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Title: A HELICALLY FLIGHTED ROTATING CYLINDER FOR CONCENTRATING MANURE SOLIDS

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A helically flighted rotating tube for concentrating dairy and swine manure solids was developed and evaluated. The solids removal and concentration factor values were measured with beet pulp, dairy manure and swine manure slurries at different influent flow rates and suspended solids concentrations. A method of estimating the performance of the device based on turbulence inside the separator was developed and evaluated. Comments on the usefulness of the device as a livestock manure solid-liquid separator and possible alternate uses were made.

A Helically Flighted Rotating Cylinder for Concentrating Manure Solids

by

Wayne Edward Verley

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HELICALLY FLIGHTED ROTATING CYLINDER FOR MANURE SOLIDS REMOVAL

I. INTRODUCTION

Demand for livestock products has been increasing both nationally and internationally. Livestock producers have met these demands and increased their own profits by adopting confinement production techniques. These techniques allow for increased production without proportional land and labor increases. However, new methods of removing large volumes of manure from a confined area were required.

Liquid manure transport systems were developed for this manure removal and have become increasingly popular within the last ten years because of their labor saving and sanitary characteristics. But as their popularity increased, the problems of manure disposal became more acute.

The manure disposal problem associated with liquid manure systems is complicated by the requirement for dilution and transport water. For the pumps used in most liquid manure systems to operate properly, the manure slurry must have a solids content of four to eight percent or less, depending upon the type of livestock and the type of pump selected. Fresh manure (prior to any dilution) has a total solids content of ten to twenty-five percent, again depending upon the type of animal, according to Ngoddy (11), Sobel (13), and

Farwest Farm Systems (14). Therefore, a dilution and volume increase of two to three times is common. More dilute slurries are common in hydraulic flush systems. The volume increase, when coupled with poor weather conditions (which create saturated or frozen soil conditions), causes runoff and odor problems when land disposal is attempted.

A secondary factor contributing to manure disposal problems is the increased residential development in livestock producing areas. This not only decreases the amount of land available for manure disposal, but it contributes to nuisance problems involving manure disposal. Increased odor and pest potential have often created conflicts between livestock producers and surrounding communities.

One proposal to minimize the problems of liquid manure disposal is water reuse. According to Ngoddy (11), water separated from manure slurries can be treated and reused for wash down procedures. Less fresh water is needed for manure removal, and therefore, less slurry requires disposal.

One problem with this system is the need for solids removal. A solids build up will occur if the solids are not removed. This build up is from two sources: (a) the manure solids which are not degraded in a practical treatment time, and (b) the solids produced during biological treatment. Ngoddy (11) reported the reuse of biologically treated flush water is technically feasible if the coarser solids in a slurry are removed before treatment.

Therefore, prior to biological treatment, a solids concentrating device is required. After flush or wash down procedures, the solids concentrating device separates the slurry into two streams. One stream has a high content of coarse solids, the other has a low solids content. Ngoddy (11) reported coarse solids in the one stream are relatively stable and easy to handle. They can be stored for use as compost or mulch. Elam (3) reported some dairymen have used these solids as bedding in free stall operations. The stream with low solids content may be treated and reused for flush down procedures.

There have been several devices developed for solids concentration. Some of these devices have been applied to manure solids separation. However, none has proved fully satisfactory for livestock producers. The current research has involved the development and evaluation of an alternate manure solids separation device for use in dairy and swine operations.

II. LITERATURE REVIEW AND BACKGROUND

Manure Slurry Properties

The physical properties of a manure slurry are critical to handling processes. A basic understanding of these physical properties is inherent to the understanding of the problem of manure solids separation.

The first important physical property is the dilution or the solids concentration of the slurry. Solids concentration is particularly important in separation devices which employ sedimentation. According to Rich (12), a particle passes through stages of unhindered settling, hindered settling, and compaction as it settles and the solids concentration increases. Kumar, Bartlett, and Mohsenin (9) found the solids concentration also has a large effect on the viscosity of the slurry which affects the particle's settling velocity.

By observation, Sobel (13) classified the dilution of manure slurries into three categories according to flowability. These categories are as follows: Semisolid slurry will not flow without mechanical assistance (fresh manure). Semiliquid slurry will flow at a velocity which can be detected by visual observation. Liquid manure slurries are a suspension of solids in a liquid and are free flowing.

Expanding on Sobel's work, Kumar, Bartlett, and Mohsenin (9) studied the flow properties of some manure slurries in relation to dilution and other factors. They concluded that a slurry of four to six percent total solids content was a good compromise between excessive volume and excessive power consumption when handled by a liquid manure system. Hart (8) concluded a good compromise between excessive volume and easy handling is a slurry with a total solids content of one to four percent.

Theoretically, therefore, a liquid manure system should handle a slurry with a total solids content of one to six percent. Data collected from the dairy and swine centers at Oregon State University, where the research for this work was conducted, have indicated the suspended solids concentrations in practice at these centers seldom exceeded two percent.

A separation process involves two major forces. One force, the separation force, moves particles through a liquid to a point for removal from the liquid. The second force, inherent to all fluids, is a friction or drag force which resists particle motion. The separation force is proportional to the mass of the particle. The drag force is proportional to the cross sectional area of the particle and the viscosity of the fluid. Since separation involves these two forces, separability of the solids in a slurry is dependent upon the cross sectional area and mass (or density) of the solid particle.

Therefore, a second important physical property of manure slurries is the density and cross sectional area of the solid particles.

A. T. Sobel (13) used three methods to describe the slurry characteristic of particle size and density. The first method was direct measurement of particle densities. The values he obtained were average particle densities for samples from fresh chicken and dairy manure samples. He did not report particle density distribution. Average values are of only limited usefulness in solid-liquid separation design calculations. Using a second method, Sobel described the particle size distribution of manures by wet sieving. The third method was an indirect measure of particle size and density. In this method, Sobel measured the solids settled from a slurry of given concentrations as a function of time. He found that about 90 percent of the suspended solids in a slurry with a solids content of about one percent will settle out in ten minutes.

Even though previous work on the physical properties of manure and manure slurries can be found, a problem arises when comparing results, as noted by Frecks and Gilbertson (5). The inconsistency in results is caused by variations in animal size, sex, breed, activity, feed ration, environmental temperatures, humidity, and operational errors. Since the physical properties of manure slurries do vary widely from source to source and from day to day within each source, the problems of solid-liquid separation are compounded. It is difficult to develop a solid-liquid separation device which will remove a large percentage of the suspended solids in a slurry when the physical properties of the slurry are unpredictable.

Separation Device Requirements

The primary purpose of a solid-liquid separation device in a manure management system is to remove the undegradeable suspended solids from slurries under a wide variety of physical conditions. However, it also must meet three other criteria to be practical for the average livestock producer. These criterion are as follows:

(a) Cost. A device should be relatively inexpensive to purchase.

(b) Power consumption. A separator which has a low power consumption will be economical to operate.

(c) Capacity. A device must make the desired separation at a flow rate which will make it possible to separate all of the slurry produced.

Calculations were made for the value of the flow rate a separating device must maintain per 1000 pound dairy animal. The volume of dairy waste produced per 1000 pound dairy animal varies between nine and twelve gallons per day (gpd) according to Davis (2) and Farwest Farm Systems (14). Assumed average values of manure production (10 gpd) and dilution requirement (20:1) produced a calculated total slurry volume of 200 gpd/1000 pound animal/day. Therefore, a device must maintain a flow rate of 0.139 gallons per minute (gpm) continuously for each 1000 pound dairy animal in the system. If a shorter run time for the device is desired, a corresponding increase in flow rate per 1000 pound animal is required. For example, if the separator can run for only twelve hours per day, the device must be capable of a flow rate of 0.278 gpm/1000 pound animal.

For swine, a similar value was obtained using the waste production values given by Davis (2) and Farwest Farm Systems (14). A 150 pound hog produces 1.5 gallons of waste per day with a dry matter content of about 15 percent. A 15:1 dilution ratio for the liquid manure system was assumed. This value for swine is 0.016 gpm/150 pound hog/day when the device is operated continuously. (The above analysis is only one method by which a device's capacity can be judged.)

Solids Concentration Devices

Several devices have been applied to manure solids concentration

However, none has totally satisfied the three criteria as previously outlined.

Sloping Screens

R. E. Graves (7) has used sloping screens to separate solids from dairy manure slurries. He reported total solids removals for 5:1, 10:1, and 20:1 dilutions of dairy manure as ranging between 35 and 80 percent. The sloping screen needs no power for operation and the device is durable. The sloping screen needs no power for operation and the device is durable. The screens are constructed of closely spaced, stainless steel bars which make the device relatively expensive. For free stall manure, Graves (7) reported maximum and minimum flow rates of 5.5 and 1.0 gpm when using a device with a screen width of 18 inches. This flow rate is dependent upon screen size, screen mesh size, and the solids concentration of the slurry. Under continuous operation, the 5.5 gpm flow rate given above could separate the solids from the slurry produced by 197 dairy animals weighing 1000 pounds. Sloping screens larger than 18 inches are available. Performance data for these larger devices on livestock waste were not found. Graves (7) reported that the flow rate for the sloping screen can best be adjusted by observation. Therefore, some operator judgment may be required for proper operation. He also reported that overloading the screens can cause blinding or flow channeling. Performance data for sloping screens separating swine manure solids was not found. A schematic diagram of the sloping screen and stream flows is shown in Figure 1.

Decanting Centrifuge

To move particles through the slurry, the decanting centrifuge uses centrifugal forces (particle inertial forces) created by high speed rotation of a cylindrical drum. The liquids are decanted from the solids and the solids removed by an auger which is rotating slightly faster than the drum. Figure 2 shows a schematic diagram of the decanting centrifuge.

The high speed rotation of the cylindrical drum and auger requires a large amount of power. Also, the high speed rotation of the decanting centrifuge requires costly machinery which makes this device too costly for most dairy or swine operations.

Performance data on decanting centrifuges with dairy manure slurries was not found. However, Glerum, Klomp, and Poelma (6) gave a maximum total solids removal value of 66 percent at a flow rate of 2.64 gpm using swine slurries. This flow rate would be sufficient for swine operations of 165 pigs if the separator was under continuous operation.

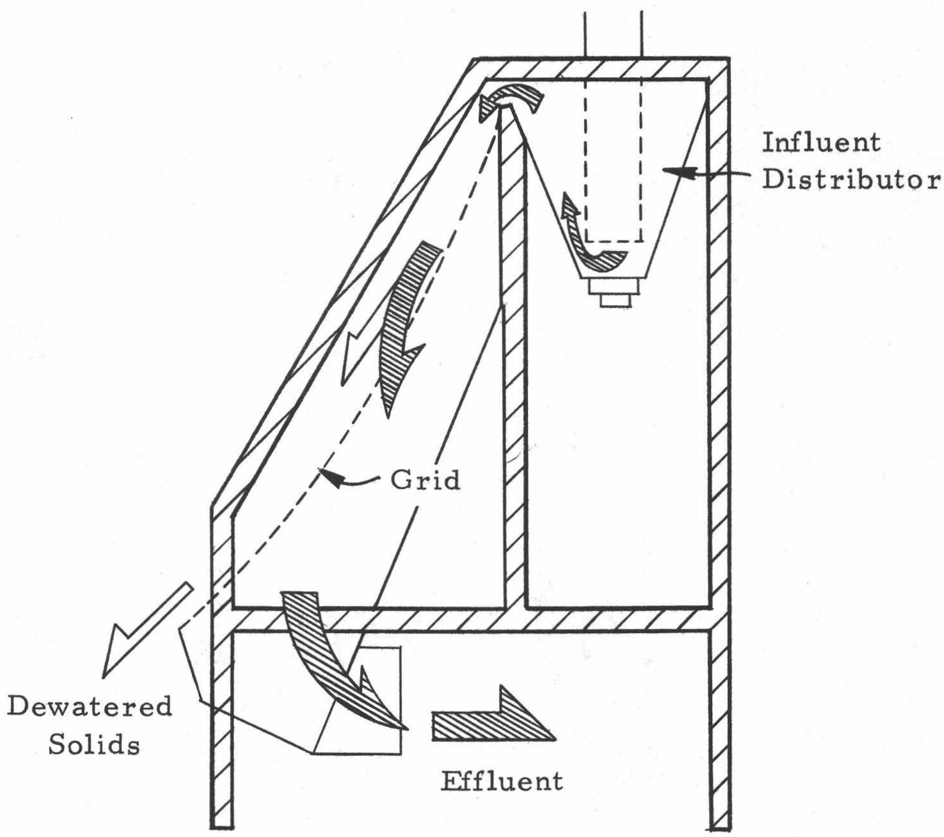

Figure 1. Sloping screen solid separation device (Courtesy Hydrasieve by Bauer Brothers Co.).

Centrisieve

Figure 3 shows a schematic of the centrisieve separation device. This device, like the decanting centrifuge, uses centrifugal force as the separation force. The untreated slurry is introduced into the center of a rotating bowl-shaped sieve, constructed of parallel stainless steel bars. The rotating screen causes an inertial force to act on the liquids which pass through the sieve. The solids are trapped on the sieve and move by their inertial force over the edge of the screen.

Glerum, Klomp, and Poelma (6) tested a centrisieve device on swine slurries. They reported a maximum total solids removal of 55 percent at a flow rate of 35.2 gpm. Since the centrisieve required high speed rotation to induce separation, the power requirement was high. The cost of the centrisieve was relatively high but the capacity was also high. Under continuous operation, the centrisieve can separate the solids from the slurry produced by 2200 pigs. Because of the bowl-shaped sieve blinding, plugging, and flow channeling might become operational problems.

Vacuum Filters

The vacuum filtration device has found a place in both industrial and domestic waste treatment processes. Figure 4 shows a schematic

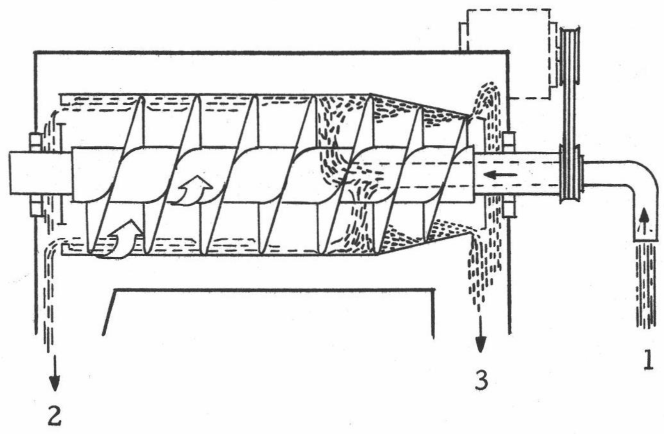

Figure 2. Decanting centrifuge: 1 slurry, 2 liquids, and 3 solids. Taken from Glerum, Klomp, and Poelma (6).

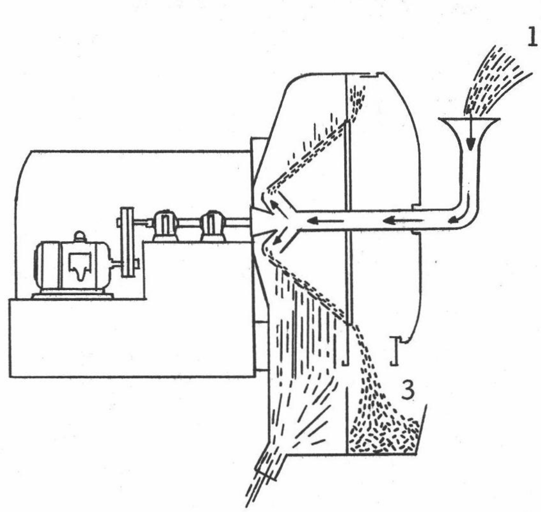

Figure 3. Centrisieve: 1 slurry, 2 liquids, and 3 solids. Taken from Glerum, Klomp and Poelma (6).

diagram of a vacuum filtration device. The vacuum filter uses a pressure difference to draw the slurry through a porous membrane. The solids are trapped on the membrane while the liquids pass through. The membrane is continuously rotated for solids removal.

