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HANDLING AND DISPOSAL OF SLUDGES FROM COMBINED SEWER OVERFLOW TREATMENT

Phase III - Treatability Studies

by

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FOREWORD

The Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimony to the deterioration of our natural environment. The complexity of that environment and the interplay between its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution and it involves defining the problems, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory, develops new and improved technology and systems for the prevention, treatment, and management of wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, for the preservation and treatment of public drinking water supplies, and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research; a most vital communications link between the researcher and the user community.

This report documents the results of an ongoing project initiated to evaluate the handling and disposal of combined sewer overflow (CSO) treatment residuals by thickening-centrifugation.

Francis T. Mayo, Director
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ABSTRACT

This report documents the results of a project initiated to evaluate the handling and disposal of combined sewer overflow (CSO) treatment residuals. Bench scale thickening and pilot and full-scale centrifugation dewatering tests were performed at dry-weather and CSO treatment sites in Kenosha, Racine, and Milwaukee, Wisconsin. CSO sludge at Kenosha is biologically generated; that at Milwaukee is physical in nature; and the Racine CSO residuals are of physical-chemical origin. In addition, bench scale anaerobic digestion studies were conducted to determine the effect of CSO sludges on the anaerobic digestion stabilization process.

The results obtained from this project indicated that the dewatering of CSO sludges appears feasible when the sludges are first degritted, where required, and thickened prior to centrifugation. Under optimum centrifuge operating conditions, thickened sludges were dewatered to cake concentrations varying from 14.0% to 32% solids with solids recoveries ranging from 80% to 99%. Similarly, the dry-weather sludges for the test sites were dewatered to haulable cakes. Moreover, at Kenosha, the dewatering characteristics of wet-dry weather sludge mixtures were similar to those for CSO sludge alone. The bench scale anaerobic digestion studies showed that no significant adverse effect was realized by adding CSO generated sludges to dry-weather digesters at feed rates similar to that expected from a typical storm event.

Preliminary economic estimates indicate that first investment capital costs for thickening-centrifigation of CSO sludges ranged from 0.31 to 2.92 million dollars with annual costs of $49,500 to $659,300 per year when handling 4.0 to 36.5 tons dry sludge per day. These cost ranges were developed respectively, for the cities of Racine, WI (population - 90,700; CSO area - 702 acres), and Milwaukee, WI (population - 670,00, CSO area - 16,800 acres).

The report recommends that a full-scale CSO sludge dewatering facility employing degritting, thickening, and centrifugation should be developed as a demonstration site for a further evaluation of the treatment of CSO residuals.

This report was submitted in fulfillment of Contract No. 68-03-0242 by the Environmental Sciences Division of Envirex Inc. under the sponsorship of the U.S. Environmental Protection Agency. Work for this report covers a period from August, 1975 to September, 1976.

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SECTION I

CONCLUSIONS

1. Characteristics of the Sludges Tested

   a. The solids concentrations observed for the combined sewer overflow (CSO) *unthickened* sludges were as follows:

      Storage-Sedimentation (Milwaukee) - 0.02-0.14%
      Screening/Flotation (Racine) - 0.05-0.1%
      Biological (Kenosha) - 1.37-1.39%

   b. The raw CSO sludges derived from physical treatment (Milwaukee) and from physical-chemical treatment (Racine) were similar in that they contained more grit and were more dilute than their dry-weather counterparts.

      The solids content of the settled sludge from storage-sedimentation (Milwaukee) was appreciably lower than that expected (2.5%-5.0%) (5) from storage-sedimentation treatment of CSO, indicating that dewatering of individual CSO sludges should be investigated individually on their own merits.

   c. The raw CSO sludge derived from biological treatment (Kenosha) was similar in nature to that of its dry-weather counterpart.

   d. The heavy metal (Zn, Pb, Ni, Cu, Cr, Hg, Cd) data generated in this study were quite variable between test sites. The dry-weather and wet-weather range of heavy metal centrifuge feed concentrations are presented below:

	Dry-weather sludge concentration range mg metal/kg solids	Wet-weather sludge concentration range mg metal/kg solids
Zinc	1450-3681	710-3125
Lead	522-6900	410-1563
Nickel	140-445	333-1563
Copper	600-1565	250-2170
Chromium	755-7600	110-3281
Mercury	0.975-4842	1.30-15.63
Cadmium	47	50

The study concluded that the heavy metals appear to be solids related with only slight concentrations observed in the soluble portion of the sample. Therefore, heavy metal removal was directly related to solids removal.

2. Sludge Thickening

Sludge thickening is the first step in the thickening-dewatering of CSO sludges and removes the major portion of the liquid associated with the raw sludge.

In this study, thickening was investigated using bench-scale techniques. The results obtained from testing the sludges from the various test sites are summarized below.

a. Milwaukee (Storage-Sedimentation)

(1) The dilute (0.2% solids) sludge could be further concentrated (to about 1.33% solids) by gravity thickening using chemicals (ferric chloride and polymer).

(2) Because of the dilute (0.2% solids) nature of the CSO sludge obtained, the possibility of bleed/pump-back of the sludge to the dry-weather plant was investigated by clarification testing to determine the effect of bleed/pump-back on dry-weather primary treatment.

The conclusions reached from the bench scale clarification tests conducted on the Milwaukee physical wet-weather sludge, dry-weather wastewater, and combinations of the two indicated that the settling characteristics of the three wastes were similar. Typical effluent solids ranged from 12-16 mg/l for influent concentrations of 200-475 mg/l. Chemical treatment included ferric chloride and polymer.

b. Racine (physical-chemical)

The Racine physical-chemical CSO sludge can be gravity thickened to as high as 14.0 percent solids. This compares to gravity thickening results of 3.0 percent for dry-weather sludge and 4.0-5.0 percent for wet-weather/dry-weather sludge combinations.

c. Kenosha (biological)

The bench scale flotation thickening tests conducted on the Kenosha biological sludges indicated that flotation thickening of the dry-weather sludge, wet-weather sludge and the wet-weather/dry-weather combined sludge was feasible and produced similar results. The expected float concentrations and thickener loadings for these sludges would be similar to current full-scale practice at the Kenosha Water Pollution Control Plant [4.0% solids at 50 $kg/m^2/day$ (10 $lb/ft^2/day$)].

3. *Centrifuge Sludge Dewatering (pilot and full-scale)*

The following conclusions were drawn from the centrifuge dewatering tests performed at the test sites.

a. Milwaukee (storage-sedimentation)

(1) It does not appear practical to dewater the gravity settled Milwaukee CSO physical sludge without pretreatment. The dilute sludge generated at this site contains significant amounts of grit and widely dispersed organic solids. Attempts were made to dewater the gritty sludge, but the basket centrifuge and feed lines continuously clogged. One of the runs completed using the 30.5 cm (12 in.) basket centrifuge to dewater the degritted dilute sludge yielded results of 28.4 percent cake and 82 percent solids recovery. Based on this result and those obtained in Phase I (1), it can be concluded that the Milwaukee wet-weather sludge is amenable to basket centrifuge dewatering provided the sludge is degritted and gravity thickened to about 2 percent solids content.

(2) The Milwaukee dry-weather primary sludge can be dewatered to a haulable cake using a decanter centrifuge. Typical cake concentrations between 14.5-17.0 percent solids were achieved with solids recoveries of 80-95 percent. Polymer requirements are estimated at 0.88-1.24 kg/metric ton (1.76-2.48 lb/ton).

b. Racine (physical-chemical)

(1) The Racine wet-weather physical-chemical sludge generated is quite similar to the Milwaukee physical CSO sludge produced. The thickened sludge is very dilute and contains large amounts of gritty material. Several dewatering runs were conducted with the dilute screened CSO sludge using a decanter centrifuge. For an optimum run, values of 32 percent cake solids and 92 percent solids recovery were obtained. Polymer requirements are estimated at 0.96 kg/metric ton (1.92 lb/ton). Based on the findings obtained, it can be concluded that the dilute sludge dewaters quite well. The results of this research, in addition to the data generated in Phase I (1), indicate that centrifuge dewatering the CSO sludge would be feasible provided degritting and gravity thickening steps preceded centrifugation.

(2) The Racine dry-weather sludge (primary and thickened WAS) can be dewatered to 30 percent haulable cakes with 99 percent suspended solids recoveries using a decanter centrifuge. An expected polymer dosage of 1.2 kg/metric ton (2.4 lb/ton) would be required.

c. Kenosha (biological)

Under optimum conditions, the Kenosha CSO biological sludge can be dewatered without polymer, to a 14.0 percent cake solids concentration with a basket centrifuge. The expected suspended solids recovery is 94.5 percent. Similarly, for dry-weather sludge, an optimum cake of 17.5 percent was obtained with a corresponding solids recovery of 93.5 percent. The dewatering characteristics of the wet-dry weather sludge mixtures were similar to those obtained for the CSO sludge alone, that is, optimum cake concentrations of 14 percent with solids recoveries in excess of 95 percent.

4. Bench Scale Anaerobic Digestion Study

The conclusions drawn from the tests performed on two laboratory digesters (test and control) are presented below.

a. Kenosha (biological)

(1) Kenosha CSO sludge added to a laboratory test digester in an amount representing the CSO solids generated by a 1.27 cm (0.5 in.) and a 2.54 cm (1 in.) rainfall had no statistically significant effect (95% confidence level) in digester gas production, methane production, pH, and CO_2/CH_4 ratio when compared to a second laboratory digester fed dry-weather sludge only, at a similar organic loading. The sludge representing the 1.27 cm (0.5 in.) rainfall was fed to the digester over a period of two days; the sludge representing the 2.54 cm (1 in.) storm was added in one day.

(2) When the laboratory test digester was fed Kenosha CSO sludge exclusively for ten days, total gas production and methane production was significantly lower (95% confidence level) than that of the control digester fed dry-weather sludge at a similar organic loading. The CO_2/CH_4 ratio was not statistically different. Volatile acid concentrations and the volatile acid/alkalinity ratio remained low. The efficiency of the wet-weather digester in terms of volume of gas produced per weight of volatile solids destroyed was higher than for the control digester.

b. Racine (physical-chemical)

(1) The laboratory digester fed Racine CSO sludge in an amount representing the solids produced by a 2.54 cm (1 in.) rainfall (added in one day) produced less gas than the laboratory fed dry-weather sludge digester at a similar organic loading. The difference was statistically significant at the 95 percent confidence level but not at the 99 percent confidence level.

(2) In the Racine tests a decrease in total gas production was the only evidence of a detrimental effect of Racine CSO sludge on the laboratory digester performance. Volatile acid concentrations and the volatile acid/alkalinity ratio remained low. The volume of gas produced per weight of volatile solids destroyed was similar for both digesters. The decrease in gas production

after the Racine wet-weather sludge was fed to the laboratory digester is not attributable to the heavy-metal concentrations in the wet-weather sludge.

5. Costs for Thickening-Centrifuge Dewatering of Sludges

It is emphasized that the costs presented are given as a first approximation. If a detailed economic evaluation is necessary or desired, the individual site must be examined separately with respect to locale, rainfall patterns, type and location of treatment system, sludge characteristics, etc. Then equipment and installation costs should be established from vendors and contractors.

As a part of this study, annual costs which include both capital and O&M costs have been developed for each site. The capital expenditures include the necessary equipment to provide a dewatered sludge. Examples of capital costs include sludge pumping costs, thickening costs (CSO sludge only), and centrifugation costs. Degritting costs have also been developed as necessary. Amortization is based upon a 20 year term and 6 percent cost of money. Zero salvage value has been assumed. The estimated costs for the sites investigated are shown in Table 1.

The costs generated were derived according to dry solids handling capacity. Wet-weather sludge volumes are those generated from a 1.27 cm (0.5 in.) rainfall on the CSO area, assuming a two day bleed/pump-back to the treatment facility.

TABLE 1. RESEARCH SITE DESCRIPTIONS, SPACE, AND COST REQUIREMENTS

Site	CSO area (acres)	Dry solids handled (ton/day)			Treatment space required (ft^2)		
		Dry-weather sludge	Wet-weather sludge	Mixture: dry-wet	Dry-weather sludge	Wet-weather sludge	Mixture: dry/wet
Kenosha	1,331	20.8	5.5	26.3	1,700	2,200	4,200
Milwaukee	16,800	54.5	35.6	-	3,100	7,600	-
Racine	702	39.7	4.0	-	1,000	1,700	-

Site	Capital costs (million $)			Annual costs ($/yr)		
	Dry-weather sludge	Wet-weather sludge	Mixture: dry/wet	Dry-weather sludge	Wet-weather sludge	Mixture: dry/wet
Kenosha	1.12	0.95	2.19	219,900	114,000	345,500
Milwaukee	1.90	2.92	-	488,400	659,300	-
Racine	1.64	0.31	-	408,900	49,500	-

NOTE: acres x 0.405 = hectares
ft^2 x 0.00929 = m^2
ton x 0.907 = metric ton

SECTION II

RECOMMENDATIONS

It is recommended that a full-scale demonstration installation be constructed to further evaluate the application of the dewatering treatment train for disposal of combined sewer overflow treatment sludges.

The dewatering treatment train recommended would be comprised of degritting (where required), thickening and centrifugation.

In selecting degritting equipment, the swirl concentrator design should be considered along with conventional grit removal equipment.

Thickening equipment may be either of the gravity or flotation type depending on the CSO sludge to be treated.

Similarly, centrifugation equipment may be either of the basket or decanter type, as appropriate.

SECTION III

INTRODUCTION

The discharge of untreated sanitary and stormwater overflows from combined sewer systems to receiving waters during and after heavy rains has been found to be one of the most significant causes of water quality deterioration. These storm generated discharges constitute a very high degree of pollutional loading to watercourses as measured by the usual standards of biochemical oxygen demand, solids, coliform organisms, and nutrients. Various alternatives have been advanced for dealing with the problems created by these discharges. Most of these alternatives include some form of treatment for the combined sewer overflow (CSO).

As with most wastewater treatment processes, treatment of CSO will result in residuals which contain, in concentrated form, the objectionable contaminants present in the raw CSO. The handling and disposal of these residual sludges from CSO treatment systems have been generally neglected, thus far, in favor of developing methods of treatment for the CSO itself. However, sludge handling and disposal should be considered an integral part of any CSO treatment system because it will significantly affect the overall efficiency and cost of the system. Despite these possible impacts there is little information available in the literature concerning the characteristics, methods of disposal, and economic impact of handling CSO sludges.

The United States Environmental Protection Agency (EPA) has recognized this need for defining the problems and establishing handling and disposal techniques for residual sludges from CSO treatment. In 1973, the EPA awarded Contract No. 68-03-0242 to Envirex Inc. to conduct a feasibility study (Phase I) of a program whose overall project objectives were:

1. Characterize the residual sludges arising from the treatment of CSO.

2. Develop and demonstrate systems for handling and disposing of the sludges arising from the treatment of CSO.

3. Develop capital and operating costs for the handling and disposal systems developed and demonstrated.

The feasibility study (Phase I) was completed in February, 1975 (1). Conclusions drawn from the work performed indicated that thickening-centrifugation and thickening-vacuum filtration were the applicable dewatering methods.

A second Phase, completed in February 1976, documented the results of an assessment of the effort that the United States will have to exert in the area of sludge handling and disposal if, in fact, full-scale treatment of combined sewer overflows is to become a reality. Evaluation of the effect of bleed/pump-back of CSO sludge on the hydraulic, solids and/or organic loadings to the dry-weather plant indicated that overloading would occur in most instances. Disregarding grit accumulation in sewers plus other transport problems, it was established that solids loadings to the secondary clarifier were limiting and required 8-22 day bleed/pump-back periods. There may also be a toxic danger to dry-weather treatment plant biological processes.

This report documents the activities for Phase III of the overall project. The objectives of the third phase were to:

1. Demonstrate and evaluate, on a pilot-scale, the effectiveness of thickening-centrifugation as a method for the handling and disposal of CSO sludges.

2. Demonstrate and evaluate, on a bench-scale basis, the effectiveness of anaerobic digestion of an appropriate CSO sludge.

3. Develop basic design criteria and operating characteristics for the thickening-centrifugation dewatering system in a form that can be translated into actual practice.

4. Develop capital and operating costs for the thickening-centrifugation dewatering system.

These objectives were met through the use of a mobile centrifuge sludge dewatering van which was taken to three selected CSO treatment sites. At the sites, the CSO sludges were thickened and then dewatered using either a 30.5 cm (12 in.) or a 121.9 cm (48 in.) basket centrifuge or a decanter centrifuge, all of which are on the mobile van. A bench-scale anaerobic digestion system was also constructed and operated to evaluate anaerobic digestion of CSO sludges.

In addition, for each CSO treatment site visited, the city's dry-weather treatment plant sludge was also tested using the thickening-centrifugation process. These data allowed comparisons to be made between the use of thickening-centrifugation for dewatering CSO generated sludges and the sludges generated by municipal sewage treatment plants.

SECTION IV

DISCUSSION OF RESULTS

Future sections of this report will individually cover in relatively great detail the results of the work performed in the field and in the laboratory with regard to:

1. The character and nature of the sludges derived from physical, physical-chemical and biological treatment of CSO.

2. The thickening/centrifugation dewatering characteristics of the CSO sludges, the dry-weather sludges and combinations of the two.

3. The heavy metal contents of the CSO sludges, the dry-weather sludges and combinations of the two.

4. The effect of loading dry-weather anaerobic digesters with CSO sludges.

In this section, the detailed information has been sifted and carried forward to summarize pertinent technical and design information which will be needed in subsequent evaluation and to bring out the similarities and differences observed between the sludges as they affect operation, performance and design. The discussion which follows includes the following items:

1. Selection of thickening method and centrifugation equipment to be used for the sludges tested.

2. Optimum operating parameters for thickening and centrifugation as well as operating problems observed and means for their solution.

3. Similarities and differences observed between the sludges investigated with regard to character, dewaterability, heavy metal content and effect on anaerobic digestion.

SLUDGE THICKENING

Biological Sludges - Kenosha, WI

The bench scale flotation thickening results on the Kenosha biological sludges yielded good sludge concentrations at low to moderate loadings. A comparison of results for the three sludges tested is presented on the following page in Table 2.

TABLE 2. COMPARISON OF RESULTS - BENCH SCALE FLOTATION THICKENING TESTS - KENOSHA, WISCONSIN

	Estimated loadings at 4% solids	
Sludge type	$kg/m^2/day$	$lb/ft^2/day$
Dry-weather WAS	48.9-73.4	10-15
Wet-weather WAS	53.8	11
Wet-weather/dry-weather combination WAS	44.0	9

The data indicate that a flotation thickener may be operated at the solids loadings shown above to yield a floated sludge concentration of 4 percent solids. The use of higher solids loadings to the flotation thickener will result in lower concentrations of thickened sludge. The data further demonstrate that the loadings to the thickener to obtain a 4 percent sludge would be slightly less for the wet-weather/dry-weather sludge combination when compared to either the dry-weather or wet-weather individual sludges. This lower loading rate however, is so minimal that it should not adversely affect the economics of thickening the combined sludges on a full-scale. The bench scale results are consistent with the data generated in the Phase I Report (1). In Phase I, a wet-weather sludge concentration of 4.0 to 5.0 percent solids was achieved at mass loading rates of 50-100 $kg/m^2/day$ (10-20 $lbs/ft^2/day$). Presently, the Kenosha Water Pollution Control Plant's full-scale flotation thickeners operate at a solids loading of 50 $kg/m^2/day$ (10 $lb/ft^2/day$) which also compares well to the bench scale thickening results.

Physical Sludges - Milwaukee, WI

The results of the bench scale clarification tests conducted on the Milwaukee sludges and wastewater indicated that excellent effluent quality could be obtained with chemical addition. The low effluent suspended solids (14-16 mg/l) of the Humboldt Avenue wet-weather supernatant makes it feasible for discharge to the receiving body or return to the municipal sewer.

Slightly better effluent solids results were obtained for both the South Shore dry-weather wastewater and the mixture of wet-weather sludge and dry-weather wastewater. This occurred even though the dry-weather raw waste suspended solids were higher than the wet-weather sludge. Based on the data presented in Table 17, Section VIII, settling characteristics of the three wastes tested were quite similar. No adverse effects were observed in any of the parameters tested which indicated interferences in settling by the addition of wet-weather sludge to the dry-weather wastewater.

The residual wet-weather sludge volume that would be obtained through chemical clarification (15-20 ml/l) (15-20 gal./1000 gal.) could then be considered for dewatering with basket centrifuges provided it had been previously pretreated to remove grit, rags, sticks, and other materials which would interfere with the centrifugation process.

Phase I (1) showed that the sludge concentration following clarification was 1.74 percent solids. This volume of sludge, which represents only about 0.9 percent of the total CSO generated (1) could be evaluated for degritting after clarification. The economic advantages of degritting only this small percentage of flow with a swirl concentrator or similar unit are most attractive. This alternative is discussed more thoroughly in the Section XI, economic evaluation.

Physical-Chemical Sludges - Racine, WI

The bench scale gravity thickening tests conducted on the Racine physical-chemical sludges demonstrated that significant differences in settling characteristics exist between the dry-weather and wet-weather sludges. The dry-weather sludge thickened to 3.0 percent at a mass loading of 1650 kg/m^2/day (338 lb/ft^2/day). Presently, the Racine Water Pollution Control Plant is obtaining an 8.9 percent sludge by returning waste activated sludge to the primary settling basins for thickening.

The Racine wet-weather sludge was gravity thickened to an underflow sludge concentration of 14.0 percent solids. This value compares favorably to an earlier report (1). Therefore, as a result of thickening, sludge volume through the CSO system could be substantially reduced. However, pumping problems could result because of the viscous and gritty nature of the sludge. This fact should be kept in mind in any future design considerations. Pretreatment requirements for this sludge will be discussed more thoroughly later in this section.

The wet-weather/dry-weather sludge combination thickened to 4.0-5.0 percent solids at mass loadings of 610-885 kg/m^2/day (125-181 lb/ft^2/day). This concentration is slightly higher than that of the "dry-weather only" sludge. The increased concentration is due primarily to the presence of the wet-weather sludge. The settling characteristics of this sludge mixture indicated that no adverse effects would occur by the bleedback of wet-weather sludge to the dry-weather plant.

It is important to note that the bench scale mass loading rates obtained are appreciably higher than typical full-scale design gravity thickener loadings. Therefore, although the above data are useful for comparative purposes, it should not be used as full-scale design criteria.

SLUDGE DEWATERING

Biological Sludges - Kenosha, WI

The results of the Kenosha biological sludge centrifugation studies indicated that the dewatering characteristics of the wet-weather sludge, dry-weather sludge, and wet-weather/dry-weather sludge combination were quite similar. Table 3 was constructed to list the optimum operating parameters for the three types of sludges tested. The wet-weather/dry-weather sludge mixture is shown for operational parameters both with and without polymer.

The overall optimum full-scale dewatering parameters for the three biological sludges studied reveal some important characteristics as shown in Table 3. One of these pertinent facts is that the dry-weather sludge dewatered to a slightly higher cake (17.5 percent) and had a slightly higher process rate (144 kg/hr) (317 lb/hr) as compared to those sludges containing all or part CSO sludge.

Comparing the results of the full-scale 121.9 cm (48 in.) basket centrifuge tests with those of the 30.5 cm (12 in.) basket centrifuge tests shows that they are very similar. The preliminary work with the small basket centrifuge indicated that an optimum dry-weather sludge (primary plus thickened WAS) feed rate would be 4.0 kg/min (8.8 lb/min). This rate would produce a cake concentration of 14.0 percent solids and a SS recovery of 94 percent. During the full-scale centrifuge testing, the optimum feed rate was 3.6 kg/min (8.0 lb/min) with a resultant cake concentration of 17.5 percent solids and 93.5 percent SS recovery. In fact, the full scale testing of dry-weather sludge indicated that the optimum feed rate may be higher than 3.6 kg/min (8.0 lb/min). It was planned to include greater feed rates than 3.6 kg/min (8.0 lb/min), but this was not achieved because the feed solids concentrations were less than expected at the time of the tests.

The results of the full-scale CSO sludge testing were similar to the results of the small basket centrifuge testing of dry-weather thickened WAS. This would be expected because both are biological sludges. The results of the 30.5 cm (12 in.) centrifuge testing of dry-weather thickened WAS showed an optimum feed rate of 2.6 kg/min (5.7 lb/min), producing a cake concentration of 11.5 percent solids and a solids recovery of 96 percent. For the 121.9 cm (48 in.) basket centrifuge testing of the CSO sludge, the optimum feed rate was 2.4 kg/min (5.3 lb/min) and it resulted in a 14.0 percent cake concentration and a SS recovery of 94.5 percent. The higher cake concentration for the sludge is attributed to more inert solids in the sludge. The presence of these inert solids in the sludge would be expected to produce better dewatering characteristics.

The full-scale CSO sludge centrifugation tests yielded better cake results than the bench scale CSO sludge dewatering study conducted in the Phase I (1). The optimum Phase I cake solids obtained was 8.9 percent with a 99.3 percent recovery. The lower cake solids value obtained in Phase I would be expected due to the scale down factors in the lab centrifuge.

The optimum operating parameters for the CSO/dry-weather sludge combination are also compared in Table 3. The results were obtained using the full-scale 121.9 cm (48 in.) basket centrifuge. For the sludge containing no polymer, the optimum feed rate was 1.97 kg/min (4.34 lb/min), yielding a cake concentration of 14.3 percent and a suspended solids recovery of 94.6 percent. At this loading, 99 kg (218 lb) of sludge could be processed per hour. For

TABLE 3. COMPARISON OF OPTIMUM OPERATING PARAMETERS
CENTRIFUGE DEWATERING TESTS - KENOSHA, WISCONSIN

	CSO sludge	Dry-weather sludge	Wet/dry-weather sludge mixture - no polymer	Wet/dry-weather[a] sludge mixture - polymer addition
Feed rate, kg/min (lbs/min)	2.4 (5.3)	3.6 (7.9)	1.97 (4.34)	2.58 (5.69)
Cake concentration, % solids	14.0	17.5	14.3	14.8
SS recovery, %	94.5	93.5	94.6	97.8
Average feed conc., % solids	2.95	3.24	3.64	4.27
Feed rate, l/min (gpm)	81 (21.4)	111 (29.3)	54.1 (14.3)	61 (16.0)
Feed time, minutes	13	10	25	22
No. of cycles/hour[b]	3.3	4.0	2.0	2.2
kg(lbs) processed/hour[c]	103 (227)	144 (317)	99 (218)	126 (277)

[a] Polymer dosage: 1.4 kg/metric ton (2.81 lb/ton)

[b] Cycles/hour = 60/(feed time + 5) where 5 minutes are added for the skimming cycle and desludging the centrifuge.

[c] Kg processed/hr = l/min x feed time x kg/l concentration of feed x cycles/hr.

the runs conducted with polymer, an optimum feed rate of 2.58 kg/min (5.69 lb/min) was obtained. This loading rate resulted in a cake concentration of 14.8 percent solids with a corresponding solids capture of 97.8 percent and a processing capacity of 126 kg (277 lb) per hour.

Based on these results, it can be concluded that polymer addition to the CSO/dry-weather sludge would be advantageous to increase overall solids capture.

In conclusion, the Kenosha CSO sludge tested is a biological sludge and thus, very homogeneous in nature. Because of pretreatment steps, the primary forms of non-volatile solids such as grit have been removed. The remainder of the non-volatile solids, such as bacterial cell mass did not interfere in the thickening or dewatering of the sludge. From the bench scale tests performed, the results indicated that the flotability of the CSO sludge and the wet-weather/dry-weather sludge combination are similar to the dry-weather sludge. Similarily, no significant adverse effects were observed in the dewatering characteristics of the proportioned wet-weather/dry-weather sludge or the CSO sludge when the results are compared to those obtained for the dry-weather sludge. At this site, it appears quite feasible to dewater any of the three types of sludges studied using the centrifugation process.

Physical Sludges - Milwaukee, WI

The Milwaukee wet-weather sludge is physically generated and, unlike the Kenosha sludge, it is heterogeneous by nature. The principal forms of the non-volatile solids are gritty material which interferes in the centrifugation process. This was well documented at the Humboldt Avenue wet-weather site where gritty sludge was fed to the full-scale 121.9 cm (48 in.) basket centrifuge. All of the runs attempted had to be terminated because of excessive vibration and machine clogging. To prevent machine damage, it was decided to centrifuge only the sludge supernatant. On-site experience indicates that the sludge must be degritted prior to centrifuging. Methods of degritting the sludge concentrate line only, such as swirl concentration, will be further developed in Section XI.

The results of the Milwaukee 30.5 cm (12 in.) basket centrifuge tests show that the sludge supernatant dewatered quite well with polymer, with values of 28.4 percent for cake and 82 percent solids recovery obtained. These results are quite encouraging, considering that the basket centrifuge was operating well below its optimum design solids loading, which was not obtainable because of the low feed solids of the sludge supernatant. In the Phase I report (1), the Humboldt Avenue sludge was chemically thickened to 1.74 percent solids, and dewatered using a bench scale centrifuge. The average cake concentration was 24.3 percent solids for 28 runs. In several of the runs, cakes in excess of 30 percent were obtained, with a maximum concentration of 64.9 percent. All of the solids recoveries were excellent, consistently in the 95 percent or above range. Based on these study results, it appears that centrifugation would be feasible providing the wet-weather sludge was previously degritted and thickened. This approach is discussed in the economic evaluation section of this report (Section XI).

The Milwaukee South Shore dry-weather primary sludge dewatered very well using the decanter centrifuge. Some pertinent discussion with regard to the dewatering characteristics of that sludge are presented below:

1. The sludge can be dewatered to a 16.7 to 26.2 percent cake without the aid of polymer. The corresponding recovery range is 41 to 53 percent.

2. With polymer addition, the sludge can be dewatered to cake concentrations as high as 20.1 percent with a corresponding recovery of 81 percent. A maximum recovery of 98 percent was achieved with a corresponding cake of 13.2 percent solids.

3. At feed rates between 118-203 kg/hr (260-450 lb/hr) and a feed concentration of 4.5-5 percent T.S., optimal conditions were obtained at a differential speed of 15 RPM, a polymer dosage of .88-1.24 kg/metric ton (1.76-2.48 lb/ton) and pool radius settings of 101 and 103 mm. At these settings, cake concentrations between 14.5-17 percent solids were obtained with recoveries of 80-95 percent.

4. Good results were also obtained at a pool depth of 103 mm with a slightly higher polymer dosage of 2.06-2.88 kg/metric ton (4.12-5.76 lb/ton) and a differential speed of 23 RPM. Cake concentrations of 13.2 and 16.3 percent solids were achieved with corresponding recoveries of 98 and 96 percent.

The results obtained from the study indicate that the scrollability of the South Shore dry-weather primary sludge is good.

The results of the Milwaukee study have shown that the optimum wet-weather dewatering method would be basket centrifugation because of the extremely low feed solids concentrations present. It is conceivable, however, that at other CSO sedimentation applications where higher solids contents are obtainable, the use of a decanter centrifuge may be more practical.

The feed concentration of the dry-weather sludge (∿5 percent solids) required the use of the decanter centrifuge, since the volume of solids generated is high and would result in very short cycle times if the basket centrifuge were used.

The dry-weather wastewater is degritted as a pretreatment operation at the South Shore Water Pollution Control Plant. Although this removes the principal source of the non-volatile solids from the wastewater, some inorganic fines remain and are concentrated in the primary sludge. However, this did not present a problem in dewatering the sludge. One problem that did develop was that the foot valve on the feed intake to the centrifuge had to be cleaned after every run due to accumulations of rags and other objectionable materials. If the centrifuge were installed on a permanent basis, a mechanical cleaning device should be installed on the feed line intake. Also, provisions should be made for a back flush system.

Physical-Chemical Sludges - Racine, WI

A comparison of results for the Racine dry-weather and wet-weather optimum dewatering characteristics using the decanter centrifuge has been prepared and is shown below in Table 4.

TABLE 4. COMPARISON OF OPTIMUM OPERATING PARAMETERS CENTRIFUGE DEWATERING TESTS - RACINE, WISCONSIN

	Dry-weather sludge	CSO sludge
Feed rate, kg/hr (lb/hr)	336 (740)	18.0 (39.6)
Cake concentration, % solids	30.8	32.1
SS recovery, % solids	99.0	92.4
Average feed concentration, % solids	9.73	0.46
Feed rate, l/min (gpm)	57.5 (15.2)	65.1 (17.2)
Polymer dosage, kg/metric ton (lb/ton)	1.2 (2.4)	0.96 (1.92)

The results of the full-scale dewatering tests on the dry-weather sludge indicated that the optimum feed rate to the decanter centrifuge is 336 kg/hr (740 lb/hr). This feed rate produces a cake concentration of 30.8 percent solids with a suspended solids recovery of 99.0 percent.

For the wet-weather sludge, an optimum cake concentration of 32.1 percent solids was obtained with a suspended solids recovery of 92.4 percent. The feed rate to the machine was 18.0 kg/hr (39.6 lb/hr). The data comparison shows that the optimum wet-weather cake concentration and suspended solids recovery is quite similar to the optimum dry-weather sludge. This is important to note since the decanter centrifuge was operating well below its design loading rate for the wet-weather sludge. Higher loading rates were not possible due to the diluteness of the feed sludge. It can be expected that the optimum cake for a more concentrated wet-weather feed sludge would be considerably higher in a practical design.

The excellent dewatering results obtained, coupled with the bench scale thickening data suggests that the Racine wet-weather sludge is very amenable to thickening-dewatering. Indeed, a true thickening step with some grit removal would be required prior to centrifugation.

The Racine screening/dissolved air flotation wet-weather sludge is a physical-chemical sludge and is therefore very similar to the Milwaukee CSO sludge in its origin. Grit and coarse material, removed in the screening process are discharged to the holding tank where it is mixed with the floated sludge. This sludge is heterogeneous in nature, unlike the very homogenous wet-weather biological sludge encountered at Kenosha. As such, the principal form of the non-volatile solids is inorganic grit and sand. To better illustrate this, Table 5 was prepared which compares the average percent total volatile solids at each of the dry-weather and wet-weather sites tested.

As shown in the table, average dry-weather total volatile solids were in excess of 55 percent for all of the test sites. As expected, wet-weather average volatile solids were lower than the dry-weather, ranging from 37.1 percent to 50.8 percent. It is important to note, however, the pattern of the CSO sludge volatile solids concentration that was extablished. For example, the purely physical sludge at the Milwaukee-Humboldt Avenue CSO site had the lowest concentration of volatile solids. As previously discussed, the sludge at this site contains significant amounts of non-volatile solids in the form of inorgan grit and sand.

TABLE 5. TEST SITE AVERAGE TOTAL VOLATILE SOLID SLUDGE CONCENTRATIONS

Test site	Average dry-weather total volatile solids, %	Average wet-weather total volatile solids, %
Kenosha	63.6	50.8
Milwaukee	62.2	37.1
Racine	56.4	49.3

Of the wet-weather sludges tested, the Kenosha sludge had the highest concentration of volatile solids. This sludge is derived from biological treatment, and as such, the principal forms of the non-volatile solids (grit, sand, and other inorganics) have been removed, resulting in a very homogeneous sludge.

The Racine physical-chemical CSO sludge fell between the Milwaukee and Kenosha sludges in volatile solids concentration. The principal form of the non-volatile solids was the inorganic grit generated in the screening backwash process.

In conducting the full-scale Racine dewatering tests, screening of the thickened sludge was required to prevent clogging and damage to the decanter centrifuge. The sludge samples for volatile solids were taken from the feed line to the centrifuge and therefore definite amounts of non-volatile solids nad been removed from the sludge sample. It can be assumed that the volatile solids concentration of the raw sludge would have been slightly lower if some non-volatile material had not been removed. In any full-scale permanent operation, grit removal would be a required pretreatment classification step to remove objectionable inorganic solids and other foreign matter. The economic advantages of degritting only the sludge or concentrate line instead of the entire flow are fully developed in the Section XI, economic evaluation.

HEAVY METALS DATA

Biological Sludges - Kenosha, WI

The results of the Kenosha heavy metals data show several similarities that exist between the three types of sludges that were tested from the Water Pollution Control Plant. A discussion of heavy metal results for the dry-weather sludge, the wet-weather sludge, and the dry-weather/wet-weather combination sludge is presented below:

1. The highest metal concentrations obtained in all three sludges were for zinc, copper, and chromium.

2. Mercury remained the least concentrated of the heavy metals in all cases.

3. The metal concentrations at the Kenosha Water Pollution Control Plant vary significantly with time and also the type of sludge being tested. For example, the dry-weather feed sludge had a zinc concentration of 3681 mg/kg which compares with the CSO sludge value of 2690 mg/kg. The zinc value for the dry-weather combination sludge, however, was 7520 mg/kg. The combination sludge sample was taken approximately one year after the dry-weather and CSO sludge samples, and zinc concentration had more than doubled. Similar comparisons were also observed for most of the other heavy metals.

4. The bulk of the heavy metals appear to be in the insoluble state. This is shown by the high concentrations of heavy metal in the sludge solids.

The combined dry-weather/wet-weather sludge was the only sludge dosed with polymer. While no major differences were noted in the metal concentrations of the skimmings or cake, centrate quality improved for zinc, lead, copper, chromium and mercury with the addition of polymer. The polymer dosage was 1.1 kg/metric ton (2.2 lb/ton). Dependent on the quality of centrate required, polymer addition could be advantageous for the reduction in concentration of certain trace metals. Any reduction in toxic metals (boron, cadmium, cobalt, chromium, copper, mercury, nickel, lead and zinc) is important to point out due to the hazardous health effects of metal toxicity to plants, man and animals.

Physical Sludges - Milwaukee, WI

The distribution of heavy metals in the Milwaukee sludges followed a pattern previously established for the Kenosha sludges. That is, the highest metal concentrations observed were for zinc and chromium, while mercury again proved to be the metal least concentrated in the sludges.

Also, as with the Kenosha sludges, metals were concentrated in the solid portion of the sludge. Reported values for feed, centrate, skimmings and cake were often of the same magnitude for the wet-weather and dry-weather sludges.

For the Milwaukee wet-weather sludge, metal concentration comparisons are possible for samples with and without polymer addition. At dosages of 1.0 kg/metric ton (2.0 lb/ton) the results in Table 21, Section VIII show that metals in the centrate are consistently lower for the samples in which polymer was added. Polymer addition on the Kenosha wet-weather/dry-weather sludge also improved the quality of the centrate with regard to heavy metal reduction.

The comparison of the Milwaukee wet-weather and dry-weather sludges demonstrates some definite metal distribution patterns. For example, concentrations of lead, nickel, copper, and mercury are consistently lower for the feed, centrate, and cake of the dry-weather sludge. This pattern was not demonstrated in the Kenosha sludge, and is probably the result of local industrial activity.

Physical-Chemical Sludges - Racine, WI

The Racine heavy metals data that are presented in Tables 25 and 26, Section IX were relatively comparable to the metal concentrations observed in the Kenosha and Milwaukee sludges. It is important to note, however, that overall concentrations of the Racine wet-weather sludge metals were slightly less than either of the corresponding wet-weather sites at Kenosha or Milwaukee. Future discussion will show that CSO sludge metal concentrations are apparently quite variable with time and therefore great difficulty occurs in attempting to characterize parameter trends. This variation also exists for the Milwaukee sludge, and to a somewhat lesser extent, the Kenosha sludge.

The comparison of the Racine wet-weather sludge to the dry-weather sludge shows that concentrations of zinc, lead, copper, chromium, and mercury are higher for the dry-weather sludge. This pattern of consistently higher heavy metals in the dry-weather sludge samples was also demonstrated at the Kenosha Water Pollution Control Plant, but not for the Milwaukee samples.

The soluble metal analyses conducted verified that only minimal amounts of heavy metals exist in the soluble state for the Racine sludges. As with the Kenosha and Milwaukee sludges, dry weight trace metals were frequently of the same magnitude for the feed, centrate, and cake. This indicates that the metals are solids related, concentrating in the solid portion of the sludge.

The cadmium analyses that were performed on the Racine sludges verified that cake cadmium concentrations were moderate, ranging from 14 mg/kg for the CSO sludge to 31 mg/kg for the dry-weather sludge.

In conclusion, the heavy metal concentrations from the three study sites can be quite variable. However, some important trends and similarities have been established from analysis of the data.

DIGESTER STUDY DATA

The digesters were operated at the same hydraulic loading (20 day hydraulic retention time) during the dry-weather feeding for both the Kenosha and Racine CSO digester tests. The volatile solids loading in the Racine tests was about 22% higher than in the Kenosha tests, however. During the control period, the Racine test digesters produced about 39% more gas than the Kenosha test digesters. The ratio of gas produced to volatile solids destroyed was only about 11% higher for the Racine digesters, however. During both studies, the standard deviation values for daily gas production during the control period were similar (0.5 to 0.6 l/day). In the Kenosha study, the difference in daily gas production between the two digesters averaged 0.015 l/day with a standard deviation of 0.79 l/day during the initial control period. During the Racine control period, the average difference between the two digesters averaged 0.11 l/day with a standard deviation of 0.35 l/day.

After the addition of CSO sludge to the regular feed sludge to simulate the solids resulting from a 2.54 cm (1 in.) rainfall, the day-to-day gas production of the digesters in both studies became more variable (standard deviations of the mean value for each digester increased).

In order to similate the addition of CSO solids resulting from a 2.54 cm (1 in.) rainfall fed to the digester in one day, the volatile solids loading to the digesters in the Kenosha tests was increased by 60%. The volatile solids loading to the digesters in the Racine tests was increased by only 26% to simulate the same rainfall conditions. In the Kenosha tests, the difference in gas production between the control and wet-weather digesters was not statistically significant at the 95% confidence level. In the Racine tests, the difference was significant at the 95% confidence level but not at the 99% confidence level. The only period during the Kenosha tests when the difference in digester gas production was statistically different at the 95% confidence level was Period #3 when the wet-weather digester was fed Kenosha CSO sludge exclusively for a period of ten days. It is quite unlikely that a sewage treatment plant digester would be fed exclusively with CSO sludge.

The statistically lower gas production after feeding CSO sludge to the wet-weather digester in the Racine tests cannot be attributed to the presence of toxic heavy metals. The simulated wet-weather sludge fed to the test digester contained lower concentrations of zinc, nickel, copper, chromium, iron and cadmium than the dry-weather sludge fed to the control digester. Although the lead concentration in the wet-weather feed was higher, the concentration of lead was less than half the geometric mean value found in the sludges fed to digesters at 33 sewage plants by the EPA (13).

