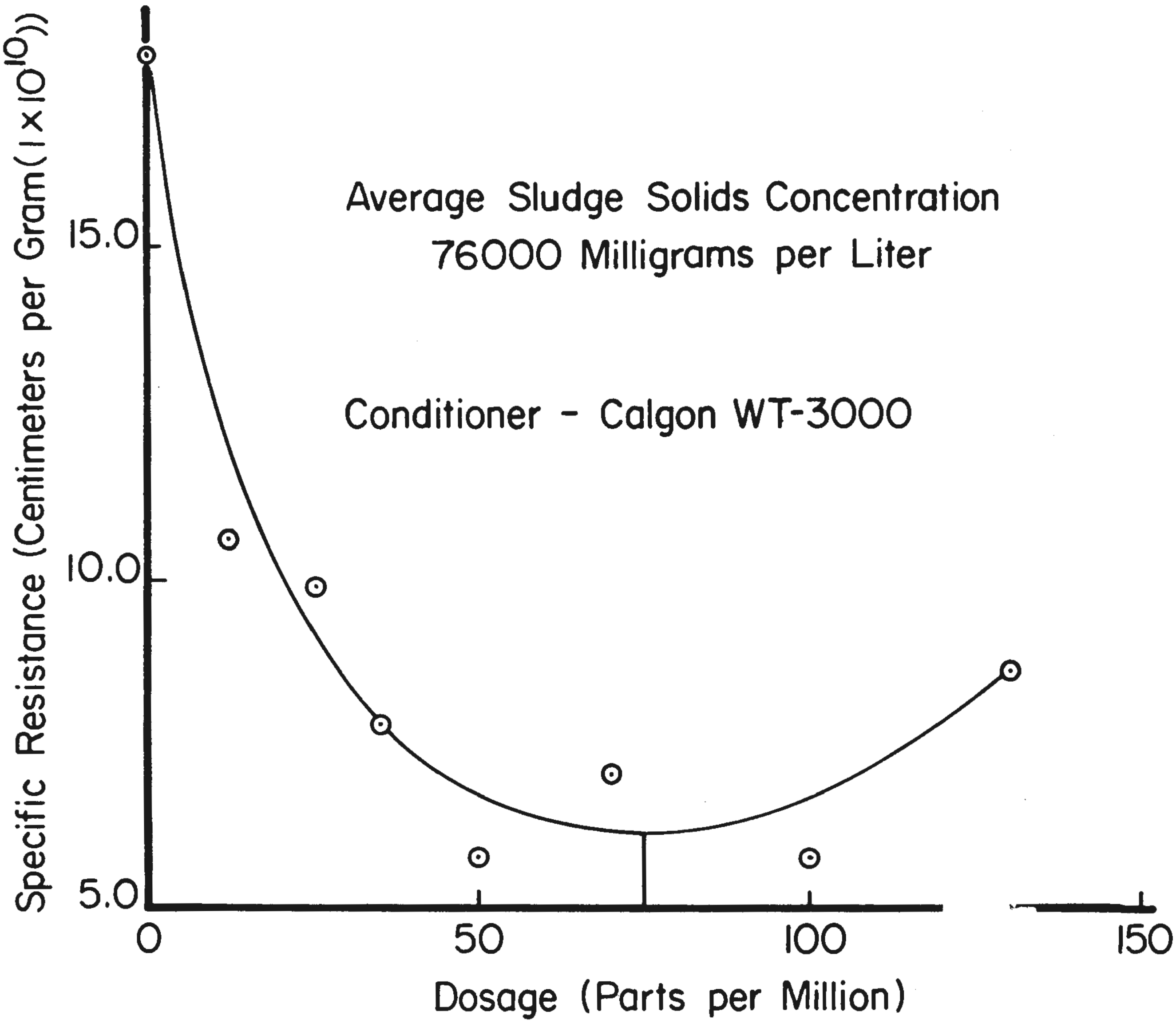


FIGURE 4-25 - SPECIFIC RESISTANCE VERSUS CONDITIONER DOSAGE

Conditioner Preparation, Feeding, and Mixing - The selected conditioning chemical, Calgon WT-3000, is distributed in product form as a dry powder. Consequently, a dry polyelectrolyte preparation system, such as that pictured in Figure A-1a, would be required. As with the initial chemical treatment process, conditioner should be diluted just prior to feeding.

Chemical-sludge mixing is a somewhat critical process. Sufficient agitation must be supplied to provide adequate chemical-solid contact, while excessive turbulence may break down particle agglomerations produced by the initial coagulation process. Pipeline turbulence, induced by pumping sludge through a series of elbows, may provide sufficient mixing. If not, use of some mechanical device, such as the drum mixer (see Figure A-6), may be required.

Due to the close proximity of individual particles in a sludge and the resulting frequency of inter-particle collisions due to "natural" causes, a separate flocculation process should not be required.

Conditioner Preparation and Feeding Controls - Figure A-1a illustrates the control system for a dry polymer preparation and feeding unit. The system includes various solenoid valves, pressure gauges, level sensing devices, and variable area flow meters. These controls should be included with a packaged chemical preparation and feeding unit.

Mechanical Dewatering (S-3) - Two mechanical sludge dewatering systems seem about equally well suited for incorporation in a hydraulic tunneling wastewater treatment system. They are basically a centrifuge system and a filtration system.

Centrifuge System - The basic component of this system is a solid bowl centrifuge (see Appendices D and E). A unit with a nine inch diameter bowl and bowl length-to-diameter ratio of 2.7 has a volumetric capacity of up to about ten gallons per minute and a mass capacity of 500 to 600 pounds per hour (16). Projected volumetric and mass flow rates from the Lamella settler are 2.5 gallons per minute and 130 pounds per hour, respectively. (While the mass flow rate cited above should be reasonably constant, volumetric flow rate could be several times the specified value, depending on the actual thickening performance of the Lamella settler. Consequently, a centrifuge with additional volumetric capacity is recommended.) Thus, the unit described above should be sufficient for dewatering of the thickened sludge, provided it is constructed so as not to be subject to extreme "wear-and-tear".

The centrifuge should produce a solids product of about seventy percent moisture (17). Thus, for a solids flow rate of 130 pounds per hour, centrifuge "cake" should be accumulated at a rate of about 5.7 cubic feet per hour or 1.3 cubic yards per shift. (The cake accumulation rate was computed as follows: 5.7 cubic feet of cake per hour multiplied by six hours per shift multiplied by 0.037 cubic yards per cubic foot. This calculation assumes that the dewatered cake contains no voids--an assumption which may or may not be justified. However, the computation does provide a method of estimating the volumetric rate of cake accumulation.) This material could spill out of the centrifuge and onto a small conveyor which would carry it to a temporary storage site. From there the cake could be loaded into dump trucks as required.

The liquid phase from the centrifuge could be returned to the head of the treatment plant or cycled into the effluent, depending upon its general clarity. The centrifuge may be equipped with an integral pump to transport the liquid outflow.

Filtration System - The filtration system mentioned above consists of a dual cell gravity filter and a belt press filter utilized in series (see Appendices B and E). Conditioned sludge is fed into the dual cell gravity filter from which the relatively free water is allowed to drain. The resulting concentrated solids product is transferred to the small belt press which squeezes the mass to remove another fraction of liquid. The combined system has a capacity of about ten gallons of sludge per minute. (This capacity value is based on actual pilot tests for dewatering of iron clarification sludge (18)).

The filtration system should produce a solids product of about seventy-five percent moisture (18) which for a solids flow rate of 130 pounds per hour, corresponds to a cake accumulation rate of seven cubic feet per hour or 1.6 cubic yards per shift. Again, this material could be allowed to spill out of the belt press and be loaded as required.

As with the centrifuge system, liquid from the filtration dewatering process could be recycled through the treatment system or included with treatment plant effluent. Consequently, a small centrifugal pump would be required to transport this liquid to the appropriate point.

Comments - The above discussion states that the centrifuge and filtration systems should produce cakes of seventy and seventy-five percent moisture, respectively. The value cited for the filtration system should be considered more reliable since it was obtained from actual pilot studies, whereas, the value given for the centrifuge system is merely speculation. In reality, cake moistures and accumulation rates for both would probably be similar. Also, since the cake accumulation rates for both systems are quite small, the error incurred by possible overestimating of centrifuge performance is trivial. The above discussion also suggests that the separated liquid should possibly be cycled back through the treatment system. As with microstrainer backwash recycling, the effects of this procedure should be thoroughly examined prior to its implementation.

Summary

The major alternatives, processes, and components of a hydraulic tunneling system have now been discussed in varying detail. The following paragraphs will briefly summarize the various options which were discussed above.

Class A Liquid Processing Option - The class A system would be utilized to produce effluent of quality suitable for disposal in public waters. The basic processes include: coarse fraction removal, flow equalization, initial chemical treatment, clarification, secondary chemical treatment, filtration, pH adjustment, and discharge monitoring.

Coarse Fraction Removal (process A-1, Figure 4-1) - Removal of coarse material (diameter greater than 0.044 millimeter) from the hydraulic tunneling waste stream. The major component of the system is a sedimentation hopper with twin compartments, each having a settling area of about 170 square feet and a storage volume of forty-two cubic yards. Hopper accessories include: top water pump(s), a sand dewatering system, and vibrators to free arched sand when loading trucks.

Flow Equalization (A-2) - Utilized to dampen minute-to-minute flow rate fluctuations (see Figure 2-1). Major components include: a 1000 gallon holding tank, a two-horsepower mixing unit, and a positive displacement, variable discharge transfer pump of capacity from 50 to 300 gallons per minute. Controls include: a vortex shedding type flow meter to measure the rate of clean water inflow to the tunneling operation, and tank level sensing devices.

Initial Chemical Treatment (A-3 and A-4) - Preparation and feeding of coagulant chemicals and thorough mixing with the waste stream so as to induce agglomeration of suspended solids. Chemical preparation and feeding would most likely be accomplished by utilization of a commercially available preparation and feed unit. The coagulant, Calgon Cat-Floc T, would be fed at a rate of ten gallons per million gallons of wastewater. Mixing should be of at least one minute duration, and a mix tank volume of 250 gallons is suggested. A one-third horsepower mixer unit is recommended.

Clarification (A-5) - Removal of suspended agglomerations in order to produce visually clean effluent. The major component of the system would be the Model 740/45 Lamella settler which has an effective clarification area of 496 square feet. A "surface-scatter" turbidimeter could be installed so as to monitor Lamella settler effluent quality.

Secondary Chemical Treatment (A-6, A-7, and A-8) - Utilized to induce agglomeration of the small portion of suspended particles which would pass through the clarification process. Basically, the process consists of chemical preparation and feeding, chemical-wastewater mixing, and flocculation. Chemical preparation and feeding could probably be accomplished in the same manner as for initial chemical destabilization. However, a chemical feed rate of one gallon per million gallons of wastewater is proposed. Mixing requirements would be identical to those recommended for initial chemical treatment. No design recommendations were presented for the flocculation process since it is largely an empirical procedure.

Filtration (A-9) - Required to remove a portion of the remaining suspended solids. Two possible systems were suggested: the microstrainer system and the pressure filter system.

A microstrainer unit with about seventy square feet of total filtering area would be required. A system should also be provided to transfer the backwash slurry to the head of the treatment plant. Finally, a "surface-scatter" turbidimeter could be utilized to monitor strainer effluent.

The pressure filtration system would consist of a 600 gallon holding tank, a centrifugal pump capable of supplying 230 gallons per minute at a pressure of about 100 pounds per square inch, and a plate-and-frame unit with about 230 square feet of filtering area. Controls would include: tank level controls, a filtration pressure sensing device, and a "surface-scatter" turbidimeter.

pH Adjustment (A-10) - Utilized to adjust fluctuating waste stream pH's into the acceptable range. Major components include: a 1150 gallon tank, a two-horsepower mixing unit, a pH monitoring device (including sensing probes), and a reagent feed system. The reagent, concentrated sulfuric acid, would be fed in at a rate proportional to the pH of the wastewater flowing out of the tank.

Discharge Monitoring (A-11) - Periodic sampling and analysis of discharged effluent to verify that effluent requirements are fulfilled. Weekly eight hour composite suspended solids samples would probably be required. These samples could be manually obtained and analyzed in a commercial laboratory. (The reader should note that information on effluent discharge rate, turbidity, and pH would also be required, but could probably be obtained from process control instrumentation.)

Class B Liquid Processing Option - This system would pretreat the hydraulic tunneling waste stream prior to its discharge to the sanitary sewer. Basic processes would include: coarse fraction removal (B-1 in Figure 4-13), flow equalization (B-2), pH adjustment (B-3), and discharge monitoring (B-4). All of these would be essentially equivalent to the corresponding processes described above (A-1, A-2, A-10, and A-11, respectively).

Class C Liquid Processing Option - This system would be utilized to produce effluent of quality adequate for re-use in the tunneling system. Treatment processes would include: coarse fraction removal (C-1 in Figure 4-14), flow equalization (C-2), initial chemical treatment (C-3 and C-4), and clarification (C-5). These processes would be identical to those described for the Class A system (A-1, A-2, A-3, A-4, and A-5 respectively). An additional process, secondary flow equalization (C-6), would assure an adequate water supply to the tunneling operation at all times. Major components would be a 600 gallon tank and a 150 gallon per minute centrifugal make-up water pump. The system would also be equipped with appropriate tank level controls.

Sludge Treatment System - The primary purpose of the sludge treatment system is to produce a solids product which may be disposed of in the most economical manner possible. Thus, solids separated in the clarification process would be thickened in the bottom of the Lamella settler. Then, depending upon the economics of the particular situation, the sludge would either be disposed of immediately or extensively dewatered before disposal. Extensive dewatering would be accomplished in two steps: chemical sludge conditioning and mechanical dewatering.

Thickening - As stated above, thickening is essentially just gravity subsidence of settled solids occurring in the lower regions of the clarification tank. Thus, for this particular situation, the only equipment component required for thickening (other than the Lamella settler) would be a positive displacement pump to provide a metered underflow from the Lamella settler. This pump should have a variable discharge of about 2.5 to 10.0 gallons per minute. Controls for the thickening process would be an ultrasonic sludge density controller and an ultrasonic interface level sensor.

Sludge Hauling - This term refers to the practice of disposing of sludge immediately after thickening. Normally, this practice would entail hauling the sludge to a sanitary land-fill or other suitable disposal site. Sludge hauling could be accomplished with a 470 cubic foot (3600 gallon) capacity sealed semi-trailer. This volume should be sufficient to contain one entire day's sludge production. In addition to the sludge hauling trailer, storage should be provided to hold sludge produced while the trailer is "on the road." The storage system should consist of a tank of at least 600 gallon capacity and a pump to transfer the stored sludge from the tank to the trailer.

Sludge Conditioning - This process consists of dosing sludge with coagulant chemicals to produce a more readily dewaterable process. As with previously discussed chemical coagulation processes, sludge conditioning would consist of a preparation-feeding stage and a mixing stage. The preparation-feeding unit would consist of a commercially available packaged system capable of preparing dry polymers. The coagulant, Calgon WT-3000, would be fed at a rate of 2.0 pounds per ton of dry solids. Mixing could probably be accomplished by directing treated sludge through a series of pipe elbows.

Mechanical Dewatering - Conditioned sludge may be treated by a number of physical processes in order to obtain a product that may be handled and disposed of by conventional means of solids handling. Two systems show promise for mechanical sludge dewatering: a centrifuge system and a filtration system.

The centrifuge system basically consists of a solid bowl centrifuge with a nine inch bowl diameter. This device has a volumetric capacity of up to ten gallons per minute, and a mass capacity of 500 to 600 pounds per hour. Dewatered solids would be conveyed out of the centrifuge and loaded into dump trucks, and the clarified liquid would be returned to the head of the treatment plant or discharged into plant effluent.

The filtration system would utilize a dual cell gravity filter for initial dewatering, followed by a belt press filter. This system also has a capacity of about ten gallons per minute. Solids and liquid from the system would be handled as with the centrifuge system.

Final Comments - The above recommendations for the various systems should not be considered as ultimate designs, but merely as "first cuts" at the problem of hydraulic tunneling wastewater treatment. Any engineer considering the design of such a treatment system should be alert to possible alterations, combinations, or other changes which could generally improve the efficiency of the system without sacrificing its overall performance. Obviously, however, any changes should be preceded by a good deal of careful and thorough consideration to determine the feasibility and practicability of the proposed changes.

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Chapter 5

ECONOMIC ANALYSIS OF HYDRAULIC TUNNELING WASTEWATER TREATMENT SYSTEMS

The previous chapter outlined the design of three major liquid processing options and three sludge handling and treatment systems. The economics of each of these individual processes will be analyzed below and the total costs of several complete wastewater treatment systems will then be determined.

Hypothetical Tunneling Operation

In order to provide a more meaningful and complete analysis, a hypothetical tunneling operation will be considered. Systems cost data will be related to the appropriate tunnel parameters to determine the unit costs for the treatment of hydraulic tunneling wastewater.

Tunnel Dimensions - The hypothetical tunnel is assumed to be constructed in the St. Peter sandstone and have a length of two miles or 10560 feet and a cross-sectional area of eighty-five square feet. The total volume of the excavation would be about 33200 cubic yards.

Tunneling Operation - The actual tunneling operation is assumed to utilize techniques which are identical to those described in Chapter 1 for excavation, solids transportation, and ground support. Furthermore, the waste stream is assumed to have characteristics which are identical to those described in Chapter 2.

Specifically, the operation is projected as having an average mass flow rate of approximately 8.7 tons per hour (see Chapter 2) which corresponds to a volumetric solids flow rate of 5.0 cubic yards per hour (8.7 tons per hour multiplied by 0.57 cubic yards per ton) or 1.6 lineal feet of tunnel advance per hour. For an average excavation time of six hours per eight hour shift, 1100 operating shifts would be required to complete the excavation phase (10560 feet of tunnel divided by the product of 1.6 feet per hour and six hours per shift). Assuming an average operational efficiency of ninety percent, a total of 1220 shifts would be required to complete the excavation phase. This value corresponds to a job duration of about 410 working days, eighty-two working weeks, 18.6 months, or 1.55 years. Furthermore, excavation is assumed to begin on approximately April 1 of the first year and to finish on approximately October 15 of the following year.

Reference Sources - Cost data for this economic analysis was obtained from a variety of sources including: City of Minneapolis personnel, equipment manufacturers and distributors, manufacturers' literature, reference books, construction cost estimating manuals, and catalogues. Complete referencing of individual cost data sources would present a near impossibility, so that only cost sources for "special" items will be referenced. All costs are presented in mid-1976 dollar values.

Economic Analysis of Liquid Processing and Sludge Treatment and Handling Systems

The discussion below will consider the Class A, B, and C liquid processing options and the sludge handling and treatment systems. For each of the above, the total equipment, installation, and disassembly costs, salvage values, and maintenance costs will be determined. Other non-cost data will be tabulated including: space requirements, operating man power, electric power demand, electric power consumption, chemical requirements, and other miscellaneous items. However, before beginning the actual economic analysis, some basic assumptions will be discussed.

Miscellaneous Assumptions Detailed estimates of equipment and installation costs are presented below for each of the individual processes of the liquid and sludge systems. The various processes are assumed to be strictly electrically powered; whereas, on construction sites equipped with air compressors, pneumatically powered components may prove more economical.

In equipment installation discussions, reference is sometimes made to a "standard crew". This crew would consist of the following: one structural steel worker, one equipment operator, one welder, and a gas welding machine. Total costs for the standard crew are assumed to be about $290 per day (including wages, fringe benefits, and equipment rental).

The net salvage value of each of the liquid processing and sludge treatment (or handling) systems is also estimated. This value is the difference of projected gross salvage value and disassembly cost. The gross salvage value is calculated as follows: certain relatively durable equipment components in a system are assumed to have resale values equal to one-half of their original costs and the sum of these resale values is the gross salvage value of the particular system.

Project maintenance costs are predicted on one of two bases. First, they may be estimated as a straight percentage of the original equipment cost, e.g., if the total equipment cost for a particular process is 'x' dollars, the total maintenance cost is estimated as 0.2 of 'x' dollars. Secondly, maintenance costs may be projected as the sum of the original equipment costs of a portion of the individual components of a particular process, e.g., clarification-thickening process equipment would consist of a high initial cost, low maintenance Lamella settler and several low initial cost, high maintenance items such as pumps and mixers. Thus, the total maintenance cost for this process is considered to be the sum of the original equipment costs of the various high maintenance items.

Space requirements are estimated for each of the liquid or sludge processing systems. These estimates reflect the actual area required for the equipment components plus a reasonable allowance for working space. Additional area (above the predicted space requirements) must be provided to allow for the access of trucks and associated vehicles utilized in the loading and hauling of coarse solids and sludge.

The maximum sustained fifteen minute electric power demand is estimated for each system. This value is calculated by adding the power demands of the individual components which conceivably could be operating simultaneously so as to obtain the maximum power demand for the system.

Electric power consumption is figured on the basis of one kilowatt of electrical input per horsepower of mechanical output (normal conversion: 0.748 kilowatts = 1.0 horsepower). System power consumptions are calculated on a "per shift" basis as the sum of the consumptions of individual components; individual component consumption is calculated as the product of a component's rated power demand and its total estimated operating time per shift. Total project power consumption values are figured over all 1220 excavation shifts (rather than the 1100 shifts of actual excavation).

Two grades of man power are assumed to be required for the treatment system operation. The first, termed Grade 1 labor, would require a reasonably good understanding of treatment processes and the capability to perform basic arithmetic calculations accurately and reliably. Grade 2 labor would require a minimal understanding of treatment processes. Man power requirements are calculated in much the same manner as electrical consumption; "per shift" estimates are made of the individual process requirements and, in turn, projected for the entire operation. (The 1220 shift figure is also utilized for calculating the total man power requirements.)

Additional assumptions will be made throughout the discussion, but will be explained as they are encountered.

Class A Liquid Processing Option - The Class A system, as previously considered, consists of the following processes: coarse fraction removal, flow equalization, initial chemical preparation and feeding, chemical-wastewater mixing, clarification, secondary chemical preparation and feeding, secondary mixing, flocculation, filtration, pH adjustment, and discharge monitoring. The discussion below will consider various of the capital and operating costs of these processes as well as another process not previously included with the Class A system: sludge thickening. The reason for including this sludge treatment process in the analysis of the Class A system is that, as stated in Chapter 4, both clarification and thickening occur simultaneously in a single unit. Thus, a separate economic analysis of these processes would be quite impractical.

Equipment and Installation Costs - Tables 5-1 through 5-18 present the basic equipment and installation costs for the various Class A processes.

Table 5-1
Equipment Costs - Coarse Fraction Removal

Component		Cost
Hopper Structure; 19000 lb. of erected structural steel @ $0.55/lb.	$	10450
Electric Vibrators; 2 @ $660 ea.		1320
Top Water Pumps (submersible sump type); 2 @ $300 each		600
Well Screens (2 in. diameter stainless steel); 80 ft. @ $20/ft.		1600
Well Screen Fittings; 10% of well screen cost		160
Well Screen Pumps (centrifugal); 2 @ $210 ea.		420
First Subtotal	$	14550
Misc.; 5% of first subtotal		730
Second Subtotal	$	15280
Sales Tax; 4% of second subtotal		610
Total	$	15890

Table 5-2
Set Up Costs - Coarse Fraction Removal

Item		Cost
Foundation; 7.25 cu.yd. conc. @ $84/cu. yd. inst.	$	610
Installation Labor (standard crew); 1 day @ $290/day		290
Crane Rental (20 ton cap.); 1 day @ $270/day		270
Inflow Piping (4 in. dia. PVC); 30 ft. @ $8.50/ft. inst.		260
Vibrator Installation and Wiring		200
Well Screen Pump Installation and Wiring		200
Piping for Well Screens (1 in. dia. steel); 80 ft. @ $5/ft. inst.		400
First Subtotal	$	2230
Misc.; 5% of first subtotal		110
Second Subtotal	$	2340
Sales Tax; 1% of second subtotal		20
Total	$	2360

Table 5-3
Equipment Costs - Flow Equalization

Component		Cost	
Tank (Cap. 1000 gal., 10 ga. steel const. w. 16 in. dia. manhole)	$	320	
Mixer (2 hp, dual propeller, gear drive)		1820	
Transfer Pump (variable discharge-65 to 275 gpm, progressive cavity type w. remote control, 10 hp motor)		6960	
Vortex Flow Meter (3 in., dia. w. graphical recorder and visual read-out)		2310	(1)
Level Controls and Monitoring Devices		480	
First Subtotal	$	11890	
Misc.; 5% of first subtotal		590	
Second Subtotal	$	12480	
Sales Tax; 4% of second subtotal		500	
Total	$	12980	

Table 5-4
Set Up Costs - Flow Equalization

Item		Cost
Foundation; 0.9 cu.yd. conc. @ $73/cu.yd. inst.	$	70
Tank Installation		100
Inflow Piping (4 in. dia. PVC); 50 ft. @ $8.50/ft. inst.		420
Mixer Installation and Wiring		200
Pump Installation Plumbing and Wiring		300
Flow Meter Installation and Wiring		300
Level Control Installation and Wiring		100
First Subtotal	$	1490
Misc.; 5% of first subtotal		70
Second Subtotal	$	1560
Sales Tax; 1% of second subtotal		20
Total	$	1580

Table 5-5
Equipment Costs - Chemical Preparation and Feeding

Component		Cost
Preparation Unit (including tank, mixer, and feed pump)	$	880
Water Supply Tank (30 gal. poly.)		100
Float Valve		100
Water Supply Pump		500
Rotameters; 2 @ $ 50 ea.		100
First Subtotal	$	1680
Misc.; 5% of first subtotal		80
Second Subtotal	$	1760
Sales Tax; 4% of second subtotal		70
Total	$	1830

Table 5-6
Set Up Costs - Chemical Preparation and Feeding

Item		Cost
Foundation; 0.4 cu.yd. conc. @ $73/cu.yd. inst.	$	30
Water Supply Piping (1.5 in. dia. PVC); 50 ft. @ $4.80/ft. inst.		240
Chem. and Dilution Water Feed Piping (0.5 in. dia. steel); 30 ft. @ $3.40/ft. inst.		100
Misc. Plumbing		70
Wire Prep. Unit and Water Supply Pump		100
First Subtotal	$	540
Misc.; 5% of first subtotal		30
Second Subtotal	$	570
Sales Tax; 1% of second subtotal		10
Total	$	580

Table 5-7
Equipment Costs - Mixing, Clarification, and Thickening

Component		Cost
Model 740/45 Lamella Settler	$	27000 (2)
Integral Mixing Attachment (230 gal. vol.)		4000 (2)
Sludge Pump (variable discharge - 0.5 to 10.5 gpm, progressive cavity type, 0.75 hp motor)		1220
Effluent Turbidimeter ("surface-scatter" type)		2000 (3)
Density Controller (ultrasonic type)		1340 (3)
Interface Level Sensor (ultrasonic type)		540
Mounting for Interface Level Sensor		1000
First Subtotal	$	37100
Misc.; 5% of first subtotal		1860
Second Subtotal	$	38960
Sales Tax; 4% of second subtotal		1560
Total	$	40520

Table 5-8
Set Up Costs - Mixing, Clarification, and Thickening

Item		Cost
Foundation; 2 cu.yd. conc. @ $84/cu.yd. inst.	$	170
Installation Labor (standard crew); 1 day @ $290/day		290
Crane Rental (20 ton cap.); 1 day @ $270/day		270
Inflow Piping (4 in. dia. PVC); 50 ft. @ $8.50/ft. inst.		420
Install, Wire, and Plumb Sludge Pump and Density Controller		300
Wire Mixing Unit		100
Wire Vibrator		100
Install and Wire Interface Level Sensor		200
Install, Wire, and Plumb Turbidimeter		200
First Subtotal	$	2050
Misc.; 5% of first subtotal		100
Second Subtotal	$	2150
Sales Tax; 4% of second subtotal		90
Total	$	2240

Table 5-9
Equipment Costs - Secondary Mixing

Component		Cost
Tank (cap. 250 gal., 12 ga. const. w. 16 in. dia. manhole)	$	140
Mixer (0.33 hp, variable speed submersible)		1240
First Subtotal	$	1380
Misc.; 5% of first subtotal		70
Second Subtotal	$	1450
Sales Tax; 4% of second subtotal		60
Total	$	1510

Table 5-10
Set Up Costs - Secondary Mixing

Item		Cost
Foundation; 0.2 cu.yd. @ $73/cu.yd. inst.	$	10
Tank Installation		30
Inflow Piping (4 in. dia. PVC); 20 ft. @ $8.50/ft. inst.		170
Install and Wire Mixer		200
First Subtotal	$	410
Miscellaneous		50
Second Subtotal	$	460
Sales Tax; 1% of second subtotal		-
Total	$	460

Table 5-11
Equipment Costs - Flocculation

Component		Cost
Tank (cap. 1150 gal., 10 ga. const.)	$	360
Drive Motor (0.75 hp, 1750 rpm), Speed Reducing Assembly (1750 to about 1 rpm), and Paddle Wheel		1000
First Subtotal	$	1360
Misc.; 5% of first subtotal		70
Second Subtotal	$	1430
Sales Tax; 4% of second subtotal		60
Total	$	1490

Table 5-12
Set Up Costs - Flocculation

Item		Cost
Foundation; 0.7 cu.yd. @ $73/cu.yd. inst.	$	50
Tank Installation		100
Tank Plumbing (4 in. dia. PVC); 10 ft. @ $8.50/ft. inst.		80
Baffle Installation		100
Paddle Wheel and Drive Assembly Installation and Wiring		400
First Subtotal	$	730
Misc.; 5% of first subtotal		40
Second Subtotal	$	770
Sales Tax; 1% of second subtotal		10
Total	$	780

Table 5-13
Equipment Costs - Microstrainer Filtration

Component		Cost	
Microstrainer Unit (5 ft. dia. by 5 ft. long drum in steel tank)	$	38000	(4)
Backwash Removal Pump (submersible sump type w. level controls)		150	
Backwash Reservoir (50 gal. poly.)		120	
Effluent Turbidimeter ("surface-scatter" type)		2000	(5)
First Subtotal	$	40270	
Misc.; 5% of first subtotal		2010	
Second Subtotal	$	42280	
Sales Tax; 4% of second subtotal		1690	
Total	$	43970	

Table 5-14
Set Up Costs - Microstrainer Filtration

Item		Cost
Foundation; 4.1 cu.yd. @ $73/cu.yd. inst.	$	300
Installation Labor (standard crew); 1 day @ $290/day		290
Crane Rental (20 ton cap.); 1 day @ $270/day		270
Inflow Piping (4 in. dia. PVC); 20 ft. @ $8.50 ft. inst.		170
Wire Microstrainer Drive Motor and Backwash Pump		200
Backwash Disposal Piping (15 in. dia. PVC); 100 ft. @ $4.80/ft. inst.		480
Install, Wire, and Plumb Turbidimeter		200
First Subtotal	$	1910
Misc.; 5% of first subtotal		100
Second Subtotal	$	2010
Sales Tax; 1% of second subtotal		20
Total	$	2030

Table 5-15
Equipment Costs - Pressure Filtration

Component	Cost
Plate and Frame Unit (230 sq.ft. of filtering area, carbon steel const., incl. pressure sensing device)	$ 10000 (6)
Pressure Pump (3 in. suction by 2 in. discharge centrifugal, 230 ft. total discharge head at 230 gpm, 25 hp, 3500 rpm)	1500
Tank (Cap. 600 gal., 12 gal. const.) w. 16 in. dia. manhole	210
Effluent Turbidimeter, ("surface-scatter" type)	2000 (5)
Tank Level Controls	270
First Subtotal	$ 13980
Misc.; 5% of first subtotal	700
Second Subtotal	$ 14680
Sales Tax; 4% of second subtotal	590
Total	$ 15270

Table 5-16
Set Up Costs - Pressure Filtration

Item	Cost
Foundation; 2.2 cu.yd. conc. @ $73/cu.yd. inst.	$ 160
Filter, Tank, and Pump Installation	380
Inflow Piping (4 in. dia. PVC); 20 ft. @ $8.50/ft. inst.	170
Wire Pressure Pump	200
Install, Wire, and Plumb Turbidimeter	200
Install and Wire Level Controls	100
First Subtotal	$ 1210
Misc.; 5% of first subtotal	60
Second Subtotal	$ 1270
Sales Tax; 1% of second subtotal	10
Total	$ 1280

Table 5-17
Equipment Costs - pH Adjustment

Component	Cost
Tank (cap. 1150 gal., 10 ga. steel const.)	$ 360
Mixer (2 hp, dual propeller, gear drive)	1810
Monitoring Device (incl. electrodes, proportioning controller, and recorder)	1650 (7)
Reagent Feed Pump (cap. 0 to 1.6 gph)	920
Reagent Storage Tank (cap. 30 gal., steel const.)	20
First Subtotal	$ 4760
Misc.; 5% of first subtotal	240
Second Subtotal	$ 5000
Sales Tax; 4% of second subtotal	200
Total	$ 5200

Table 5-18
Set Up Costs - pH Adjustment

Item		Cost
Foundation; 0.6 cu.yd. @ $73/cu.yd. inst.	$	40
Tank Installation		100
Inflow Piping (4 in. dia. PVC); 20 ft. @ $8.50/ft. inst.		170
Mixer Installation and Wiring		200
pH Monitor Installation and Wiring		200
Feed Pump Installation and Wiring		100
Reagent Feed Piping (0.5 in. dia. steel); 15 ft. @ $3.40/ft.		50
First Subtotal	$	860
Misc.; 5% of first subtotal		40
Second Subtotal	$	900
Sales Tax; 1% of second subtotal		10
Total	$	910

Equipment and installation costs are not cited above for either the secondary chemical preparation and feeding or discharge monitoring processes. The former is assumed to have equipment and installation costs identical to those estimated for the initial preparation and feeding process (equipment cost - $1830, installation costs - $580). The discharge monitoring process would require an estimated $50 for miscellaneous sampling apparatus (such as sample bottles) with essentially no installation costs.

Table 5-19 summarizes the total equipment and installation costs for the Class A system utilizing microstrainer filtration of effluent.

Table 5-19
Equipment and Set Up Costs - Class A Liquid Processing Option*

Process	Equipment Cost	Set Up Cost	Total Cost
Coarse Fraction Removal	$ 15890	$ 2360	$ 18250
Flow Equalization	12980	1580	14560
Initial Chemical Preparation and Feeding	1830	580	2410
Mixing, Clarification, and Thickening	40520	2240	42760
Secondary Chemical Preparation and Feeding	1830	580	2410
Secondary Mixing	1510	460	1970
Flocculation	1490	780	2270
Microstrainer Filtration	43970	2030	46000
pH Adjustment	5200	910	6110
Discharge Monitoring	50	-	50
Total	$ 125270	$ 11520	$ 136790

* including microstrainer filtration system

The costs of an equivalent system utilizing pressure filtration of effluent are obtained by substituting appropriate pressure filtration costs for the microstrainer expenses. Thus, this alternate system would have the following costs: equipment - $96580, installation - $10720, and total - $107300.

System Salvage Values - The net salvage value of the Class A system is the sum of the gross salvage values of all resaleable items minus the disassembly costs. Gross salvage values for the selected components of the Class A system are presented in Table 5-20.

Table 5-20
Gross Salvage Values - Class A Liquid Processing Option*

Process	Component	Original Cost	Salvage Value
Coarse Fraction Removal	Hopper Structure	$ 10450	$ 5220
Coarse Fraction Removal	Well Screens & Fittings	1760	880
Flow Equalization	Tank	320	160
Flow Equalization	Transfer Pump	6960	3480
Flow Equalization	Flow Meter	2310	1160
Init.Chem.Prep. & Feed	Preparation Unit	880	440
Init.Chem.Prep. & Feed	Water Supply Pump	500	250
Mixing, Clarification, & Thickening	Lamella Settler	27000	13500
Mixing, Clarification, & Thickening	Mixing Unit	4000	2000
Mixing, Clarification, & Thickening	Turbidimeter	2000	1000
Mixing, Clarification, & Thickening	Density Controller	1340	670
Secondary Chem.Prep. & Feed	Preparation Unit	880	440
Secondary Chem.Prep. & Feed	Water Supply Pump	500	250
Secondary Mixing	Tank	140	70
Flocculation	Tank	360	180
Microstrainer Filtration	Microstrainer	38000	19000
Microstrainer Filtration	Turbidimeter	2000	1000
pH Adjustment	Tank	360	180
pH Adjustment	Monitoring Apparatus	1650	820
pH Adjustment	Reagent Feed Pump	920	460
Total			$ 51160

*including microstrainer filtration system

As indicated, the gross salvage value from Table 5-20 ($51160) is for the Class A system utilizing microstrainer filtration of effluent. The salvage value for the pressure filtration system is presented in Table 5-21.

Table 5-21
Gross Salvage Values - Pressure Filtration System

Component	Original Cost	Salvage Value
Plate-and-Frame Unit	$ 10000	$ 5000
Pressure Pump	1500	750
Tank	210	100
Turbidimeter	2000	1000
Total		$ 6850

The gross salvage value of the Class A option including the pressure filtration system would be about $38010 (the total from Table 5-20 minus the microstrainer system salvage value ($20000) plus the total from Table 5-21).

Tables 5-22, 5-23, and 5-24 outline the disassembly costs for the Class A system.

Table 5-22
System Disassembly Costs - Class A Liquid Processing Option *

Process		
Coarse Fraction Removal	Hopper Disassembly Labor (standard crew); 1 day @ $290/day	$ 290
Coarse Fraction Removal	Crane Rental; 1 day @ $270/day	270
Flow Equalization	Tank Removal	100
Flow Equalization	Pump Removal	100
Flow Equalization	Flow Meter Removal	100
Init.Chem.Prep.and Feed	Equipment Removal	100
Mixing,Clarification, and Thickening	Sludge Pump Removal	50
Mixing,Clarification, and Thickening	Instrumentation Removal	200
Mixing,Clarification, and Thickening	Lamella Settler Disassembly Labor (standard crew); 1 day @ $290/day	290
Mixing,Clarification, and Thickening	Crane Rental; 1 day @ $270/day	270
Secondary Chem.Prep. and Feed	Equipment Removal	100
Secondary Mixing	Tank Removal	50
Flocculation	Tank Removal	100
pH Adjustment	Instrumentation Removal	100
pH Adjustment	Reagent Feed System Disassembly	100
pH Adjustment	Tank Removal	100
All of Above	Found.Demo.; 12.5 cu.yd. @ $15/cu.yd.	200
All of Above	Miscellaneous	600
Total		$ 3120

*excluding microstrainer and pressure filtration systems

Table 5-23
Disassembly Costs - Microstrainer
Filtration System

Item		Cost
Turbidimeter Removal	$	150
Microstrainer Disassembly Labor (standard crew); 1 day @ $290/day		290
Crane Rental; 1 day @ $270/day		270
Foundation Demolition; 4.1 cu.yd. @ $15/cu.yd.		60
Miscellaneous		100
Total	$	870

Table 5-24
Disassembly Costs - Pressure Filtration System

Item		Cost
Turbidimeter Removal	$	150
Filter, Pump, and Tank Removal		380
Foundation Demolition; 2.2 cu.yd. @ $15/cu.yd.		30
Miscellaneous		100
Total	$	660

The total disassembly costs for the Class A system utilizing the microstrainer and pressure filtration processes are $3990 and $3780 respectively.

From the above data, the net salvage values of the two Class A systems may be obtained. These are: Class A system with microstrainer filtration - $47170 and Class A system with pressure filtration - $34230.

Maintenance Costs - Table 5-25 contains estimates of the total project maintenance costs for a Class A system employing microstrainer filtration of effluent.

Table 5-25
Maintenance Costs - Class A Liquid Processing Option*

Process	Estimate Basis	Cost
Coarse Fraction Removal	Cost of New Pumps and Vibrators	$ 2300
Flow Equalization	20% of Original Equip. Cost	2400
Init.Chem.Prep.and Feed	20% of Original Equip. Cost	400
Mixing,Clarification, and Thickening	Costs of New Mixing Unit ($700) and Sludge Pump and 50% of Cost of Controls	3900
Secondary Chem.Prep. and Feed	20% of Original Equip. Cost	400
Secondary Mixing	Cost of New Mixing Unit	1200
Flocculation	20% of Original Equip. Cost	300
Microstrainer Filtration	20% of Original Equip. Cost	8800
pH Adjustment	20% of Original Equip. Cost	1000
Total		$ 20700

*including microstrainer filtration system

The maintenance costs for the pressure filtration system are projected as twenty percent of the original equipment cost, or $3100. By substituting this value for the microstrainer maintenance cost in Table 5-27, a total maintenance expenditure of $15000 is estimated for the Class A system with pressure filtration of effluent.