Glerum, Klomp, and Poelma (6) reported this type of device to have high power requirements. This is attributed to the device creating the separation force in the form of a pressure difference across the membrane. Because of the device's requirement for pressurizing equipment, the cost is high. Glerum, Klomp, and Poelma (6) gave a total solids removal value for swine slurries of 51 percent at a flow rate of 1.1 gpm. This flow rate is low and would only handle about 69 pigs. The flexible membrane of this device may not be desireable in dairy applications because of low durability.

Sedimentation Silo

Figure 5 shows a schematic diagram of a sedimentation silo coupled with an oxidation ditch. The sedimentation silo is basicly a tank which uses gravitational force acting on the solid particles as the separation force. The solids settle to the bottom of the tank and the liquids are decanted from the top.

This device will obviously require no power while separating solids. However, the device tested by Glerum, Klomp, and Poelma (6) possessed no means of solids removal after settling the solids.

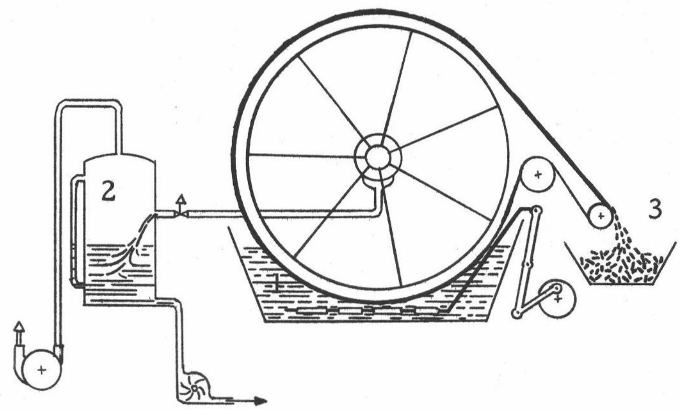

Figure 4. Vacuum filtration solids separator: 1 slurry, 2 liquids, and 3 solids. Taken from Glerum, Klomp, and Poelma (6).

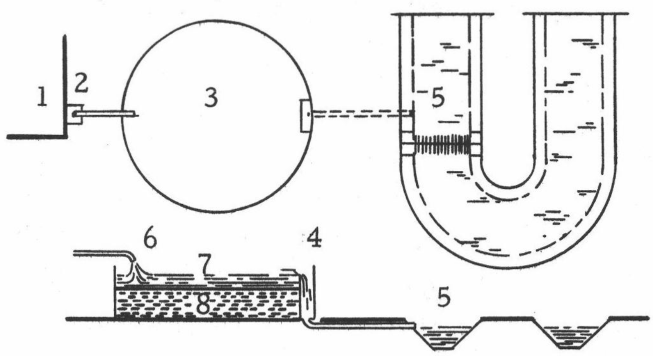

Figure 5. Sedimentation silo: 1 piggery, 2 pump, 3 silo, 4 overflow, 5 oxidation ditch, 6 slurry, 7 liquids, and 8 solids. Taken from Glerum, Klomp, and Poelma (6).

Therefore, when the solids level reached the top of the overflow, the tank required labor for solids removal. They did not give the frequency of the solids removal activity.

The cost of a sedimentation tank is high but within the capabilities of most livestock producers when no solids removal equipment is added. However, if solids removal equipment is included, the cost may again become prohibitive. Glerum, Klomp, and Poelma (6) reported total solids removal values of 80 to 86 percent for the sedimentation silo they tested on swine slurries. No flow rates were given.

Vibrating Screens

The solids separation device most widely used in livestock operations in the United States is the vibrating screen. Figure 6 shows a schematic diagram of this device. The vibrating screen separator employs gravitational force to pull the slurry through a horizontally oscillating screen. The vibration is caused by the rotation of eccentric weights connected to the shaft of an electric motor. The liquids pass through the screen depositing the solids on the screen. The oscillating screen transports the solids off the screen and is supposed to prevent plugging of the screen. A modification of the device diagrammed in Figure 6 was made by adding a second screen layer and short hollow cylinders between the two screen

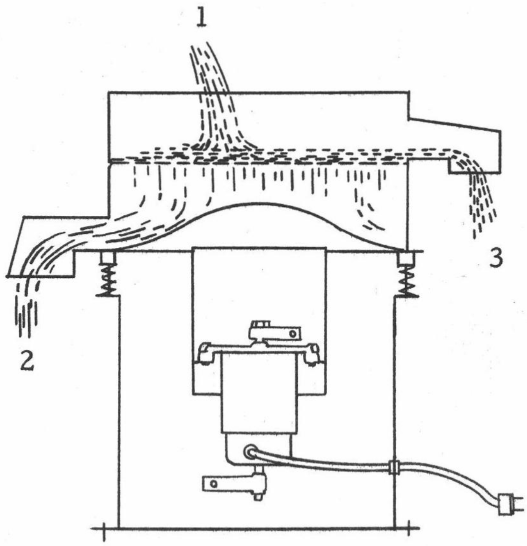

Figure 6. Vibrating screen separator: 1 slurry, 2 liquids, and 3 solids. Taken from Glerum, Klomp, and Poelma (6).

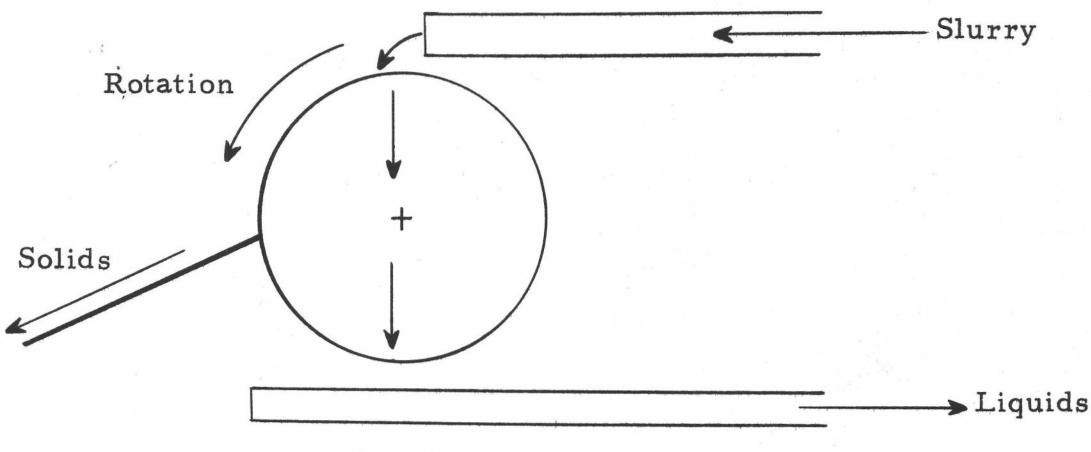

Figure 7. Rotating cylindrical screen.

layers. The cylinders are allowed to slide freely between the screens. By vibrating the screens, these small cylinders cut long solids strands lodged in the screens and scrape the screens clean.

Since the only power required is for solids transport, the power requirement is quite low. The vibration, which is a necessary part of its operation, causes a shorter operation life than might be desired. Glerum, Klomp, and Poelma (6) reported a vibrating screen which had a cost of 700 dollars and a capacity of 0.88 gpm. This device is much to small for operation in a large dairy or swine operation. They reported no solids removal values for swine slurries.

Fairbank and Bramhall (4) did some preliminary investigations of the vibrating screen on dairy slurries in 1968. They reported total suspended solids removals of about 13 percent on limited observations. They did not report the capacity, cost or power requirement of the device.

Rotating Cylindrical Screens

The final device which will be discussed here is the rotating cylindrical strainer. The trade name for this device is Rotostrainer (15). The device is a stainless steel sieve wrapped in a 24 inch diameter cylindrical configuration. The sieve rotates while the slurry passes through the cylinder as shown in Figure 7. The solids are scraped from the screen as it is rotated. This device has an advantage over other screening separators because of the backwashing done by the screened liquids. An evaluation of this device is currently being conducted in Minnesota, but sufficient data are not yet available. The list price for this device is 5640 dollars.[1]

Summary of Previously Discussed Separation Devices

A summary of the available information on the previously discussed devices is given in Tables 1 and 2. Table 1 gives information on devices tested on swine manure slurries and Table 2 gives information on devices which have been tested on dairy manure slurries.

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[1] J. F. Benkovich. Private communication. Hydrocyclonics Corporation. Lake Bluff, Illinois. 1973.

Table 1. Performance comparison for devices tested on swine manure slurries.

Device	Cost ($)	Total Solids Removal (%)	Slurry Solids Conc. (%)	Solids Conc. in Solids Stream (%)	Power Required (Hp)	Cost Per Unit Capacity ($/gpm)	Power Per Unit Capacity (Hp/gpm)	Capacity (gpm)
Settling Silo	1100	80-86	7-12	16	---	---	---	---
Vibrating Screen	700	---	---	---	0.25	796	0.28	0.88
Vacuum Filter	8350	51	7.54	21.5	4.0	773	3.64	1.10
Decanter Centrifuge	8350	66	7.58	37.4	25.0	3164	9.48	2.64
Centri-sieve	2100	55	12.0	19.4	15.0	60	0.43	35.18

Note: Information developed from Glerum, Klomp, and Poelma (6).

Table 2. Performance comparison for devices tested on dairy manure slurries.

Device	Cost ($)	Total Solids Removal (%)	Slurry Solids Conc. (%)	Solids Conc. in Solids Stream (%)	Power Required (Hp)	Cost Per Unit Capacity ($/gpm)	Power Per Unit Capacity (Hp/gpm)	Capacity (gpm)
Sloping Screens*	---	58	0.50 (apprx.)	12.5	---	---	---	5.0
Vibrating Screens*	---	10	0.40	20.0	---	---	---	---

*Information taken from Graves (7).

**Information taken from Fairbank and Bramhall (4).

III. BASIC CONCEPT AND OPERATION PRINCIPLE OF THE HELICALLY FLIGHTED ROTATING CYLINDER SEPARATOR

As the advantages and disadvantages of the previously described devices were studied, it was recognized that the devices which mechanically produced the separation force had the highest costs and required the most power. Examples of this are the decanting centrifuge, the centrisieve, and the vacuum filter.

Contrasting these devices are the devices which do not create the separation force. These separators usually employ gravity as the separation force and, therefore, require no power to create the separation. Examples of this type of device are the vibrating screen, the sloping screen, the sedimentation silo, and the Rotostrainer.

Some separators in this second group do require a small amount of power to remove the solids from the device; such as the Rotostrainer and the vibrating screen. The sedimentation silo requires no power but requires labor to remove the solids from the tank after a period of operation.

Therefore, a low cost, durable livestock manure solids separator which consumes very little power should depend upon gravity for the separation force. Screens should be avoided because of flow channeling, blinding, and wear problems. Therefore, sedimentation was the separation process chosen for the separation device to be developed and evaluated. This device also required some means of removing solids from the separator.

The basic design of the separator was developed by Dr. J. R. Miner of the Agricultural Engineering Department at Oregon State University. The basic concept behind its operation was a series of small settling basins on an incline as shown in Figure 8. As the solids settle from the flow, they are trapped in the basins. The basins are then moved slowly up the incline where the basins dump the solids along with whatever water is also trapped. The basin movement is accomplished in the design of the separator. This design involves a rotating cylinder with a helical fin attached to the inside surface. By mounting the cylinder on an incline, manure slurries, when introduced at the highest end of the tube, encounter a structure similar to Figure 8. The basins formed by the helical fin are, in effect, moved up the incline as the cylinder is rotated.

The sheet metal tube of the first experimental model was 8 inches in diameter and 57 inches long. The 2 inch high, sheet metal helical fin attached to the inside of this tube had 2 1/4 inch spacings between successive wraps of the helix. A frame was built on which the tube was mounted allowing the incline to be varied between 0 and 20 degrees. Tube rotation was accomplished by an electric motor and worm-gear speed reducer. Tube speed was varied by a series of

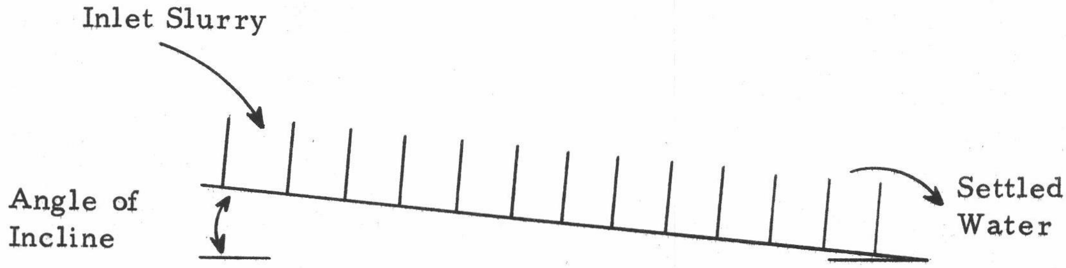

Figure 8. Concept of solid-liquid separation based on a series of settling traps.

different diameter pulleys. A sketch of this separator is shown in Figure 9.

This first model was too small to be practical for large scale manure solids separation. However, the information gained from this model's performance would assist in the design of a larger model.

Since this device consists of a series of settling basins, the overall separation efficiency of the separator is controlled by the performance of the individual basins. The solids removed by each basin is controlled by three design parameters. These parameters are: (a) the settling velocities of the solids being separated, (b) the detention time of the fluid in each settling basin, and (c) the turbulence of the fluid in the settling basins.

Of the three design parameters, turbulence was believed to have the greatest effect on scale up procedures. This was because an increase in device size would not affect the solid particle properties. The detention time was a straight forward calculation involving basin volume and the flow rate. Because turbulence was considered the critical factor when increasing device size, it was given the greatest consideration.

The turbulence in each settling basin is a function of flow rate, fluid viscosity, and the geometry of the flow area cross section. The Reynold's Number for open channel flow also is a function of flow rate,

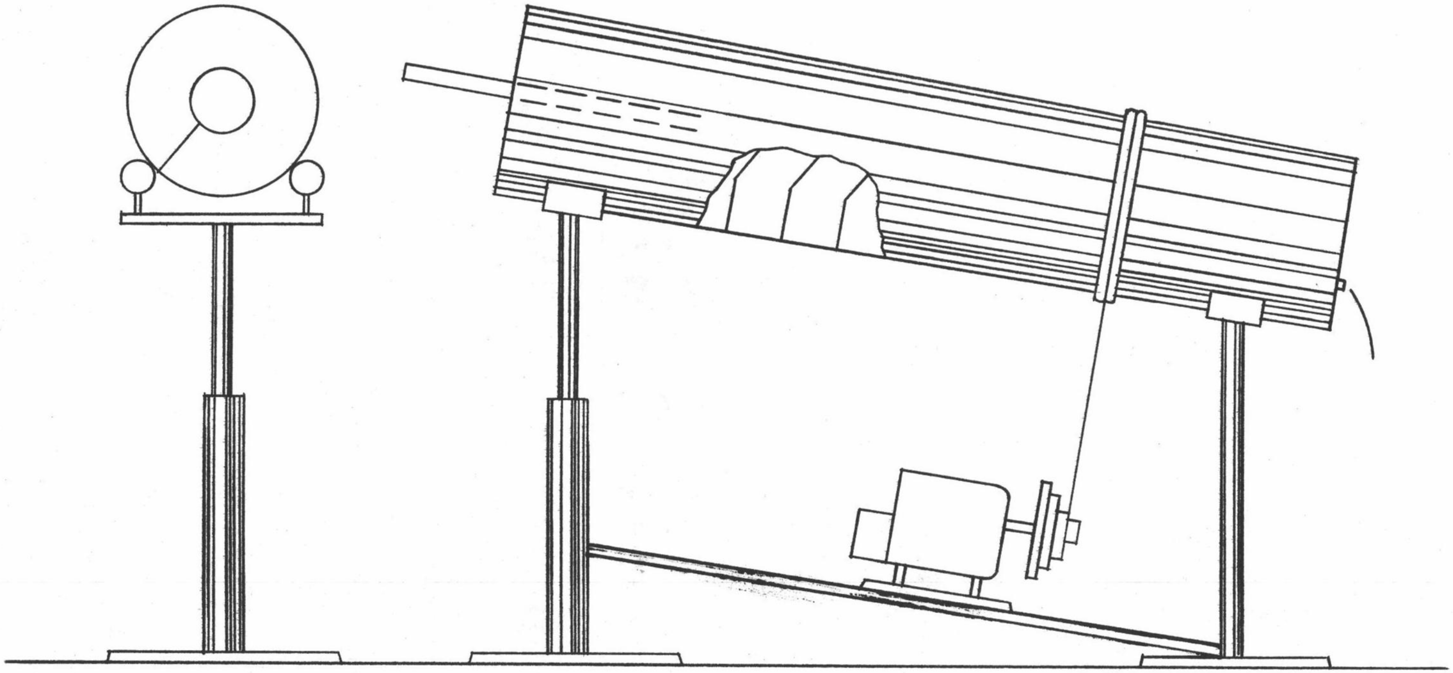

Figure 9. Schematic diagram of the first experimental rotating flighted cylinder solid-liquid separator.

fluid viscosity, and the geometry of the flow area cross section. Therefore, this Reynold's Number could be used as a measure of the turbulence.