In spite of the lower gas production of the test digester after being fed Racine CSO sludge, the volatile acid/alkalinity ratio of the digesting sludge was less than 0.01 the day after the wet-weather feeding and was 0.13 the fourth day after the wet-weather feeding. These values are well below the 0.3 to 0.4 ratio which indicates that the digester may be approaching upset (MOP 16).

Summary

1. In general, the dewatering treatment train for handling CSO treatment sludges would be comprised of degritting where required, thickening (gravity or flotation, with or without chemicals) and centrifugation (basket or decanter, with or without chemicals).

   a. The raw and thickened CSO sludges derived from physical treatment (Milwaukee) and from physical-chemical treatment (Racine) were similar in that they contained significantly more grit than their dry-weather counterparts. The grit does not adversely affect the gravity thickening process. However, to prevent excessive machine wear and pluggage, degritting would be required prior to any further dewatering by centrifugation.

   b. The raw and thickened CSO sludge derived from biological treatment was similar in nature to that of its dry-weather counterpart and pretreatment prior to thickening is not indicated.

   c. The dilute physical CSO sludge (Milwaukee) investigated may be futher thickened by gravity with chemicals.

      The physical-chemical CSO sludge (Racine, screening/dissolved air flotation) may be further thickened by gravity without chemicals.

      The biological CSO sludge (Kenosha, contact stabilization) may be further thickened by flotation without chemicals.

   d. Further dewatering of the Milwaukee thickened sludge (from physical CSO treatment) may be obtained using a basket centrifuge with the aid of polymer.

      The Racine thickened sludge (from physical-chemical CSO treatment) may be further dewatered using a decanter centrifuge with the aid of polymer.

      The Kenosha sludge (from biological CSO treatment) may be dewatered using a basket centrifuge without chemicals.

2. In general, the dewatering train for handling dry-weather treatment sludges would be comprised of thickening, where required (gravity or flotation, with or without chemicals) and centrifugation (basket or decanter, with or without chemicals).

   a. The Milwaukee (South Shore Plant) dry-weather primary sludge can be dewatered to a haulable cake using a decanter centrifuge with the aid of polymer.

   b. The Racine dry-weather sludge (primary plus activated) can be dewatered to a haulable cake using a decanter centrifuge with the aid of polymer.

   c. The dewatering characteristics of dry-weather biological sludge and combinations of dry-and wet-weather biological sludges were similar to those for the CSO biological sludge alone. Satisfactory results were obtained using flotation thickening and basket centrifuging without the aid of chemicals.

3. The heavy metal concentrations were quite variable between the test sites investigated. However, the heavy metals present appear to be solids related with only slight concentrations observed in the soluble metal portion of the sample. Therefore, heavy metal removal was directly related to solids removal.

4. The bench scale anaerobic digestion studies showed that no significant adverse effect was realized by adding CSO generated sludges to dry-weather digesters. If the CSO sludge is generated by physical or physical-chemical treatment, prior discussion suggests that sludge degritting will be necessary.

SECTION V

DESCRIPTION OF THE CSO TEST SITES INVESTIGATED

Three CSO treatment plants were selected as study sites for thickening-centrifugation dewatering of CSO sludges. The sites are located in Kenosha, Wisconsin; Racine, Wisconsin; and Milwaukee, Wisconsin.

The selection of the test sites was based on a desire to study the CSO sludges produced by three different CSO treatment processes; a physical process, a physical/chemical process, and a biological process. In Milwaukee, a physical process is employed. The raw CSO is held in a storage facility and then bled back to the sewer system when the CSO event is over. Sedimentation is the only removal mechanism utilized. In Racine, a physical/chemical treatment system is operated, which consists of screening followed by dissolved-air flotation. A biological treatment process, contact stabilization, is the method employed in Kenosha to treat CSO.

As mentioned previously, each test site city's dry-weather treatment plant sludge was also studied in addition to the city's CSO sludge. This made it possible to compare the dewatering characteristics of each city's CSO sludge and the sludge being generated at the dry-weather treatment plant. Following is a description of all the project test sites.

MILWAUKEE, WISCONSIN

CSO Treatment Facility

The Milwaukee CSO physical treatment facility is a storage tank. A schematic of the facility is shown in Figure 1.

The capacity of the storage tank is 15,140 m^3 (4 million gal.). Flows are directed to the tank by gravity through a 198 cm (78 in.) sewer. Upon entering the tank inlet channel, the flow passes through a mechanically cleaned 3.8 cm (1.5 in.) bar screen. All materials retained on the screen are deposited in a portable refuse container.

Only one of seven rotary mixers in the tank is operated during a CSO event. It is used to disperse chlorine. Therefore, during this period the detention tank acts as a settling basin. When the CSO volume exceeds the 15,140 m^3 (4 million gal.) capacity of the tank, the excess overflow begins to discharge from the effluent end of the tank.

After the overflow has subsided, all seven mixers are activated to resuspend the settled solids. When this has been completed, the contents of the tank are pumped back to the sewer.

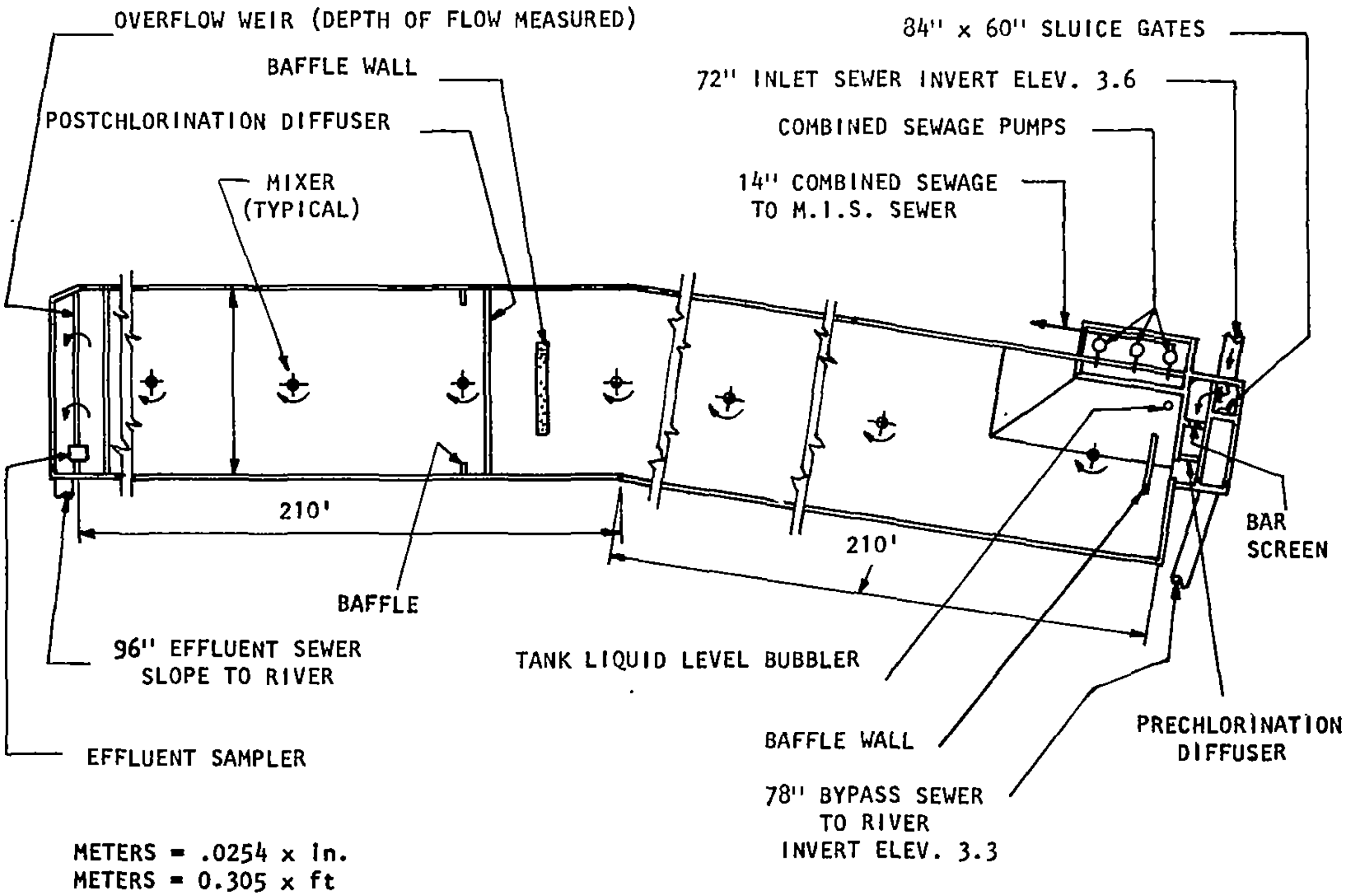


Figure 1. Schematic diagram of the Milwaukee, Wisconsin CSO demonstration storage facility.

Facilities for pre- and post-chlorination of the CSO are also provided. The pre-chlorination diffuser is located in the tank inlet channel. The post-chlorination diffuser distributes chlorine across the entire width of the tank at a point about 3.66 m (12 ft.) above the tank floor and 53.95 m (177 ft.) from the effluent overflow weir.

As described, it is obvious that the facility does not produce a residual CSO sludge that could be used for testing centrifuge dewatering. Therefore, for this project, the operation of the tank was changed. Overall operation during a CSO event remained the same but during pumpback of the tank's contents to the sewer, the mixers were not turned on. This resulted in the supernatant being pumped to the sewer and a residual settled sludge remaining in the bottom of the tank. This settled sludge was treated as the CSO sludge produced at the Milwaukee CSO treatment facility.

Dry-Weather Sewage Treatment Facility

Two dry-weather treatment facilities serve the Milwaukee Metropolitan Sewerage District. The older of these plants is the Jones Island plant. It utilizes fine screening in lieu of primary sedimentation and provides secondary treatment for flows up to 757,000 m^3/day (200 mgd). The South Shore plant is the newer of the two. It has conventional primary treatment and is capable of treating 1.2 million m^3/day (320 mgd flow). New conventional secondary treatment facilities capable of treating 454,000 m^3/day (120 mgd) were completed at the plant in 1974.

For this study, the South Shore plant was selected as the site from which Milwaukee's dry-weather sludge would be obtained.

RACINE, WISCONSIN

CSO Treatment Facilities

The Racine CSO physical-chemical treatment facilities (there are two separately located treatment systems are designed for a total flow of 219,500 m^3/day (58 mgd). A schematic of one of the units is given in Figure 2. Treatment consists of two basic unit operations: screening followed by dissolved-air flotation.

The raw CSO enters the site wetwell and then passes through a mechanically cleaned bar screen to a spiral screw pump. The pump discharges into a channel leading to the drum screen influent channel. The screens employed to remove suspended matter in the CSO have 297 micron openings (50 mesh). When headloss through the screens becomes excessive, backwash water is drawn from the screen effluent chamber by a backwash water pump and sprayed on the outer surfaces of the screens to flush solids from the inner surface. These solids, along with the backwash water, are collected in a hopper and then flow by gravity to a screw conveyor which delivers them to the sludge holding tanks where they remain until the CSO event is over.

The screened CSO then flows to the flotation tanks where it is blended with

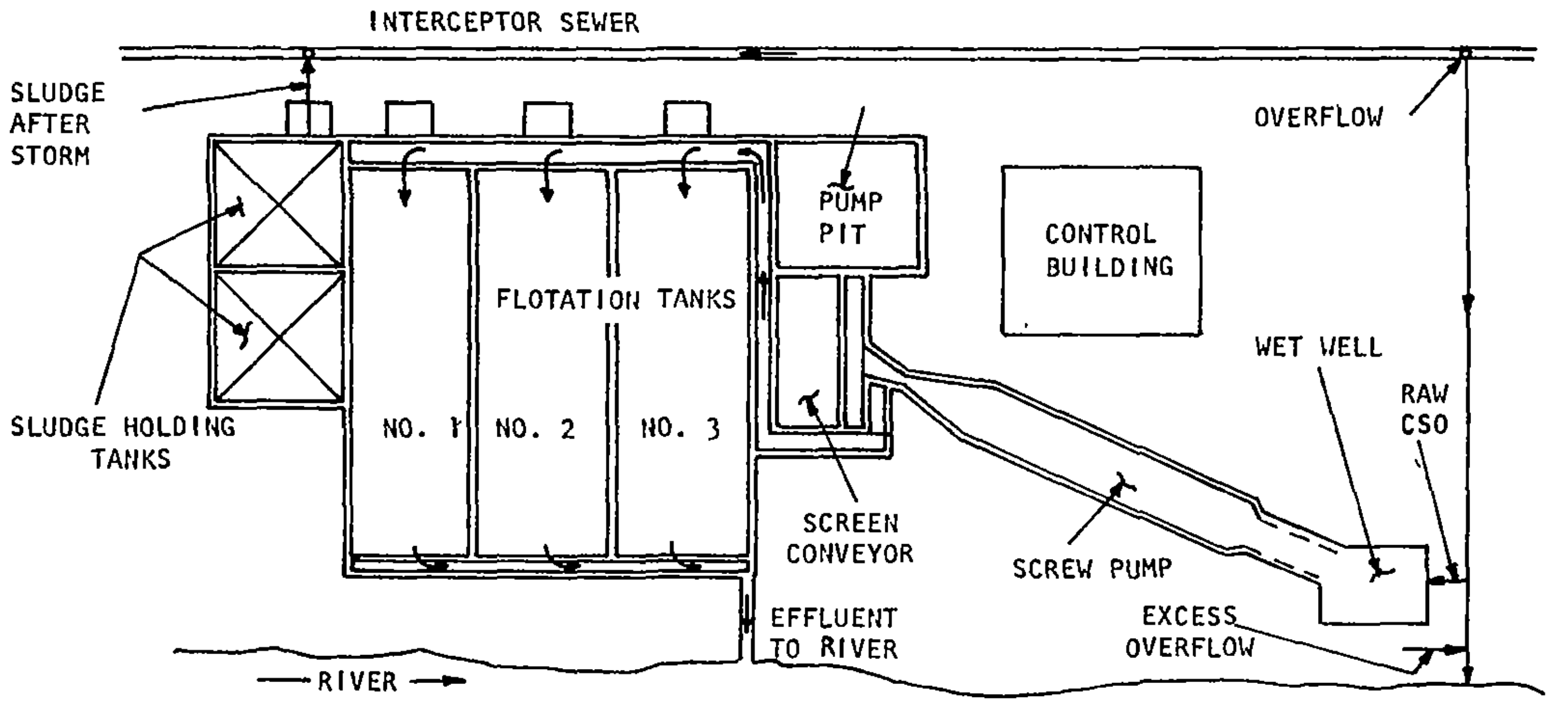


Figure 2. Schematic of Racine CSO treatment facility.

air-saturated pressurized flow. The system does not employ effluent recycle. Instead, approximately 20 percent of the raw flow is pressurized. The floated sludge is periodically skimmed from the top of the tanks and is deposited in the screw conveyor which delivers it to the sludge holding tanks.

Ferric chloride and polymer are added to the CSO to facilitate the coagulation of particulate matter before flotation. Ferric chloride is added in the wetwell ahead of the spiral screw pump. Polymer is added in the drum screen effluent channel. Chlorine is also added in the drum screen effluent channel for disinfection purposes.

The CSO sludge produced by the system (screen backwash water and floated sludge) is drained back to the city sewer system when the water level in the sewer has decreased to the point where the tank contents can be drained without causing an overflow at a point farther downstream in the interceptor sewer.

Dry-Weather Sewage Treatment Facility

The conventional treatment of dry-weather wastewater in Racine is accomplished by a 79,500 m^3/day (21 mgd) primary treatment plant, a 45,400 m^3/day (12 mgd) secondary treatment plant, chlorination, sludge digestion and vacuum filtration. The average flow to the plant is 79,500 m3/day (21 mgd).

The wastewater flows through a mechanically cleaned bar screen and then to four comminutors. Each comminutor has a rated capacity of 45,400 m^3/day (12 mgd). After comminution, the wastewater flows to the grit chambers. The settled grit is removed from the chambers by scrapers. A screw conveyor and screw type grit washer remove and further cleanse the grit for satisfactory disposal as a fill material. The wastewater then flows to four primary sedimentation tanks with a total surface area of 1760 m^2 (18,947 ft.^{2}) and a total volume of 4,920 m3 (1,300,000 gal.). At the average flow rate of 79,500 m^3 (21 mgd), this results in a surface overflow rate of 45 m^3/m^2/day (1,108 gal./ft.^{2}/day) and a detention time of 1.49 hours.

The primary effluent then flows to secondary treatment which consists of an activated sludge process. There are two mixed liquor aeration tanks with a total volume of 8,500 m3 (2,250,000 gal.). The aeration tanks can be operated in several alternate modes. The wastewater can be introduced into both tanks, together with return activated sludge. The first aeration tank can also be utilized as a sludge reaeration tank for the contact stabilization process, or as a nitrification tank for the Kraus process. For both of these processes, all of the primary effluent is introduced into the second aeration tank.

After aeration the mixed liquor flows to two final clarifiers. Each clarifier has a volume of 1,893 m3 (500,000 gal.) and a detention time of 2 hours. The surface overflow rate is 43m^3/m^2/day (1,060 gal./ft.^{2}/day). The clarified effluent is then transported to a chlorine contact chamber for disinfection prior to discharge.

The waste activated sludge generated by secondary treatment is returned to the primary sedimentation tanks where it is settled out with the primary sludge. This sludge is then pumped to two-stage anaerobic digestion. The total volume of the digestion system is 7,570 m^3 (2 million gal.) and an average of 341 m^3/day (90,000 gal./day) of sludge at a solids concentration of 7.5 percent or 25,547 kg/day (56,270 lbs/day) dry sludge are handled.

The digested solids are then dewatered by vacuum filtration. Two 3m (10 ft.) by 3m (10 ft.) vacuum filters are utilized. Each filter has its own conditioning tank where chemicals are added to aid in coagulation and to improve filterability. The chemicals used are lime and ferric chloride. The resulting filter cake is disposed of at a landfill site.

KENOSHA, WISCONSIN

CSO Treatment Facility

The CSO treatment system in Kenosha is unique in that it is located adjacent to the existing conventional dry-weather treatment plant. In fact, since the system utilizes biological treatment it depends on the dry-weather plant as a source of active biomass. Figure 3 presents a schematic of the CSO contact stabilization process, the dry-weather treatment plant, and the interconnections between the two.

The CSO treatment facility has a design capacity of 75,700 m^3/day (20 mgd). It consists of a grit chamber, mixed liquor contact tank, sludge stabilization tank and final clarifier. The grit chamber is designed to handle a flow of 75,700 m^3/day (20 mgd) with a flow-through velocity of 0.06 m/sec (0.2 ft./sec). Any deposited grit on the floor of the tank is flushed to the west wall where it is suction pumped to a truck and hauled to a landfill site.

The contact and stabilization tanks are located in one large concrete basin which is divided by concrete walls into four compartments, two contact tanks and two sludge stabilization tanks. The contact tanks are designed to handle a maximum flow of 75,700 m^3/day (20 mgd) and a sludge flow of 11,355 m^3/day (3 mgd) with a 15 minute contact period. This requires a volume of approximately 946 m^3 (250,000 gal.). The two contact compartments have volumes of 621 m^3 (164,000 gal.) and 305 m^3 (80,465 gal.) for a combined volume of 926 m^3 (244,465 gal.).

The stabilization tank also has two compartments which can be used separately or together so that the sludge stabilization times can be varied. Both tanks are identical, having a volume of 1,387 m^3 (366,329 gal.) each. Two 37,850 m^3/day (10 mgd) pumps are provided to transfer the stabilized sludge to the contact tanks during system operation. A 1,893 m^3/day (0.5 mgd) pump is also provided to transfer unused, stabilized sludge to the dry-weather treatment plant's flotation thickeners during periods of dry weather.

The final clarifier is designed on a settling rate of 3 m/hr (10 ft./hr.).

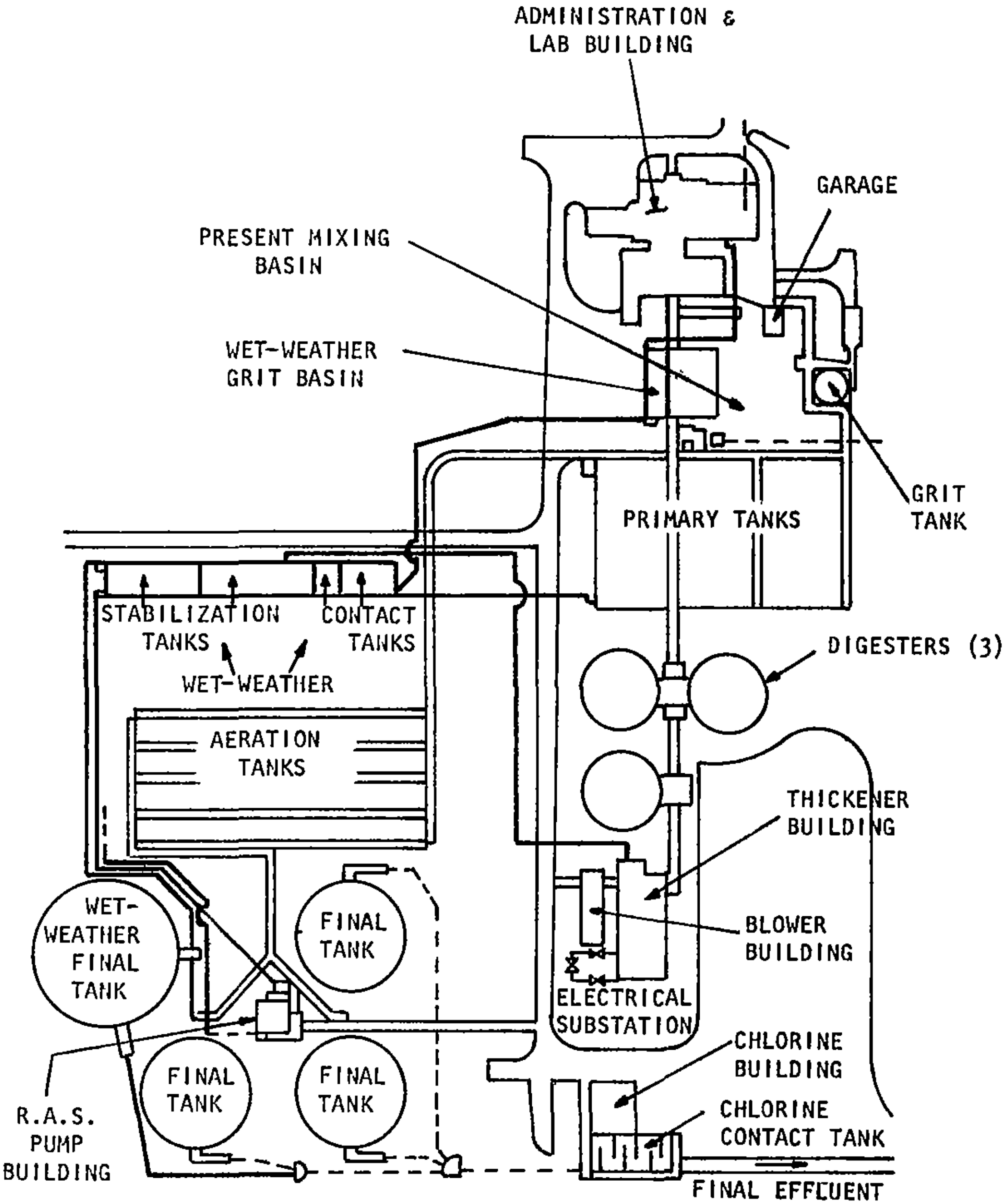


Figure 3. Relationship between the Kenosha, WI CSO demonstration treatment system and the conventional treatment plant.

The design overflow rate is 72.7 m^3/m^2/day (1,790 gal./ft.^{2}/day). At a flow rate of 75,700 m^3/day (20 mgd), this requires a 42.7 m (140 ft.) diameter clarifier which has a surface area of 1,430 m^2 (15,394 ft.^{2}) and a volume of 5,230 m^3 (1,381,754 gal.). The clarifier is designed for use during both dry-weather flow and CSO conditions. During dry-weather, the mixed liquor from the dry-weather plant is fed to the clarifier and the settled sludge is pumped back into the dry-weather plant's sludge return system. During CSO conditions, the mixed liquor from the contact tank is fed to the clarifier and the settled sludge is pumped to the sludge stabilization tanks.

During a CSO event, raw sewage flows in excess of the dry-weather plant's capacity of 87,055 m^3/day (23 mgd) are pumped to the CSO treatment facility. After passing through the grit chamber, the raw flow goes to the contact tanks. Before entering the contact tanks, the raw CSO is mixed with stabilized sludge which is pumped from the stabilization tanks. After 10 to 15 minutes of aeration in the contact tanks, the mixed liquor flows to the final clarifier. After settling is achieved the effluent flows to the dry-weather treatment plant's chlorination facilities. The settled sludge is pumped back to the sludge stabilization tanks.

After a CSO event has ended, all of the solids produced by the contact stabilization process are fed to the dry-weather treatment plant's sludge handling facilities.

During dry-weather conditions, the only activity within the CSO treatment system is a constant flow of waste activated sludge from the dry-weather plant to the stabilization tanks. The waste activated sludge is then pumped from the stabilization tanks to the dry-weather plant's handling facilities. This procedure insures the availability of an active biomass in the stabilization tanks when a CSO event occurs.

Dry-Weather Sewage Treatment Facility

The raw sewage entering the plant during dry-weather is pumped through two grit removal chambers which operate in parallel. The discharge from the grit chambers flows by gravity to six primary sedimentation basins which have a total surface area of 2,300 m^2 (24,760 ft.^{2}) and a volume of 7,295 m^3 (257,600 ft.^{3}). The maximum hydraulic capacity of the tanks is 113,500 m^3/day (30 mgd), resulting in surface overflow rates of 49.3 m^3/m^2/day (1212 gal./ft.^{2}/day) and a detention time of 1.54 hours. The effluent from the primary tanks flows to the mixed liquor aeration tanks where it is mixed with return activated sludge. There are four aeration tanks having a total volume of 13,480 m^3 (476,000 ft.^{3}). The aeration time in these tanks is 3.72 hours at a maximum design capacity of 87,055 m^3/day (23 mgd). The mixed liquor then flows to three 25.9 m (85 ft.) diameter final clarifiers having a total surface area of 1,581 m^2 (17,020 ft.^{2}). At a flow rate of 87,055 m^3/day (23 mgd), the surface overflow rate is 54.9 m^3/m^2/day (1,350 gal./ft.^{2}/day) and the detention time is 1.32 hours. The effluent is then chlorinated and discharged.

The waste activated sludge, approximately 314 m^3/day (83,000 gal./day) at a solids concentration of 1.5 percent is flotation thickened to about a 4 percent solids concentration before going to anaerobic digestion. The daily loading on the digesters, primary and waste activated sludge combined, is 189 m^3 (50,000 gpd) resulting in a dry solids weight of 11,035 kg/day (24,307 lbs/day). The digested sludge is then further dewatered by means of a filter press which produces a cake of approximately 35 percent solids for disposal.

SECTION VI

SAMPLING, TESTING, AND EVALUATION PROCEDURE

At each of the six sites (3 dry-weather treatment plants and 3 CSO treatment facilities) utilized for this project, the following investigations were carried out:

1. Bench scale thickening tests, either flotation or gravity, depending on the method in use at the site being considered (at Milwaukee, bench scale sedimentation tests were performed).

2. Centrifuge dewatering of the thickened sludge using either the 121.9 cm (48 in.) basket centrifuge or the decanter centrifuge on the mobile centrifuge van.

3. Auxiliary centrifuge dewatering of the thickened sludge using a 30.5 cm (12 in.) basket centrifuge to augment the data obtained during the full scale centrifuge testing, when necessary.

4. Heavy metals analysis of composite samples of feed, centrate, skimmings (for basket centrifuge runs only), and cake taken during centrifuge testing.

In addition to the preceding tests, bench scale anaerobic digestion studies were also conducted using dry-weather sludges and CSO sludges as the feed source. The anaerobic digestion studies were conducted for sludges obtained from Racine and Kenosha, WI.

BENCH SCALE SLUDGE THICKENING TESTS

One of the conclusions drawn from Phase I (1) of this project was "a combination of gravity thickening and centrifugation provided optimum treatment for most CSO sludges evaluated . . . .". Therefore, one of the objectives of this Phase III study was to evaluate the thickening-centrifugation process for handling CSO sludges on a pilot scale.

The three sites selected for this project (Milwaukee, Racine, and Kenosha) all contain built-in sedimentation or thickening processes. Kenosha provides for flotation thickening of the waste activated sludge as it is wasted from the CSO treatment facility's sludge stabilization tank. In Milwaukee, gravity sedimentation of the solids is actually the treatment process employed. At the Racine site, gravity thickening of the CSO treatment residuals can be achieved in the sludge storage tank.

Since the sedimentation or thickening processes at the sites are built into the actual operation of the systems, the respective sedimentation/thickening characteristics of the sludges were evaluated on a bench scale basis. In the case of Kenosha, where the thickening unit handles both the dry-weather and CSO sludges, the results of the bench scale tests were also compared to the recorded operational data for the flotation thickener.

For the Racine and Kenosha sites, three sets of bench scale thickening tests were conducted. The first was for the CSO sludge; the second for the corresponding dry-weather sludge; and, the third for a mixture of the CSO sludge and the dry-weather sludge. The mixture of the CSO sludge and the dry-weather sludge for each site was calculated as follows:

1. The volume of CSO sludge generated by a 1.27 cm (0.5 in.) rain over the city's combined sewer area was calculated based on complete CSO treatment using the prevailing CSO treatment process.

2. This CSO sludge volume was then fed to the dry-weather treatment plant over 48 hours and the daily flow calculated.

3. From dry-weather plant records, the daily flow of dry-weather sludge was obtained. The CSO sludge, liters/day (gpd), divided by the dry-weather sludge, liters/day (gpd), then gave a ratio of CSO sludge to dry-weather sludge over the 48 hours of CSO sludge bleedback.

4. The calculated ratio was then used to prepare the mixture of CSO sludge and dry-weather sludge for the bench scale thickening tests.

The procedures used for conducting the bench scale thickening tests, both gravity and flotation, were identical to those used in Phase I of this project (1).

Using the data obtained, the solids rise or settling rates, the corresponding overflow rates, the estimated final sludge concentrations, and the mass loadings were calculated. Plots were then made of the point of sludge interface versus time, and the mass loading versus the estimated final sludge concentration. From these plots, comparisons of the thickening properties of the three sludges were made and conclusions drawn about the differences between the thickening characteristics of the city's CSO sludge and the city's dry-weather sludge; and, the change in the dry-weather sludge thickening characteristics as CSO sludges are introduced into the sludge mass.

CENTRIFUGE DEWATERING TESTS

As with the thickening studies, the centrifuge dewatering studies were conducted for the CSO sludge and dry-weather treatment plant sludge for each city. Full scale centrifuging of an appropriate combination of dry-weather and CSO sludges were also conducted at Kenosha. Full scale centrifuge tests using dry-weather CSO sludge combinations in Milwaukee and Racine were not conducted because the sludges had to be obtained from two different locations in the city, the site of the CSO treatment facility and the site of the dry-weather sewage treatment plant.

Three centrifuge procedures were used during the course of this project to evaluate dewatering of the CSO sludges and dry-weather sludges in the three cities. Full scale centrifugation tests were achieved by either using a 121.9 cm (48 in.) basket centrifuge or a decanter centrifuge. Both of these centrifuges were available on the mobile centrifuge van. The third centrifuge procedure utilized a 30.5 cm (12 in.) basket centrifuge. This smaller centrifuge was used when necessary, to establish the optimum operating ranges before the larger 121.9 cm (48 in.) basket centrifuge was used, and to obtain data to supplement that generated by the 121.9 cm (48 in.) basket centrifuge tests. The selection of whether to use the decanter centrifuge or the basket centrifuges was dependent on sludge concentration. Basket application is generally restricted to sludges of less than 3% concentration. However, for purposes of comparison between the test sites' dry-weather sludge and the wet-weather sludge, only one type of centrifuge was used at both locations where possible. Thus, only the basket centrifuges (121.9 cm and 30.5 cm) were used at the Kenosha test site. At the Racine sites, the decanter centrifuge was used for both the wet-and dry-weather sludges. In Milwaukee, however, the dry-weather sludge was amenable to decanter application, while the wet-weather sludge was not. Therefore, the basket centrifuge was used in lieu of the decanter on the Milwaukee wet-weather sludge.

30.5 cm (12 in.) Basket Centrifuge Tests

Basket centrifuge tests are conducted using either the 30.5 cm (12 in.) or 121.9 cm (48 in.) basket centrifuge. In most cases, it was desirable to conduct tests with the 30.5 cm (12 in.) basket to optimize performance and then operate the 121.9 cm (48 in.) full scale unit to duplicate the established, optimized mode of operation. In addition, in some cases, the logistics of sample source or volume; power available; or centrifuge van site accessibility made the 30.5 cm (12 in.) basket test work the primary source of data. The use of the 30.5 cm (12 in.) basket also supplied valuable data to supplemnt the results of the full scale basket centrifuge work. An illustration of the 30.5 cm (12 in.) basket centrifuge and its companion pump package is shown in Figure 4. A section view of this centrifuge is presented in Figure 5.

The independent test parameters for basket centrifugation are the feed rate in kg/hr (lbs/hr) (analyzed as total solids and then corrected for dissolved solids); and, the polymer dose rate (if used) in kg/met. ton (lbs/ton) of feed solids. The dependent variables to be observed are the resultant cycle

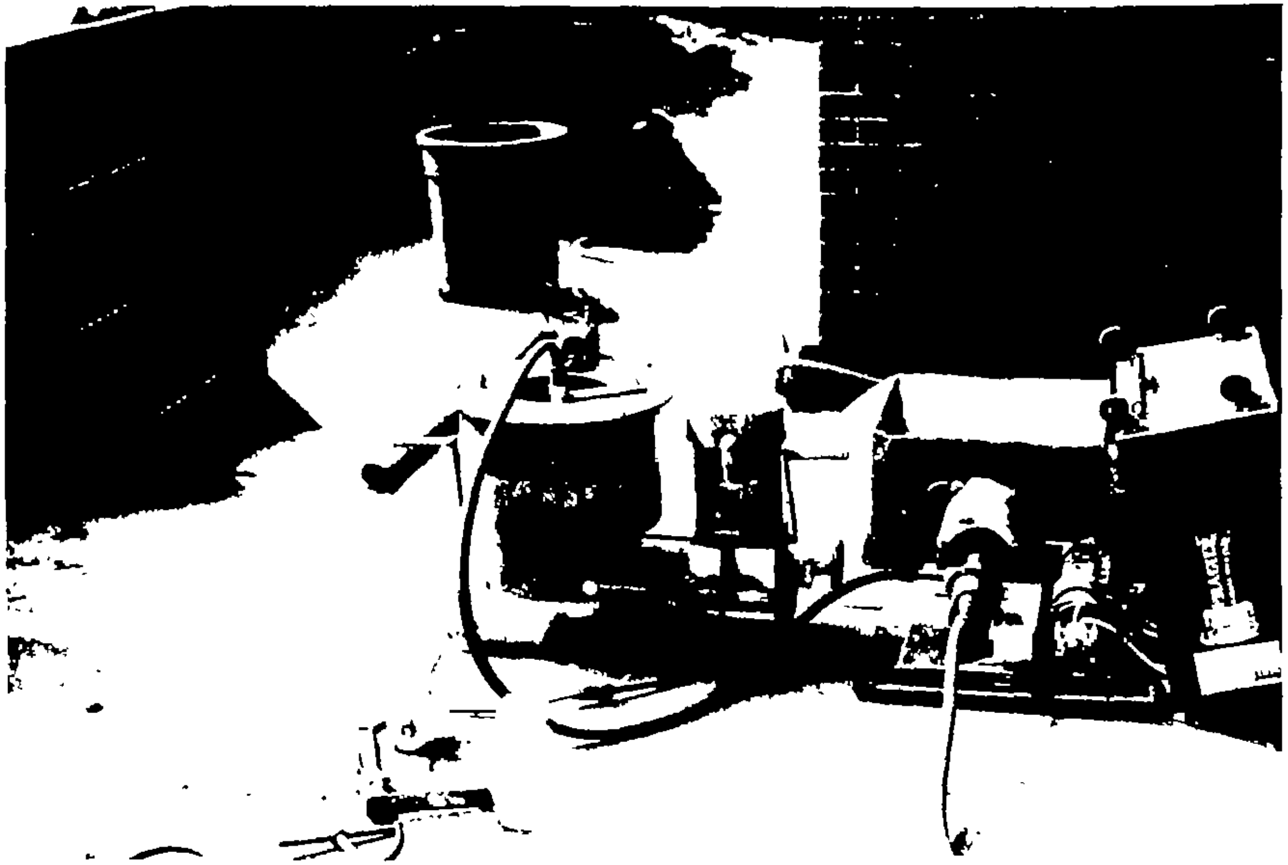


Figure 4. Envirex 30.5 cm (12 in.) basket centrifuge and pump package.

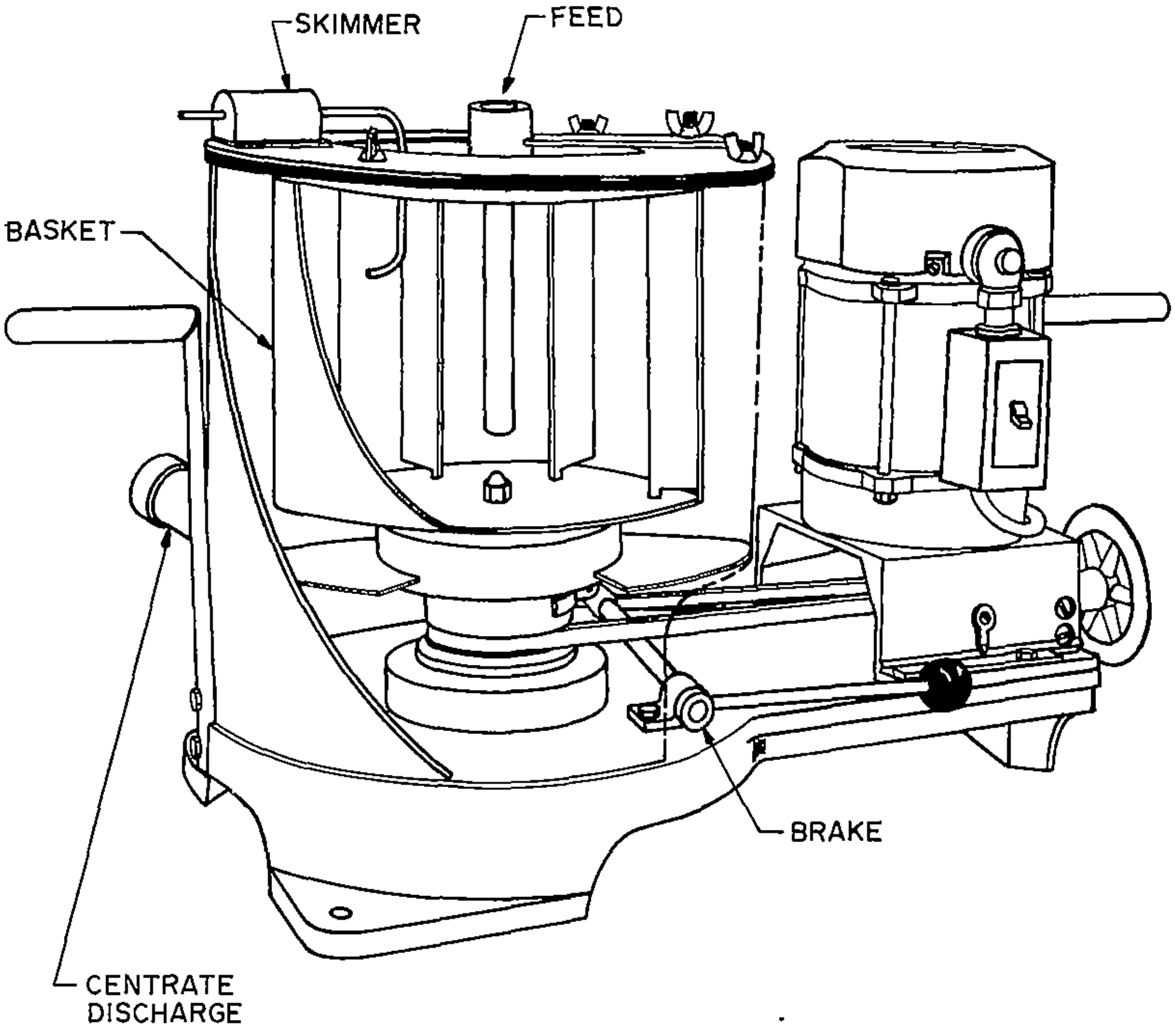


Figure 5. 30.5 cm (12 in.) basket centrifuge-section view

time in minutes; skimming volumes and concentration; the cake concentration; and the centrate quality in mg/l suspended solids.

To assure that all of the necessary variables were monitored for each of the 30.5 cm (12 in.) basket centrifuge tests, data recording sheets were developed. A sample data sheet is shown in Figure 6. The feed samples were analyzed for total solids and total volatile solids; the centrate samples for total solids, total volatile solids, suspended solids, and volatile suspended solids; and the cake samples for total solids and total volatile solids. All analyses were conducted according to "Standard Methods" (2).

Basket centrifuge operation can be best described as a batch-continuous process where 50 to 90 percent of the time may be available for continuous sludge feed. A specific volume, 5.7 liters (1.5 gal.) in the 30.5 cm (12 in.) basket is available for sludge cake accumulation as the feed and dewatering cycle progresses. Once the dewatered cake occupies this volume, the feed cycle is complete and the feed flow is stopped.

At the beginning of a test, the feed pump and polymer addition pump (if polymer is used) are calibrated at the desired rate. While the feed rate is being set, a sample of the feed sludge is obtained from the sludge container. When the pumps are set, the run is started by turning on the centrifuge and allowing it to accelerate up to a constant speed. At its design speed, the 30.5 cm (12 in.) basket centrifuge produces a force of 1300 "G's" at the outer wall. Once constant speed is reached, the feed pump and the polymer pump are turned on and sludge feeding begins. At this point, timing of the run also starts.

When centrate begins flowing from the centrate outlet, the time is recorded. This time is used to determine the exact feed rate: 5.7 liters (1.5 gal.)/ time until centrate discharge beings = pumping rate. If polymer is being added, the polymer pumping rate must be subtracted from this calculated rate to obtain the actual sludge feed rate.