Space Requirements - Table 5-26 lists the surface area requirements for the Class A system.

Table 5-26
Space Requirements - Class A Liquid Processing Option*

Process	Area (sq.ft.)
Coarse Fraction Removal	380
Flow Equalization	100
Initial Chemical Preparation and Feeding	40
Mixing, Clarification, and Thickening	110
Secondary Chemical Preparation and Feeding	40
Secondary Mixing	20
Flocculation	50
Microstrainer Filtration	220
pH Adjustment	60
Total	1020

* including microstrainer filtration system

The pressure filtration system requires an estimated 120 square feet of working area so that the Class A system including this option would require about 920 square feet of surface.

Power Demand - The maximum sustained fifteen minute power demand for the Class A system is estimated in Table 5-27.

Table 5-27
Electric Power Demand - Class A Liquid Processing Option*

Process	Function	Power Demand(kw)
Coarse Fraction Removal	Slurry Pumping	3.2
Flow Equalization	Mixing	2.0
Flow Equalization	Transfer Pumping	10.0
Init.Chem.Prep. and Feed	Mixing	0.1
Init.Chem.Prep. and Feed	Chem. and Water Feed	0.7
Mixing,Clarification, and Thickening	Mixing	0.3
Mixing,Clarification, and Thickening	Sludge Pumping	0.8
Mixing,Clarification, and Thickening	Turbidity Measurement	0.1
Secondary Chem.Prep.and Feed	Mixing	0.1
Secondary Chem.Prep.and Feed	Chem. and Water Feed	0.7
Secondary Mixing	Mixing	0.3
Flocculation	Mixing	0.8
Microstrainer Filtration	Screen Drive	1.0
Microstrainer Filtration	Backwashing	0.5
Microstrainer Filtration	Backwash Disposal Pumping	0.3
Microstrainer Filtration	Turbidity Measurement	0.1
pH Adjustment	Mixing	2.0
pH Adjustment	Monitoring	0.1
pH Adjustment	Reagent Feed	0.1
Subtotal		23.2
Misc.; 10% of subtotal		2.3
Total		25.5

* including microstrainer unit

The total in Table 5-27 represents the power demand for the Class A system with a microstrainer unit incorporated. The pressure filtration system would have a maximum power demand of about 25.1 kilowatts (25.0 kilowatts for pressure pumping and 0.1 kilowatts for turbidity measurement). Thus, the power demand for the Class A system utilizing pressure filtration would be about 51.0 kilowatts (the subtotal from Table 5-27 plus the pressure filtration demand minus the microstrainer demand; the entire quantity multiplied by a factor of 1.1).

Power Consumption - Table 5-28 summarizes the "per shift" electrical power consumption of the Class A system with microstrainer filtration of effluent.

Table 5-28
Electric Power Consumption - Class A Liquid Processing Option*

Process	Function	Consumption(kw-hr/shift)
Coarse Fraction Removal	Slurry Pumping; 3.2 kw @ 6 hr	19.2
Coarse Fraction Removal	Top Water Pumping; 0.5 kw @ 0.2 hr	0.1
Coarse Fraction Removal	Well Screen Pumping; 0.8 kw @ 2.0 hr	1.6
Coarse Fraction Removal	Hopper Vibration; 0.5 kw @ 0.5 hr	0.2
Flow Equalization	Mixing; 2.0 kw @ 6.0 hr	12.0
Flow Equalization	Transfer Pumping; 10.0 kw @ 6.0 hr	60.0
Init.Chem.Prep.and Feed	Chem. Mixing; 0.07 kw @ 6.0 hr	0.4
Init.Chem.Prep.and Feed	Chem. Feeding; 0.33 kw @ 6.0 hr	2.0
Init.Chem.Prep.and Feed	Dil.Water Feed; 0.33 kw @ 6.0 hr	2.0
Mixing,Clarification, and Thickening	Mixing; 0.33 kw @ 6.0 hr	2.0
Mixing,Clarification, and Thickening	Sludge Pumping; 0.75 kw @ 6.0 hr	4.5
Mixing,Clarification, and Thickening	Turbidity Measurement; 0.06 kw @ 6.0 hr	0.4
Second Chem.Prep. and Feed	Chem. Mixing; 0.07 kw @ 6.0 hr	0.4
Second Chem.Prep. and Feed	Chem. Feeding; 0.33 kw @ 6.0 hr	2.0
Second Chem.Prep. and Feed	Dil.Water Feed; 0.33 kw @ 6.0 hr	2.0
Secondary Mixing	Mixing; 0.33 kw @ 6.0 hr	2.0
Flocculation	Flocculation; 0.75 kw @ 6.0 hr	4.5
Microstrainer Filtration	Screen Drive; 1.0 kw @ 6.0 hr	6.0
Microstrainer Filtration	Backwashing; 0.5 kw @ 6.0 hr	3.0
Microstrainer Filtration	Backwash Disposal Pumping; 0.33 kw @ 6.0 hr	2.0
Microstrainer Filtration	Turbidity Measurement; 0.06 kw @ 6.0 hr	0.4
pH Adjustment	Mixing; 2.0 kw @ 6.0 hr	12.0
pH Adjustment	Monitoring; 0.1 kw @ 6.0 hr	0.6
pH Adjustment	Reagent Feeding; 0.1 kw @ 6.0 hr	0.6
Total		139.9

*including microstrainer filtration system

Assuming that 1220 shifts are required to complete the tunnel excavation phase, a total of about 171000 kilowatt-hours would be consumed by this Class A system.

The pressure filtration process would consume electric power as follows: pressure pumping - 25.0 kilowatts for 4.5 hours or 112.5 kilowatt-hours and turbidity measurement - 0.06 kilowatts for 6.0 hours or 0.4 kilowatt-hours. Substituting these values for the microstrainer power consumption values in Table 5-28, a total "per shift" power consumption of 241.4 kilowatt-hours is obtained. This figure corresponds to a project total of 295000 kilowatt-hours.

Operating Man Power - The "per shift" labor requirements for the Class A system utilizing microstrainer filtration of effluent are presented in Table 5-29.

Table 5-29
Operating Man Power - Class A Liquid Processing Option*

Process	Function	Req'd. Grade 1 Labor(hr/shift)	Req'd. Grade 2 Labor(hr/shift)
Coarse Fraction Removal	Direct Truck Traffic	-	0.6
Coarse Fraction Removal	Check Hopper Solids Level	-	0.5
Coarse Fraction Removal	Pump Top Water	-	0.5
Flow Equalization	Monitor Pumping Rate and Tank Level	1.0	-
Flow Equalization	Adjust Pumping Rate	0.5	-
Init.Chem.Prep. and Feed	Adjust Chem. Feed Rate	1.0	-
Init.Chem.Prep. and Feed	Preparation of Chemical	0.3	-
Mixing,Clarification and Thickening	Monitor Turbidity	0.5	-
Mixing,Clarification and Thickening	Monitor Sludge Density and Pumping Rate	1.0	-
Second.Chem.Prep. and Feed	Adjust Chem. Feed Rate	1.0	-
Second.Chem.Prep. and Feed	Preparation of Chemical	0.3	-
Secondary Mixing	None	-	-
Flocculation	None	-	-
Microstrainer Filtration	General Monitoring	1.0	-
pH Adjustment	Monitoring pH	0.5	-
pH Adjustment	Fill Reagent Storage Tank	0.2	-
Total		7.3	1.6

*including microstrainer filtration system

In addition to the above requirements, about one-half hour per week of Grade 2 labor would be utilized for discharge monitoring (suspended solids sampling). Thus, for the project, a total of approximately 8900 Grade 1 hours and 1990 Grade 2 hours would be required for the operation of <u>this</u> Class A system.

The following labor breakdown is assumed for the operation of the pressure filtration process: general monitoring - one Grade 1 man-hour per <u>shift</u> and filter cake removal - one and one-half Grade 2 man-hours per <u>day</u> (or for calculation purposes, one-half hour per shift). Thus, a total of 8900 Grade 1 and 2560 Grade 2 man-hours are projected for the operation of the Class A system with pressure filtration.

Chemical Usage - The Class A option would utilize polyelectrolytic coagulants to aid in the clarification and filtration processes and concentrated sulfuric acid for pH adjustment (see Chapter 4).

The following feed rate was recommended for the initial coagulation process: ten gallons of Calgon Cat-Floc T (cationic polyelectrolyte) per million gallons of wastewater to be treated. Thus, assuming a total excavated volume of 33200 cubic yards and a water usage rate of 2100 gallons per cubic yard (see Chapter 2), a total of approximately 69.3 million gallons of wastewater would be produced. Therefore, about 690 gallons of polymer would be fed over the duration of the project. An additional ten percent is added to account for chemical wasting, bringing the projected usage to a total of 760 gallons.

The suggested feed rate for the secondary coagulation process was one gallon of chemical per million gallons of wastewater, or one-tenth of that used for the initial process. Thus, the total usage is also assumed to be one-tenth of the above value, or about 80 gallons.

A reagent feed rate of not greater than 1.6 gallons per hour of concentrated sulfuric acid was recommended for the pH adjustment process. For calculation purposes, the assumption is made that the average feed rate is about one-half of the maximum or 0.8 gallons per hour. Thus, about 4.8 gallons would be fed per shift which corresponds to a total feed volume of 5300 gallons (based on 1100 actual excavation shifts).

This value is increased by ten percent to compensate for losses, bringing the project total to 5800 gallons.

Solids Hauling - The solids separated in the coarse fraction removal process must be transported from the treatment site and suitably disposed of. However, in many urban areas, these excavation spoils would actually have a real value as fill material, and the assumption is made that returns from the sale of the spoils would balance the costs of hauling. Consequently, solids hauling costs are ignored. (This assumption will apply to the following liquid processing options as well.)

Class B Liquid Processing Option - The following Class B processes are discussed below: coarse fraction removal, pH adjustment, and discharge monitoring.

Equipment and Installation Costs - The costs of the coarse fraction removal process are projected as being equal to those for the Class A alternative. Thus, equipment and installation costs of $15890 and $2360, respectively, are estimated.

Tables 5-30 and 5-31 outline the equipment and installation costs for the pH adjustment system.

Table 5-30
Equipment Costs - pH Adjustment

Component		Cost
Tank (cap. 1500 gal., 7 ga. const., w. 16 in. dia. manhole)	$	760
Mixer (2 hp, gear driven, extended shaft, dual propl.)		1880
Monitoring Device (incl. electrodes, "on-off" controller, and graphic recorder)		1940 (7)
Reagent Feed Pump (cap. 1.6 gph)		290
Reagent Storage Tank (cap. 30 gal., steel const.)		20
Vortex Flow Meter (3 in. dia. w. graphical recorder and visual read-out)		2310
First Subtotal	$	7200
Misc.; 5% of first subtotal		360
Second Subtotal	$	7560
Sales Tax; 4% of second subtotal		300
Total	$	7860

Table 5-31
Set Up Costs - pH Adjustment.

Item		Cost
Foundation; 1.3 cu.yd. conc. @ $73/cu.yd.	$	90
Tank Installation		130
Inflow Piping (4 in. dia. PVC); 20 ft. @ $8.50/ft.		170
Mixer Installation and Wiring		200
pH Monitor Installation and Wiring		200
Feed Pump Installation and Wiring		100
Reagent Feed Piping (0.5 in. dia. steel); 15 ft. @ $3.40/ft.		50
Flow Meter Installation and Wiring		300
First Subtotal	$	1240
Misc.; 5% of first subtotal		60
Second Subtotal	$	1300
Sales Tax; 1% of second subtotal		10
Total	$	1310

The equipment costs for discharge monitoring would again total about $50 for miscellaneous suspended solids monitoring apparatus.

Equipment, installation, and "total" costs of the Class B system are presented in Table 5-32.

Table 5-32
Equipment and Set Up Costs - Class B Liquid Processing Option

Process	Equipment Cost	Set Up Cost	Total Cost
Coarse Fraction Removal	$ 15890	$ 2360	$ 18250
pH Adjustment	7860	1310	9170
Discharge Monitoring	50	-	50
	$ 23800	$ 3670	$ 27470

System Salvage Values - Tables 5-33 and 5-34 summarize the gross salvage values and disassembly costs for the Class B system.

Table 5-33
Gross Salvage Values - Class B Liquid Processing Option

Process	Component	Original Cost	Salvage Value
Coarse Fraction Removal	Hopper Structure	$ 10450	$ 5220
Coarse Fraction Removal	Well Screens and Fittings	1760	880
pH Adjustment	Tank	760	380
pH Adjustment	Monitoring Apparatus	1940	970
pH Adjustment	Reagent Feed Pump	290	140
pH Adjustment	Flow Meter	2310	1160
Total			$ 8750

Table 5-34
System Disassembly Costs - Class B Liquid Processing Option

Process	Item	Cost
Coarse Fraction Removal	Hopper Disassembly Labor (standard crew); 1 day @ $290/day	$ 290
Coarse Fraction Removal	Crane Rental; 1 day @ $270/day	270
pH Adjustment	Tank Removal	130
pH Adjustment	Flow Meter Removal	100
All of Above	Foundation Demo.; 8.5 cu.yd. @ $15/cu.yd.	130
Miscellaneous		200
Total		$ 1120

From the above information, the net salvage value of the Class B system is projected as $7630.

Maintenance Costs - The maintenance costs assumed for the Class B processes are: coarse fraction removal - $2300 (total original costs of all pumps and vibrators), and pH adjustment - $1570 (twenty percent of the original equipment cost). Thus, a total of $3870 in maintenance expenses is predicted.

Space Requirements- The following surface area requirements are estimated for the Class B treatment processes: coarse fraction removal - 380 square feet and pH adjustment - 70 square feet. Thus, a total area of about 450 square feet would be required for the system components.

Power Demand - Table 5-35 summarizes the maximum fifteen minute sustained electric power demand for the Class B system.

Table 5-35
Electric Power Demand - Class B Liquid Processing Option

Process	Function	Power Demand(kw)
Coarse Fraction Removal	Slurry Pumping	3.2
pH Adjustment	Mixing	2.0
pH Adjustment	pH Monitoring	0.1
pH Adjustment	Reagent Feed	0.1
Subtotal		5.4
Misc.; 10% of subtotal		0.5
Total		5.9

Power Consumption - Table 5-36 contains estimates of electric power consumption for the Class B system.

Table 5-36
Electric Power Consumption - Class B Liquid Processing Option

Process	Function	Power Consumption (kw-hr/shift)
Coarse Fraction Removal	Slurry Pumping; 3.2 kw @ 6 hr	19.2
Coarse Fraction Removal	Top Water Pumping; 0.5 kw @ 0.2 hr	0.1
Coarse Fraction Removal	Well Screen Pumping; 0.8 kw @ 2 hr	1.6
Coarse Fraction Removal	Hopper Vibration; 0.5 kw @ 0.2 hr	0.1
pH Adjustment	Mixing; 2 kw @ 6 hr	12.0
pH Adjustment	pH Monitoring; 0.1 kw @ 6 hr	0.6
pH Adjustment	Reagent Feeding; 0.1 kw @ 3 hr	0.3
Total		33.9

On the basis of the above information, a total power consumption of 41000 kilowatt-hours is projected.

Operating Man Power - Labor requirements for the operation of the Class B system are presented in Table 5-37.

Table 5-37
Operating Man Power - Class B Liquid Processing Option

Process	Function	Req'd. Grade 1 Labor(hr/shift)	Req'd. Grade 2 Labor(hr/shift)
Coarse Fraction Removal	Directing Truck Traffic	-	0.6
Coarse Fraction Removal	Check Hopper Solids Level	-	0.5
Coarse Fraction Removal	Pump Top Water	-	0.5
pH Adjustment	Monitor Flow Rate and Adjust Reagent Feed	1.0	-
pH Adjustment	Monitor pH	0.5	-
pH Adjustment	Fill Reagent Storage Tank	0.2	-
Total		1.7	1.6

As with the Class A system about one-half hour per week or a total of forty hours would be required for discharge monitoring (Grade 2 labor). Therefore, the total labor requirements for the project would be: Grade 1 labor - about 2070 hours and Grade 2 labor - about 1990 hours.

Chemical Usage - The total reagent usage estimated for the Class A option is also assumed for this system. Thus, a total requirement of 5800 gallons of concentrated sulfuric acid is predicted.

Class C Liquid Processing Option - This discussion considers the following processes: coarse fraction removal, flow equalization, chemical preparation and feeding, chemical-wastewater mixing, clarification, secondary flow equalization, and as with the Class A discussion, sludge thickening.

Equipment and Installation Costs - The equipment and installation costs for coarse fraction removal, flow equalization, chemical preparation and feeding, mixing, clarification, and thickening are assumed to be identical to the corresponding processes of the Class A option. The equipment and installation costs for the secondary flow equalization system are presented in Tables 5-38 and 5-39.

Table 5-38
Equipment Costs - Secondary Flow Equalization

Component		Cost
Tank (cap. 600 gal., 12 ga. const., w. 16 in. dia. manhole)	$	210
Make-up Water Pump (3 in. suction and 2.5 in. discharge, 20 ft. total discharge head at 150 gpm, 1.5 hp, 1750 rpm)		790
Level Controls		270
First Subtotal	$	1270
Miscellaneous; 5% of first subtotal		60
Second Subtotal	$	1330
Sales Tax; 4% of second subtotal		50
Total	$	1380

Table 5-39
Set Up Costs - Secondary Flow Equalization

Item		Cost
Foundation; 0.4 cu.yd. conc. @ $73/cu.yd.	$	30
Tank Installation		80
Piping (4 in. dia. PVC); 50 ft. @ $8.50/ft. inst.		420
Pump Installation, Plumbing, and Wiring		200
Level Control Installation and Wiring		100
First Subtotal	$	830
Misc.; 5% of first subtotal		40
Second Subtotal	$	870
Sales Tax; 1% of second subtotal		10
Total	$	880

Equipment and installation costs for the entire Class C system are presented in Table 5-40.

Table 5-40
Equipment and Set Up Costs - Class C
Liquid Processing Option

Process	Equipment Cost	Set Up Cost	Total Cost
Coarse Fraction Removal	$ 15890	$ 2360	$ 18250
Flow Equalization	12980	1580	14560
Chem.Prep.and Feed	1830	580	2410
Mixing,Clarification, and Thickening	40520	2240	42760
Secondary Flow Equalization	1380	880	2260
Total	$ 72600	$ 7640	$ 80240

System Salvage Values - The gross salvage values of selected Class C components are estimated in Table 5-41. Estimates of system disassembly costs are found in Table 5-42.

Table 5-41
Gross Salvage Values - Class C Liquid Processing Option

Process	Component	Orig. Cost	Salvage Value
Coarse Fraction Removal	Hopper Structure	$ 10450	$ 5220
Coarse Fraction Removal	Well Screens & Fittings	1760	880
Flow Equalization	Tank	320	160
Flow Equalization	Transfer Pump	6960	3480
Flow Equalization	Flow Meter	2310	1160
Init.Chem.Prep. & Feed	Preparation Unit	880	440
Init.Chem.Prep. & Feed	Water Supply Pump	500	250
Mixing,Clarification & Thickening	Lamella Settler	27000	13500
Mixing,Clarification & Thickening	Mixing Unit	4000	2000
Mixing,Clarification & Thickening	Turbidimeter	2000	1000
Mixing,Clarification & Thickening	Density Controller	1340	670
Secondary Flow Equalization	Tank	210	100
Secondary Flow Equalization	Pump	790	400
Total			$ 29260

Table 5-42
System Disassembly Costs - Class C Liquid Processing Option

Process	Item		Cost
Coarse Fraction Removal	Hopper Disassembly Labor (standard crew); 1 day @ $290/day	$	290
Coarse Fraction Removal	Crane Rental; 1 day @ $270/day		270
Flow Equalization	Tank Removal		100
Flow Equalization	Pump Removal		100
Flow Equalization	Flow Meter Removal		100
Chem.Prep.and Feed	Equipment Disassembly		100
Mixing,Clarification, and Thickening	Sludge Pump Removal		50
Mixing,Clarification, and Thickening	Instrumentation Removal		200
Mixing,Clarification, and Thickening	Lamella Settler Disassembly Labor (standard crew); 1 day @ $290/day		290
Mixing,Clarification, and Thickening	Crane Rental; 1 day @ $270/day		270
Secondary Flow Equalization	Tank Removal		80
Secondary Flow Equalization	Pump Removal		50
All of Above	Found.Demo.; 11 cu.yd. @ $15/cu.yd.		160
All of Above	Miscellaneous		400
Total		$	2460

Thus, the Class C system has a net salvage value of $26800.

Maintenance Costs - Table 5-43 presents projected maintenance costs for the Class C system.

Table 5-43
Maintenance Costs - Class C Liquid Processing Option

Process	Estimate Basis		Cost
Coarse Fraction Removal	Costs of New Pumps and Vibrators	$	2300
Flow Equalization	20% of Original Equip. Cost		2400
Init.Chem.Prep.and Feed	20% of Original Equip. Cost		400
Mixing,Clarification, and Thickening	Cost of New Mixing Unit ($700), Sludge Pump, and 50% of Cost of Controls		3900
Secondary Flow Equalization	20% of Original Equip. Cost		280
Total		$	9280

Space Requirements - Table 5-44 lists the surface area requirements for the Class C system.

Table 5-44
Space Requirements - Class C Liquid Processing Option

Process	Area (Sq.Ft.)
Coarse Fraction Removal	380
Flow Equalization	100
Chem. Prep. and Feed	40
Mixing, Clarification, and Thickening	110
Secondary Flow Equalization	70
Total	700

Power Demand - Table 5-45 summarizes maximum power demand for the Class C system.

Table 5-45
Electric Power Demand - Class C Liquid Processing Option

Process	Function	Power Demand(kw)
Coarse Fraction Removal	Slurry Pumping	3.2
Flow Equalization	Mixing	2.0
Flow Equalization	Transfer Pumping	10.0
Chem. Prep. and Feed	Mixing	0.1
Chem. Prep. and Feed	Chem. and Water Feed	0.7
Mixing, Clarification, and Thickening	Mixing	0.3
Mixing, Clarification, and Thickening	Sludge Pumping	0.8
Mixing, Clarification, and Thickening	Turbidity Measurement	0.1
Secondary Flow Equalization	Make-up Water Pumping	1.5
Subtotal		18.7
Misc.; 10% of subtotal		1.9
Total		20.6

Power Consumption - Projected electric power consumption values are presented in Table 5-46.

Table 5-46
Electric Power Consumption - Class C Liquid Processing Option

Process	Function	Power Consumption (kw-hr/shift)
Coarse Fraction Removal	Slurry Pumping; 3.2 kw @ 6 hr	19.2
Coarse Fraction Removal	Top Water Pumping; 0.5 kw @ 0.2 hr	0.1
Coarse Fraction Removal	Well Screen Pumping; 0.8 kw @ 2.0 hr	1.6
Coarse Fraction Removal	Hopper Vibration; 0.5 kw @ 0.5 hr	0.2
Flow Equalization	Mixing; 2.0 kw @ 6.0 hr	12.0
Flow Equalization	Transfer Pumping; 10.0 kw @ 6.0 hr	60.0
Init.Chem.Prep.and Feed	Chem. Mixing; 0.07 kw @ 6.0 hr	0.4
Init.Chem.Prep.and Feed	Chem. Feeding; 0.33 kw @ 6.0 hr	2.0
Init.Chem.Prep.and Feed	Dil. Water Feeding; 0.33 kw @ 6.0 hr	2.0
Mixing,Clarification, and Thickening	Mixing; 0.33 kw @ 6.0 hr	2.0
Mixing,Clarification, and Thickening	Sludge Pumping; 0.75 kw @ 6.0 hr	4.5
Mixing,Clarification, and Thickening	Turbidity Measurement; 0.06 kw @ 6.0 hr	0.4
Secondary Flow Equalization	Make-up Water Pumping; 1.5 kw @ 1.0 hr	1.5
Total		105.9

The "per shift" total above corresponds to a project total of 129200 kilowatt-hours.

Operating Man Power - The estimated labor breakdown for Class C system operation is presented in Table 5-47.

Table 5-47
Operating Man Power - Class C Liquid Processing Option

Process	Function	Req'd. Grade 1 Labor(hr/shift)	Req'd. Grade 2 Labor(hr/shift)
Coarse Fraction Removal	Directing Truck Traffic	-	0.6
Coarse Fraction Removal	Check Hopper Solids Level	-	0.5
Coarse Fraction Removal	Pump Top Water	-	0.5
Flow Equalization	Monitor Pumping Rate and Tank Level	1.0	-
Flow Equalization	Adjust Pumping Rate	0.5	-
Init.Chem.Prep. and Feed	Adjust Chem.Feed Rate	1.0	-
Init.Chem.Prep. and Feed	Prepare Chemical	0.3	-
Mixing,Clarification, and Thickening	Monitor Turbidity	0.5	-
Mixing,Clarification, and Thickening	Monitor Sludge Density and Pumping Rate	1.0	-
Secondary Flow Equalization	None	-	-
Total		4.3	1.6

The "per shift" values from Table 5-49 correspond to project totals of 5250 Grade 1 man-hours and 1950 Grade 2 man-hours.

Chemical Usage - Chemical coagulants would be utilized by the Class C system in the same proportions as for the initial coagulation process of the Class A system. Thus, a total usage of 760 gallons of Calgon Cat-Floc T is predicted for the Class C option.

Sludge Hauling - The sludge hauling system outlined in Chapter 4 would consist of a sealed semi-trailer, a sludge storage tank, and a sludge transfer pump (to transfer sludge from the storage tank to the trailer).

Equipment and Installation Costs - Tables 5-48 and 5-49 outline the equipment and installation costs for the sludge hauling system.

Table 5-48
Equipment Costs - Sludge Hauling

Component		Cost
Sludge Hauling Trailer (length - 19 ft., cap. 19 cu.yds.)	$	16700
Truck Accessories (power take-off, etc.)		1000
Tank (cap. 600 gal., 12 ga. const., w. 16 in. dia. manhole)		210
Sludge Transfer Pump (0.5 hp centrifugal sump type)		300
Level Controls		300
First Subtotal	$	18510
Misc.; 5% of first subtotal		930
Second Subtotal	$	19440
Sales Tax; 4% of second subtotal		780
Total	$	20220

Table 5-49
Set Up Costs - Sludge Hauling

Item		Cost
Tank Foundation; 0.4 cu.yd. @ $73/cu.yd.	$	30
Tank Installation		80
Sludge Transfer Piping (2 in. dia PVC), 70 ft. @ $5.40/ft. inst.)		380
Level Control Installation and Wiring		100
First Subtotal	$	590
Misc.; 5% of first subtotal		30
Second Subtotal	$	620
Sales Tax; 1% of second subtotal		10
Total	$	630

The above information indicates that an initial equipment and installation investment of about $20930 would be required.

System Salvage Values - The following gross salvage values are assumed for the sludge hauling system: trailer - $8350, sludge storage tank - $100, and total - $8450. Disassembly of the sludge haulage system would consist essentially of removal of the storage tank and other miscellaneous tasks. Costs for these items are estimated as $80 and $100 respectively for a total of $180. Thus, the system would have a net salvage value of $8270.

Maintenance Costs - Maintenance costs are projected as twenty percent of the original equipment cost or $4040.

Space Requirements - The sludge hauling system would require about 320 square feet of surface area for trailer parking and tank storage.

Power Demand - The sludge hauling system utilizes only one major component requiring electric power: a one-half kilowatt (0.5 horsepower) sludge transfer pump. In addition, a miscellaneous demand of one kilowatt is estimated to account for lighting, etc. Therefore, a total power demand of 1.5 kilowatts is projected.

Power Consumption - The electric power consumption of the sludge hauling system is negligible and will be ignored here.

Operating Man Power - Man power would be required for the transferring of the sludge flow from the storage tank to the trailer (and vice versa), monitoring sludge level in the storage tank, transferring stored sludge from the tank to the trailer, and other miscellaneous tasks. An average time requirement of 0.7 hours per day is projected which would correspond to approximately 250 hours for the entire project (Grade 2 labor).

Sludge Hauling - Laboratory studies indicate that sludge should be produced at a rate of about 2.5 gallons per minute (see Chapter 4). Thus, about 900 gallons or 4.1 tons of sludge would be produced per shift. (The weight value cited above was based on a unit sludge density of 68.6 pounds per cubic foot (specific gravity of sludge (1.1) multiplied by the density of water (62.4 pounds per square foot)). This value is somewhat higher than the actual density of a sludge containing ten percent solids by weight, but it constitutes a conservative assumption when figuring costs of sludge hauling.) The sludge trailer recommended above (see Table 5-50) has a volume of about nineteen cubic yards or 3850 gallons; so, a trailer-load of sludge would be generated about every four shifts. Over the duration of the project, about 275 loads would be hauled (based on 1100 shifts of actual excavation). Assuming an average haulage time of four hours per load, a total haulage time of 1100 hours is projected. (The reader should note that the above calculations for sludge haulage were based on a sludge production rate of 2.5 gallons per minute. As stated in Chapter 4, this may be a very optimistic assumption and actual sludge production rates may be several times larger.)

Centrifuge Sludge Dewatering - The centrifuge system of sludge dewatering would actually consist of a combination of the sludge conditioning and centrifuge-type mechanical dewatering processes described in Chapter 4.

Equipment and Installation Costs - Tables 5-50 through 5-53 present the equipment and installation costs for the sludge conditioning and centrifuge dewatering processes.

Table 5-50
Equipment Costs - Sludge Conditioning

Component		Cost
Dry Polymer Chem. Prep. and Feeding Unit (incl. dry feeder, wetting cones, dissolving tank, mixer, feed pump, and control panel)	$	5500 (8)
Water Supply Pump		500
Water Supply Tank (cap. 50 gal., poly. const.)		120
Float Valve		100
Rotameters; 2 @ $50 ea.		100
First Subtotal	$	6320
Misc.; 5% of first subtotal		320
Second Subtotal	$	6640
Sales Tax; 4% of second subtotal		270
Total	$	6910

Table 5-51
Set Up Costs - Sludge Conditioning

Item		Cost
Foundation; 0.6 cu.yd. conc. @ $73/cu.yd.	$	40
Install and Wire Prep. Unit		400
Install and Wire Water Supply Pump		200
Water Supply Piping (1.5 in. dia. PVC); 50 ft. @ $4.80/ft. inst.		240
Chem. and Dilution Water Feed Piping (0.5 in. dia. steel); 20 ft. @ $4.80/ft. inst.		100
Misc. Plumbing		70
First Subtotal	$	1050
Misc.; 5% of first subtotal		50
Second Subtotal	$	1100
Sales Tax; 1% of first subtotal		10
Total	$	1110

Table 5-52
Equipment Costs - Centrifuge Dewatering

Component		Cost
Solid Bowl Centrifuge (9 in. dia. bowl, cap. 10 gpm and 600 lbs./hr, stainless steel const.)	$	25000 (9)
Solids Conveyor (belt type, length - 10 ft., width - 12 in.)		780
First Subtotal	$	25780
Misc.; 5% of first subtotal		1290
Second Subtotal	$	27070
Sales Tax; 4% of second subtotal		1080
Total	$	28150

Table 5-53
Set Up Costs - Centrifuge Dewatering

Item		Cost
Foundation; 2.0 cu.yd. conc. @ $84/cu.yd.	$	170
Centrifuge and Conveyor Inst. (standard crew); 1 day @ $290/day		290
Crane Rental; 0.5 day @ $270/day		140
Inflow Piping (2 in. dia. PVC); 40 ft. @ $5.40/ft. inst.		220
Wire Centrifuge		200
Effluent Piping (2 in. dia. PVC); 100 ft. @ $5.40/ft. inst.		540
First Subtotal	$	1560
Misc.; 5% of first subtotal		80
Second Subtotal	$	1640
Sales Tax; 1% of second subtotal		20
Total	$	1660

The total equipment and installation costs for this system would be about $35060 and $2770 respectively.

System Salvage Values - Gross salvage values and disassembly costs for the centrifuge sludge dewatering system are presented in Tables 5-54 and 5-55.

Table 5-54
Gross Salvage Values - Centrifuge Sludge
Dewatering System

Process	Component	Original Cost	Salvage Value
Sludge Conditioning	Chem.Prep.and Feed Unit	$ 5500	$ 2750
Sludge Conditioning	Water Supply Pump	500	250
Mechanical Dewatering	Centrifuge	25000	12500
Mechanical Dewatering	Conveyor	780	390
Total			$ 15890

Table 5-55
Disassembly Costs - Centrifuge Sludge Dewatering System

Process	Item	Cost
Sludge Conditioning	Chem. Prep. Unit Disassembly	$ 200
Mechanical Dewatering	Centrifuge and Conveyor Disassembly Labor (standard crew); 1 day @ $290/day	290
Mechanical Dewatering	Crane Rental; 0.5 day @ $270/day	140
Both of Above	Found. Demo.; 2.6 cu.yd. @ $15/cu.yd.	40
Both of Above	Miscellaneous	200
Total		$ 870

Thus, the centrifuge sludge dewatering system has a predicted net salvage value of $15020.

Maintenance Costs - Maintenance costs for the sludge conditioning and dewatering equipment are respectively projected as twenty and thirty percent of the original equipment costs, or $1380 and $8440. (The higher fraction was utilized for dewatering equipment to reflect the increased "wear-and-tear" due to the high speed operation of the centrifuge.) Thus, a total maintenance cost of $9820 is projected.

Space Requirements - The entire centrifuge sludge dewatering system would require about 270 square feet of working area for the conditioning apparatus, centrifuge and solids conveyor installations, and dewatered solids storage.

Power Demand - Table 5-56 outlines the maximum sustained fifteen minute power demand for the centrifuge sludge dewatering system.

Table 5-56
Electric Power Demand - Centrifuge Sludge Dewatering System

Process	Function	Power Demand(kw)
Sludge Conditioning	Control Panel Operation	0.2
Sludge Conditioning	Dry Polymer Feeding	0.5
Sludge Conditioning	Mixing	0.1
Sludge Conditioning	Chem. and Water Feed	0.7
Centrifuge Dewatering	Centrifuge Motive Power	20.0
Centrifuge Dewatering	Solids Conveying	0.3
Subtotal		21.8
Misc.; 10% of subtotal		2.2
Total		24.0

Power Consumption - Projected "per shift" power consumption estimates are presented in Table 5-57.

Table 5-57
Electric Power Consumption - Centrifuge Sludge Dewatering System

Process	Function	Power Consumption (kw-hr/shift)
Sludge Conditioning	Control Panel; 0.2 kw @ 0.5 hr	0.1
Sludge Conditioning	Dry Polymer Feed; 0.5 kw @ 0.5 hr	0.2
Sludge Conditioning	Mixing; 0.07 kw @ 7 hr	0.5
Sludge Conditioning	Chem. Feed; 0.33 kw @ 6 hr	2.0
Sludge Conditioning	Dil. Water Feed; 0.33 kw @ 6 hr	2.0
Centrifuge Dewatering	Centrifuge Drive; 20.0 kw @ 6 hr	120.0
Centrifuge Dewatering	Solids Conveying; 0.33 kw @ 6 hr	2.0
Total		126.8

From the above value, a total electric power consumption of 155000 kilowatt-hours is projected.

Operating Man Power - The following "per shift" labor breakdown is projected for the centrifuge dewatering system: check and fill dry polymer storage bin - 0.2 hours of Grade 2 labor, general inspection and cleanup of chemical preparation equipment - 0.5 hours of Grade 1 labor, and general inspection of centrifuge performance - 1.0 hours of Grade 1 labor. Thus, total man power requirements of 1830 hours of Grade 1 labor and 240 hours of Grade 2 labor are predicted.

Chemical Usage - The discussion of sludge conditioning in Chapter 4 cited an optimum chemical dosage of 2.0 pounds of Calgon WT-3000 (anionic polyelectrolyte) per ton of dry solids treated. Furthermore, a solids flow rate of 130 pounds per hour or 0.4 tons per shift was also cited. Thus, over the course of the project, a total of about 440 tons of solids would be treated with about 880 pounds of chemical (based on 1100 shifts of actual excavation). This value is increased by ten percent (to 970 pounds) to compensate for losses.

Solids Loading and Hauling - Chapter 4 described the operation of the centrifuge system and stated that solids would be spilled onto the ground and occasionally loaded into dump trucks and hauled away with the coarse material. (Dewatered solids would accumulate at a rate of about 1.3 cubic yards per shift.) In most cases, some sort of a wheel loader would be utilized for the loading of these solids. Assuming that an average of 0.3 hours per shift was required to load this material, a project total of 330 hours of loader time would be accumulated (based on 1100 actual excavation shifts). Haulage volumes are considered to be negligible.

<u>Filtration Dewatering System</u> - The system considered here is a modular set up which includes dual cell gravity and belt press filters as well as the chemical conditioning apparatus.

Equipment and Installation Costs - Tables 5-58 and 5-59 summarize equipment and installation costs for the filtration sludge dewatering system.

Table 5-58
Equipment Costs - Filtration Dewatering System

Component	Cost
Filtration Unit (incl. dual cell gravity and belt press filters, chemical conditioning apparatus, sludge pump, internal conveyors, piping, and control panel, cap. 10 gpm)	$ 60000 (10)
Solids Conveyor (belt type, length - 10 ft., width - 12 in.)	780
Sludge Storage Tank (cap. 30 gal., poly. const.)	100
Filtrate Storage Tank (cap. 30 gal., poly. const.)	100
Filtrate Pump (submersible sump type)	60
First Subtotal	$ 61040
Misc.; 5% of first subtotal	3050
Second Subtotal	$ 64090
Sales Tax; 4% of second subtotal	2560
Total	$ 66650

Table 5-59
Set Up Costs - Filtration Dewatering System

Item	Cost
Foundation; 4.9 cu.yd. conc. @ $73/cu.yd.	$ 360
Equipment Installation	400
Inflow Piping (2 in. dia. PVC); 20 ft. @ $5.40/ft. inst.	110
Effluent Piping (2 in. dia. PVC); 100 ft. @ $5.40/ft. inst.	540
System Wiring	300
First Subtotal	$ 1710
Misc.; 5% of first subtotal	90
Second Subtotal	$ 1800
Sales Tax; 1% of second subtotal	20
Total	$ 1820

From the above information, a total equipment and installation investment of $68470 would be required.

Salvage Values - The following gross salvage values are assumed for the filtration sludge dewatering system: conditioning and filtration unit - $30000, conveyor - $390, and total - $30390. The disassembly costs are estimated as follows: filtration unit and conveyor disassembly - $400, foundation demolition (4.9 cubic yards at $15 per cubic yard) - $70, miscellaneous - $200, and total - $670. Thus, the system has a net salvage value of $29720.

Maintenance Costs - Maintenance costs for the filtration system are projected as twenty percent of the original equipment cost or $13330.

Space Requirements - This system would require about 550 square feet of surface area for the conditioning apparatus, filters, conveyors, and solids storage.

Power Demand - The filtration sludge dewatering system would have the following electric power demands: sludge conditioning and filtration apparatus - 5.0 kilowatts, solids conveying - 0.3 kilowatts, and filtrate pumping - 0.3 kilowatts. Assuming an additional ten percent demand for lighting and other miscellaneous applications, the filtration system would have a maximum power demand of about 6.2 kilowatts.

Power Consumption - The following power consumption breakdown is estimated for the system: filtration unit - 5.0 kilowatts for six hours or 30.0 kilowatt-hours, solids conveying - 0.33 kilowatts for six hours or 2.0 kilowatt-hours, and filtrate pumping - 0.33 kilowatts for one hour or 0.3 kilowatt-hours. Thus, the average power consumption would be about 32.3 kilowatt-hours per shift and the total for the project would be about 39400 kilowatt-hours.