It was not obvious whether the best measure of turbulence was to be obtained by the Reynold's Number for the flow over the weir crest (as in Figure 10) or by the Reynold's Number for the flow through the settling basin cross section (as in Figure 11). The helical fin formed a circular weir between the basins. Since this circular weir was the flow outlet for one basin and the flow inlet for the next lower basin, an analysis of the flow characteristics over the weirs was in order. Because the actual sedimentation occurred at the basin cross section, the characteristics of the flow occurring in this area were also analyzed.

The analysis first required an expression describing the relationship between the flow rate and the depth of flow over the weir. Mavis (10) described the flow over a vertical, circular weir with the expression.

$$Q = CA\sqrt{H} \qquad (1)$$

where

Q = flow rate over the weir with units of $ft^3\text{-}sec^{-1}$,

C = a discharge coefficient with units of $ft^{1/2}\text{-}sec^{-1}$,

A = cross sectional area of the flow at the weir crest with units of ft^2, and

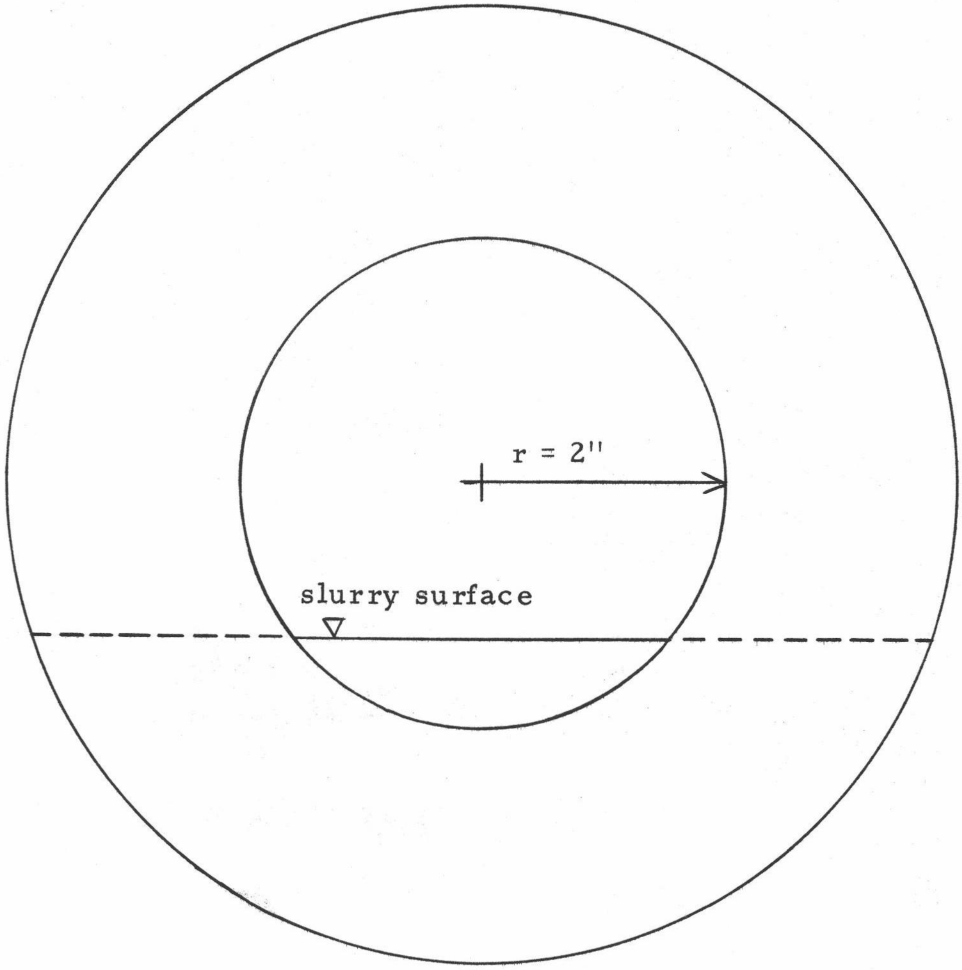

Figure 10. Cross sectional view of the area used for the calculations of the Reynold's Number for the flow occurring at the weir crest.

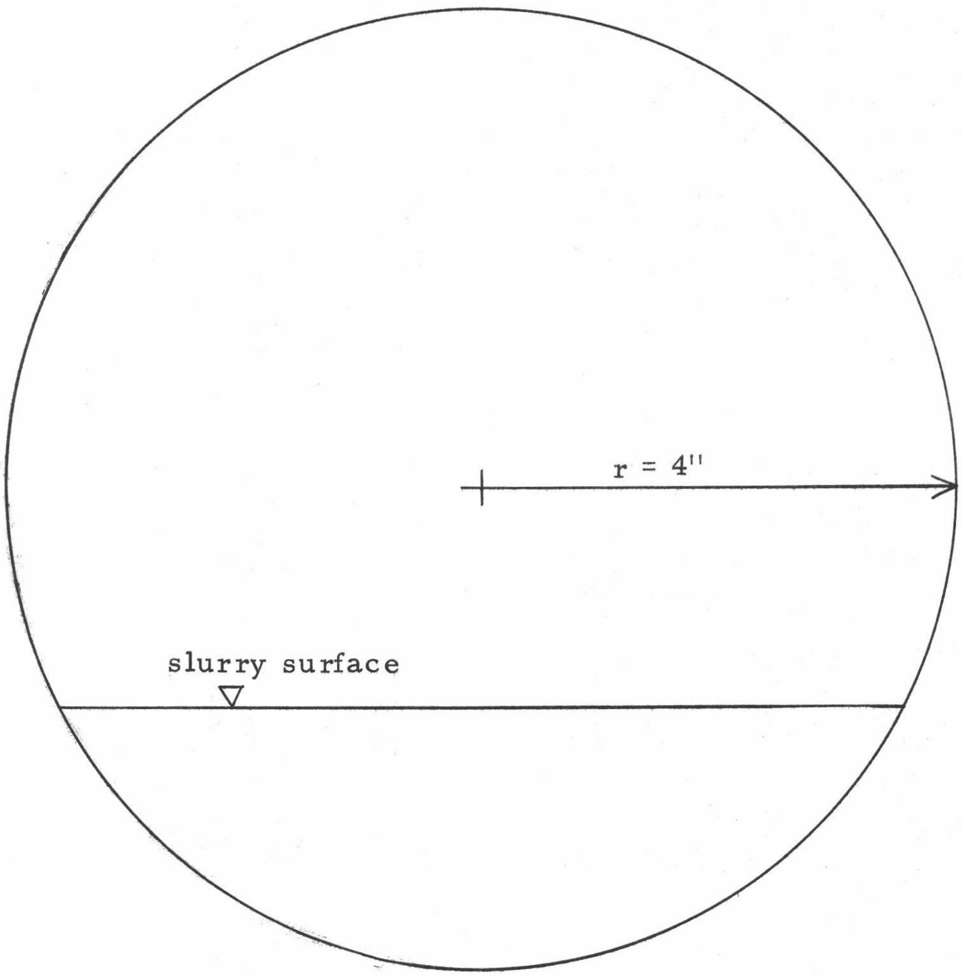

Figure 11. Cross sectional view of the area used for the calculations of the Reynold's Numbers for the flow occurring at the basin cross section.

H = head of fluid upstream from the weir which is essentially equal to the depth of fluid flow at the weir crest in units of ft.

The weirs formed by the helical fin were not vertical. However, because the angle of incline of the tube was small (7 degrees on the first model and 17.5 degrees on the later model), it was decided that very little error would be caused by this variation and Mavis' expression was used.

Mavis (10) explained that the discharge coefficient (C) was dependent only on a value he called the shape factor which is determined by the weir notch geometry. This shape factor is given by the relationship

$$m = \frac{Hx}{A} \qquad (2)$$

where

m = a shape factor describing weir notch geometry (unitless) and

x = width of the weir notch at a distance H above the bottom of the notch (at pond level) in units of ft.

Mavis (10) plotted a graph of the discharge factor (C) as a function of the shape factor (m). Using equations (1) and (2) and Mavis' graph, the head (H) was calculated and plotted as a function of flow rate (Q) for circular weirs of 2 and 6 inch radii. The plot is shown in Figure 12.

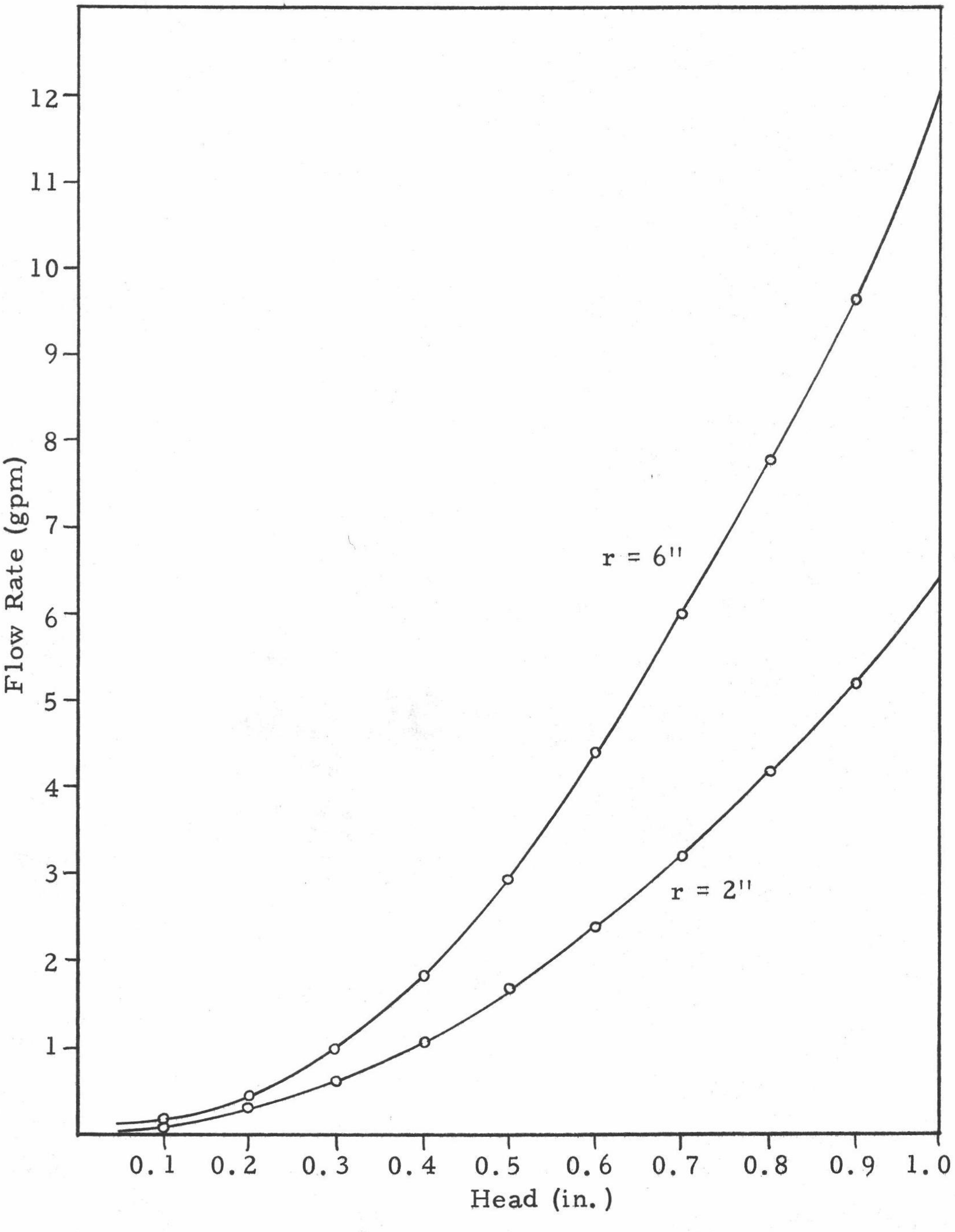

Figure 12. Flow rate as a function of head over circular weirs of 2 and 6 inch radii.

The plot of head against flow rate was then used to calculate the Reynold's Numbers (Re) for the flows occurring at the basin cross section and the weir crest. According to Albertson, Barton, and Simons (1), these Reynold's Numbers for open channel flow are given by the relationship

$$Re = \frac{4RV}{\mu} \tag{3}$$

where

R = hydraulic radius = cross sectional area of flow divided by the wetted perimeter (units of ft),

V = flow velocity (units of $ft\text{-}sec^{-1}$), and

μ = kinematic viscosity (units of $ft^2\text{-}sec^{-1}$).

The flow velocity was found by dividing flow rate by the flow area. The flow area and the wetted perimeter were found by using the values of head (H) and the circle section values calculated from standard mathematical tables. The kinematic viscosity of the fluid was assumed to be that of water. It was previously noted that manure slurries have higher viscosities than water, depending upon the solids concentration. However, for simplicity, and because more precise values were not justified, this assumption was taken as sound. Figure 13 is a plot of the Reynold's Numbers of the flow at the weir crest against the flow rate. Figure 14 is a plot of the Reynold's Numbers of the flow at the basin cross section against the flow rate.