A centrate sample is taken approximately 2 minutes after centrate discharge begins and every 2 minutes thereafter, until the test has ended. This interval can be increased if a low feed rate is being used and a very long cycle time is expected. The end of the feed cycle is established by visual monitoring of the centrate quality. A sudden deterioration of the centrate quality indicates the end of the test. The time of this deterioration of effluent quality is recorded on the data sheet. Without polymer, centrate suspended solids may be in the 1000 to 2000 mg/l range in the intitial stages of the feed cycle and deteriorate to 4000 to 6000 mg/l in 15 to 30 minutes. With polymer, the intital centrate may be as low as 100 mg/l. If initial centrate without polymer is in the 3000 mg/l or greater range, it would indicate a difficult to dewater sludge and then polymer may have to be used to achieve satisfactory solids recovery.

When the feed cycle has ended, the skimming device is advanced into the cake wall to remove any partially thickened cake, normally the last portion of the feed flow which has not been exposed to the 1300 "G" force long enough for

30.5 CENTIMETER (12 INCH) BASKET CENTRIFUGE DATA SHEET

Date	______________
Site	______________
Sludge Type	______________
Run No.	______________
Time of Centrate Discharge	______________
Time of Solids Breakover	______________
Time Cycle Ended	______________
Pump Feed Rate	______________
Chemical Addition	
Type	______________
Feed Rate of Chemical	______________
Chemical Solution Concentration	______________
Volume of Skimmings	______________

Samples

DESCRIPTION	TIME OF SAMPLE
Feed	______________
Centrate 1	______________
Centrate 2	______________
Centrate 3	______________
Centrate 4	______________
Centrate 5	______________
Skimmings	______________
Cake 1	______________
Cake 2	______________

SKETCH OF FINAL CAKE CONDITION

Recorded By: ______________

Figure 6. Sample 30.5 cm (12 in) Basket Test Data Sheet

dewatering. The skimming volume is usually in the 0.1 to 5.0 percent range of the complete volume processed in the batch cycle. The actual volume of skimmings is noted on the data sheet and a sample of the skimmings is taken for analysis.

After skimming is completed, the basket is decelerated to a complete stop. The 30.5 cm (12 in.) basket centrifuge does not include mechanical provisions for sludge removal. Thus, two cake samples are carefully scooped out from mid-depth of the basket at two points, 180 degrees apart. Once these samples are obtained, the basket is cleaned out, all pump lines are cleaned with water, and the pumps are reset for the next test.

The evaluation of the test results is based on the cake concentration and solids recoveries achieved for the varying feed rates and polymer addition rates. Plots of cake concentration versus feed rate and solids recovery versus feed rate can be developed and from the plots an optimum feed rate can be selected for a desired cake concentration and/or solids recovery rate. After selection of the feed rate, similar plots can be developed for varying polymer dosages at a constant feed rate and, then, an optimum polymer dosage selected. Comparisons among these plots for the different sludges studied also gives an indication of the suitability of the different sludges for basket centrifuge dewatering.

For overall sizing, the optimum feed rate is adjusted for the cycle time plus skim time plus plow time (desludging) plus acceleration time (this total is usually assumed to be 5 minutes per cycle) and an overall kg/hr (lbs/hr) and average liters/hr (gal./hr) production rate is established.

121.9 cm (48 in.) Basket Centrifuge Tests

Basket centrifuge tests using the full scale 121.9 cm (48 in.) basket centrifuge are conducted in a manner similar to the 30.5 cm (12 in.) basket centrifuge tests. The independent variables are again the feed rate and the rate of polymer addition (if used) and the dependent variables are the centrate quality, cake concentrations, volume and concentration of the skimmings, and the cycle time. The 121.9 cm (48 in.) basket centrifuge is shown on the mobile centrifuge van in Figure 7. A section view of this centrifuge is presented in Figure 8.

Upon arrival at the test site, the van must be placed in a position such that it is no more than 22.9 m (75 ft) from a source of electrical power, 440 volt, 3 phase, 150 amperes; the sludge source; and, a water source. The location of the van should also be on concrete or asphalt since this will make it easier to level and facilitate cleanup operations. Once the van has been placed at the selected location, the front and back outriggers are set up and the van is leveled. It is critical to have the van as level as possible to prevent excessive vibration during testing. At this time, the power is also connected to the van, the 10.2 cm (4 in.) suction hoses can be put together and placed in the sludge source, and the 2.54 cm (1 in.) water hose can be connected to the water source. The physical set up of the van is now complete. Illustrations of the mobile centrifuge van are shown in Figure 9.

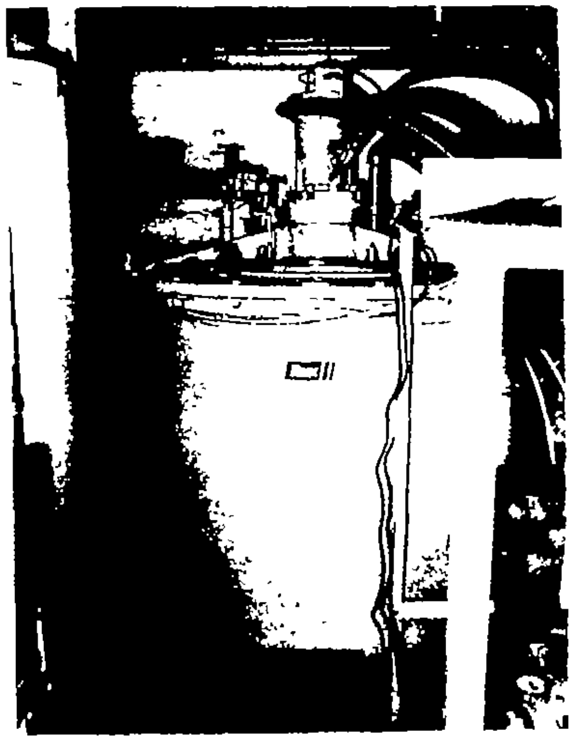


Figure 7. Envirex mobile centrifuge van's 121.9 cm (48 in.) basket centrifuge.

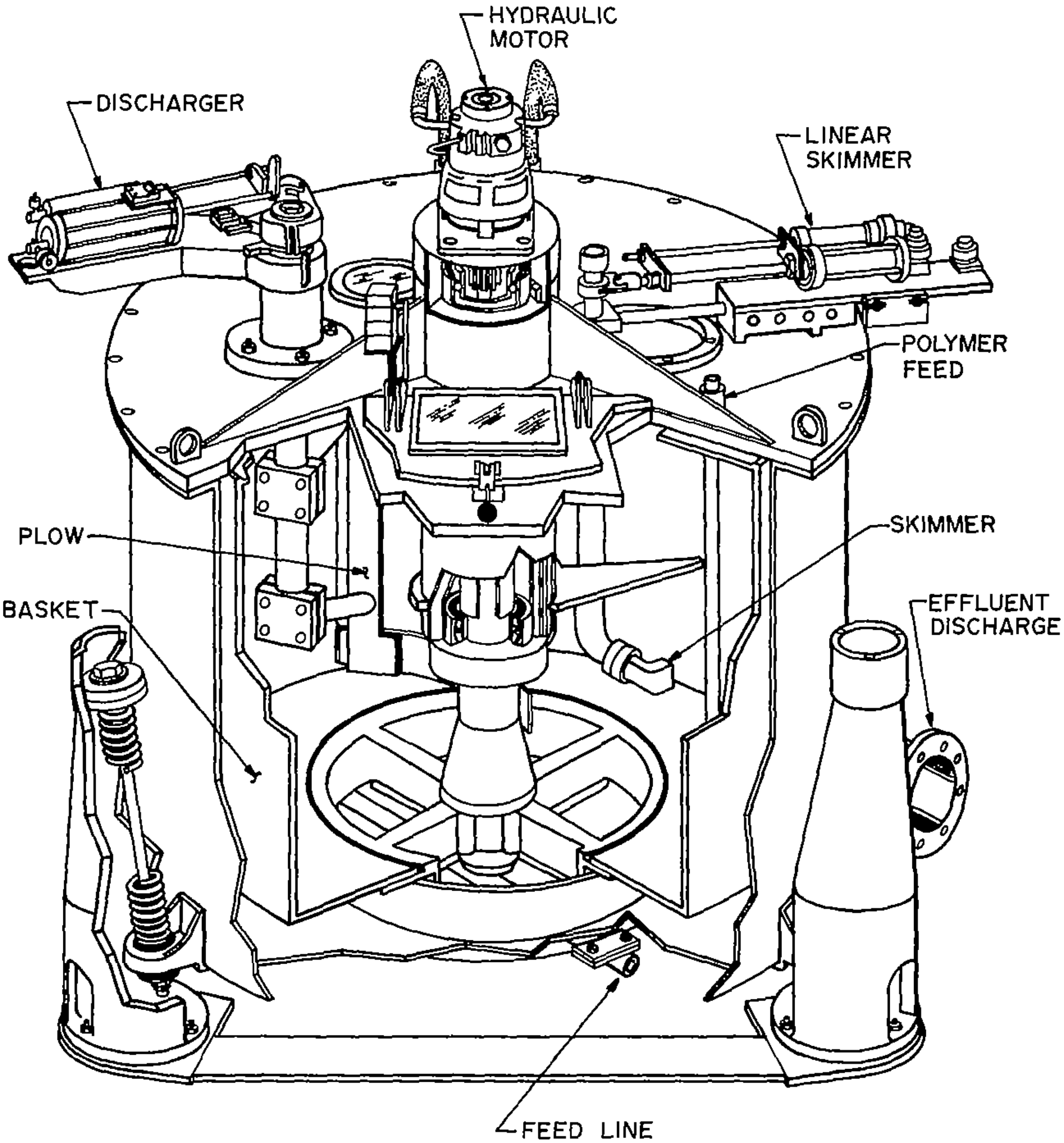


Figure 8. 121.0 cm (48 in.) basket centrifuge - section view

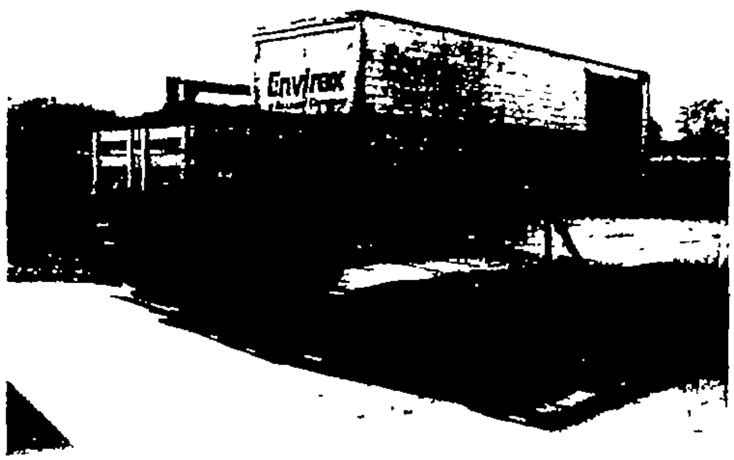


Figure 9. Forward and rear side views of the Envirex centrifuge van.

The 121.9 cm (48 in.) basket centrifuge was then operated for testing using the detailed procedures provided by the manufacturer.

Decanter Centrifuge Tests

Decanter centrifuges are horizontal, cylindrical-conical, solid bowl machines. In a typical unit, Figure 10, sludge is fed through a stationary feed tube along the centerline of the bowl through the hub of the screw conveyor. The screw conveyor is mounted inside the rotating conical bowl. It usually rotates at a lower speed than the bowl. Sludge leaves the end of the feed tube, is accelerated, passes through the ports in the conveyor shaft, and is distributed to the periphery of the bowl. Solids settle through the liquid pool, are compacted by centrifugal force against the walls of the bowl, and are conveyed by the screw conveyor to the drying or beach area of the bowl. The beach area is an inclined section of the bowl where further dewatering occurs before the solids are discharged. Separated liquid is discharged continuously over adjustable weirs at the opposite end of the bowl (3). The decanter centrifuge on the mobile centrifuge van is shown in Figure 11.

The setup of the centrifuge van for use of the decanter centrifuge is the same as previously presented for use of the 121.9 cm (48 in.) basket centrifuge.

Once the setup has been completed, the following steps are taken before the decanter testing begins.

1. Select a desired pool depth by adjusting pool radius disc.
2. Make sure the bowl rotates freely by hand in a clockwise direction.
3. Make sure the decanter's cover is securely closed.
4. Turn "decanter drive" on and slowly crank the varidrive up to the selected speed.
5. Select a direction of rotation for the decanter conveyor motor.
    a) forward: conveyor rotates in the same direction as the bowl: differential speed (Δn) = (bowl speed-conveyor speed)/159.5
    b) off: conveyor does not rotate: Δn = bowl speed/159.5
    c) reverse: conveyor rotates in the direction opposite the bowl: Δn = (bowl speed-conveyor speed)/159.5

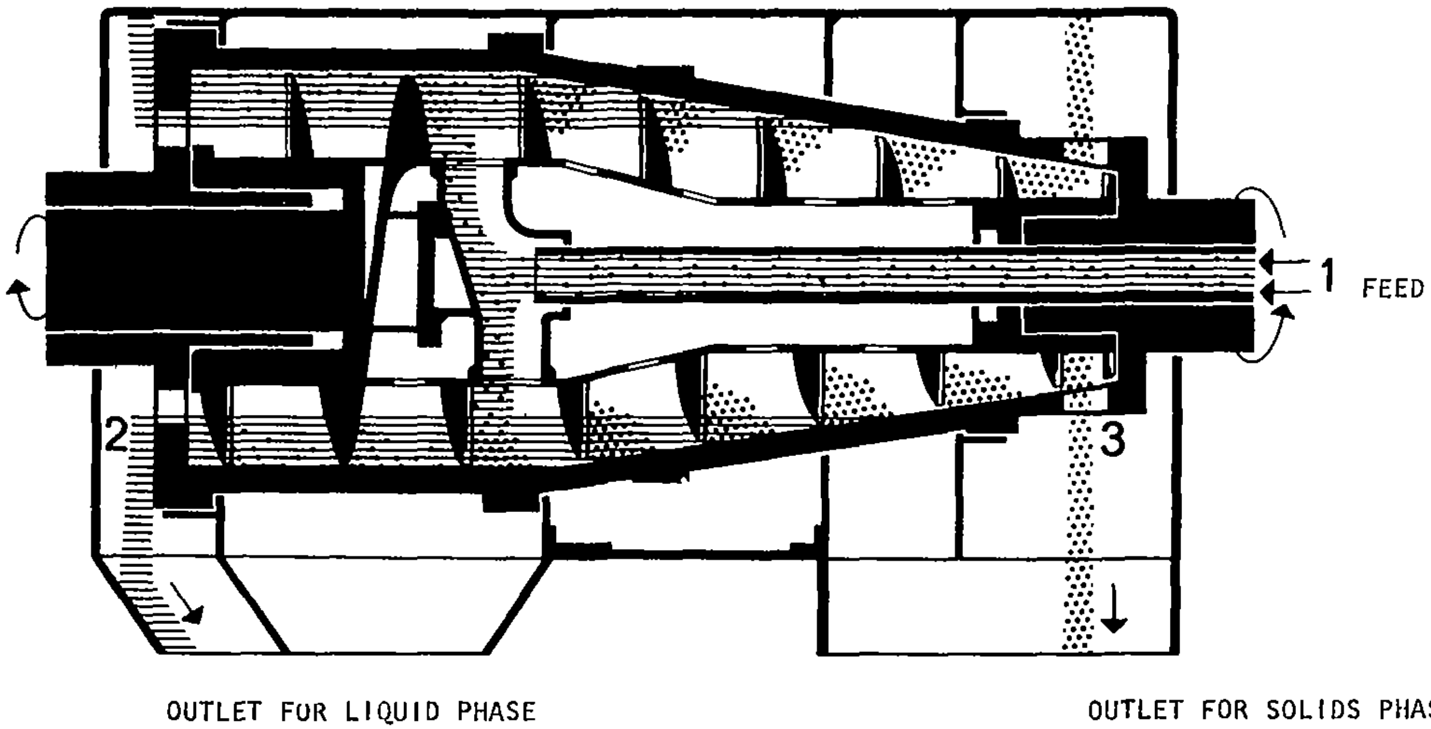


Figure 10. Schematic diagram of a decanter centrifuge.

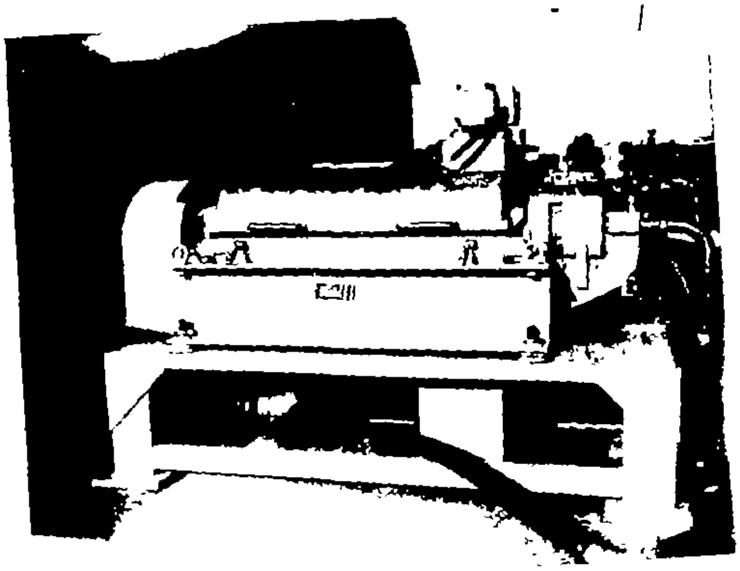


Figure 11. Envirex mobile centrifuge van's decanter centrifuge.

6. Turn "decanter conveyor" on and slowly crank the varidrive up to the desired speed.

7. Make sure that the valves of the feed lines are open so that the sludge goes only to the decanter centrifuge.

8. Turn the sludge pump on. The flow rate should have been set during initial setup and can be checked by monitoring the cake and centrate flows with a 37.9 liter (10 gal.) bucket and a stopwatch.

The operation of the decanter centrifuge is continuous and therefore, sludge pumping, centrate discharge, and cake discharge are continuous. After 30 minutes of testing one set of conditions, the machine variables can be changed to begin testing a new set of conditions. Feed rates can be monitored during operation by using a 37.9 liter (10 gal.) bucket and stopwatch to determine the cake and centrate flow rates.

Each test will produce 9 samples. Samples of the feed, centrate, and cake are normally taken after equilibrium of each run. Feed and cake samples were analyzed for total solids and total volatile solids, and the centrate samples were analyzed for total solids, total volatile solids, suspended solids, and volatile suspended solids.

Evaluation of the data obtained from the decanter centrifuge testing is more complex than for the 121.9 cm (48 in.) basket centrifuge because there are five independent variables that can affect the solids recoveries and the cake concentrations achieved. These are the bowl speed, the differential speed, the pool radius, the feed rate, and polymer addition (if used). To evaluate these independent variables, the test procedures are set so that all of the variables are fixed except for one and that one is varied from one extreme to another and the results plotted. For example, fix all the variables except for the feed rate. Then, make three runs at 37.9, 75.8, and 113.7 liters/min (10, 20, and 30 gpm). From these 3 tests select an optimum feed rate and keep it constant with all the other variables except for the differential speed. Make 3 more runs at 6, 16, and 26 rpm and again plot the results. Continue this process until all of the independent variables have been studied. In this manner, the optimum conditions for decanter operation can be developed for each sludge tested while the number of tests are kept at a minimum. Comparisons among these developed optimums for each sludge tested can also be used to determine the sludges amenability to the decanter centrifuge dewatering process.

A system of parameter plots (4) were also used for the evaluation of the data developed during the decanter centrifuge testing. These plots were used in an attempt to develop optimums that indicate the relationship of each of the independent variables on the dependent variable, either solids recovery or cake concentration.

Finally, the optimum conditions developed for each sludge tested are used for the overall sizing of decanter centrifuges for the dewatering of CSO sludges and dry-weather treatment plant sludges.

In addition to the standard evaluations performed for the centrifuge tests, heavy metals determinations were also performed. This involved heavy metal analyses of the centrifuge feed sludge, the centrate, the skimmings, and the cake for both the dry-weather sludge dewatering tests and the CSO sludge dewatering tests in each city visited. The heavy metals evaluated were zinc, lead, copper, nickel, chromium, and mercury.

The samples used for the heavy metal analyses were obtained by the following procedure.

1. For each condition at one site, CSO sludge or dry-weather sludge, several days were required to complete the necessary centrifuge tests. One of these days was selected as the day the samples would be obtained for the heavy metals analyses.

2. For one day of centrifuge testing, an average of 4-10 individual tests were usually conducted. Samples were taken for heavy metal analyses from the visually determined optimum runs from that day. All of these discrete samples were transported back to the laboratory.

3. At the laboratory, the individual samples were composited by equal volume into feed, centrate, skimmings, and cake samples.

4. The four composite samples were then analyzed for zinc, lead, copper, nickel, chromium, and mercury. The analyses were conducted according to the procedures given in the literature (6)(7).

Evaluation of the heavy metals data consisted of an individual determination of the heavy metals through the centrifuge dewatering process. Two separate determinations, CSO sludge and dry-weather sludge, were performed for each of the three cities visited for the project.

BENCH SCALE ANAEROBIC DIGESTION STUDIES

The objective of this study was to evaluate the short and long term effect of feeding sludge containing storm generated solids to bench scale anaerobic digesters on an intermittent basis under controlled laboratory conditions. The two digesters used in this study were intended to simulate high rate, single stage anaerobic digesters operated in the mesophilic temperature range with intermittent (once daily) feeding and withdrawal. The digesters were operated according to the guidelines presented in the literature (8)(9).

The bench scale digesters (See Figure 12) consisted of 20 liter (5.3 gal.) plastic carboys fitted with teflon paddle agitators and a glass tube for adding and withdrawing sludge. The agitators were operated at 35 rpm using

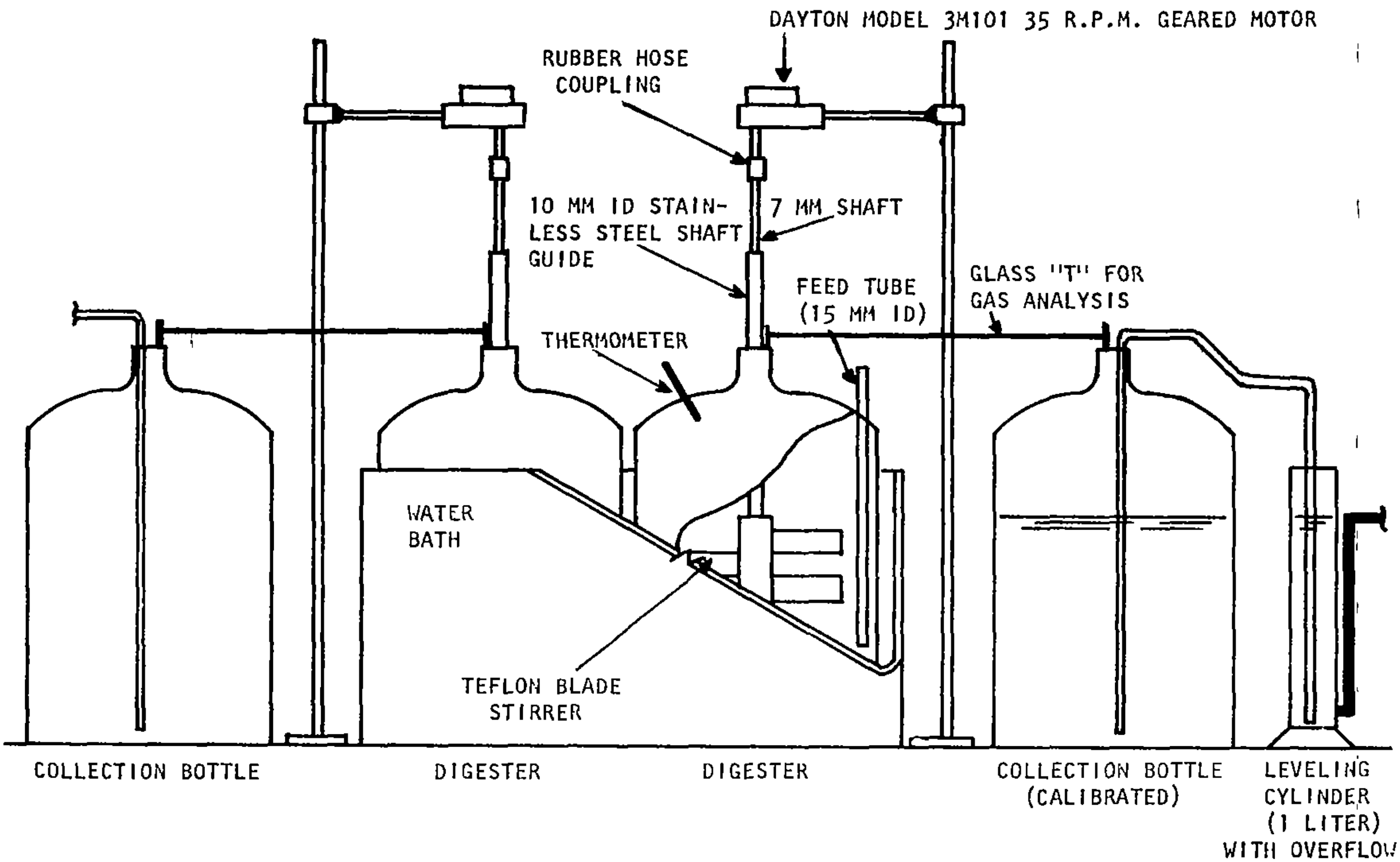


Figure 12. Laboratory scale anaerobic digesters.

constant speed motors (Dayton Model 3M101). Stainless steel tubes were used as guides for the agitator shafts. Each tube extended from 5 cm (2 in.) below the sludge surface to about 7 cm (2.76 in.) above the top of the carboy. The sludge forced into the shaft guide by the pressure in the digester acted as an effective seal. The lower end of the glass tubes used to add and withdraw sludge were located near the path of an agitator paddle in the lower half of each digester. The upper end of the glass tube was positioned so that the pressure in the digester kept the sludge level near the top of the tube. The suction end of a hand-operated bilge pump was attached to the tube to withdraw sludge. Sludge was added by reversing the position of the bilge pump and pumping the sludge into the digester. Sludge could be withdrawn and added without allowing the addition of undesirable amounts of air. The upper end of each glass tube was sealed with a rubber stopper except during the daily sludge transfer operations.

Gas produced by the digesting sludge was collected in 20 liter (5.3 gal.) calibrated collecting bottles over a 5% brine solution acidified with 2 ml H_2SO_4 (conc)/l. The displaced brine solution was passed through a one liter leveling cylinder and collected in a 15 liter (4.0 gal.) plastic container. The outlet tube from the leveling cylinder was positioned so that a slight positive pressure [approximately 6 cm (2.36 in.) water pressure] was maintained in the digesters. Thermometers were used to measure the temperature of the gas in the headspace of each digester and in each collection bottle. Samples of gas for analysis were withdrawn from a rubber hose atop each gas collection bottle using a 5 ml syringe. After taking the daily gas samples and measurements, the excess gas was vented from the top of each collection bottle while replacing the displaced brine solution by siphon. The two digesters were placed in the same 80 liter (21.2 gal.) water bath controlled by a Precision Scientific Porta-Temp heater-agitator.

The digesters were started using digester sludge from the test site sewage treatment plants. The sludge was transported under nitrogen and transferred to the bench-scale digesters with a minimum amount of exposure to air. Thereafter, the digesters were maintained with daily feedings of primary and secondary sludges from the respective plants. Sludge volumes of 18 liters (4.8 gal.) were maintained in each digester by withdrawing an equivalent volume of sludge before each feeding. The digesters were fed with dry-weather sludge at loadings similar to those used at the test sites for a period of at least two weeks. When monitoring showed that the two digesters were operating in a similar manner, one of the digesters was fed wet-weather sludge at a loading similar to that which would be used at the sewage plant after a typical storm. The other digester was fed dry-weather sludge at the same organic loading as the wet-weather digester. After one or two days of wet-weather feed, dry-weather sludge and dry-weather loading rates were again used for both digesters.

The feed sludge and the digesting sludge were routinely analyzed for pH value, total solids, volatile solids and alkalinity. The volatile acid concentration of the digesting sludge was also measured. Daily gas production, gas composition and rate of methane production were routinely monitored. Total and soluble concentrations of mercury, lead, zinc, nickel, chromium, copper and cadmium in the feed and digesting sludges were analyzed. Analyses for pH, total solids, volatile solids, volatile acids, and alkalinity were performed as specified in Standard Methods (2). Metals, with the exception of mercury, were determined by atomic absorption spectrophotometry after digestion with nitric and hydrochloric acid using procedures described in Standard Methods (2). Mercury was digested in a closed system and analyzed by flameless atomic absorption (6). Gas composition was measured by gas chromatography using a thermal conductivity detector. A series column consisting of a 30 cm x 6 mm (11.8 in. x .24 in.) ID copper column packed with 70/80 mesh silica gel and a 305 cm x 6 mm (120 in. x .24 in.) ID copper column packed with 80/100 mesh 5A Molecular Sieve was used (10). Typical chromatograph operating conditions were: 40 cc/min carrier gas (He) flow rate, 25°C column temperature, 40°C detector temperature and 150 ma filament current. Quantitation was performed by comparing sample injections with known standards of nitrogen, oxygen, methane and carbon dioxide.

The experimental design was based on the paired t-statistic (11) utilizing a control and a variable digester operated under identical conditions except that storm generated solids were included in the sludge fed to the variable digester. It was felt that paired t-distribution (control digester parameter versus variable digester parameter) would generate the most useful data for interpreting the long range effects of storm generated solids on a microbiological process of large variance such as anaerobic digestion. The long range effects were evaluated using the 95 percent confidence interval (assuming normal distribution) on the statistics generated during a background period when both digesters were fed dry-weather sludge at dry-weather rates before wet-weather sludge was added to either digester.

SECTION VII

RESULTS OF SLUDGE THICKENING-CENTRIFUGATION STUDIES CONDUCTED IN KENOSHA, WISCONSIN

As discussed in Section V, the Kenosha CSO treatment system is located on the grounds of the city's dry-weather treatment plant and the system shares the sludge handling facilities of the dry-weather plant. The original dry-weather test procedure for the project was to obtain sludges for centrifuge dewatering which consisted of primary and flotation thickened waste activated sludge. Dry-weather conditions were assumed to exist after 5 days without a CSO event. Wet-weather sludge was also obtained from the flotation thickeners. Detention times through the Kenosha treatment plant were calculated to insure that true CSO sludge was being used for the dewatering tests. The length of time that the CSO sludge continued to discharge from the flotation thickeners was dependent on the duration of the CSO event.

The flotation thickening characteristics of the wet-and-dry weather sludges were evaluated by obtaining samples of the two sludges prior to the thickening unit and running separate bench scale flotation thickening tests. After completing all of these tests using the dry-weather sludge and the CSO sludge, an appropriate combination of the two sludges was also tested for its thickening-centrifugation characteristics.

The Kenosha site, however, presented a problem in the area of obtaining a CSO sludge produced by the biological treatment process. When the first preliminary visit was made to the Kenosha Water Pollution Control Plant, it was discovered that the contact stabilization process used for treating CSO was not in operation due to equipment problems. Discussions with the plant superintendent revealed that both of the sludge transfer pumps had been removed because of shaft and bearing breakdowns and that some of the aeration equipment used in the stabilization tanks was inoperative. Further discussions with the superintendent and city water utility manager indicated that because of the high cost of the repairs required and the uncertainty of what role the treatment system would have in a plan for complete CSO abatement as ordered by EPA, the necessary repairs were not expected to be made until late 1976 at the earliest. Obviously, to meet the objectives of the project, it became imperative to develop an alternative plan for studying the thickening-centrifugation process for dewatering a CSO sludge generated by a biological treatment process.

The alternative decided upon was to use the dry-weather treatment plant's conventional activated sludge process to produce a sludge as similar as possible to the sludge produced by the contact stabilization process.

During a CSO event, the CSO treatment facility receives the flows in excess of the dry-weather plant's capacity. Therefore, both treatment systems receive the same raw flow. The contact stabilization process is a modification of the activated sludge process and it was, therefore, assumed that the two processes will produce a very similar biological sludge if they receive essentially the same influent. The major difference between the two treatment systems is that the raw flow to the dry-weather plant undergoes primary treatment before going to the activated sludge process while the flow to the contact stabilization process does not receive primary treatment. Therefore, in order to assume that the dry-weather plant's conventional activated sludge process will produce a sludge similar to the contact stabilization process during a CSO event, the effects of the dry-weather plant's primary treatment would have to be minimized.

An investigation of the Kenosha treatment plant's records indicated that primary treatment achieves an average suspended solids (SS) removal of 42 percent. The raw sewage averages 127 mg/l SS and the primary effluent 74 mg/l SS. If the conventional activated sludge process is to be considered as the biological CSO treatment process, this primary effluent would have to be considered as the raw CSO. A SS concentration of only 74 mg/l would not be typical of a raw CSO. Therefore, the SS concentration of the flow going to the activated sludge process would have to be increased, if possible.

A major CSO event occurred in Kenosha on August 28-29, 1975. During this event, all six of the primary sedimentation tanks were in operation. Samples of the primary effluent were taken every hour for six hours beginning at 10:00 AM on August 29. This, however, was about 10.5 hours after the CSO event began. The results were as follows:

Sample	Primary effluent SS concentration (mg/l)
10:00 AM	58
11:00	62
12:00	80
1:00 PM	66
2:00	72
3:00	70

It can be seen that all of the results are similar to the average primary effluent SS concentration and no perceptible increase occurred due to the CSO event. However, because any "first flush" effects may have been missed during the first 10.5 hours, it was decided to conduct further sampling of the primary effluent during CSO events. It was also decided that during the next major CSO event which was sampled, one of the six primary sedimentation tanks would be taken out of service in order to increase the primary effluent SS concentration.

The next sampling program was carried out during the CSO event that occurred in Kenosha on October 24, 1975. A primary effluent sample was obtained at 5:30 PM, 1.5 hours after the event began; and at 7:30 PM. During the sampling, one primary sedimentation tank was out of service. The results were:

Sample	Primary Effluent SS concentration (mg/l)
5:30 PM	151
7:30 PM	154

The dual effects of the high plant flow during the CSO event and the removal of one sedimentation tank from service, apparently resulted in a primary effluent concentration that was 106 percent greater than the average. These excess solids, then, would be carried to the activated sludge process and their presence in the secondary sludge would make it similar to the sludge produced by the contact stabilization method of CSO treatment.

The next step was to remove two of the six primary sedimentation tanks from service during a major CSO event in order to further increase the primary effluent SS concentration. However, when this was discussed with the plant superintendent, he stated that he did not want this done. He said that having one primary sedimentation tank out of service had resulted in a significant increase in the SS concentration of the plant's final effluent. This seems to indicate a solids overload on the secondary treatment plant and that excess solids should also be present in the secondary sludge. For this reason, CSO sludge for Kenosha was obtained from the activated sludge process after a major CSO event occurred while one primary sedimentation tank was out of operation.

Table 6 gives the ranges of SS concentration found for raw CSO for various U.S. cities (5). The average of 152 mg/l found during sampling of the primary effluent on October 24, 1975 falls below the average SS concentration for raw CSO but does fall within many of the ranges reported. Therefore, the primary effluent could be considered as a raw CSO with a slightly below average pollutional concentration.

On November 3, 1975, another CSO event occurred in Kenosha and a primary effluent sample was again taken with one of the primary sedimentation tanks out of service. The sample was taken 7.5 hours after the overflow began and the SS concentration was 114 mg/l, 54 percent greater than the average. This result provided another indication that the conditions being used did result in an increased carryover of solids to the activated sludge process.

It was finally decided that one primary sedimentation tank would be taken out of service during a major CSO event, one that produced maximum flow through the primary treatment plant, so that the sludge produced by the activated sludge process could be used as the CSO sludge from Kenosha.

The mobile centrifuge sludge dewatering van arrived in Kenosha on November 10, 1975 and a major CSO event occurred on November 9-10. It was assumed

TABLE 6. COMPARISON OF QUALITY OF COMBINED SEWAGE FOR VARIOUS CITIES[a]

Type of wastewater location, year, ref. no. 5	SS, mg/l	
	avg.	range
Typical Treated Municipal		
Primary effluent	80	40-120
Secondary effluent	15	10-30
Selected Combined		
Berkeley, CA, 1968-69[b]	100	40-150
Brooklyn, NY, 1972	1,051	132-8,759
Bucyrus, OH, 1968-69	470	20-2,440
Cincinnati, OH, 1970	1,100	500-1,800
Des Moines, IA, 1968-69	295	155-1,166
Detroit, MI, 1965	274	120-804
Kenosha, WI, 1970	458	--
Milwaukee, WI, 1969	244	113-848
Northampton, U.K., 1960-62	400	200-800
Racine, WI, 1971	439	--
Roanoke, VA, 1969	78	--
Sacramento, CA, 1968-69	125	56-502
San Francisco, CA, 1969-70	68	4-426
Washington, D.C., 1969	622	55-2,000

[a] Data presented here are for general comparisons only. Since different sampling methods, number of samples, and other procedures were used, the reader should consult the references before using the data for specific planning purposes.

[b] Infiltrated sanitary sewer overflow.

that CSO sludge conditions existed (one primary sedimentation tank was out of service and the primary treatment plant was receiving maximum flow).

Ten hours after the start of the CSO event, an 18.9 liter (5 gal.) sample of the waste activated sludge (WAS) was obtained. This sample was used for the bench scale flotation thickening tests. The 10 hour waiting period was based on the time from the arrival of CSO at the plant to the time the CSO sludge would be withdrawn from the final clarifiers. Thirteen hours after the start of the CSO event 11,355 liters (3,000 gal.) of thickened sludge was pumped into a tank truck. The sludge was used for the centrifuge CSO sludge dewatering tests using the 121.9 cm (48 in.) basket centrifuge on the centrifuge van. The results of these tests will be described later.

While the CSO sludge was being obtained, the treatment plant operator mentioned that the volume of grit being generated that day was significantly greater than usual. This was another indication that the CSO event did increase the solids loading on the plant and that many of these solids would be present in the WAS being used as CSO sludge.

FLOTATION THICKENING TESTS

The sludges used for the flotation thickening tests were obtained from the holding tank from which the WAS was fed to the full-scale flotation thickening facility. No chemical addition was studied because the Kenosha Water Pollution Control Plant does not use chemical addition in its flotation thickening process. From preliminary tests using dry-weather WAS, an optimum recycle rate (ratio of pressurized flow to WAS flow) of 242 percent was selected. This recycle rate was held constant for all the tests so that the results of the tests could be directly compared among the following three sludges tested: dry-weather plant WAS, CSO sludge, and a combination of dry-weather WAS and CSO sludge.

The following calculations were used in determining the appropriate combination of dry-weather and CSO sludges to be used.

1. Kenosha CSO area 539 hectares (1331 acres).
2. Assume 50 percent of rainfall results in CSO.
3. Assume 1.27 cm (0.5 in.) rainfall = 34,197,323 liters (9,034,960 gal.) of CSO.
4. Contact stabilization treatment will produce a sludge volume equal to 3.5 percent of volume treated (1).
5. CSO sludge produced = 1,196,908 liters (316,224 gal.)
6. Assuming a two day bleedback: flow of CSO sludge to thickener = 598 m^3/day (158,112 gpd).
7. Average flow of dry-weather plant's WAS = 594 m^3/day (157,000 gpd).
8. Ratio of CSO sludge/dry-weather WAS $\approx$ 1.

Therefore, for the CSO sludge/dry-weather WAS combination flotation thickening tests, equal volumes of the two sludges were used.

The results of the flotation thickening tests performed are summarized in Figures 13, 14, 15, and 16 for the flotation thickening of the dry-weather WAS (2 tests), the CSO sludge, and the combination, respectively. It should be noted that the full-scale thickeners at Kenosha produce a thickened floated sludge of about 4% solids at a mass loading of approximately 49 kg/m^2/day (10 lb/ft^2/day).

For the dry-weather sludge (Figures 13 and 14), a sludge concentration of 4 percent can be obtained at a mass loading of 48.9-73.4 kg/m^2/day (10-15 lbs/ft^2/day). For the CSO sludge (Figure 15), a sludge concentration of 4 percent can be obtained at a mass loading of about 53.8 kg/m^2/day (11 lbs/ft^2/day), and for the combination of dry-weather and CSO sludge (Figure 16), a 4 percent sludge concentration can be obtained at a mass loading of about 44.0 kg/m^2/day (9 lbs/ft^2/day).

The results indicate that the flotability of the three sludges is fairly similar with the CSO sludge and the CSO sludge/dry-weather sludge combination possibly being slightly more difficult to float than the dry-weather WAS alone. One possible reason for the slight decrease in allowable mass loadings to achieve a 4 percent thickened sludge concentration could be the presence of more non-volatile solids, which are more difficult to float, in the CSO sludge.

CENTRIFUGE DEWATERING TESTS

30.5 cm (12 in.) Basket Centrifuge - Dry-Weather Sludges

Preliminary centrifuge sludge dewatering tests were conducted at the Kenosha Water Pollution Control Plant from August 7 through August 13, 1975. Tests were conducted using dry-weather thickened WAS; and a combination of dry-weather thickened WAS and dry-weather primary sludge. The combination of the two sludges was based on the average daily flows of each sludge to the anaerobic digesters. These values were obtained from the plant operating records. The two sludges were both tested at this point in order to develop data on their dewatering characteristics which could be compared between the two and compared to the dewatering characteristics of the Kenosha CSO sludge which were expected to be similar. Both sludges were tested with and without polymer addition. The polymer used was Percol 728, a high molecular weight cationic polymer, which was selected on the basis of experience and on preliminary screening tests.