Operating Man Power - The following "per shift" labor breakdown is projected for the filtration sludge dewatering system operation: check and fill dry polymer storage bin - 0.2 hours of Grade 2 labor, general inspection and cleanup of the chemical preparation equipment - 0.5 hours of Grade 1 labor, and general inspection of filter performance - 1.0 hours of Grade 1 labor. Thus, about 1.5 hours of Grade 1 and 0.2 hours of Grade 2 labor would be required per shift; these values correspond to project totals of 1830 and 240 hours respectively.

Chemical Usage - The total chemical usage calculated for the centrifuge system is also assumed for the filtration system. Thus, a usage of 970 pounds of Calgon WT-3000 is predicted.

Solids Loading and Hauling - A total of 330 hours of solids loading time was predicted for the centrifuge sludge dewatering system; this value is also assumed for the filtration system. Additional solids haulage volume is again considered to be negligible.

Economic Analysis of Complete Treatment Systems

All of the individual liquid processing and sludge treatment and/or handling systems have now been analyzed. This section will combine the various analyses to determine the costs of several complete treatment systems. The discussion below will consider all of the following capital cost items: equipment costs, installation costs, net salvage values, engineering costs, temporary construction costs, contingency costs, other miscellaneous capital expenses, and interest accrued on the initial investment. Operating costs to be considered include: maintenance costs, insurance costs, control room costs, electric power demand costs, electric power consumption costs, operating man power costs, winter heating costs, chemical costs, and any other miscellaneous operating expenses. Before beginning the analyses of the complete treatment systems, various assumptions will be discussed.

Miscellaneous Assumptions - Engineering cost for the required treatment system structural or hydraulic design is assumed to equal about five percent of the original equipment and installation costs.

Temporary construction would be required to provide the treatment system components with at least minimal protection from the "outside" environment. The various temporary construction items and installed unit costs include: framing and sheathing of basic structures (two-by-four framing and three-quarter inch thick sheathing) - \$1.00 per square foot of required wall and roof area, temporary structure footings (concrete, eighteen inches wide by twelve inches deep) - \$4.70 per lineal foot, roofing (fifty-five pound felt) - \$16 per square (100 square feet), temporary lighting - \$0.06 per square foot of surface area, frame doors (three foot by seven foot) - \$220 each, and overhead doors (ten foot by ten foot) -

$560 each. Furthermore, a temporary structure's gross salvage value and disassembly costs are assumed to be equal; so, the structure has no net salvage value.

A contingency cost is included to account for errors and oversights in original estimates and unforeseen fluctuations in prices. The contingency cost is assumed to equal ten percent of the original equipment and installation costs.

The assumption is made that the contractor borrows all of the required capital for the assemblage of the treatment system at an interest rate of one percent per month and repays the loan in eighteen equal payments over the duration of the project. Furthermore, the contractor is assumed to receive the net salvage value of the system twenty-four months after the original investment or approximately six months after completion of the tunnel excavation phase. Thus, the net capital cost of the treatment system chargeable to the project is the difference of the total capital cost (one individual monthly payment multiplied by eighteen months) and the "present worth" of the net salvage at the time of the original investment.

One final comment should be made concerning treatment system capital costs. The assumption is made in the cost estimates below that the waste treatment system would be set up on a single site location and would remain there for the duration of the project. (Normal practice is to move the separation process at least once during the project to reduce slurry pumping expenses.) Although no consideration is given here to the economics of moving the treatment system versus paying the higher pumping costs, such a study should be undertaken if a hydraulic tunneling wastewater treatment program is implemented.

Table 5-60 presents the electric power demand rate schedule.

Table 5-60
Monthly Electric Power Demand Charge Rates (11)

Demand	October-to-May Rate	June-to-September Rate
First 10 kw	$2.50	$2.50
Excess kw	$2.78/kw	$3.23/kw

Table 5-60 indicates that the "first" ten kilowatts of power demand are assessed at a total cost of $2.50 per month while excess demands are assessed at a "per kilowatt" monthly charge. The entire tunneling operation including the treatment system would probably draw many times the ten kilowatt figure. Thus, the treatment system power demands are considered as "excess kilowatts" and monthly costs are figured accordingly. Furthermore, eleven October-to-May months and eight June-to-September months are assumed for the calculation of total electric power demand costs.

Table 5-61 presents the rate schedule for electric power consumption (11).

Table 5-61
Monthly Electric Power Consumption Charge Rates (11)

Consumption	October-to-May Rate	June-to-September
First 500 kw-hr	$0.055/kw-hr	$0.055/kw-hr
Next 500 kw-hr	$0.045/kw-hr	$0.045/kw-hr
Next 1000 kw-hr	$0.031/kw-hr	$0.036/kw-hr
Excess kw-hr	$0.018/kw-hr	$0.036/kw-hr

A hydraulic tunneling operation would generally consume much more than 2000 kilowatt-hours of electric energy per month; so, consumption costs will be calculated using the "excess kw-hr" rate. Again, eleven October-to-May and eight June-to-September months are assumed for the project.

The following wage rates are assumed for operating man power (including fringe benefits): Grade 1 labor - $10.00 per hour and Grade 2 labor - $9.40 per hour. Although these wage rates may seem somewhat low for the construction industry, they are the approximate rates currently paid by the City of Minneapolis for equipment operators and laborers (12).

Three chemical types would be extensively utilized by the wastewater treatment systems. Two of these, Calgon Cat-Floc T and WT-3000, are organic polyelectrolytes and have unit costs of $3.60 per gallon and $2.10 per pound, respectively (8). The third chemical, concentrated sulfuric acid, is assumed to have a unit cost of $0.40 per gallon.

Insurance costs are assumed to be assessed at a rate of one percent of the total equipment cost per year (13).

Some sort of a structure would be required to house the operator controls and monitoring read-out devices; the assumption is made that a standard office trailer would be rented and used for this purpose. A monthly rental rate of $150 is used for calculation purposes (13). Costs of control installation and wiring are reflected in installation costs for the individual processes.

Heating costs for temporary structures are figured on an area basis; a unit rate of $0.30 per square foot of structure area per week is assumed (13). A total of seventeen weeks of heating is estimated for the project (mid-November of the first year to mid-March of the second year).

Other assumptions are made in the text, but will be discussed as they are encountered.

Option 1 Systems These systems are combinations of the Class A liquid processing option and the various sludge handling and/or treatment systems. Thus, they produce an effluent of a quality which is adequate for disposal in public waters. Before beginning the actual analysis, however, the Class A systems utilizing microstrainer and pressure filtration will be compared.

Comparison of Class A Systems - Table 5-62 presents the various costs for the Class A system utilizing the microstrainer and pressure filtration of effluent.

Table 5-62
Cost Comparison of Class A Systems

Item	Class A System w. Microstrainer Filtration	Class A System w. Pressure Filtration
Equipment *	$125270	$ 96580
Installation *	11520	10720
Maintenance *	20700	15000
Engineering *!	7000	5000
Contingency *!	14000	11000
Power Demand *!	1440	2880
Power Consumption *!	4360	7510
Man Power (Grade 1) *!	89000	89000
Man Power (Grade 2) *!	18710	24060
Insurance !	1940	1500
Total	$293940	$263250

* see Class A system discussion

! see Miscellaneous Assumptions above

Other costs, such as those for chemical usage and temporary construction, should be about equal for both systems. The following net salvage values were determined: the Class A system with microstrainer filtration of effluent - $47170 and the Class A system with pressure filtration of effluent - $34230. Thus, the two systems would have costs to the project of about $247000 and $229000 respectively; the Class A system utilizing microstrainer filtration would be substantially more expensive than the equivalent system with pressure filtration of effluent. This fact, combined with the microstrainer's questionable ability to filter hydraulic tunneling wastes, should eliminate the first system from consideration.

Option 1a System - This system combines the Class A liquid processing option and the sludge hauling/land-fill disposal alternative. Basic capital costs for the system would include: equipment, installation, engineering, temporary construction, and contingency costs. Computation of all the above is fairly direct with the exception of temporary construction costs which are computed as follows. The Option 1a system would require about 1240 square feet of surface area (920 square feet for liquid processing components and 320 square feet for sludge hauling equipment). The majority of the system components could be housed in a single twelve foot high shed while the sedimentation hopper and Lamella settler would be housed individually. Area requirements for the hopper and Lamella settler are 380 and 110 square feet, respectively; so, the remainder of the system requires about 750 square feet. This value is increased by twenty percent to account for inefficient use of space, bringing the total projected floor area to 900 square feet. Thus, the following building dimensions are assumed: length - thirty feet, width - thirty feet, height - twelve feet. This building would have a total roof and wall area of about 2460 square feet, and a corresponding framing and sheathing cost of about $2460. Other cost items would include: 120 lineal feet of footing - $560, 10.2 squares of roofing felt - $160, temporary lighting for 900 square feet - $50, two frame doors - $440, and one overhead door - $560. Thus, the total cost of this structure would be about $4230.

The hopper structure would have the following approximate dimensions: length - twenty-seven feet, width - fourteen feet, height - twenty-four feet. The total wall and roof area of the structure would be about 2430 square feet which has a framing and sheathing cost of about $2430. Other cost items include: eighty-two lineal feet of footing - $390, 4.6 squares of roofing felt - $70, lighting for 378 square feet - $20, one frame door - $220, and two overhead doors - $1120. Thus, temporary construction for the sedimentation hopper would cost about $4250.

The Lamella settler shelter would have the following approximate dimensions: length - seventeen feet, width - six feet, height - nineteen feet. Required roof and wall area would total about 1030 square feet, with a corresponding framing and sheathing cost of $1030. Other cost items include: 46 lineal feet of footings - $220, 1.5 squares of roofing - $20, lighting for 102 square feet - $10, and one frame door - $220. Thus, the total cost of the Lamella settler structure would be about $1500. The total cost of all three temporary structures would be about $9980.

Table 5-63 summarizes the capital costs for the Option 1a system.

Table 5-63
Capital Costs - Option 1a System

Item	Liquid Processing Costs	Sludge Hauling Costs	Total Costs
Equipment	$ 96580	$ 20300	$ 116880
Installation	10780	630	11410
Engineering	-	-	6000
Temporary Construction	-	-	9980
Contingency	-	-	13000
Total			$157270

Individual payments on a loan of the required capital could be computed by the following equation (14):

$$MP = ILA \left(\frac{i(1+i)^n}{(1+i)^n - 1}\right)$$

where: MP = monthly payment (dollars)

ILA = initial loan amount (dollars)

i = interest rate per period (dimensionless)

n = number of interest periods (dimensionless)

Assuming an interest rate of one percent per month and a total of eighteen months to repay the loan, individual payments would amount to about $9600. Thus, over the duration of the project, a total of $172800 would be repaid on the loan.

The treatment system has a projected net salvage value of $42500 ($34230 and $8270 for liquid processing and sludge hauling equipment, respectively). The "present worth" of this salvage value at the time of initial investment may be computed by the following formula (14):

$$PW = \frac{NSV}{(1+i)^n}$$

where: PW = present worth of net salvage value (dollars)

NSV = net salvage value (dollars)

i = interest rate (dimensionless)

n = number of interest periods "between" PW and NSV

Assuming an interest rate of one percent and twenty-four months from the time of purchase to resale, the system would have a "present worth" of \$33470. The net capital cost of the treatment system chargeable to the project is the difference of the total loan payment (\$172800) and the "present worth" of the net salvage value (\$33470), or \$139330.

Operating costs for the Option 1a system would include: maintenance, electric power demand, electric power consumption, operating man power, chemical, insurance, control room, heating, sludge hauling, and land-fill disposal costs.

Maintenance costs are projected as about \$19050 (\$15000 and \$4050 respectively for Class A and sludge hauling equipment).

The Option 1a system has a maximum electric power demand of 52.5 kilowatts (51.0 and 1.5 kilowatts respectively for the liquid processing and sludge hauling systems). Thus, October-to-May and June-to-September monthly charges would be about \$146 and \$170 respectively, and a total cost of approximately \$2970 would be incurred.

The liquid processing system would consume about 295000 kilowatt-hours of electric power over the duration of the project while power consumption by the sludge hauling system would be negligible. Thus, a total power consumption cost of \$7540 is projected (171000 kilowatt-hours at \$0.018 per kilowatt-hour and 124000 kilowatt-hours at \$0.036 per kilowatt-hour).

Projected operating man power requirements are: Grade 1 labor - 8900 hours (for operation of the liquid processing equipment) and Grade 2 labor - 2810 hours (2560 hours for the liquid processing operations and 250 hours for sludge hauling operations). Thus, a total man power cost of \$115410 is estimated (\$89000 for Grade 1 labor and \$26410 for Grade 2 labor).

The following chemical usages are predicted for the system: Calgon Cat-Floc T - 840 gallons and concentrated sulfuric acid - 5300 gallons. From these figures, a total chemical cost of \$5140 is projected (\$3020 for Cat-Floc T and \$2120 for sulfuric acid).

Insurance costs would be assessed at a rate of about \$1170 per year (one percent of the equipment cost) which would amount to about $1810 for the entire project (1.55 years).

Control room costs should total about $2790 (18.6 months at $150 per month).

The three temporary structures described above have a combined area of 1380 square feet; consequently, winter heating costs should total about $7040 ($0.30 per square foot per week multiplied by 1380 square feet and seventeen weeks).

Sludge hauling expenses would consist of the rental and operating costs of an "over-the-road" tractor to transport the sludge trailer to a suitable disposal site and back again. A unit cost of $21 per hour is utilized here (including: tractor rental - $6 per hour, operator cost - $12 per hour, and fuel - $3 per hour(13)). A total haulage time of 1100 hours was cited above; thus, a total sludge hauling cost of $23100 is predicted.

Sludge produced by the Option 1a system would not, in most cases, be suitable as fill material and would probably be disposed of in a sanitary land-fill. Unit costs for land-fill disposal would probably be on the order of $4.25 per ton (15), and an estimated 4840 tons would be produced over the duration of the project (68.6 pounds per cubic foot multiplied by 27 cubic feet per cubic yard multiplied by nineteen cubic yards per load multiplied by 275 loads divided by 2000 pounds per ton). Thus, a total land-fill disposal cost of about $20570 would be incurred.

All foreseeable operating costs for the Option 1a system have now been determined and are summarized in Table 5-64.

Table 5-64
Operating Costs - Option 1a System

Item	Cost
Maintenance	$ 19050
Electric Power Demand	2970
Electric Power Consumption	7540
Operating Man Power	115410
Chemical	5140
Insurance	1810
Control Room	2790
Winter Heating	7040
Sludge Hauling	23100
Land-fill Disposal	20570
Total	$ 205420

The total of the capital and operating costs of the Option 1a system chargeable to the hypothetical project is about $344750 ($139330 in capital costs and $205420 in operating costs). This value corresponds to the following unit costs: $33 per lineal foot of tunnel or $10 per cubic yard of excavation.

Option 1b System - This system utilizes Class A liquid processing and centrifuge-type sludge dewatering equipment. Capital costs for the system would include: equipment, installation, engineering, temporary construction, and contingency costs. As in the previous discussion, only temporary construction costs will be discussed in detail since the determination of other costs is very direct.

The Option 1b system, like the previous system, would require three temporary structures: the sedimentation hopper and Lamella settler shelters plus a third structure to house the remaining system components. The first two structures would be identical to those previously discussed while the third would require about 700 square feet of working area (system total of 1190 square feet minus 380 and 110 square feet respectively for the sedimentation hopper and Lamella settler); this value is increased by twenty percent to compensate for inefficient use of space bringing the total required structure area to 840 square feet. Thus, the following dimensions are proposed: length - twenty-nine feet, width - twenty-nine feet, and height - twelve feet. Total wall and roof area would be about 2350 square feet and a framing and sheathing cost of $2350 is estimated. Other cost items include: 116 lineal feet of footings - $550, 9.6 squares of roofing - $150, lighting for 840 square feet - $50, two frame doors - $440, and one overhead door - $560. Thus, the cost of this structure would be about $4100, and the total cost of all three required structures would be about $9850.

Capital costs for the Option 1b system are presented in Table 5-65.

Table 5-65
Capital Costs - Option 1b System

Item	Liquid Processing Costs	Sludge Dewatering Costs	Total Costs
Equipment	$ 96580	$ 35060	$ 131640
Installation	10780	2770	13550
Engineering	-	-	7000
Temporary Construction	-	-	9850
Contingency	-	-	15000
Total			$ 177040

Monthly payments on a loan of the total capital cost shown in Table 5-65 would equal about $10800, and the total repayment on the loan would amount to about $194400. The system has a projected net salvage value of $49250 ($34230 and $15020 respectively for liquid processing and sludge dewatering equipment); the "present worth" of this salvage value at the time of the initial investment would be about $38790. Thus, the net capital cost of the Option 1b system is about $155610.

Operating costs for the Option 1b system would include all of the following: maintenance, electric power demand, electric power consumption, operating man power, chemical, insurance, control room, winter heating, and solids loading costs.

Maintenance costs would total about $24820 ($15000 and $9820 respectively for the liquid processing and sludge dewatering equipment).

The Option 1b system would have a maximum electric power demand of 75.0 kilowatts (51.0 and 24.0 kilowatts respectively for the liquid processing and sludge dewatering equipment). Thus, October-to-May and June-to-September monthly rates of $208 and $242 are projected. These values correspond to a total power demand charge of $4220.

A total electric power consumption of 450000 kilowatt-hours is projected (295000 and 155000 kilowatt-hours respectively for liquid processing and sludge dewatering equipment). Furthermore, this total corresponds to October-to-May and June-to-September usages of 260500 and 189500 kilowatt-hours, respectively. Thus, a total power consumption cost of $11510 is estimated ($4690 for all October-to-May months and $6820 for all June-to-September months).

The system would have the following man power breakdown: Grade 1 labor - 10730 hours (8900 and 1830 hours respectively for liquid processing and sludge dewatering system operations) and Grade 2 labor - 2800 hours (2560 and 240 hours respectively for liquid processing and sludge dewatering system operations). Thus, the total cost of operating man power would be about $133620 ($107300 for Grade 1 labor and $26320 for Grade 2 labor).

The Option 1b system would use the same quantities of Calgon Cat-Floc T (840 gallons at a total cost of $3020) and concentrated sulfuric acid (5300 gallons at a total cost of $2120) as the previous system. In addition, the system would utilize about 880 pounds of Calgon WT-3000 at a total cost of $1850. Thus, total chemical costs for the entire operation would be about $6990.

Insurance premiums would total about $1320 per year or $2050 for the entire project.

Control room costs would be identical to those for the previous system, or about $2790.

The temporary structures described above encloses a combined surface area of about 1330 square feet. Thus, a total heating cost of about $6780 is projected ($0.30 per square foot per week multiplied by 1330 square feet and seventeen weeks).

A value of 330 hours of wheel loader time was cited earlier in this chapter as being required for the loading of dewatered solids into trucks for their transport to a final disposal site. Unit costs for loader operation are estimated as about $22 per hour (13) (loader rental - $9 per hour, operator wages - $10 per hour, and fuel - $3 per hour).

Thus, a total solids loading cost of $7260 is projected.

Operating costs for the Option 1b system are summarized in Table 5-66.

Table 5-66
Operating Costs - Option 1b System

Item	Cost
Maintenance	$ 24820
Electric Power Demand	4220
Electric Power Consumption	11510
Operating Man Power	133620
Chemical	6990
Insurance	2050
Control Room	2790
Winter Heating	6780
Solids Loading	7260
Total	$ 200040

The total cost of the Option 1b system chargeable to the hypothetical tunneling operation is about $355650 ($155610 in capital costs and $200040 in operating costs). This value corresponds to the following unit costs: $34 per lineal foot of tunnel and $11 per cubic yard of excavation.

Option 1c System - This system combines the Class A liquid processing option and the filtration - type sludge dewatering alternative. Capital costs would include: equipment, installation, engineering, temporary construction, and contingency costs. As in the previous discussions, only temporary construction costs will be considered in detail here.

Temporary shelters would be required for the sedimentation hopper, the Lamella settler, and the remaining system components. The third structure would have an enclosed area of about 980 square feet (total required area (1470 square feet) minus hopper and Lamella settler areas (380 and 110 square feet respectively); the difference multiplied by a factor of 1.2). Thus, the following dimensions are assumed for the structure: length - thirty-one feet, width - thirty-one feet, and height - twelve feet. The total wall and roof area for the structure would be about 2580 square feet incurring a framing and sheathing cost of $2580.

Additional cost items include: 124 lineal feet of footing - $580, 10.9 squares of roofing - $170, lighting for 961 square feet - $60, two frame doors - $440, and one overhead door - $560. Thus, the structure has an estimated cost of $4390. The combined cost of all three temporary structures would be about $10140.

Table 5-67 presents all capital costs for the system.

Table 5-67
Capital Costs - Option 1c System

Item	Liquid Processing Costs	Sludge Dewatering Costs	Total Costs
Equipment	$ 96580	$ 66650	$ 163230
Installation	10780	1820	12600
Engineering	-	-	9000
Temporary Construction	-	-	10140
Contingency	-	-	18000
Total			$ 212970

Monthly payments on a loan of the required capital would be about $12990, and the total repayment would amount to about $233820. The net salvage value of the system would be about $63950 ($34230 and $29720 respectively for liquid processing and sludge dewatering equipment) which would have a "present worth" at the time of initial investment of $50360. Thus, the system would have a net capital cost to the project of about $162610.

Operating costs for the Option 1c system would include all of the following: maintenance, electric power demand, electric power consumption, operating man power, chemical, insurance, control room, winter heating, and solids loading costs.

Total projected maintenance costs for the Option 1c system are about $28330 ($15000 and $13330 respectively for the liquid processing and sludge dewatering systems).

A maximum electric power demand of 57.2 kilowatts is projected for Option 1c (51.0 and 6.2 kilowatts respectively for liquid processing and sludge dewatering equipment). Thus, rates of $159 for October-to-May months and $185 for June-to-September months are predicted. These values correspond to a total power demand cost of $3230.

A total electric power consumption of 210400 kilowatt-hours is estimated (171000 and 39400 kilowatt-hours respectively for liquid processing and sludge dewatering systems). Of this total, about 121800 kilowatt-hours would be consumed in October-to-May months and the remaining 88600 kilowatt-hours in June-to-September months. The projected total cost for electric power consumption is about $5380 ($2190 and $3190 respectively for October-to-May and June-to-September months).

Insurance premiums are estimated as about $1630 per year or $2530 for the entire project.

The total area of the three temporary structures described above is about 1450 square feet. Thus, a total winter heating cost of about $7400 is predicted ($0.30 per square foot per week multiplied by 1450 square feet and seventeen weeks).

Additional operating costs, including those for operating man power, chemicals, control room space, and solids loading should be approximately equal to those determined for the Option 1b system.

Table 5-68 summarizes the operating costs of the Option 1c system.

Table 5-68
Operating Costs - Option 1c System

Item	Cost
Maintenance	$ 28330
Electric Power Demand	3230
Electric Power Consumption	5380
Operating Man Power	133620
Chemical	6990
Insurance	2530
Control Room	2790
Winter Heating	7400
Solids Loading	7260
Total	$ 197530

The total cost of the Option 1c system chargeable to the hypothetical project is about $360140 ($162610 in capital costs and $197530 in operating costs). This value corresponds to the following unit costs: $34 per lineal foot of tunnel and $11 per cubic yard of excavation.

Option 2 System - This system pretreats hydraulic tunneling wastewater for discharge into the sanitary sewer. Thus, unlike the other complete systems, Option 2 utilizes no sludge treatment processes and the equipment layout is essentially that of the Class B liquid processing option. Basic processes include: coarse fraction removal, pH adjustment, and discharge monitoring.

Capital costs of the Option 2 system would include: equipment, installation, temporary construction, sewer hookup, and contingency costs. Of these, only temporary construction and sewer hookup costs will be considered in detail.

Two temporary structures would be required for the Option 2 system: one housing the sedimentation hopper and the other sheltering the pH adjustment system. The cost of the hopper structure was computed earlier as $4250. The pH adjustment system would require a shed of approximately the following dimensions: length - ten feet, width - eight feet, and height - ten feet. Thus, a total roof and wall area of about 480 square feet would be required and a corresponding framing and sheathing cost of $480 is estimated. Other cost items would include: thirty-six lineal feet of footing - $170, 0.9 squares of roofing felt - $10, lighting for eighty square feet - $10, and two frame doors - $440. The cost for the pH adjustment shed would be about $1110, and the total cost for the Option 2 temporary structures would be about $5360.

Chapter 3, in discussing the disposal of hydraulic tunneling wastewater into the sanitary sewer, stated that a user (of the MWCC sewer systems) would be assessed a charge at the time of hookup to the sewer. This "Service Availability Charge" would be computed by the following formula:

SAC Charge = (Q day/274 gallons) x $350
where: Q day = total volume of wastewater discharged to the sewer per day (gallons)

Assuming an average flow rate from the tunneling operation of 170 gallons per minute, the average daily flow volume to the sewer would be about 184000 gallons (170 gallons per minute multiplied by sixty minutes per hour multiplied by six hours per shift multiplied by three shifts per day). Thus, the tunneling operation would be assessed a connection charge of about $235000.

(As previously stated, this sum may be negotiable.)

Table 5-69 summarizes capital expenses for the Option 2 system.

Table 5-69
Capital Costs - Option 2 System

Item	Cost
Equipment	$ 23800
Installation	3710
Engineering	2000
Temporary Construction	5380
Sewer Hookup	235000
Contingency	5000
Total	$ 274870

Individual monthly payments on a loan of the required capital would be about $16770. Over the duration of the project, a total of $301860 would be repaid. After completion of the hypothetical project, the Option 2 system would have a net salvage value of $7630; the "present worth" of this amount at the time of the initial investment would be about $6010. Thus, the net capital cost of the treatment system chargeable to the hypothetical project is estimated as about $295850.

Operating costs for the Option 2 system would include: maintenance, electric power demand, electric power consumption, operating man power, chemical, insurance, control room, heating, volumetric wastewater discharge, and high strength wastewater discharge costs.

A total maintenance cost of $3870 is projected for the Option 2 system.

A maximum electric power demand of 5.9 kilowatts is estimated. This figure corresponds to rates of $16 and $19 respectively for October-to-May and June-to-September months. A total cost of $330 is predicted for power demand.

A total electric power consumption of 41000 kilowatt-hours is anticipated for which the following usage breakdown is assumed: October-to-May months - 23800 kilowatt - hours and June-to-September months - 17200 kilowatt - hours. From these values, a total cost of $1050 is predicted ($430 and $620 respectively for October-to-May and June-to-September months).

Operation of the Option 2 system would require about 2070 and 1990 hours respectively of Grade 1 and 2 labor. Thus, a total man power cost of $39410 is estimated ($20700 for Grade 1 labor and $18710 for Grade 2 labor).

The Option 2 system would use approximately the same amount of reagent (sulfuric acid) as the previous systems. Thus, a total chemical cost of $2120 is projected.

Insurance premiums would be assessed at a rate of about $240 per year which for the entire project would total about $370.

The assumption was made for the Option 1 systems that an office trailer would be rented and used as a control room at a total cost to the project of $2790. The Option 2 system, while necessitating the use of some control room area, would certainly not require an entire office trailer. Thus, half of the trailer could be used for system control and the other half used for various other purposes. The control room charges for the Option 2 system are projected as one half of the previous cost, or $1400.

Temporary structures for this system have a total enclosed surface area of about 460 square feet. Thus, a total winter heating cost of $2450 is estimated ($0.30 per square foot per week multiplied by 480 square feet and seventeen weeks).

Chapter 3 discussed charges assessed on the basis of volume of wastewater discharged to the sewer and charges based on the concentration of pollutants in the waste stream. Volumetric charges are assessed at a unit rate of about $350 per million gallons discharged. Thus, assuming that approximately sixty-seven million gallons of wastewater were discharged over the course of the tunneling operation (170 gallons per minute multiplied by sixty minutes per hour multiplied by six hours per shift multiplied by 1100 shifts of actual excavation), a total volumetric charge of about $23450 would be assessed.

High strength wastewater charges are computed as described below. First, a Strength Charge Factor is calculated and multiplied by the basic unit cost for "high strength" wastewater ($140.60 per million gallons). This adjusted unit cost is in turn multiplied by the volume of high strength wastewater (in millions of gallons) to determine the high strength surcharge.

The Strength Charge Factor is determined by the following formula:

$$SCF = 0.60 \left(\frac{0.50(SS-317)}{317} + \frac{0.50\ (COD-684)}{684} \right)$$

where:

SCF = Strength Charge factor (dimensionless multiplier)

SS = suspended solids concentration (milligrams per liter)
COD = chemical oxygen demand (milligrams per liter)
Operating costs of the Option 2 system are presented in Table 5-70.

Table 5-70
Operating Costs - Option 2 System

Item	Cost
Maintenance	$ 3870
Electric Power Demand	330
Electric Power Consumption	1050
Operating Man Power	39410
Chemical	2120
Insurance	370
Control Room	1400
Winter Heating	2450
Volumetric Wastewater Discharge	23450
High Strength Wastewater Discharge	10360
Total	$ 84810

The total costs of the Option 2 system chargeable to the hypothetical tunneling operation would be about $359680 (capital costs of $274870 and operating costs of $84810). Corresponding unit costs are: $34 per lineal foot of tunnel and $11 per cubic yard of excavation.

Option 3 Systems These systems are combinations of the Class C liquid processing option and the various sludge treatment and/or handling systems. Thus, the systems produce effluent of a quality which is adequate for re-use in the tunneling operation.

Option 3a System - This system consists of the Class C processes and the sludge hauling/land-fill disposal alternative. Capital costs for the system include: equipment, installation, engineering, temporary construction, and contingency costs.

As with the various Option 1 systems, three temporary shelters would be required for the Option 1 system: one to house the sedimentation hopper, one for the Lamella settler, and one for the remaining system components. The third shelter would have a total enclosed area of about 640 square feet (Option 3a total (1020 square feet) minus sedimentation hopper and Lamella settler areas (380 and 110 square feet, respectively); the entire quantity multiplied by a factor of 1.2). Thus, the following dimensions are assumed: length - twenty-five feet, width - twenty-five feet, and height - twelve feet. Thus, the structure would have a total roof and wall area of about 1930 square feet and a framing and sheathing cost of about $1930. Other cost items would include: 100 lineal feet of footings - $470, 7.3 squares of roofing - $120, lighting for 625 square feet - $40, two frame doors - $440, and one overhead door - $560. The cost of the completed structure would be about $3560. The total cost of all three structures would be approximately $9310.

Captial costs of the Option 3a system are presented in Table 5-71.

Table 5-71
Capital Costs - Option 3a System

Item	Liquid Processing Costs	Sludge Dewatering Costs	Total Costs
Equipment	$ 72600	$ 20300	$ 92900
Installation	7660	630	8290
Engineering	-	-	5000
Temporary Construction	-	-	9310
Contingency	-	-	10000
Total			$ 125500

Monthly payments on a loan of the required capital would be about $7660. Over the duration of the project, these payments would total about $137880. The system has a projected net salvage value of about $35070 ($26800 and $8270 for liquid processing and sludge hauling equipment). At the time of initial investment, this salvage value would have a "present worth" of about $27620. Thus, the net capital cost of the treatment system chargeable to the hypothetical tunneling operation is about $110260.

Operating costs for the Option 3a system would include the following: maintenance, electric power consumption, operating man power, chemical, insurance, control room, winter heating, sludge hauling, and land-fill disposal costs.

Maintenance costs for the Option 3a system would be approximately $13330 ($9280 and $4050 respectively for liquid processing and sludge hauling equipment).

A maximum electric power demand of 22.1 kilowatts is projected for the Option 3a system (20.6 and 1.5 kilowatts respectively for liquid processing and sludge hauling equipment). From this value the following monthly rates are predicted: October-to-May months - $61 and June-to-September months - $71. Thus, a total cost of $1240 is estimated.

The total electric power consumption for the project should be about 129200 kilowatt-hours. Of this total, 74800 kilowatt-hours would be utilized in October-to-May months and the remaining 54400 kilowatt-hours would be consumed in June-to-September months. These values correspond to a total cost of $3310 ($1350 and $1960 respectively for liquid processing and sludge hauling systems).

The following labor requirements are projected: Grade 1 labor - 5250 hours (for operation of the liquid processing equipment) and Grade 2 labor - 2200 hours (1950 and 250 hours respectively for liquid processing and sludge hauling equipment). Thus, a total labor cost of $73180 is estimated ($52500 and $20680 respectively for Grade 1 and 2 labor).

The Option 3a system would use about 760 gallons of Calgon Cat-Floc T over the duration of the project (the same amount as would be utilized by the initial coagulation process of the Option 1 systems). Thus, a total chemical cost of $2740 is anticipated.

Insurance premiums would total about $930 per year or $1440 for the entire project.

Total enclosed surface area of the three temporary structures described above is about 1115 square feet. Thus, a total heating cost of $5690 is projected ($0.30 per square foot per week multiplied by 1115 square feet and seventeen weeks).

Other Option 3a operating costs, including those for control room space, sludge hauling, and land-fill disposal, are assumed equal to those for the Option 1a system.

Table 5-72 outlines the operating costs of the Option 3a system.

Table 5-72
Operating Costs - Option 3a System

Item		Cost
Maintenance	$	13330
Electric Power Demand		1240
Electric Power Consumption		3310
Operating Man Power		73180
Chemical		2470
Insurance		1440
Control Room		2790
Winter Heating		5690
Sludge Hauling		23100
Land-fill Disposal		20570
Total	$	147120

The complete cost of the Option 3a system would be about $257380 (including $110260 and $147120 respectively in capital and operating costs). This figure corresponds to the following unit costs: $24 per lineal foot of tunnel and $8 per cubic yard of excavation.

Option 3b system - This system is a combination of the Class C liquid processing and centrifuge-type sludge dewatering alternatives. Capital costs for the system would include: equipment, installation, engineering, temporary construction, and contingency costs.

The Option 3b system would require three temporary structures; one each for the sedimentation hopper and Lamella settler, and one for the remaining system components. The third structure would have an enclosed area of about 580 square feet (total required area (970 square feet) minus hopper and Lamella settler areas (380 and 110 square feet, respectively) the entire quantity multiplied by a factor of 1.2). Thus, the following dimensions are assumed: length - twenty-four feet, width - twenty-four feet, and height - twelve feet. The structure would have a total roof and wall area of about 1830 square feet with a corresponding framing and sheathing cost of $1830. Other cost items would include: ninety-six lineal feet of footing - $450, 6.8 squares of roofing - $110, lighting for 560 square feet - $30, two frame doors - $440, and one overhead door.- $560. The total cost of this structure would be about $3420, and the combined total cost of all three temporary structures would be about $9170.

Captial costs for the Option 3b system are presented in Table 5-73

Table 5-73
Capital Costs - Option 3b System

Item	Liquid Processing Costs	Sludge Dewatering Costs	Total Costs
Equipment	$ 72600	$ 35060	$ 107660
Installation	7660	2770	10430
Engineering	-	-	6000
Temporary Construction	-	-	9170
Contingency	-	-	12000
Total			$ 145260

Monthly payments on a loan of the required capital would be about $8860,and the total repayment would amount to about $159480. The net salvage value of the system would be about $41820 ($26800 and $15020 respectively for the liquid processing and sludge dewatering systems). The system has a "present worth" at the time of initial investment of $32940. Thus, a net capital cost of $126540 would be charged against the hypothetical tunneling operation.

Operating costs for the Option 3b system would include: maintenance, electric power demand, electric power consumption, operating man power, chemicals, insurance, control room, winter heating, and solids loading costs.

Maintenance costs for the project are estimated as about $19100 ($9280 and $9820 respectively for liquid processing and sludge dewatering equipment).

Maximum electric power demand for the Option 3b system should be about 44.6 kilowatts (20.6 and 24.0 kilowatts respectively for liquid processing and sludge dewatering systems). Corresponding monthly rates would be about $124 and $144 respectively for October-to-May and June-to-September months. From these values, the total electric power demand cost would be about $2520.

A total electric power consumption of 284200 kilowatt-hours is estimated (129200 and 155000 kilowatt-hours respectively for liquid processing and sludge dewatering systems) for which 164500 kilowatt-hours would be utilized during October-to-May months and 119700 kilowatt-hours would be consumed during June-to-September months. Thus, a total electric power consumption cost of $7270 is anticipated ($2960 and $4310 respectively for October-to-May and June-to-September consumptions).

The following breakdown is predicted for Option 3b operating man power: Grade 1 labor - 7080 hours (5250 and 1830 hours respectively for liquid processing and sludge dewatering systems operation) and Grade 2 labor - 2190 hours (1950 and 240 hours respectively for liquid processing and sludge dewatering systems operation). Thus, a total labor cost of $91390 is predicted ($70800 and $20590 respectively for Grade 1 and 2 labor).

The Option 3b system would have the following chemical usage: Calgon Cat-Floc T - 760 gallons and WT-3000 - 880 pounds. Thus, a total chemical cost of $4590 is projected ($2740 and $1850 respectively for Cat-Floc T and WT-3000).

Insurance premiums for the Option 3b system would amount to about $1080 per year or $1670 for the entire project.

The Option 3b temporary structures would have a total enclosed area of about 1070 square feet. Thus, a total heating cost of $15460 is estimated ($0.30 per square foot per week multiplied by 1070 square feet and seventeen weeks).

Control room and solids loading costs should approximately equal those determined for the Option 1b system. Table 5-74 summarizes these and other operating costs for the Option 3b system.

Table 5-74
Operating Costs - Option 3b System

Item	Cost
Maintenance	$ 19100
Electric Power Demand	2520
Electric Power Consumption	7270
Operating Man Power	91390
Insurance	1670
Control Room	2790
Winter Heating	5460
Solids Loading	7260
Total	$ 142050

The total cost of the Option 3b system chargeable to the hypothetical tunneling operation would be about $268590 ($126540 and $142050 respectively in capital and operating costs). Corresponding unit costs are $25 per lineal foot of tunnel and $8 per cubic yard of excavation.

Option 3c System - This final system consists of a combination of the Class C liquid processing option and the filtration sludge dewatering alternative. Capital cost items for the system would include: equipment, installation, engineering, temporary construction, and contingency costs.

The Option 3c system would require temporary shelters for the sedimentation hopper, the Lamella settler, and the remaining system components. The third shelter would require an enclosed surface area of about 910 square feet (total for the Option 3c system (1250 square feet) minus the hopper and Lamella settler areas (380 and 110 square feet), the entire quantity multiplied by a factor of 1.2). The following dimensions are assumed for the structure: length - thirty feet, width - thirty feet, and height - twelve feet. The total roof-and-wall area of this structure would be about 2460 square feet with projected framing and sheathing cost of $2460. Other cost items would include: 120 lineal feet of footing - $560, 10.2 squares of roofing - $160, lighting for 900 square feet - $50, two frame doors - $440, and one overhead door - $560. The total cost of this structure would be about $4230 and the combined cost of all three structures is estimated as approximately $9980.

Capital costs for the Option 3c system are presented in Table 5-75.

Table 5-75
Capital Costs - Option 3c System

Item	Liquid Processing Costs	Sludge Dewatering Costs	Total Costs
Equipment	$ 72600	$ 66650	$ 139250
Installation	7660	1820	9480
Engineering	-	-	7000
Temporary Construction	-	-	9980
Contingency	-	-	15000
Total			$ 180710

Monthly payments on a loan of the required capital would amount to about $11020 which over the entire project would accumulate to about $198360. The net salvage value of the system is estimated as about $57190 ($26800 and $30390 respectively for liquid processing and sludge dewatering equipment). Thus, the Option 3c system would have a capital cost to the hypothetical project of about $141110.

Operating costs for the system would include: maintenance, electric power demand, electric power consumption, operating man power, chemicals, insurance, control room, winter heating, and solids loading costs.

Maintenance costs for the Option 3c system should amount to about $22610 ($9280 and $13330 respectively for liquid processing and sludge dewatering equipment).

Maximum electric power demand for the system is projected as about 26.8 kilowatts (20.6 and 6.2 kilowatts respectively for the liquid processing and sludge dewatering systems). From this figure, the following monthly charges are estimated: October-to-May - $75 per month and June-to-September - $87 per month. Thus, a total cost of $1520 is estimated ($820 for October-to-May months and $700 for June-to-September months).