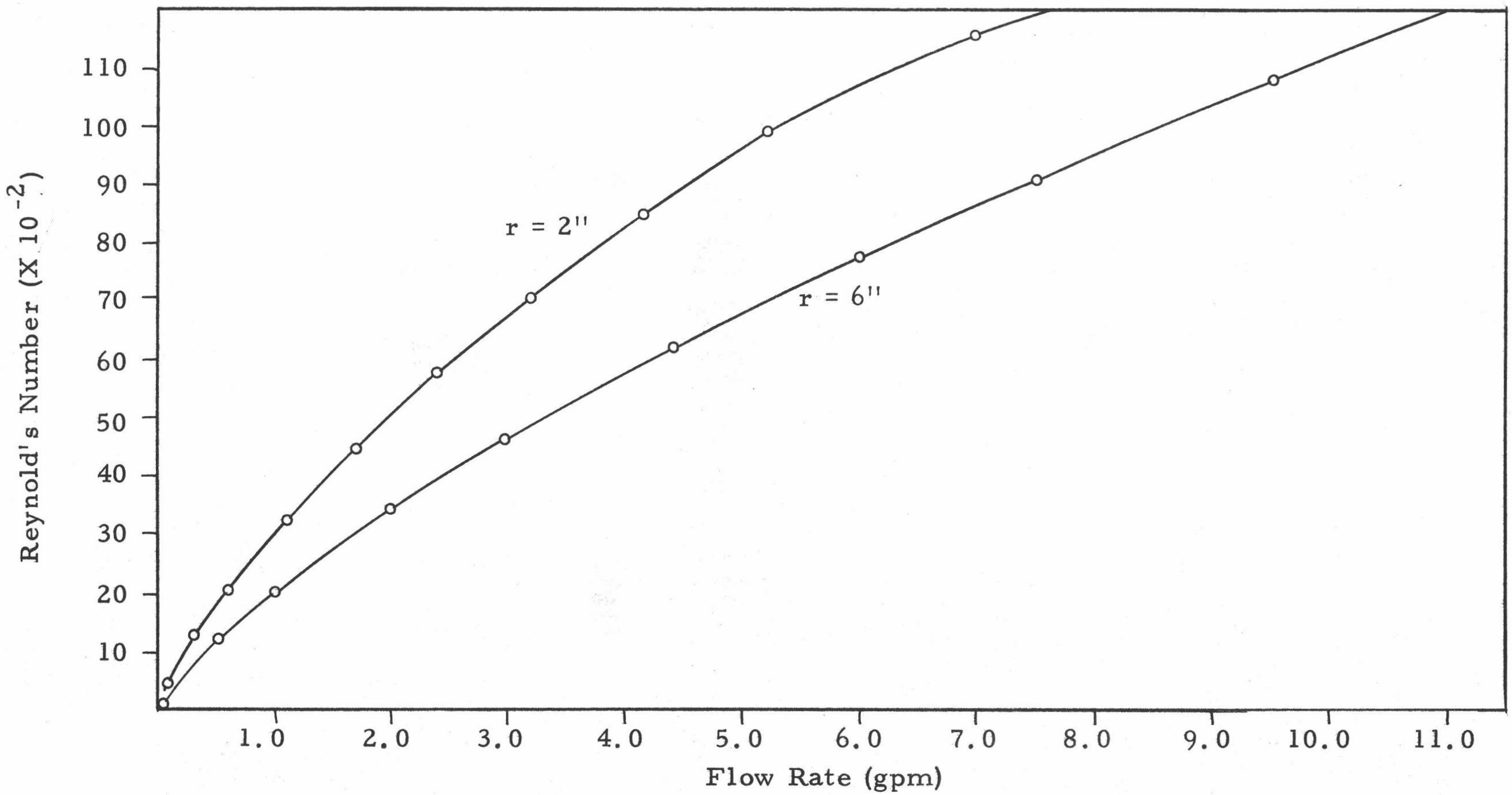

Figure 13. Reynold's Numbers at the weir crest plotted against flow rate.

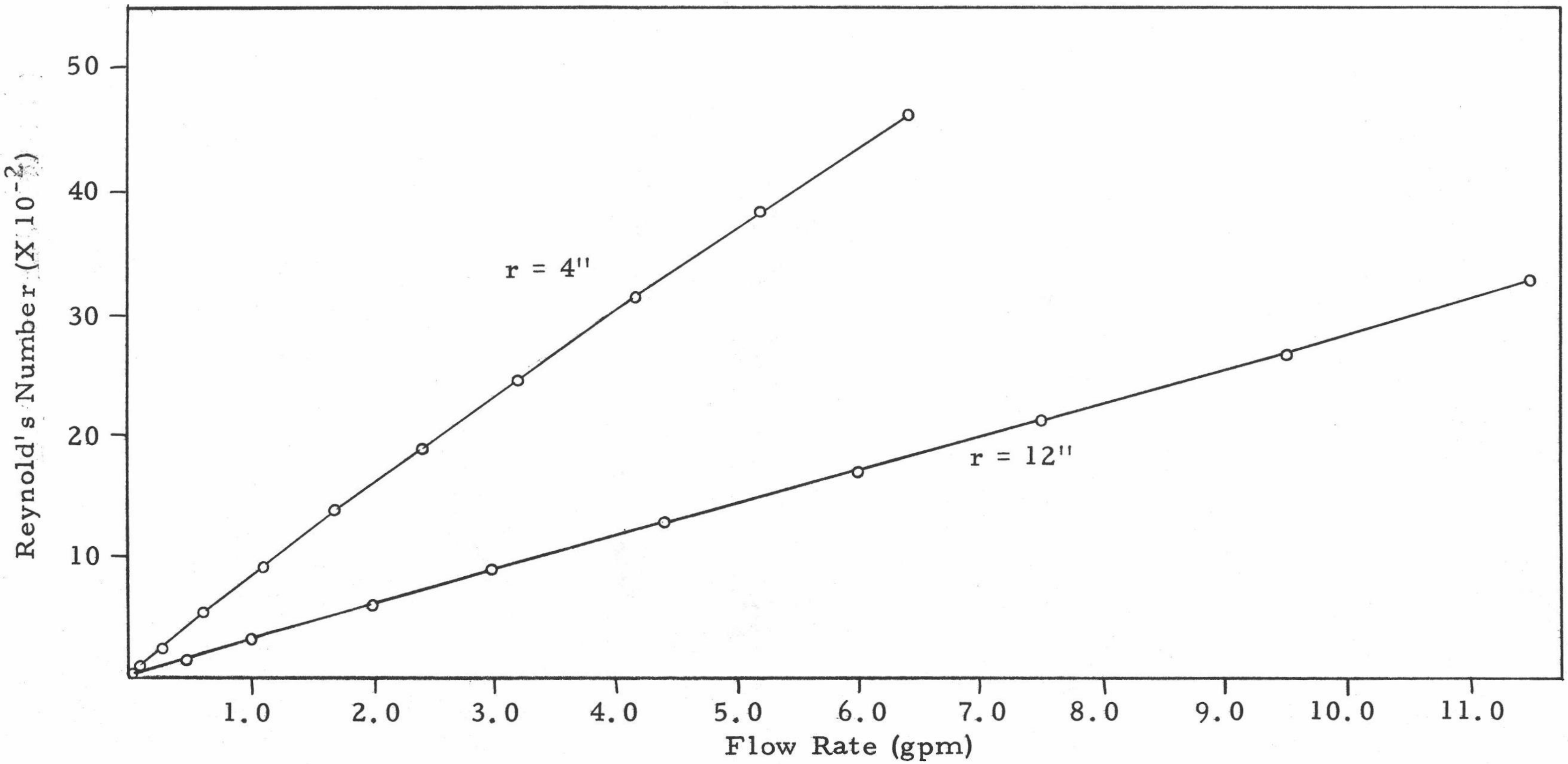

Figure 14. Reynold's Numbers at the basin cross section plotted against flow rate.

From this analysis of flow characteristics, a theory evolved for scaling up from the 8 inch diameter tube to a larger model with a higher capacity. This theory is as follows:

> The helically flighted rotating cylinder separator has a given flow rate associated with a desired performance value for a given set of slurry characteristics. The turbulence in the device is dependent upon the flow rate. If the slurry characteristics are held constant, and the device radius is increased or decreased, then the flow rate associated with the desired performance will increase or decrease proportionally to the change in radius.

During the evaluation and development period of the separator, this theory was also evaluated.

IV. DEVELOPMENT AND EVALUATION

During the evaluation and development of the helically flighted rotating cylinder separator, the practical problems of manure handling became very evident. The first and most persistent problem was encountered as the performance of the eight inch diameter device was measured. Delivering a slurry of uniform solids concentration at a flow rate compatible with the device was difficult. This problem was solved initially by using an agitated supply tank. The cylindrical tank was agitated by a series of paddles on an electrically driven shaft. The liquid volume of the supply tank was 250 gallons. At the beginning of each experimental run, a given weight of solids was added to the supply tank, which was filled with fresh water. When the solids were thoroughly mixed, fresh water at a known flow rate was run into the tank. The slurry was allowed to flow out of the tank through an overflow. The slurry then flowed, by gravity, to the separator. This created a slurry supply at flow rates ranging from zero to five gpm. The solids concentration decreased exponentially with time.

Another problem experienced early in the device testing program was obtaining representative samples. Momentary surges of solids in the stream flow being sampled made grab sampling techniques difficult to use. However, because of convenience and ease of analysis, grab sampling was the most attractive technique. This type of sampling worked well if the sample was collected over a relatively long period. Long sampling duration times averaged out surges in solids concentration. However, they made the sampling volume too large for convenient analysis.

The sampling technique decided upon used 265 ml. plastic bottles to capture the total stream flow at a sampling point. This created sampling times ranging from two to five seconds for influent and lower effluent streams and one to three minutes for the solids or upper effluent stream. This sampling technique made the laboratory analyses easier and more accurate. A variability in results was still expected due to the sampling technique.

There were three sampling points for the runs in which the agitated supply tank was used. Figure 15 is a diagram of the testing arrangement showing these sampling points. For each observation (observed suspended solids removal value), at least two samples were required. These samples were an influent sample at point 1 and a lower effluent sample at point 2. For the first two experimental runs, samples were taken at all three points for each observation. However, this proved unnecessary and time consuming. Therefore, after the second run, the sample from point three was taken only on the fourth, seventh, tenth, eleventh, and twelfth observations.

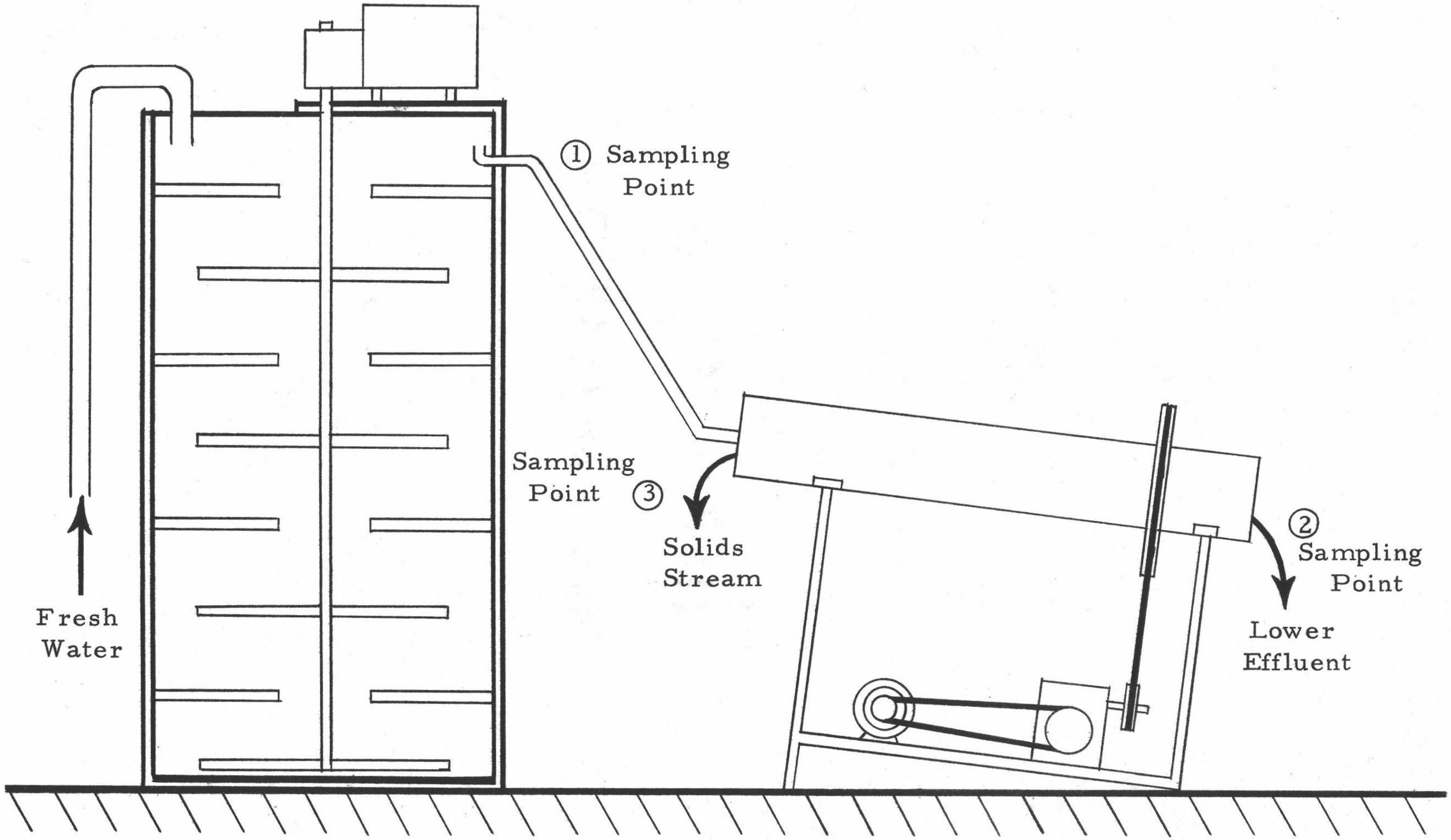

Figure 15. Testing arrangement for eight inch diameter model.

Because it is a sedimentation device, the helically flighted rotating cylinder separator was not expected to affect the soluble solids concentrations of a slurry. Therefore, the main interest was in the suspended solids of a slurry and a sample analysis technique was needed.

The sample analysis technique first used was to separate the 265 ml. sample into the soluble and suspended solids by centrifugation. The samples were centrifuged at 1800 rpm for 15 minutes. Each fraction was then dried at 103^{o} C for 24 hours to determine the dry weights. When the dry weights were known, the soluble, suspended, and total solids concentrations for the sample could be calculated by dividing the weight of the appropriate solids fraction by the sample volume.

With the suspended solids concentration for each sample known, the suspended solids removal and the solid concentration factor for the observation could be determined. The suspended solids removal was calculated by the equation

$$\eta = (1 - \frac{C_1}{C_2})(100) \qquad (4)$$

where

C_2 = the suspended solids concentration of the lower effluent or liquid stream (units of gm - L^{-1}),

C_1 = suspended solids concentration of the influent stream (units of $gm - L^{-1}$), and

η = suspended solids removal (units of percent).

The solids concentration factor is a measure of the device's ability to concentrate suspended solids and was calculated by the equation

$$K = \left(\frac{C_3}{C_1}\right) \tag{5}$$

where

K = the solids concentration factor (unitless) and

C_3 = the suspended solids concentration of the solids stream (units of $gm - L^{-1}$).

Initially, beet pulp slurry was used in conjunction with the agitated supply tank to test the eight inch diameter model. The beet pulp offered more uniform solids characteristics but still approximated manure solids behavior. Therefore, the data developed gave a better indication of the important performance parameters of the device than was possible with manure solids. The beet pulp also proved to be easier to handle than manure slurries.

Two runs were made with the beet pulp slurry and the agitated supply tank to determine the combination of influent flow rate and suspended solids concentration that produced the best solids removal.

The data from these two runs are shown in Tables 1A and 2A of Appendix A. Some observations had effluent suspended solids concentrations greater than the influent values. This would indicate solids production by the device which obviously cannot occur. Therefore, these observations were considered errors caused by solids residence time in the device and sampling technique.

These data indicated better solids removal occurred at flow rates less than 1.25 gpm and at lower influent suspended solids concentrations. This was expected as low flow rates allow for longer detention times and less turbulence in the device. It was also observed that the device was not concentrating the beet pulp solids in the solids stream until late in each run. Through both runs, the suspended solids concentrations of the solids stream indicated the device was not working as expected eventhough the suspended solids concentrations of the effluent indicated some solids removal. An explanation of this observation was not immediately obvious.