The samples of thickened WAS and primary sludge were obtained from the sampling points used by the treatment plant personnel to obtain their required samples. A volume of sludge was obtained each day sufficient to conduct all of the tests scheduled for that day. The sludge was then poured into a 113.5 liter (30 gal.) container and the feed pump intake was placed in it. When primary sludge was used, it was screened with a 0.64 cm (0.25 in.) mesh screen as it was poured into the container. This was necessary to prevent plugging of the sludge feed pump during operation. During the testing, the contents of the container were periodically mixed to insure that solids

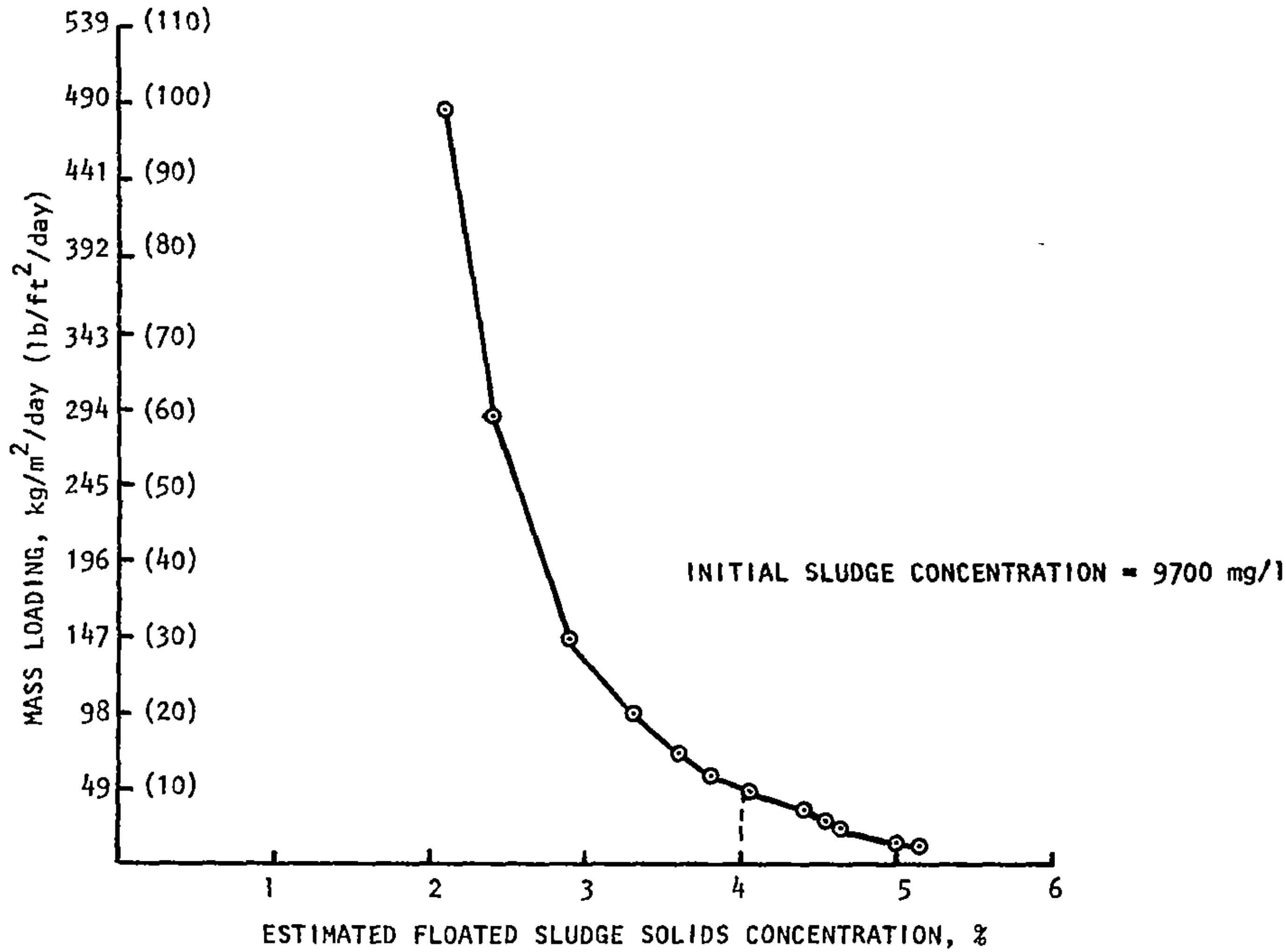


Figure 13. Flotation thickening tests run I - Kenosha dry-weather WAS.

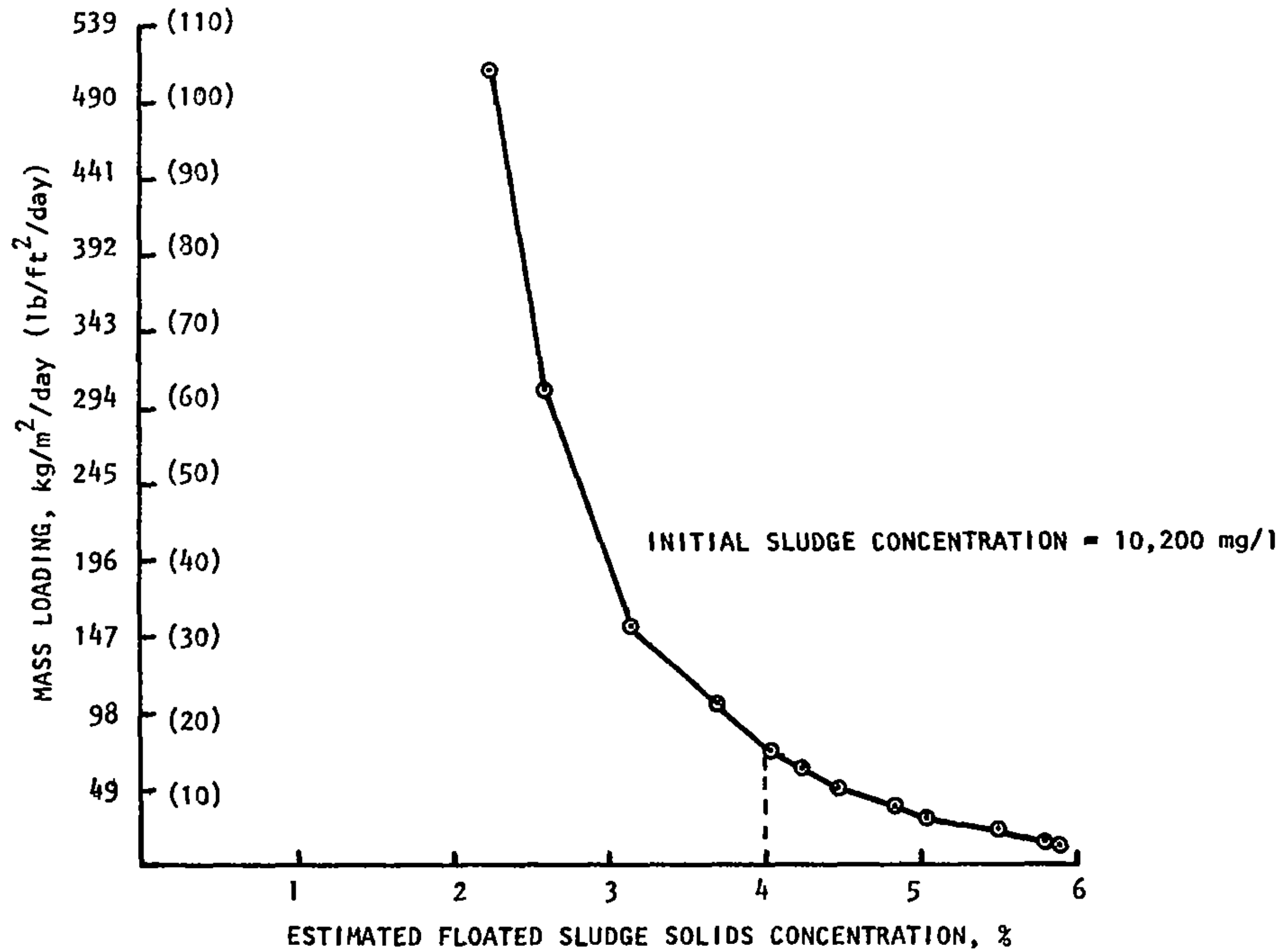


Figure 14. Flotation thickening tests run 2 - Kenosha dry-weather WAS.

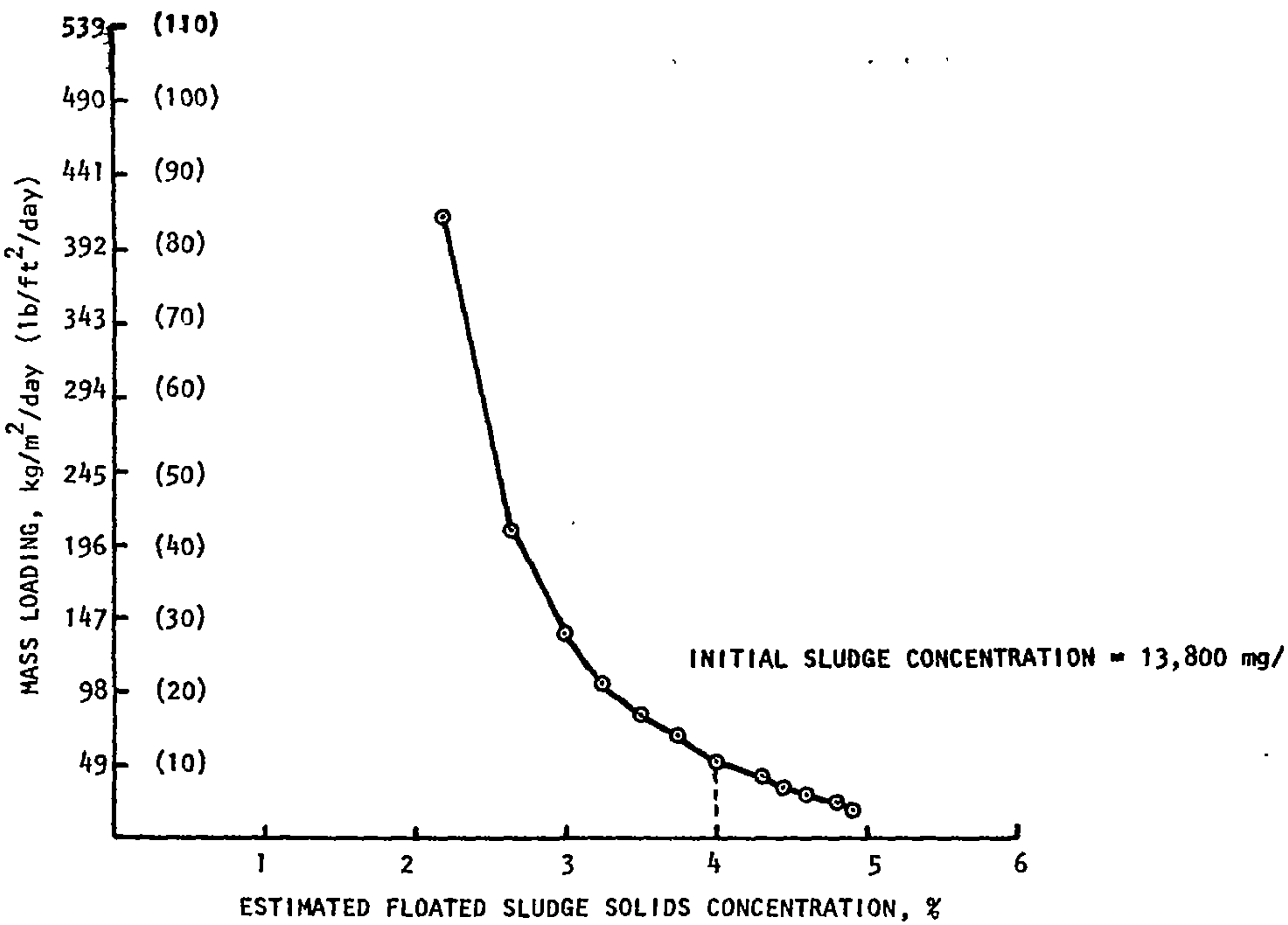


Figure 15. Flotation thickening tests run 3 - Kenosha wet-weather WAS.

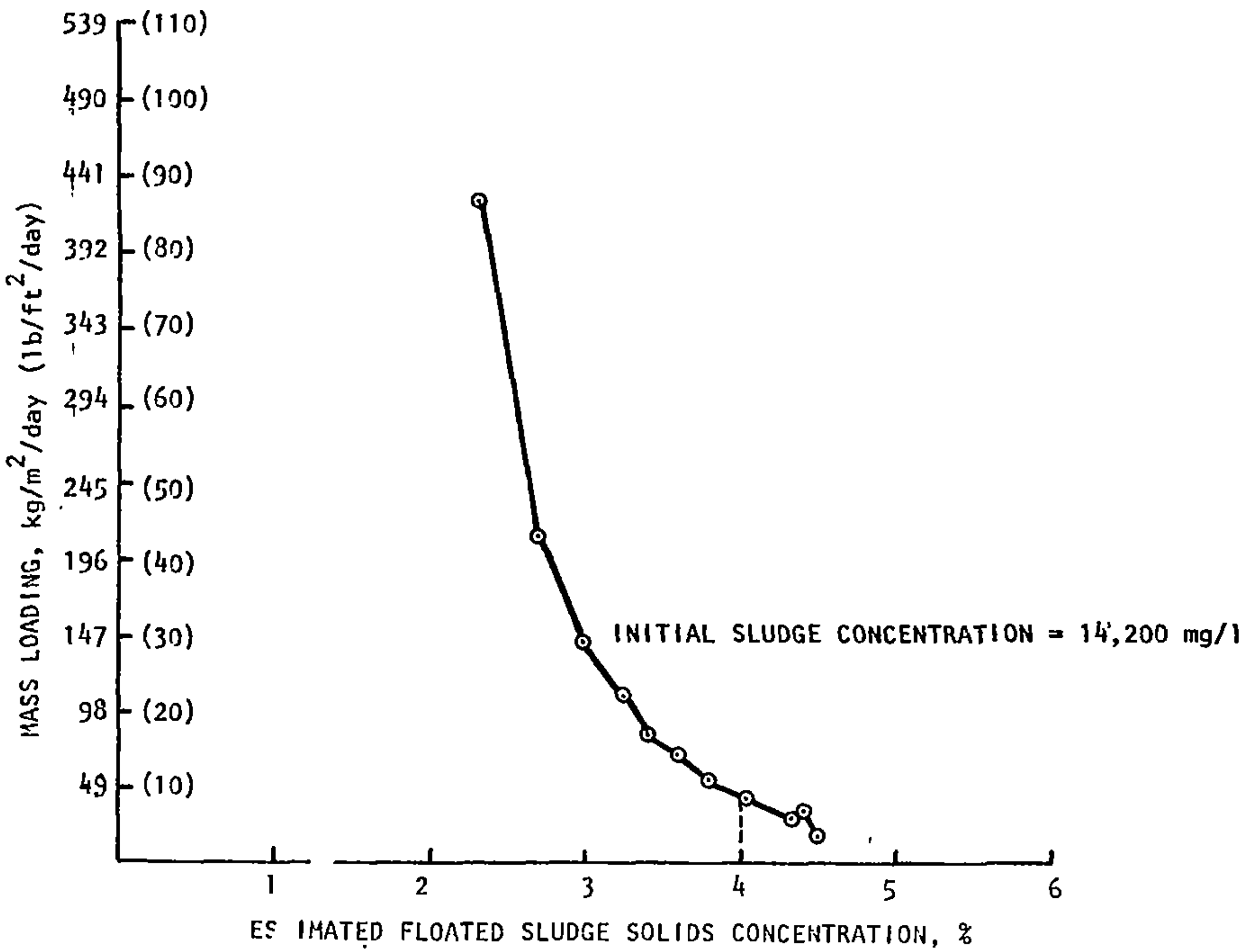


Figure 16. Flotation thickening tests run 4 - Kenosha wet- and dry weather WAS combination.

separation did not occur.

Thirteen tests were conducted and the tabulated results are presented in Tables A1 to A13 in Appendix A. Tables A1 to A3 present the results for the tests using dry-weather thickened WAS; Tables A4 to A6 for tests using the combination of dry-weather primary sludge and thickened WAS; Tables A7 to A10 for tests using dry-weather thickened WAS with polymer addition; and Tables A11 to A13 for tests using the sludge combination with polymer addition.

Figure 17 presents the cake concentrations (% solids) achieved for the two dry-weather sludges at varying rates without polymer addition. It can be seen that the mixture of primary sludge and thickened WAS consistently dewatered to a greater cake concentration than did thickened WAS alone. Figure 18 shows the corresponding percentage SS recoveries achieved for the two types of sludges tested. In this case, the percentage SS recovery is higher for the thickened WAS alone, without the primary sludge included.

From Figures 17 and 18 and other data in Appendix Tables A1 through A6, the following operating parameters and corresponding performance appear to be optimum in centrifuge dewatering the Kenosha dry-weather sludges without chemicals.

Sludge tested	Feed rate (kg/hr)	Cake solids concentration %	Solids recovery %
Thickened WAS	2.6	11.5	96
Primary sludge plus thickened WAS	4.0	14.0	94

Chemicals, as an adjunct to centrifuge dewatering, were also investigated for the Kenosha dry-weather sludges using the organic polymer, Percol 728. The effect of polymer on centrifuge performance was investigated at the developed optimum feed rates (see above) obtained when no chemicals were used. Figure 19 presents the resultant cake concentrations and percentage SS recoveries when polymer addition was employed to the centrifuge dewatering of thickened WAS alone at a constant feed rate of 3.0 kg dry solids/hr (6.6 lb/hr), and Figure 20 presents the results for the sludge combination when polymer was added where the feed rate was constant at 4.6 kg/hr (10.0 lb/hr). Again, the sludge combination of primary and thickened WAS achieved higher cake concentrations and lower solids recoveries than for the thickened WAS alone. For example, from the polymer (Percol 728) testing, it was found that for a constant feed rate of 3.0 kg/hr (6.6 lb/hr) of thickened WAS, the addition of 2.3 g of polymer/kg of dry solids (2.3 lb/1000 lb/solids) increased the solids recovery rate from 96.5 to 99.3 percent whereas the cake concentration decreased from 11.4 to 10.2 percent. This decrease in the cake concentration is attributed to the fact that as polymer is added, higher

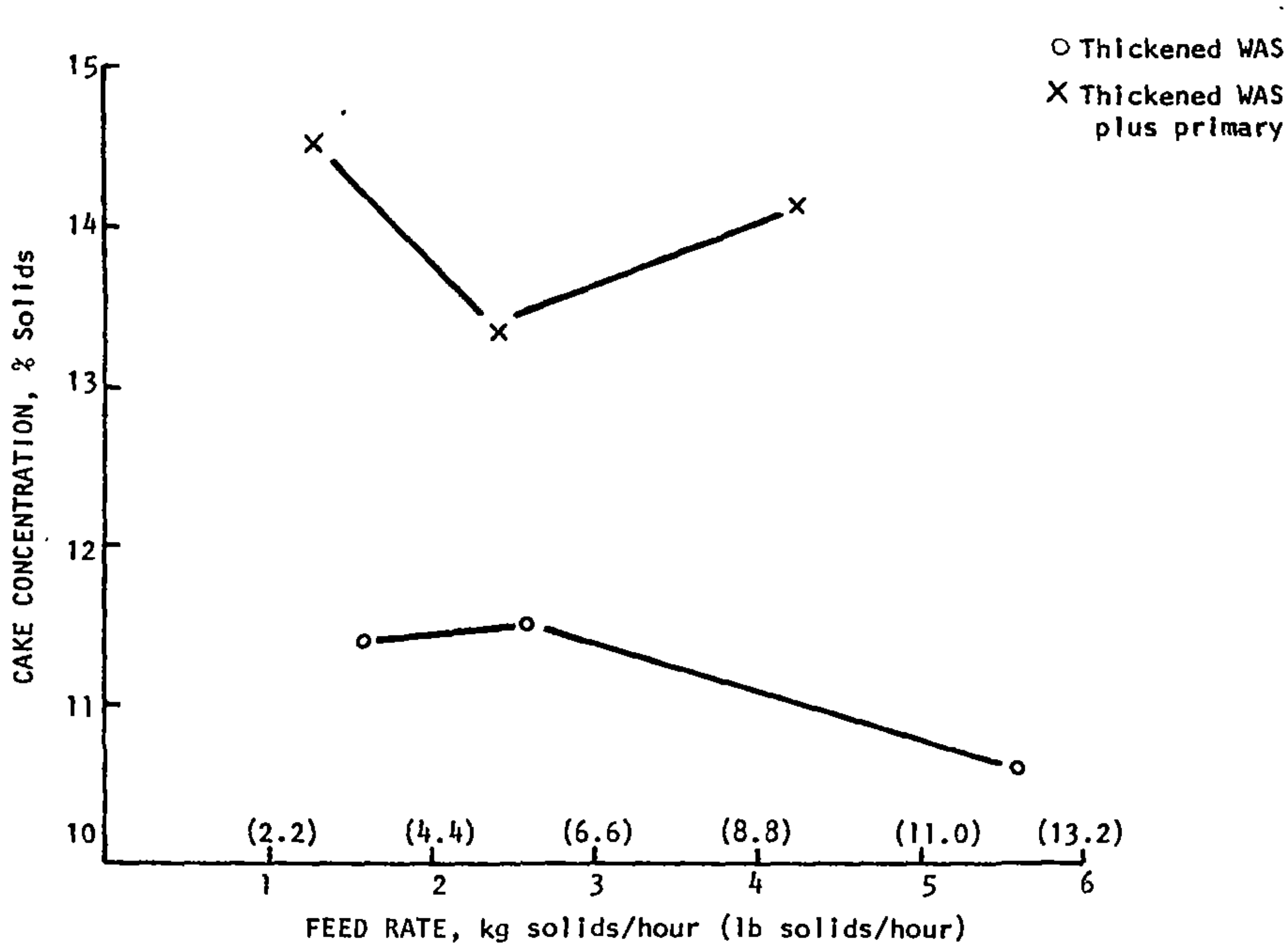


Figure 17. 30.5 cm (12 in.) Basket centrifuge tests on Kenosha dry-weather sludges (without chemicals).

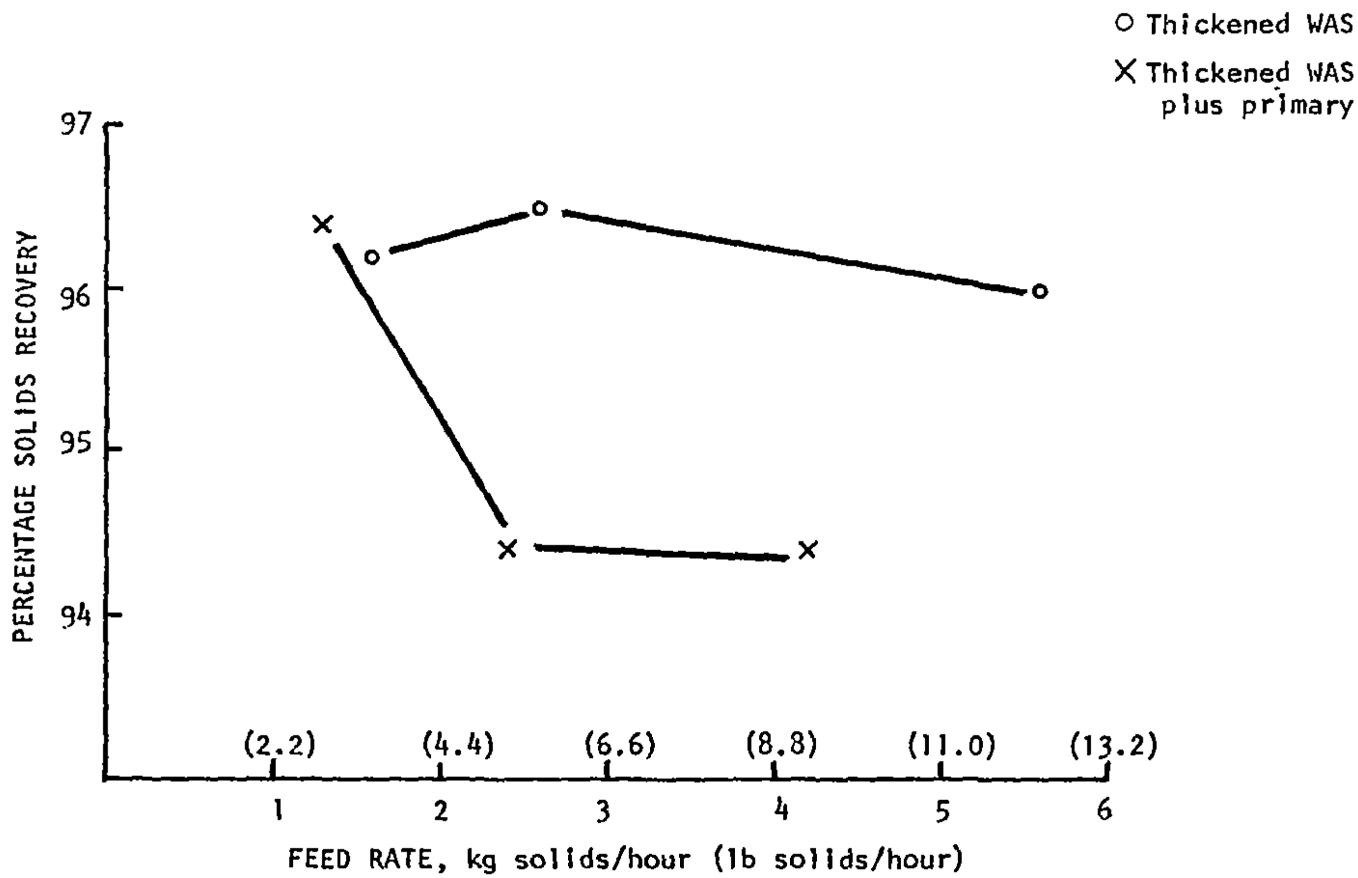


Figure 18. 30.5 cm (12 in.) Basket centrifuge tests on Kenosha dry-weather sludges (without chemicals).

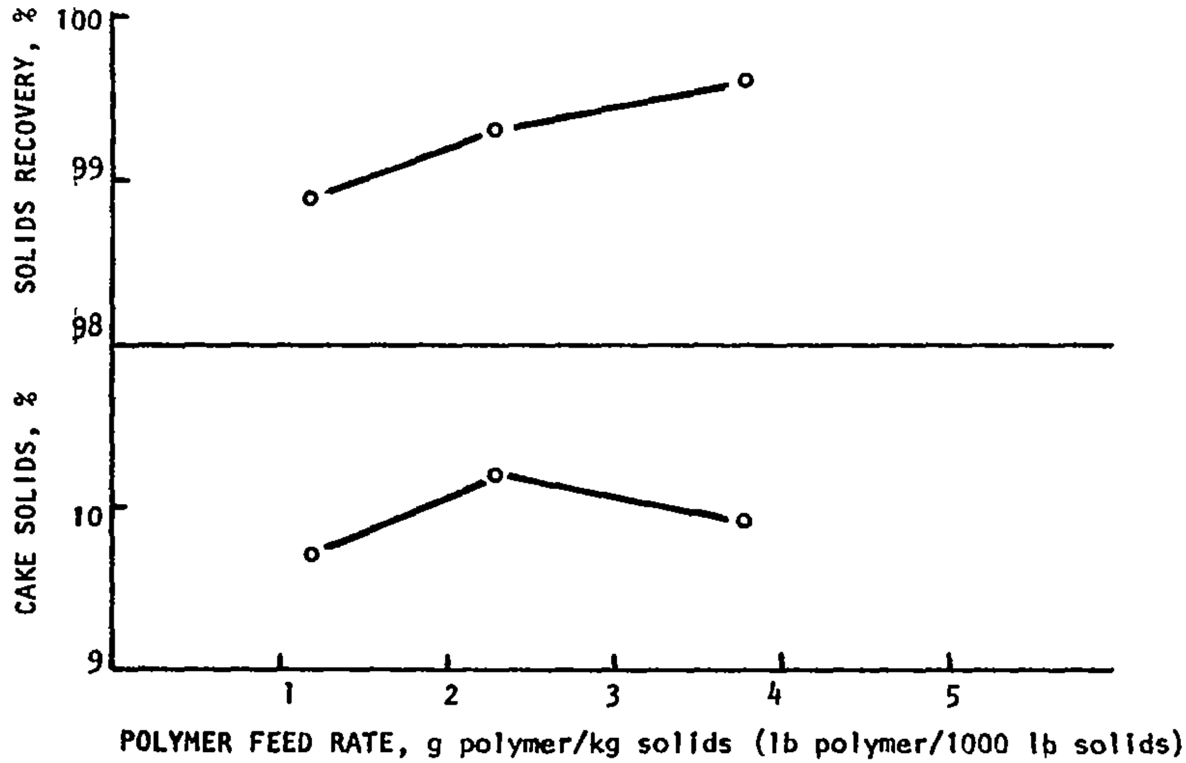


Figure 19. 30.5 cm (12 in.) Basket centrifuge tests on Kenosha dry-weather thickened WAS alone (with polymer and feed rate = 3.0 kg/hr).

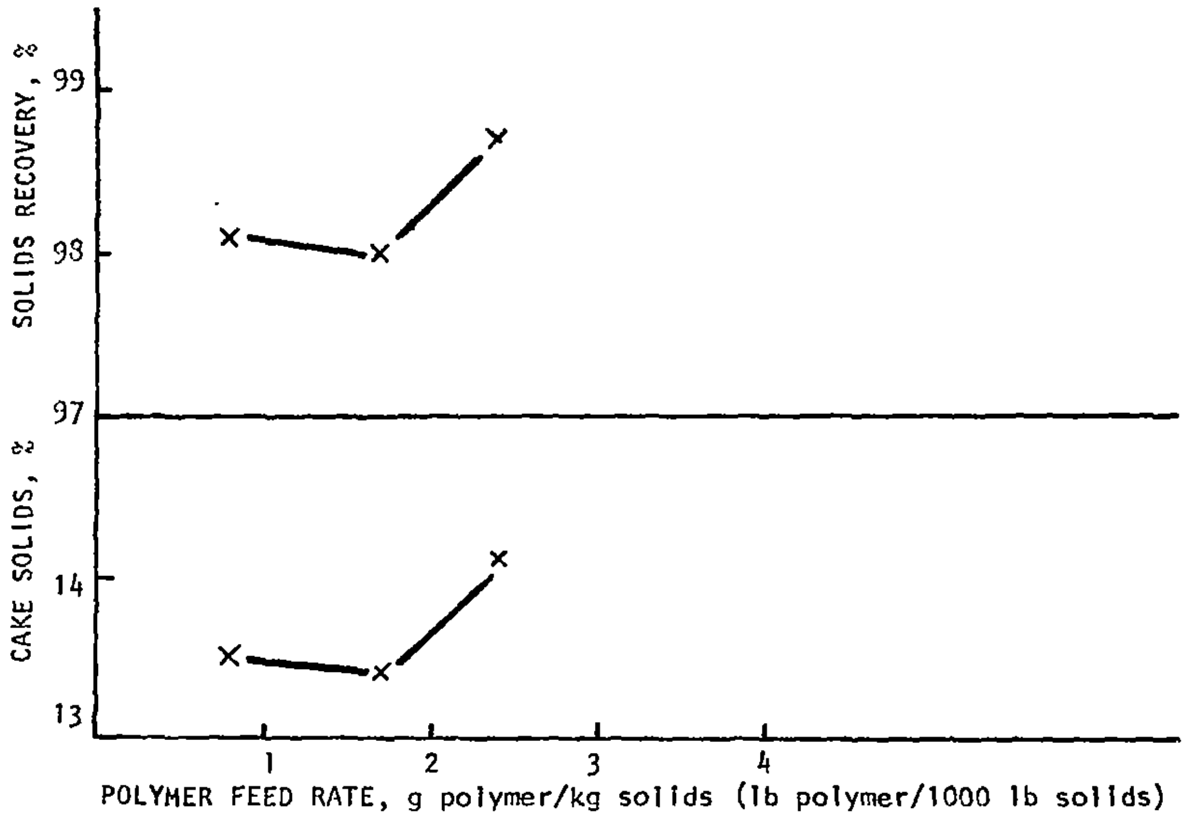


Figure 20. 30.5 cm (12 in.) Basket centrifuge tests on Kenosha combined dry-weather sludges (with polymer and feed rate = 4.6 kg/hr).

recoveries are achieved but the cake concentration can decrease because more and more smaller and lighter particulates are retained in the cake. For a constant feed rate of 4.6 kg/hr (10.1 lb/hr) of the combination of primary sludge and thickened WAS, a polymer addition rate of 0.8 g/kg (0.8 lb/1000 lb solids) increased the SS recovery from about 94.4 to 98.1 percent, but again the resultant cake concentration decreased from 13.8 percent to 13.5 percent solids. The polymer rates selected as optimum are based on the considerations of acceptable results at a minimum use of the polymer.

From these preliminary tests, the following conclusions were drawn and later applied as a guide to the centrifuge dewatering tests using the full-scale 121.9 cm (48 in.) basket centrifuge.

1. Because of the minimal benefits achieved by the polymer during testing and the additional costs and handling problems associated with a polymer addition system, polymer addition was eliminated as a parameter to be considered during full-scale testing.

2. As expected, significantly higher loadings may be used when centrifuging combined sludges than when centrifuging WAS alone.

<u>121.9 cm (48 in.) Basket Centrifuge (CSO and Combined Dry-Weather Sludge)</u>

The full-scale sludge dewatering tests for CSO sludge and dry-weather sludges using the 121.9 cm (48 in.) basket centrifuge on the mobile centrifuge van were conducted at the Kenosha Water Pollution Control Plant from November 11 through November 19, 1975. A major CSO event occurred in Kenosha on November 9-10 and the mobile centrifuge van arrived at the treatment plant on the morning of November 10. Therefore, CSO sludge was immediately available for testing.

For purposes of this discussion, CSO sludge refers to thickened WAS sludge derived from the treatment of CSO. Moreover, dry-weather sludge hereinafter refers to the combined sludges comprised of thickened WAS and primary sludge produced from the treatment of dry-weather sewage.

The CSO sludge was obtained as it came off the full-scale flotation thickening units. The thickened sludge was pumped into a 11,355 liter (3,000 gal.) tank truck and this sludge supply was then used for six 121.9 cm (48 in.) basket centrifuge tests over the next two days. The data obtained from these six thickened WAS CSO sludge tests are given in Tables A14 to A19 in Appendix A. They are summarized in Table 7.

After completion of the CSO sludge tests, 121.9 cm (48 in.) basket centrifuge tests were conducted using the dry-weather sludges from the Kenosha treatment plant. Dry-weather sludge was obtained by pumping 5,678 liters (1500 gal.) of dry-weather thickened WAS into a tank truck and adding to that 5,678 liters (1500 gal.) of primary sludge. Six tests were again performed and the results are presented in Tables A20 to A25 in Appendix A. The results of these dry-weather tests are summarized in Table 8.

TABLE 7. RESULTS OF 121.9 CM (48 IN) BASKET CENTRIFUGE TESTS USING WET-WEATHER, THICKENED WAS SLUDGE FROM KENOSHA, WISCONSIN

Run no.	Feed rate ℓ/min	(gpm)	kg/min	(lb/min)	Cake concentration, % by balance[1]	samples[2]	maximum[3]	Percent recovery	Cycle time, min
1	95	(25.1)	3.14	(6.92)	12.1	15.5	47.4	82.1	12
2	54	(14.3)	0.82	(1.80)	6.5	17.5	31.0	93.1	32
3	111	(29.4)	4.00	(8.80)	11.1	13.0	27.1	74.2	10
4	60	(15.8)	1.94	(4.27)	7.4	17.4	37.9	92.5	15
5	69	(18.1)	2.35	(5.18)	14.1	15.0	32.3	95.2	14
6	40	(10.6)	1.05	(2.32)	3.9	9.0	33.7	96.5	16 1/2

1. Mass balances computed using the following formula: $C = \frac{FR \times FC \times FCT - CE - S}{K}$

   Where: C = cake concentration (% T.S.)
   FR = sludge feed rate lpm (gpm)
   FC = sludge feed concentration (% T.S.)
   FCT = sludge feed cycle time (min.)
   CE = liters (gallons) of centrate generated x % T.S. of centrate
   S = liters (gallons) of skimmings generated x % T.S. of skimmings
   K = liters (gallons) of cake generated

2. The values reported in this column represent the average analytical values obtained from the actual cake samples that were taken.

3. The values reported in this column represent the maximum value obtained for the cake sample for each respective run.

TABLE 8. RESULTS OF 121.9 CM (48 INCH) BASKET CENTRIFUGE TESTS USING DRY-WEATHER, THICKENED WAS AND PRIMARY SLUDGES FROM KENOSHA, WISCONSIN

Run no.	Feed rate ℓ/min	(gpm)	kg/min	(lb/min)	Cake concentration, % by balance[1]	samples[2]	maximum[3]	Percent recovery	Cycle time, min
7	88	(23.2)	3.59	(7.90)	17.8	15.2	18.0	93.6	10
8	54	(14.2)	2.18	(4.18)	12.3	13.5	23.0	94.7	14
9	39	(10.2)	1.56	(3.43)	6.0	21.5	23.8	95.8	14
10	35	(9.3)	0.54	(1.19)	9.0	12.2	27.9	90.3	73
11	38	(10.1)	1.25	(2.75)	8.7	9.0	23.5	96.1	26
12	58	(15.4)	3.31	(7.28)	8.6	7.5	37.5	88.2	11

1. Mass balances computed using the following formula: $C = \frac{FR \times FC \times FCT - CE - S}{K}$

   Where:
   - C = cake concentration (% T.S.)
   - FR = sludge feed rate lpm (gpm)
   - FC = sludge feed concentration (% T.S.)
   - FCT = sludge feed cycle time (min.)
   - CE = liters (gallons) of centrate generated x % T.S. of centrate
   - S = liters (gallons) of skimmings generated x % T.S. of skimmings
   - K = liters (gallons) of cake generated

2. The values reported in this column represent the average analytical values obtained from the actual cake samples that were taken.

3. The values reported in this column represent the maximum value obtained for the cake sample for each respective run.

From Tables 7 and 8, it can be seen that three different values are given for the centrifuge cake concentrations. The first value by balance, was determined by a mass balance using the feed, centrate, and skimmings data and, then calculating the average centrifuge cake concentration. The second value by sampling, is the average value obtained from the actual cake samples that were taken. The third value, maximum, is the maximum value found for the cake samples taken. It represents the concentration of the last portion of cake to be removed from the basket centrifuge.

The cake concentrations determined by the mass balance were the ones used for the evaluation of the data because of the difficulty encountered in obtaining representative samples. Examination of Tables 7 and 8 indicates that the mass balance usually predicts a lower cake concentration than is obtained by sampling. The discharge of the cake from the 121.9 cm (48 in.) centrifuge progresses from the very wet cake to the very dry as the automatic plow scrapes the cake away from the wall of the centrifuge. While the dryer portions of the cake are easier to sample, the very wet cake that discharges initially flows freely and it is difficult to sample. Failure to obtain a representative sample of this very dilute cake would result in the average of the cake samples indicating a dryer cake than would actually be produced. Therefore, the cake concentration predicted by the mass balance was used as the most indicative of the 132 liters (35 gal.) to 348 liters (92 gal.) of cake remaining in the basket after skimming has been completed.

Figure 21 presents the cake concentrations achieved for varying feed rates of both CSO sludge and the dry-weather sludges. It appears that a drier cake is obtained when centrifuging the dry-weather sludges than when centrifuging CSO sludge. The CSO sludge achieves a maximum cake concentration of 14 percent at a solids feed rate of 2.35 kg/min (5.2 lb/min.). As the feed rate increases above 2.35 kg/min (5.2 lb/min.), the resultant cake concentration decreases. On the other hand, the cake concentration for the dry-weather sludges continued to increase over the range of solids feed rates investigated. The driest cake, 17.5 percent solids, was achieved at the highest feed rate tested, 3.6 kg/min (8.0 lb/min). The plot in Figure 21 indicates that the cake concentration may increase further as the feed rate is increased up to some maximum point as was found for the CSO sludge.

Figure 22 shows the percentage SS recoveries achieved at varying feed rates for the CSO sludge and the dry-weather sludges. The recoveries were similar for the two types of sludges up to a feed rate of 2.35 kg/min (5.2 lb/min). Above 2.35 kg/min (5.2 lb/min), the solids recovery for the CSO sludge decreased rapidly, dropping from 95.5 percent at 2.35 kg/min (5.2 lb/min) to 74 percent at 4.0 kg/min (8.8 lb/min). The recovery rate for the dry-weather sludges also decreased, but only slightly; from 95 percent at 2.35 kg/min (5.2 lb/min) to 93.5 percent at 3.6 kg/min (8.0 lb/min).

The reason for the centrifuge dewatering differences observed between the two sludges could be that the dry-weather sludge, while containing thickened WAS, contains a relatively large amount of raw primary sludge solids. The CSO sludge, on the other hand, is mainly a biological sludge. The raw pri-

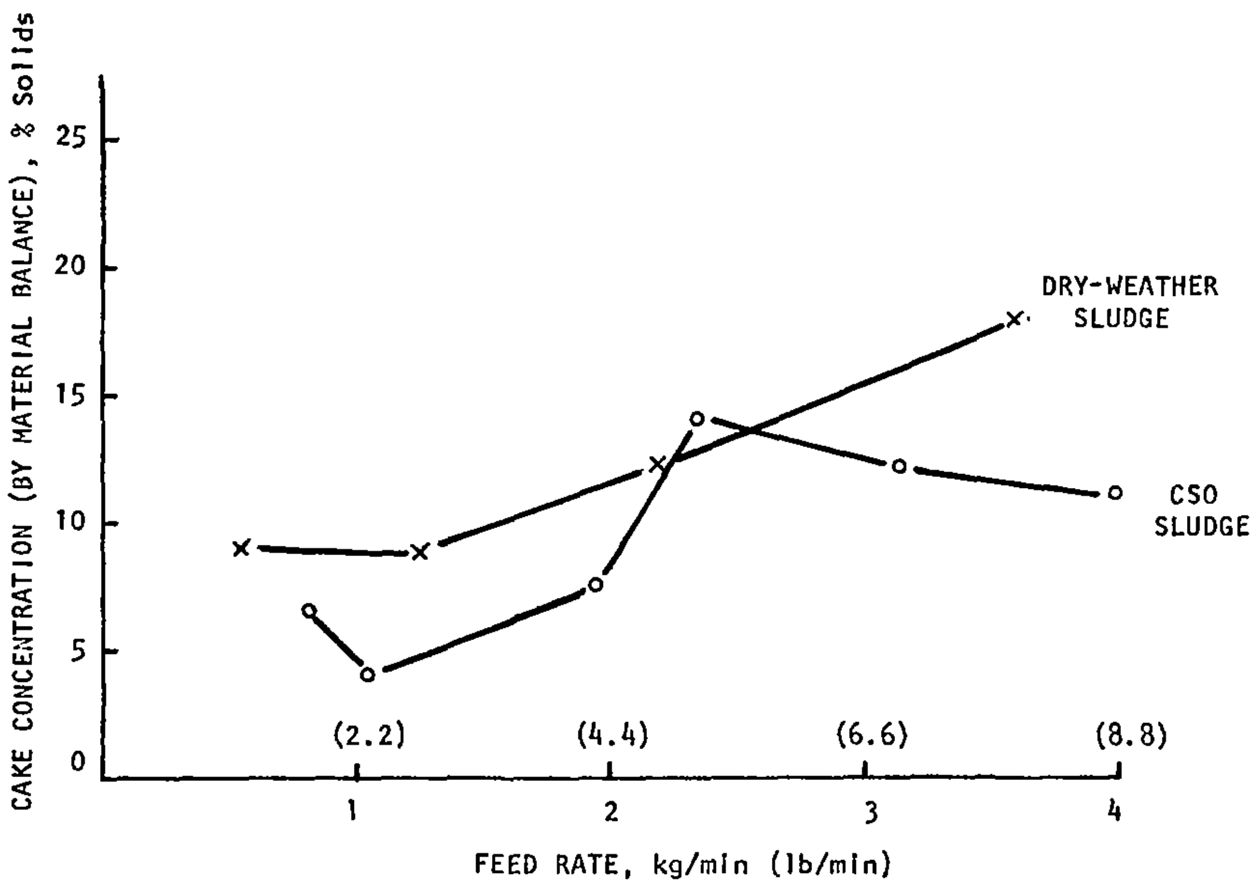


Figure 21. Relationship between cake concentration and solids feed rate [121.9 cm (48 in.) basket centrifuge tests - Kenosha sludges].