A total electric power consumption of 168600 kilowatt hours is anticipated for the Option 3c system (129200 and 39400 kilowatt-hours respectively for liquid processing and sludge dewatering systems). Of this total, an estimated 97600 kilowatt-hours would be utilized in October-to-May months with the remaining 71000 kilowatt-hours consumed in June-to-September months. The total cost of this usage would be about $4320 ($1760 and $2560 respectively for liquid processing and sludge dewatering systems).

Insurance premiums for the Option 3c system would amount to about $1390 per year or $2150 for the entire project.

The temporary structures described above have a total enclosed surface area of about 1390 square feet. Thus, a winter heating cost of $7010 is projected ($0.30 per square foot per week multiplied by 1390 square feet and seventeen weeks).

Other operating costs, including those for operating man power, chemicals, control room space, and solids loading, would be nearly identical to the corresponding Option 3b system costs. Table 5-76 presents all foreseeable operating costs of the Option 3c system.

Table 5-76
Operating Costs - Option 3c System

Item	Cost
Maintenance	$ 22610
Electric Power Demand	1520
Electric Power Consumption	4320
Operating Man Power	91930
Chemicals	4590
Insurance	2150
Control Room	2790
Winter Heating	7010
Solids Loading	7260
Total	$ 144180

The total cost for the Option 3c system is about $285290 ($141110 and $144180 respectively for capital and operating costs). Corresponding unit costs would be: $27 per lineal foot of tunnel and $9 per cubic yard of excavation.

Summary

This chapter describes a hypothetical hydraulic sandstone tunneling operation, and discusses the costs of wastewater treatment for the operation. The following parameters were assumed for the hypothetical tunnel: length - two miles, cross-sectional area - eighty-five square feet, and total volume of excavation - 33200 cubic yards. Some of the assumptions made for the tunneling operation included: advance rate - 1.6 feet per hour, excavation time - six hours per eight hour shift (three shifts per day), crew efficiency - ninety percent, and total duration of the excavation phase - 1220 shifts.

Costs for each of the liquid processing and sludge treatment options designed in Chapter 4 were determined. These values were combined in various ways to determine the costs of several treatment systems utilizing: public water discharge of effluent (Option 1 system), sanitary sewer discharge of effluent (Option 2 system), and re-use of effluent in the tunneling system (Option 3 system).

Table 5-77 presents the various costs for the treatment systems.

Table 5-77
Costs for the Treatment of
Hydraulic Tunneling Wastewater

Cost Item	Option 1	Option 2	Option 3
Initial Investment	$157000-$213000	$272000 *	$126000-$181000
Total Cost !	$345000-$360000	$377000 *	$257000-$285000
Cost per Lineal Foot of Tunnel	$33-$34	$36	$24-$27
Cost per Cubic Yard of Excavation	$10-$11	$11	$ 8-$ 9

* Includes a $235000 sewer connection charge which may be negotiable

! Includes all foreseeable capital and operating costs minus salvage value

Typical costs for tunneling in the St. Peter Sandstone range from $500 to $600 per lineal foot of tunnel (based on an eighty-five square foot cross-sectional area and including costs for hydraulic excavation, temporary ground support, and permanent lining). Thus, the costs of the various wastewater treatment systems are not excessive in comparison.

The figures in Table 5-76 do indicate that the re-use of the treatment system effluent would be most advantageous from an economic standpoint. However, sewer discharge of effluent would be an extremely attractive option if the connection charge could be reduced.

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PART II

<u>DISCUSSION OF LIQUID-SOLIDS SEPARATION PROCESSES, EQUIPMENT COMPONENTS, AND ACCESSORIES AND THEIR POSSIBLE APPLICATIONS TO HYDRAULIC TUNNELING WASTEWATER TREATMENT</u>

Appendix A

CHEMICAL TREATMENT FOR SUSPENDED SOLIDS REMOVAL

Suspended particles in a waste stream may vary in diameter from less than one micron (0.001 millimeter) to several hundred microns. Size and density are major factors in the removal of such suspended material from a liquid medium. Larger particles are normally removed by processes such as sedimentation. However, clays and colloidal particles (diameters less than 0.005 and 0.001 millimeters respectively (1)) which are responsible for most residual turbidity are difficult or impossible to remove by conventional physical processes. Consequently, certain chemicals, called coagulants, are dispersed in these slow-settling or non-settling suspensions to bond individual particles into larger and more readily removable masses.

Coagulant Chemicals

Coagulant Types Most coagulants can be grouped into one of the following categories: inorganics or organic polyelectrolytes.

The most widely used inorganics are di- and tri-valent metallic salts of calcium, aluminum, and iron. These chemicals coagulate suspended solids in wastewater by a variety of mechanisms described in reference 2.

Organic polyelectrolytes (or polymers) are large molecules composed of numerous covalently bonded repeating units, some or all of which are ionizable in water. Organics may be subdivided by their charge characteristics as: anionics (negative charge), non-ionics (no net charge), and cationics (positive charge). Anionics and nonionics are long, chain-like molecules which attach themselves to numerous colloidal particles to form settleable masses. Cationics, while they also possess chain structures, function primarily by absorbing on particle surfaces and neutralizing negative surface charges which often form; when these repulsive electrostatic forces are neutralized, natural attractive forces between particles may cause agglomeration. Polyelectrolyte dosage is quite critical because insufficient dosage will not adequately destabilize a suspension while excessive dosage may actually restabilize it (2).

Selection of a Coagulant Type In the design of a chemical destabilization system, the engineer is eventually faced with the selection of a coagulant type best suited for the particular problem. Obviously, determination of the optimum choice depends on numerous factors including: characteristics of the chemical and wastewater, separation processes to be used in conjunction with the chemical treatment phase, sludge handling and treatment processes, and economics. However, by observing some general characteristics of different coagulant types, one may gain some preliminary insight into the actual selection of a suitable chemical.

Inorganic coagulants are normally required in relatively high dosages; typical dosages for coagulation of raw sewage are 50 to 400 parts per million. Thus, chemical transportation, storage, and feeding are significant cost items. In addition, coagulation by inorganics results in a significant increase in total sludge volume produced, proportionally increasing handling and disposal problems. Finally, sludge produced by inorganics has a sticky texture and is quite difficult to dewater.

Polyelectrolytes, while having much higher unit costs than inorganics, perform so efficiently that they are required in much smaller doses; typical polymer dosages for coagulation of raw sewage are one to ten parts per million. Consequently, chemical storage and handling problems are greatly reduced, and the increase in sludge volume due to polyelectrolyte addition is negligible. Also, the polyelectrolyte-produced sludge generally has better dewatering characteristics than that produced by inorganics.

From the discussion above, polyelectrolytes appear to be the obvious preference over inorganics from the operational standpoint. Detailed study would almost certainly show polymers economically comparable to inorganics on small waste treatment operations (such as would be utilized on a tunnel construction site). Consequently, the remainder of this appendix will consider polyelectrolytes as the only practical coagulant chemical type for this particular application.

Physical Process of Chemical Treatment

Any wastewater coagulation process requires certain physical processes for satisfactory solids suspension destabilization. These are:

(1) Chemical preparation and feeding to the waste stream.
(2) Mixing of chemical with the waste stream.
(3) Flocculation, or agitation of the treated waste stream to produce inter-particle contacts which result in grain growth.

These processes may vary greatly in appearance and importance from one application to the next, but each is present in a properly operating chemical coagulation system. Only the applications of these processes relating to polyelectrolytes will be discussed.

Preparation and Feeding Preparation of polyelectrolytes can be divided into two categories: preparation of dry chemicals and preparation of wet chemicals. Dry polyelectrolytes are normally anionic or non-ionic; they are available in this form because they are high molecular weight substances with short shelf lives in solution form (3). Cationics, by contrast, have lower molecular weights and longer solution lives and are usually available as liquids in product form (3).

Figure A-1a is a schematic of a typical packaged and automated dry polyelectrolyte preparation and feeding system. Polymer is fed from the vibratory storage hopper to the wetting cones via a screw-type volumetric feeder. Water is fed into the wetting cones through a series of valves which automatically maintain the desired flow rate. In the wetting cones, the water stream is atomized and mixed with the tiny flakes of polymer (see Figure A-1b). (Good wetting is critical since the high molecular weight polymer is relatively hard to dissolve. Improper wetting can lead to the formation of sticky, round balls of polymer called "fish-eyes".)

Eductors on the bottoms of the wetting cones draw the polymer solution out of the cones and on to the aging tank where the dissolving is completed. (A slow-speed mixer keeps undissolved particles in suspension). Here the polymers' molecular chain structures begin to form.

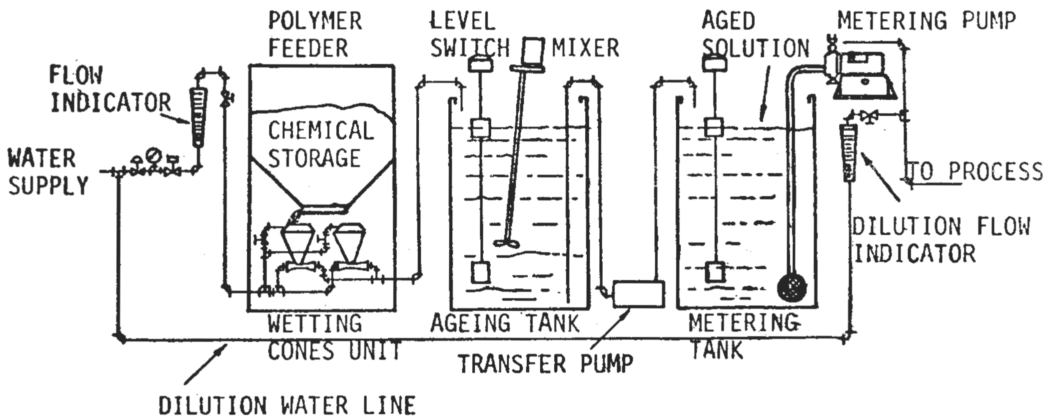


FIGURE A-1a — DRY POLYELECTROLYTE PREPARATION AND FEEDING SYSTEM

(Courtesy of Wallace and Tiernan Co.)

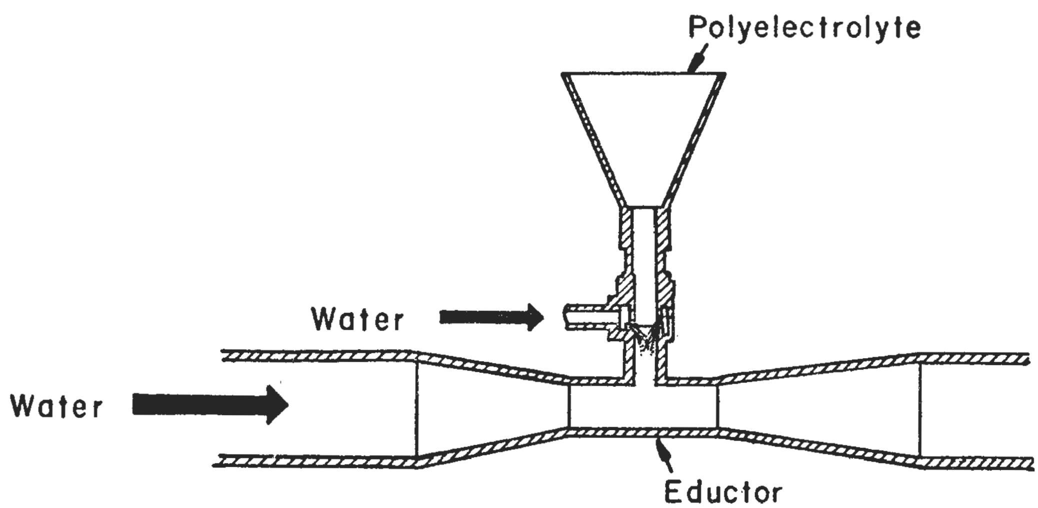


FIGURE A-1b — DRY POLYELECTROLYTE WETTING CONE

After sufficient aging, the polymer solution is pumped into the metering tank where it is held until feeding. If the feeding of some unaged polymer is permissible, or if the required aging time is relatively short, the aging tank may be deleted, and the solution may be fed directly from the wetting cones into the metering tank.

Level sensors in the aging and metering tanks control the wetting of polymer and the transfer of solution so that the preparation system may function automatically. However, the systems should be provided with manual override controls as well.

Figure A-2 is a schematic of a typical wet polymer preparation system. Concentrated polymer product is simply pumped to a reservoir where it is mixed with the desired quantity of dilution water and held until feeding.

Chemical feed (and transfer) pumps, shown in Figures A-3, F-15, and F-16, are invariably of the positive displacement type, such as plunger, piston, gear, diaphragm, and progressive cavity pumps. The selection of the proper type depends upon desired flow rates, fluid viscosities, suction and discharge heads, conditions of internal shear, and other miscellaneous considerations.

In both the wet and dry preparation systems, polymer solution is diluted just prior to entering the waste stream. A partial explanation is that more uniform blending is possible when mixing a relatively large quantity of "weak" solution as compared to mixing a small quantity of "strong" solution. However, the primary reason for dilution at this particular point is that the polymer just seems to perform more efficiently if diluted with fresh water just prior to mixing with the waste stream. A more suitable explanation is not presently available, but the beneficial effects of this final dilution are widely recognized (3). If the mixing of the polymer solution and final dilution water is desired, the combined flow may be directed through a static in-line mixer (see Figure A-4) just prior to its entry into the waste stream.

Mixing To destabilize non-settling or slow-settling supensions efficiently, coagulant chemicals must thoroughly and uniformly coat the individual particles (2). Thus, most chemical coagulation processes

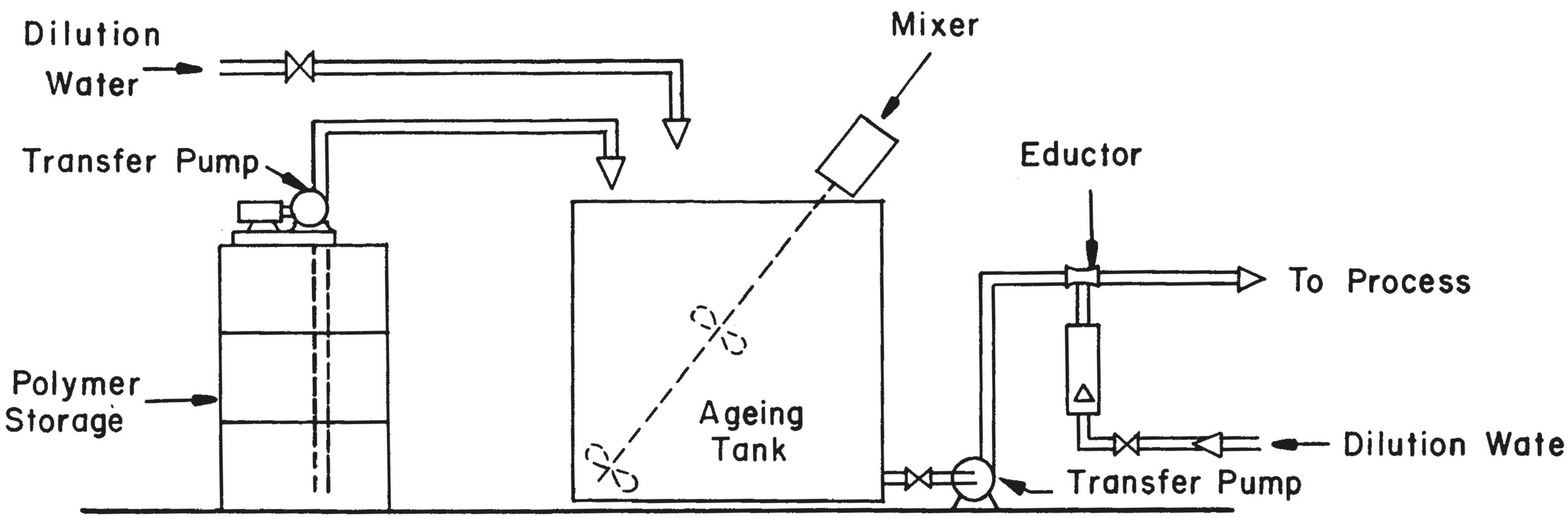
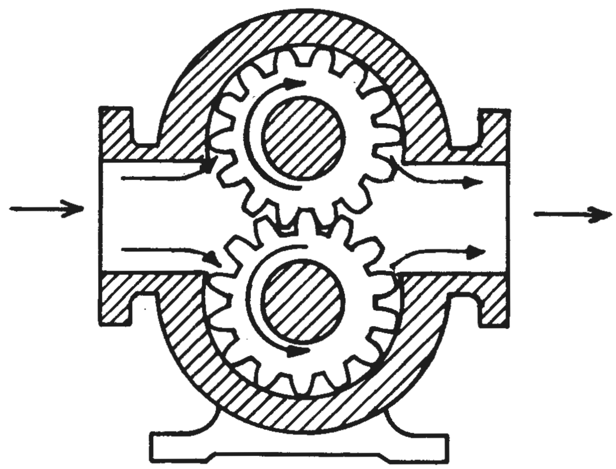
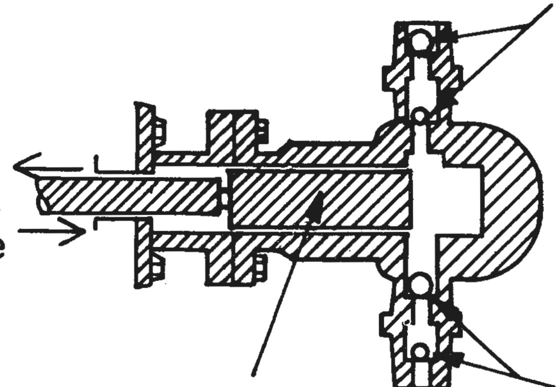


FIGURE A-2 — WET POLYELECTROLYTE PREPARATION AND FEEDING SYSTEM

(Courtesy of Hercules Chemical Co.)



Gear Pump



Piston Pump

FIGURE A-3 – CHEMICAL FEED PUMPS (4)

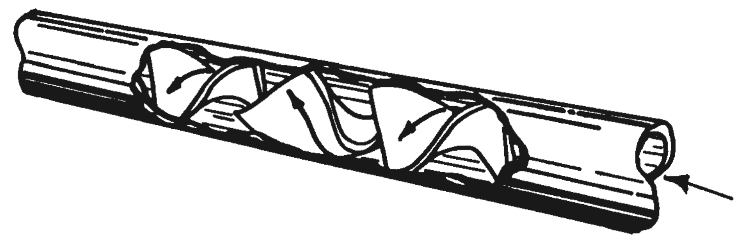


FIGURE A-4 — STATIC IN-LINE MIXER(4)

include some short term, high intensity mixing operation to assure adequate chemical-particle contacts.

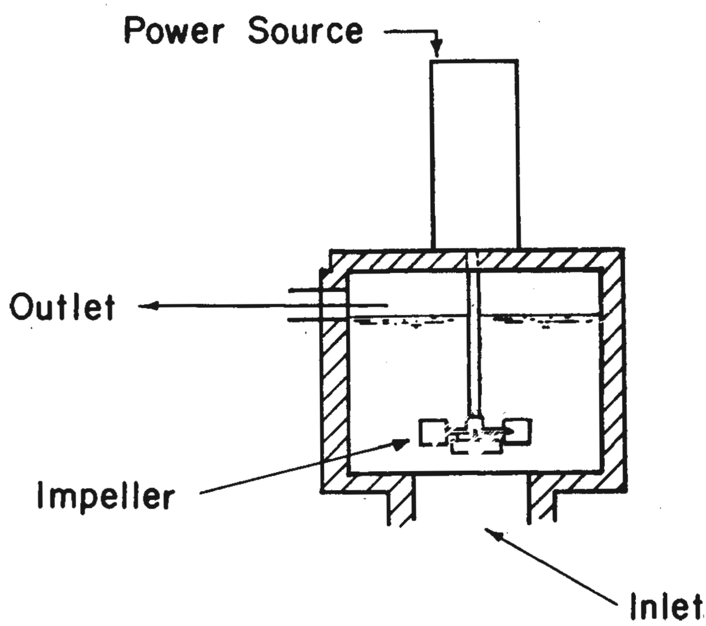
The most common types of rapid mix units are those using horizontally or vertically shafted rotating turbines or impellers (see Figure A-5)(5). Vertical shaft mixers may be mounted eccentrically or at an angle to the vertical. Baffles may also be used to promote mixing and/or prevent vortexing. (Usually four or less baffles are used.) Flow is normally from bottom to top so as to inhibit particle settling. Detention times are usually less than one minute (5).

Another mixing unit, the rotating drum type, is illustrated in Figure A-6. The horizontally mounted drum rotates on its axis with wastewater entering one end and leaving the other. This type generally produces less violent agitation than impeller-type mixers.

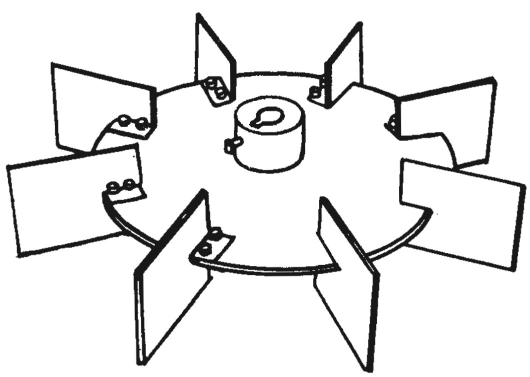
A third mixing technique utilizes simple pipe turbulence to provide agitation. Chemicals are injected into the waste stream which is in turn directed through a series of pipe elbows to achieve the desired degree of mixing (3).

Flocculation When a solids suspension has been treated with coagulant chemicals and thoroughly mixed, two natural phenomena, differential particle settling velocities and Brownian motion (the random zig-zag movement of colloidal particles), interact to produce particle collisions necessary to induce agglomeration (2). However, when dealing with dilute suspensions (low particle concentration per unit volume), the frequency of collisions induced by natural phenomena may be insufficient to produce rapid grain growth. Consequently, some "artificial" agitation, (flocculation) may be required to increase the rate of agglomeration. Major factors in the effectiveness of flocculation include: effectiveness of the coagulation process, concentration of particles, and amount of mixing (2).

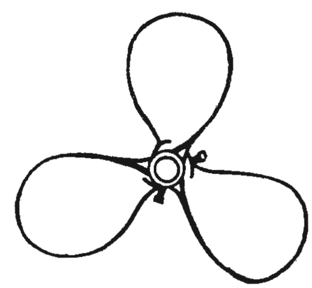
Several types of flocculators are in common use. The baffled flocculator, Figure A-7, utilizes turbulence produced by multiple bends to promote agglomeration. The paddle flocculator, Figure A-8, consists of one or a series of vertically or horizontally shafted paddle wheels which slowly rotate to induce mild turbulence in the through-flowing liquid.



Mix Tank



Turbine Mixer



Propeller Mixer

FIGURE A-5 - IMPELLER-TYPE MIXERS

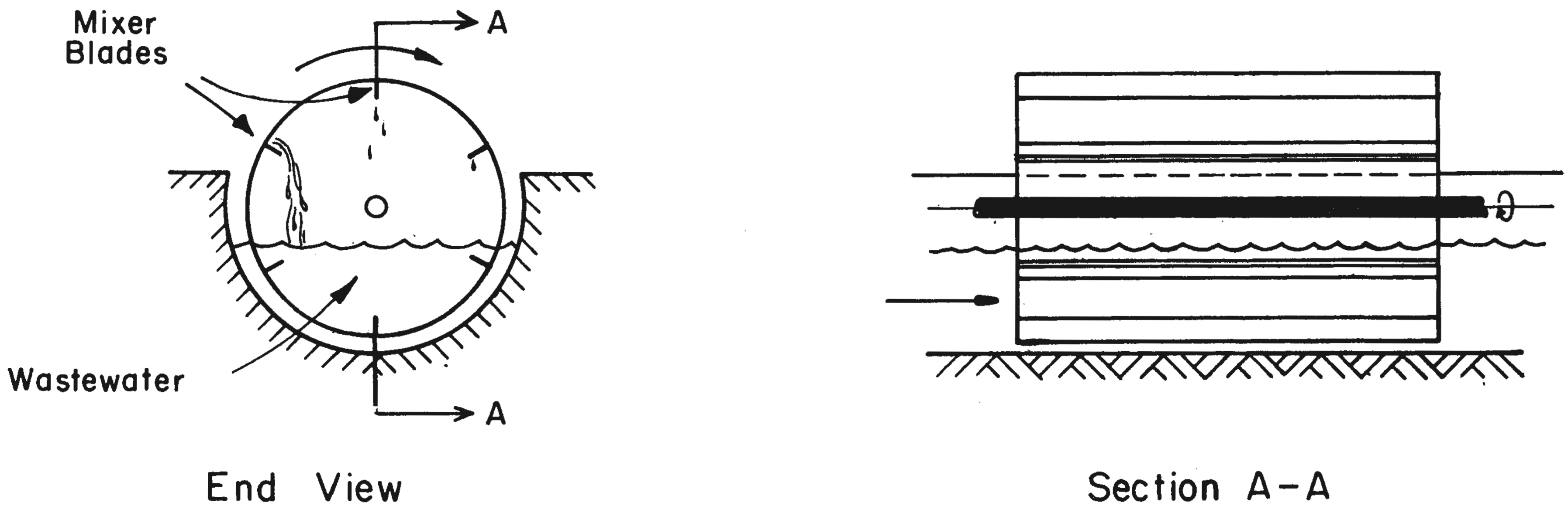


FIGURE A-6 — ROTATING DRUM MIXER

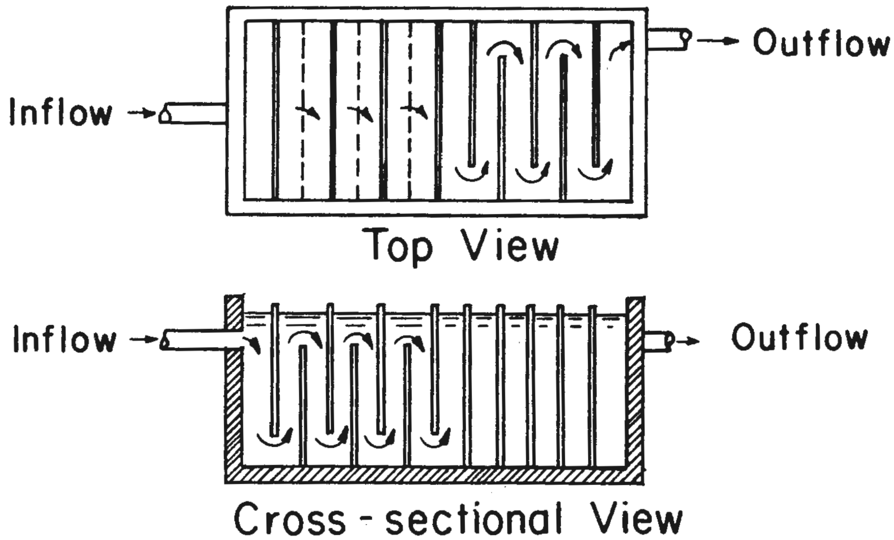


FIGURE A-7 - BAFFLED FLOCCULATOR (4)

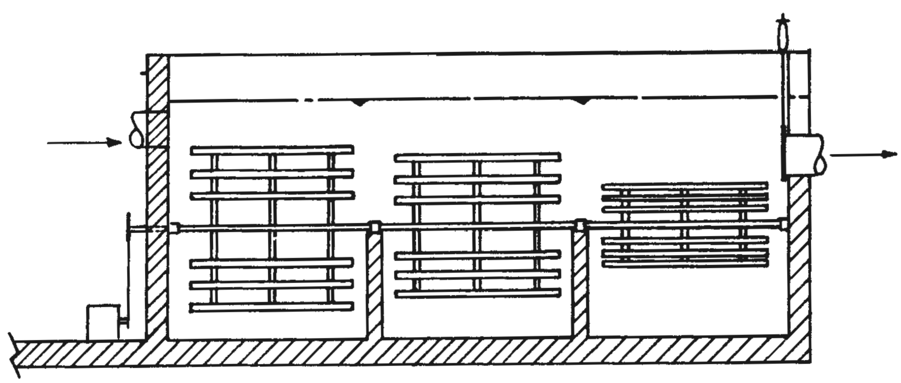


FIGURE A-8 - PADDLE FLOCCULATOR (4)

Stator, or "picket fence" blades are more effective in inducing turbulence than continuous blades, since mixing occurs over the entire paddle area rather than just along the edges (5).

A frequently encountered phenomenon of flocculation (and mixing) tanks is short-circuiting, (a portion of the influent leaving the basin in less than the desired retention time). The problem is best alleviated by utilizing several smaller tanks in series (5).

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Appendix B

FILTRATION

Filtration is defined as the trapping and removal of suspended solids from a liquid by passing the mixture through a porous material. Filtering devices may be categorized in a number of ways, but the discussion below will group them into one of the following: deep bed filters or physical strainers.

Deep Bed Filtration

Deep bed filtration occurs when the filtering media has significant thickness in the direction of suspension flow (see Figure B-1). The media is usually particulate in nature; sand, coal, and garnet have all been used. Suspended solids are removed by a combination of straining, flocculation, and sedimentation. Such a process is normally utilized as a "polishing" step for water containing low initial suspended solids concentrations, i.e., a deep bed filter may be used to reduce the suspended solids concentration of a particular wastewater from fifty to twenty milligrams per liter (1).

A complete deep bed filtration unit is generally a permanent installation requiring a large capital investment for filtration equipment, buildings, concrete tanks, etc. Furthermore, the process is relatively complicated requiring the services of a skilled operator for operations such as chemical pretreatment and backwashing. Consequently, a deep bed filtration process is an investment not generally warranted for a semi-permanent industrial wastewater treatment system. Thus, the process will not be discussed in further detail in this paper.

Physical Straining

Physical straining differs from deep bed filtration in that the filtering media of the strainer has very little thickness in the direction of flow; the media is two-dimensional rather than three-dimensional.

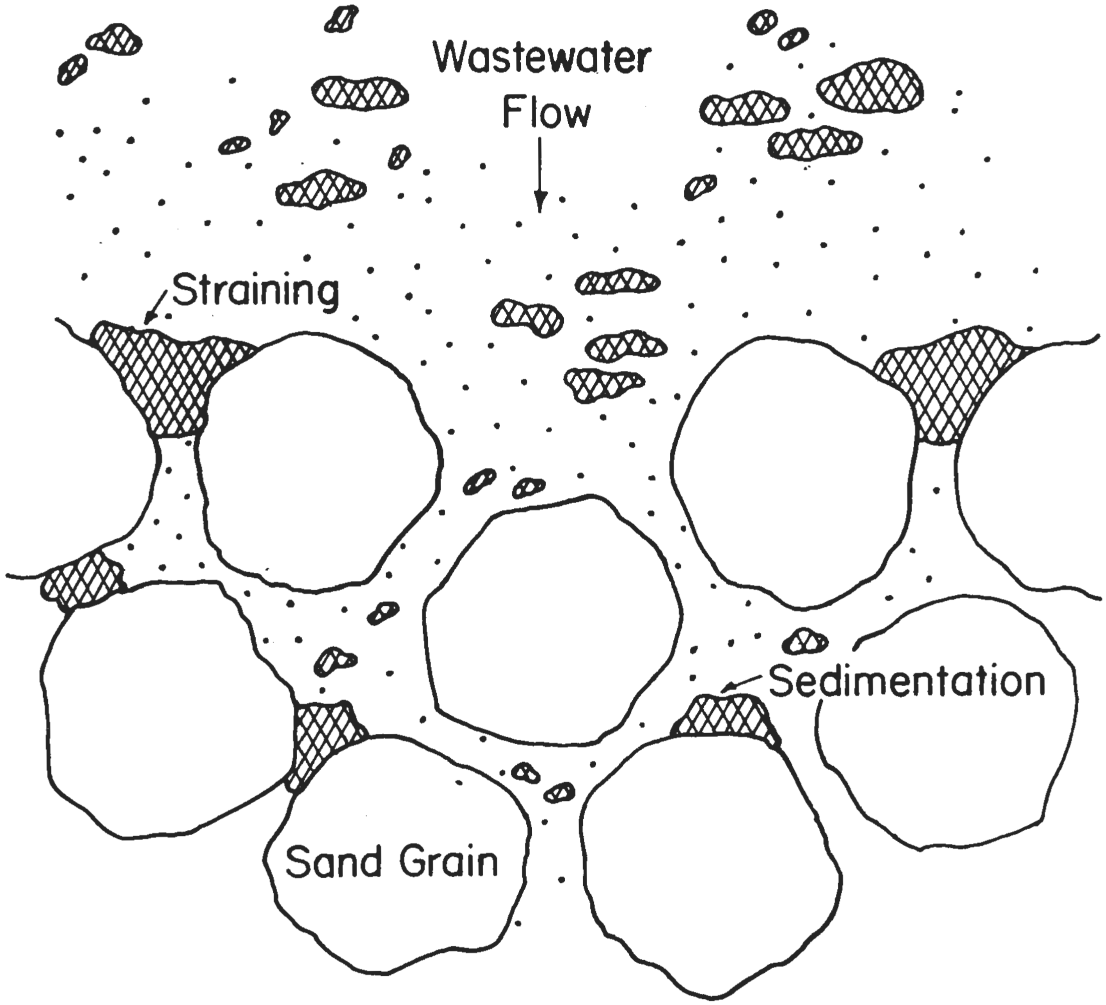

FIGURE B-1 - DEEP BED FILTER MEDIA

The operation of the basic physical strainer is very simple; the media has sufficient porosity to allow liquid to pass, but is fine enough to retain suspended solids. Since most wastewater contains a gradation of particle sizes, some in the colloidal size range, a physical strainer is generally unable to remove all suspended material. However, the minimum particle size removed by the strainer may be considerably smaller than the media opening size due to build-up of a solids mat on the media surface. This mat tends to act as a deep bed media, reducing the effective size of openings and enhancing separation. However, the mat build-up is accompanied by an increase in hydraulic headloss across the strainer.

The performance of physical strainers has been described quantitatively, but the analysis is quite complex and beyond the scope of this discussion. For interested readers, the analysis is presented in reference 2.

Vibrating Screen - The vibrating screen, Figure B-2, is used primarily for removing coarse particles from a waste stream. The screen assembly is usually sloped to facilitate movement of coarse particles off from the media, but for best performance, this slope should be less than the angle of repose of the solid material. Vibratory motion should be adequate to insure all particles have contact with the screen, but not so excessive that undersize material is unable to penetrate the screen.

Sieve Bend (DSM Screen) - Figure B-3a illustrates the sieve bend or Dutch State Mines screen. This device, like the vibrating screen, is also used for coarse fraction removal. The feed box, located at the top of the unit, distributes slurry evenly over the width of the wedge bar screen. The wedge bars act as knife edges, peeling off thin slices of liquid and "undersize" particles (see Figure B-3b). Coarse material tumbles down the screen face and off the sieve bend.

Pipeline Strainer - This screening device, shown in Figure B-4, is used to remove small quantities of coarse material from a waste stream (3). (It is often installed upstream of a centrifuge or other device that may be damaged by oversize material.) Wastewater enters through the inlet,

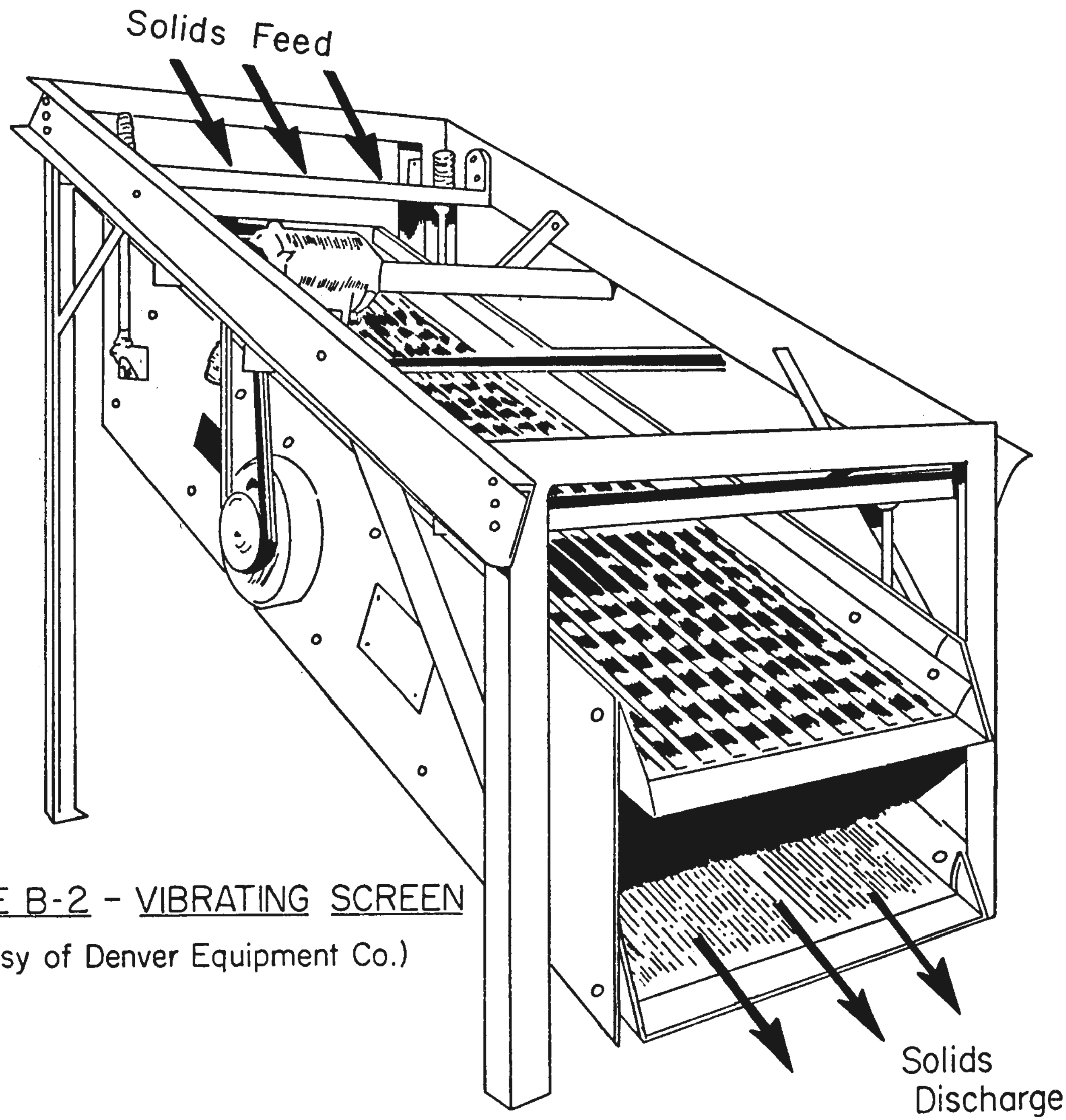

FIGURE B-2 - VIBRATING SCREEN

(Courtesy of Denver Equipment Co.)