To verify these observations, three more runs at constant flow rates of 0.50 gpm, 0.75 gpm, and 1.20 gpm were made with beet pulp slurry in the agitated supply tank. The data from these runs are shown in Tables 3A, 4A, and 5A of Appendix A.

The data from runs 3, 4, and 5 indicated the best suspended solids removal values again occurred at low flow rates. Table 3 shows the average beet pulp solids removal values for given flow rates from

Table 3. Average suspended solids removed from beet pulp slurries by the eight inch diameter tube.

Flow rate (gpm)	Average suspended solids removal (%)
0.50	62.9
0.75	56.0
1.20-1.25	50.1
1.50	41.9
1.75	29.0
2.00	39.0
3.00	5.5
4.00	7.2

the first five runs. This table shows a definite trend towards higher solid removal values at low flow rates. Runs 3, 4, and 5 also indicated the influent suspended solids concentration in the range of 0.50 gm/L to 3.00 gm/L had little effect on the solids removal ability of the device. Therefore, the major factor determining beet pulp suspended solid removal values for the helically flighted rotating cylinder was flow rates. It was again observed that the device was not satisfactorily concentrating solids in the solids stream.

Visual observations of the upper end indicated the solids were being separated as the data indicated. However, the solids were sticking to the sides of the cylinder and the helical fin at the upper end. Until a layer of solids accumulated on the sides of the device and overcame the cohesion forces between the solids and the metal, no solids would come out the top of the device. This build up occurred about 190 minutes after the run began. The capability of the device to concentrate solids would have been more accurately measured if longer runs had been made. However, because the apparatus set up and clean up procedures required a great deal of time, longer runs were not possible. This restriction was considered in all subsequent data analysis.

After the five runs with beet pulp slurry were made and the samples analyzed, two runs using manure slurries in the agitated supply tank were attempted. Fresh manure from the OSU Dairy Center was collected and mixed with fresh water in the supply tank. The two manure slurry runs and data analysis were carried out in the same manner as the beet pulp tests. During the course of the manure slurry tests, severe plugging problems were experienced. The manure slurries did not work well in the agitated supply tank. Flow rates for these tests were at 0.50 and 0.75 gpm. The data from these tests are shown in Tables 6A and 7A of Appendix A.

These data tables again indicated the separator removed suspended solids best at low flow rates. They further supported the observation that the influent concentrations had little affect on the suspended solids removal. These data also indicated the device was less effective for removing manure solids than beet pulp solids. The reason for this decrease in solids removal was the heavier manure solids were remaining in the bottom of the supply tank, even under vigorous agitation. Therefore, the separator was not receiving the solids which it could best remove from the slurries. It was receiving the lighter particles which did not settle well.

Modifications to the Eight Inch Diameter Tube

After the seventh test run was completed and the samples analyzed, the data were reviewed. The suspended solids concentration of the solids stream was not as high as desired. Therefore, a physical modification of the separator was deemed necessary.

The goal of the modification was to increase the solids concentration or decrease the water coming out the top of the tube. The actual modification consisted of drilling four holes in the upper four fins of the separator. These holes were 1/4 inch in diameter and were drilled at a six degree angle to the tube walls. The six degree angle was chosen because testing completed to that time had been done at a tube incline of seven degrees. When the tube was in testing position after the modification, the angle of the drilled holes was one degree (downslope). A schematic diagram of the modification is shown in Figure 16. The holes were to decant a portion of the fluids from the upper four basins, making the solids concentration higher in the solids stream.

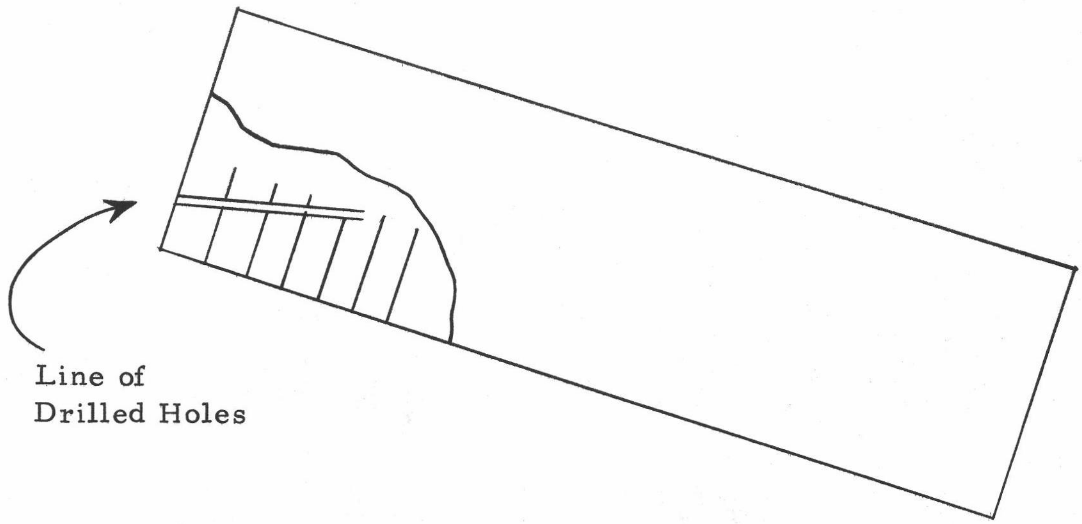

Figure 16. Schematic diagram of the modified 8 inch separator tube.

Upon completion of the modification, two tests with beet pulp and one test with manure were made. The tests were run in the same manner as previously described at flow rates of 0.50 gpm. The samples from these runs were also analyzed in the same manner. The data developed from these runs are shown in Tables 8A, 9A, and 10A, respectively. A summary of the average suspended solids removals, and average maximum concentration factors for the first ten test runs at flow rates of 0.50 gpm and 0.75 gpm is shown in Table 4.

Table 4 indicates a slight increase in suspended solids of the solids stream due to the modification in tests using beet pulp slurry. However, due to the feed systems inability to handle manure slurries, only one run with manure slurries was made at 0.50 gpm before and after the modification. Therefore, it would be difficult to make a judgement on any changes in the concentration factor for the manure slurry test runs.

At the end of the tenth test of the first model separator, some general observations were made on the separator and the testing procedure and equipment. These observations were as follows:

(a) The sampling and laboratory analysis techniques were sufficiently accurate to provide general indications of the first model's behavior.

Table 4. Eight inch diameter tube solids separation performance before and after modification of upper four fin flights.

Slurry Solids	Averaged suspended solids removal for first ten runs (percent)		Averaged concentration factor for first ten runs (unitless)		Flow Rate (gpm)
	Before Modification	After Modification	Before Modification	After Modification	
Beet Pulp	62.9	63.9	6.13	3.60	0.50
Dairy Manure	31.1	43.5	1.48	1.12	0.50

(b) The helically flighted rotating cylinder separator had potential as a device for concentrating solids in manure slurries.

(c) The helically flighted rotating cylinder separator was operating satisfactorily in that no plugging or other mechanical problems were occurring.

(d) The feed system was not delivering representative samples to the separator when manure slurries were being used.

(e) The solids concentration in the solids stream being discharged at the upper end was not high enough even with the modifications to the upper four fin flights.

Development of the Second Generation Separator

As the previous mentioned observations were made, it was decided to revise the design of the device and fabricate a second generation separator. The second generation device had a tube diameter of 24 inches and a helical fin height of 6 inches. The fins were on a 4 inch spacing. To decrease the amount of water carried out the upper end in the solids stream, the upper six fin flights were decreased in height in a stepwise manner as shown in Figure 17. The physical characteristics of the first and second generation devices are compared in Table 5.

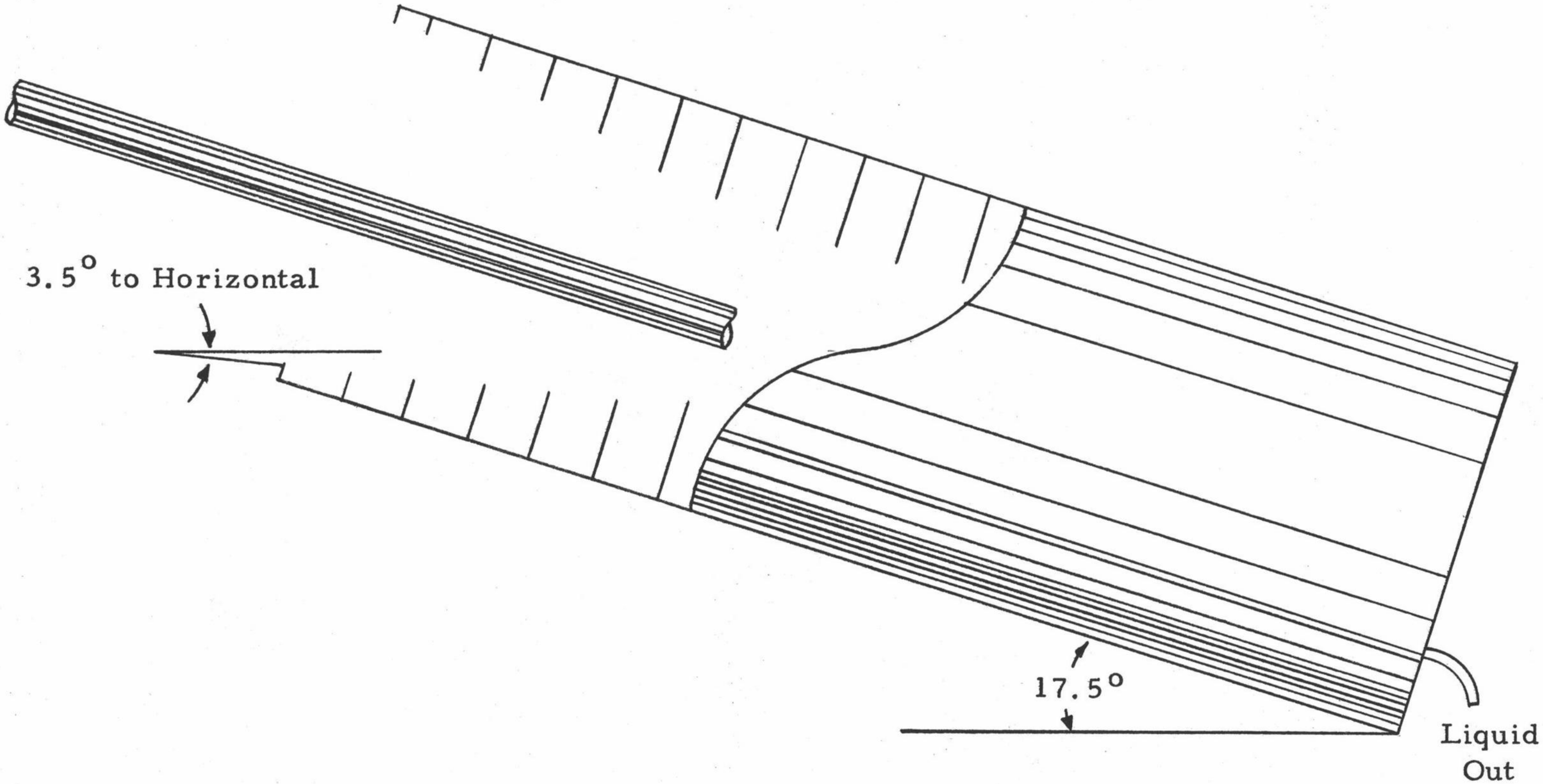

Figure 17. Sketch of the 24 inch diameter separator tube.

Table 5. Physical parameters of the 8 inch and 24 inch diameter tubes for solid-liquid separation.

	8 inch tube	24 inch tube
Tube diameter (inches)	8	24
Tube length (inches)	57	60
Fin height (inches)	2	6
Fin spacing (inches)	2.25	4
Mounting angle to horizontal (degrees)	7	17.5
Volume of water between fins (cubic inches)	22	355
(gallons)	0.095	1.54
Tube rotational speed (rpm)	1.33	0.44
Tube peripheral speed (in/min)	33.43	33.43

Notes:

1) Upper five rounds of the fin in the 24 inch diameter tube have heights of 1, 2, 3, 4, and 5 inches, respectively.

2) The slurry influent tube introduced slurry into the seventh basin by means of an open end pipe in the 8 inch tube.

3) The slurry influent tube in the 24 inch tube had a 90° elbow on the end of the tube directing influent slurry upwards to dissipate part of the flow energy. The slurry was introduced into sixth basin.

The stand used for the eight inch diameter model was modified for the 24 inch model. The speed reducing mechanism remained the same. This made the peripheral speed of the second model equal to that of the first model. In doing this, it was believed any turbulence caused by the rotation would be similar in both models. The tube rotational and peripheral speeds for both devices are shown in Table 5.

Testing Apparatus and Procedure for 24 Inch Diameter Model

With the development of the second generation separator, a different feed system was required. Low capacity mechanical pumps were attempted and proved unsuccessful. The pump which finally proved effective for transporting manure slurry streams which were representative of the larger source was a simple air lift pump. A diagram of this pump is shown in Figure 18.

Manure slurries were pumped from a 35,000 gallon manure storage tank to the 55 gallon metal drum with a high capacity, open impeller, centrifugal irrigation pump used to transport manure slurries to land disposal sites at the OSU Dairy Center. An overflow in the top of the drum was provided for the excess flow. A two inch diameter plastic pipe was placed vertically in the drum. As shown in Figure 18, a flow of compressed air was introduced just inside the

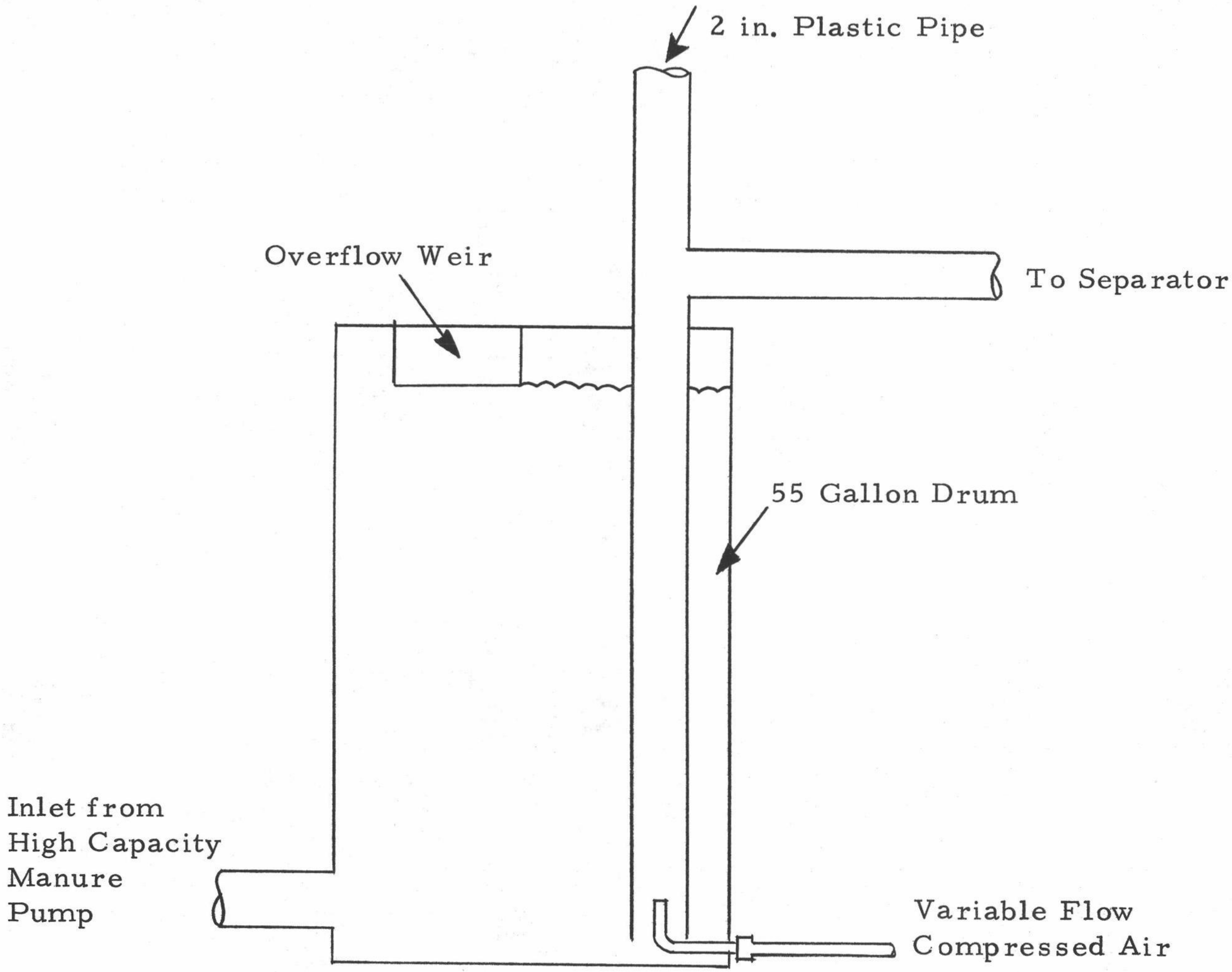

Figure 18. Schematic diagram of the air lift pump used to feed manure slurry to the separator.

lower end of the vertical pipe. The compressed air mixed with the manure slurry in the pipe creating a fluid with a density less than that of the fluid outside the pipe. The pressure differences caused by the variation in fluid densities forced the surface of the less dense fluid to raise above the level of the horizontal pipe connected to the vertical pipe. This allowed the fluid to flow through the horizontal pipe to the separator. Excess air was exhausted through the upper end of the vertical pipe. The fluid flow through the horizontal pipe could be controlled with variations of the compressed air flow. There was some concern that air would become trapped by the solid particles and thus hinder settling. However, the data did not indicate this to be a problem.