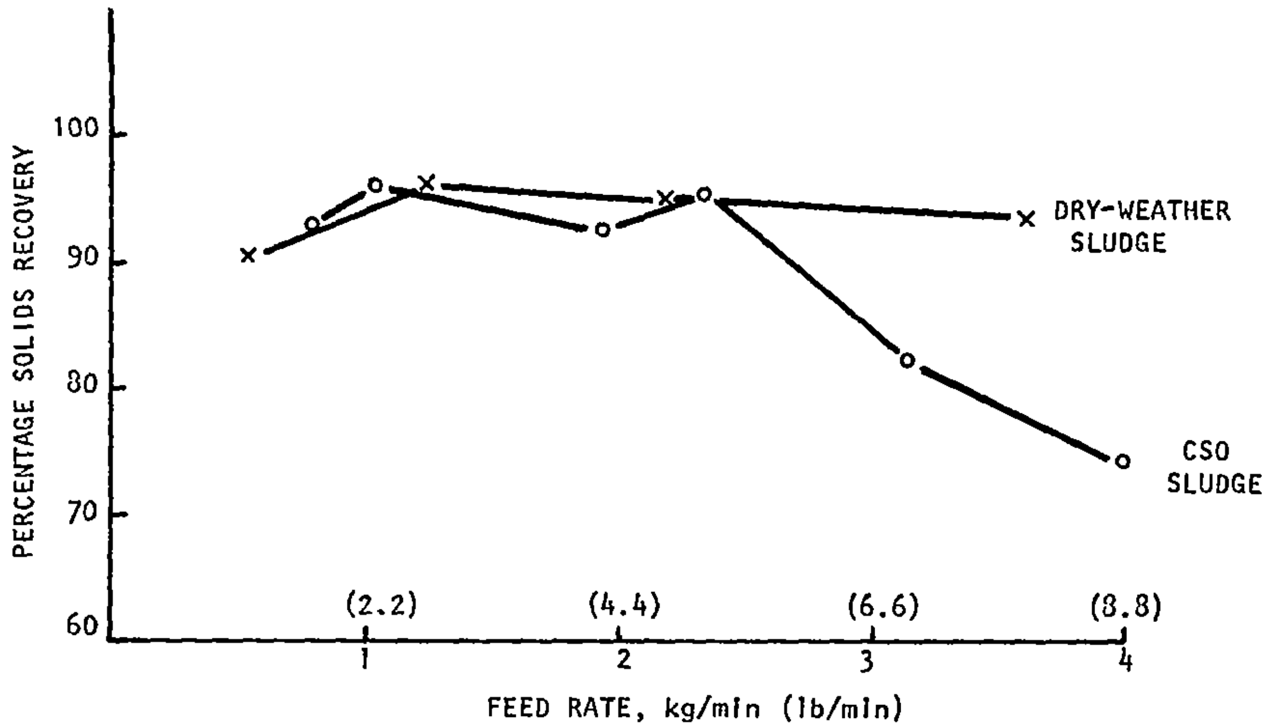


Figure 22. Relationship between solids recovery and solids feed rate [121.9 cm (48 in.) basket centrifuge tests - Kenosha sludges].

mary solids will dewater quite readily at low centrifuge detention times, (high loadings) whereas the biological sludge is more difficult to dewater with high loadings resulting in less solids capture and a wetter cake due to a reduction in the time the captured solids are exposed to the centrifugal force.

121.9 cm (48 in.) Basket Centrifuge Tests - Wet-Weather and Dry-Weather Combined Sludges

The full-scale centrifuge dewatering tests using the Kenosha wet-weather/dry-weather sludge combination were conducted on September 10-15, 1976. A CSO event occurred in Kenosha on September 8, 1976. At the beginning of the event, one primary sedimentation basin was removed from service. This increased suspended solids in the primary effluent, thus simulating a CSO generated wastewater. Next, a 22,710 liter (6,000 gal.) tank truck was filled with 7,950 liters (2,100 gal.) of dry-weather primary sludge from the primary tank that had been removed from service. To this, 6,050 liters (1,600 gal.) of dry-weather flotation-thickened waste activated sludge was added to the tanker. Twelve hours after the CSO event, the tanker was filled with 8,700 liters (2,300 gal.) of flotation thickened WAS consisting of 1,900 liters (500 gal.) of dry-weather sludge and 6,800 liters (1,800 gal.) of wet-weather sludge. The twelve hour waiting period was required because of detention times through the Kenosha Water Pollution Control Plant. The sludge ratios used were based on average daily sludge production at the dry-weather plant and on the CSO sludge generated from a 1.27 cm (0.5 in.) rainfall using a two day bleedback.

The thickened sludge supply was continuously mixed by means of a recirculation pump and fed to the 121.9 cm (48 in.) basket centrifuge. A total of nine test runs were conducted. Five of the runs were conducted without polymer. The data obtained from these nine tests using the wet-weather/dry-weather combination sludge are presented in Tables A-26 to A-34 in Appendix A. The results are summarized in Table 9. As in the previous sections, cake concentrations were reported by mass balance, average sample concentration, and maximum sample concentration. All of the percent recoveries were calculated from mass balance cake concentraiton.

Figure 23 presents a plot of feed rate versus cake concentration for the nine test runs. Cake concentrations for the runs conducted without polymer varied from a low of 6.4 percent to a high of 14.3 percent. For the runs with polymer, the cake concentration range was 5.2 to 14.8 percent. Optimum cakes for both sludges were obtained at feed rates of 2.0-3.0 kg/min (4.4-6.6 lb/min). The graph demonstrates that the cake concentration of the two sludges reacted in a similar manner for variations in feed rate.

A plot of feed rate versus solids recovery is shown in Figure 24 for the test runs conducted both with and without polymer. Percentage suspended solids recovery for the tests without polymer varied from 64.2 percent to 94.6 percent. All of the runs conducted with polymer had solids capture values in excess of 90 percent. From the graph, it can be seen that solids recoveries decrease rapidly for runs without polymer at centrifuge loadings in excess of 2.0 kg/min (4.4 lb/min). The recoveries for the tests in which polymer was

TABLE 9. RESULTS OF 121.9 CM (48 IN.) BASKET CENTRIFUGE TESTS USING A MIXTURE OF WET-WEATHER/DRY-WEATHER THICKENED SLUDGE FROM KENOSHA, WISCONSIN

Run No.	Feed rate				Cake concentration, %			Percent recovery	Cycle time (min)
	l/min	gpm	kg/min	lb/min	By balance[1]	Samples[2]	Maximum[3]		
13	54	14.3	1.97	4.34	14.3	13.2	14.6	94.6	25
14	95	25.0	1.76	3.88	6.4	45.1	46.5	77.8	17
15	38	10.0	1.90	4.18	12.7	31.6	38.2	87.7	23
16	70	18.5	1.30	2.87	8.1	28.4	35.7	87.0	24
17	109	28.8	3.99	8.78	12.7	22.6	28.7	64.2	15
18	44	11.7	1.07	2.36	5.7	24.1	24.6	94.2	20
19	44	11.7	1.09	2.41	5.2	25.9	31.5	97.2	25
20	61	16.0	2.58	5.69	14.8	20.2	21.0	97.8	22
21	81	21.5	4.51	9.93	12.9	18.2	20.1	93.1	11

Note: Runs 13-17 No polymer addition
Runs 18-21 Polymer addition

continued

TABLE 9. (continued)

1. Mass balances computed using the following formula: $C = \frac{FR \times FC \times FCT - CE - S}{K}$

Where:
- C = cake concentration (% T.S.)
- FR = sludge feed rate lpm (gpm)
- FC = sludge feed concentration (% T.S.)
- FCT = sludge feed cycle time (min.)
- CE = liters (gallons) of centrate generated x % T.S. of centrate
- S = liters (gallons) of skimmings generated x % T.S. of skimmings
- K = liters (gallons) of cake generated

2. The values reported in this column represent the average analytical values obtained from the actual cake samples that were taken.

3. The values reported in this column represent the maximum value obtained for the cake sample for each respective run.

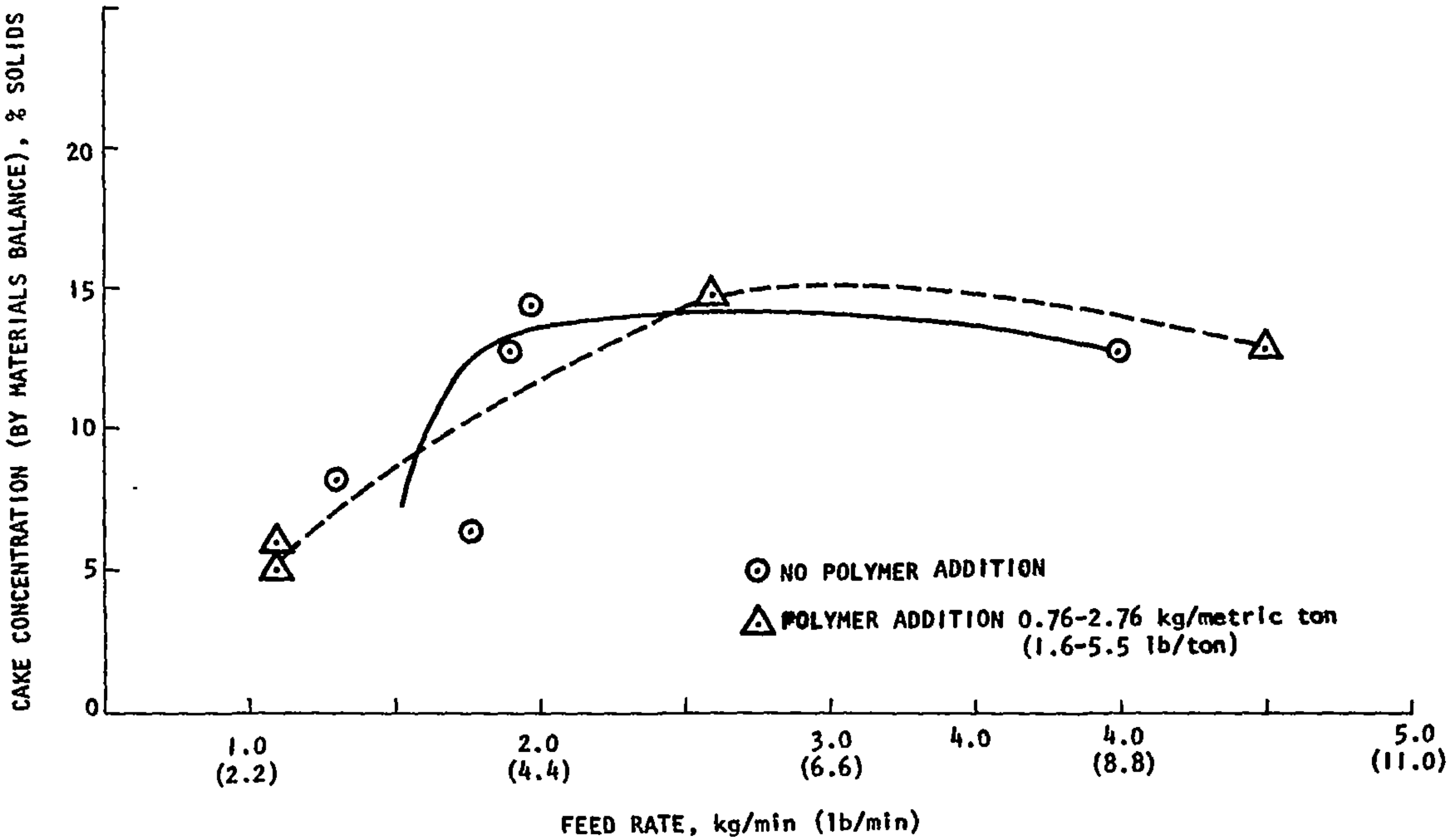


Figure 23. Relationship between cake concentration and solids feed rate 121.9 cm (48 in.) basket centrifuge tests-Kenosha wet-weather/dry-weather sludge combination.

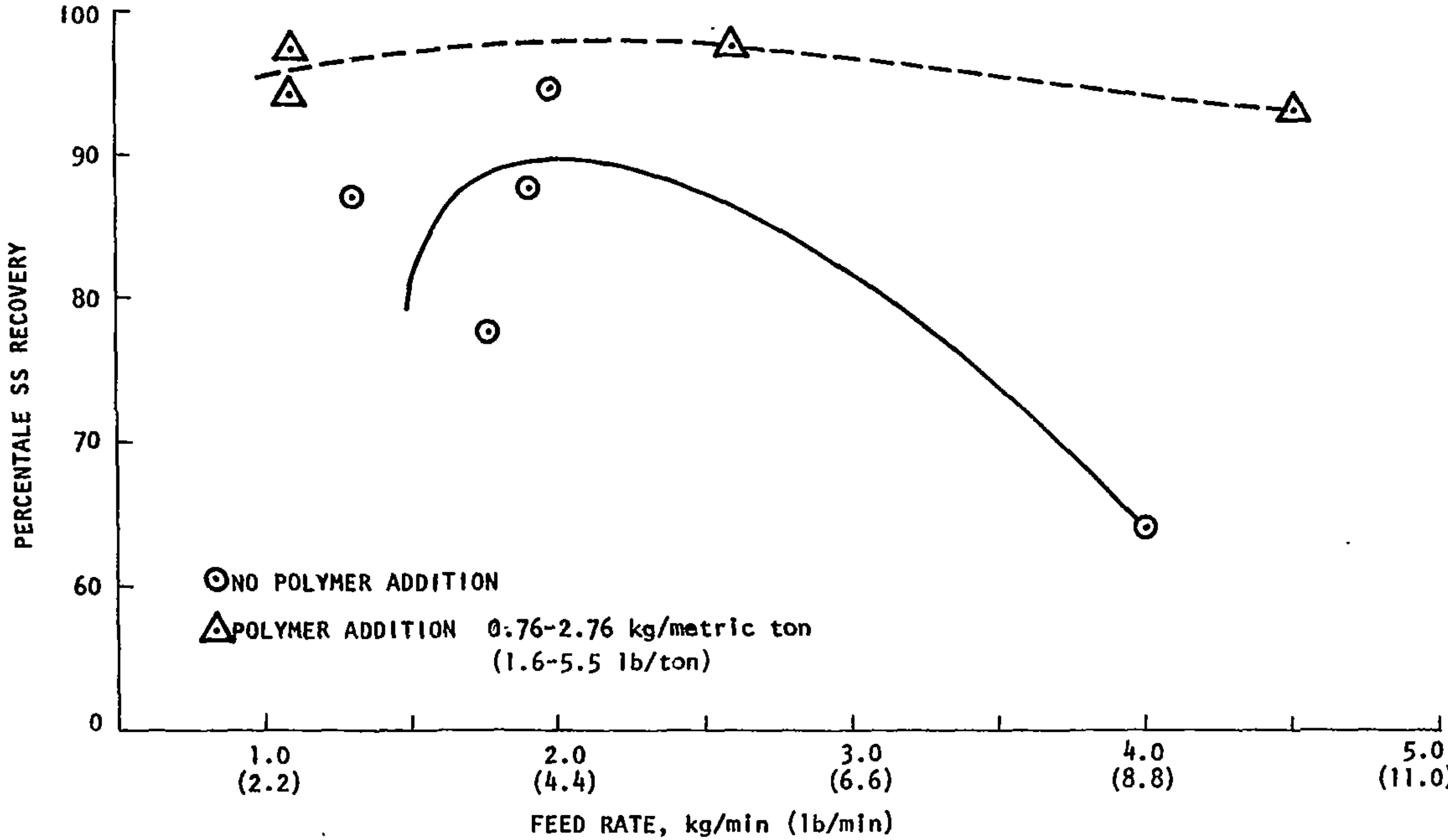


Figure 24. Relationship between solids recovery and solids feed rate 121.9 cm (48 in.) basket centrifuge tests - Kenosha wet-weather/dry-weather sludge combination.

used remained uniform over the entire feed range of 1.0 to 4.5 kg/min (2.2-10.0 lb/min).

Figure 25 is a plot of cake concentration and solids recovery versus polymer dosage. The graph demonstrates decreasing cake concentration with increasing polymer addition. Solids recovery remained uniform over the polymer dosage range. The test runs determined that the optimum polymer dosage was 1.40 kg/metric ton (2.8 lb/ton), which yielded a cake concentration of 14.8 percent with a corresponding 97.8 percent suspended solids recovery.

EFFECT OF CENTRIFUGATION ON HEAVY METALS DISTRIBUTION

Heavy metal determinations for the feed to the centrifuge, the skimmings and cake retained by the centrifuge and the centrate discharged from the centrifuge were made during centrifugation of the Kenosha dry-weather and CSO sludges. The determinations were made on composite samples which were prepared from the grab samples taken from expected optimum testing runs. The samples for the dry-weather determinations were taken during the 30.5 cm (12 in.) basket centrifugation tests using Kenosha dry-weather thickened WAS on August 7, 1975. The results are presented in Table 10. The samples for the CSO sludge determinations were taken during the 121.9 cm (48 in.) basket centrifugation tests using Kenosha thickened CSO waste activated sludge on November 12, 1975. These results are given in Table 11.

Examination of Tables 10 and 11 shows that the two sludges investigated have the following common characteristics:

1. The heavy metals appear to be solids related, that is, they are a part of or are attached to the solids. For example, for a given heavy metal, the concentration is consistently of the same magnitude, irrespective of the sample (feed, centrate, skimmings and cake).

2. The highest metal concentrations observed were those associated with zinc and copper.

3. The lowest metal concentration noted was that for mercury.

4. In general, for a given heavy metal or sample taken (feed, centrate, skimmings or cake), the CSO and dry-weather sludge metal concentrations are similar and of the same magnitude.

The above similarities are noteworthy in view of the fact that the results obtained were derived from samples taken about three months apart.

Comparisons of the data in Tables 10 and 11 also show that for the heavy metals investigated, the dry-weather cake concentrations were consistently higher than those for the CSO centrifuge cake.

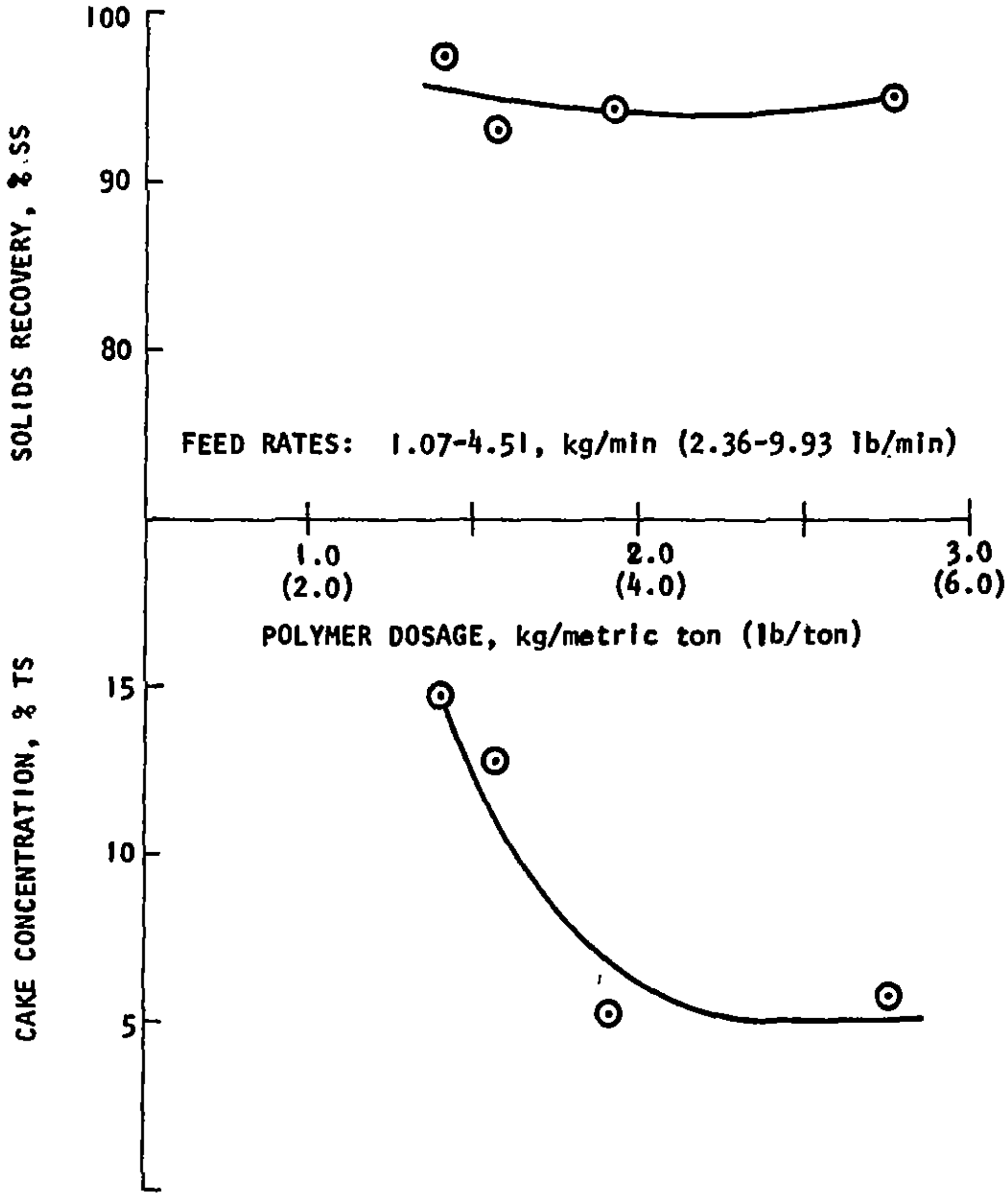


Figure 25. Cake concentration and solids recovery vs. polymer dosage 121.9 cm (48 in) basket centrifuge tests - Kenosha wet-weather/dry-weather sludge combination.

TABLE 10. HEAVY METAL CONCENTRATIONS FOR CENTRIFUGE TESTS USING KENOSHA DRY-WEATHER SLUDGE (THICKENED WAS)

	Concentrations in mg metal/kg solids			
	Feed	Centrate	Skimmings	Cake
Zinc	3681	3418	3832	3900
Lead	522	633	571	587
Nickel	145-290	<380	109-217	470
Copper	1565	1266	1413	1650
Chromium	783	759	842	709
Mercury	1.62	2.03	1.71	3.57

(No Polymer Addition)

TABLE 11. HEAVY METAL CONCENTRATIONS FOR CENTRIFUGE TESTS USING KENOSHA CSO SLUDGE

	Concentrations in mg metal/kg solids			
	Feed	Centrate	Skimmings	Cake
Zinc	2690	2905	3770	1980
Lead	410	405	435	254
Nickel	333	405	330	234
Copper	2110	1280	1945	1375
Chromium	877	842	1170	424
Mercury	1.30	1.24	1.12	0.47

(No Polymer Addition)

Comparison of the CSO feed data in Table 11 with that of a similar previous Kenosha CSO sludge sample recorded in the literature (1) shows that the heavy metal concentrations are similar for the two samples with the exception of zinc which was 7,154 mg/kg as opposed to 2,690 mg/kg in Table 11.

Presented in Table 12 are data obtained from mass balances performed to show the effect of centrifugation on the mass distribution of the heavy metals. As expected, since the metals are solids related and centrifugation is a solids removal process, the major portion of the heavy metals are retained in the cake and skimmings. This effect was slightly more pronounced in the centrifugation of CSO sludge than for dry-weather sludge.

The results of the heavy metals analysis on the Kenosha wet-weather/dry-weather sludge combination are presented in Table 13. The samples were taken from the optimum runs of September 14-15, 1976. The metal analyses were performed on the sludge feed, centrate, skimmings, and cake for samples both with and without polymer. Cadmium analyses were included due to increased environmental concern with regard to this element.

Zinc and copper were found to be the two most concentrated metals with cake concentrations of 8,475 mg/kg and 4,155 mg/kg reported respectively, for samples without polymer. Mercury was the least concentrated of the metals analyzed. The cadmium value of the cake was 45 mg/kg while the centrate concentration was reported at 32 mg/kg for samples without polymer addition.

A comparison between the samples in which polymer was added and those in which it was not shows a definite pattern in metal distribution. With regard to centrate quality, heavy metal concentrations were significantly reduced for zinc, lead, copper, and chromium for samples dosed with polymer. Concentrations of nickel, mercury, and cadmium showed no significant change between samples in which polymer was added and those in which it was not.

A mass heavy metals balance has been prepared for the Kenosha wet-weather/dry-weather sludge combination for samples with polymer addition and those without. This information is shown in Table 14. The majority of the metals had a lower concentration value by mass balance when compared to the actual sample value. This is due in part to the difficulty in obtaining representative cake samples from the basket centrifuge. Metals recovery are also listed in the Table. The samples to which polymer was added show consistently higher removals with all values in excess of 95 percent. This compares to a recovery range of 77.4 - 85.8 percent for the metal samples with no polymer addition.

All of the data presented here contributed to our storehouse of knowledge as it relates to the presence and magnitude of heavy metals in sewage plant sludges derived from dry- and wet-weather operations. As importantly, the data provide an insight into the effect of the distribution of the heavy metals from centrifuge dewatering and thereby permit other necessary engineering evaluations related to the ultimate disposal of the two streams arising from centrifugation. For example, the residual centrate is usually

TABLE 12. EFFECT OF CENTRIFUGATION ON THE DISTRIBUTION OF HEAVY METALS (BASED ON ONE LITER OF FEED SLUDGE) (ALL VALUES IN mg)

	Dry-weather sludge				
	Feed	Retained (cake & skimmings)	Percent retained	Centrate	Percent discharged
Zinc	140.2	122.8	87.6	17.4	12.4
Lead	19.9	17.0	85.3	2.91	14.7
Nickel	8.29	7.32	88.3	0.97	11.7
Copper	59.6	53.0	88.9	6.58	11.1
Chromium	29.8	25.4	85.3	4.38	14.7
Mercury	.0617	.0564	91.4	.0052	8.6

	CSO sludge				
	Feed	Retained (cake & skimmings)	Percent retained	Centrate	Percent discharged
Zinc	82.9	75.9	91.6	7.04	8.4
Lead	12.6	11.4	90.4	1.20	9.6
Nickel	10.3	9.16	88.9	1.14	11.1
Copper	65.0	60.9	93.7	4.06	6.3
Chromium	27.0	24.4	90.4	2.55	9.6
Mercury	.0400	.0347	86.8	.0052	13.2

TABLE 13. HEAVY METAL CONCENTRATIONS FOR CENTRIFUGE TESTS USING KENOSHA CSO/DRY-WEATHER SLUDGE COMBINATION

Concentrations in mg metal/kg solids

	Feed		Centrate		Skimmings		Cake	
	Without polymer	With polymer	Without polymer	With polymer	Without polymer	With polymer	Without polymer	With polymer
Zinc	7520	7530	5200	1085	9980	8920	8475	7510
Lead	632	621	640	445	775	662	648	620
Nickel	305	345	280	310	370	330	340	315
Copper	4050	3800	2515	1240	3720	4235	4155	3740
Chromium	1520	1475	1265	668	1995	1785	1610	1325
Mercury	0.90	0.33	0.85	0.70	1.30	1.00	0.63	1.20
Cadmium	44	39	32	36	55	47	45	36

Polymer Addition: 1.1 kg/metric ton (2.2 lb/ton)

TABLE 14. HEAVY METAL MASS BALANCES FOR THE 121.9 CM (48 IN.) BASKET CENTRIFUGE TESTS KENOSHA CSO/DRY-WEATHER SLUDGE COMBINATION

Cake concentration mg metal/kg wet sample

	By mass balance		Sample		Maximum		Percent recovery	
	No polymer	With polymer	No polymer	With polymer	No polymer	With polymer	No polymer	With polymer
Zinc	532.5	523.3	1064	1438	1065	1450	84.0	98.2
Lead	40.8	45.4	81	118	81	118	76.8	96.4
Nickel	20.2	26.5	44	61	46	64	78.6	99.5
Copper	307.7	273.1	521	716	532	726	85.8	98.3
Chromium	104.1	101.1	203	253	204	258	81.2	97.7
Mercury	.057	.001	.08	.145	.08	.145	77.4	-
Cadmium	3.1	2.6	5.56	6.84	5.63	6.85	83.4	95.5

returned to the treatment plant and its heavy metal contribution and effect on treatment and effluent quality has not heretofore been taken into account in the treatment plant design. Moreover, the heavy metal concentration in the centrifuge cake will have a bearing on the extent to which it can be disposed of on land (by spreading or landfill).

SECTION VIII

RESULTS OF SLUDGE THICKENING - CENTRIFUGATION STUDIES CONDUCTED IN MILWAUKEE, WISCONSIN

Milwaukee was the second of three test locations visited during the course of this project. The experimental tests were conducted between April and June, 1976. The Milwaukee Humboldt Avenue CSO site was chosen as the study location to evaluate the thickening-centrifugation process from a physically generated wet-weather sludge. The corresponding dry-weather test facility selected was the Milwaukee South Shore Water Pollution Control Plant.

As with the Kenosha CSO sludge, problems were encountered in obtaining a representative thickened sludge from the Humboldt Avenue site. This site consists of a storage facility as discussed previously in Section V. The procedure used to obtain the CSO sludge was as follows: During a CSO event, the detention tank mixers were removed from service. The facility thus acts as a sedimentation basin. Following the CSO event, supernatant was continuously drawn off over a period of days until only 30.5 cm (12 in.) of sludge remained in the detention tank. This sludge was then pumped to above-ground thickening facilities which consisted of a series of 1892.5 liter (500 gal.) circular tanks. The sludge was allowed to thicken for 12 hours with the decant being returned to the detention tank.

Following the final decant, a visual inspection of the thickened sludge was made. Its appearance indicated that the sludge was very stratified by particle size, consisting of a very dilute supernatant and a coarse, gritty subnatant. Prior to conducting dewatering tests, samples of the two stratified sludges were obtained for laboratory analysis. The solids analyses are presented below in Table 15. The total solids of the thickened supernatant was 0.14 percent with a suspended solids value of 900 mg/l. The corresponding total solids of the thickened subnatant was 67.37 percent, consisting primarily of gritty material. To substantiate the particle size of the gritty subnatant, a sieve analysis was conducted and is presented in Table 16. The data obtained indicated that 40.7 percent of the gritty sludge would be retained on a No. 20 sieve (0.841 mm). Since the Humboldt Avenue Detention Tank utilizes settling and resuspension of solids, it appears that the tank mixers are not capable of resuspending all of the higher density particles from the tank bottom. This has resulted in a gradual build-up of grit and gravel over a period of time, and is not truly representative of typical CSO sludge.

In an effort to obtain a more realistic wet-weather sludge, a different approach was used during the next CSO event. The detention tank was allowed

TABLE 15. RESULTS OF THE THICKENED SLUDGE SOLIDS ANALYSIS

Humboldt Avenue Detention Tank
Milwaukee, Wisconsin

Parameter	Supernatant	Subnatant
Total solids	0.14%	67.37%
Total volatile solids	0.04%	7.9%
Suspended solids	0.09%	--
Volatile suspended solids	0.04%	

TABLE 16. RESULTS OF THE THICKENED SLUDGE SUBNATANT SIEVE ANALYSIS

Humboldt Avenue Detention Tank
Milwaukee, Wisconsin

number	Percent of total retained	Cumulative percent retained	Mesh opening (millimeters)
14	23.5	23.5	1.41
20	17.2	40.7	0.841
30	12.6	53.3	0.595
40	17.4	70.7	0.420
60	19.3	90.0	0.250
80	5.7	95.7	0.177
Pan	4.3	100.0	--

Dry bulk density = 1.478 gm/cc

to fill, and was gradually decanted off in a manner similar to the one discussed previously. When the drawdown reached the 1.22 m (4.0 ft) depth, all of the tank mixers were turned on. This depth was selected because it is the minimum depth obtainable in which the mixers are sufficiently submerged to allow adequate solids agitation. A grab sample of this sludge was taken after 15 minutes of mixing and allowed to gravity thicken. Following decantation, the sample was analyzed for solids concentration. The results are shown below:

	Total solids mg/l	Total volatile solids mg/l	Suspended solids mg/l	Volatile suspended solids mg/l
Sample No. 1	197	68	94	35

The total solids concentration value of 197 mg/l was actually less than the 1400 mg/l total solids value obtained from the thickened sludge supernatant discussed previously. Because of these results, it was decided to conduct all testing using the initial procedure developed.

The test intentions at the Milwaukee South Shore Water Pollution Control Plant were to obtain dry-weather primary sludge, assumed to be the primary sludge available after 5 days of dry-weather flow, and dewater it by the centrifugation process. The gravity settled primary sludge was selected because it most closely resembled the sludge generated by the Humboldt Avenue CSO Detention Tank. Sufficient sludge to complete each day's testing was drawn from the primary settling basins and stored in a sludge pumping pit. At the completion of each day's runs, the remaining sludge was pumped from the pit. Prior to filling with fresh sludge, the pit was thoroughly washed down and pumped dry.

BENCH SCALE CLARIFICATION TESTS

Bench scale clarification tests using Milwaukee wet-weather thickened sludge supernatant, Milwaukee dry-weather influent wastewater, and a mixture of the two in the proportion in which they are produced were conducted on June 29, 1976. Because of the relatively dilute residuals present in the wet-weather sludge, bench scale clarification tests were conducted in lieu of thickening tests. For purposes of comparison, the wet-weather sludge settling characteristics were compared to Milwaukee South Shore incoming wastewater. Six bench tests were conducted. Two each on the wet-weather sludge, the dry-weather wastewater, and the combination of wet-weather sludge and dry-weather wastewater. From Phase I (1), solids clarification was obtained by addition of ferric chloride followed by two minutes of flocculation. The bench scale clarification tests followed this procedure, facilitated by polymer addition to strengthen the floc and a 15 second rapid mix prior to the 2 minute flocculation.

The proportioned mixture of the wet-weather sludge and the dry-weather wastewater was based on the following calculations:

1. Milwaukee CSO area = 6804 hectares (16,800 acres).

2. Assume 50 percent of rainfall results in CSO.

3. Assume 1.27 cm (0.5 in.) rainfall = 431,641,400 liters (114,040,000 gal.) of CSO.

4. Physical treatment of the CSO will produce a sludge volume equal to 0.9 percent of volume treated (1).

5. CSO sludge produced = 3,884,772 liters (1,026,360 gal.).

6. Assuming a two day bleedback: amount of CSO sludge produced = 1,942 m^3/day (0.513 mgd).

7. Average dry-weather wastewater flow - 258,894 m^3/day (68.5 mgd).

8. Ratio of CSO sludge/dry-weather wastewater = 0.01.

Thus, for every liter (0.264 gal.) of CSO sludge produced, 100 liters (26.4 gal.) of dry-weather wastewater are produced. The results of the gravity clarification tests for the wet-weather sludge, the dry-weather wastewater, and the combination are presented in Table 17. For the wet-weather sludge, a settling rate of 27.4 cm/min (0.9 fpm) was obtained. The detention time was 30 minutes. The sludge volume obtained was equivalent to 17.5 ml/l (17.5 gal./1000 gal.). The dry-weather wastewater had a gravity settling rate of 24.4 cm/min (0.8 fpm) with a sludge volume of 45 ml/l (45 gal./1000 gal.) after 30 minutes of settling. The results of the combination mixture were identical to that of the dry-weather wastewater. Effluent suspended solids were quite uniform varying from a high of 16 mg/l for the wet-weather sludge to a low of 12 mg/l for the combination sludge.

The results of the settling tests show that the wet-weather sludge has a slightly higher settling rate than either the dry-weather wastewater or the combination sludge. The results also indicate that the addition of wet-weather sludge to dry-weather wastewater did not hinder the settling rate or effluent quality.

CENTRIFUGE DEWATERING TESTS

121.9 cm (48 in.) Basket Centrifuge - Wet-Weather Sludge

The full scale CSO sludge dewatering tests using the mobile van's 121.9 cm (48 in.) basket centrifuge were conducted at the Humboldt Avenue detention tank on May 10-12, 1976.

In the initial full-scale test runs, the thickened feed sludge supernatant and subnatant were mixed and screened through 0.64 cm (0.25 in.) mesh prior to being fed to the 121.9 cm (48 in.) basket centrifuge. The screening was required since the centrifuge intake is restricted to particles less than 0.64 cm (0.25 in.) diameter. Three runs were attempted, all of which had to be terminated due to excessive basket vibration and plugging of the feed line. The plugging developed as a result of stratification in the feed line resulting from the high specific gravity of the grit particles.

To prevent damage to the feed pump and the 121.9 cm (48 in.) basket centrifuge, it was decided to feed only the thickened sludge supernatant to the centrifuge. The decision to use only the supernatant was also based on the assumption that the gritty subnatant would be settled out in a CSO treatment plant designed for the use of centrifuges.

One full scale run was conducted using the 121.9 cm (48 in.) basket to centrifuge the thickened sludge supernatant. The length of run was 73 minutes at a feed rate of 223 liters/min (59 gpm). The individual test data obtained from this run are presented in Appendix B, Table B1, and are summarized below in Table 18.

TABLE 17. RESULTS OF BENCH SCALE CLARIFICATION TESTS
MILWAUKEE, WISCONSIN

	Humboldt Avenue wet-weather sludge		South Shore dry-weather wastewater		Mixture of wet-weather sludge and dry-weather wastewater	
Run No.	1	2	3	4	5	6
Raw waste pH	8.2	8.2	7.85	7.85	7.9	7.9
Raw waste suspended solids, mg/l	198*	198*	475	475	469	469
Chemical Treatment						
$FeCl_3$, mg/l	10	20	10	20	10	20
Percol 728, mg/l	2	2	3	3	3	3
Rapid mix, sec.	15	15	15	15	15	15
Flocculation time, min.	2	2	2	2	2	2
Settling Data						
Settling rate, cm/min (fpm)	27.4 (0.9)	27.4 (0.9)	24.4 (0.8)	24.4 (0.8)	24.4 (0.8)	24.4 (0.8)
Detention time, min.	30	30	30	30	30	30
Sludge volume, ml/l (gal./1000 gal.)	15 (15)	20 (20)	45 (45)	45 (45)	45 (45)	45 (45)
Scum volume, ml/l (gal./1000 gal.)	0	0	0	0	0	0
Effluent pH	7.35	7.1	7.5	7.4	7.5	7.4
Effluent suspended solids, mg/l	16	14	15	14	13	12

* During the testing program, wet-weather sludge solids concentrations varied between 198-1400 mg/l. This value represents the actual gravity thickened sludge concentration at the time of sampling and should not be confused with a similar value (197 mg/l) reported previously for a sample taken with the settling tank mixers running.

TABLE 18. RESULTS OF 121.9 CM (48 IN.) BASKET CENTRIFUGE TEST USING WET-WEATHER, THICKENED SLUDGE SUPERNATANT FROM THE MILWAUKEE HUMBOLDT AVENUE SITE

Run	Feed rate				Cake concentration, %		
No.	lpm	gpm	kg/min	lb/min	by balance	samples	maximum
1	223.3	59	.205	.452	1.77	0.135	0.140

Percent recovery = 92.5
Cycle time = 73 min.

The cake concentration obtained by mass balance was 1.77 percent compared to a sample value of 0.135 percent. It should be noted that the cake concentrations are an actual composite of cake plus skim. No independent skim samples were taken due to the diluteness of the sludge.

Since the thickened sludge supernatant feed concentration was very dilute (920 mg/l), the maximum solids loading was 0.205 kg/min (0.452 lb/min). Theoretically, at this loading, it would take a run time of 65 hours to completely fill the 454.2 liters (120 gal.) basket centrifuge. This is equivalent to centrifuging 870,550 liters (230,000 gal.) of thickened sludge supernatant. Because of the dilute concentration of the sludge and the impractical theoretical length of run time to fill the 121.9 cm (48 in.) basket centrifuge, it was decided to terminate full scale testing. However, supplementary test data were obtained from the Humboldt Avenue wet-weather site using the 30.5 (12 in.) basket centrifuge. This information is presented in the following section.

30.5 cm (12 in.) Basket Centrifuge - Wet-Weather Sludge

Supplementary centrifuge sludge dewatering tests were conducted at the Milwaukee Humboldt Avenue Detention Tank on June 8-9, 1976. As with the full scale testing, runs were conducted using the thickened sludge supernatant obtained from the CSO event of May 28, 1976. The data obtained from the two test runs are detailed in Appendix Tables B2 and B3, with a summary of the results shown in Table 19.

Excessively long cycle times were required (240 min) because of the low feed solids concentration (0.066 percent). Run No. 1 was conducted without polymer. Cake concentration for Run No. 1 was 18.3 percent with a 76.6 percent recovery. Run No. 2 was conducted with a cationic polymer, Percol 728. This polymer was selected from laboratory screening tests. A cake concentration of 28.4 percent was obtained with a corresponding recovery of 82 percent at a polymer dosage of 1.05 kg/metric ton (2.1 lb/ton). The cake concentrations reported were obtained from sample analysis. No further testing was conducted due to the low feed solids concentrations.

TABLE 19. RESULTS OF 30.5 CM (12 in.) BASKET CENTRIFUGE TEST USING WET-WEATHER THICKENED SLUDGE FROM MILWAUKEE - HUMBOLDT AVENUE SITE

Run No.	Feed rate lpm	Feed rate gpm	Feed rate kg/min	Feed rate lb/min	Cake concentration % TS	Percent recovery	Cycle time, min
1	10.2	2.7	0.0006	0.0014	18.3	76.6	240
2	10.2	2.7	0.001	0.0023	28.4	82.0	240

Run No. 1 - no polymer
Run No. 2 - Percol 728 polymer added.