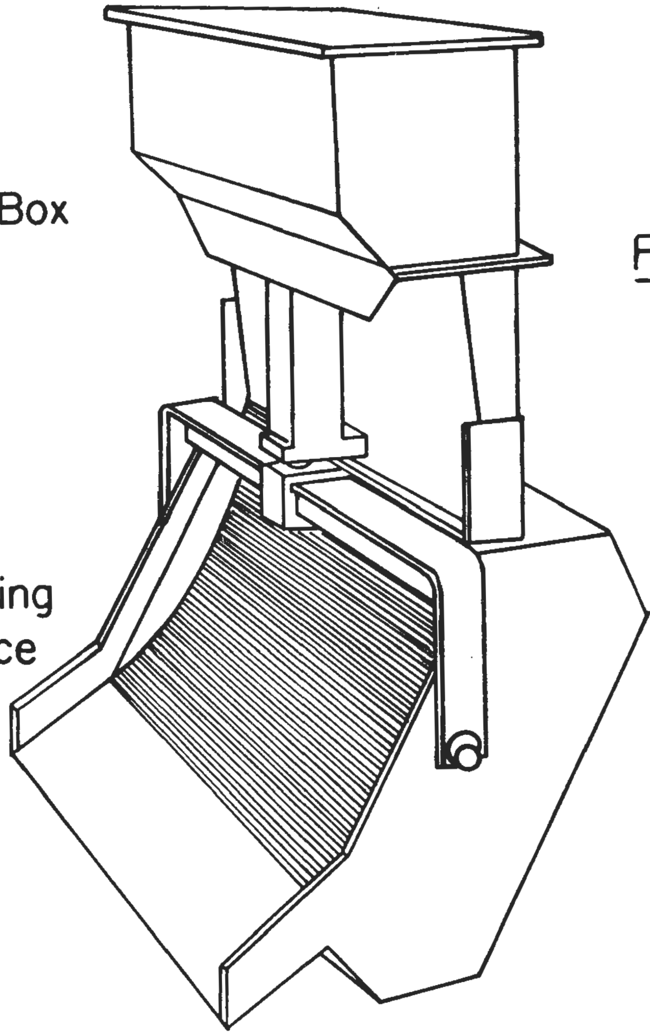

FIGURE B-3a

SIEVE BEND (DSM SCREEN) (4)

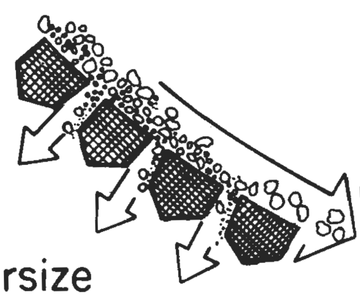

FIGURE B-3b - SIEVE BEND MESH CROSS-SECTIONAL VIEW

(Courtesy of Dorr-Oliver, Inc.)

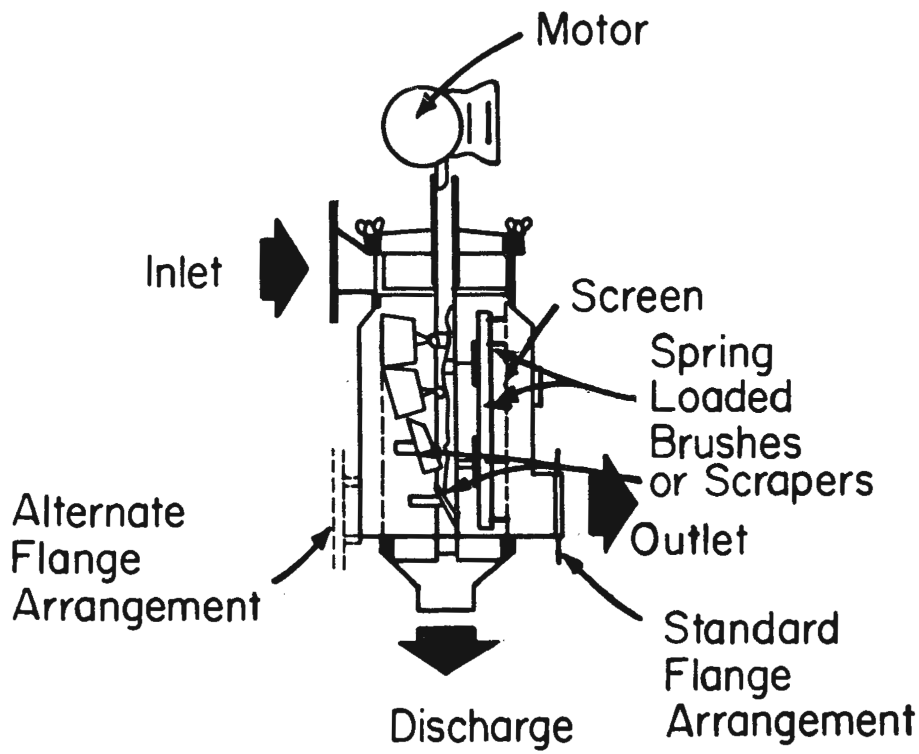

FIGURE B-4 - PIPELINE STRAINER (Courtesy of Dorr-Oliver, Inc.)

flows down through the screen and exits via the outlet. Rotating paddles or brushes convey deposited solids from the screen to the discharge port. Solids removal from the discharge may be intermittent or constant depending on the concentration of oversize material in the waste stream.

Microstrainer - The microstrainer, Figure B-5, consists of a rotating drum with a fine metal screen media mounted on its periphery. The drum is mounted in a tank, and during operation, is partially submerged. Wastewater enters the drum through an open end, and passes through the screen after depositing a layer of solids on the inner surface. The solids layer adheres to the rotating drum and is lifted from the wastewater. Backwashing jets above the drum wash the mesh, and deposit solids in a trough which removes them for final dewatering.

Since the build-up of a solids mat increases removal efficiency, a slow drum rotation rate improves effluent quality. The increased headloss due to mat build-up may be compensated by increasing velocity and flow rate of backwash jets (1).

Vacuum filter - The drum-type vacuum filter superficially resembles the microstrainer discussed above. The filtration media, usually some sort of fibrous cloth or plastic, may be integrally attached to the drum circumference or may be a continuous belt as shown in Figure B-6.

The drum rotates partially submerged in wastewater. A vacuum is applied to the submerged portion drawing the liquid phase into the drum while a solids mat is deposited on the media surface (see Figure B-6). As the drum rotates, the solids mat is drawn out of the liquid and dried by the continuing vacuum. At some point in the cycle, vacuum is terminated, and the cake is removed as shown in Figure B-6 or by some equivalent mechanism. The media is then washed and returned to the wastewater for another cake formation period. At any given time in the operation, all four phases (cake formation, drying, and discharge, and media washing) are occurring simultaneously. The ratio of drum diameter to submergence depth controls the ratio of formation time to drying time while media

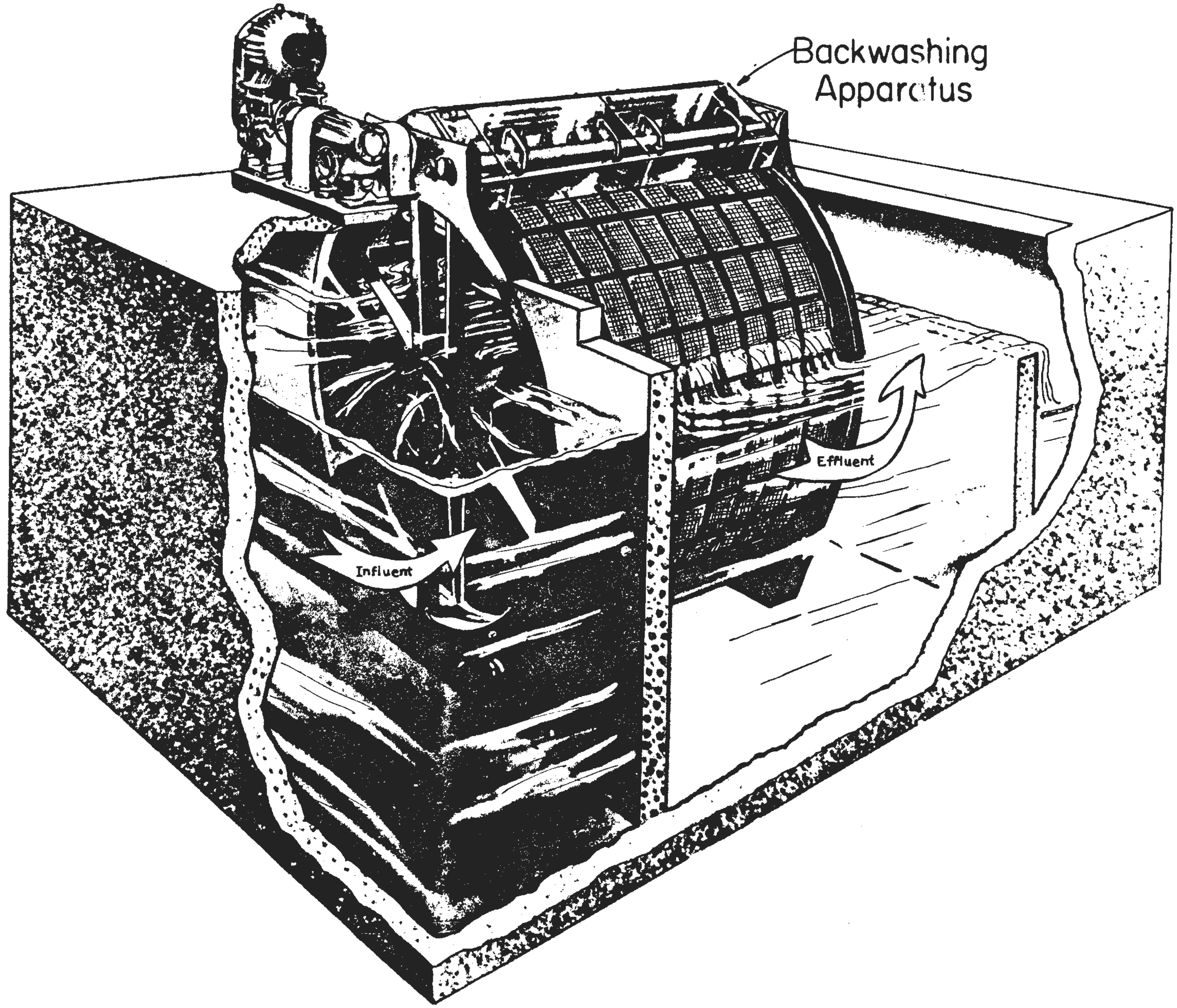

FIGURE B-5 - MICROSTRAINER (Courtesy of Crane-Cochran Co.)

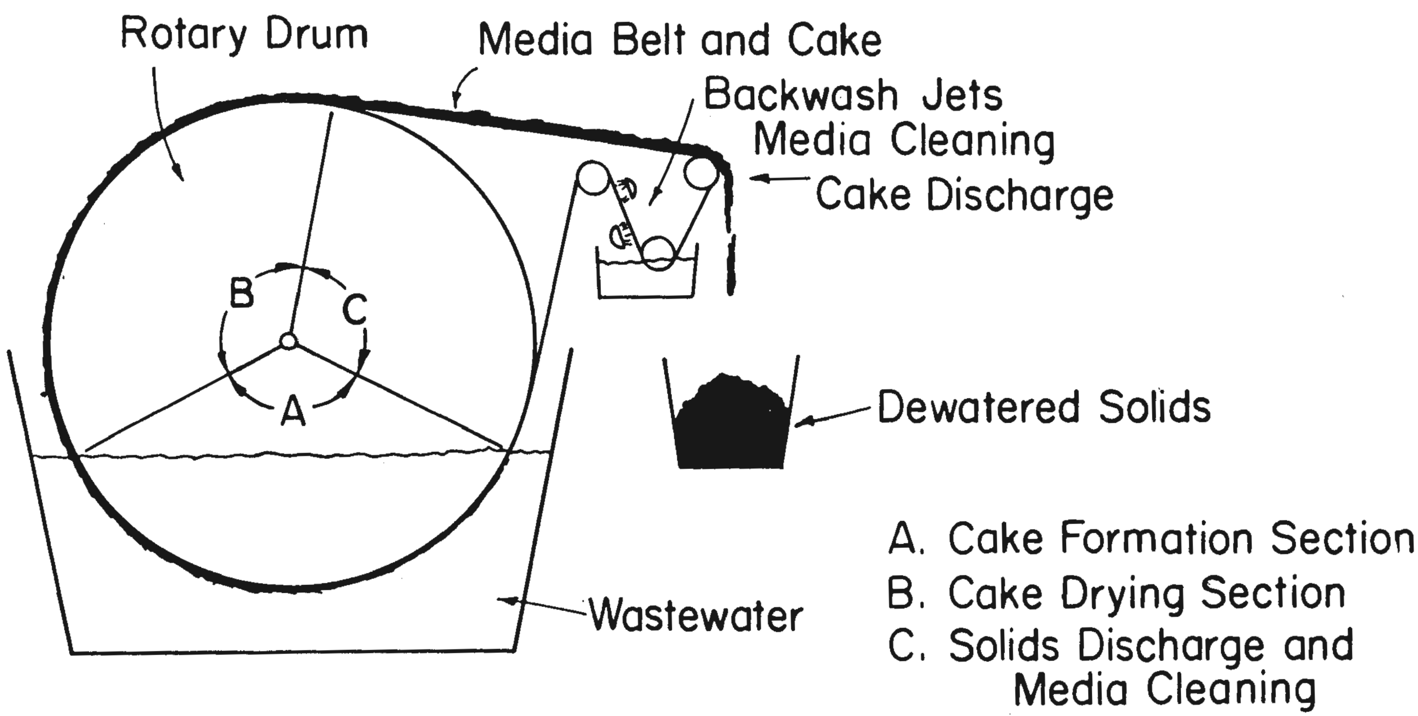

FIGURE B-6 - DRUM-TYPE ROTARY VACUUM FILTER length and drum rotational speed place absolute values on form and dry times (5).

Another frequently used vacuum filter is the disc type, shown in Figure B-7. This geometry increases the total available filtration surface per unit "floor area".

Pressure Filter - Figure B-8a illustrates the entire plate-and-frame type pressure filter, while Figure B-8b schematically illustrates a single section of the device. The desired number of plates and frames are placed in the supporting mechanism and clamped together (see Figure B-8a). Wastewater is then pumped into the spaces between the media-covered plates. Liquid seeps through the media and out the clean filtrate ports, while solids accumulate in the spaces between plates. (The media may be covered with a pre-coat for better separation efficiency.) When the spaces become filled with solids, the plate-and-frame apparatus is dismantled and solids are manually removed. After cleaning, plates and frames are reassembled and clamped, and more wastewater is introduced.

Other Filter Types - The majority of the filtration devices discussed above have been accepted and used by industry for many years. The following paragraphs will discuss two relatively new filtration types becoming increasingly popular in industry (6).

The dual cell gravity filter, Figure B-9, is essentially two rotating drums covered by a belt-type media. Wastewater is introduced to the first drum from which liquid drains downward through the media. Solids are carried by the moving media belt to the second drum, where they roll, compress, and eventually discharge out the ends.

The belt press filter, illustrated in Figure B-10, consists of two parallel, continuous media belts which "rotate" in opposite directions. Inflowing wastewater is fed onto the top belt, from which a portion of the liquid phase drains by gravity. Concentrated suspension is then deposited on the second belt, which, in combination with the first, squeezes the suspension to force additional water out. Near the end of the squeezing phase, the belts are distorted to loosen the solids mat, and scrapers remove the cake. Water jets scrub the belts before re-use.

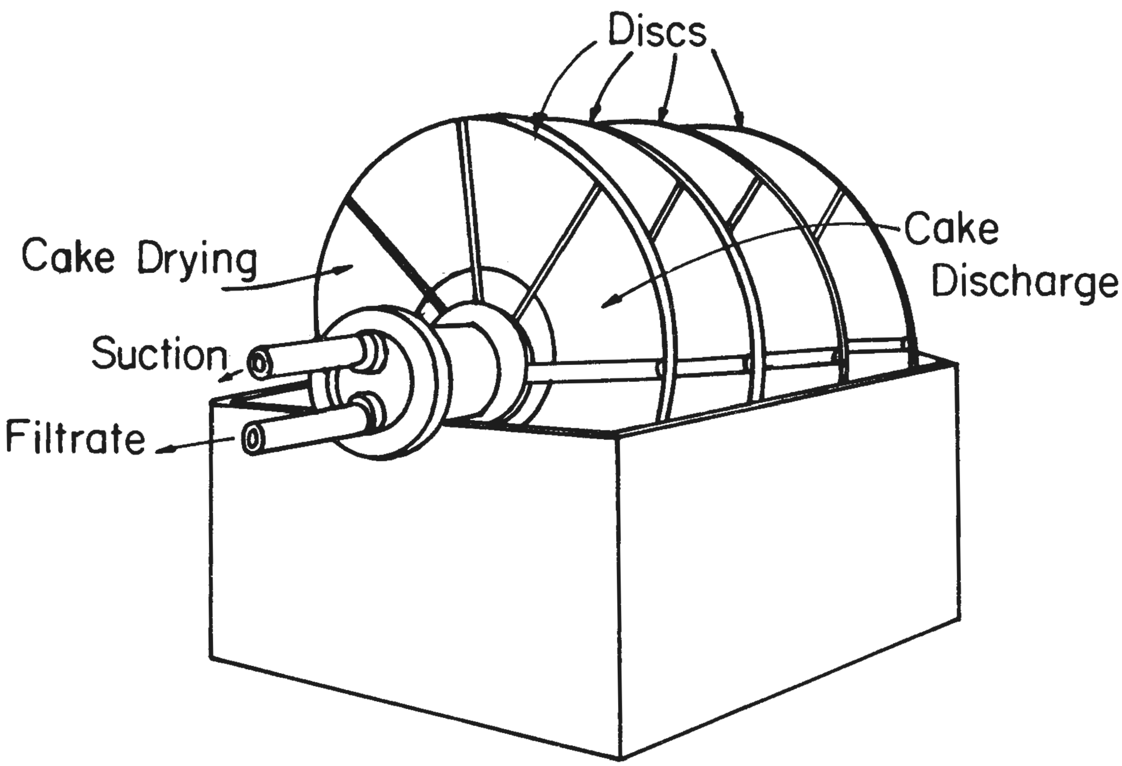

FIGURE B-7 - DISC-TYPE ROTARY VACUUM FILTER

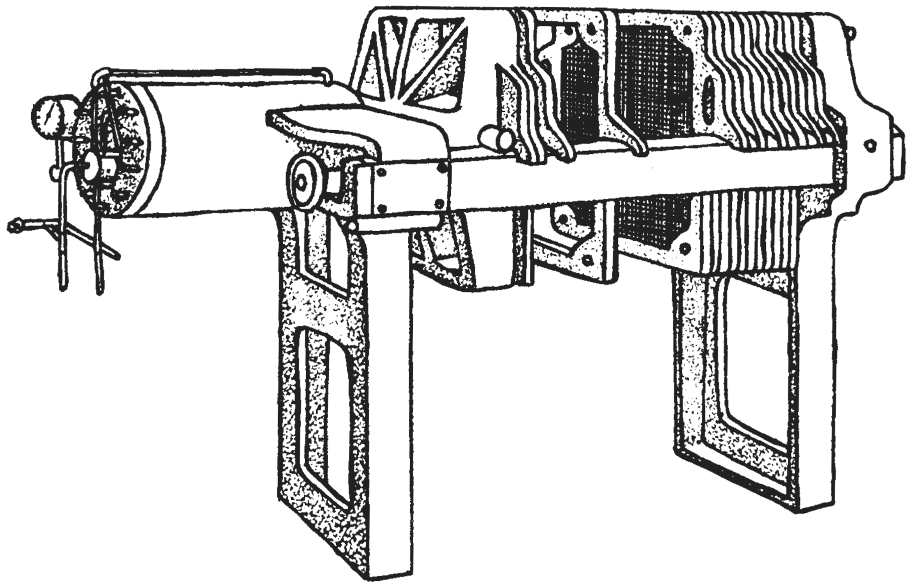

FIGURE B-8a - PRESSURE FILTER (1)

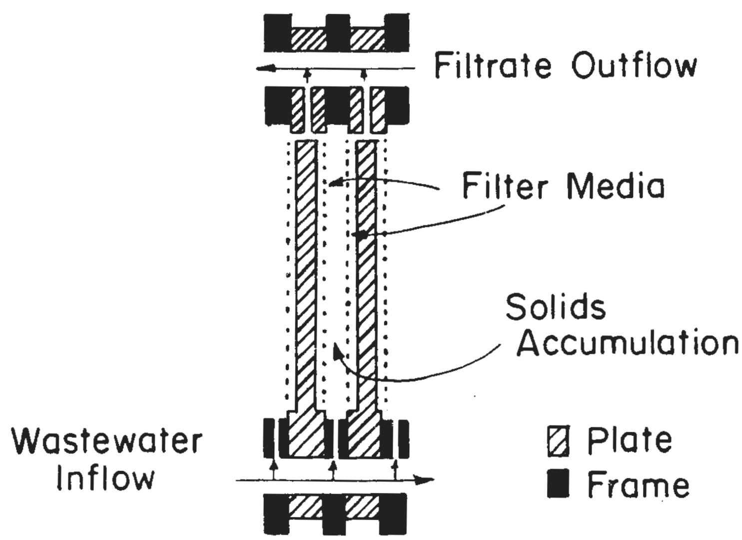

FIGURE B-8b - SCHEMATIC OF A SECTION OF A PRESSURE FILTER

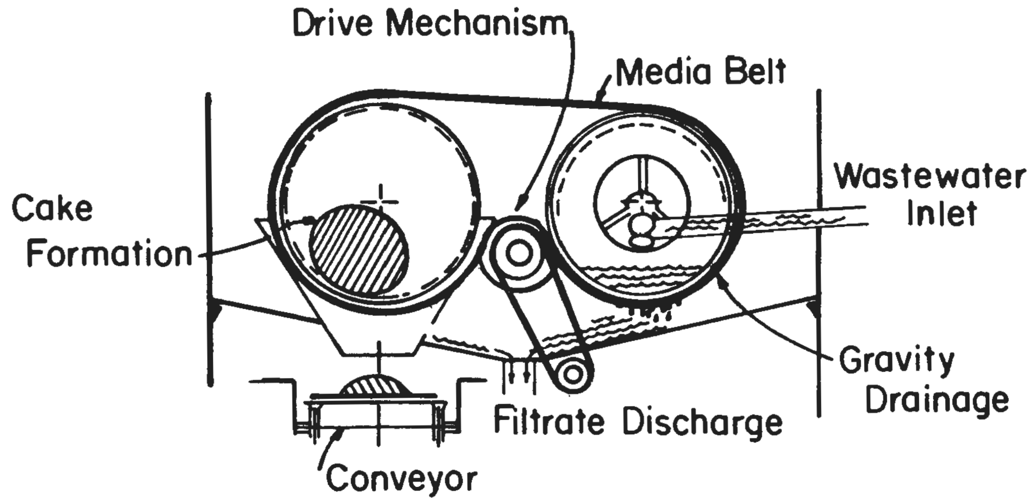

FIGURE B-9 - DUAL CELL GRAVITY FILTER
(Courtesy of Permutit Co.)

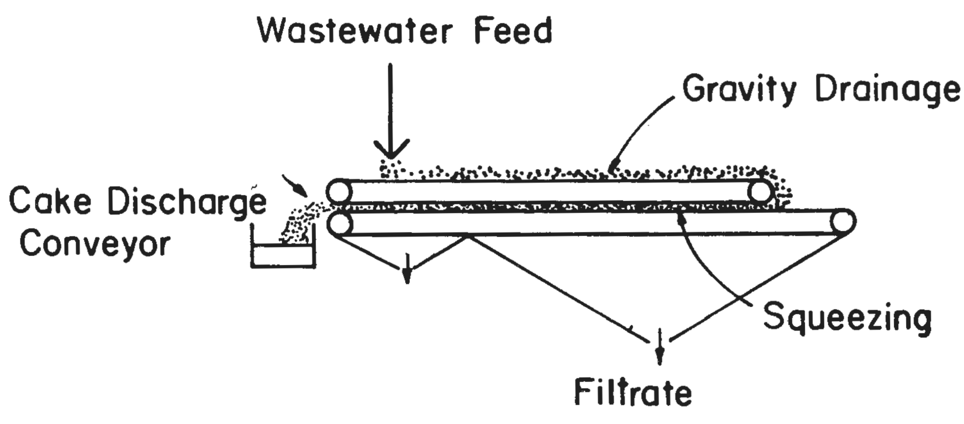

FIGURE B-10 - HORIZONTAL BELT PRESS

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Appendix C

GRAVITY SEDIMENTATION

Gravity sedimentation consists, very simply, of providing quiescent conditions in which suspended particles may settle through a liquid under the force of gravity. However, in practice, sedimentation is a relatively complex process, as discussed below.

Sedimentation Types

Four types of sedimentation are of interest in wastewater treatment. These are:

(1) Discrete Particle Settling - Individual particles settle independent of one another and at their terminal settling velocities.

(2) Flocculent Particle Settling - During settling, individual particles interact to form agglomerations. Thus, settling velocities of particles increase with depth.

(3) Zone Settling - Particles settle in constant contact with one another, forming, in effect, a porous mass. Settling rate depends on the density of the mass.

(4) Compression - Particles, through physical contact with one another, are mechanically supported by the walls and floor of the vessel. Settling rate decreases exponentially, gradually approaching zero.

Figure C-1 illustrates that the types mentioned above may occur simultaneously as a suspension settles. Detailed discussion of the various sedimentation types is found in reference 1.

Sedimentation Equipment

Although sedimentation equipment components take numerous forms, they all have the same basic components, including: inlet, settling, sludge,and outlet zones. Discussed here are the sedimentation hopper, spiral classifier, settling pond, clarification tank, solids contact clarifier, and Lamella

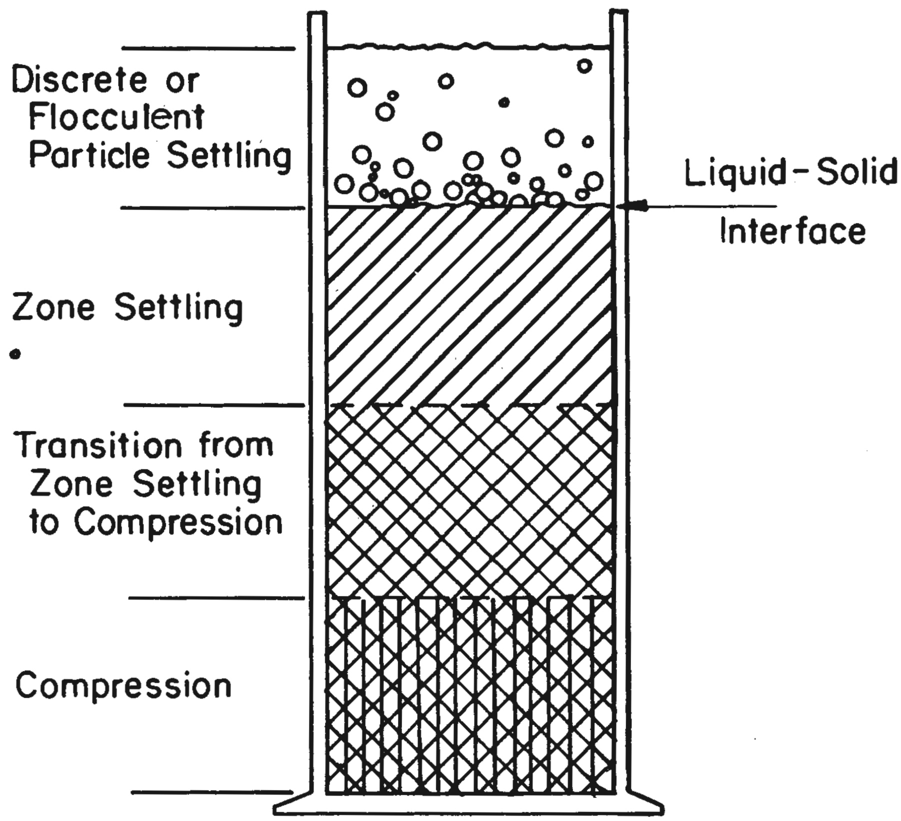


FIGURE C-1 - SEDIMENTATION TYPES IN A BATCH SETTLING PROCESS settler.

Sedimentation Hopper - Figure C-2 is a sketch of a sedimentation hopper in operation. The device actually consists of two identical compartments. Slurry is pumped into one compartment where coarse material settles out while water and fines overflow. Meanwhile, coarse material is removed from the other compartment via trap gates at the bottom. Two accessories may be used to enhance the general performance of the sedimentation hopper: a well screen system in each hopper to dewater sand and a vibrator on each "cone" to free arched sand.

Spiral Classifier - Figure C-3 is a cross sectional view of the spiral classifier. Slurry is fed into the classifier pool where coarse solids settle to the bottom of the tank,from which they are removed by a helical screw mechanism. Meanwhile, liquid and undersize material overflow via the weir.

Numerous options are available with the spiral classifier (2). Solids removal capability depends on effective settling area which may be increased in three primary ways: utilization of a flared tank as opposed to a straight-walled one, increasing of the weir height to increase tank submergence, or reduction of tank slope to increase submergence.A dryer solids product may be obtained by any one or combination of the following: increasing tank length, increasing tank slope, or decreasing auger rotational speed. Increased solids handling capacity may be obtained by: using a double or triple pitch auger rather than a single pitch type, or using two augers in parallel.

Settling Pond - Earthen settling ponds, where feasible, provide reliable, low maintenance treatment alternatives. Unfortunately, inherent characteristics such as turbulence caused by weather conditions make ideal performance nearly impossible. Furthermore, many construction project settling ponds are built solely on the basis of least cost, with little consideration given to efficient performance.

Several possibilities are available for general improvement of settling pond durability and performance. Roundish ponds are normally

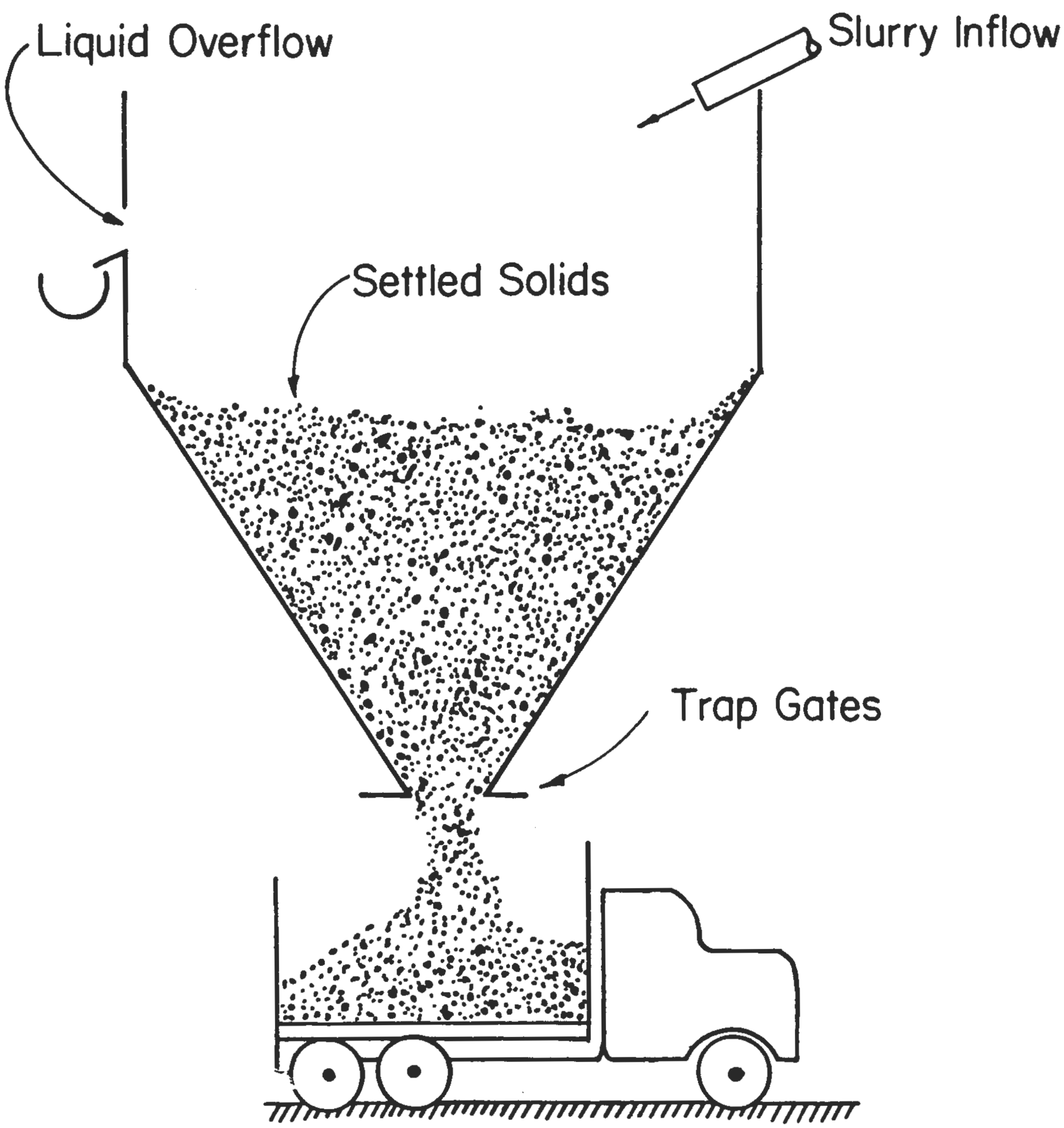


FIGURE C-2 - CROSS-SECTIONAL VIEW OF SEDIMENTATION HOPPER

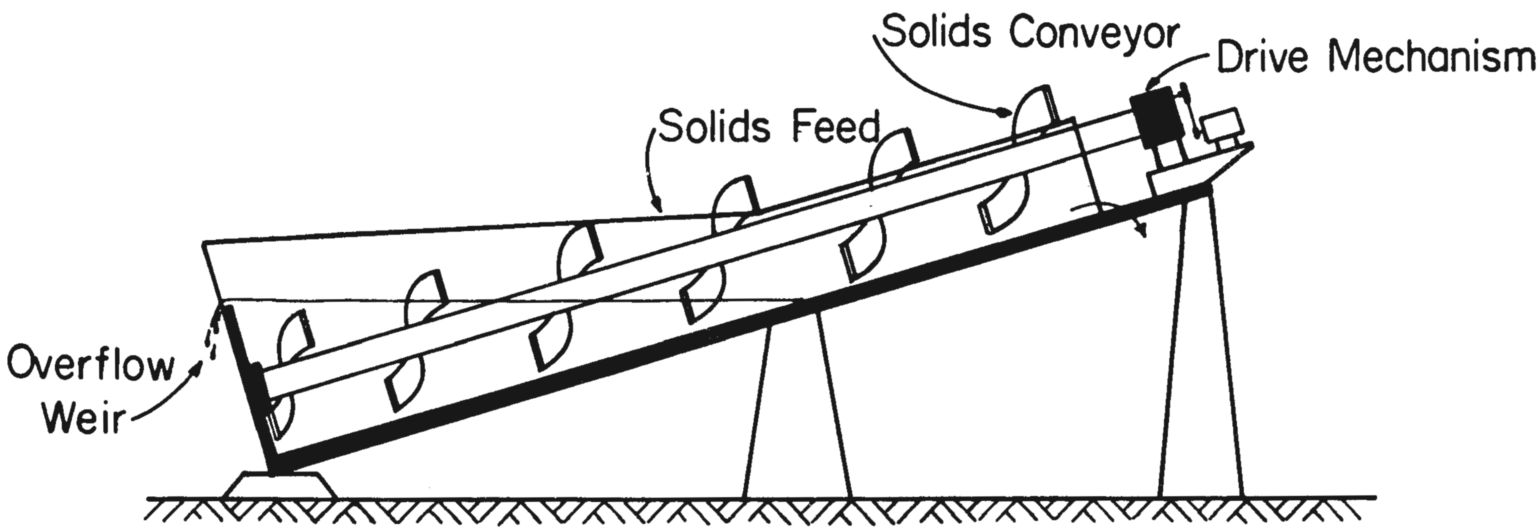
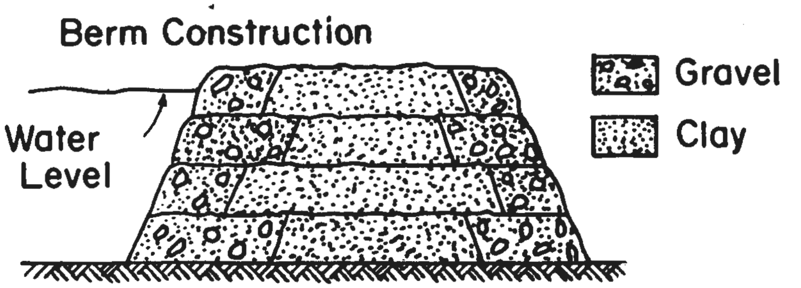


FIGURE C-3 - SPIRAL CLASSIFIER

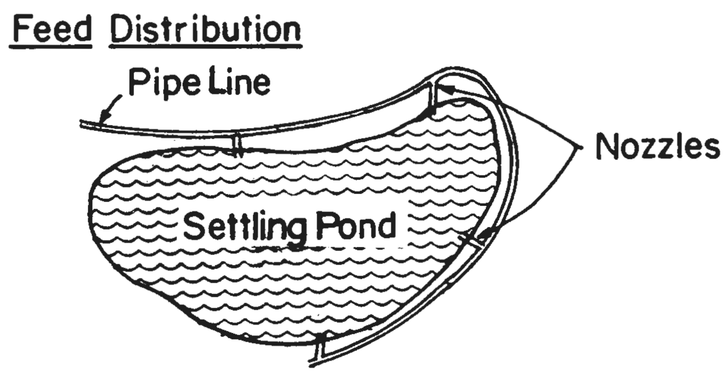
preferred for their compact geometry and low flow velocities. Retaining berms should be constructed so as to prevent slope failure; Figure C-4 illustrates a berm cross section used successfully by the mineral industry (3). Rubber liners may be used to protect berms and bottom from erosion, and prevent water loss by seepage. Inflow should not be piped directly into a pond, but rather, some effort should be made to dissipate energy and distribute flow; one possible method is to feed wastewater via several nozzles located around the pond (see Figure C-4). Baffles may be used at appropriate locations to increase retention time and prevent "short-circuiting". One successfully used type of effluent discharge apparatus is the "chimney" arrangement pictured in Figure C-4. (As pond and turbid water levels fluctuate, chimney holes may be plugged or unplugged to compensate.) Settled solids are normally either pumped out or mucked with a drag line.

The following rule of thumb may be used for approximating required pond area (3). About one acre of settling area is required per twenty tons of rapidly settling material produced daily; for slow settling material, one acre per ten tons (produced daily) may be required. If the above rule is followed, visually clean effluent should result. (The reader should note that in a situation of limited "working space", the practicality of utilization of a settling pond is also limited.)

Clarification Tank - This term usually refers to a large, shallow sedimentation tank such as the one in Figure C-5. Inflow is usually fed through the center column, and effluent is discharged into launders on the tank periphery. The tank floor is generally sloped inward, and a rake assembly mounted on the central shaft propels settled solids toward the removal outlet at the center. Other feed and discharge arrangements are occasionally used, and options such as a centrally mounted flocculation unit are available from some manufacturers. The clarification tank is sometimes referred to as a "thickener".



Clay core retards seepage. Interlocking gravel provides weight and prevents uplift.