The high flow rates from the 24 inch diameter model demanded a different sampling technique and sample analysis method. The heart of the sampling technique developed for testing the second generation separator was a large funnel with a removable 16 mesh screen attached to the orifice of the funnel. This funnel was mounted over a four liter stainless steel beaker as shown in Figure 19. The 16 mesh sampling screen was chosen as the appropriate size because it allowed particles of 1.19 mm in diameter to pass through the screen while trapping the larger particles. It was estimated that particles larger than the 1.19 mm size could not be easily treated and transported in a water reuse system.

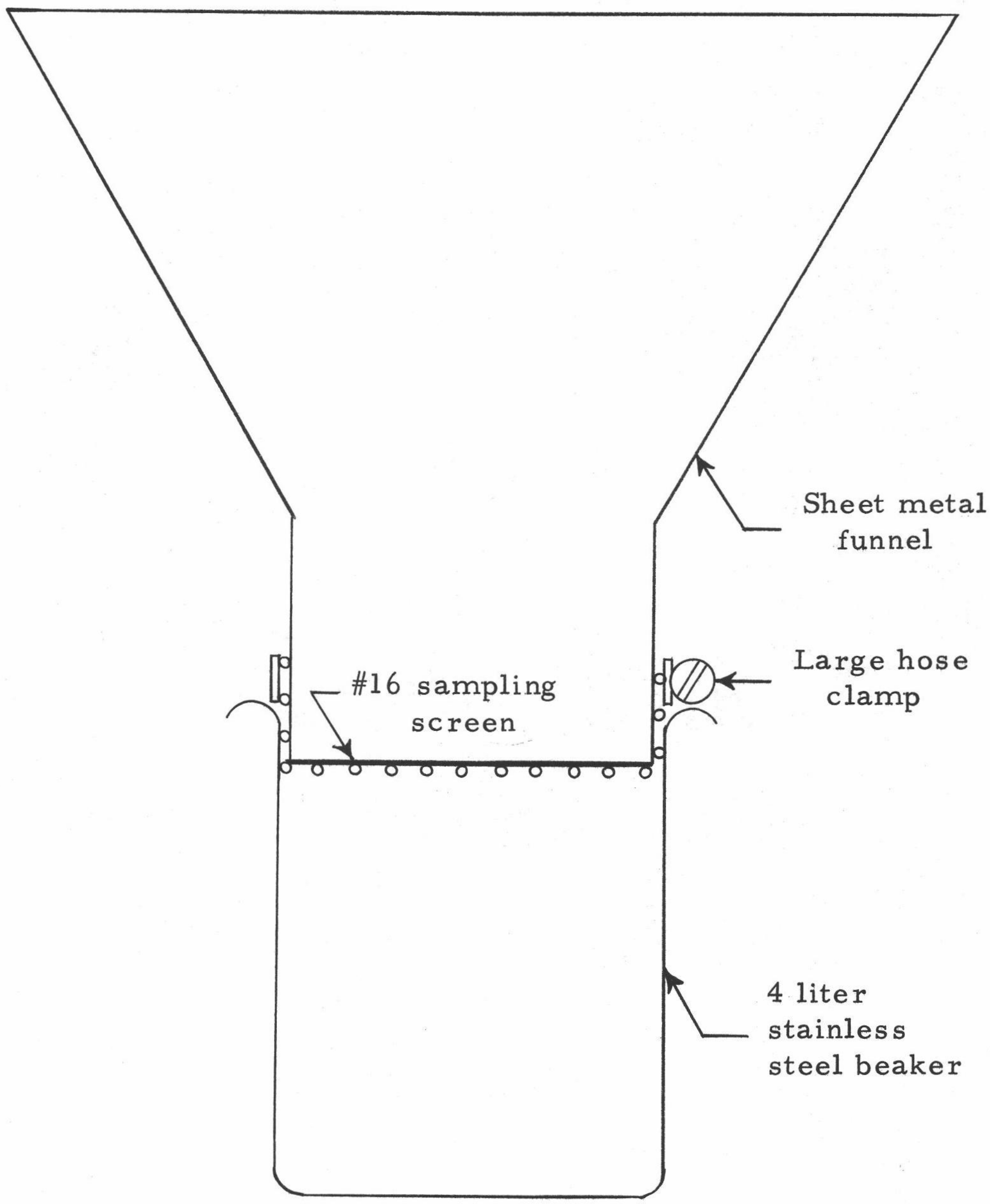

Figure 19. Sampling funnel for collection of samples from the 24 inch diameter model.

When the 24 inch diameter model was tested, samples were taken only at the lower end effluent and the upper end solids stream for each observation. The samples were taken by catching the total flow at a given sampling point in the sample funnel. The time required to capture the sample was measured with a stop watch and recorded as the sampling duration time. Solid particles larger than the mesh size of the screen were retained on the screen while all other portions of the sample were caught in the four liter beaker. The solids retained on the screen were kept for dry solids determination. The fluid volume captured in the beaker was measured and recorded as the captured sample volume.

At the end of each run, the solids samples retained on the screen were taken to the laboratory to determine dry solids content. This determination was made in an indirect method because some samples had large amounts of solids and would have been difficult to analyze in any other method. The wet weight of each solids sample was first measured. Then, two small, representative portions were taken from each captured solids sample. These representative portions were used to determine a ratio of dry solids weight to wet solids weight for each captured solids sample. The ratio was then applied to the wet weight of the captured solids samples. From this application, both the dry solids weight and the weight of the fluids trapped in the captured solids sample could be calculated. The calculations were made with the equations

$$DSW = K(WSW) \tag{6}$$

and

$$WSW - DSW = TFW \tag{7}$$

where

DSW = the dry solids weight of the captured solids sample (units of gm),

WSW = the wet solids weight of the captured solids sample (units of gm),

K = the ratio of dry solids weight to wet solids weight calculated from the small representative portions taken from the captured sample (unitless), and

TFW = the weight of the fluids trapped in the captured solids sample (units of gm).

With these calculations completed, the dry weight of the retained solids and the total sample volume were used to calculate the concentration of the solid particles larger than the 16 mesh screen. This was done with the equations

$$\frac{DSW}{TSV} = C_{2 \text{ or } 3} \tag{8}$$

and

$$TSV = TFV + CFV \tag{9}$$

where

$C_{2\ or\ 3}$ = the retained solids concentration (the concentration of the dry solids which will be retained on a screen of a given mesh size as a sample is passed through it) in units of $gm\text{-}L^{-1}$,

TSV = the total sample volume (units of L),

TFV = the trapped fluid volume (units of L), and

CFV = the captured fluid volume which was measured from the four liter beaker when the sample was taken (units of L).

It was assumed that the fluids in the manure slurries had a specific weight of 1 gm/ml. This is a reasonable assumption since the slurry fluids are primarily water. The solids volume was assumed to be negligible.

For each retained solids concentration removal value (one observation), two samples were necessary. Each retained solids concentration removal value was calculated from the analyses of these two samples. The removal values were calculated by first writing a solids mass flow balance for the separator under steady state operation conditions. In equation form, this mass flow balance is written

$$M_1 = M_2 + M_3 \qquad (10)$$

where

M_1 = the solids mass flow rate of the influent (units of gm-min^{-1}),

M_2 = the solids mass flow rate of the lower effluent (units of gm-min^{-1}), and

M_3 = the solids mass flow rate of the solids stream (units of gm min^{-1}).

These mass flow rates were in terms of the total mass of particles larger than the 16 mesh screen (1.19 mm) used in the sampling funnel.

Equation 10 can be rewritten as

$$C_1V_1 = C_2V_2 + C_3V_3 \qquad (11)$$

where

C_1 = the influent solids concentration of the solid particles larger than 1.19 mm (units of gm-L^{-1}),

V_1 = the influent volumetric flow rate (units of L-min^{-1}),

C_2 = the lower effluent solids concentration of the solid particles larger than 1.19 mm (units of gm-L^{-1}),

V_2 = the lower effluent volumetric flow rate (units of L-min^{-1}),

C_3 = the solids stream concentration of solids particles larger than 1.19 mm (units of gm-L^{-1}), and

V_3 = the solids stream volumetric flow rate (units of L-min ^{1}).

V_2 and V_3 were calculated from the sampling duration time measured when the samples were taken and the total sample volume (TSV) calculated earlier. This was done with the equation

$$\frac{TSV}{t} = V_{2 \text{ or } 3} \qquad (12)$$

where

t = the sampling duration time (units of min).

V_1 was calculated by summing V_2 and V_3.

Equation 11 can be rewritten as

$$C_1 = \frac{C_2V_2 + C_3V_3}{V_1} \ . \qquad (13)$$

The retained solids concentration reduction value (η) was then given by the equation

$$\eta = (1 - \frac{C_2}{C_1})(100) \ . \qquad (14)$$

Testing the 24 Inch Diameter Model With Dairy Slurries

Fifty retained solids concentration removal values on dairy manure were observed for the 24 inch diameter model. The samples for three of these observations were discarded immediately because of equipment failure or sampling errors. The data from these observations are shown in Table 1B of Appendix B. Two more observations (13 and 38) were disregarded because reasoning indicated these observations to be in error.

The data from Table 1 B were rearranged and grouped according to flow rates. The retained solids concentration removal values associated with each flow rate group were averaged together as shown in Table 2B of Appendix B. A summary of this data has been shown in Table 6.

Table 6 indicates the 24 inch diameter separator's ability for removal is dependent largely upon the flow rate of the slurry introduced to the device. This was expected as the flow rate determines the turbulence and detention time in the second generation device, just as it did in the eight inch diameter model. However, the concentration factor values in Table 6 do not appear to be dependent upon flow rates. It appears that the separator is capable of concentrating the dairy manure solid particles larger than 1.19 mm about 12 times over the influent slurry value.

Table 6. Summary of performance data from tests on the 24 inch diameter model with dairy manure slurries.

Flow Rate Grouping (gpm)	Group Average Retained Solids Removal* (%)	Group Average Concentration Factor (Unitless)
1.0 - 3.0	54.1	11.7
3.0 - 4.0	46.4	12.3
4.0 - 5.0	34.6	13.9
5.0 - 6.0	28.6	14.0
6.0 - 7.0	10.5	7.5
7.0 - 9.0	14.3	10.2
9.0 - 13.0	13.1	12.5

*The percentage of solid particles larger than 1.19 mm removed from the slurry by passing through the separator.

It was recognized that erratic readings were much more pronounced in the data from the second generation tests than in the first generation test data. This can be readily observed with observations 8 and 31 in Table 1B. A flow rate of 4.06 gpm produced a retained solids removal value of about 57 percent when the almost equal flow rate of observation 8 allowed the separator to remove very few of the retained solids.

The reason for this high variability in the second generation data as compared to first generation data was because beet pulp slurry was primarily used in the first model and manure slurries were exclusively used in the second generation. The beet pulp offered relatively uniform particle sizes and particle densities which allowed for reproduceable results. The manure, however, did not have uniform particle size and density distributions which produced widely varying settling characteristics.

During the testing of the 24 inch diameter model, several measurements of power consumption were made while the device was under a variety of loads. This was done with a watt-hour meter and a stop watch. It was found that the device required an almost constant 0.136 Hp. Power consumption seemed to be independent of the loading.

For the second generation tests, the retained solids concentration of the solids stream flowing from the upper end was generally higher than those developed by the first model. The concentration factors of the second model indicated better concentration was taking place. This increased concentrating ability was attributed to the decreasing height of the upper fin flights. However, this modification of the upper flights did not produce only desireable effects. Several visual observations were made while tests of the second model were in progress. A large concentration of solids in the fourth and fifth basin was noticed. Upon closer inspection, it was recognized that a large percentage of the solids in the upper end of the tube were moving down the tube against the helix rotation. Figure 20 demonstrates this phenomenon. A particle having been trapped at point A in the fourth basin experienced a cohesion force and adhered to the separator wall at point A. As the tube rotated, point A with the trapped solid particle traveled along a path perpendicular to the tube sides (indicated by a dotted line in Figure 20). When the particle traveled through some angle of rotation greater than 90°, the particle weight overcame the cohesion force (at point A' in Figure 20) and the particle fall, by gravity, along the path of the arrow. As a result, the particle came to rest in the next lower basin.