Decanter Centrifuge Tests - Dry-Weather Sludge

The solids dewatering van was relocated at the Milwaukee South Shore Water Pollution Control Plant on May 18, 1976. Full scale field testing of the Milwaukee South Shore dry-weather primary sludge using the decanter centrifuge began on May 25, 1976. The dewatering tests continued until June 3, 1976. The decanter centrifuge was selected in preference to the basket because the primary sludge had a solids concentration of about 5 percent.

The results of the test data from the 21 runs conducted are presented in Appendix Tables B4 to B24. A composite of these data are summarized in Table 20. Runs No. 1-7 were conducted without polymer. Solids feed rates were varied between 98.5 kg/hr (217 lb/hr) and 337.8 kg/hr (744 lb/hr) during the testing. For the twenty-one runs, cake concentrations ranged from 13.2 percent to 26.2 percent. The lowest recovery obtained during the testing was 41 percent, while the maximum was 98 percent. For the seven tests conducted without polymer, cake solids remained generally higher than when polymer was added. However, solids capture was poor. This is illustrated in the bar graph of cake solids and recovery versus the dewatering run no. presented in Figure 26. For Runs No. 8-21, the bar graph demonstrates the overall improvement in centrate quality that results from polymer addition to the feed sludge. Polymer dosages of the cationic polymer, Percol 728 ranged from 0.95-5.0 kg/metric ton (1.9-10.0 lb/ton).

Figure 27 is a plot of feed rate versus cake concentration and solids recovery for Runs No. 1-7 in which no polymer was added. Differential speeds of 15 and 23 were used with pool radii settings of 101 mm and 103 mm. The dry-weather primary sludge dewatered to a 16.7 to 26.2 percent cake. Corresponding recoveries ranged from 41 to 53 percent. The poor solids capture results indicated that polymer addition would be required to effectively dewater the South Shore Water Pollution Control Plant dry-weather primary sludge.

TABLE 20. RESULTS OF THE DECANTER CENTRIFUGE TESTS USING DRY-WEATHER SLUDGE - MILWAUKEE SOUTH SHORE WATER POLLUTION CONTROL PLANT

Run No.	Feed rate gal./min.	l/min.	lb/hr.	kg/hr.	Cake concentration (% TS)	Recovery (% SS)
1	27.9	105.6	744	337.8	26.2	41
2	27.9	105.6	726	329.6	19.9	47
3	9.6	36.3	249	113.0	17.3	50
4	9.6	36.3	245	111.2	16.9	52
5	17.9	67.8	465	211.1	21.7	41
6	9.9	37.5	260	118.0	20.1	47
7	9.9	37.5	255	115.8	16.7	53
8	9.9	37.5	260	118.0	14.5	90
9	9.9	37.5	260	118.0	15.4	95
10	17.6	66.6	436	197.9	16.0	66
11	17.6	66.6	444	201.6	14.9	71
12	14.4	54.5	352	159.8	16.1	61
13	15.9	58.3	304	138.0	13.2	98
14	15.4	58.3	367	166.6	17.4	95
15	15.4	58.3	341	154.8	17.4	90
16	15.3	57.9	339	153.9	17.0	82
17	15.3	57.9	338	153.4	16.2	81
18	17.6	66.6	217	98.5	17.8	87
19	17.6	66.6	498	226.1	16.3	96
20	17.6	66.6	403	183.0	20.1	81
21	17.6	66.6	449	203.8	16.4	80

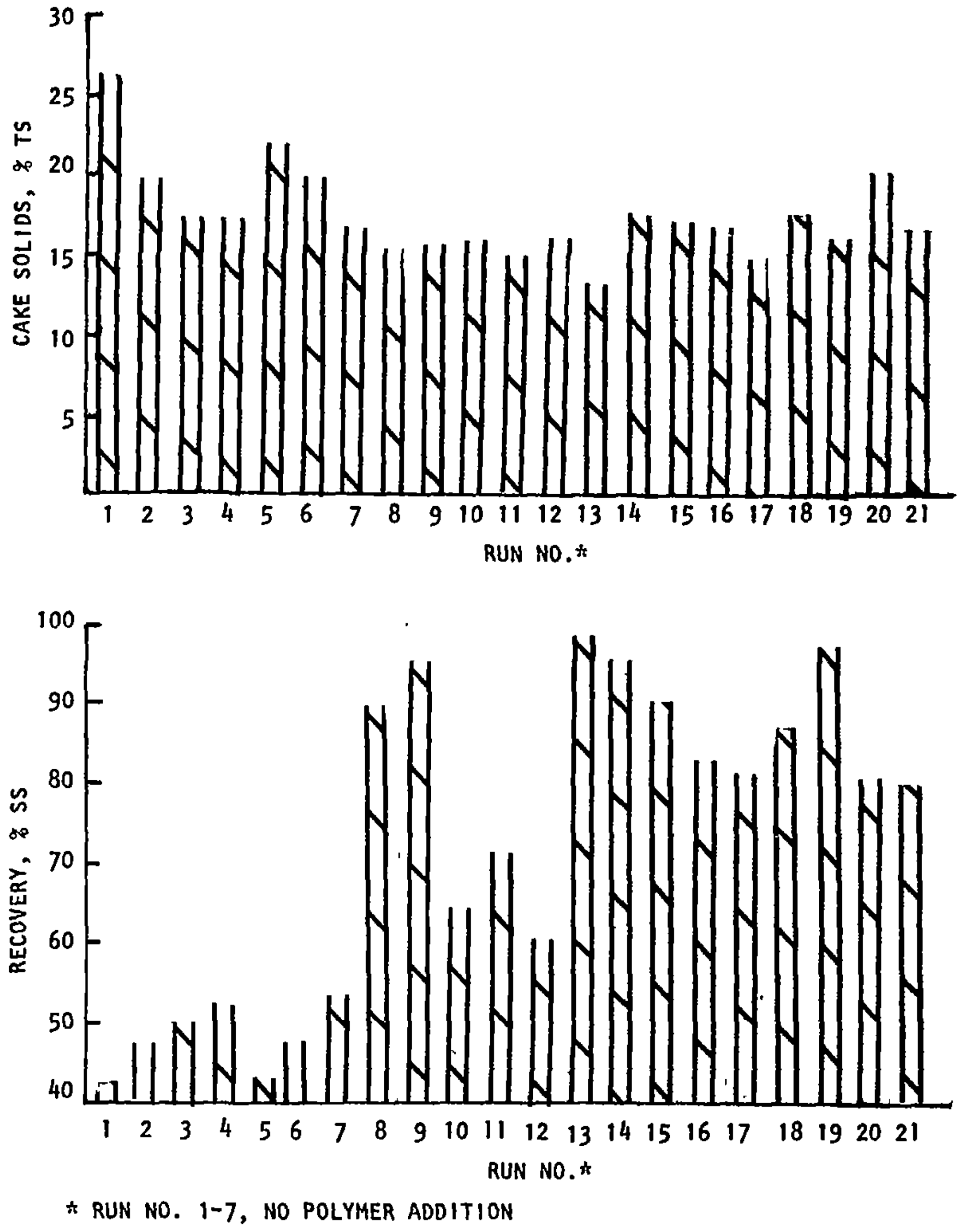


Figure 26. Bar graph of cake solids and recovery vs. test runs dry-weather sludge, Milwaukee, WI.

INDEPENDENT VARIABLES
BOWL SPEED: 2700 RPM
POLYMER ADDITION: NONE

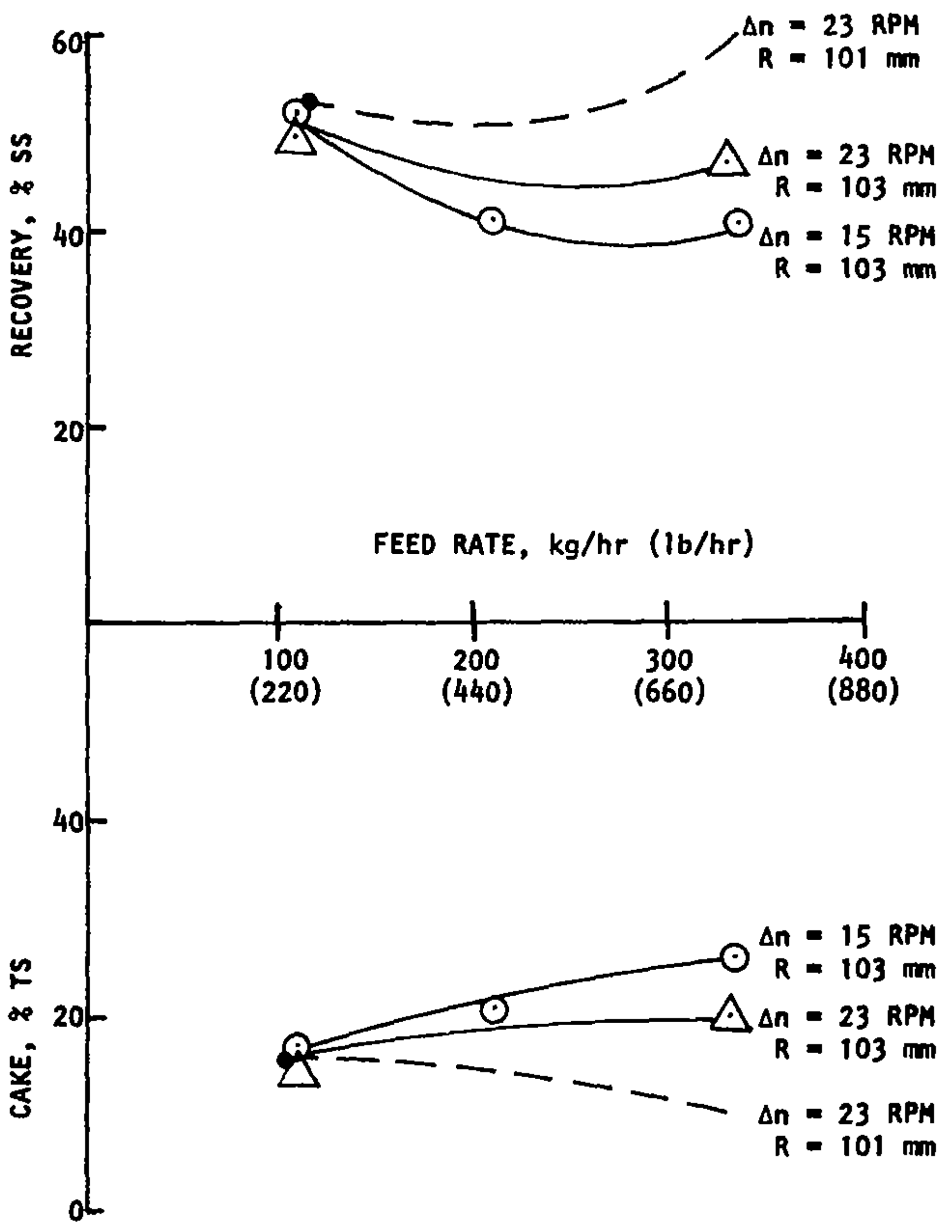


Figure 27. Cake solids and recovery vs. feed rate (kg/hr) dry-weather sludge, Milwaukee, WI

The graph also shows that at a constant solids loading, as differential speed is increased, solids recovery increases while cake solids decrease. At a constant feed rate and differential speed, recovery will increase while cake concentration decreases if the pool radius is decreased. This occurs because liquid level in the centrifuge is directly related to the pool radius setting and cake dryness directly corresponds with the pool depth.

Shown in Figures 28 and 29 are plots of feed rate versus cake solids and solids recovery for typical runs conducted with polymer. As can be seen in Figure 28, cake solids concentration ranged from a low of 13.2 percent total solids to a high of 17.0 percent. Feed rates varied between 118-204 kg/hr (260-450 lb/hr). The graph also demonstrates a decreasing cake concentration with increasing differential speed (Δn) for the South Shore Water Pollution Control Plant primary sludge. This is verified by isolating on the four highest solids loading points on the graph. For the differential speeds of 15, 20 and 25 RPM, polymer dosage for these points are almost identical at rates of approximately 2.0 kg/metric ton (4.0 lb/ton). At a uniform solids feed rate of 200 kg/hr (440 lb/hr), cake concentration increases with decreasing differential speed. The fourth point at this feed rate is for a run of Δn = 23 rpm. Although this cake is slightly higher than the point for Δn = 20 rpm, it is reasonable to assume that if additional testing were conducted, the runs for a differential speed of 23 rpm would follow the general pattern established. The data also indicate that cake solids will be slightly reduced at a lower pool radius setting. Variations in polymer dosage do not seem to significantly affect the cake concentrations within the range of dosages examined in this plot.

Figure 29 shows the variations in solids recovery obtained at selected feed rates, differential speeds, and pool radius settings for runs conducted with polymer addition. Solids recovery varied from a low of 61 percent to a high of 98 percent. Optimum captures were obtained at differential speeds of 15 and 23 rpm. For a differential speed of 15 rpm, a pool radius setting of 101 mm provided slightly better recoveries when compared to the 103 mm pool radius data.

The excellent results obtained at a differential speed of 23 rpm and a 103 mm pool radius setting are due in part to the slightly higher polymer dosages that were used when compared to the other differential speed settings. Polymer addition for a Δn = 23 was in the 2.4-3.2 kg/metric ton (4.8-6.4 lb/ton) range.

A graph of differential speed (Δn) versus cake solids and recovery was also plotted and is presented in Figure 30. The runs were conducted at a feed rate of 111-183 kg/hr (245-403 lb/hr) and a pool radius of 103 mm. The plot indicates that variations in differential speed (Δn) between 10 and 23 rpm without polymer addition do not significantly affect cake concentrations or centrate quality. For the runs with polymer, decreases in cake concentration and increases in solids recovery are observed with increasing differential speed.

INDEPENDENT VARIABLES
BOWL SPEED: 2700 RPM

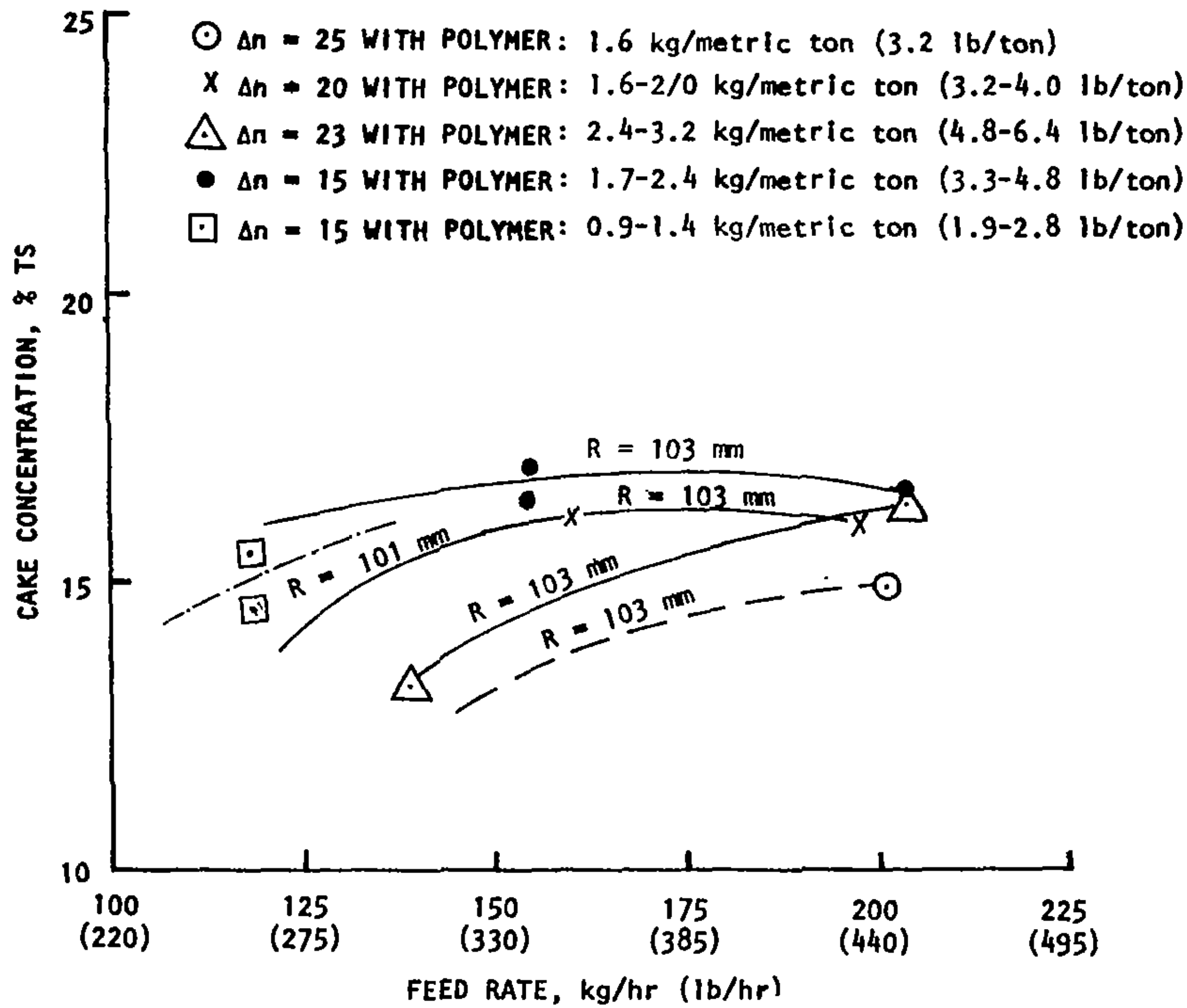


Figure 28. Cake solids vs. feed rate (kg/hr) dry-weather sludge, Milwaukee, WI.

INDEPENDENT VARIABLES
BOWL SPEED: 2700 RPM

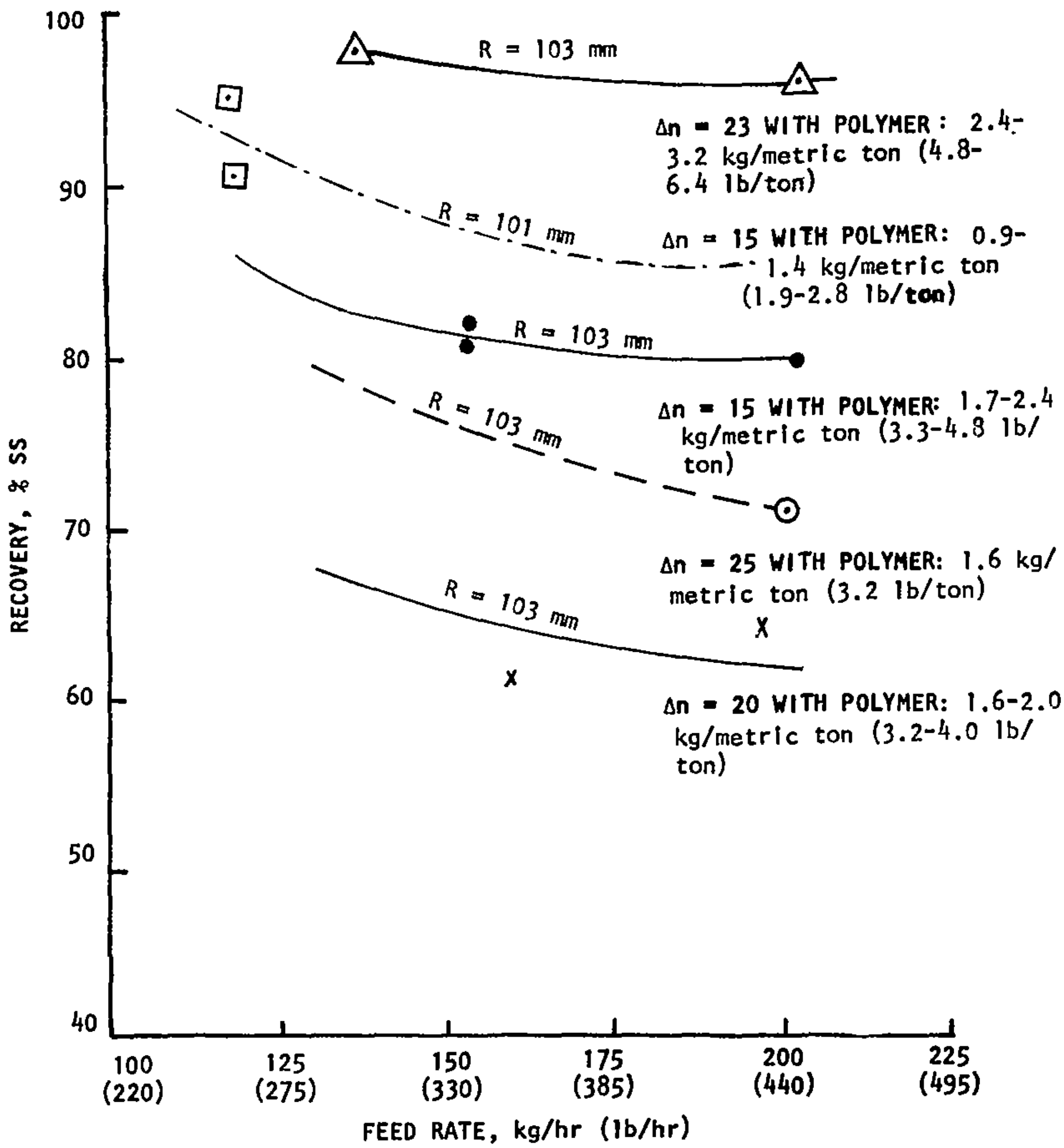


Figure 29. Recovery vs. feed rate (kg/hr) dry-weather sludge, Milwaukee, WI

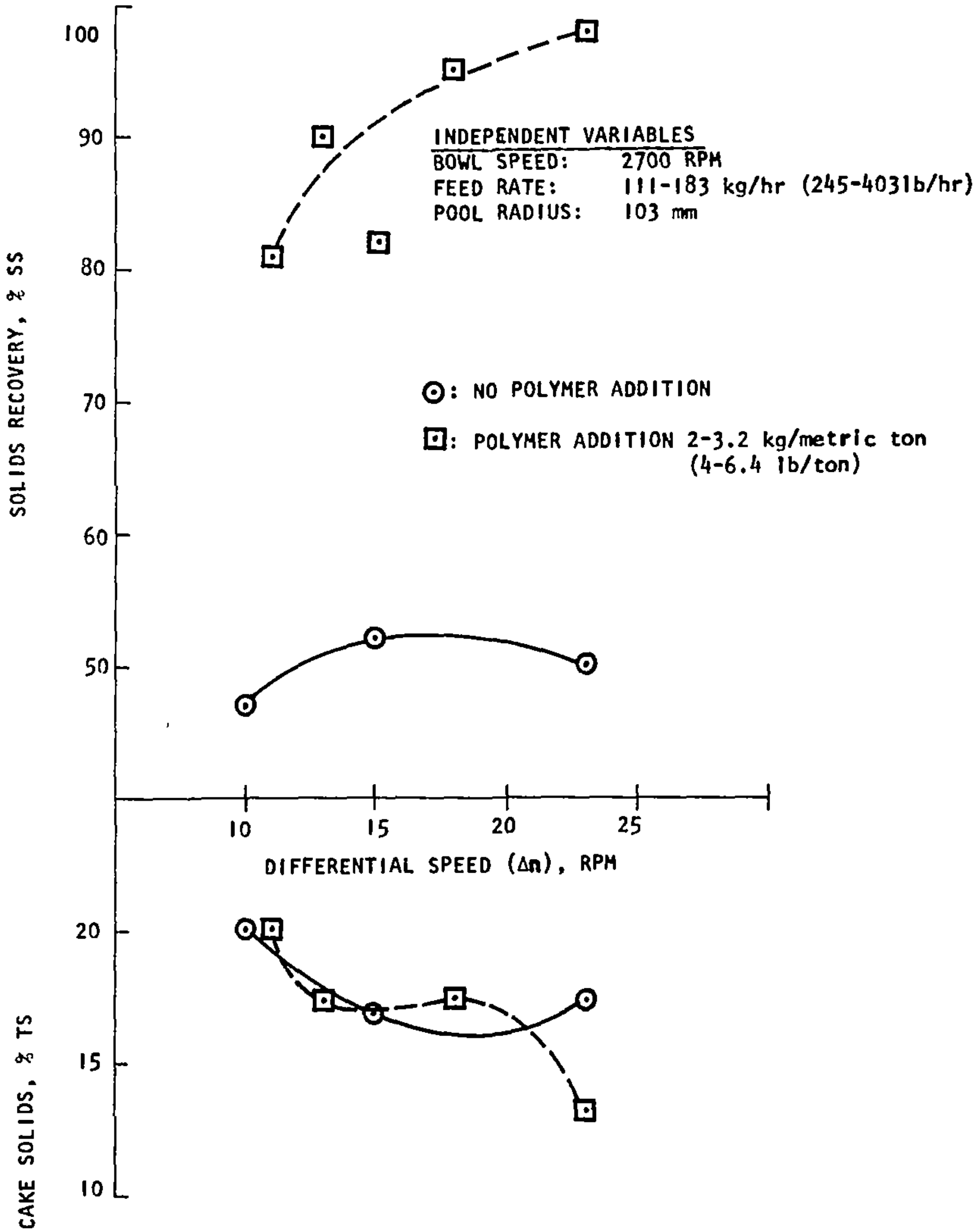


Figure 30. Cake solids and recovery vs. differential speed (Δn) dry-weather sludge, Milwaukee, WI.

Figure 31 plots polymer dosage against cake solids and solids recovery for differential speeds of 15 and 23 rpm. Feed rates for these runs were varied between 111-226 kg/hr (245-498 lb/hr). At a Δn = 15 rpm, cake solids remained relatively uniform with increasing polymer dosage. Solids recovery increased up to 1.4 kg/metric ton (2.8 lb/ton), then decreased rapidly. At a differential speed of 23 rpm, cake solids decreased with increasing polymer dosage, while solids capture increased.

EFFECT OF CENTRIFUGATION ON HEAVY METALS DISTRIBUTION

Heavy metals samples were obtained from centrifuge feed sludge, the centrate and skimmings discharge, and the cake solids from the Milwaukee Humboldt Avenue wet-weather sludge. The samples were obtained from the 30.5 cm (12 in.) basket centrifuge runs of June 8-9, 1976. The results of these heavy metal determinations are presented in Table 21.

TABLE 21. HEAVY METAL CONCENTRATIONS FOR CENTRIFUGE TESTS USING MILWAUKEE WET-WEATHER SLUDGE

Concentrations in mg metal/kg solids

	Feed		Centrate		Skimmings		Cake	
	without polymer	with polymer	without polymer	with polymer	without polymer	with polymer	without polymer	with polymer
Zinc	3125	1415	2667	2632	7500	4545	2186	2200
Lead	1563	943	6667	5263	12500	4545	1694	2025
Nickel	1563	943	6667	5263	12500	4545	770	1060
Copper	1719	2170	2000	1579	2500	2273	765	1761
Chromium	3281	1887	6667	5263	8750	7273	3104	1514
Mercury	15.63	11.32	46.67	36.84	*	31.82	1.17	2.20

* Insufficient sample to conduct analysis (Polymer Dosage: 1.0 kg/metric ton, 2.0 lb/ton)

The data are compared for runs conducted with and without polymer. The table shows that for the most part, slightly higher metal concentrations were obtained in the cake from the runs in which polymer was used. The highest metal concentrations in the cake were obtained for zinc, lead, and chromium.

In addition, for all of the metals tested, centrate metal concentrations were higher for the samples without polymer. The data appear to indicate that polymer is responsible for increasing metal retention in the cake while reducing metal concentrations in the centrate.

It should be noted that the dry weight metal concentrations are based on samples containing very low amounts of solids. Therefore, some variation

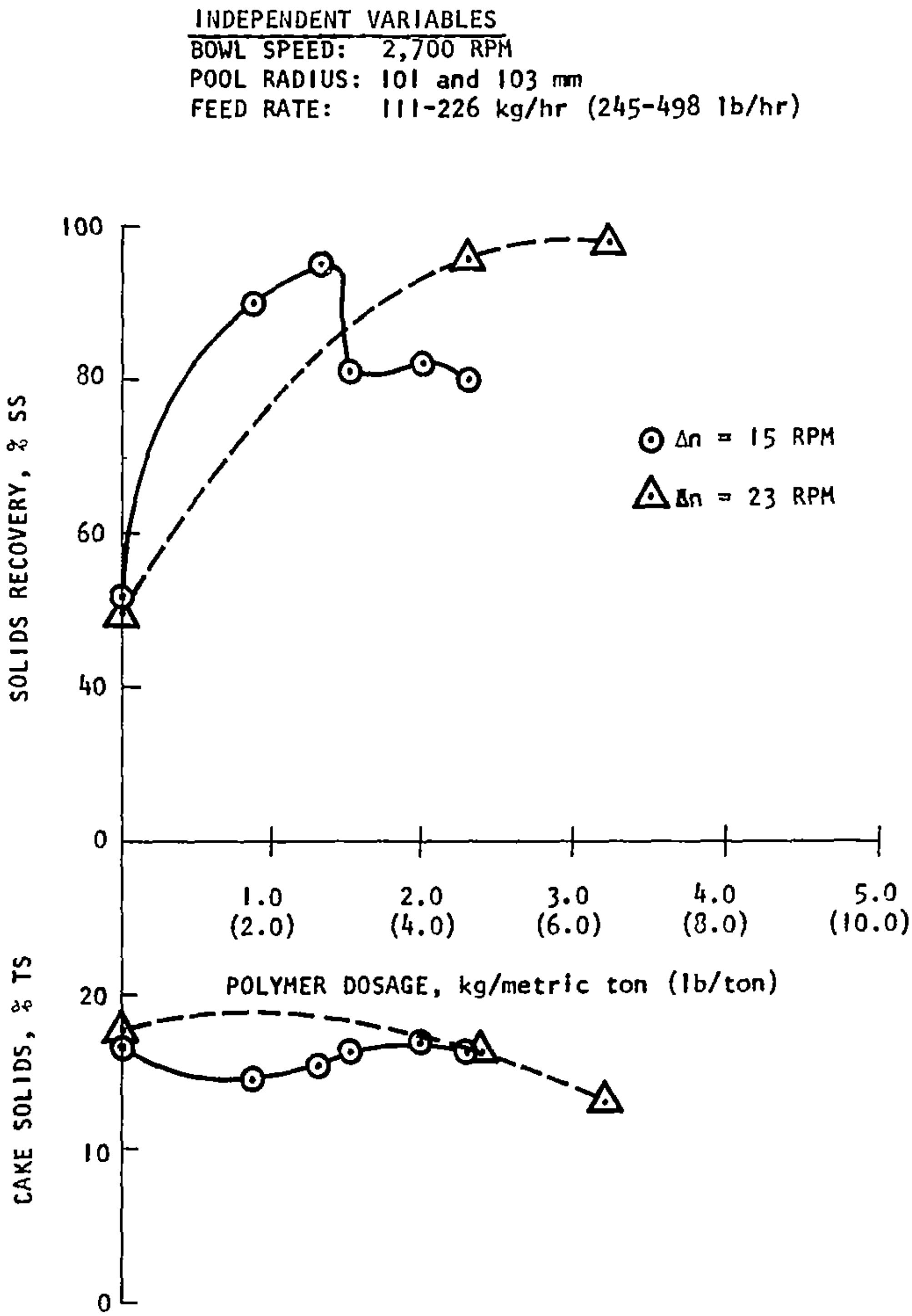


Figure 31. Cake solids and recovery vs. polymer dosage dry-weather sludge, Milwaukee, WI.

in metal consistency exists from parameter to parameter in Table 21. The trend established by the data, however, indicates that the heavy metals are mostly of the same magnitude for the feed, centrate, skimmings, and cake, and thus appear to be solids related.

The Milwaukee wet-weather sludge heavy metal concentrations are quite variable when compared to a previous sludge sample (1). For comparable samples with chemical addition, zinc increased from 799 mg/kg to 1415 mg/kg while lead decreased from 2063 mg/kg to 943 mg/kg. Nickel increased from 159 mg/kg to 943 mg/kg. Copper and chromium were up from previous values of 201 mg/kg and 243 mg/kg to present values of 2170 mg/kg and 1887 mg/kg. Mercury concentration also increased. These data indicate that heavy metal concentrations of the Humboldt Avenue CSO sludge are quite variable and cannot be adequately characterized by analyzing only a small number of samples.

The distribution of these wet-weather sludge heavy metals will play an important role in any future CSO pollution abatement studies.

The Milwaukee South Shore dry-weather heavy metal composites were obtained from the optimum full-scale decanter centrifuge runs of June 3, 1976. The results of these heavy metal analyses for the primary sludge feed, and the centrifuge centrate and cake are shown in Table 22. The heavy metal samples were taken from test runs in which polymer was utilized.

Zinc and chromium had the highest metallic concentration in the cake samples with values of 3300 mg/kg and 8550 mg/kg being obtained. Suprisingly, the distribution of lead in the samples indicated a low cake concentration (528 mg/kg), with an unexpected high centrate value (1430 mg/kg). These data would indicate metallic lead did not concentrate in the cake, which was typically found for the other metals.

The data generated at the two Milwaukee test sites are comparable to the Kenosha heavy metal data (Tables 10 and 11). That is, the heavy metals appear to be concentrated in the solids through centrifugation. Also, the highest metal concentrations observed at both Milwaukee and Kenosha were for zinc, copper, and chromium, while the lowest metal concentration was for mercury.

TABLE 22. HEAVY METAL CONCENTRATIONS FOR CENTRIFUGE TESTS USING MILWAUKEE DRY-WEATHER SLUDGE (PRIMARY)

Concentrations in mg metal/kg solids

	Feed	Centrate	Cake
Zinc	2700	1735	3300
Lead	750	1430	528
Nickel	445	240	525
Copper	705	380	840
Chromium	7600	4800	8550
Mercury	0.975	0.365	1.50

Polymer Dosage: 2.89 kg/metric ton (5.78 lb/ton)

SECTION IX

RESULTS OF SLUDGE THICKENING - CENTRIFUGATION STUDIES CONDUCTED IN RACINE, WISCONSIN

Racine, Wisconsin was the final thickening-dewatering test site utilized during this study. The test procedure for this third phase of the project was to conduct thickening-dewatering tests independently on both the dry-weather sludge and on the CSO generated wet-weather sludge. The dry-weather sludge was obtained from the Racine Water Pollution Control Plant and consisted of a proportional mixture of primary sludge, thickened digester supernatant, and thickened waste activated sludge. Dry-weather conditions were assumed to exist after five days without a CSO event. The primary plus thickened WAS sludge was used since it most closely resembled the gravity thickened CSO sludge. Also, if CSO sludge were returned to the Water Pollution Control Plant, it would be thickened in the primary settling basins. The wet-weather sludge consisted of a mixture of screening backwash water and floated sludge from the Dissolved-Air Flotation units which had been allowed to gravity thicken in a sludge holding tank.

BENCH SCALE GRAVITY THICKENING TESTS

The Racine bench scale gravity thickening tests were performed during the latter part of August, 1976. Tests were conducted on the dry-weather sludge, wet-weather sludge, and on an appropriate mixture of the wet-weather/dry-weather sludges. Dry-weather sludge consisted of a proportional mixture of waste activated sludge, digester supernatant, and primary wastewater. This mixture was used since WAS and digester supernatant are returned to the primary settling tanks for thickening. The wet-weather sludge consisted of screening backwash water and floated sludge combined proportionally by flow. Chemical addition was not studied since neither the Water Pollution Control Plant or the Screening/Dissolved Air Flotation CSO site utilizes chemical in their gravity thickening processes.

The method used to determine the correct amount of dry-weather and wet-weather sludge to be used in deriving the wet-weather/dry-weather sludge combination ratio is presented below:

1. Racine CSO area = 284 hectares (702 acres) (1).

2. Assume 50 percent of rainfall results in CSO.

3. Assume 1.27 cm (0.5 in.) of rainfall = 18,036,430 liters (4,765,250 gal.) of CSO.

4. Screening/dissolved air flotation will produce a sludge volume equal to 4.8 percent (1).

5. CSO sludge produced = 865,750 liters (228,732 gal.).

6. Assuming a two day bleedback: flow of CSO sludge to the holding tank = 433 m^3/day (114,366 gpd).

7. Average flow of dry-weather plant = 72,407 m^3/day (19,130,000 gpd).

8. Ratio of CSO sludge/dry-weather flow = .01/1.

Therefore, for each liter (.26 gal.) of CSO sludge produced, 100 liters (26.4 gal.) of dry-weather wastewater are generated. The results of the gravity thickening tests performed on the dry-weather sludge, the wet-weather sludge, and the wet-weather/dry-weather sludge combination are presented in Figures 32, 33, and 34. All of the thickening tests were conducted using the Coe and Clevenger method of gravity thickening analysis.

The flux concentration curve for the dry-weather sludge (Figure 32) determined that a thickened sludge concentration of 3.0 percent could be obtained at a mass loading of 1650 kg/m^2/day (338 lb/ft^2/day). If the solids loading to the thickener were reduced to 1150 kg/m^2/day (236 lb/ft^2/day), the resultant underflow sludge concentration could be increased to 3.5 percent. The wet-weather sludge settled very well and showed an excellent amenability to gravity thickening. The wet-weather flux concentration curve is presented in Figure 33. Good settling characteristics were also observed for this CSO sludge in the Phase I Report (1). In the Phase I gravity thickening tests, an underflow solids concentration of 15 percent was expected at an extremely high solids rate in excess of 2000 kg/m^2/day (400 lb/ft^2/day). In this report, underflow sludge concentrations of 14.0 percent were achieved at mass loadings of 1475 kg/m^2/day (302 lb/ft^2/day). The results of the wet-weather/dry-weather sludge combination thickening tests demonstrated that a 4.0 percent thickened sludge would be obtained at a 885 kg/m^2/day (181 lb/ft^2/day) mass loading. The flux concentration curve is shown in Figure 34. Although the resultant sludge concentration is slightly higher than those expected for the dry-weather sludge, the loading is lower.

It was recognized that all of the above mass loadings are appreciably higher than the typical design loadings suggested for gravity thickeners (14). Because of this, it is recommended that the above data be used only for comparative purposes and not as actual design criteria.

CENTRIFUGE DEWATERING TESTS

Decanter Centrifuge Results - Dry-Weather Sludge

The Racine dry-weather sludge centrifugation tests were conducted between August 2-9, 1976 using a horizontal decanter centrifuge. The sludge used for the dewatering tests consisted of a combination of primary sludge, thickened digester supernatant, and thickened waste activated sludge. This sludge mixture was pumped from the bottom of the Racine Water Pollution Control Plant's primary settling basins into a tank truck and transported

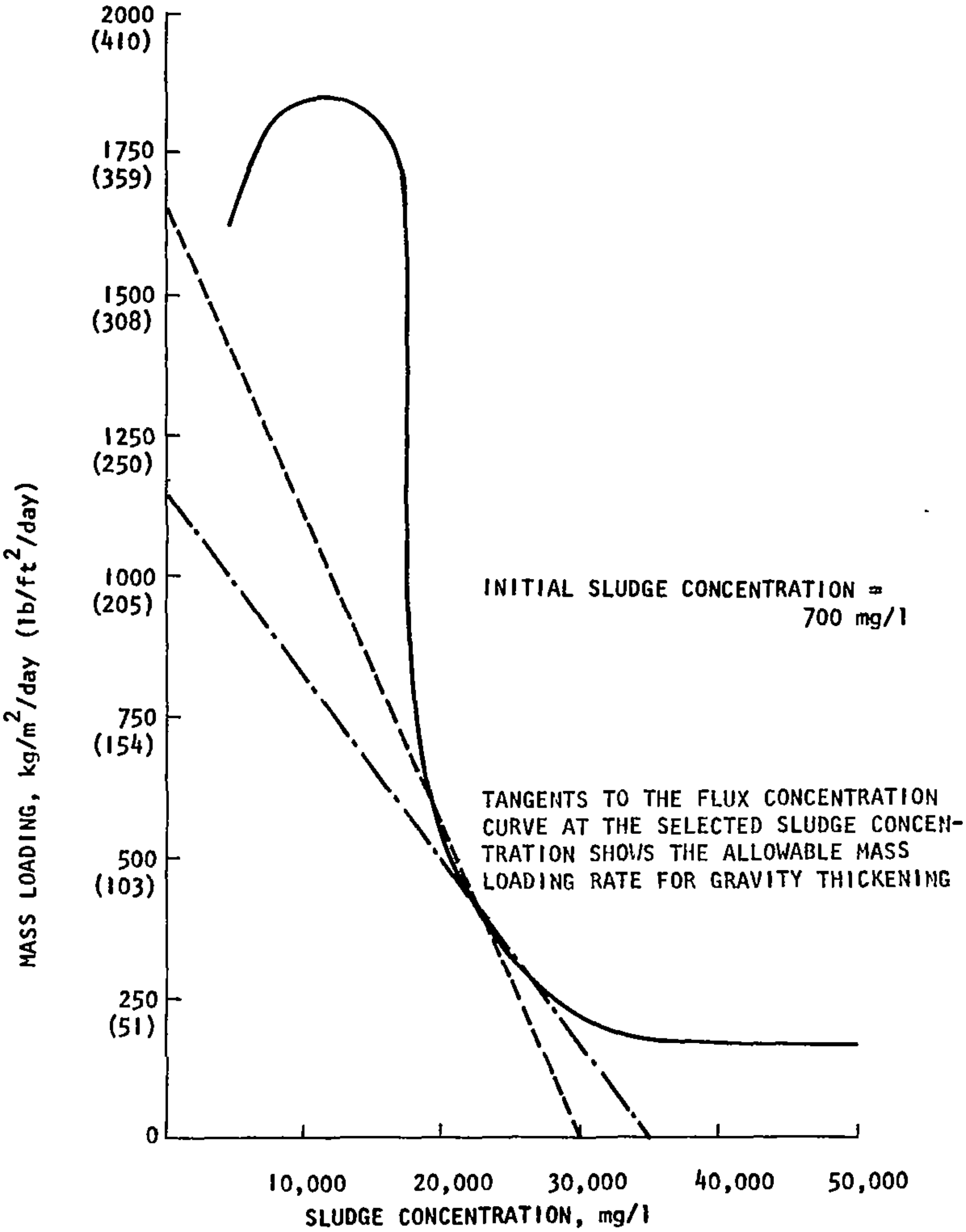


Figure 32. Flux concentration curve for dry-weather sludge, Racine, WI.