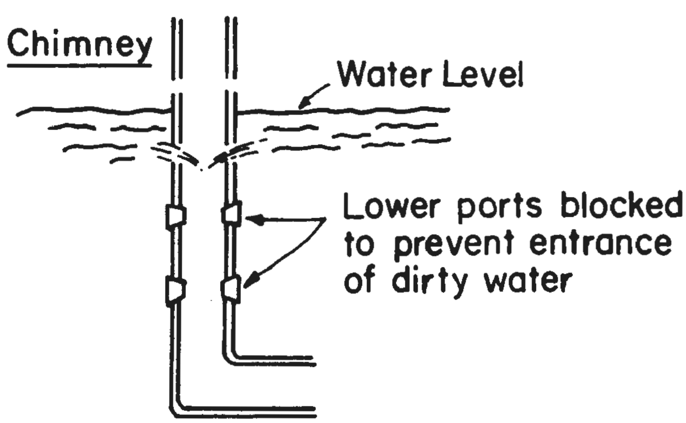


FIGURE C-4 - SETTLING POND DETAILS

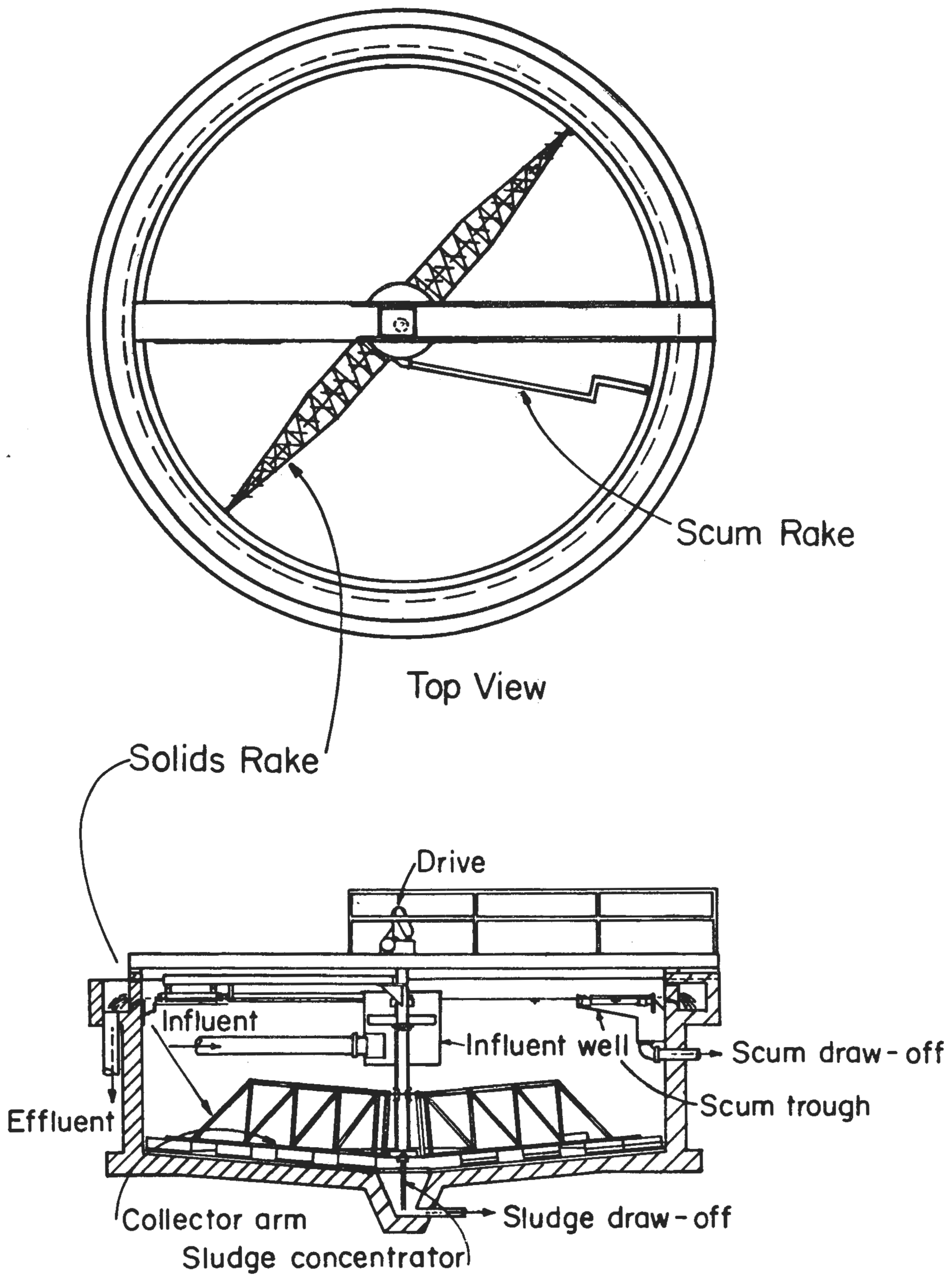


FIGURE C-5 - CLARIFICATION TANK

Solids Contact Clarifier - This device, illustrated in Figure C-6, combines the processes of chemical mixing, flocculation, and sedimentation into a single unit. (The unit is generally more sophisticated than the standard clarifier with its optional attachments.) Raw wastewater, chemicals, and treated sludge are simultaneously introduced to the mix unit, which, in addition to supplying agitation, also "pumps" the mixture to the flocculation chamber. Here, hydraulic turbulence induces inter-particle collisons and agglomeration. Particles settle from the flocculation chamber to the sludge blanket from which they are either recirculated through the mix-flocculation unit or withdrawn via the underflow.

Lamella Settler - Figure C-7 is a cutaway view of the Lamella settler, which is essentially a packaged clarification tank. Figure C-8 illustrates the basic principle of operation; liquid flow and particle settling velocities combine to produce resultant velocities such that particles settle onto the plate surfaces. Once on or near a plate surface, particles are trapped in a downward flowing sludge blanket and carried to the sludge hopper. Clarified effluent is removed via ports above the plates. The total settling area of the Lamella settler is the sum of the horizontally projected areas of all plates. The large settling-to-surface area ratio is particularly advantageous when treatment system mobility and total space requirements are factors.

Rapid mix and flocculation units are available as options with the Lamella settler.

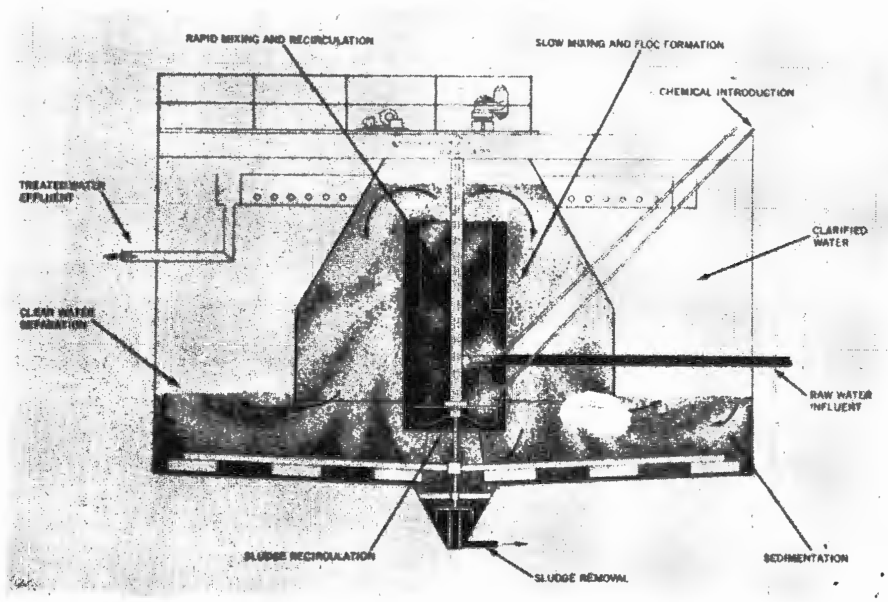


FIGURE C-6 - SOLIDS CONTACT CLARIFER

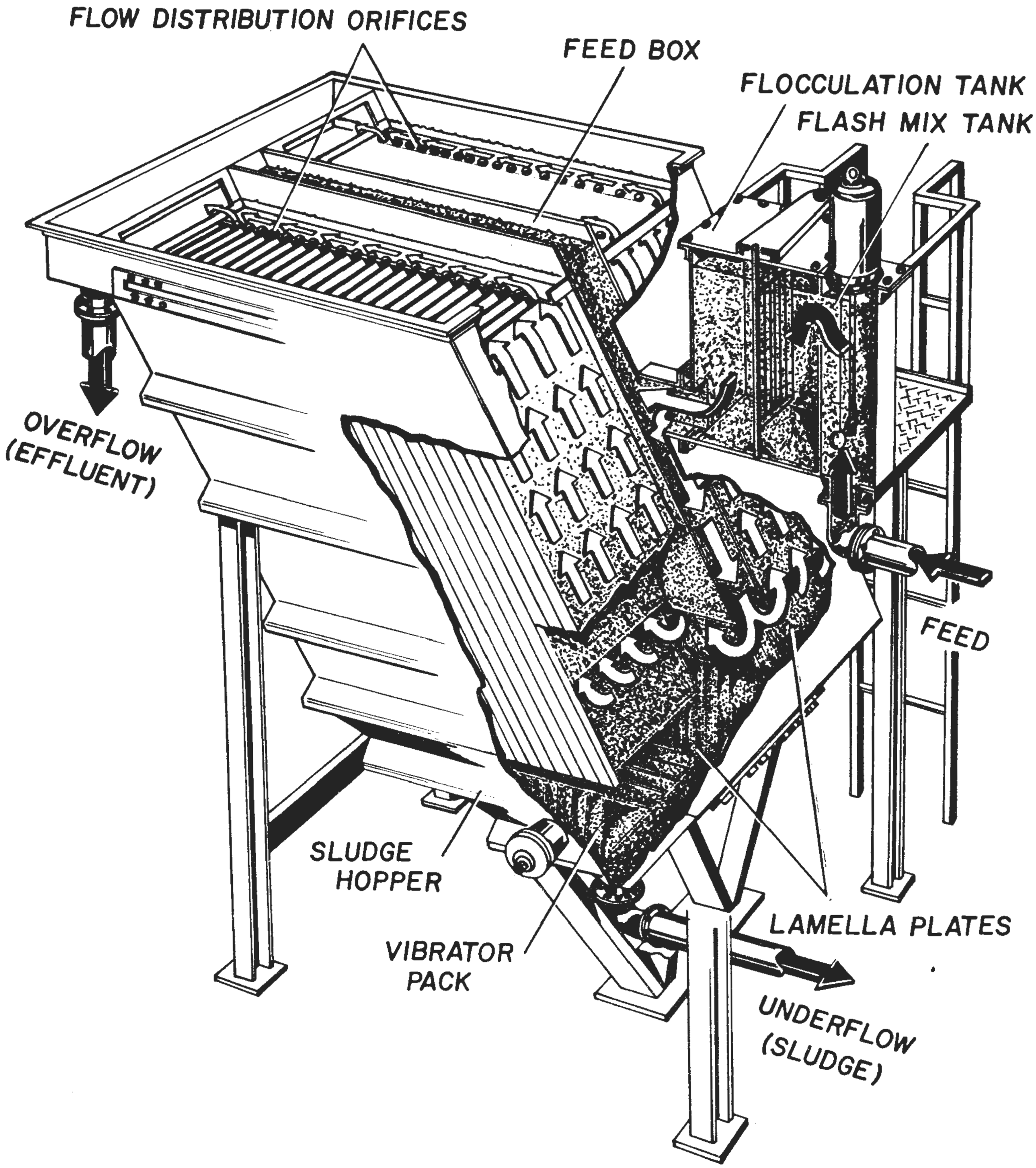


FIGURE C-7 - CUTAWAY VIEW OF LAMELLA SETTLER

(Courtesy of Parkson Corp.)

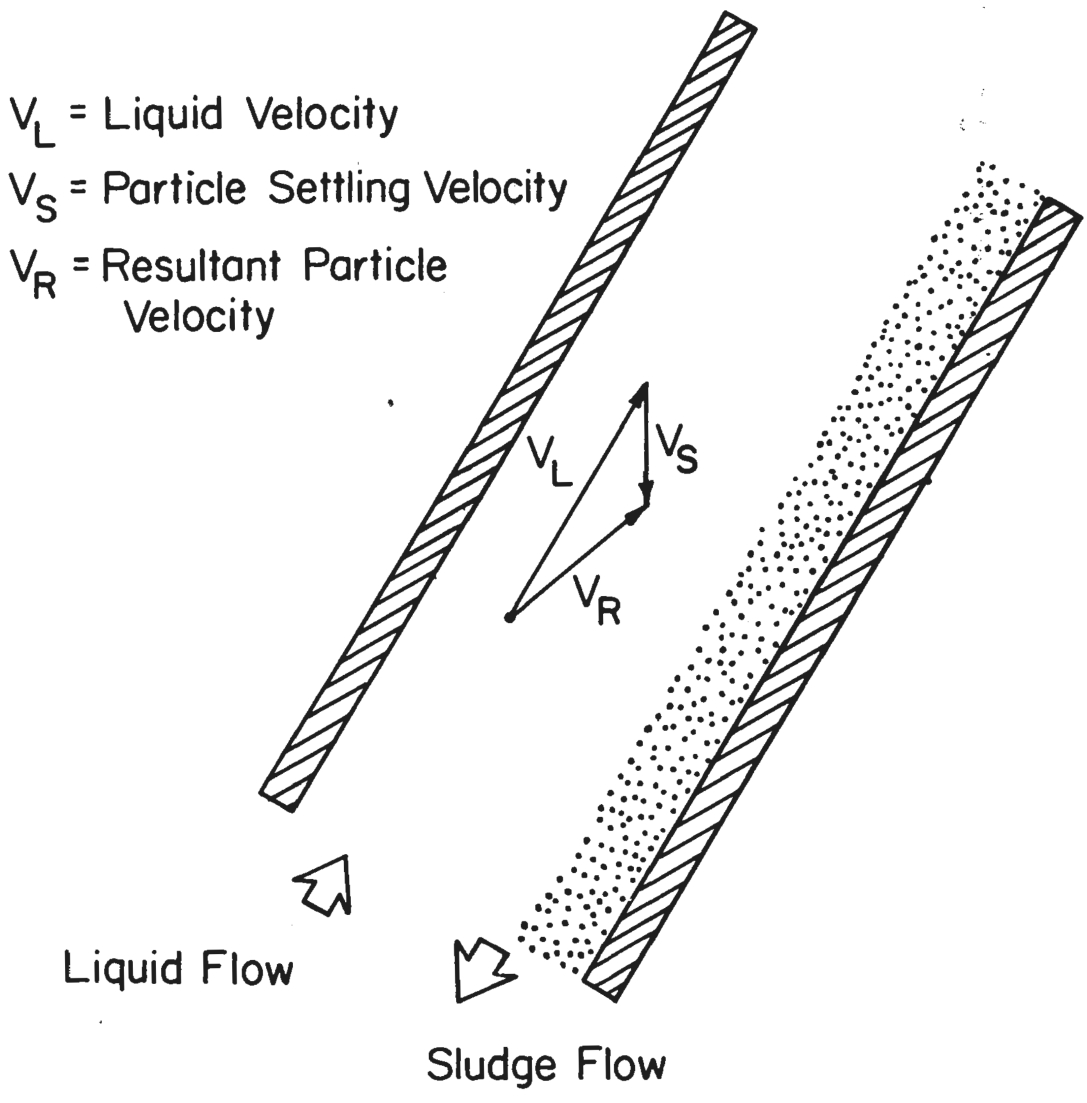


FIGURE C-8 - OPERATING PRINCIPLE, LAMELLA SETTLER (4)

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Appendix D

CENTRIPETAL FORCE SEPARATION

The previous appendices have discussed chemical processes which increase effective particle sizes of waste stream solids, and physical processes of filtration and sedimentation which remove particles from the waste stream by media entrapment and gravity settling. This appendix is concerned with a third physical process which utilizes the principle of centripetal force to separate particles from a fluid. Equipment types utilizing this principle include hydrocyclones and centrifuges.

Separation Principles

All centripetal force separators, in one way or another, make use of the following principle: a suspended particle traveling on a fluid streamline will tend to continue in a straight line if the streamline should curve. Figure D-1 illustrates a particle traveling along a fluid streamline. The particle's momentum tends to keep it in a straight line path while a drag force of the fluid tends to resist radially outward movement. The radial acceleration acting on the particle may be considered in light of Newton's Second Law as:

$$A = \frac{F}{M}$$

where A = radial acceleration

F = drag force

M = particle mass

The force, F, in the above equation represents drag force on the particle, which is directly proportional to the cross-sectional area of the particle, or, stated in a slightly different manner, proportional to the square of the particle diameter. The mass term, M, refers to the particle mass, which is directly proportional to particle volume or the cube of the diameter. Therefore, the acceleration, A (acting on the particle in a radially inward direction), is inversely proportional to the particle's

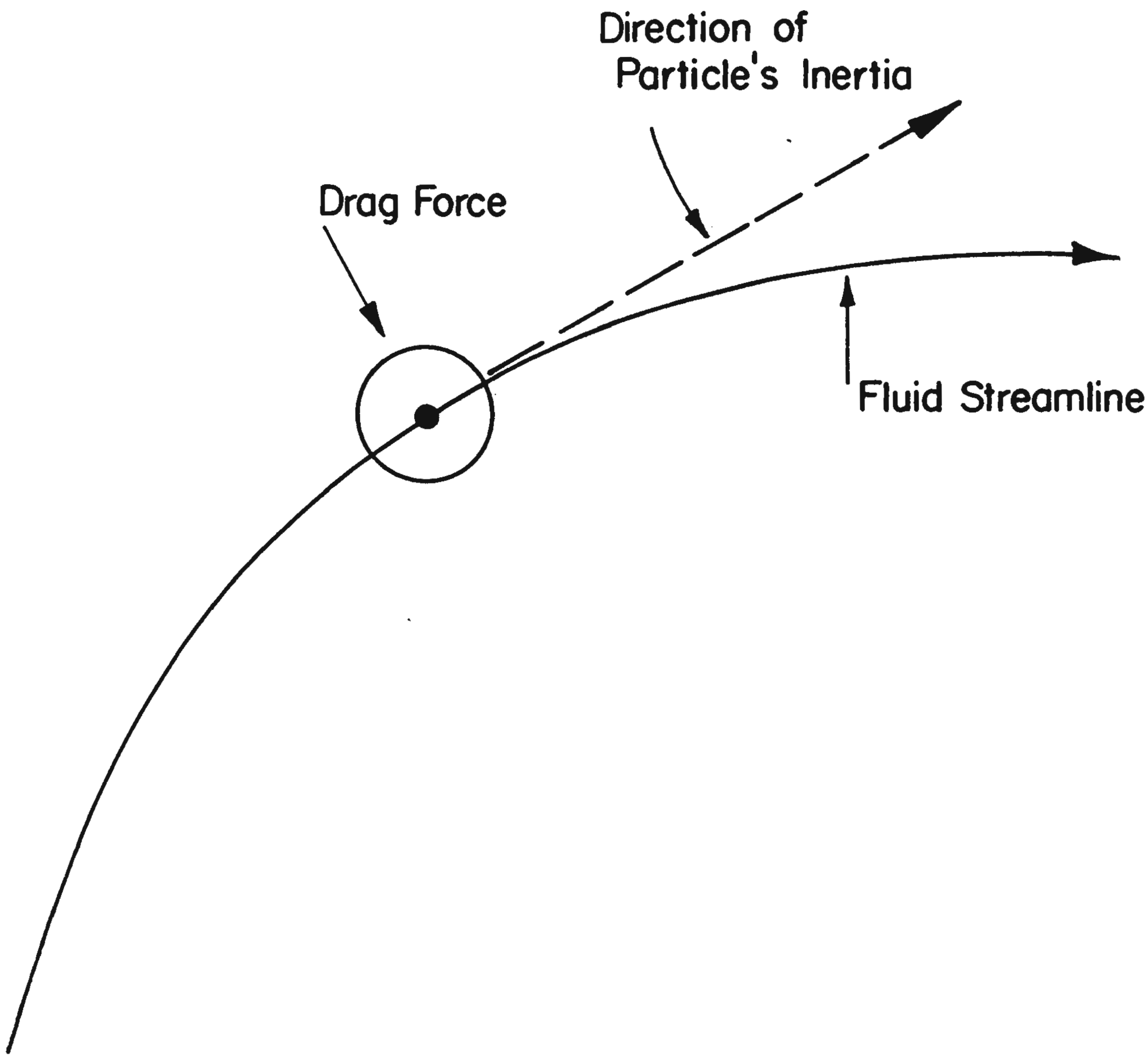

FIGURE D-1 - PARTICLE ON CURVED STREAMLINE IN VISCOUS LIQUID diameter. Consequently, a larger particle is acted on by less inward acceleration relative to its mass than a smaller particle, and tends to travel more rapidly "outward" from the original streamline.

Hydrocyclones and centrifuges function on this basic premise. However, the hydrocyclone utilizes the principle of a free vortex; sources external to the hydrocyclone supply energy for fluid rotation. By contrast, the centrifuge operates on the principle of a forced vortex; the spinning motion of centrifuge rotor transfers rotational energy to the fluid.

Hydrocyclones

Three major configurations of hydrocyclones are commonly utilized: the open underflow hydrocyclone, the closed underflow hydrocyclone, and the manifolded hydrocyclone. Of these, the open underflow type will be discussed in greatest detail since the others are merely variations of it. Quantitative discussion of the hydrocyclone is found in reference 1.

Open Underflow Hydrocyclone - Figure D-2 illustrates the major components of this hydrocyclone configuration. The solids suspension enters the inlet head with a relatively high tangential velocity. More massive solids spiral outward and collect on the walls of the hydrocyclone. Occurring simultaneously with the concentration of solids at the walls, is the withdrawal of solids at the cone apex, thus providing for the continuous removal of separated particles. Meanwhile, the liquid (displaced inward by the accumulation of "coarse" solids at the cyclone wall) and fine material (which was unable to reach the cyclone walls) form a suspension which flows upward through the vortex finder and out of the hydrocyclone.

A parameter frequently used to describe the separation capability of a hydrocyclone is the d_{50} size. This term simply refers to the particle diameter for which approximately half of the total number of particles in the feed (of this diameter) exit through the underflow and half through

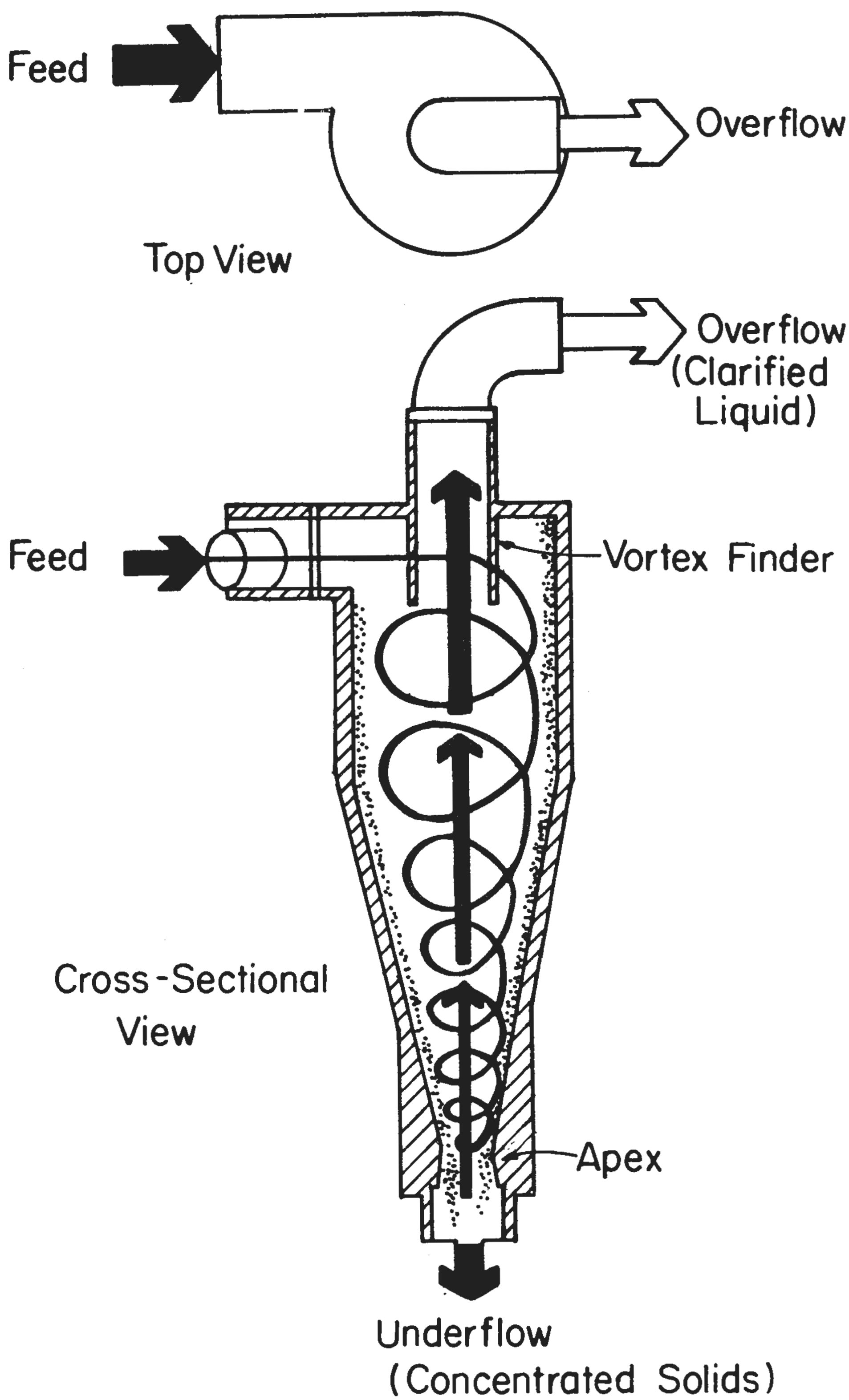

FIGURE D-2 - OPEN UNDERFLOW HYDROCYCLONE (2) the overflow. The d_{50} size is dependent upon various design and operating variables. Design variables include (2): diameters of cyclone body, feed nozzle, vortex finder, and underflow orifice, cylindrical section length, cone angle, feed nozzle and apex shape, internal surface conditions, and inclination of cyclone axis. Operating variables include: fluid flow rate, solids feed rate, and pressure drop.

Closed Underflow Hydrocyclone - This device, illustrated in Figure D-3a, is utilized when a continuous underflow discharge is undesirable or when minimum underflow moisture content is desired. The basic cyclone is the same unit described in the previous section with an intermittently discharging sand pot attached to the underflow. Turbulent conditions in the sand pot may result in re-entrainment of solids in the outflowing liquid (see Figure D-3b). re-entrainment may be controlled by utilization of a contamination trap as shown in Figure D-3c (3). Some degradation of the cyclone overflow may result from increased back-pressure caused by the sand pot attachment.

Manifolded Hydrocyclones - The d_{50} size of hydrocyclone is roughly proportional to the diameter of the cyclone cylindrical section. Thus, when a "fine" separation of a large volume of slurry is desired, parallel manifolding of multiple small diameter hydrocyclones often provides a satisfactory solution. Radial manifolding is usually preferred over in-line manifolding because radial manifolding produces more uniform pressure drops and distribution of solids, resulting in better overall performance (2).

Centrifuges

Two primary types of centrifuge are currently used in wastewater treatment work. They are the disc and solid bowl types. Mathematical discussion of each is found in reference 4.

Disc Centrifuge - Figure D-4 is a cutaway view of a disc type centrifuge. Influent enters the feedwell as shown, and then flows on into the separation chamber of the rotor. Here the coarser feed solids are

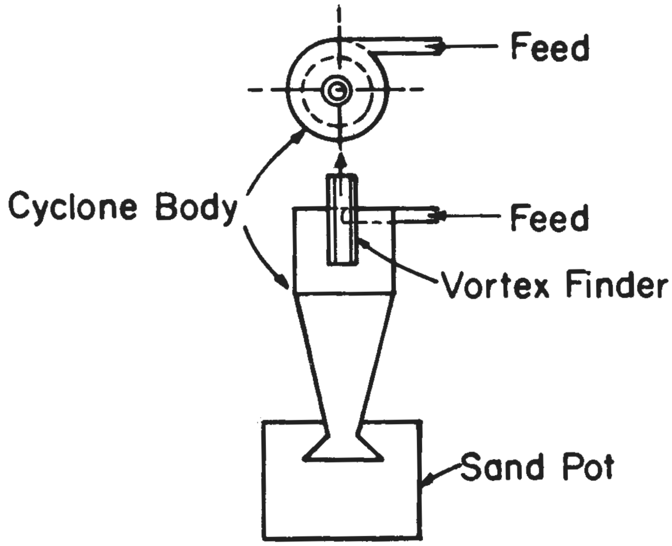

FIGURE D-3a - CLOSED UNDERFLOW HYDROCYCLONE (3)

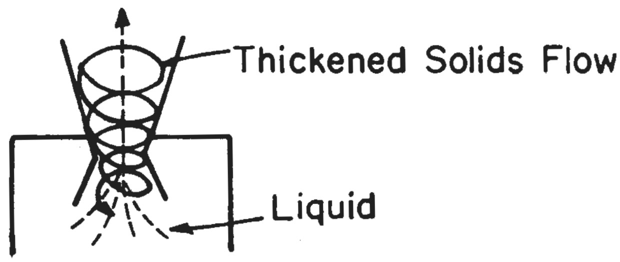

FIGURE D-3b - FLOW CONDITIONS AT APEX OF CLOSED UNDERFLOW HYDROCYCLONE

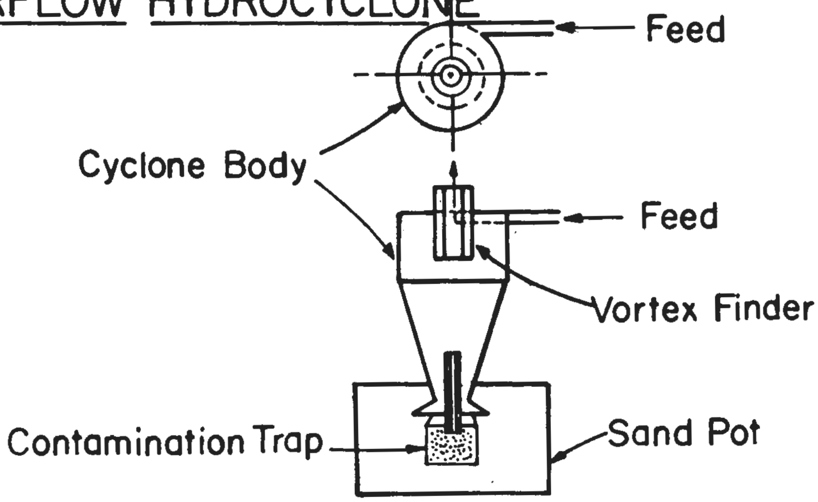

FIGURE D-3c - CLOSED UNDERFLOW HYDROCYCLONE WITH A CONTAMINATION TRAP (3)

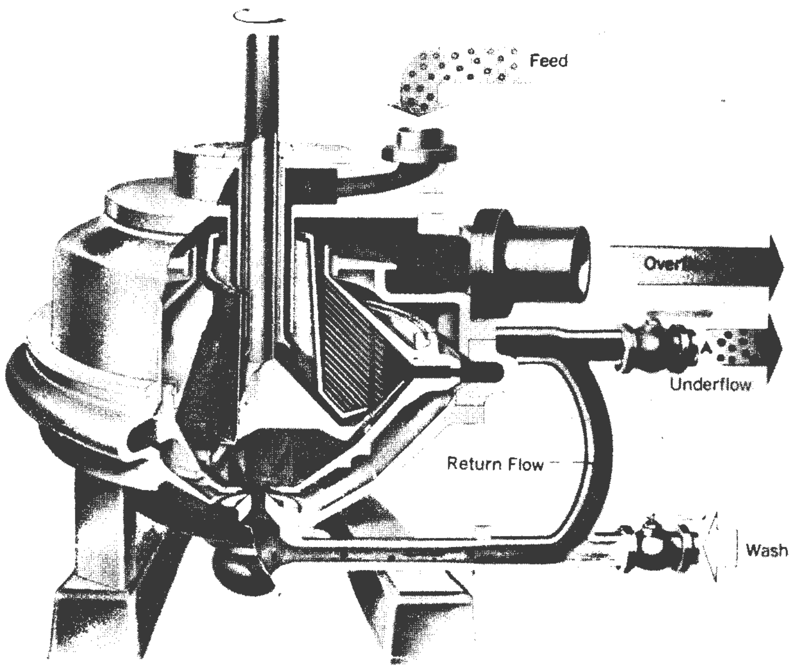

FIGURE D-4 - DISC CENTRIFUGE

deposited against the chamber walls and gradually spiral outward to the nozzles at the rotor periphery through which they are removed. Liquid and small unsettled solids continue past the nozzle point and enter the disc stack. Individual discs act like the multiple plates in the Lamella settler to remove slowly settling particles. These settled fines are drawn by the spinning motion of the disc stack to the discharge nozzles, while clarified effluent flows up through the disc stack and is removed as shown. Some of the underflow solids may be recycled back to preload the nozzles (as illustrated), thus thickening the outflow stream and producing a drier solids product. The nozzle size and discharge interval should be coordinated to prevent clogging or re-entrainment of solids (4).

Solid Bowl Centrifuge - Figure D-5 illustrates the principle components of the solid bowl centrifuge. Feed is introduced to the centrifuge "bowl" through a concentric tube. The rotation of the bowl causes the formation of a cylindrical "pool" with its water surface essentially parallel to the bowl axis. Feed solids settle out, accumulate on the walls of the bowl, and are transported toward the solids discharge port by a helical screw conveyor which rotates at a slightly slower rate than the bowl. Solids are drawn out of the pool and onto the drying beach where they are allowed to drain before discharge. Clarified effluent is discharged over a "weir" at the opposite end of the centrifuge bowl.

Separation performance of the solid bowl centrifuge may be improved by treating the influent with coagulant chemicals, or by "raising" the weir level so as to increase settling area (4). The second alternative, raising the weir level, results in a shorter drying beach, and consequently, a wetter solids product. When fluid containing abrasive solids is centrifuged, conveyor flights, beach, and solids discharge port may be subject to significant abrasion.

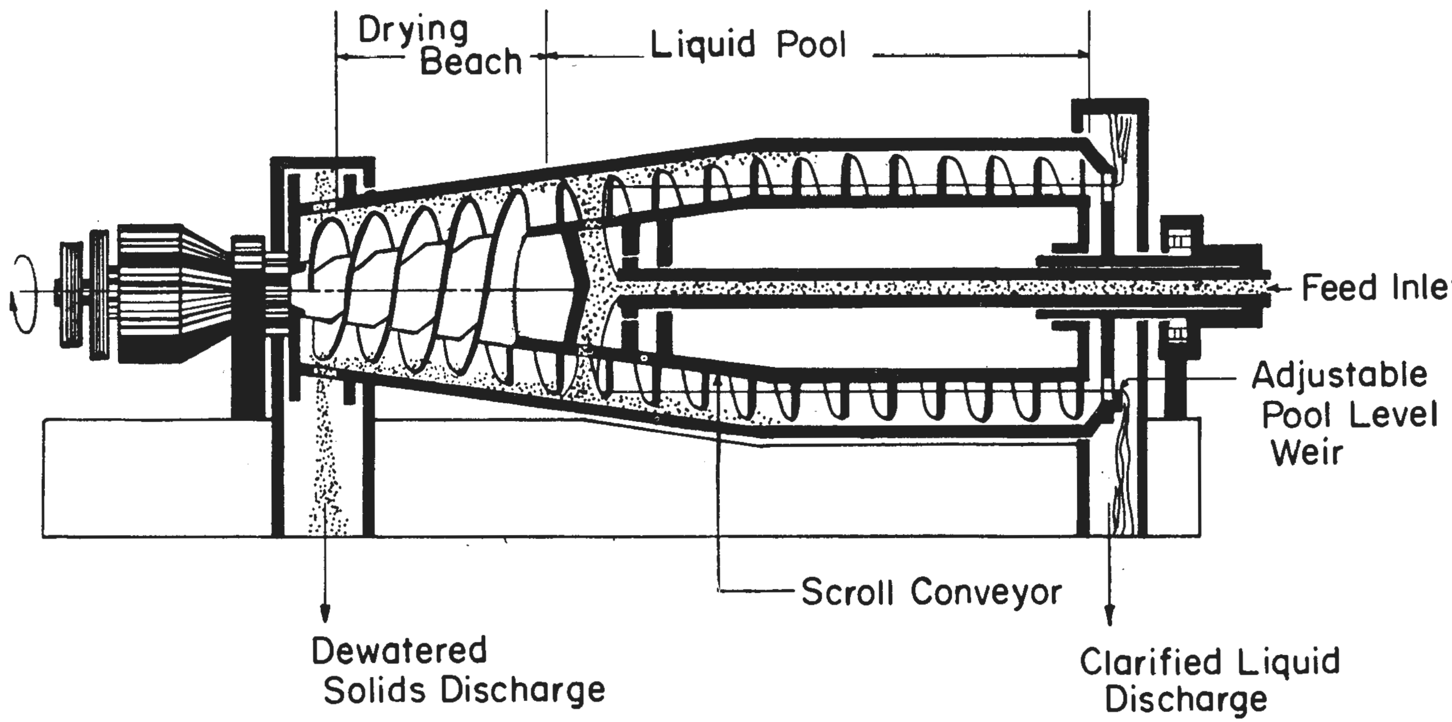

FIGURE D-5 - SOLID BOWL CENTRIFUGE
(Courtesy of Dorr-Oliver, Inc.)

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Appendix E

PROCESSES IN HYDRAULIC TUNNELING WASTE TREATMENT

The previous four appendices have discussed processes and equipment which could be utilized for the removal of the principal pollutant in a hydraulic tunneling waste stream--suspended solids. This appendix will discuss the various steps involved in the treatment of the waste stream and will suggest specific equipment types to fill the various applications. First, however, a brief discussion of desirable system criteria will be presented.

System Criteria

Listed below are some basic desirable criteria for waste treatment system design (1). This list is intended only to identify significant criteria for the treatment system design; it is not meant to speculate as to their relative importance. The treatment system should:

(1) Produce effluent of a quality which is adequate for one of the following: disposal in public waters, economical discharge to the sanitary sewer, or re-use in the tunneling system.

(2) Produce a muck or sludge that is economically transportable by conventional means such as truck or rail.

(3) Be of acceptable size, configuration, and character for location at a portal site within an urban environment.

(4) Be reasonably portable so that it may be moved from one portal site to another.

(5) Be reasonably capable of year-round operation.

(6) Utilize rugged, proven, readily maintainable components.

(7) Utilize operating procedures that are simple and readily understandable.

(8) Have sufficiently low capital, operating, and maintenance costs so that it does not place an extreme economic burden on the hydraulic tunneling process as a whole.

Waste Treatment Processes

A waste treatment system usually consists of numerous steps or processes, each of which plays a role in efficient overall treatment. Described below are processes that would (or may be) required for the successful treatment of hydraulic tunneling wastes:

(1) Coarse Fraction Removal - A hydraulic tunneling waste stream (from St. Peter Sandstone tunneling) normally contains a large portion of sand-size particles which are relatively easy to remove by physical straining, sedimentation, or centripetal force separation.

(2) Initial Chemical Destabilization - The waste stream also typically contains a small portion of fine material not removed by the previous process. If the material is sufficiently fine and present in significant quantities, chemical coagulation may be required to aid in its removal.

(3) Clarification - After the fines-bearing wastewater has been chemically treated, some process must be utilized to remove suspended agglomerations. Gravity settling is most commonly used, with centripetal force processes gaining some acceptance.

(4) Final Suspended Solids Removal - Some quantity of suspended material invariably passes through the clarification process with the effluent. If the removal of this fraction is desired, some form of filtration is normally utilized.

(5) Thickening - The clarification process normally produces a thin, watery solids product. Thickening is utilized to increase the solids concentration of this phase. (Thicker sludge is desirable because it may be disposed of more economically or dewatered more efficiently than a thinner sludge.) Sedimentation and centripetal force processes are both utilized.

(6) Chemical Sludge Conditioning - If further dewatering of the thickened sludge is desired, the sludge is treated with coagulants to obtain a product more amenable to dewatering.

(7) Sludge Dewatering - This process is utilized to remove as much water as is practical from sludge so as to minimize costs of final hauling and disposal. Filtration and centripetal force processes have both been successfully utilized.

Evaluation of Equipment Components

The previous section discussed the various steps in a hydraulic tunneling waste treatment process. This section will discuss the specific equipment components and their suitability for the various applications.

Coarse Fraction Removal - The following equipment components are normally used for coarse fraction removal:

(1) Filtration
   (a) Vibrating Screen
   (b) Sieve Bend
   (c) Pipeline Strainer

(2) Sedimentation
   (a) Sedimentation Hopper
   (b) Spiral Classifier
   (c) Settling Pond

(3) Centripetal Force
   (a) Open Underflow Hydrocyclone
   (b) Closed Underflow Hydrocyclone

The vibrating screen is a device utilized for making separations in the coarse sand range. (Minimum available screen opening is about Number 48 Tyler mesh size (1).) Thus, for a waste stream containing solids with a grain size distribution such as that of St. Peter sandstone (see Figure 1-3), the vibrating screen would remove very little suspended material. Consequently, this device is of little value for that particular application.

The sieve bend requires a nearly constant flow rate and solids loading to obtain a uniform separation performance (2). Since both parameters are continually fluctuating in the tunneling waste stream, the sieve bend would not be practical for coarse fraction removal.

The pipeline strainer is a small device placed in a pipeline to trap an occasional coarse particle (3), whereas the solids flow rate from a tunneling operation is measured in terms of tons per hour and may contain as much as fifty percent coarse solids. Thus, the pipeline solids strainer is obviously inadequate for this application. (However, the device could find application in the system straining the inflow to certain equipment components which could be damaged by oversize material.)