To verify these visual observations, the separator was not cleaned out at the end of one run. Samples were taken from the 14 settling basins and the retained solids concentrations determined in

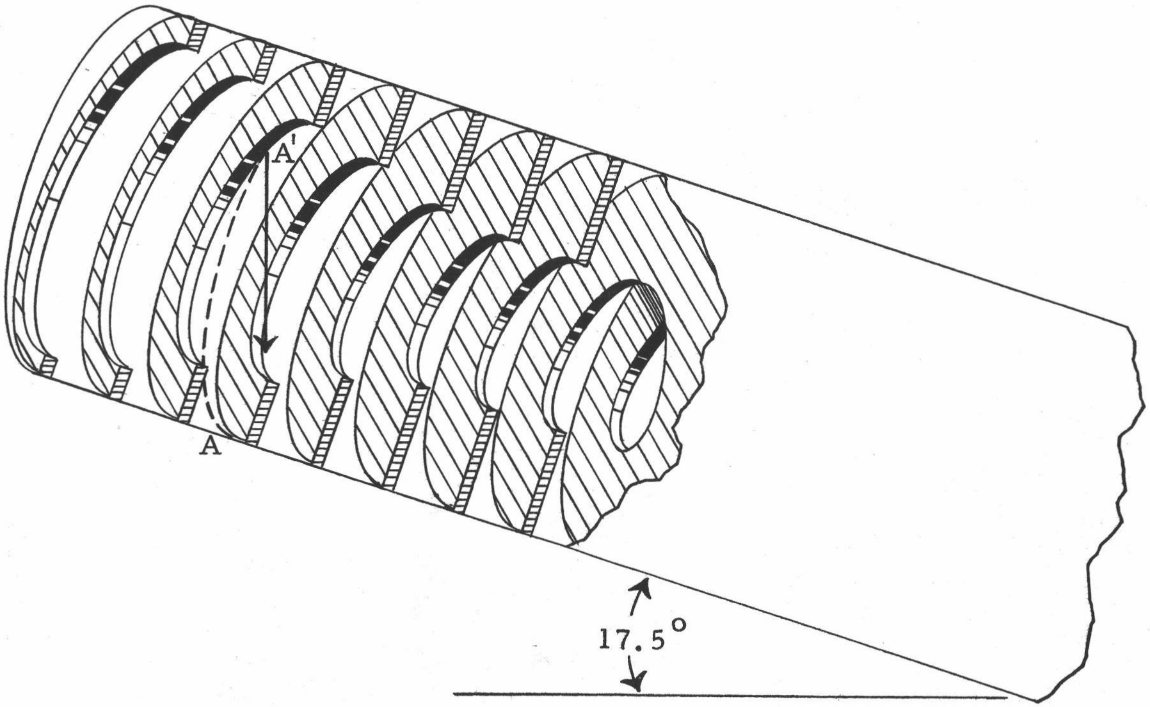

Figure 20. Demonstration of reverse particle flow phenomenon in the upper fin flights due to cohesion of particles to metal.

each basin. The samples from the basins were analyzed in the same manner as the samples taken during the test runs. The data developed from the basin samples are shown in Table 7.

Table 7. End of run observation data to determine the concentration characteristics of the upper fin flights in the 24 inch diameter separator.

Basin Number	Retained Solids Concentration* ($gm\text{-}L^{-1}$)
1	37.12
2	95.14
3	98.64
4	102.04
5	163.80
6	43.60
7	3.58
8	3.98
9	2.61
10	2.03
11	1.98
12	2.11
13	2.75
14	1.63

*The concentration of solid particles which will not pass through the number 16 sampling screen (particles larger than 1.19 mm).

Table 7 indicated the visual observations of excessively high solids concentrations in the fourth and fifth fin flights were accurate. The highest concentration of solids did not occur at the first basin as was expected. This was not the desired effect of the decreasing fin height modification.

Overload Tests on the 24 Inch Diameter Model With Dairy Slurries

Two tests were run on the device at flow rates which were too high for acceptable performance. The purpose of these tests was to determine if the device could be overloaded and if so, what damage was done. Four sets of samples from these tests were inadvertently discarded. Therefore, there were only three observations completed.

Because the air lift pump was not capable of delivering flow rates greater than 12.0 gpm another slurry pumping system was required for these tests. The new system employed a high capacity diaphragm pump. The flow from the diaphragm pump was split into two smaller streams. One stream delivered slurry to the separator and the other returned slurry to the storage tank. To control the flow rate to the separator, a variable diameter venturi was used to restrict the flow in the return stream. The variable diameter venturi was constructed from a 2 1/2 inch outside diameter and 2 inch inside diameter length of Tygon tubing. The constriction was accomplished with a hose clamp. By restricting flow through the return stream and controlling pump output with engine rpm, reasonable control of flow rate was accomplished. This system worked well at high flow rates but tended to plug frequently and control was lost at lower flow rates.

The data from the overload tests are shown in Table 8. These data indicate flow rates of these magnitudes did not overload the device if plugging and mechanical damage were the only factors to be considered. However, the device removed very few solids at high flow rates because the turbulence associated with these flow rates was too great.

Another series of samples were taken from the 14 settling basins inside the separator after the overload runs were completed. These basin samples were taken and analyzed in the same manner as those previously taken. The data from these samples are shown in Table 9. The basin samples were taken shortly after the test samples which make up the data in Table 8 were collected.

The last observation from Table 8 shows a lower effluent retained solids concentration of 10.00 grams per liter. The fourteenth basin has a retained solids concentration of 12.83 grams per liter. This indicated that the fourteenth basin was retaining some of the solids particles which were larger than 1.19 mm even though the turbulence was high.

Table 8. Performance data for overload tests on 24 inch diameter model using dairy manure slurries.

Flow Rate (gpm)	Influent Retained Solids Conc. ($gm\text{-}L^{-1}$)	Effluent Retained Solids Conc. ($gm\text{-}L^{-1}$)	Solids Stream Retained Conc. ($gm\text{-}L^{-1}$)	Retained Solids Removal (%)	Conc. Factor (Unitless)
34.41	1.02	1.00	14.10	2.3	13.82
54.74	1.21	1.20	8.60	---	7.11
47.72	10.01	10.00	21.00	0.1	2.10

Note: All concentration values are given in terms of solid particles larger than 1.19 mm (#16 sampling screen).

Table 9. End of run observation data to determine the concentration characteristics of the settling basins in the 24 inch diameter model after overload test completion on dairy slurries.

Basin Number	Retained Solids Concentration* ($gm\text{-}L^{-1}$)
1	57.26
2	78.82
3	82.78
4	106.77
5	47.03
6	43.86
7	30.60
8	26.61
9	22.60
10	21.30
11	16.05
12	17.08
13	14.95
14	12.83

*The concentration of solid particles which will not pass through the number 16 sampling screen (particles larger than 1.19 mm).

Testing the 24 Inch Diameter Model With Swine Manure Slurries

Performance values for the helically flighted rotating cylinder separator were desired when the device was applied to swine manure slurries. Therefore, at the completion of the dairy runs, the separator was moved to the Swine Center at Oregon State University.

The device for pumping manure slurries to the separator was changed slightly. The high capacity diaphragm pump used in the overload tests was used to pump the manure slurry from the manure storage area to the 55 gallon metal drum for air lift pump transport to the separator. The sampling procedure and analysis was the same used in the dairy manure tests.

Thirteen observations were made using swine manure slurries. The data from these observations are shown in Table 3B of Appendix B. It was found that 100 percent of the solid particles larger than 1.19 mm in swine manure slurries could be removed at the tested flow rates. This indicates that the mass and size distributions of swine manure solid particles are quite different from those of the dairy manure solid particles.

Analysis of Scaling Up Procedures by Turbulence Parameter

An acceptable average total suspended solids removal value for the eight inch diameter tube separator was chosen to be around 50 percent. From the testing of the first model, it was found that a flow rate of about 1.00 gpm produced a 50 percent removal of suspended solids in beet pulp slurries. Again, it was assumed that the beet pulp solid particles would behave similarly to manure solid particles. From Figure 14, a flow rate of 1.00 gpm corresponds to a Reynold's Number of 800 at the basin cross section. When the Reynold's Number of 800 at the basin cross section was used for a basin with the 12 inch radius of the second generation device, the flow rate given by Figure 14 was 2.8 gpm. A similar analysis using Figure 13 gives an expected flow rate for the second model of about 1.7 gpm if the turbulence at the weir crest is the critical parameter.

From tests run on the 24 inch diameter model using dairy manure, it was found that flow rates of 1.0 to 3.0 gpm removed an average of 54 percent of the solids larger than 1.19 mm.

The 54 percent removal of solid particles at a 1.0 to 3.0 gpm flow rate coincided well with the 2.8 gpm flow rate value developed from the turbulence values calculated at the basin cross-section. However, there were restrictions on the 54 percent removal value obtained from the second generation testing. The 54 percent value was not 54 percent of the total suspended solids as was the 50 percent removal value of the first model tested at 1.0 gpm. A series of size distribution analysis of the manure slurries used would have allowed calculation of the percentage value of the true total suspended solids removal. However, no such analyses were made because of the time involved in analyzing each sample.

This analysis indicates turbulence is undoubtedly the single most important control factor concerning device performance. It can be used to estimate the performance of larger or smaller devices of the same type. However, it is not the sole factor determining performance and variations will occur in performance estimates based on turbulence measurement alone. Other factors determining the performance of the helically flighted rotating cylinder separator are the solid particles density and size distributions, the spacing of fin flights, and the height of the fin flights.

The tube incline may have some effect on performance but at small inclination angles such as the ones used in this testing, the effect is small.

V. SUMMARY AND CONCLUSION

An eight inch diameter helically flighted rotating cylinder was used to separate manure solids and beet pulp solids from slurries. After modifying the upper fin flights of the first generation device, tests were again run on the device using beet pulp slurries. It was found that a slightly higher solids concentration could be obtained by draining part of the fluids out of the upper basins. From the data developed from testing this first model a method of estimating performance of larger devices based on turbulence in the separator was developed.

Using what was learned in testing the first model, a second generation device was fabricated and tested. This device was capable of an average removal of 54 percent of the suspended solids particles larger than 1.19 mm in dairy manure slurries at flow rates in the range of 1.0 to 3.0 gpm. Removals of 100 percent of the solids particles larger than 1.19 mm were obtained for swine manure slurries. It was found that decreasing fin height in a stepwise manner in the upper end of the tube was not the best method for draining excess fluids from the upper basins. This method of fluid drainage caused the highest retained solids concentration to occur at the fourth and fifth basin instead of the first basin as desired.

The device was simple, inexpensive, and durable. It could not be plugged by overloading and power consumption was quite low. Because of these favorable characteristics, the helically flighted rotating cylinder separator is attractive for livestock waste treatment. However, the device did not consistently remove all suspended solid particles which might make further treatment and subsequent water reuse difficult. The device will remove very coarse and heavy solids in slurries and makes a good separation if only this coarse separation is desired. Therefore, this device is not a totally satisfactory device for solids removal.

The basic concept of the device as a solids separator is sound. In an application where the solid particles are relatively uniform in size and density, this device would do a very satisfactory job. The device has possibilities as a combination cleaner and separation device. The capabilities of the device to aerate fluids as a treatment process should be considered.

VI. RECOMMENDATIONS FOR FURTHER RESEARCH

If continued research is to be carried out on the helically flighted rotating cylinder separator, the work should be carried in two major areas. These areas are:

1) Further studies as a separation device.

Research completed to date has not been exhaustive in terms of solids separation. Data on the device is needed with size and density distribution analyses run on the samples. This will determine the effect of particle characteristic variations on solids removal. Also, different methods of solids concentration in the upper fin flights should be explored.

2) Secondary treatment capabilities.

The device has potential as an aerobic treatment device. By allowing aerobic bacteria to grow on the helical fin, aerobic decomposition of wastes might be affected during solid-liquid separation. Studies on the device's ability to aerate liquids and aerobically treat slurries should be attempted.

Additional studies on the quality of water necessary for water reuse would also be beneficial. At this time, no information is available quantifying the actual values of suspended solids in a slurry which can be treated for water reuse. Such information would be helpful in determining what percentage of solids must be removed by a separation device. Since solid particle characteristics play an important role in solid-liquid separation, information on techniques for quickly and easily describing the solid particle size and density would also be beneficial to future separator development.

BIBLIOGRAPHY

1. Albertson, M. L. J. R. Barton, and D. B. Simons. Fluid mechanics for engineers. 1st ed. Prentice-Hall, Inc. Englewood Cliffs, N. J. 1960.

2. Davis, E. H. Animal waste data and population equivalents. Washington Cooperative Extension Service Bulletin, E. M. 2592 (Rev.). 2pp. Washington State University, Pullman. 1968.

3. Elam, L. Cows rest on manure mattresses. Hoard's Dairyman. 116:1239. 1071.

4. Fairbank, W. C., and E. L. Bramhall. Dairy manure liquid-solids separation. University of California Agricultural Extension Service Bulletin No. AXT-271. Riverside, California. 1968.

5. Frecks, G. A., and C. B. Gilbertson. The effect of ration on engineering properties of beef cattle manure. ASAE Paper No. 73-442. St. Joseph, Michigan. 1973.

6. Glerum, J. C., G. Klomp and H. R. Poelma. The separation of solid and liquid parts of pig slurry. pp. 345-347. In: Proc. International Symposium on Livestock Wastes. ASAE Publ. PROC.-271. St. Joseph, Michigan. 1971.

7. Graves, R. E., and J. T. Clayton. Stationary sloping screen to separate solids from dairy cattle manure slurries. ASAE Paper No. 72-751. St. Joseph, Michigan. 1972.

8. Hart, S. A., J. A. Moore, and W. F. Hale. Pumping manure slurries. pp. 34-38. In: Management of farm animal waste (Proceedings, National Symposium). American Society of Agricultural Engineers. 1966.

9. Kumar, M., H. D. Bartlett, and N. N. Mohsenin. Flow properties of animal waste slurries. ASAE Paper No. 70-911. St. Joseph, Michigan. 1970.

10. Mavis, F. T. There's no mystery in weir flow calculations. Engr. News-Record. 142:76-78. 1949.

11. Ngoddy, P. O., J. P. Harper, R. K. Collins, G. D. Wells, and F. A. Heidar. Closed system waste management for livestock. U. S. Environmental Protection Agency, Water Pollution Control Research Report No. 13040 DKP 06/71. 110 pp. East Lansing, Michigan. 1971.

12. Rich, L. G. Sedimentation. pp. 81-109. In: Unit operations of sanitary engineers. John Wiley and Sons, Inc. New York, New York. 1961.

13. Sobel, A. T. Some physical properties of animal manures and their association with handling. ASAE Paper No. NA65-111. St. Joseph, Michigan. 1965.

14. ______________ Plan for waste disposal before adding more cows. Farwest Farm Systems. Cleaning Bulletin No. 1B. 2pp. Spanaway, Washington. No date.

15. ______________ Rotostrainer for solids dewatering. Hydrocyclonics Corporation. Bulletin No. RS-200B. 8 pp. Lake Bluff, Illinois. 1973.

APPENDICES

APPENDIX A

Table 1A. Performance data for first test on eight inch diameter model using beet pulp slurry.

Influent Suspended Solids Conc. (%)	Effluent Suspended Solids Conc. (%)	Solids Stream Suspended Solids Conc. (%)	Conc. Factor (Unitless)	Suspended Solids Removal (%)	Flow Rate (gpm)
1.53	1.57	0.35	---	---	4.0
0.92	0.87	0.25	---	5.5	3.0
0.74	0.52	0.12	---	29.6	2.0
0.49	0.31	0.09	---	37.4	1.75
0.40	0.26	0.10	---	36.3	1.50
0.33	0.21	0.07	---	37.7	1.25
0.38	0.19	0.26	---	49.8	1.00
0.31	0.15	0.97	3.13	52.9	0.75

Table 2A. Performance data for second test on eight inch diameter model using beet pulp slurry.

Influent Suspended Solids Conc. (%)	Effluent Suspended Solids Conc. (%)	Solids Stream Suspended Solids Conc. (%)	Conc. Factor (Unitless)	Suspended Solids Removal (%)	Flow Rate (gpm)
1.39	1.29	0.26	---	7.2	4.0
0.86	1.17	0.12	---	---	3.0
0.62	0.32	0.07	---	48.4	2.0
0.44	0.35	0.07	---	20.5	1.75
0.38	0.20	0.04	---	47.4	1.50
0.32	0.07	0.03	---	78.1	1.25
0.48	0.20	0.05	---	41.6	1.00
0.27	0.15	2.16	8.0	44.4	0.75

Table 3A. Performance data for third test on eight inch diameter model using beet pulp slurry.

Influent Suspended Solids Conc. (%)	Effluent Suspended Solids Conc. (%)	Solids Stream Suspended Solids Conc. (%)	Conc. Factor (Unitless)	Suspended Solids Removal (%)	Flow Rate (gpm)
2.50	1.46		---	41.5	0.75
2.49	1.16		---	53.5	0.75
2.41	0.72	1.22	---	70.3	0.75
2.07	1.13		---	45.5	0.75
1.88	1.07		---	43.4	0.75
1.65	0.22	1.11	---	86.7	0.75
1.34	0.59		---	56.0	0.75
1.18	0.43		---	63.8	0.75
1.02	0.60	1.42	1.40	40.9	0.75
0.91	0.38	3.11	3.42	58.7	0.75

Table 4A. Performance data for fourth test on eight inch diameter model using beet pulp slurry.