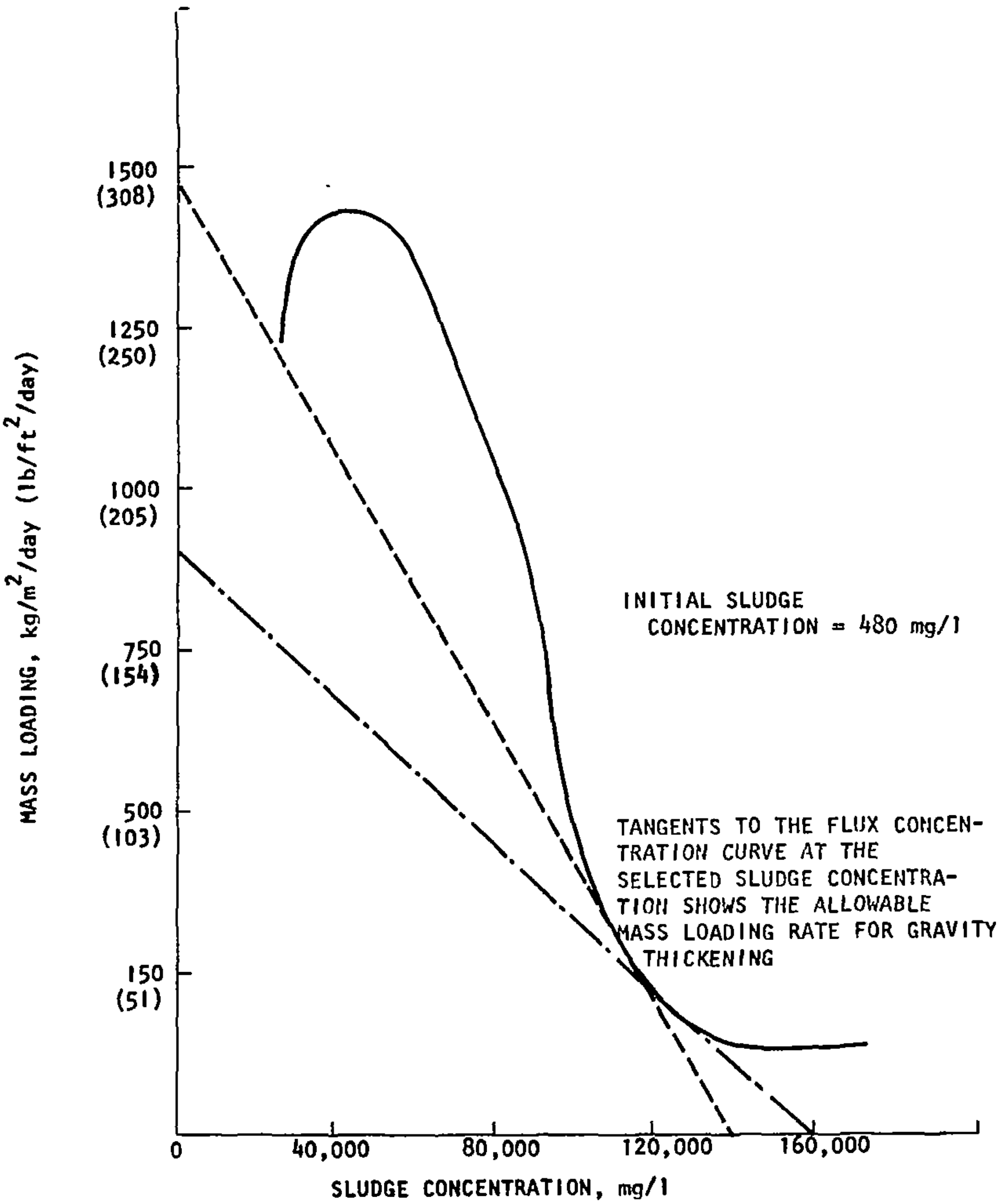


Figure 33. Flux concentration curve for wet-weather sludge Racine, WI.

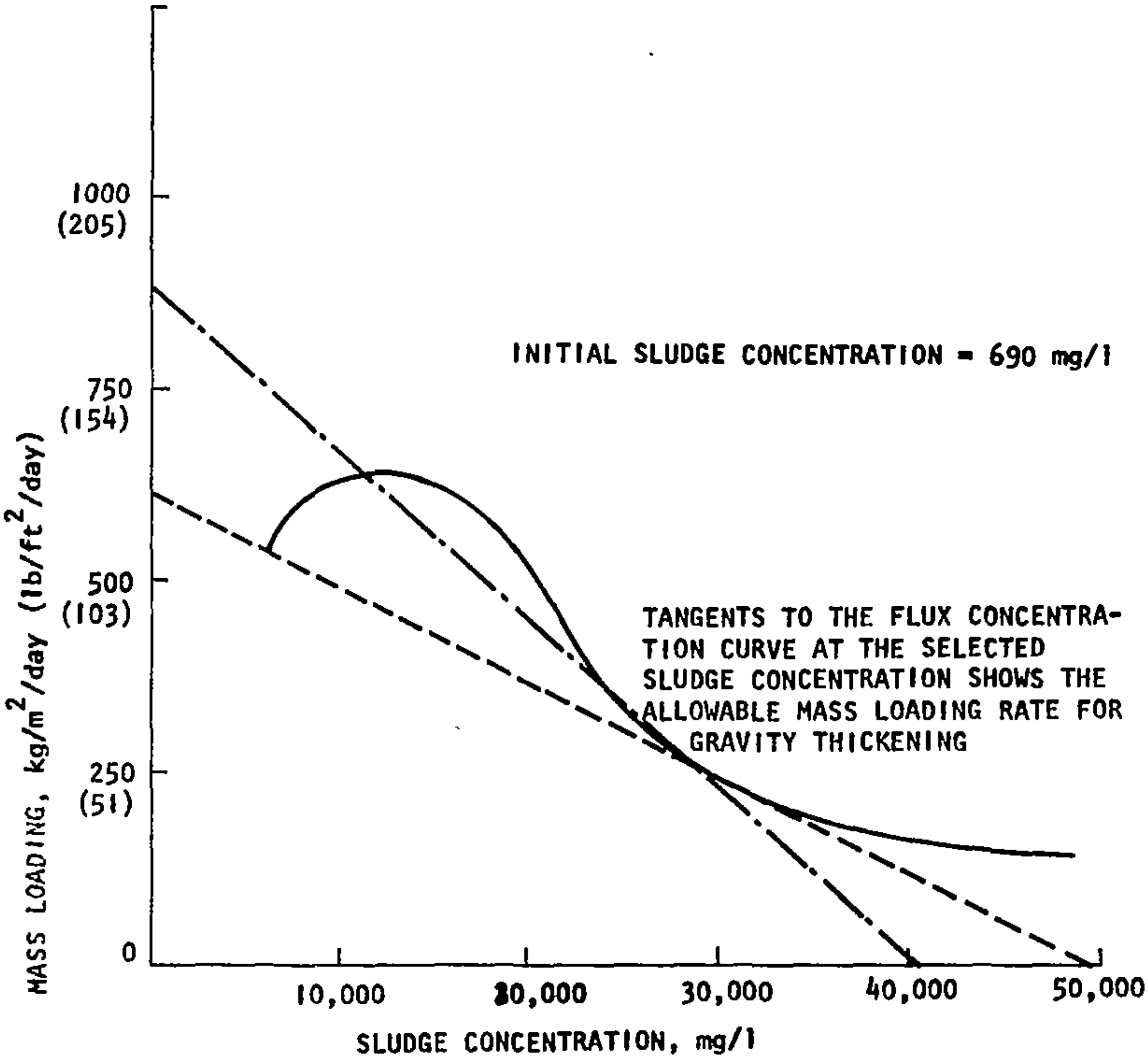


Figure 34. Flux concentration curve for wet-weather/dry-weather sludge combination Racine, WI.

to the mobile centrifuge van, which was located at the Racine wet-weather site. It became necessary to truck the dry-weather sludge because of the extensive construction being conducted at the Racine Water Pollution Control Plant.

In all, a total of 27 decanter centrifuge dewatering tests were conducted. Sludge in the tank truck was continuously recirculated by means of a high rate centrifugal pump and fed to the decanter centrifuge. The duration of each test run was 20-30 minutes, which is more than a sufficient amount of time required for the centrifuge to reach and maintain equilibrium. When equilibrium was reached, grab samples were taken of the feed, centrate, and cake. The samples from each day's test runs were returned to the lab and analyzed for total and total volatile solids, suspended and volatile suspended solids (when possible), or dissolved and volatile dissolved solids.

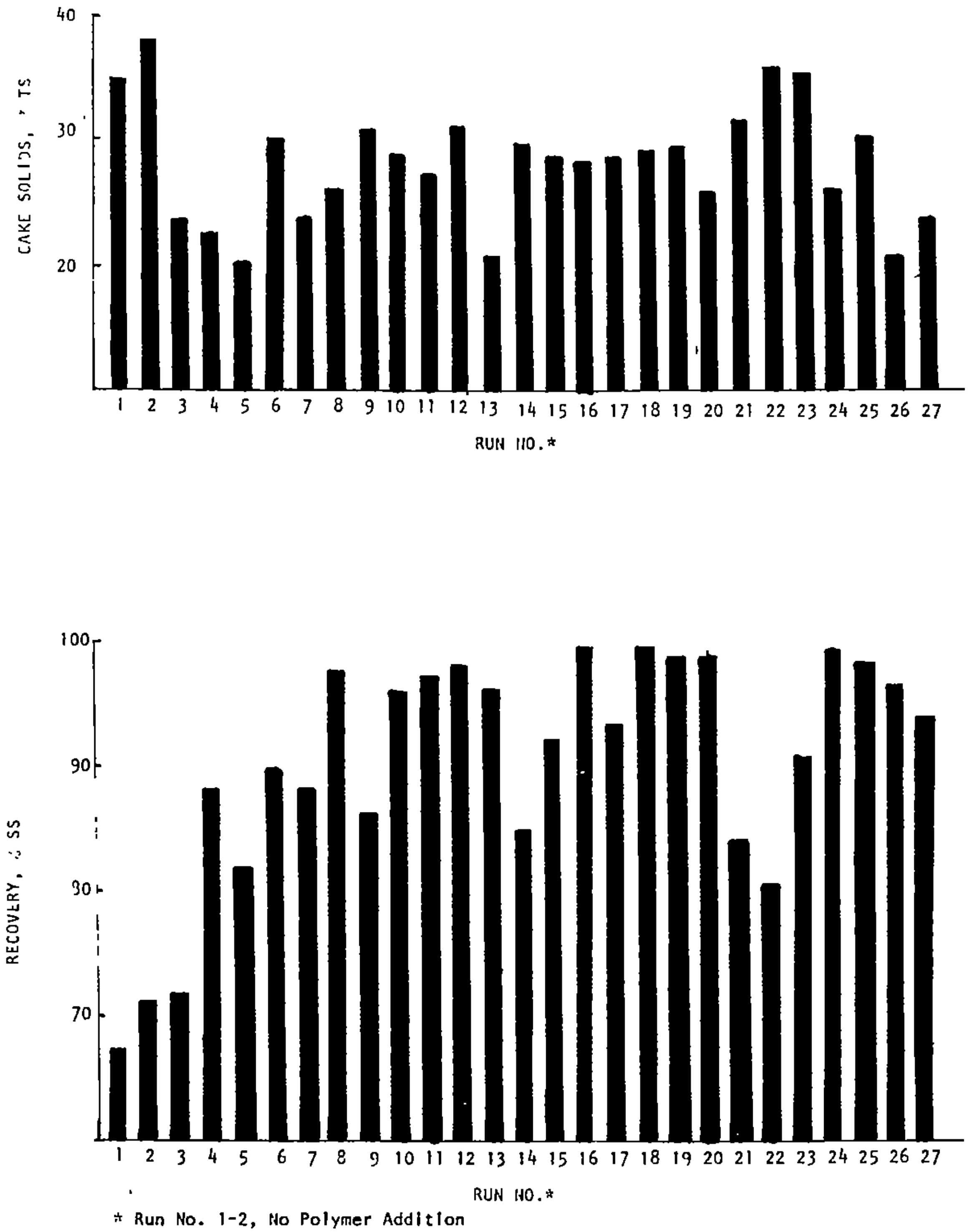
The majority of the tests were conducted with polymer, which was added to aid the dewatering process. Preliminary lab screening tests indicated that a cationic polymer, Percol 728, was the most effective. The polymer solution was prepared in concentrations of 0.1-0.2 percent.

Presented in Table 23 are the dewatering results of the 27 runs. Runs 1 and 2 were conducted without polymer addition. Although cake concentrations were high for these two runs (34.8 and 38.1 percent), solids capture was poor (67.1 and 71.5 percent), indicating the use of polymer would be required. Thus, runs 3-27 were conducted with polymer. The bar graph in Figure 35 demonstrates the increased recoveries obtained by adding polymer to the sludge at dosages ranging from 0.7-3.9 kg/metric ton (1.4-7.9 lb/ton). In several of the runs with polymer, capture rates in excess of 98 percent were achieved.

Figures 36 and 37 are typical plots of cake solids and recovery versus sludge feed rate for polymer dosages of 1.0-3.95 kg/metric ton (2.0-7.9 lb/ton). Differential speeds of 5, 15, 23 and 26 RPM are plotted. As shown in Figure 36, the sludge dewatered to a 20.0 to 30.8 percent cake. The highest cake solids with polymer addition were obtained at low feed rates and low differential speeds. However, the higher differential speeds provided more uniform cakes in an optimum feed range from 200-350 kg solids/hr (440-770 lb solids/hr). The plot also illustrates the effects of polymer on cake concentration. For example, for the plot of differential speed equal to 23 RPM, and reading right to left on the graph, cake solids decrease as polymer dosage increases from 1.6 kg/metric ton (3.2 lb/ton) to 1.8 kg/metric ton (3.5 lb/ton) and finally to 4.0 kg/metric ton (7.9 lb/ton). This pattern of decreasing cake concentration with increasing polymer dosage is also illustrated for Δn = 15 RPM. For a differential speed of 5 RPM, cake concentrations remain high at polymer dosages of 1.3 kg/metric ton (2.6 lb/ton) and 2.0 kg/metric ton (4.0 lb/ton), but decreases rapidly when polymer dosage is decreased to 1.0 kg/metric ton (2.0 lb/ton). All of the above information indicates that independent of feed rate, an optimum polymer dosage appears to occur between 1.3-2.5 kg/metric ton (2.5-5.0 lb/ton).

TABLE 23. RESULTS OF THE DECANTER CENTRIFUGE TESTS USING DRY-WEATHER SLUDGE - RACINE WATER POLLUTION CONTROL PLANT

Run No.	Feed Rate gal./min	Feed Rate l/min	Feed Rate lb/hr	Feed Rate kg/hr	Cake Concentration (% TS)	Recovery (% SS)
1	10.1	38.2	455	207	34.8	67.1
2	6.7	25.4	466	212	38.1	71.5
3	20.3	76.8	394	179	24.1	72.0
4	20.8	78.7	60	27	23.0	87.4
5	20.8	78.7	46	21	20.0	82.3
6	20.8	78.7	96	44	30.0	89.4
7	20.8	78.7	276	125	24.3	87.1
8	20.8	78.7	536	243	26.3	97.4
9	19.1	72.3	275	125	30.8	86.2
10	15.2	57.5	425	193	28.8	96.3
11	15.2	57.5	455	207	27.0	98.1
12	15.2	57.5	740	336	30.8	99.0
13	20.3	76.8	98	45	20.6	96.1
14	15.3	57.9	988	449	29.4	84.9
15	12.0	45.4	767	348	28.5	92.0
16	12.5	47.3	775	352	28.0	99.5
17	12.5	47.3	866	393	28.6	93.3
18	6.7	25.4	459	208	29.0	99.4
19	6.7	25.4	452	205	29.2	98.7
20	6.7	25.4	459	208	25.6	98.7
21	6.7	25.4	459	208	31.6	83.9
22	6.7	25.4	452	205	35.5	80.6
23	6.7	25.4	459	208	35.1	90.7
24	6.7	25.4	459	208	26.2	99.1
25	6.7	25.4	466	212	30.1	98.3
26	20.3	76.8	183	83	20.9	96.6
27	19.1	72.3	73	33	23.3	92.7



* Run No. 1-2, No Polymer Addition

Figure 35. Bar graph of cake solids and recovery vs. test runs, dry-weather sludge, Racine, WI.

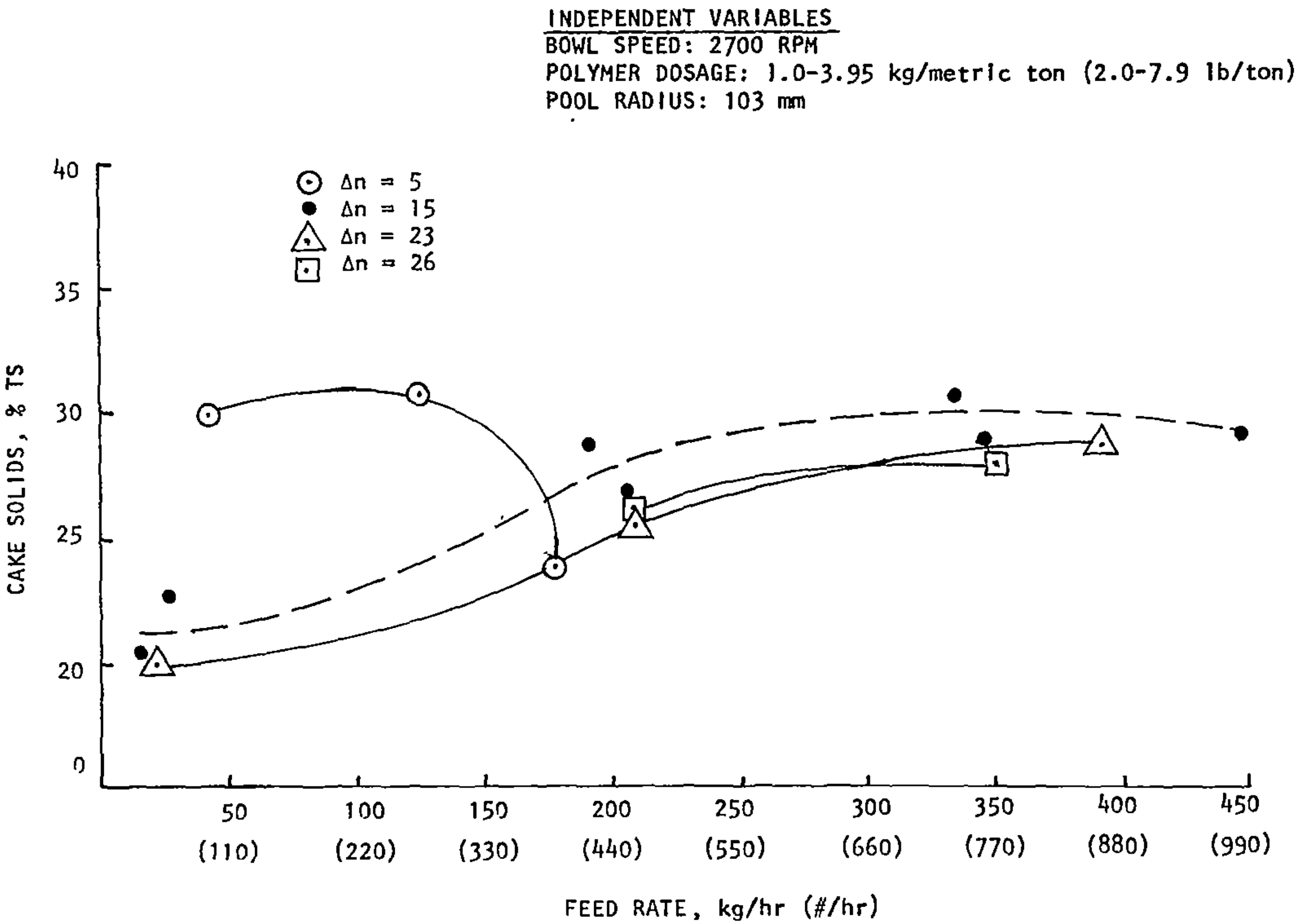


Figure 36. Cake solids vs. feed rate dry-weather sludge, Racine, WI.

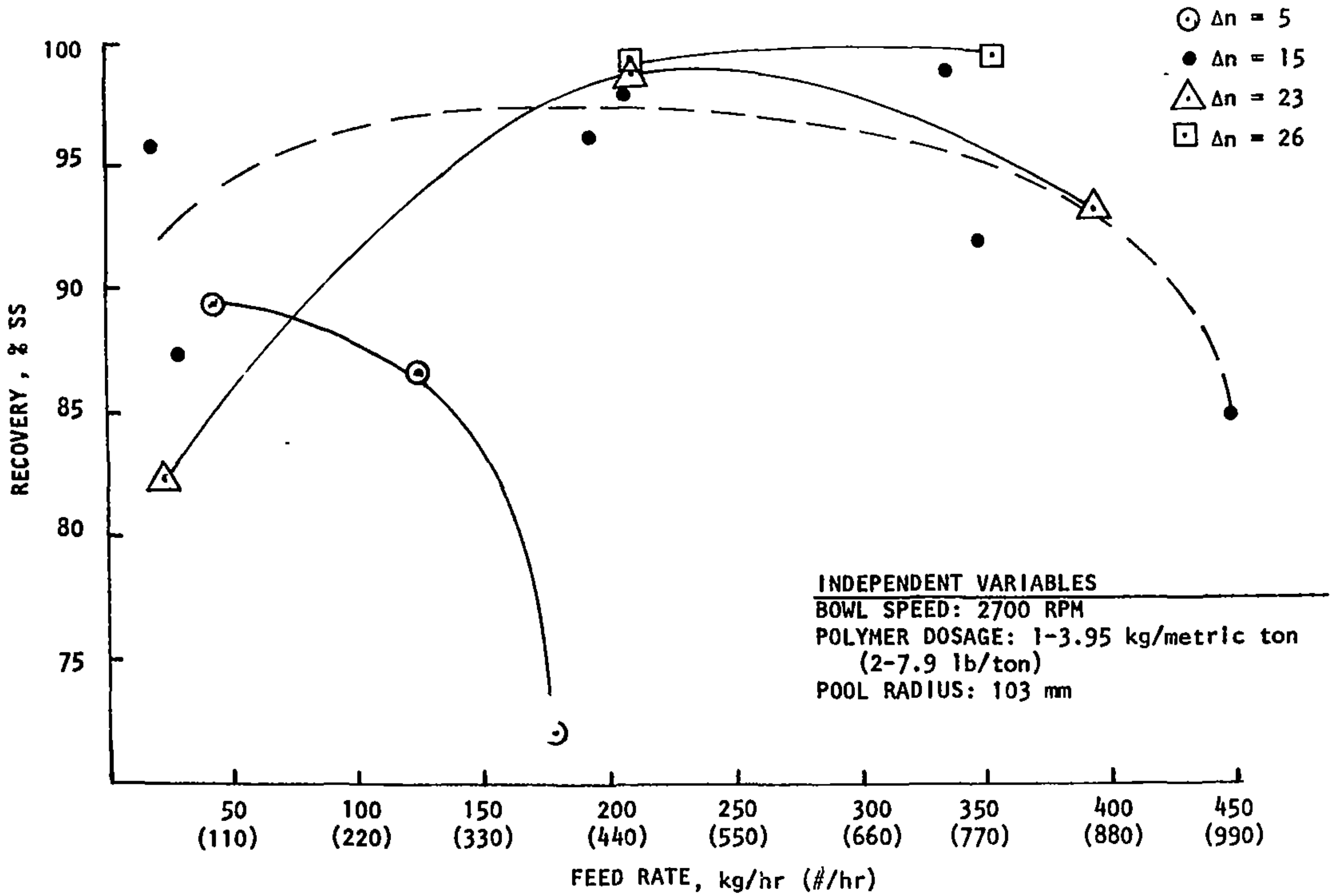


Figure 37. Recovery vs. feed rate (kg/hr) dry-weather sludge, Racine, WI.

The plot in Figure 37 shows the effects of varying feed rate, differential speed, and polymer dosage on solids capture. Recoveries ranged from 82 to 99 percent. The best solids captures were obtained at conditions similar to those observed for optimum cakes , that is, at high differential speeds of 15, 23 and 26 RPM, and at polymer dosages in the 1.3-2.5 kg/metric ton (2.5-5.0 lb/ton) range. Also, the optimum sludge feed rate for maximum solids recovery was again in the solids range of 200-350 kg/hr (440-770 lb/hr).

Polymer dosage versus cake concentration and solids recovery is plotted in Figure 38 for selected runs. Typically, as shown in the plot, the addition of polymer increases solids capture, while lowering the cake concentration. Optimum solids recoveries occurred in the 1.3-2.5 kg/metric ton (2.5-5.0 lb/ton) dosage range at differential speeds of 15 and 26 RPM. Figure 39 plots cake concentration and solids recovery against selected differential speeds (Δn) for polymer dosages of 1.75 and 2.55 kg/metric ton (3.5 and 5.1 lb/ton). As can be seen by the graph, optimum cake yields and solids captures were obtained at the higher differential speeds. Also, the higher polymer dosage of 2.55 kg/metric ton (5.1 lb/ton) provided more concentrated cakes with higher recoveries than the lower polymer dosage.

Decanter Centrifuge Results - Wet-Weather Sludge

Wet-weather sludge dewatering was conducted at the Racine screening/dissolved air flotation site between August 11-18, 1976. A CSO event occurred in Racine on August 10, 1976. The CSO screening backwash and floated sludge for the Racine wet-weather site are conveyed to a common holding tank. The sludge obtained from the CSO event was allowed to gravity thicken overnight in the sludge holding tank. On the following day, August 11, the supernatant in the holding tank was decanted off and the thickened sludge was dewatered using the decanter centrifuge. Although the thickened sludge was very dilute in nature, the decanter centrifuge was used to provide a comparison of data with the Racine dry-weather sludge. In all, a total of 12 dewatering runs was conducted. The individual test run data are detailed in Appendix Tables C-28 to C-39 with the tabulated results summarized in Table 24. The low solids feed rates are due to the diluteness of the thickened sludge. During the dewatering tests, thickened feed solids varied between a low of 0.05 percent to a maximum of 0.58 percent. Runs No. 1-4 were conducted without polymer. The effect of polymer addition on cake solids and recovery is illustrated in the bar graph of Figure 40. Concentration of Percol 728 polymer varied from 0.96-3.16 kg/metric ton (1.92-6.31 lb/ton). Solids capture generally improved with the addition of polymer. No significant decrease in cake solids concentration was observed when polymer was added to the feed sludge. All sludge was screened through a (.64 cm) (.25 in.) mesh screen to prevent machine damage.

The plot of cake solids and recovery versus feed rate for the dewatering runs in which polymer was not used is presented in Figure 41. The cake solids curve shows relatively uniform concentrations can be maintained at low loadings to the centrifuge. As expected at this low feed rate, recovery increases with increased loading to the machine. Recoveries

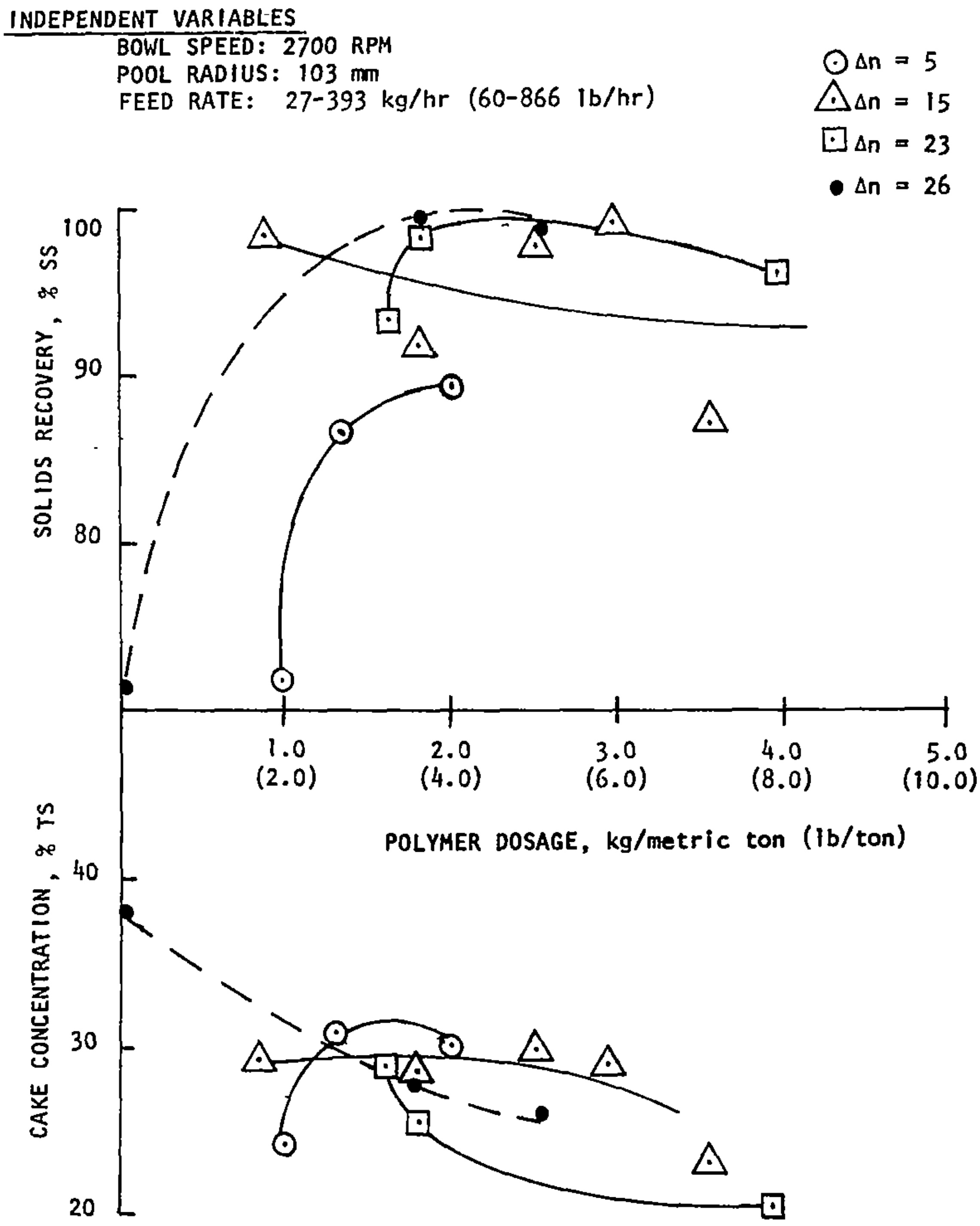


Figure 38. Cake solids and recovery vs. polymer dosage (kg/metric ton) dry-weather sludge, Racine, WI.

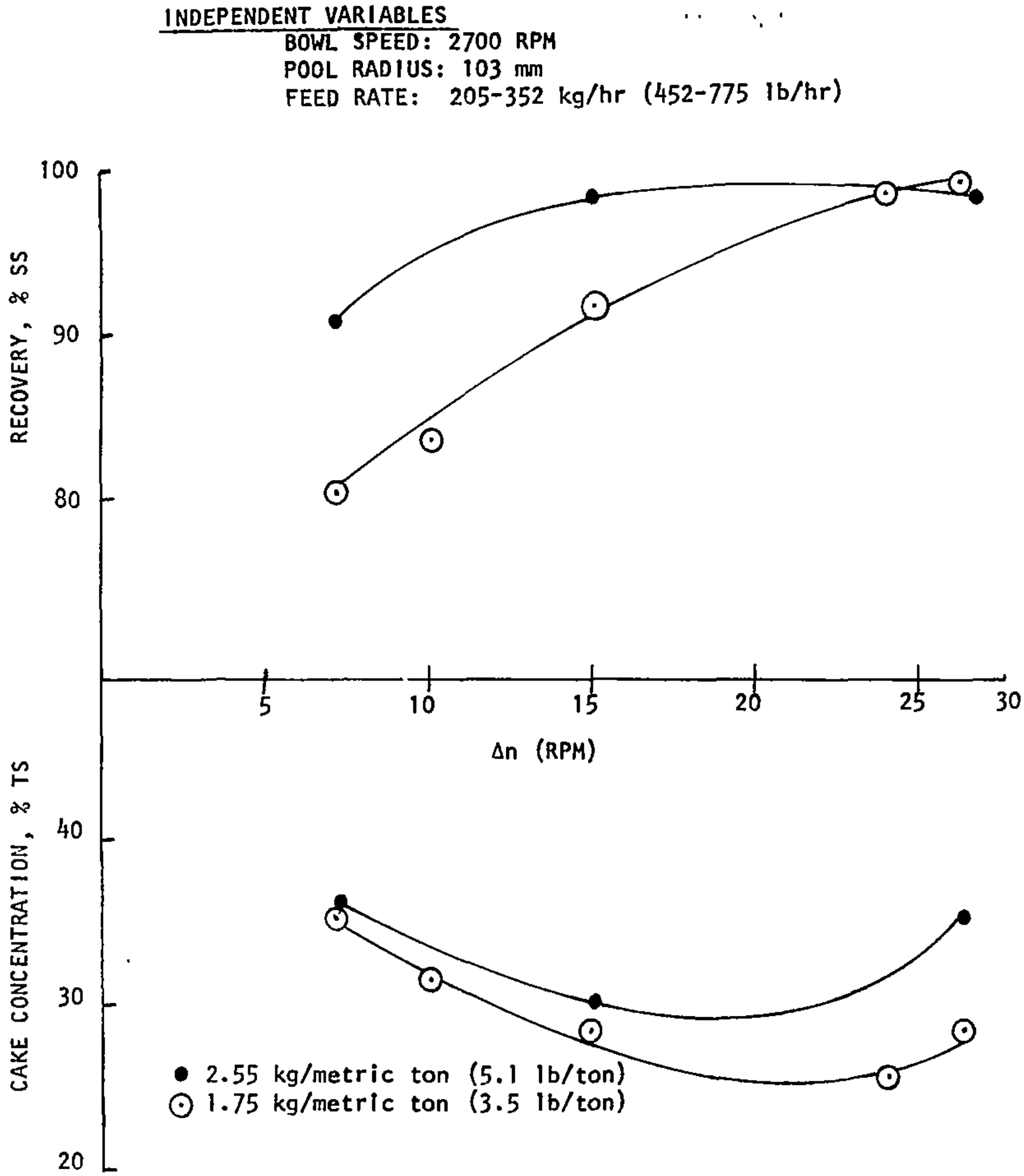


Figure 39. Cake solids and recovery vs. differential speed (Δn), rpm dry-weather sludge, Racine, WI.

TABLE 24. RESULTS OF THE DECANTER CENTRIFUGE TESTS USING WET-WEATHER SLUDGE - RACINE WET-WEATHER SITE NO. 1

Run No.	Feed Rate gal./min	Feed Rate l/min	Feed Rate lb/hr	Feed Rate kg/hr	Cake Concentration % TS	Recovery (% SS)
1	13.5	51.1	16.2	7.4	18.6	69.0
2	12.8	48.5	37.1	16.8	25.9	63.4
3	18.0	68.1	4.8	2.2	30.8	52.4
4	33.3	126.0	15.0	6.8	33.7	60.9
5	12.8	48.5	14.7	6.7	30.1	91.3
6	17.2	65.1	39.6	18.0	32.1	92.4
7	17.2	65.1	16.3	7.4	30.8	89.9
8	17.2	65.1	12.0	5.5	23.4	89.9
9	33.3	126.0	28.3	12.8	25.5	89.8
10	33.3	126.0	12.1	5.5	30.5	71.4
11	12.8	48.5	25.0	11.4	26.2	92.5
12	12.8	48.5	22.4	10.2	26.4	63.0

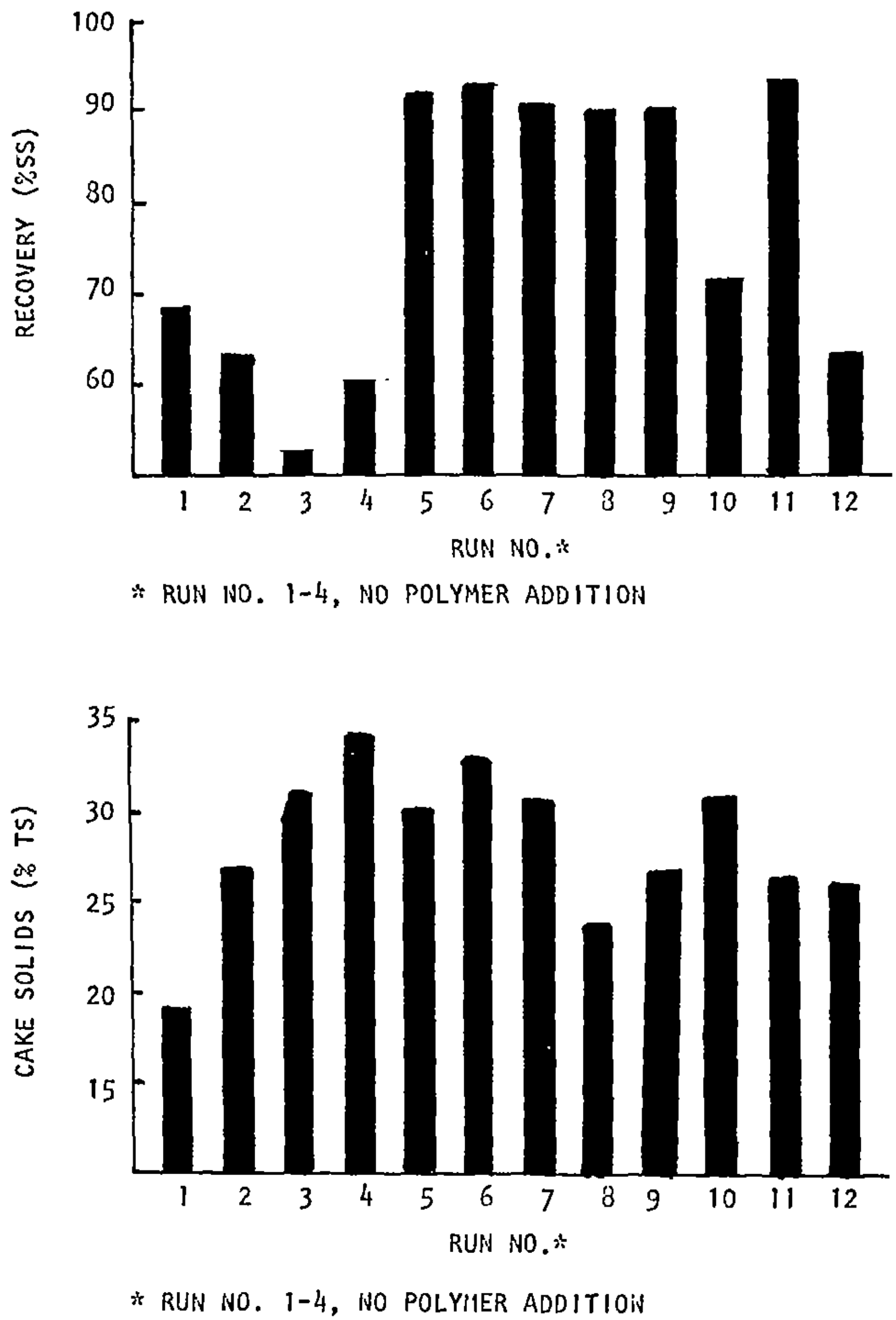


Figure 40. Bar graph of cake solids and recovery vs. test runs wet-weather sludge, Racine, WI.

INDEPENDENT VARIABLES
BOWL SPEED: 2,700 RPM
POLYMER DOSAGE: NONE
POOL RADIUS: 103 mm
DIFFERENTIAL SPEED: 15 RPM

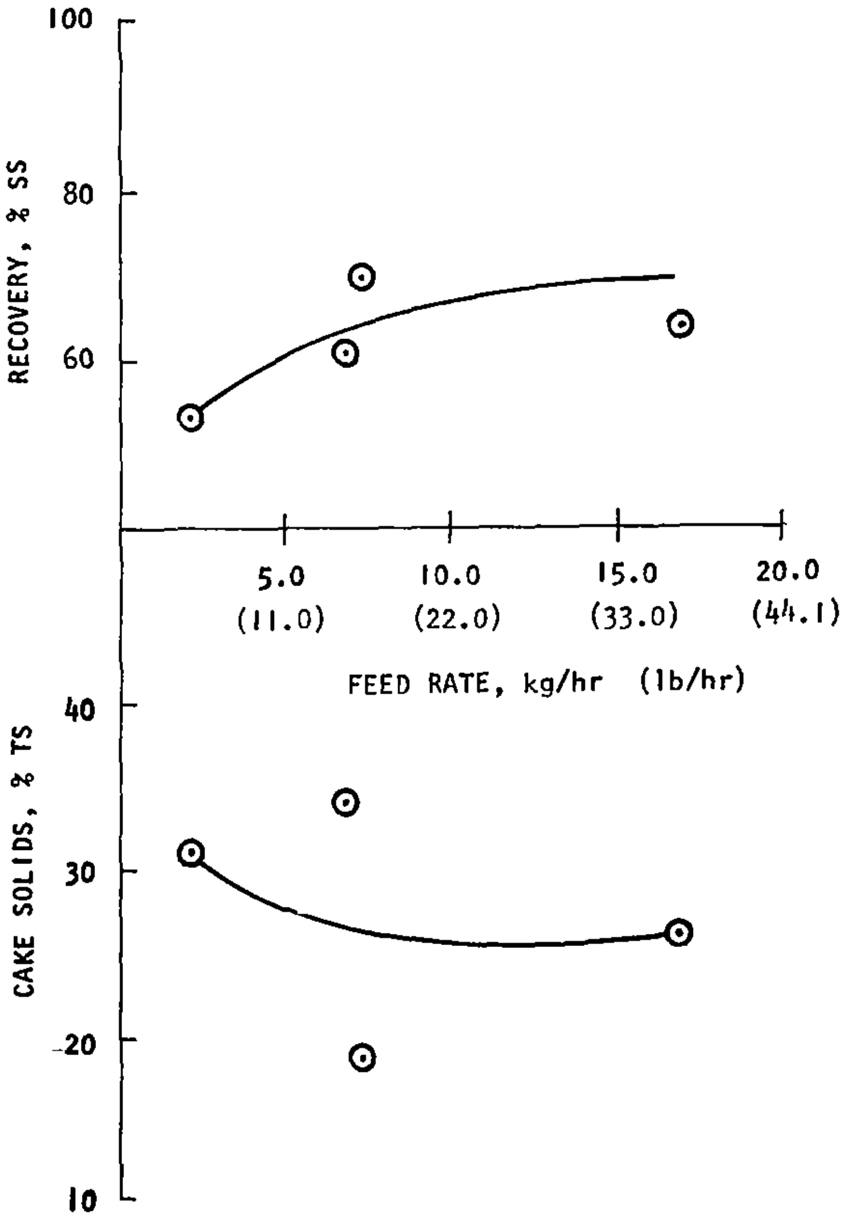


Figure 41. Cake solids and recovery vs. feed rate wet-weather sludge, Racine, WI.

without polymer varied between 52-69 percent. A similar graph for the eight runs in which polymer was used is shown in Figure 42. Three independent plots for differential speeds of 6, 10 and 15 RPM are shown. As in the previous graph, cakes remained uniform with concentrations ranging from 23.4 to 32.1 percent. The highest cakes were obtained at the higher feed rates and lower differential speeds. Solids recoveries varied from a low of 63 percent to a high of 92.4 percent. The bulk of the test runs were in the 90 percent capture range. Increasing feed rate had little or no effect on recovery. Variations in polymer dosage between 1.0-3.2 kg/metric ton (2.0-6.4 lb/ton) had only minimal effects on cake solids and recovery.