The sedimentation hopper has performed well enough to be an industry standard ever since the inception of hydraulic tunneling in St. Peter sandstone, and consequently, should be a leading candidate for coarse fraction removal in any future system.

The spiral classifer has served a similar duty in the mineral processing industry as the sedimentation hopper has in hydraulic tunneling operations. However, a spiral classifier of a given settling area would probably have a capital cost of several times that of a hopper with equivalent settling area (4) while operation and maintenance costs would probably be similar for both. Consequently, the spiral classifier would not be an economical choice and will not be considered further.

The earthen settling pond could suffice as a coarse fraction removal device if sufficient land area was available. However, this "component" is completely lacking in mobility and requires a separate system to remove settled solids. Thus, although the earthen settling pond cannot positively be ruled out, it is somewhat deficient when examined in light of the specified system criteria (see above).

Open- and closed-underflow hydrocyclones both require relatively constant liquid and solids flow rate for proper performance (2). Therefore, like the sieve bend, they probably would not perform properly in treating the hydraulic tunneling waste stream.

<u>Initial Chemical Destabilization</u> - Appendix A recommended organic polyelectrolytes (polymers) as the most practical coagulants for chemical treatment of hydraulic tunneling wastes. Listed below are the equipment components used in preparation, feeding and mixing of polymers, and

flocculation of the treated wastewater:

(1) Preparation Units
   (a) Dry Polyelectrolyte Preparation Unit
   (b) Wet Polyelectrolyte Preparation Unit
(2) Feeding Pumps
   (a) Plunger Type
   (b) Piston Type
   (c) Gear Type
   (d) Diaphragm Type
   (e) Progressive Cavity Type
(3) Mixing Units
   (a) Rotating Impeller (or Turbine) Type
   (b) Rotating Drum Type
   (c) Pipeline Turbulence
(4) Flocculation Units
   (a) Baffled Type
   (b) Paddle Type

The particular type of preparation unit to be utilized depends on the product form of the selected polyelectrolyte. Thus, either the wet or dry types could conceivably be used. Feed pump selection, like the selection of a preparation unit, depends on chemical characteristics. In addition, system parameters such as those discussed in Appendix A may also influence the selection.

Of the three mixing processes listed above, the rotating impeller (or turbine) type would probably be selected because it would provide the intensity of agitation which is required to contact the chemical with the dilute wastewater. By contrast, the rotating drum type would probably be unable to supply mixing of the required intensity. Pipeline turbulence could be used in conjunction with other types of mixing if further agitation was required.

The paddle flocculator is generally preferred over its baffled counterpart, because of the degree of process control possible with the former. Paddle speed may be adjusted to produce the optimum amount of agitation from the paddle unit while geometry must be altered to change agitation characteristics of the baffle unit. Furthermore, the baffled flocculator requires substantially less hydraulic head than the paddle flocculator (5).

Clarification - The following equipment components have potential application in the clarification process:

(1) Sedimentation
  (a) Settling Pond
  (b) Clarification Tank
  (c) Solids Contact Clarifier
  (d) Lamella Settler

(2) Centripetal force
  (a) Manifolded Hydrocyclones

The settling pond was previously suggested as a possible coarse fraction removal component, and likewise, could be utilized for clarification. However, it is not recommended for the reasons outlined above.

The clarification tank and solids contact clarifier are similar devices which theoretically could be used for hydraulic tunneling waste stream clarification but require large amounts of surface area and are definitely not portable; therefore, they are not satisfactory for the particular application. The Lamella settler provides a large settling area in one compact, portable unit. Thus, the device shows excellent promise for the clarification process.

The use of manifolded small-diameter hydrocyclones for clarification presents somewhat of a dilemma. Attempts to clarify clay suspensions with small diameter hydrocyclones have had limited success. (For one hydrocyclone clarification study (6), two test units were examined: the first had a cone diameter of 2.46 inches and a flow rate of 6.3 gallons per minute while the second had a diameter of 1.00 inches and a flow rate of 2.0 gallons per minute. A test suspension of kaolinite clay in water was utilized. During the first phase of testing, intermittent recycling was utilized, and reported effluent solids separation and underflow concentrations efficiencies were very low. During the second phase, effluent was continuously recycled back through the hydrocyclone. For the kaolinite-water suspension, suspended solids concentration was reduced from about ninety to about eight milligrams per liter after about fifteen minutes of continuous recycling. During several test runs, suspensions were treated with coagulant chemicals, but the use of coagulants did not appear to improve hydrocyclone performance.) The earlier discussion of hydrocyclones stated that a constant solids feed rate was a prerequisite for good hydrocyclone performance; since solids concentrations of the clarification influent vary considerably (see Figure 2-5), some fluctuation in cyclone performance could be expected. Consequently, at the present time, the use of hydrocyclones for clarification must be ruled out.

Final Suspended Solids Removal - The following equipment is used for final suspended solids removal:

(1) Filtration
  (a) Deep Bed Filter
  (b) Microstrainer
  (c) Pressure Filter

As stated in Appendix B, deep bed filtration is a complex process involving a large capital investment, high operating costs (skilled operator required, etc.) and detailed operating procedures. Consequently, utilization of a deep bed filtration system is probably not warranted for a tunneling operation waste treatment operation.

Although the microstrainer generally lacks the removal capabilities of the deep bed filter, it is much simpler to operate, is relatively portable, and has a much lower capital cost. Consequently, the microstrainer provides a more suitable final suspended solids removal device.

The pressure filter has been successfully used for the final filtration of wastewater (7), and since it is relatively compact, portable, and low in cost, it should also be considered as a possible alternative.

Before leaving the discussion of final suspended solids removal, one final point should be emphasized: for successful final suspended solids removal, an additional chemical treatment process would probably be required just prior to filtration.

Thickening - Gravity thickening of settled solids may occur simultaneously with clarification in a single sedimentation tank; clarification occurs in the upper regions while thickening proceeds near the bottom. Thus, thickening, as well as clarification performance, must be examined when selecting a sedimentation tank for fines removal. A portion of the total settling area of the Lamella settler is reserved solely for thickening, and consequently, the device should perform acceptably.

The disc and solid bowl centrifuges have been utilized as thickening devices. However, neither is recommended for thickening; the solid bowl centrifuge because it has difficulty maintaining constant operation, and the disc type because of its various operational problems (mainly clogging) (8).

Sludge Conditioning - Organic polyelectrolytes were also suggested for sludge conditioning use. The equipment used for sludge conditioning is essentially the same as that used for initial chemical destabilization (see equipment list - Initial Chemical Destabilization).

As before, the selection of a preparation system and feeding pump depends on characteristics of the chemical and wastewater, and operating conditions.

Where violent agitation was necessary for the mixing of the chemical in the initial destabilization process, more gentle agitation is desirable in sludge conditioning so that previously formed agglomerations will not be destroyed. Thus, the rotating drum mixer and/or pipeline turbulence are suggested in lieu of impeller-type mixing.

Due to the close proximity of individual particles and the resulting grain growth due to "naturally" induced inter-particle collisions, a separate flocculation process is usually not required in sludge conditioning.

Sludge Dewatering - The following devices find application in the area of dewatering:

(1) Filtration

(a) Vacuum Filter

(b) Pressure Filter

(c) Dual Cell Gravity Filter

(d) Belt Press Filter

(2) Centripetal Force

(a) Disc Centrifuge

(b) Solid Bowl Centrifuge

The vacuum filter, although well established in the area of sludge dewatering, has several major disadvantages, including: an extensive equipment layout, high maintenance requirements, and operational problems such as screen blinding (9). Consequently, this device is not well suited to applications such as hydraulic tunneling wastewater treatment and will not be considered further.

The pressure filter is essentially a "batch treatment" apparatus, requiring relatively frequent operator attention. Thus, it will not be considered as an option.

The dual cell gravity and belt press filters have been successfully utilized to dewater industrial clarification sludges (10). In addition, they may be trailer-mounted, providing a great deal of mobility. Therefore, they should be considered as possible alternatives for the dewatering process.

The disc centrifuge, with its close tolerence disc stock and discharge nozzles, is subject to clogging due to the presence of trash in the sludge or unexpected power failures (9). Thus, the device is not considered further as an option.

The solid bowl centrifuge is gaining popularity as a dewatering device. Although problems are sometimes encountered with clogging and abrasion, the device has a relatively low capital cost and simple operating procedures (9).

Summary

The table below summarizes the equipment selections made above:

Table E-1
Equipment Selections

Process	Equipment Component(s)
Coarse Fraction Removal	Sedimentation Hopper
Initial Chemical Destabilization	
a. Preparation	*
b. Feeding	*
c. Mixing	Impeller or Turbine Mixer
d. Flocculation	Paddle Flocculator
Clarification-Thickening	Lamella Settler
Final Suspended Solids Removal+	Microstrainer or Pressure Filter
Sludge Conditioning	
a. Preparation	*
b. Feeding	*
c. Mixing	Rotary Drum
d. Flocculation	None
Sludge Dewatering	Solid Bowl Centrifuge, Dual Cell Gravity Filter, or Belt Press Filter

* Depends on type of coagulant used
+ May require additional chemical treatment equipment

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Appendix F

TREATMENT SYSTEM ACCESSORIES

The previous appendices have dealt with equipment components whose principal function is the separation of solids from a liquid. This appendix will deal with two classes of accessories necessary for the treatment system operation. These are:

(1) Controls and Monitoring Devices

(2) Pumps

Discussion of each class is presented below.

Controls and Monitoring Devices

Controls and monitoring devices are necessary parts of a treatment system because they measure various wastewater and treatment system parameters, detect changes in wastewater characteristics, provide for the assessment of treatment effectiveness, and, in some cases, actually initiate or terminate treatment processes. The following controls and monitoring devices are considered:

(1) Pressure Conduit Flow Meters

(2) Open Channel Flow Meters

(3) Fluid Density Meters

(4) Interface Level Sensors

(5) Turbidimeters

(6) pH Sensor/Controllers

Pressure Conduit Flow Meters - Inherent to any wastewater treatment system is the need for the continuous measurement of flow rates of wastewater inflow, effluent, sludge, chemicals, or dilution water. Just as the various applications differ, the optimum meter type for each particular application also differs. Several meter types are discussed below, including:

(1) Differential Pressure

(2) Variable Area

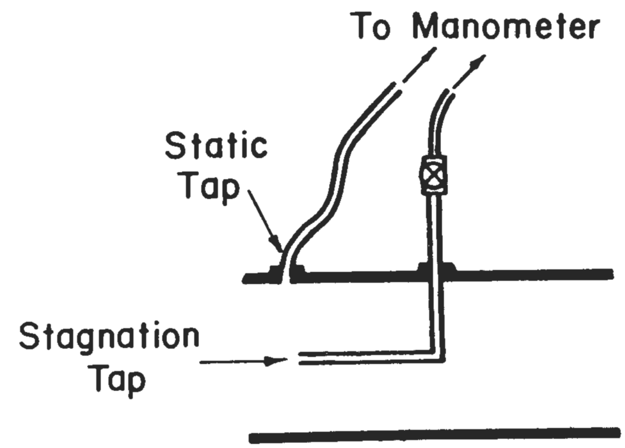


FIGURE F-1 - PITOT TUBE FLOW METER

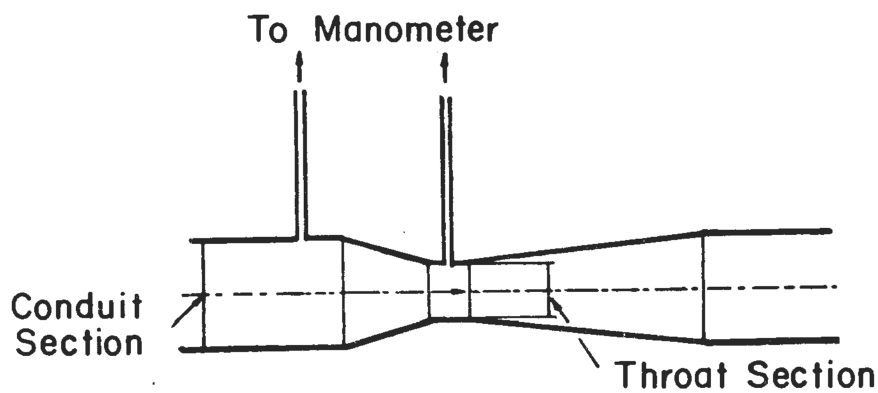


FIGURE F-2 - VENTURI FLOW METER

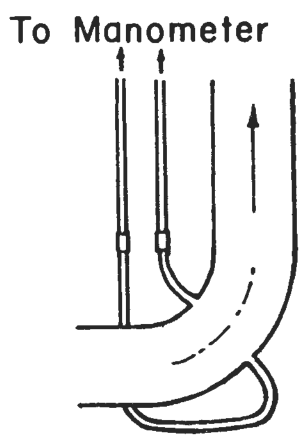


FIGURE F-3 - ELBOW FLOW METER

(3) Electromagnetic

(4) Vortex Shedding

The basic principles of each type and the potential application in a hydraulic tunneling waste treatment system are also discussed.

Differential pressure flow meters induce a change in the pressure head in a conduit which can, in turn, be related to flow rate (1).

Figure F-1 schematically illustrates the principle of the pitot tube. The wall tap of the pitot tube senses static pressure of the liquid while the projecting tap senses stagnation (total static and dynamic) pressure. The difference in pressures may be correlated to flow rate (1).

Another common differential pressure device is the Venturi meter shown in Figure F-2. The constriction, or throat, of the Venturi induces an increase in flow velocity with a corresponding pressure drop. The difference in pressure is sensed by taps "above" and in the throat section, and this difference is again related to flow rate (1).

A third differential pressure meter is the elbow meter, illustrated in Figure F-3. This device senses the pressure difference between the inner and outer radii of an elbow and relates the difference to flow rate (2).

Although differential pressure meters are simple and widely utilized, they have certain operational limitations. First, since all use Bernoulli's principle in one form or another to determine flow rate, the density of the fluid is a factor; if density fluctuates randomly and is <u>not</u> recorded as a function of time (as may be the case for a slurry flow), nonsense pressure data will be transmitted (3). Other problems include: limited flow range, the possibility of a non-uniform flow velocity profile (a length of straight pipe upstream of the meter is a necessity), the plugging of pressure taps by suspended solids, and the presence of gases in pressure lines (3).

Differential pressure meters may be read visually from standard manometers or may be set up for electronic read-out by the utilization of pressure transducers.

Generally, differential pressure devices are most suitable for clean water flows with fluctuations of not more than three to one (maximum to minimum flow rate) (3). A possible application would be the measurement of the rate of clean water supply to the tunneling operation.

Variable area meters use the principle which is opposite to that used by differential pressure meters; variable area meters maintain a constant pressure while varying flow area (1). Figure F-4 illustrates the most common type, usually known as a rotameter. The meter consists basically of a freely translating disc in a vertical tapered tube. As liquid flows upward through the tube, the disc is lifted to a position of equilibrium between weight and drag. Flow rate is determined by the position of the disc in the tube. The term "rotameter" is derived from the fact that the disc is equipped with small vanes which cause it to spin in the flowing liquid, thus increasing stability. A sphere or other shape could be used, but the disc seems to "behave" more uniformly over a range of flow rates.

Numerous other types of variable area meters are available; the most common being the spring-loaded gate type. Visual read-out is normally utilized although electronic systems are available.

Variable area meters would most likely be used for the measurement of small clean water or chemical flows as part of a chemical treatment system.

The electromagnetic flow meter operates on Faraday's principle of induction which states that a conductor moving through a perpendicular magnetic field induces a voltage proportional to the conductor velocity and normal to the plane of flow and magnetic flux lines (see Figure F-5a) (1).

Figure F-5b illustrates a standard commercial magnetic flow meter. The magnetic field is set up by two saddle-shaped electric coils. Flowing liquid induces a voltage which is sensed by two strategically placed electrodes. (Obviously, the flowing liquid must be electrically conductive for the meter to be effective, but the required threshold

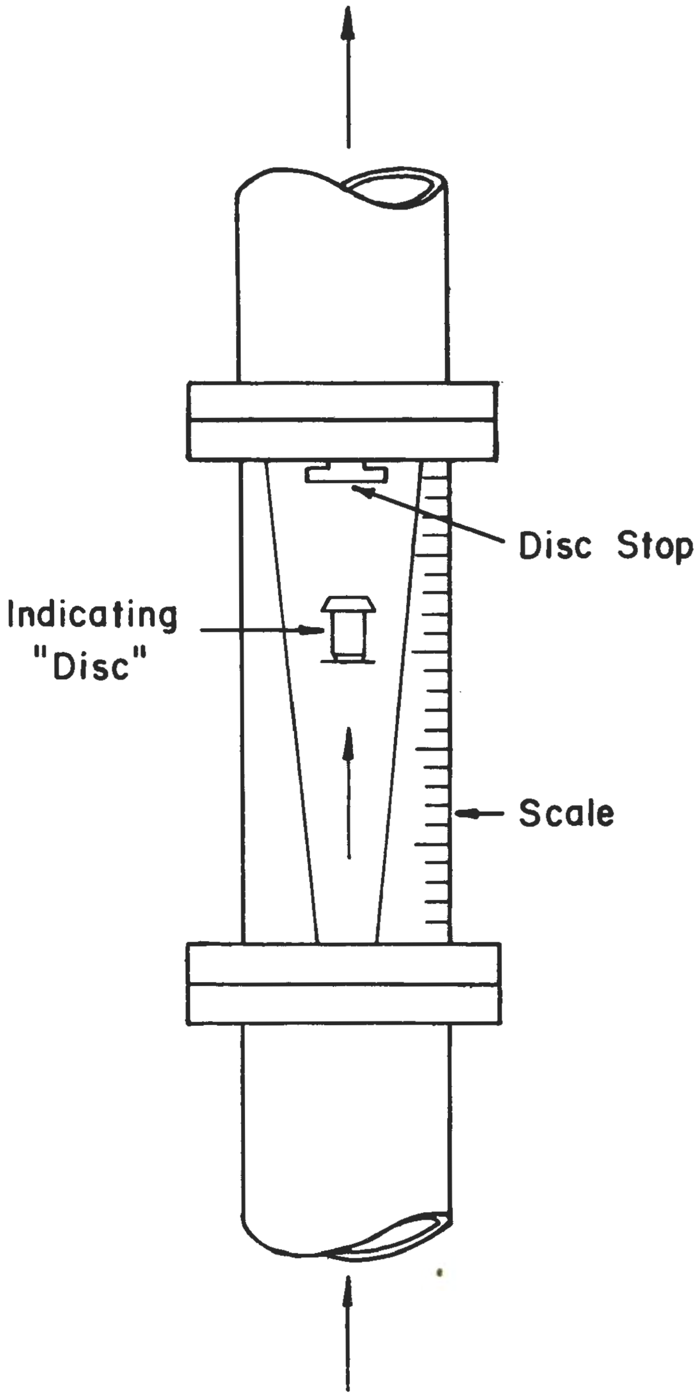


FIGURE F-4 — VARIABLE AREA FLOW METER

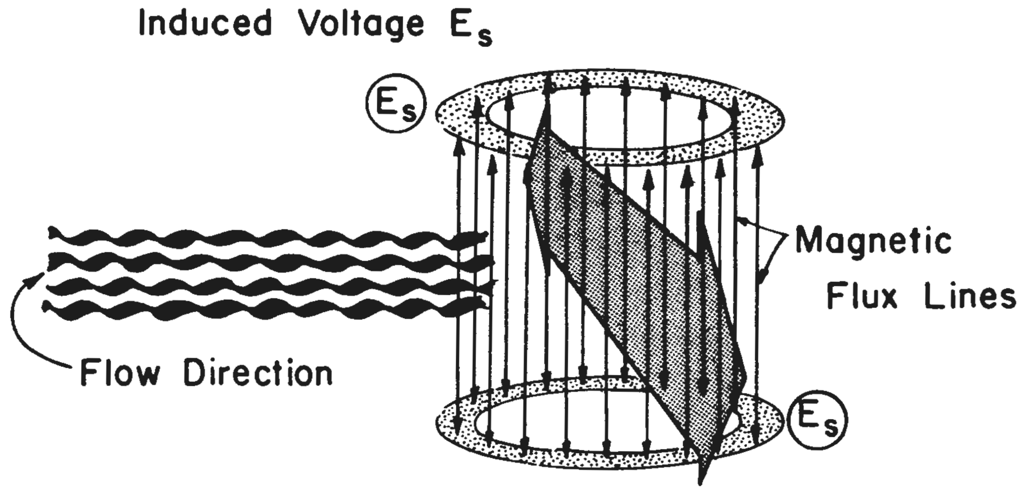


FIGURE F-5a – ELECTROMAGNETIC FLOW METER PRINCIPLES

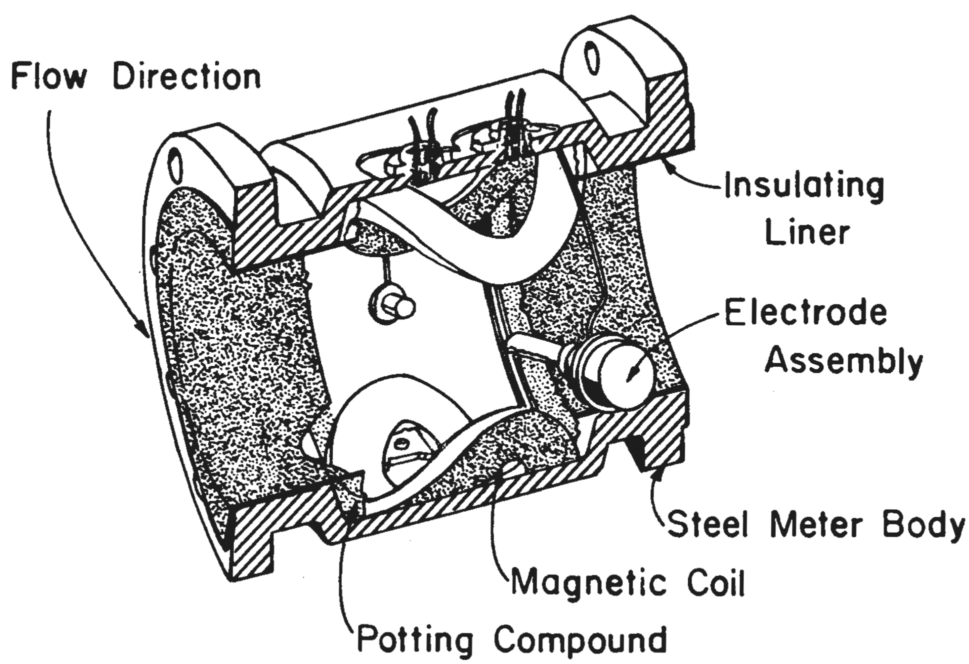


FIGURE F-5b – WORKING ELECTROMAGNETIC FLOW METER conductance is very small.) The induced voltage is a linear function of conductor (liquid) velocity, independent of flow turbulence or liquid characteristics such as temperature, density, viscosity, or conductance (above minimum required).

Several problems are inherent with the utilization of the electromagnetic flow meter. First, magnetic interference generated by electrical circuitry in the vicinity, may cause the "magmeter" to sense and transmit erroneous readings. However, proper shielding can eliminate this difficulty. Secondly, solid materials from the flowing liquid may adhere and accumulate on the sensing electrodes impairing the meter's sensitivity and performance. Solids build-up may be counteracted by either utilizing a meter diameter slightly smaller than the pipeline diameter (thus increasing flow velocity and scour) and/or equipping electrodes with ultrasonic cleaning attachments.

The magnetic flow meter is an extremely versatile device. It is capable of measuring a wide range of flow rates for fluids such as slurries, sludges, and most "clean water" flows.

Figure F-6a illustrates the basic operating principle of the vortex shedding flow meter; the circle in the figure represents the cross section of a long cylinder and the horizontal lines represent fluid streamlines. At low flow velocities, liquid flows smoothly around the cylinder while at higher velocities, a wake is generated. This wake consists of a series of vortices which alternately form on and detach from either side of the cylinder as shown in Figure F-6a. Over a certain range of Reynolds numbers, the frequency of vortex "shedding" is linearly related to liquid flow rate.

Figure F-6b illustrates the shape of vortex shedding body in a working flow meter (4). (This body is mounted in a special cylindrical pipe section which is the flow meter housing.) This shedding body is used in place of the cylinder because of the larger, more uniform, and generally enhanced vortices produced by the former. When each vortex is detached, the force configuration on the shedding body changes, and

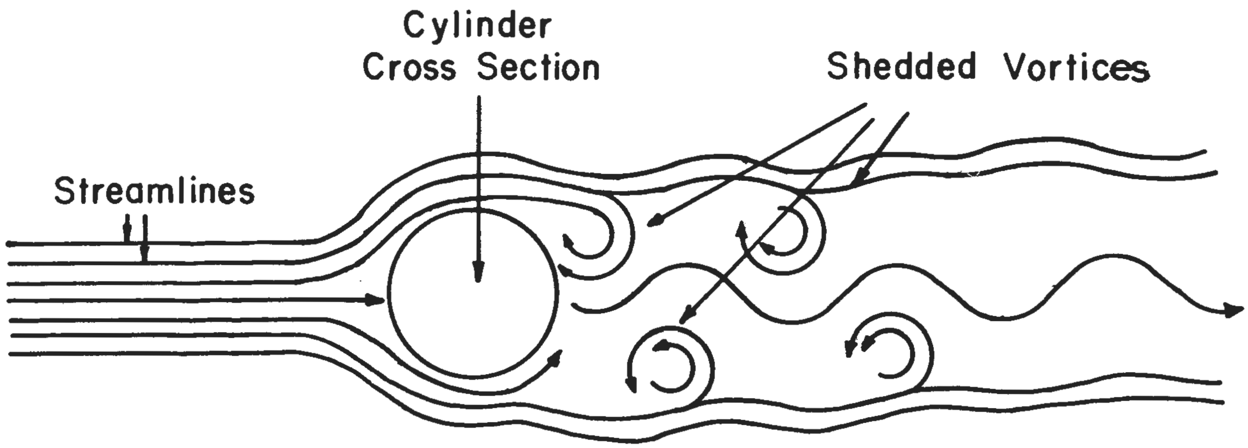


FIGURE F-6a – CROSS SECTION OF A LONG CYLINDER IN A FLOWING LIQUID

(Courtesy of Fischer-Porter Co.)

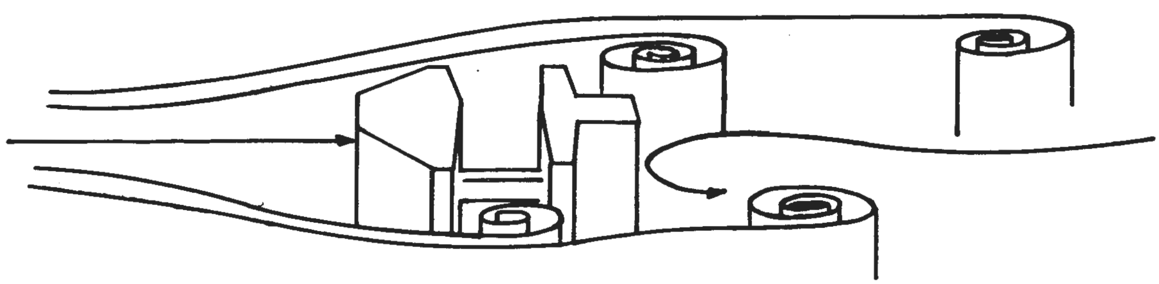


FIGURE F-6b – IDEALIZED VIEW OF VORTEX SHEDDING BODY IN A WORKING FLOW METER

(Courtesy of Fischer-Porter Co.)

the tailpiece deflects by an infinitesimal amount. Deflections are sensed by a strain gauge mounted in the tailpiece. Electronic signals from the strain gauge are transmitted to a secondary unit which, in turn, converts the information to flow rate data.

The vortex shedding flow meter is generally a clean-liquid measuring device, although satisfactory metering of liquids containing small concentrations of solid material is also feasible (4).

Four major types of flow meters are discussed above. Numerous other types are available and may be more desirable under certain circumstances. For further discussion of flow meters in general, the reader is referred to references 1 and 2, and the trade literature.

Open Channel Flow Meters - These devices could be utilized for measuring wastewater flow rates at various points in a treatment system. The basic types of open channel meters are the weir and the flume. Although the physical appearances of the weir and flume are quite different, both utilize the same basic principle of inducing critical depth in the channel. (Critical depth is a characteristic depth of flow in an open channel for which specific energy, the sum of depth and velocity head, is minimum. Any flow of lesser or greater depth will have greater specific energy.) Critical depth usually occurs near a change of channel slope. For a channel section of regular geometry, critical flow depth can be calculated from depth measurement and channel dimensions.

A weir is basically a dam structure designed to create a backwater and force the overflowing liquid through critical depth (1). The weir may be of the broad or sharp-crested type, but the sharp-crested type, shown in Figure F-7a, is most commonly used. Figure F-7b illustrates two frequently used notch configurations, the V-notch is preferred where a range of small to large flows must be measured. Flow is measured by determining the head upstream and using the proper equation to calculate discharge.

Two major drawbacks associated with the utilization of a weir are solids deposition and hydraulic headloss. Suspended solids in the flow stream

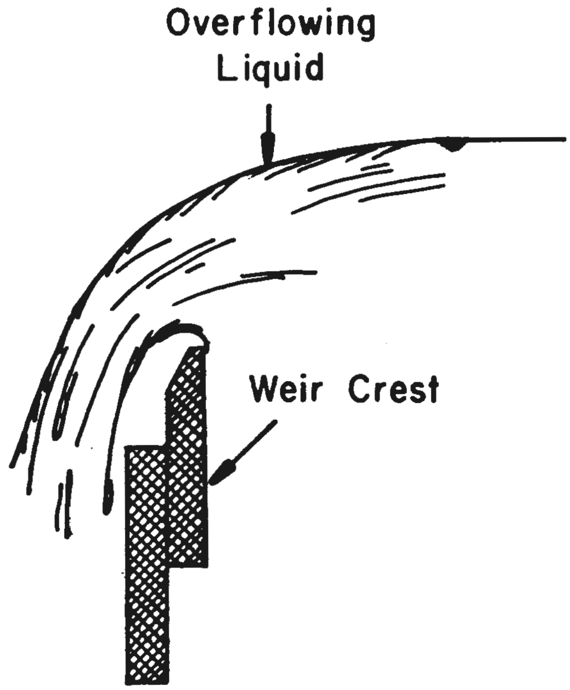


FIGURE F-7a — CROSS-SECTIONAL VIEW OF SHARP CRESTED WEIR

Cross-sectional views of weir notch shown in Figure F-7a

FIGURE F-7b — STANDARD WEIR NOTCHES

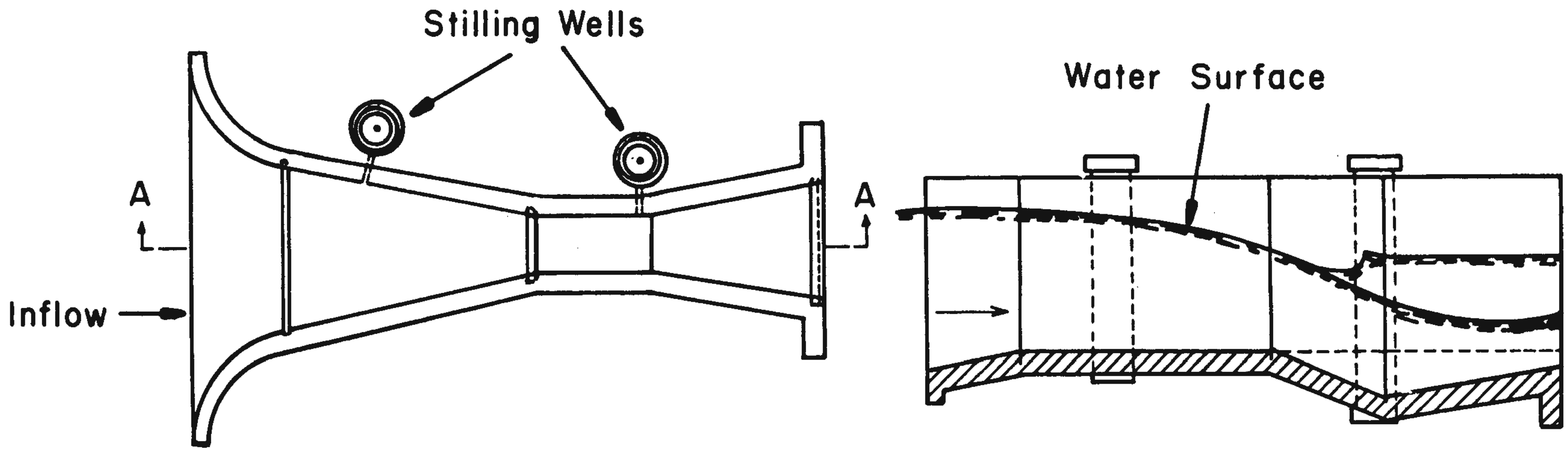
may be deposited in the quiescent pool above the weir to the extent that flow behavior is adversely affected. Also, the drop in water surface elevation across the weir may be so large relative to the total available hydraulic head in the system, that it constitutes inefficient use of energy.

As a weir resembles a dam, a flume resembles a constriction similar to the throat of a Venturi in a pressure conduit (1). The Parshall flume is the most widely used of common flume types. It consists of three parts: the converging section, throat, and diverging section. Geometry is critical as rating curves have been developed for standard dimension flumes (see Figure F-8). The flow is determined by measurement of the water surface elevations at the points shown. The accelerated flow velocities in the throat section tend to scour the constriction, giving the flume a self-cleaning nature, and the change in water surface elevation across the weir is normally minimal.

The Palmer-Bowlus flume, Figure F-9a, while not as widely used as the Parshall type, has certain advantages over the latter (5). It is much simpler to construct, is readily adaptable to existing rectangular or circular channel cross sections, and has hydraulic characteristics which allow a rating curve to be theoretically developed (5). The self-cleaning and headloss features of the Parshall flume are also inherent to the Palmer-Bowlus type.

Figure F-9b illustrates two possible trapezoidal throat configurations and corresponding rating curves. (Rectangular throats can also be used.) Flow rate is determined by measuring the upstream head (see Figure F-9a) and applying the rating curve.

Before closing the discussion of open channel flow meters, two final points should be made. First, any of the devices just discussed will require some sort of instrumentation to measure, record, and/or transmit head measurements. Numerous schemes of head measurement are available among the various flow measurement instrumentation dealers.



Top View

Cross Section A-A

FIGURE F-8 — PARSHALL FLUME

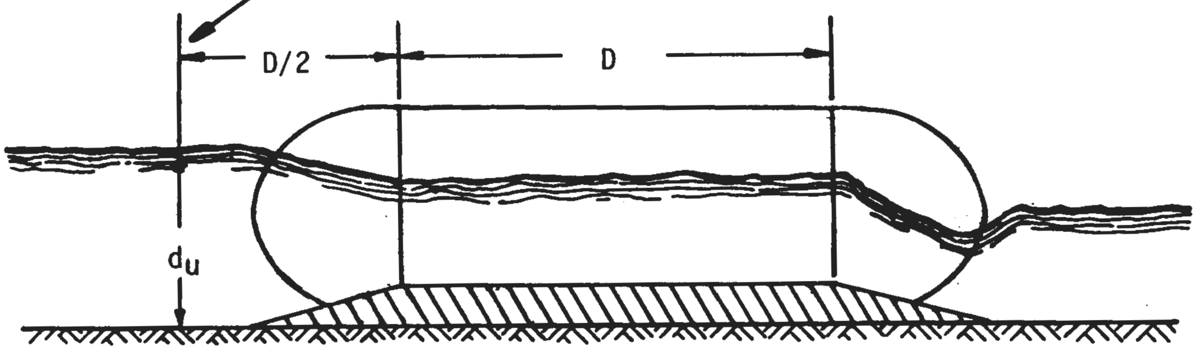
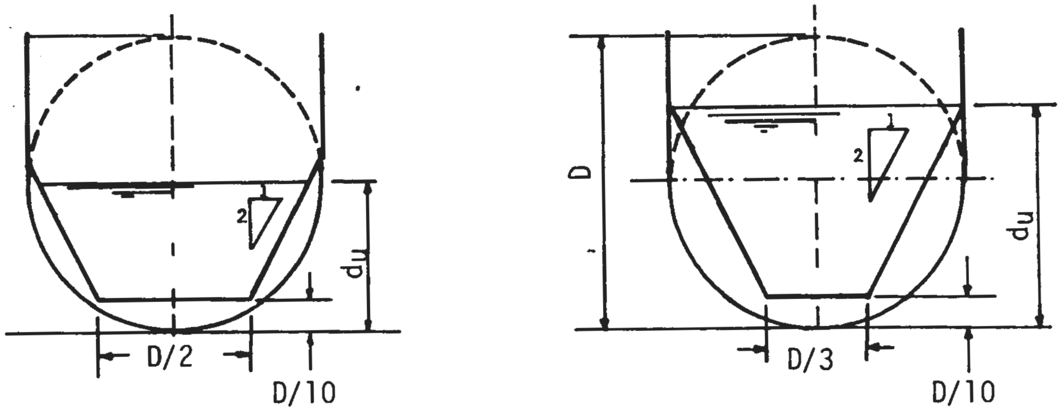


FIGURE F-9a — LONGITUDINAL SECTION OF PALMER-BOWLUS FLUME



Rating Table

d_u/D	SECTION 1 $Q/D^{5/2}$ (cfs)	SECTION 2 $Q/D^{5/2}$ (cfs)
0.20	0.055	0.037
0.30	0.172	0.116
0.40	0.343	0.238
0.50	0.571	0.396
0.60	0.864	0.604
0.70	1.233	0.864
0.80	1.690	1.187
0.90	2.177	1.560

FIGURE F-9b – STANDARD CROSS SECTIONS FOR THE PALMER-BOWLUS FLUME(5)

Secondly, the reader should note that although rating curves are available for most open channel flow meters, peculiar flow geometry and/or errors in meter construction and installation may cause the meter to yield significantly inaccurate data. Therefore, some method of field calibration should be utilized to provide the user with a more correct rating curve or at least provide him with some idea of the magnitude of error.

For a detailed discussion of open channel flow meters, the reader is referred to references 1 and 5.

Fluid Density Meters - These devices could be used to continuously monitor the solids content of slurry flowing into the treatment system or of sludge flowing from one process to another within the system. Meters discussed here are the continuous weighing and ultrasonic types.

Figure F-10 schematically illustrates the basic components of the continuous weighing fluid density meter. Fluid is directed through a flexibly connected section of pipe which tends to "sag" and "rebound" as fluid density increases and decreases. The pipe section is continuously weighed, and the weight data is in turn correlated to fluid density. The meter may be installed so as to measure the density of the entire fluid stream or a portion thereof.

The ultrasonic sludge density controller operates on the principle of attenuation of a sonic signal by suspended solids; a "heavier" suspension has more attenuating or dampening effect on the signal than a "lighter" suspension (7).

The density control device consists essentially of two ultrasonic transducers: one of which produces a signal which is transmitted through the suspension, and the other which receives the signal. The transducers are mounted directly opposite one another in a special pipe section, which is installed in the suspension pipeline.