Influent Suspended Solids Conc. (%)	Effluent Suspended Solids Conc. (%)	Solids Stream Suspended Solids Conc. (%)	Conc. Factor (Unitless)	Suspended Solids Removal (%)	Flow Rate (gpm)
3.11	2.11		---	32.1	1.20
2.81	1.91		---	32.3	1.20
2.58	1.69	1.55	---	34.3	1.20
2.95	0.83		---	71.8	1.20
1.94	1.74		---	10.5	1.20
1.36	1.38	1.22	---	---	1.20
1.29	2.09		---	---	1.20
0.81	0.59	0.30	---	26.5	1.20
0.71	1.24	0.96	1.35	---	1.20

Table 5A. Performance data for fifth test on eight inch diameter model using beet pulp slurry.

Influent Suspended Solids Conc. (%)	Effluent Suspended Solids Conc. (%)	Solids Stream Suspended Solids Conc. (%)	Conc. Factor (Unitless)	Suspended Solids Removal (%)	Flow Rate (gpm)
2.98	1.28		---	57.0	0.50
2.55	1.56		---	38.9	0.50
2.80	1.12	2.14	---	60.1	0.50
2.47	0.74		---	69.9	0.50
2.30	0.96		---	58.4	0.50
2.23	0.79	5.52	2.48	64.8	0.50
1.96	0.72		---	63.3	0.50
1.96	0.45		---	77.0	0.50
1.66	0.51	6.76	4.07	69.2	0.50
1.53	0.46	4.50	2.94	70.3	0.50

Table 6A. Performance data for sixth test on eight inch diameter model using manure slurries.

Influent Suspended Solids Conc. (%)	Effluent Suspended Solids Conc. (%)	Solids Stream Suspended Solids Conc. (%)	Conc. Factor (Unitless)	Suspended Solids Removal (%)	Flow Rate (gpm)
6.51	4.36		---	33.1	0.50
6.05	3.85		---	36.1	0.50
5.83	4.41	4.21	---	24.3	0.50
5.59	3.83		---	31.6	0.50
5.30	3.57		---	32.7	0.50
4.95	3.53	3.17	---	28.7	0.50
4.23	3.33		---	21.3	0.50
3.63	2.84		---	21.7	0.50
3.24	2.39	1.84	---	26.3	0.50
2.99	2.19	4.41	1.48	26.8	0.50
2.83	2.03	1.87	---	28.2	0.50

Table 7A. Performance data for seventh test on eight inch diameter model using dairy manure slurries.

Influent Suspended Solids Conc. (%)	Effluent Suspended Solids Conc. (%)	Solids Stream Suspended Solids Conc. (%)	Conc. Factor (Unitless)	Suspended Solids Removal (%)	Flow Rate (gpm)
6.87	5.50		---	20.0	0.75
6.70	5.01		---	25.2	0.75
6.07	6.13	6.38	1.05	---	0.75
5.76	4.36		---	24.3	0.75
4.80	3.94		---	17.9	0.75
4.14	4.81	5.13	1.24	---	0.75
3.58	3.00		---	16.2	0.75
3.14	2.18		---	30.5	0.75
2.74	2.80	3.25	1.19	---	0.75
2.20	1.69	11.44	5.20	23.3	0.75
2.10	1.46	2.03	---	30.8	0.75

Table 8A. Performance data for eighth test on modified eight inch diameter model using beet pulp slurry.

Influent Suspended Solids Conc. (%)	Effluent Suspended Solids Conc. (%)	Solids Stream Suspended Solids Conc. (%)	Conc. Factor (Unitless)	Suspended Solids Removal (%)	Flow Rate (gpm)
3.27	1.23		---	62.6	0.50
3.17	1.31		---	58.6	0.50
3.27	0.82	2.52	---	75.0	0.50
2.81	0.51		---	81.7	0.50
2.82	0.85		---	70.0	0.50
2.55	0.86	1.97	---	66.3	0.50
2.21	1.04		---	53.0	0.50
2.23	0.93		---	58.2	0.50
2.29	0.50	5.21	2.27	78.1	0.50
1.45	1.46	9.74	6.72	---	0.50

Table 9A. Performance data for ninth test on modified eight inch diameter model using beet pulp slurry.

Influent Suspended Solids Conc. (%)	Effluent Suspended Solids Conc. (%)	Solids Stream Suspended Solids Conc. (%)	Conc. Factor (Unitless)	Suspended Solids Removal (%)	Flow Rate (gpm)
3.66	1.34		---	63.3	0.50
3.78	1.11		---	68.9	0.50
3.41	1.00	2.28	---	70.6	0.50
3.29	1.17		---	64.5	0.50
2.85	0.98		---	65.6	0.50
2.66	0.84	3.75	1.41	68.4	0.50
2.41	0.99		---	59.0	0.50
2.20	0.93		---	57.5	0.50
1.97	0.99	2.22	1.13	50.0	0.50
1.92	0.70	9.00	4.69	63.7	0.50
1.40	0.79	5.07	3.62	43.3	0.50

Table 10A. Performance data for tenth test on modified eight inch diameter model using dairy manure slurries.

Influent Suspended Solids Conc. (%)	Effluent Suspended Solids Conc. (%)	Solids Stream Suspended Solids Conc. (%)	Conc. Factor (Unitless)	Suspended Solids Removal (%)	Flow Rate (gpm)
2.33	2.05		---	12.0	0.50
2.50	1.26		---	49.7	0.50
2.41	1.16	2.69	1.12	51.6	0.50
2.51	1.29		---	48.6	0.50
2.24	2.60		---	---	0.50
2.30	1.55	1.93	---	32.8	0.50
1.95	1.04		---	47.0	0.50
2.20	1.10		---	50.0	0.50
1.85	0.99	1.67	---	46.3	0.50
1.91	0.89	1.78	---	53.5	0.50

APPENDIX B

Table 1B. Performance data from tests on 24 inch diameter model using dairy manure slurries.

Observ. Number	Flow Rate (gpm)	Calculated Influent Retained Solids Conc. (gm/L)	Lower Effluent Retained Solids Conc. (gpm)	Solids Stream Retained Solids Conc. (gpm)	Conc. Factor (Unitless)	Retained Solids Removal (%)
1	8.00	0.57	0.20	45.10	79.1	64.8
2	6.51	1.17	1.10	5.90	5.0	5.8
3	5.26	0.53	0.10	21.00	39.6	81.1
4	12.63	2.43	2.39	6.19	2.5	1.2
5	6.08	1.37	1.23	11.56	8.4	12.0
6	6.39	0.48	0.40	9.14	19.0	15.5
7	6.94	0.32	0.29	2.42	7.6	7.5
8	4.09	0.65	0.63	1.69	2.6	1.2
9	1.45	2.66	1.80	12.40	4.7	32.4
10	5.51	5.74	5.00	40.20	7.0	12.9

Table 1B. Continued.

Observ. Number	Flow Rate (gpm)	Calculated Influent Retained Solids Conc. (gm/L)	Lower Effluent Retained Solids Conc. (gm/L)	Solid Stream Retained Solids Conc. (gm/L)	Conc. Factor (Unitless)	Retained Solids Removal (%)
11	6.04	4.65	4.60	7.40	1.6	1.1
12	6.32	4.52	4.50	5.70	1.3	0.4
13	6.48	2.99	3.00	2.50	---	---
14	6.57	2.71	2.50	12.10	4.8	7.9
15	3.42	2.79	1.30	37.30	13.4	53.4
16	3.07	5.72	0.80	110.50	19.3	86.0
17	3.22	11.75	9.30	71.90	6.1	20.8
18	3.11	10.00	5.30	112.80	11.3	47.1
19	3.16	3.96	3.10	28.20	6.9	21.8
20	3.90	2.81	2.20	25.30	9.0	21.6

Table 1B. Continued.

Observ. Number	Flow Rate (gpm)	Calculated Influent Retained Solids Conc. (gm/L)	Lower Effluent Retained Solids Conc. (gm/L)	Solids Stream Retained Solids Conc. (gm/L)	Conc. Factor (Unitless)	Retained Solids Removal (%)
21	2.80	3.18	1.20	47.00	14.8	62.2
22	2.72	0.34	0.20	2.30	6.8	40.7
23	2.69	2.12	0.40	43.90	20.7	81.2
24	3.76	2.82	0.60	70.10	24.9	78.7
25	3.80	1.13	0.50	16.60	14.7	35.6
26	3.13	0.67	0.30	5.60	8.4	55.1
27	3.63	0.65	0.60	3.60	5.5	23.0
28	3.59	0.62	0.20	9.60	15.5	67.8
29	6.65	0.67	0.60	2.40	3.7	10.8
30	4.65	1.37	1.20	9.00	7.5	12.5

Table 1B. Continued.

Observ. Number	Flow Rate (gpm)	Calculated Influent Retained Solids Conc. (gm/L)	Lower Effluent Retained Solids Conc. (gm/L)	Solids Stream Retained Solids Conc. (gm/L)	Conc. Factor (Unitless)	Retained Solids Removal (%)
31	4.06	2.54	1.10	51.90	20.4	56.7
32	6.00	2.87	1.30	90.40	31.5	54.7
33	5.15	1.51	1.30	17.90	11.8	14.1
34	5.44	0.45	0.20	9.30	20.6	55.1
35	5.09	0.59	0.40	6.60	16.5	32.3
36	7.53	0.70	0.50	14.00	28.0	28.3
37	7.07	0.46	0.40	2.90	7.2	12.5
38	6.64	0.49	0.50	0.20	---	---
39	9.96	0.50	0.40	12.70	25.4	20.0
40	9.86	0.44	0.30	11.20	25.5	31.2

Table 1B. Continued.

Observ. Number	Flow Rate (gpm)	Calculated Influent Retained Solids Conc. (gm/L)	Lower Effluent Retained Solids Conc. (gm/L)	Solids Stream Retained Solids Conc. (gm/L)	Conc. Factor (Unitless)	Retained Solids Removal (%)
41	9.72	0.32	0.20	9.40	29.4	37.2
42	8.08	2.11	2.00	8.60	4.1	5.4
43	8.87	1.01	1.00	1.60	1.6	0.9
44	10.53	2.07	2.00	8.98	4.3	3.2
45	9.31	0.60	0.60	0.70	1.2	0.0
46	9.73	0.43	0.40	2.50	5.8	6.5
47	11.68	0.32	0.30	1.80	5.6	5.5

Table 2B. Performance data grouped and averaged according to flow rates.

Flow Rate Grouping (gpm)	Flow Rate (gpm)	Retained Solids Removal (%)	Group Ave. Retained Solids Removal (%)	Conc. Factor (Unitless)	Group Ave. Conc. Factor (Unitless)
1.0 - 3.0	1.45	32.4		4.7	
	2.80	62.2		14.8	
	2.72	40.7		6.8	
	2.69	81.2	54.1	20.7	11.7

Table 2B. Continued.

Flow Rate Grouping (gpm)	Flow Rate (gpm)	Retained Solids Removal (%)	Group Ave. Retained Solids Removal (%)	Conc. Factor (Unitless)	Group Ave. Conc. Factor (Unitless)
3.0 - 4.0	3.42	53.4		13.4	
	3.07	86.0		19.3	
	3.22	20.8		6.1	
	3.11	47.1		11.3	
	3.16	21.8		6.9	
	3.90	21.6		9.0	
	3.76	78.7		24.9	
	3.80	35.6		14.7	
	3.13	55.1		8.4	
	3.63	23.0		5.5	
	3.59	67.8	46.4	15.5	12.3

Table 2B. Continued.

Flow Rate Grouping (gpm)	Flow Rate (gpm)	Retained Solid Removal (%)	Group Ave. Retained Solids Removal (%)	Conc. Factor (Unitless)	Group Ave. Conc. Factor (Unitless)
4.0 - 5.0	4.65	12.5		7.5	
	4.06	56.7		20.4	
	4.09	1.3*	34.6	2.6*	13.9

Table 2B. Continued.

Flow Rate Grouping (gpm)	Flow Rate (gpm)	Retained Solids Removal (%)	Group Ave. Retained Solids Removal (%)	Conc. Factor (Unitless)	Group Ave. Conc. Factor (Unitless)
5.0 - 6.0	5.51	12.9		7.0	
	5.15	14.1		11.8	
	5.44	55.1		20.6	
	5.09	32.3		16.5	
	5.26	81.1*	28.6	39.6*	14.0

Table 2B. Continued.

Flow Rate Grouping (gpm)	Flow Rate (gpm)	Retained Solids Removal (%)	Group Ave. Retained Solids Removal (%)	Conc. Factor (Unitless)	Group Ave. Conc. Factor (Unitless)
6.0 - 7.0	6.04	1.1		1.6	
	6.32	0.4		1.3	
	6.48	0.0		0.0	
	6.57	7.9		4.8	
	6.65	10.8		3.7	
	6.00	54.7		31.5	
	6.64	0.0		0.0	
	6.51	5.8		5.0	
	6.08	12.0		8.4	
	6.39	15.5		19.0	
	6.94	7.6	10.5	7.6	7.5

Table 2B. Continued.

Flow Rate Grouping (gpm)	Flow Rate (gpm)	Retained Solids Removal (%)	Group Ave. Retained Solids Removal (%)	Conc. Factor (Unitless)	Group Ave. Conc. Factor (Unitless)
7.0 - 9.0	7.53	28.3		28.0	
	7.07	12.5		7.2	
	8.08	5.4		4.1	
	8.87	0.9		1.6	
	8.00	64.8*	14.3	79.1*	10.2

Table 2B. Continued.

Flow Rate Grouping (gpm)	Flow Rate (gpm)	Retained Solids Removal (%)	Group Ave. Retained Solids Removal (%)	Conc. Factor (Unitless)	Group Ave. Conc. Factor (Unitless)
9.0 - 13.0	9.96	19.3		25.4	
	9.86	31.2		25.5	
	9.72	37.2		29.4	
	10.53	3.2		4.3	
	9.31	0.3		1.2	
	9.78	6.5		5.8	
	11.68	5.5		5.6	
	12.63	1.2	13.1	2.5	12.5

*These data points were not used to calculate average values for the flow rate group because they do not appear to be consistent with other data in the group.

Table 3B. Performance data for tests on 24 inch diameter model using swine manure slurries.

Influent Retained Solids Conc. (gm/L)	Effluent Retained Solids Conc. (gm/L)	Solids Stream Suspended Solids Conc. (gm/L)	Conc. Factor (Unitless)	Suspended Solids Removal (%)	Flow Rate (gpm)
0.44	0.0	34.70	78.8	100.0	5.47
0.39	0.0	43.80	112.2	100.0	7.00
0.17	0.0	19.00	112.2	100.0	6.66
0.27	0.0	30.30	112.2	100.0	7.03
0.02	0.0	2.00	100.0	100.0	6.16
0.86	0.0	0.80	---	100.0	4.70

Table 3B. Continued.

Influent Retained Solids Conc. (gm/L)	Effluent Retained Solids Conc. (gm/L)	Solids Stream Suspended Solids Conc. (gm/L)	Conc. Factor (Unitless)	Suspended Solids Removal (%)	Flow Rate (gpm)
0.01	0.0	0.40	40.0	100.0	5.72
0.01	0.0	0.40	40.0	100.0	6.03
0.01	0.0	0.20	20.0	100.0	5.98
0.17	0.0	10.50	61.8	100.0	5.47
0.03	0.0	1.50	50.0	100.0	6.36
0.01	0.0	0.50	50.0	100.0	5.10

Note: All concentration values are in terms of solid particles larger than 1.19 mm (#16 sampling screen).