The apparatus constantly monitors the density of the flowing suspension. If the density remains above the specified set-point, the actual control mechanism is not activated. However, if the density

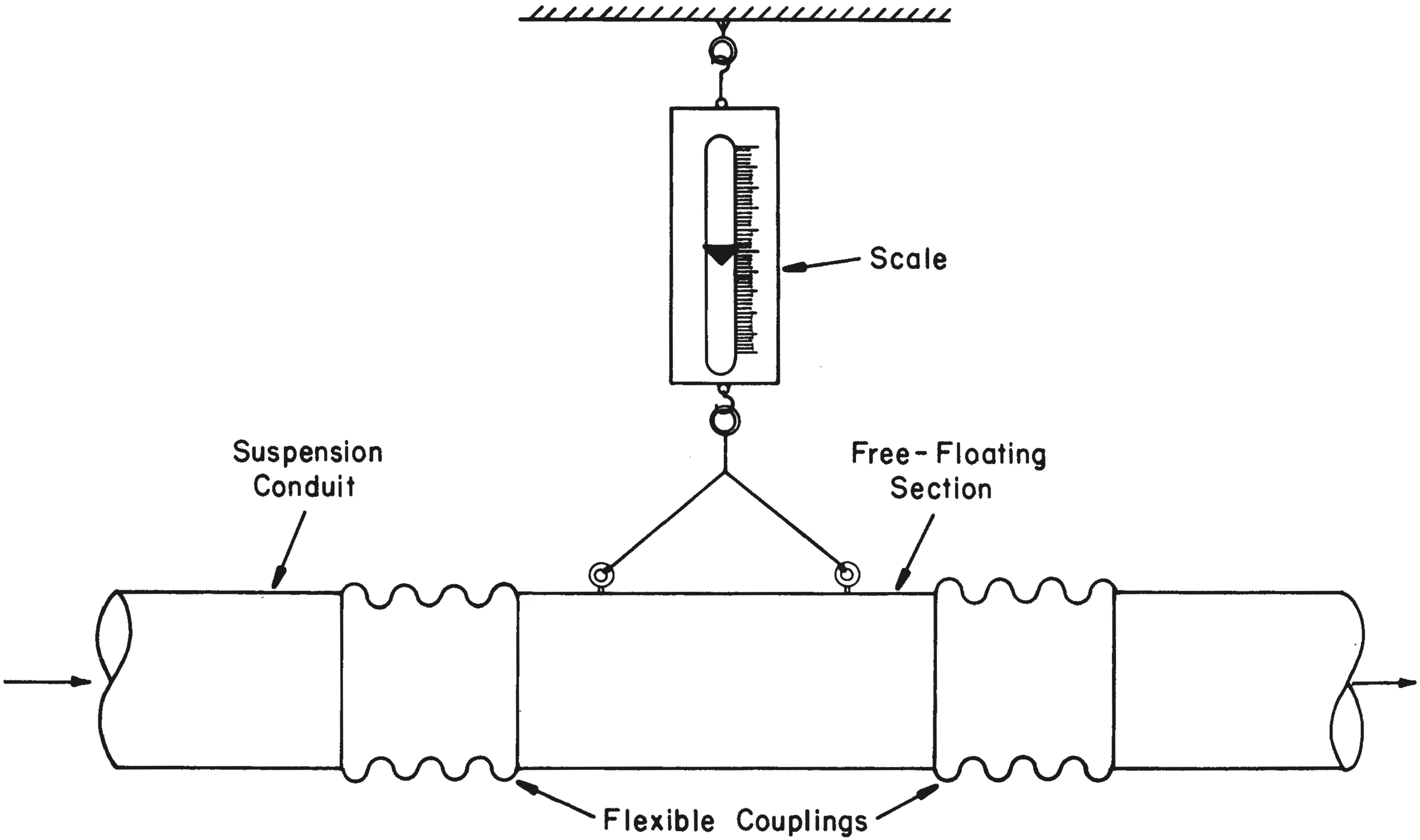


FIGURE F-10 — IDEALIZED VIEW OF THE CONTINUOUS WEIGHING FLUID DENSITY METER should fall below the specified lower limit, a "stronger-than-normal" signal is received by the sensing transducer, which, in turn, transmits a signal to an electronic control box. The control box may be programmed to sound an alarm, terminate suspension flow, or perform various other functions. If the unit is set up to terminate pumping of low density suspension, a timer may be incorporated in the system to restart the pump after a sufficient time lag.

The above discussion is intended only to provide the reader with a general description of continuous fluid density measurement devices. Several variations of the above mentioned components are utilized, and other devices employing completely different techniques are also available. For more complete coverage of fluid density measurement, the reader is referred to references 6 and 7.

Interface Level Sensor - Figures F-11a and b illustrate the basic components of the ultrasonic interface sensing device (8). This apparatus is useful for determining the level of an interface between two immiscible liquids in a remote or inaccessible reservoir.

The device operates on the principle of sonic reflection by an interface; when a sonic signal passes from one liquid to another at a suitable angle, most of the signal is reflected or refracted at the interface so that only a small portion reaches the receiver (8). Like the ultrasonic fluid density controller, the interface sensor consists primarily of two ultrasonic transducers: a transmitter and a receiver. When the sensing probe is completely submerged in a single liquid, as shown in Figure F-11a, the sonic signal is transmitted relatively unhindered from the transmitter to the receiver. However, when an interface is present between the transducers, as shown in Figure F-11b, much of the signal is refracted and reflected, and a weaker signal reaches the receiver. The receiving transducer, upon detecting the weakened sonic signal, transmits an electrical impulse to a control box which may trigger an alarm or perform various other functions.

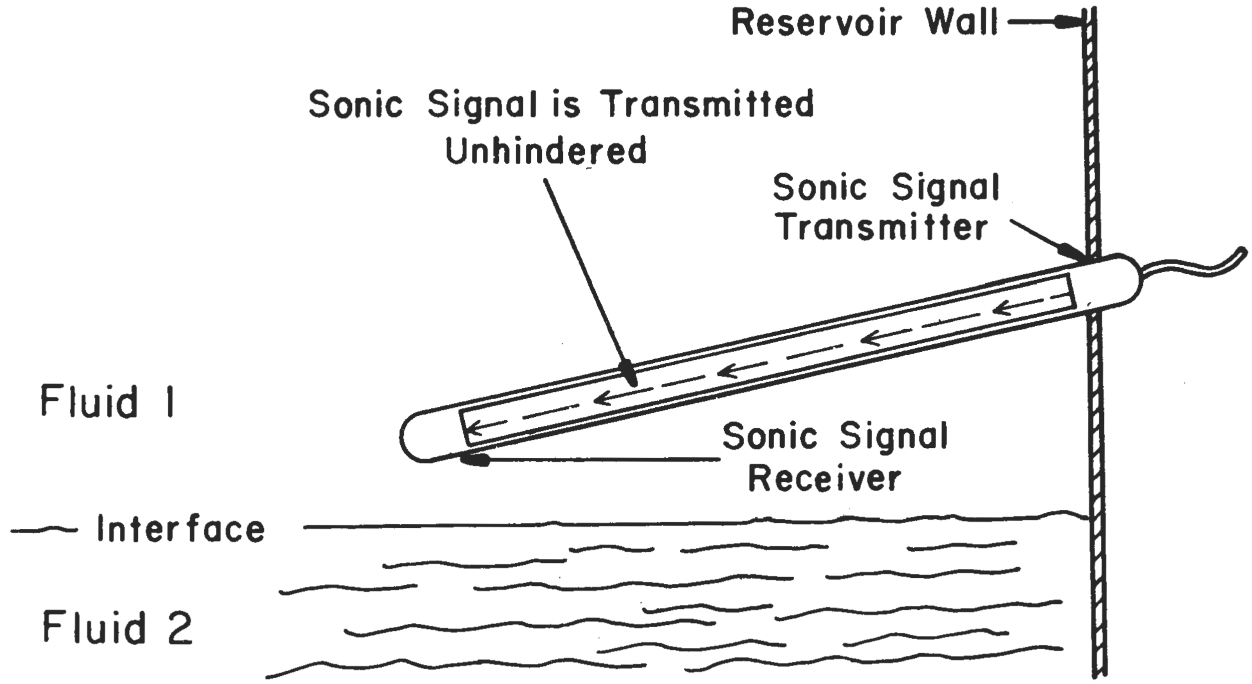


FIGURE F-11a - NORMAL OPERATION OF THE INTERFACE LEVEL SENSOR

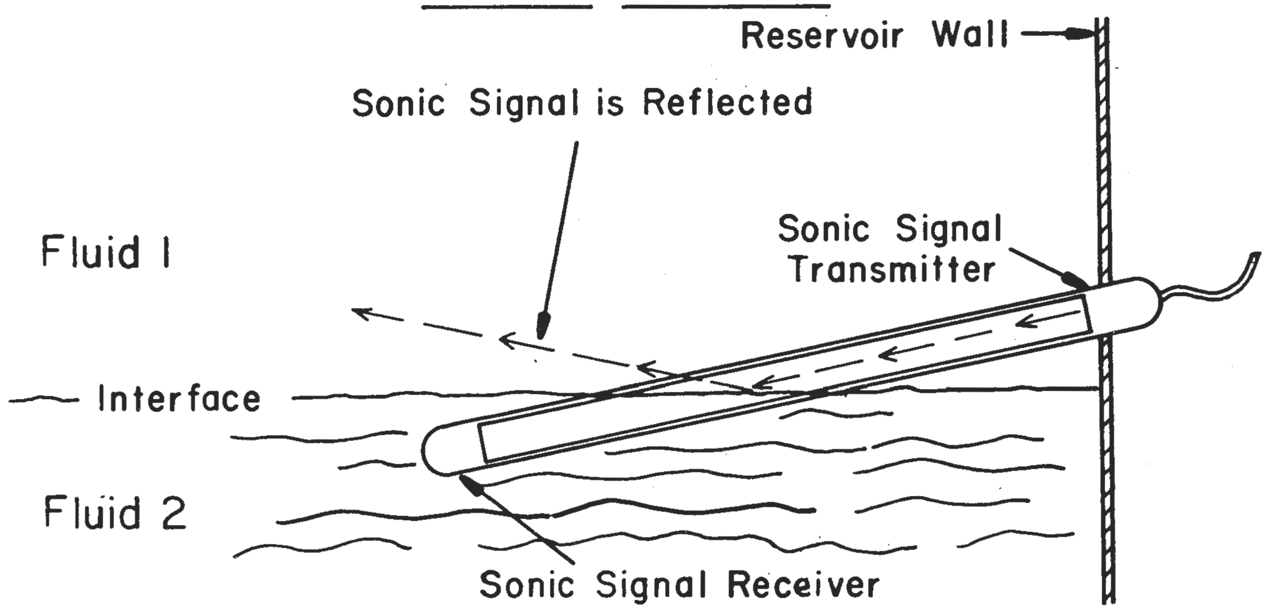


FIGURE F-11b - OPERATION OF INTERFACE LEVEL SENSOR WITH INTERFACE PRESENT

For further discussion of the ultrasonic interface sensor, the reader is referred to reference 9.

Turbidimeters - Turbidity, a key index of water quality, is usually defined as the optical property of a suspended solids sample that causes light to be scattered and absorbed rather than transmitted in straight lines through the sample. Although turbidity is often compared with suspended solids concentration, in actuality, no universal relationship exists between the two. (For example, if turbidities of two solids suspension samples are compared, the first containing 1000 milligrams per liter of 0.5 millimeter diameter silica spheres and the second containing an equal concentration of 0.005 millimeter diameter silica spheres, the latter suspension will obviously scatter and absorb more light because it possesses a much larger total particle cross sectional area.) In some cases, correlations of turbidity to solids content may be established for an individual waste stream provided the suspension particles' light scattering and absorbing properties and grain size distribution remain fairly constant.

Turbidity is a somewhat arbitrary parameter; turbidity values of a single sample, measured by several supposedly equivalent methods, may vary widely (9). The method of measurement currently preferred by the American Public Health Association is nephelometry, or the measurement of the quantity of light scattered by a sample, as opposed to absorptometry which is essentially measurement of the quantity of light absorbed by a sample (10). Figure F-12a illustrates the basic principle of the nephelometer; a beam of light is directed through a vial containing a turbidity sample, and a photocell located "outside" of the beam of light measures the quantity of light scattered in its direction. This quantity of light represents the turbidity of the suspension. Since the amount of light scattered varies with numerous equipment parameters such as light beam intensity, distance of sample from light source and photocell, photocell position, sample vial properties, etc., turbidimeters

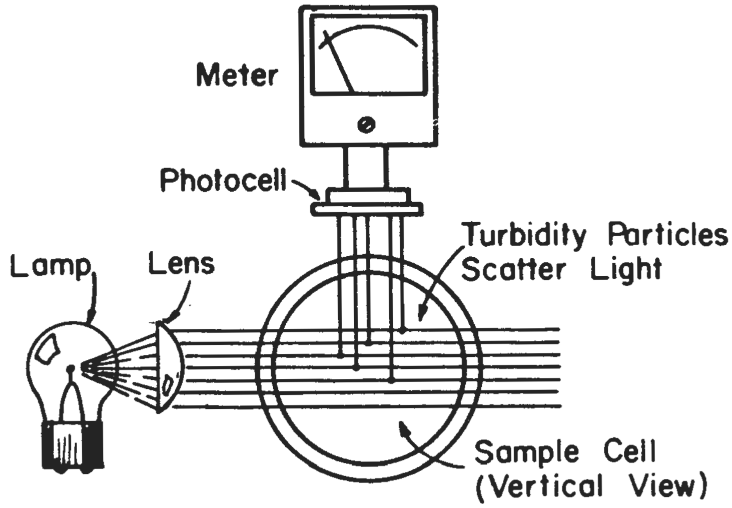


FIGURE F-12a - NEPHELOMETRY PRINCIPLES

(Courtesy of Hach Chemical Co.)

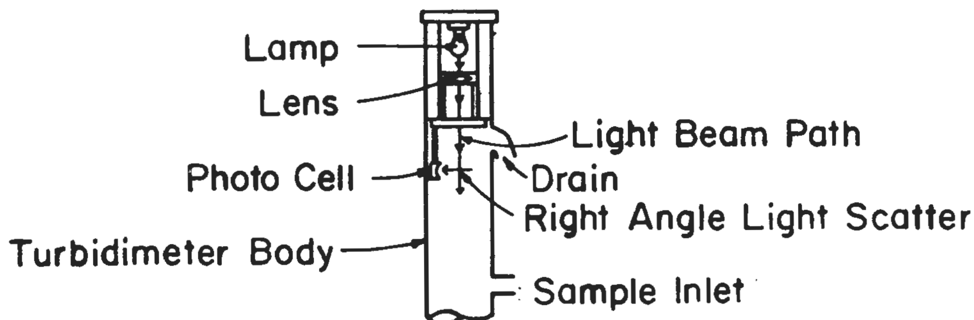


FIGURE F-12b - "LOW RANGE" TURBIDIMETER

(Courtesy of Hach Chemical Co.)

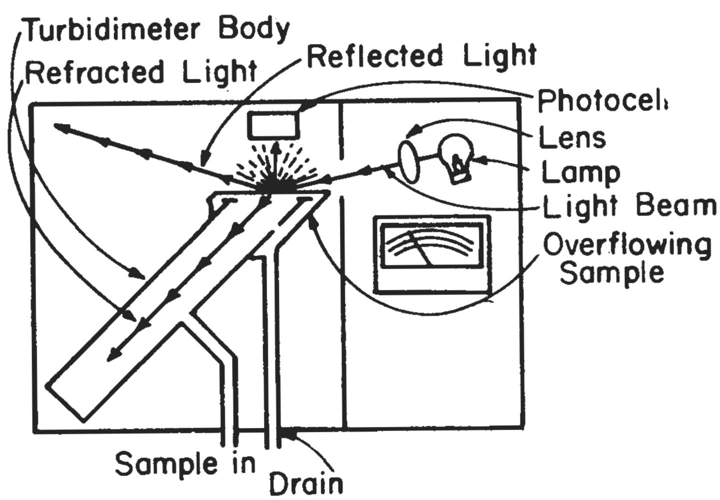


FIGURE F-12c - "SURFACE-SCATTER" TURBIDIMETER

(Courtesy of Hach Chemical Co.)

must be rigidly standardized to produce consistent results.

Just as turbidity measuring equipment must be standardized, so must calibration samples. The most satisfactory standard sample discovered to date is formazin polymer suspension. (In fact, the Formazin Turbidity Unit, or FTU, is becoming increasingly popular as a turbidity unit.) Instructions for preparation of standard formizin polymer suspensions are found in reference 10.

Figure F-12b is a cross sectional view of the continuously operating "low range" turbidimeter. A strong light beam is passed into the sample reservoir of the apparatus. There, a portion of the light beam is scattered by suspended particles and a fraction of the scattered light contacts a submerged photocell. The photocell, in turn, transmits a signal to a secondary unit which registers a proportional turbidity read-out. The low range turbidimeter is normally utilized for the measurement of wastewater containing small concentrations of suspended soils; maximum turbidity read-out range is zero to thirty FTU (11).

A device designed to measure turbidities of suspensions containing higher solids concentrations is the "surface-scatter" turbidimeter, shown in Figure F-12c. A narrow beam of light is directed onto the surface of the liquid overflowing the reservoir. A portion of the light striking the liquid surface passes into the reservoir and is absorbed. Another portion is reflected at the angle of incidence of the incoming beam, and is absorbed by the black walls of the turbidimeter case. A third portion is scattered and absorbed by suspended particles near the liquid surface, and a fraction of the scattered light is detected by the photocell and indicated on the reading meter as turbidity. The "surface-scatter" turbidimeter has a maximum range of zero to 5000 FTU (11).

The above discussion of turbidity and turbidimeters is very brief and incomplete. For further discussion, references 9 and 10 are suggested.

pH Sensor/Controllers - Fluctuations of waste stream pH have been recorded on at least one hydraulic tunneling operation (see Chapter 2). Detection and control of pH fluctuations (outside of allowable limits) are necessary prerequisites for the discharge of wastewater to public waters or sanitary sewers.

The primary detecting elements in pH sensing are a pair of glass electrodes (6). In the primary electrode, a potential is developed across a glass membrane due to differences in the hydrogen ion activity of the process liquid and a standard solution contained inside the electrode. The difference of this potential and the potential of the reference electrode gives a voltage which is expressed as pH.

The sensing unit is only part of the actual pH control system, as shown in Figure F-13. The sensing unit transmits its information to an electronic controller which, in turn, either intermittently starts and stops a constant discharge reagent feed pump or continuously adjusts a variable discharge feed pump. The reagent enters a detention tank where it is mixed with the process liquid. Locations of reagent feed and sensing electrodes are significant; reagent should enter the reservoir near the process liquid inlet, and electrodes should be located near the tank outlet (12). As with any mixing tank, inlet and outlet should be located so as to minimize short-circuiting.

The above described system is by no means the only method of pH control. For example, if extremely "tight" pH control is desired, a two tank system is utilized; the first tank is used for "coarse adjustment" while the second is used for "fine tuning". Also, when waste stream pH fluctuates from acidic to basic, a two-reagent system is utilized. If the process stream contains constituents that could form coatings on the sensing electrodes, the electrodes should be equipped with ultrasonic cleaning mechanisms. For further information on pH sensing and control, the reader is referred to reference 12 or an equivalent source.

Pumps

Pumps are an integral part of any liquid waste treatment system; they provide energy for the transfer of liquid, via conduits, from one process to another. Possible applications include: providing required

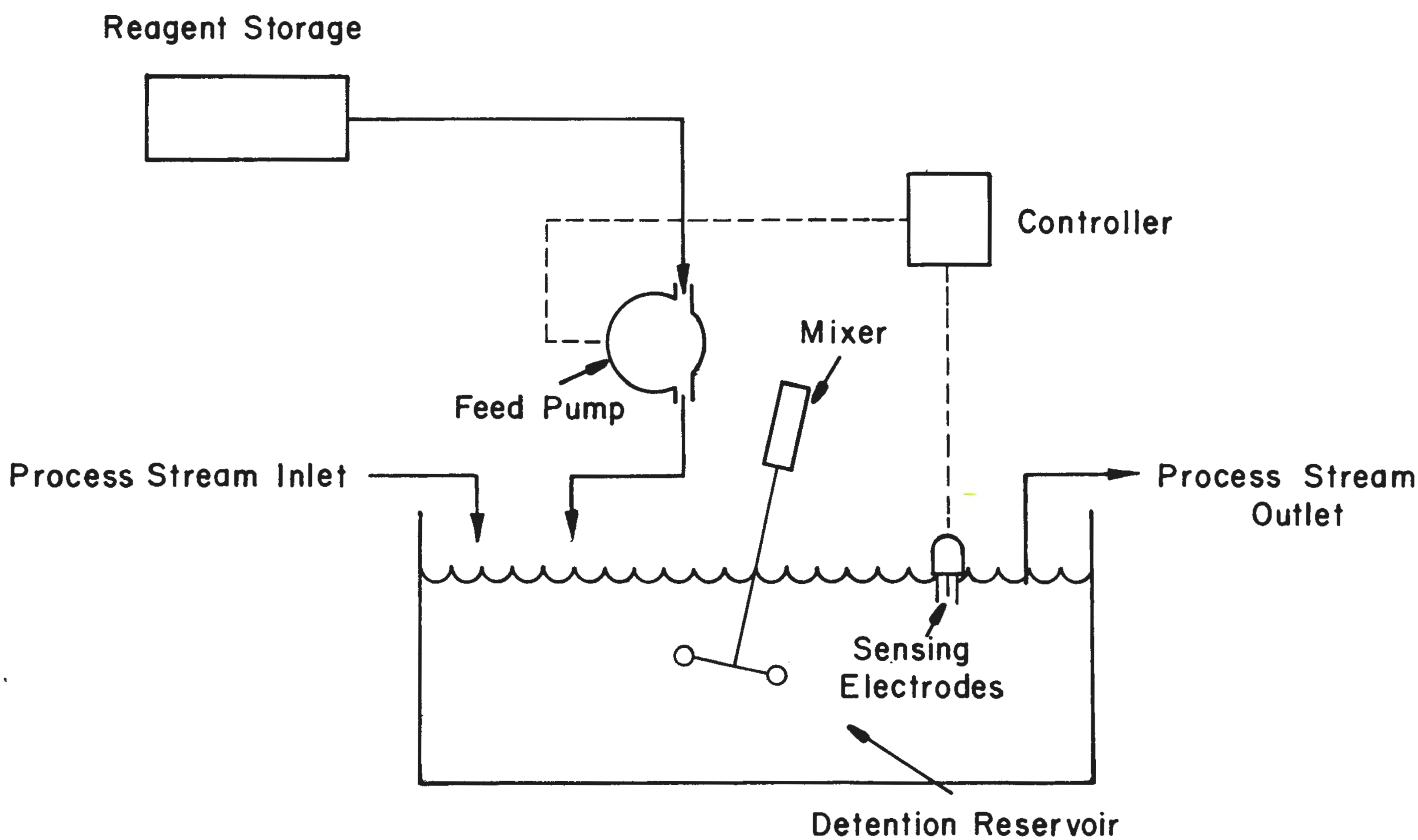


FIGURE F-13 – pH CONTROL SYSTEM

(Courtesy of Leeds and Northrup Co.)

hydraulic head for various processes, providing metered influent flows to the various processes, and providing metered withdrawal of sludge from various processes. Another application, chemical feeding, was discussed in an earlier section.

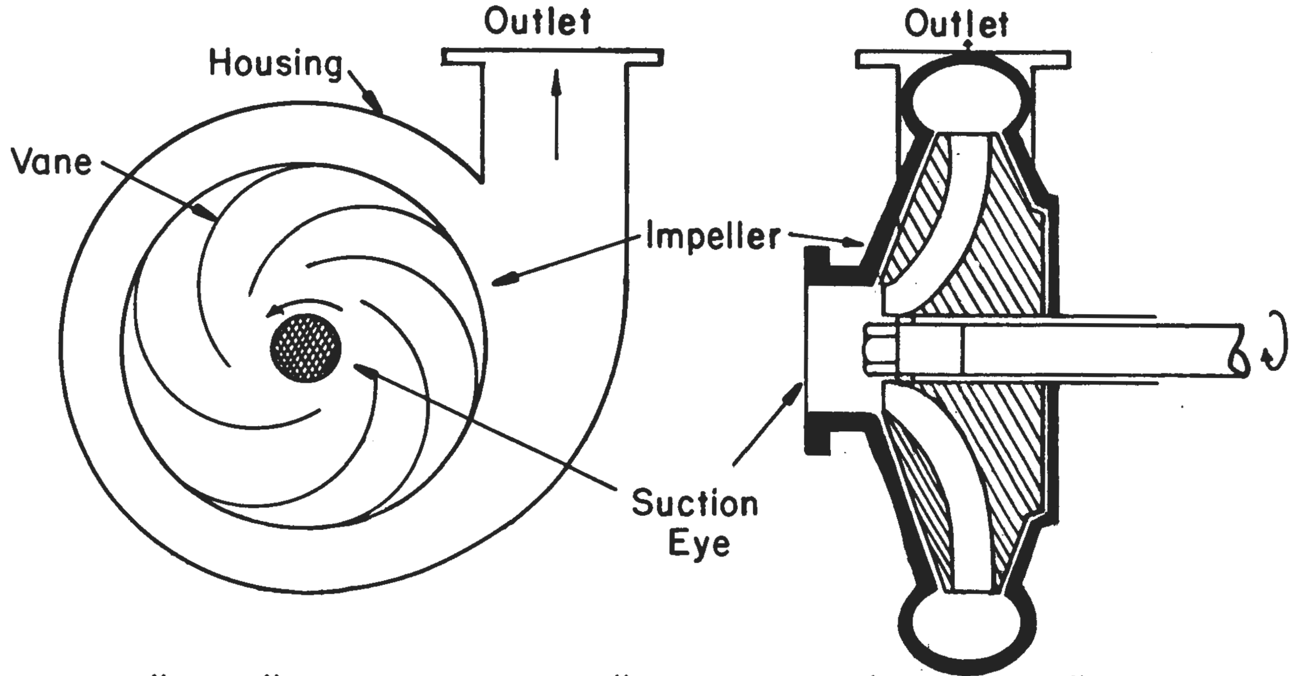
Pumps can be roughly classified into two groups: the variable discharge type whose discharge is directly dependent on external conditions (such as "downstream" resistance to flow), and the positive displacement type whose discharge is relatively independent of external conditions. One variable discharge type (the centrifugal pump) and two positive displacement types (diaphragm and progressive cavity pumps) are discussed below.

Centrifugal Pump - The centrifugal pump, Figure F-14a, is so frequently utilized that its operational principles require no verbal explanation. However, some of the specialized features of solids-handling centrifugals are discussed below.

Because of the high shear conditions existing in its interior, a centrifugal slurry pump must be protected against abrasion. Usually one of the following means of protection is utilized: constructing the pump volute and impeller of abrasion-resistant steel, lining critical areas with replaceable metal wear plates, or lining the interior with special rubbers or plastics. (Rubber or plastic liners may be replaceable or permanently bonded.) Also, the pump casing should be readily dismantled for quick inspection and/or maintenance of impeller, volute, and lining.

Solids handling centrifugals generally have some type of modified impeller. One alternative is the "open-faced" type, for which the impeller consists of a single disc with several vanes protruding from it. Another type has a closed face but utilizes only two vanes.

A frequent trouble spot of solids-handling centrifugals is the region between impeller face(s) and pump housing. Since the slurry pump is designed to avoid close tolerences, no mechanical barrier is present



"TOP" VIEW "CROSS-SECTIONAL" VIEW

FIGURE F-14a — CENTRIFUGAL PUMP

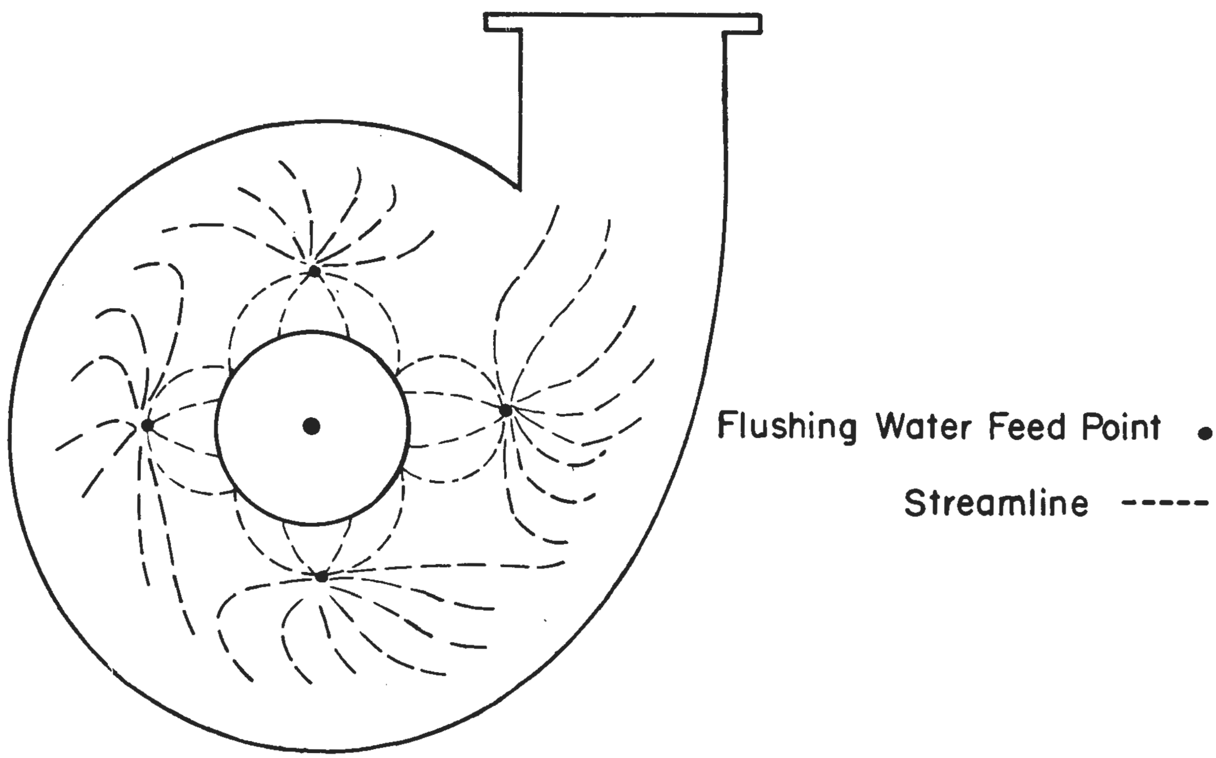


FIGURE F-14b — FLOW PATTERNS OF IMPELLER FLUSHING WATER to prevent solids-laden liquid from traveling from the high pressure zone through this region to the suction eye. A frequently used method of preventing the entrance of solids is to supply clean water under sufficient pressure such that flow is always "outward" from this region (see Figure F-14b).

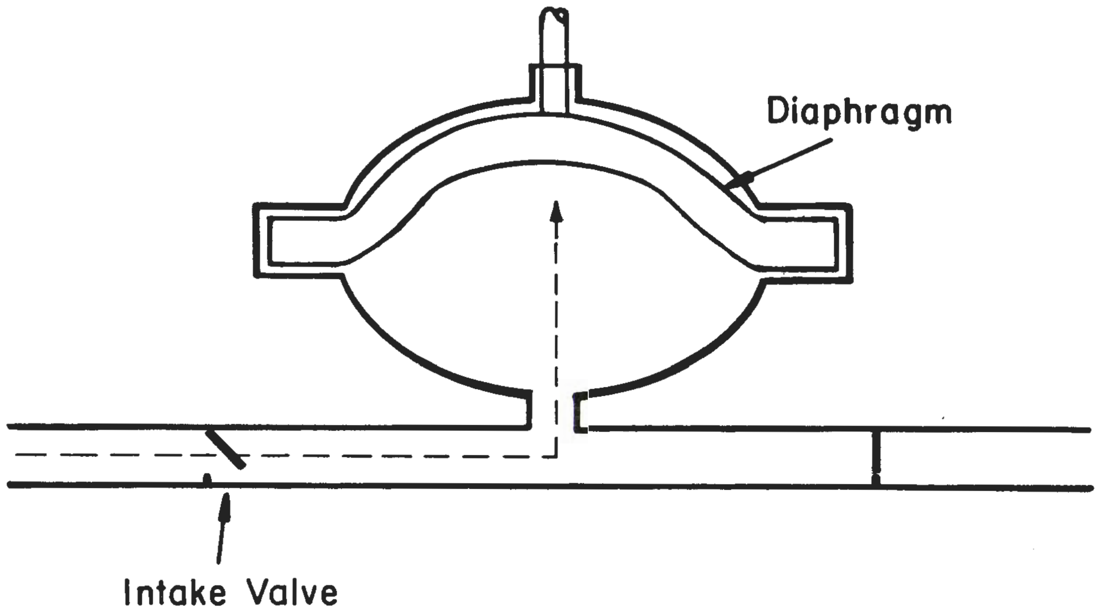
In a treatment system, the need often arises to control flow rate. For a centrifugal pump driven by a constant speed motor, control is usually obtained by valving the pump discharge. Commonly, a section of rubber hose is placed in the discharge line near the pump, and a pinch clamp is placed on the hose section. Thus, opening or closing the clamp decreases or increases pump back pressure and discharge is regulated.

Diaphragm Pump - Figure F-15 is an illustration of the construction and operation of a simplex diaphragm pump. Liquid is drawn through a one-way valve by the "upward" motion of the diaphragm. When the diaphragm stroke is reversed, the intake valve closes and the outlet opens, allowing liquid to flow out of the pump. When the stroke reverses again, the cycle is repeated.

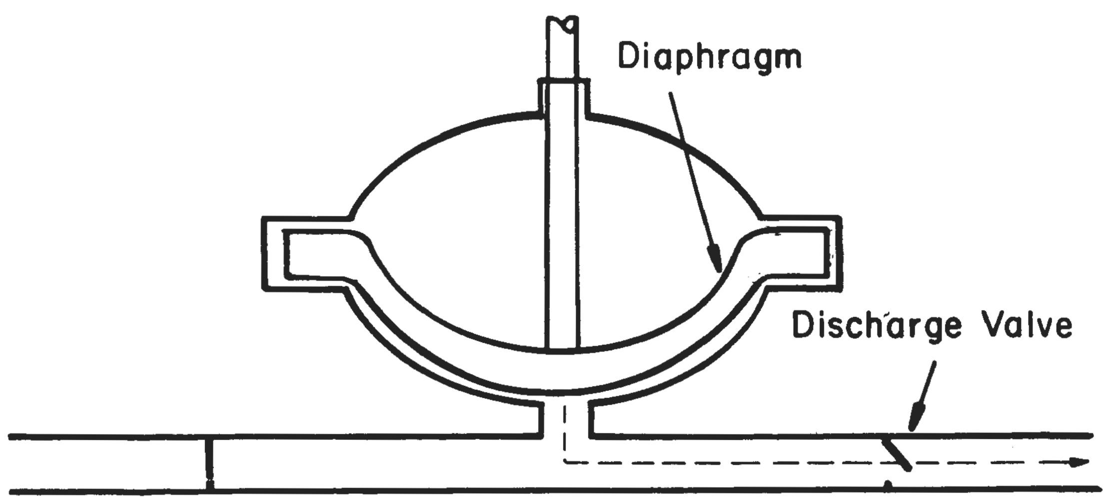
The flow rate produced by the simplex diaphragm pump is time dependent as illustrated by the opening and closing of the discharge valve. The most common method of averaging the flow is to utilize a duplex diaphragm pump which is actually two parallel simplex pumps in one housing operating 180^0 out of phase with one another. Thus, one chamber is receiving fluid while the other is discharging.

Normally, the function of a diaphragm pump is to provide a metered flow of abrasive (or corrosive) liquid over a variety of external conditions (such as changing intake or discharge heads). The flow rate of a diaphragm pump is normally adjusted in one of two ways: changing the stroke length or regulating the power supply. Some diaphragm pumps are equipped with positive methods of adjusting the stroke length to the desired flow rate. Most air-powered types are adjusted by increasing or decreasing air flow.

Progressive Cavity Pump - This type of pump, shown in Figure F-16, basically



INTAKE STROKE



DISCHARGE STROKE

FIGURE F-15 — SIMPLEX DIAPHRAGM PUMP

(Courtesy of Dorr - Oliver, Inc.)

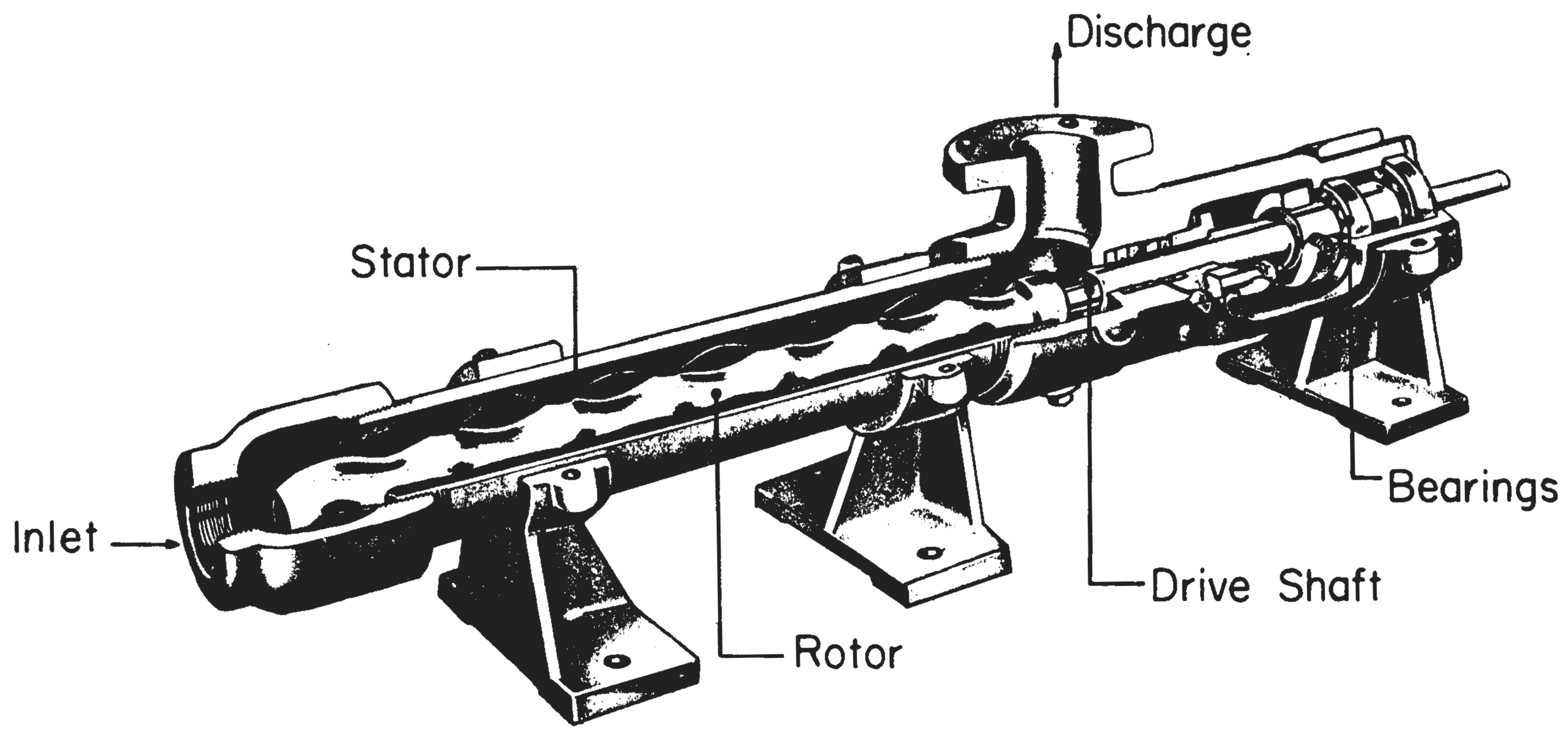


FIGURE F-16 - PROGRESSIVE CAVITY PUMP (Courtesy of Robbins and Meyers Co.)

serves the same function as the diaphragm pump, supplying hydraulic head and providing a metered flow of abrasive liquid under a variety of external conditions.

The essential elements of the progressive cavity pump are a single helix rotor and a double helix stator with a pitch length twice that of the rotor (13). The rotor rotates eccentrically in the stator, and, as it turns, cavities form and progress from one end of the apparatus to the other carrying the material to be handled. This progressing cavity action provides a non-pulsating, low shear, measured flow which is accurately repeatable. Flow rate is controlled by varying shaft rotation speed.

The progressive cavity pump has no valves which could become clogged, and the interaction of the rotor and stator induces a self-cleaning action in the pumping element. (The rotor is normally constructed of some type of wear-resistant steel while the stator is usually natural or synthetic rubber, depending upon the application.) Inspection and maintenance ports are provided with some models.

The progressive cavity pump has several degrees of flexibility not found in other pumps (13). First, it operates equally well "backward" or "forward", simply by changing the direction of rotor rotation. Also, pressure and/or flow capacity characteristics may be varied by simply replacing pumping elements (rotor and stator) with those of the desired geometry and performance characteristics.

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