Differential speed versus cake solids and recovery for the runs with polymer addition has been plotted in Figure 43. The graph shows a uniform decrease in cake concentration with increasing differential speed. Optimum cakes were obtained at a differential speed of 6 RPM. Solids recoveries were good at Δn's of 6 and 15 RPM. However, a sharp decrease in centrate quality was observed at a differential speed of 10 RPM. If additional testing were conducted, it can be assumed that the recovery at $\Delta n = 10$ RPM would approach 90 percent. Presented in Figure 44 is the plot of polymer dosage versus cake solids and solids capture for differential speeds of 6, 10 and 15 RPM. The graph illustrates the increasing recoveries obtained by the addition of polymer. Cake concentrations only decreased slightly. Optimum polymer dosages were in the range of 1.0-3.2 kg/metric ton (2.0-6.4 lb/ton).

EFFECT OF CENTRIFUGATION ON HEAVY METALS DISTRIBUTION

Heavy metal composite samples were obtained from the Racine dry-weather sludge for the optimum runs of August 9, 1976. The wet-weather metal samples were composited from the best runs of August 11, 1976. For the Racine dry- and wet-weather sites, it was decided to analyze for both the total and soluble metal portions. Cadmium was also added to the list of analyses at both sites because of recent discussions with regard to plant uptake of this metal resulting from land application of municipal sludges. The results of the Racine dry-weather and wet-weather heavy metal determinations for the decanter centrifuge feed, centrate, and cake samples are presented in Tables 25 and 26. The metal analyses are reported on a dry basis of sludge with results shown as milligrams of metal per kilogram of dry sludge. Soluble metal data are reported in milligrams metal per liter of wet sludge. For the dry-weather sludge, the highest concentrations of metal observed were for lead and zinc with cake values of 7350 mg/kg and 2100 mg/kg, respectively, being reported. The lowest metal concentration observed was for mercury, which had a cake value of 1.507 mg/kg. The dry-weather sludge data also show that the soluble concentrations of the heavy metals are very low, with a centrate sample range from 0.02 mg/l for cadmium and chromium to 0.22 mg/l for zinc. Polymer was added to the sludge at a rate of 1.8 kg/metric ton (3.5 lb/ton).

The wet-weather heavy metal concentrations were typically less than the dry-weather concentrations for the metals analyzed. However, metal concentrations of the two sludges were often of the same magnitude. For the CSO sludge cake, lead and zinc were the most prevalent trace metals

INDEPENDENT VARIABLES
BOWL SPEED: 2,700 RPM
POLYMER DOSE: 0.96-3.16 kg/metric ton, (1.92-6.31 lb/ton)
POOL RADIUS: 103 mm

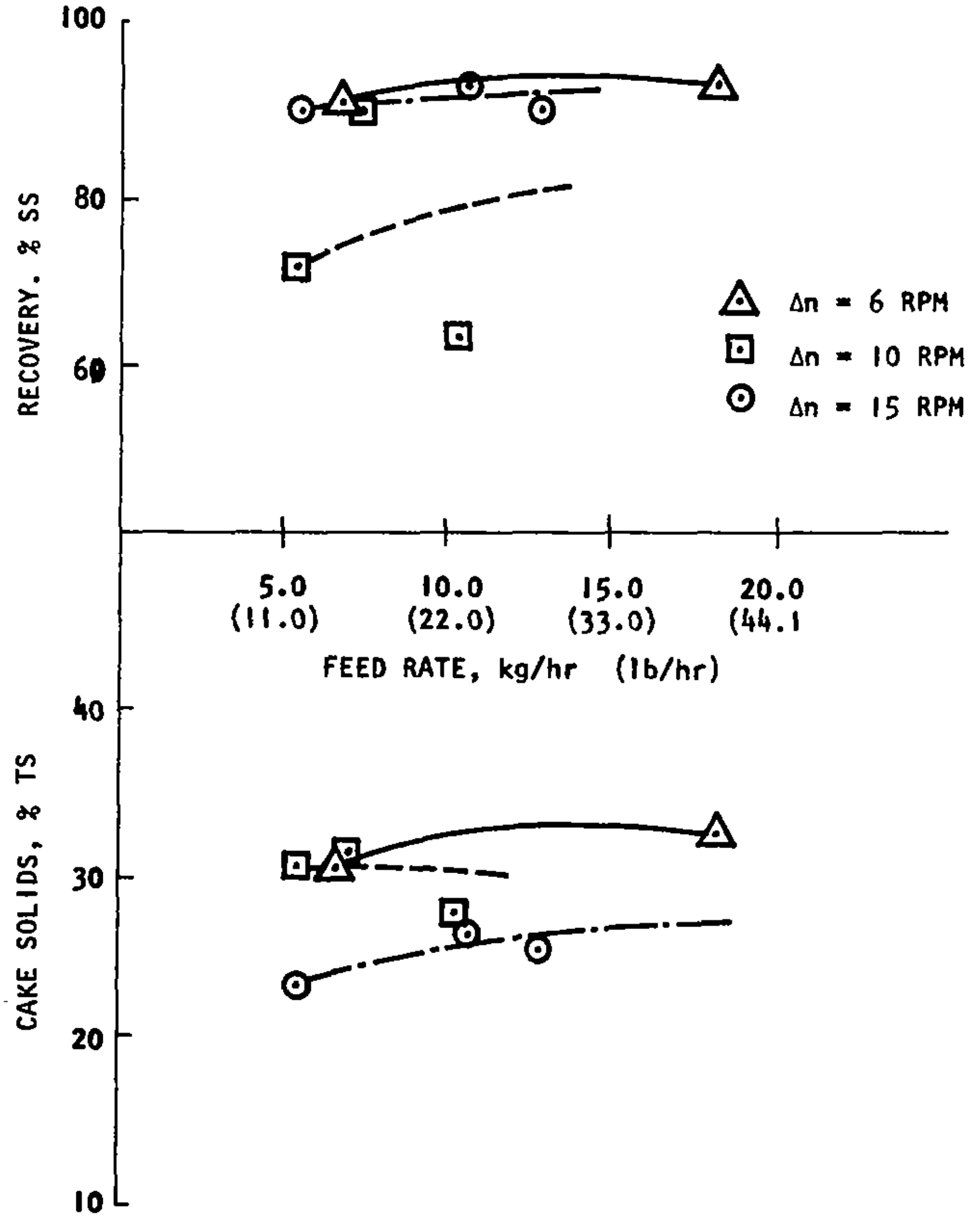


Figure 42. Cake solids and recovery vs. feed rate wet-weather sludge, Racine, WI.

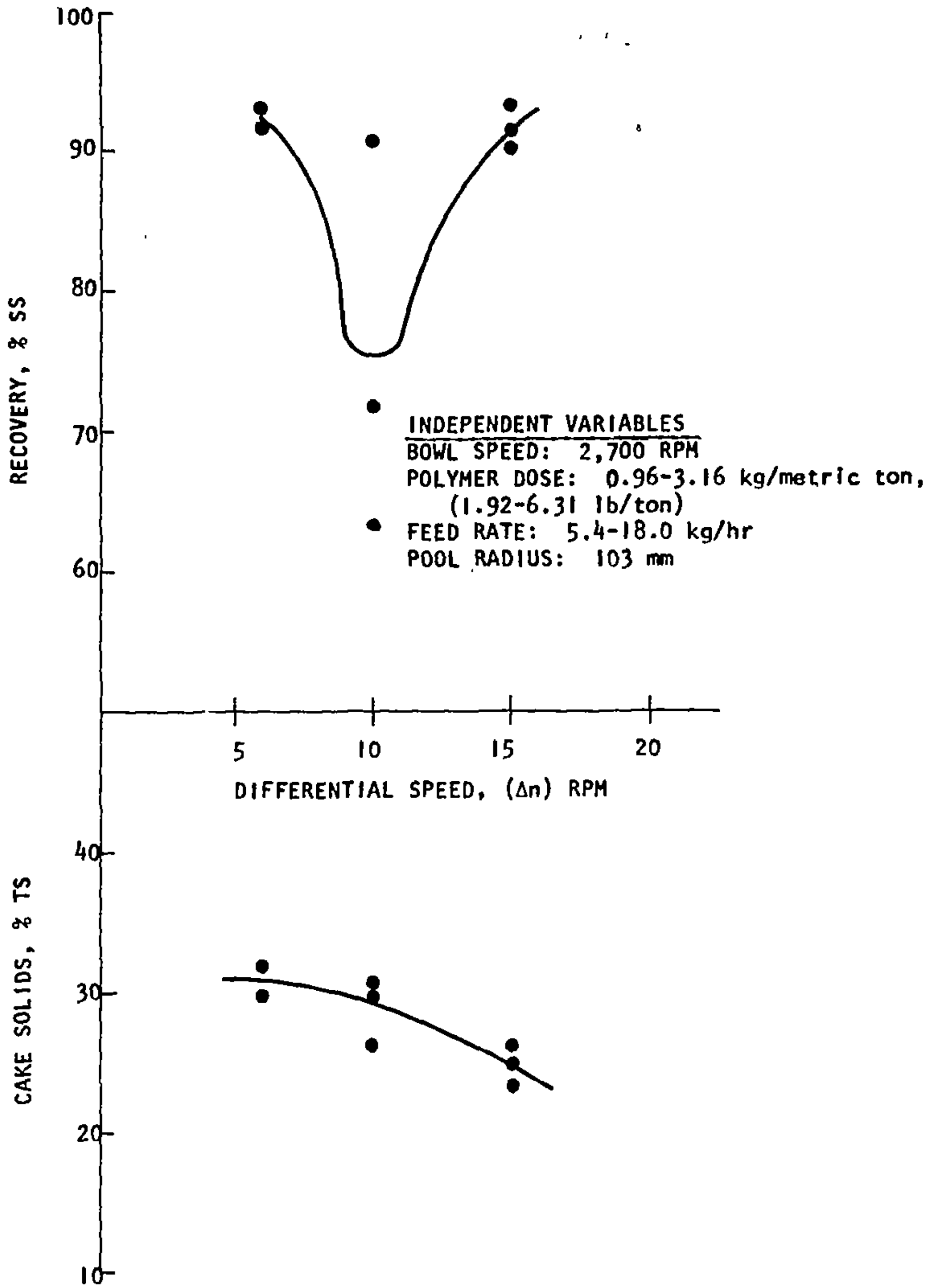


Figure 43. Cake solids and recovery vs. differential speed wet-weather sludge, Racine, WI.

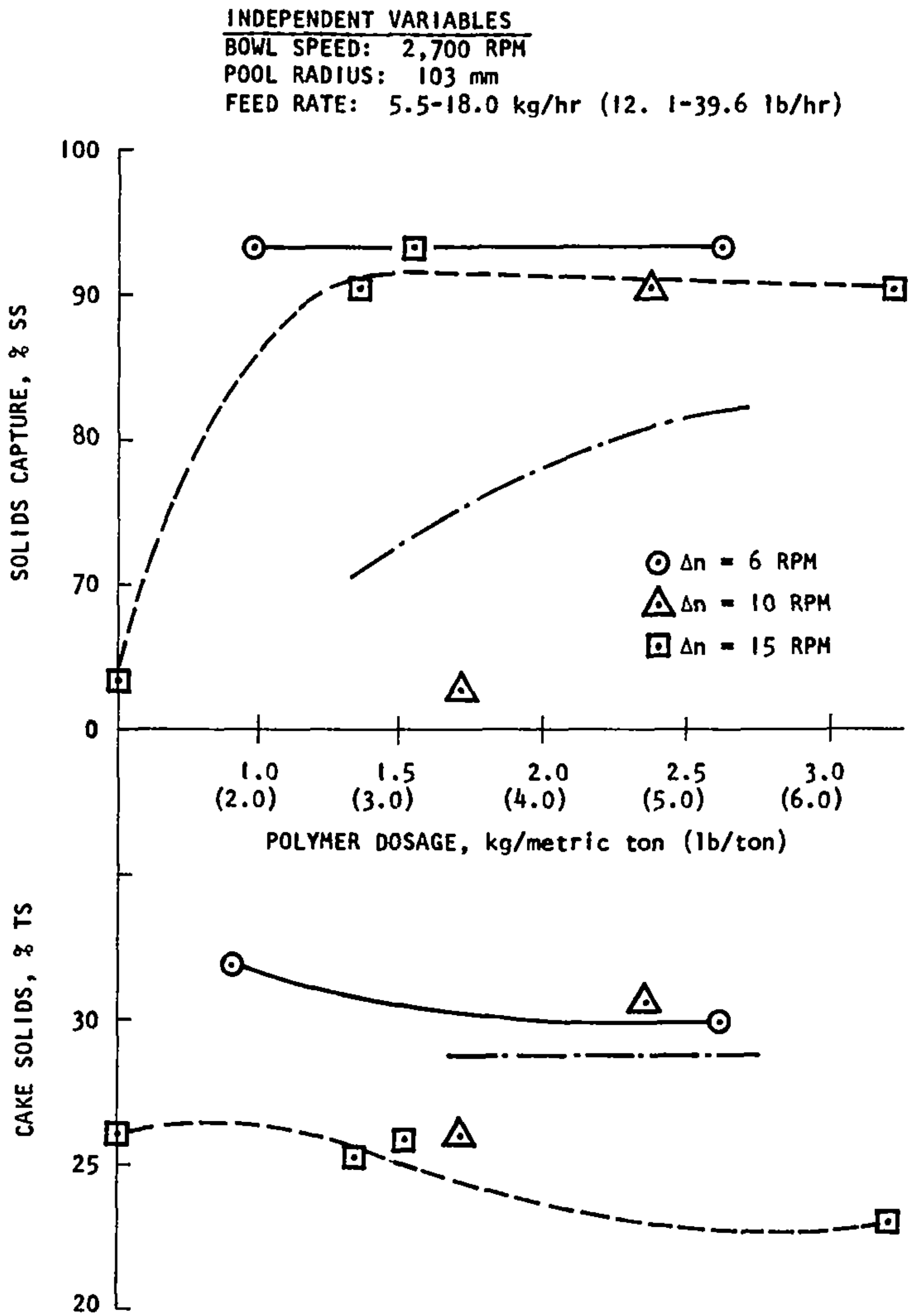


Figure 44. Cake solids and recovery vs. polymer dosage wet-weather sludge, Racine, WI.

TABLE 25. HEAVY METAL CONCENTRATIONS FOR CENTRIFUGE TESTS USING RACINE DRY-WEATHER SLUDGE

	Feed		Centrate		Cake
	mg metal/ kg solids	mg/l soluble	mg metal/ kg solids	mg/l soluble	mg metal/ kg solids
Zinc	1450	0.28	302	0.22	2100
Lead	6900	0.34	313	0.1	7350
Nickel	140	0.1	134	0.1	113
Copper	600	0.07	96	0.03	466
Chromium	755	0.13	154	0.02	550
Mercury	4.842	-	0.738	-	1.507
Cadmium	47	0.02	9	0.02	31

Polymer dosage: 1.8 kg/metric ton (3.5 lb/ton)

TABLE 26. HEAVY METAL CONCENTRATIONS FOR CENTRIFUGE TESTS USING RACINE WET-WEATHER SLUDGE

	Feed		Centrate		Cake
	mg metal/ kg solids	mg/l soluble	mg metal/ kg solids	mg/l soluble	mg metal/ kg solids
Zinc	710	0.08	247	0.02	640
Lead	420	<0.05	205	<0.05	1850
Nickel	490	<0.1	219	<0.1	80
Copper	250	0.03	164	0.03	380
Chromium	110	0.02	82	<0.01	180
Mercury	1.633	-	1.370	-	0.485
Cadmium	50	0.21	41	0.02	14

Polymer dosage: 2.28 kg/metric ton (4.56 lb/ton) with reported values of 1850 mg/kg and 640 mg/kg respectively. Mercury was the least prevalent with a cake concentration of 0.485 mg/kg. As with the dry-weather sludge, soluble CSO metal concentrations were low. The span for centrate was from <0.01 mg/l for chromium to 0.03 mg/l for copper. The low soluble concentrations suggest that the heavy metals are primarily insoluble and are associated with the solids present in the sludge. The polymer addition rate to the wet-weather sludge was 2.28 kg/metric ton (4.56 lb/ton), which is slightly higher than the 1.8 kg/metric ton (3.5 lb/ton) polymer dosage to the dry-weather sludge. The variations in polymer addition did not appear to significantly affect metal retention in the cakes.

From the Phase I report (1), heavy metal data for the Racine CSO feed sludge were higher by an approximate factor of two when compared to the values obtained from the August, 1976 data, except for nickel. In Phase I, (1), a nickel value of 215 mg/kg was reported as opposed to the 490 mg/kg value shown in Table 26. Significant variations in metal concentrations in differing samples were also observed in the Milwaukee CSO sludge.

SECTION X

RESULTS OF ANAEROBIC DIGESTION STUDIES

Laboratory anaerobic digestion studies were performed to evaluate the short and long term effects of feeding sludge containing storm-generated solids to bench scale anaerobic digesters on an intermittent basis under controlled conditions. The testing, sampling and evaluation procedures used as well as a description of the laboratory anaerobic digesters employed in the study have previously been described in Section VI.

The following provides the details of the investigations conducted using Kenosha and Racine, Wisconsin dry-weather and storm-generated sludges.

RESULTS OBTAINED USING KENOSHA, WISCONSIN DRY-AND WET-WEATHER SLUDGES

Start-Up, Debugging and Initial Testwork with Dry-Weather Sludges

Kenosha operates their full-scale digesters in the mesophilic temperature range using a mixture of primary and thickened waste activated sludge with a hydraulic detention time of 20 days and an organic loading of 1.1 to 1.4 kg volatile solids/m3/day (0.069 to 0.086 lb/ft3/day).

Initially, the two laboratory digesters were started up by feeding both digesters with dry-weather primary and waste activated sludges. This start-up period was preliminary to the actual investigation and was used to debug and shakedown the laboratory digester equipment, refine operating, sampling and analytical procedures, ensure that both systems were operating alike (to establish the normal variations in operating parameters that might result when feeding the two laboratory digesters alike), and to minimize any effect of previous storms to the digesting sludge initially obtained from Kenosha.

During the preliminary start-up period which extended for about 60 days, minimal data were obtained which are presented in Appendix D, Table D-1.

Digester Operation and Loadings with Wet-Weather Sludge

When a storm event occurs and the resulting CSO is treated to produce a waste sludge, the wet-weather sludge is proportioned to the digesters in addition to the dry-weather sludges. The additional full-scale digester loadings for various storm simulated CSO solids accumulations were developed and are presented in Table D-2 in Appendix D for various total rainfall amounts and for given full-scale digester feed addition times. This information was used in determining for a given storm event how the wet-weather sludge could be proportioned to the full scale digesters in relation to the addition of the dry-weather sludges. Having this information for the full-scale digesters permitted a sound basis for loading the laboratory digesters.

For example, for this study, the first storm event that occurred simulated a 1.27 cm (0.5 in.) rain event. The quantity of wet-weather sludge produced by this event was determined from Table D-2, Appendix D, allowing a forty-eight hour period (two feedings) to proportion the wet-weather sludge into the digester. The calculations for loading for full-scale digesters under this condition are presented in Table D-3, Appendix D, and the results indicated that the total hydraulic loading to the digesters would be increased by 40% for the two day period over the normal dry-weather loading. Therefore, for the laboratory digesters, the amount of sludge fed to the two digesters for the two day period was increased by 20% per day over the normal dry-weather feed, that is, the control laboratory digester received the increase in dry-weather sludge whereas the test (or variant) digester received the increase in actual CSO sludge.

The laboratory digesters, both control and test (variant), also had a 20 day hydraulic retention time and an organic loading rate within the range of that for the Kenosha full-scale digesters (see Table 27).

From Table 27, this study was comprised of four periods of investigation which are described below. The raw data obtained for each period of study are tabulated in Table D-4, Appendix D.

In Table 27, the control period (day 1 to 14) represented that period during which both digesters were fed only dry-weather primary and waste activated sludges in the same manner as during the preliminary start-up period except that more complete analyses and data were obtained during the control period. Again, the purpose of the control period was to show that both digesters were operating in a similar manner and to establish the normal variations in operating parameters that might result when feeding the two laboratory digesters alike.

The first simulated storm event occurred on day 15 (period #1, Table 27) and simulated a 1.27 cm (0.5 in.) rain event. The effect of this event upon the feeding of the two laboratory digesters was previously described. The second simulated rainfall (day 25, period #2, in Table 27) imposed a potentially more severe shock load to the digesters in that it simulated a 2.54 cm (1 in.) rain and the entire sludge accumulated was added with the normal daily loading amounting to an increased loading of 62 percent over normal, (again both digesters were subjected to the loading shock under similar conditions as outlined for simulated storm #1).

During Period #3, an attempt was made to determine if the wet-weather waste activated sludge used was measurably different from dry-weather waste activated sludge. During period #3, only waste activated sludge (no primary) was fed to both digesters.

The volatile solids were monitored in the feed and withdrawn sludge on a

TABLE 27. MONITORING PARAMETERS FOR CONTROL AND VARIANT LABORATORY DIGESTERS (KENOSHA SLUDGES)

Period	Control		#1		#2		#3	
Day from test start	1 to 13		14 to 24		25 to 32		33 to 43	
Digester*	C	W	C	W	C	W	C	W
Volatile solids loading ($kg/day/m^3$)	1.14	1.14	1.14	1.14	1.11	1.09	0.98	0.97
Gas production (ℓ/day)	6.3	6.2	7.6	7.4	8.6	9.1	5.8	5.2
standard deviation	±0.5	±0.5	±1.1	±1.1	±1.1	±0.9	±0.8	±0.8
Methane production (ℓ/day)	4.2	4.2	5.2	5.1	5.8	6.2	4.0	3.6
standard deviation	±0.4	±0.3	±0.7	±0.8	±0.6	±0.5	±0.5	±0.5
Ratio, CO_2: CH_4	47	47	46	45	49	46	41	40
standard deviation	±3.1	±4.1	±2.4	±1.6	±3.8	±2.9	±2.8	±3.6
m^3 gas/kg vol. sol destroyed	0.81	0.81	1.03	1.00	1.05	1.23	0.72	0.83
Volatile solids								
feed sludge, %	60	60	60	60	61	60	63	60
digested sludge, %	48	49	49	49	48	48	48	49
% reduction **	38	36	36	36	41	38	46	36
Average temperature, °C	33	38	29	37	32	37	32	37
standard deviation	±1	±1	±1	±1	±1	±1	±1	±2
Storm simulation rainfall - cm(in.)	None		1.27 (0.5)		2.54 (1)		--	

Note: In all tests performed, volumetric retention time = 20 days.

* C = control or dry-weather digester; W = test (variant) or wet-weather digester.

** Calculated as per Reference (8).

daily basis and were used as a measure of organic loading. The volatile solids data in Table 27 indicate very little change was detected in the organic content of the feed or in the subsequent reduction of volatile solids until the third period (waste activated sludge feed only) during which time the control showed a 10% increase in the reduction of volatile solids compared to the digester being fed the storm generated waste activated sludge. This apparent improvement in digester performance may be attributed to the fact that the volatile solids fraction of the dry-weather waste activated sludge was 3% higher than the wet-weather digester feed (8). The total solids were about 0.7% lower for period #3 than for the entire preceding time (3.1 vs. 3.8%). The actual loading in kg volatile solids/m^3/day dropped from 1.1 to 0.98 for the control digester from period #2 to period #3. A similar decline in organic loading was observed in the digester receiving wet-weather waste activated sludge.

pH, Volatile Acids and Alkalinity of Digester Sludge

A plot of the difference in digester sludge pH (control digester minus test digester) is presented in Figure 45a. The line $\bar{x}_c$ represents the average difference for the control period. The two horizontal lines above and below $\bar{x}_c$ represent the limits of the range in which 95% of the individual difference values may be expected to occur. These upper and lower range lines are based on the standard deviation (±1.96 times standard deviation) of the differences measured during the control period. During the 43 days of operation the pH exceeded the confidence interval of the control period seven times. The actual pH for both digesters was in the range of 7.3 to 7.7. The pH tended to be slightly more basic in the control digester as indicated by the fact that the plot crossed the upper confidence interval 5 times. The pH exceeded the imposed confidence interval 3 times during the actual feeding of wet-weather/dry-weather sludges; once on day 25 (after the simulated 1 inch rain with 24 hr. bleed-in) and twice during the feeding of wasted activated sludge only in period #3. The other four times the pH difference fell outside the interval both digesters were receiving the same feed. The paired t-statistic for each period (used to interpret long term effects) indicated the pH was statistically equal during the entire 43 day run (95% confidence level, see Table 28).

The raw data in Table D-4, Appendix D show very little change in digester alkalinity for the periods investigated, which averaged 4,000 mg/l as $CaCO_3$. The same observation can be made for volatile acids which were typically between 110 and 210 mg/l as acetic acid. This range occurs on the lower end of the useful range of the analytical procedure and must be considered as much method induced as digester induced.

Gas Production

Table 27 summarized the gas production parameters typically monitored or suggested as sensitive indicators of digester performance for each of the four periods. These include total gas production (dry gas at standard temperature and pressure) in l/day, rate of methane production in l/day,

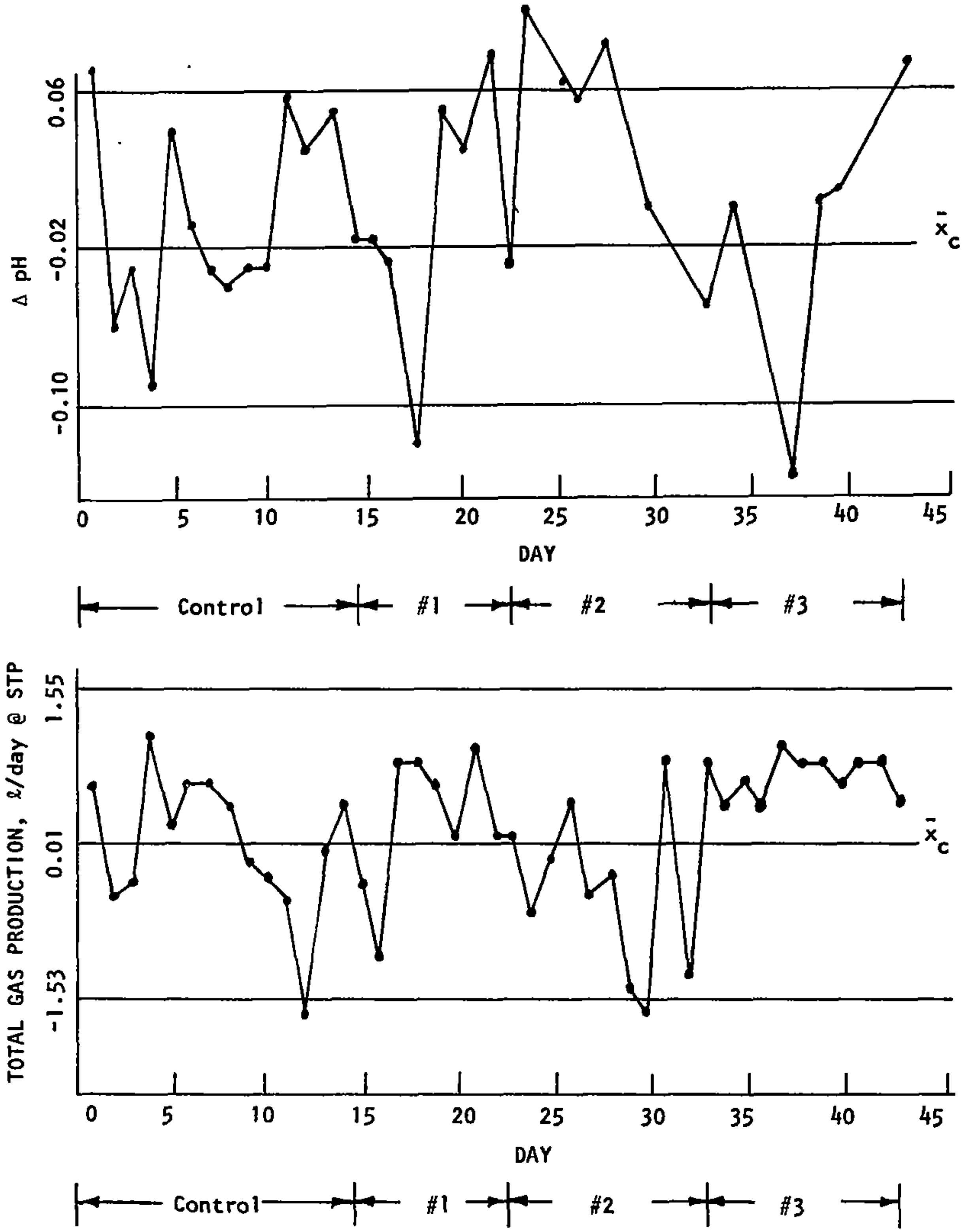


Figure 45a and 45b. Effect of wet-weather sludge on anaerobic digestion - Kenosha study (control digester minus test digester pH and total gas production values).

ratio of methane to carbon dioxide, and an efficiency parameter of volume of gas produced per unit weight of volatile solids destroyed (m3/kg). Both the average total gas production and the efficiency of conversion of volatile solids to gas tended to increase through day 32. The plot of differences in Figure 45b for total gas production shows the increase was consistent for both digesters and could not be related to wet-weather sludge effects as measured by the paired t-test (see Table 28) except for period #3. There were no apparent short term effects of storm generated sludge on total gas production during this phase of the study. The total gas production exceeded the 95% confidence interval only twice and both times were during identical loadings.

During period #3, when the digesters were fed waste activated sludge only, all the monitored gas production parameters were at a lower level. The control digester, however, produced significantly more total gas and methane than the test digester (see Table 28 and Figures 45b and 46b). The greater gas production observed for the control digester is probably due to the higher reduction in volatile solids during this period (8).

There was no apparent significant difference in the carbon dioxide to methane ratio between the two digesters for the periods investigated that could be related to the addition of wet-weather sludge (see Figure 46a and Table 28).

TABLE 28. T-STATISTIC TEST RESULTS (KENOSHA STUDY)
(5% SIGNIFICANCE LEVEL)

Parameter	Control period	Period #1	Period #2	Period #3
Gas production (l/day)	C = W(11)*	C = W(10)	C = W(7)	C ≠ W(9)
Methane production (l/day)	C = W(11)	C = W(9)	C = W(7)	C ≠ W(8)
Ratio: CO_2/CH_4	C = W(11)	C = W(9)	C = W(7)	C = W(7)
pH	C = W(11)	C = W(8)	C = W(3)	C = W(5)

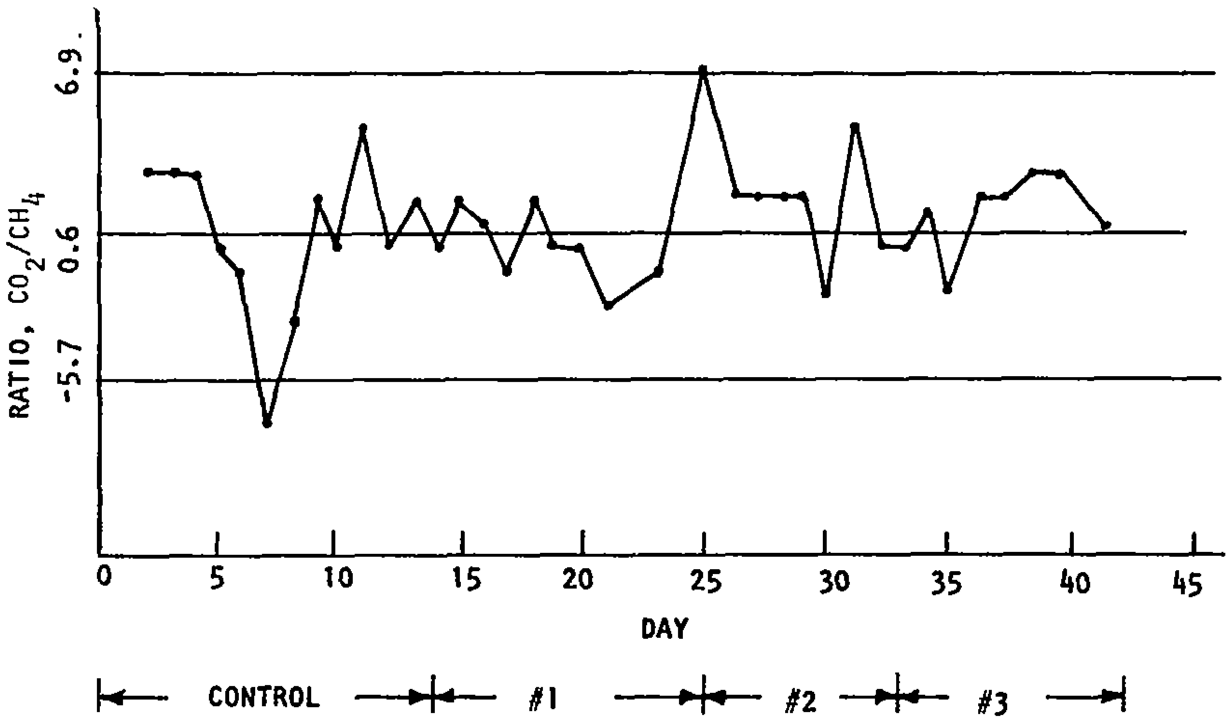
Notes

* Numbers in parentheses are degrees of freedom

C = Control or dry-weather digester
W = Test (variant) or wet-weather digester

Heavy Metals

Total heavy metal (mercury, lead, zinc, nickel, copper, chromium, iron



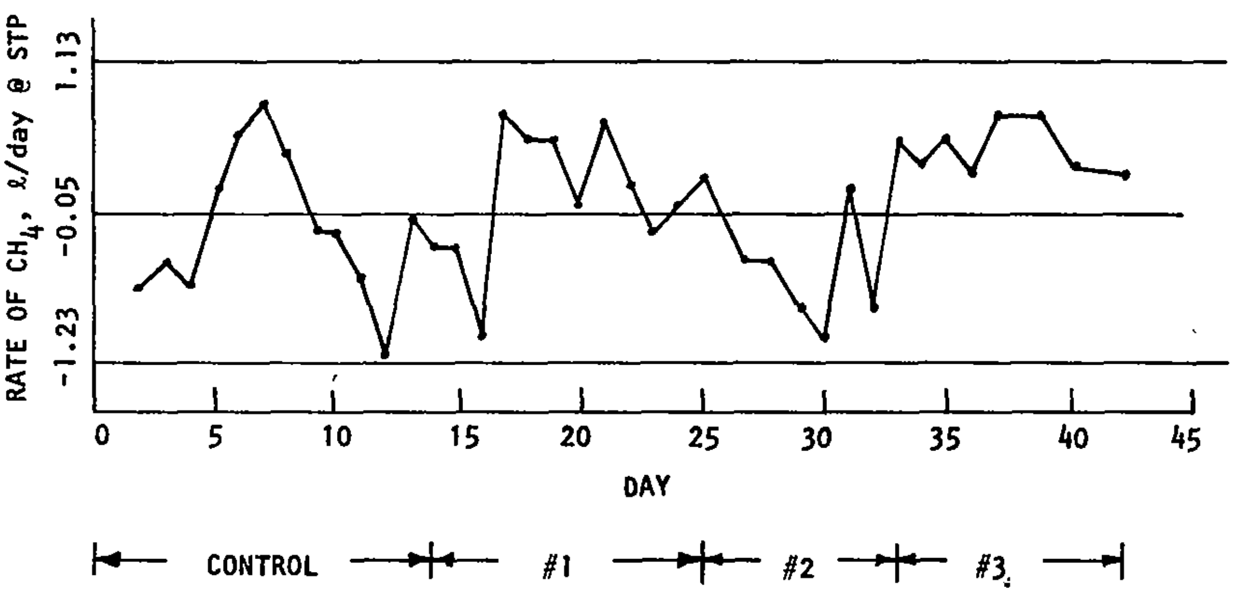


Figure 46a and 46b. Effect of wet-weather sludge on anaerobic digestion - Kenosha study (control digester minus test digester CH_4 and CO_2/CH_4 values).

and cadmium) analyses were performed six times during this investigation on wet-and dry-weather digester feed sludges and on digester sludges from both control and test digesters. The raw metals data obtained are presented in Table D-5, Appendix D and are reported on both a wet weight and dry weight basis. The metal analyses of the digester feed samples are in agreement with those previously obtained from Kenosha dry-weather WAS and CSO waste sludges and reported in Tables 10 and 11.

Soluble heavy metal (lead, zinc, nickel, copper, iron and cadmium) analyses were also performed, near the beginning and end of the investigation, for both digester feed and digester sludge samples for the two laboratory digesters. The raw data obtained are presented in Table D-6, Appendix D. The data show that the soluble concentrations of the heavy metals are very low, ranging from <0.01 mg/l for cadmium to 0.93 mg/l for copper. These low soluble concentrations indicate what was expected, that the heavy metals are insoluble and associated with the sludge solids in question.

No clear cut trend of metal accumulation or dilution in the digesters fed with storm generated sludge or dry-weather sludge is indicated from the data. Soluble metal concentrations were on the order of 0.001 of the total wet concentrations and indicated very little change over the 43 day investigation. In any event, no adverse effect of the metals present or their concentrations on digester performance was observed for the two laboratory digesters for the conditions investigated as indicated by the data in Tables 27 and 28 and by previous discussions covering those performance data.

Discussion of Kenosha Results

The Kenosha full-scale anaerobic digesters are fed once daily and presently operate at a low rate volatile solids loading. The low organic loading in combination with the once-daily feed cycle have been shown to cause digesters to be less stable (12). However, at Kenosha, these unstabilizing effects were countered by a relatively high retention time (20 day), high alkalinity and low volatile acids concentration, factors which have been demonstrated to be stabilizing (12). As previously reported, the two laboratory digesters in this investigation were operated in a manner similar to the Kenosha full-scale digesters. During this investigation, digester failure was not induced in either laboratory digester system.

The most dramatic short term effects were increased gas production and pH fluctuation. Figure 47 is a plot of the total gas production during the study. The dramatic rise and subsequent decline following a simulated storm solids addition which occurred in days 14, 15, and 25 are the result of the temporary high organic loading. After simulating the 0.5 in. rain (days 14 and 15) both digesters had returned to slightly above normal gas production by day 16 and remained relatively stable. The second simulated rain event (period #2 - 1 inch rain, 1 day bleed-in, 60 percent increase in hydraulic load) caused both digesters to fluctuate more in total gas production, suggesting less stability. The observation is substantiated

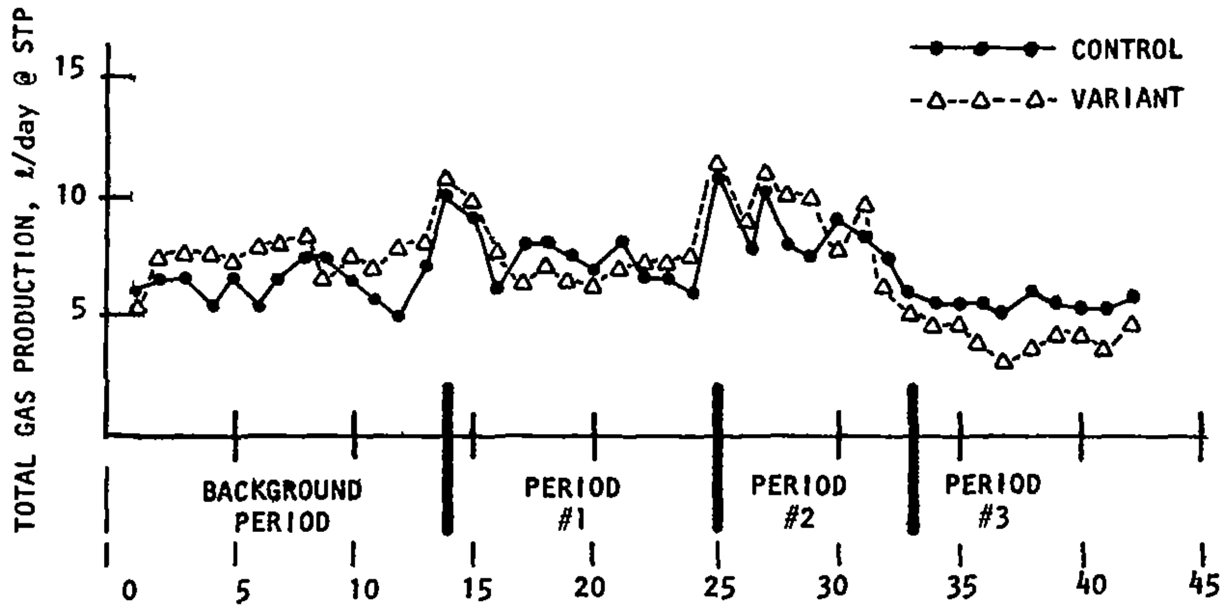


Figure 47. Total gas production of control and variant digesters.

quantitatively by a comparison of the standard deviations of these periods, excluding the days of actual increased loading (14, 15, 25) (the standard deviations listed in Table 27 include values from the days of increased loading). During the background period the standard deviation of total gas production for both digesters was ±0.5 l/day, from day 16 to day 24 (period #1), the standard deviation was ±0.68 for the control and ±0.25 for the test digester. The total gas production during the days following the second and most severe simulated storm event (days 26-32, period #2) had standard deviations of ±0.82 for the control and ±0.88 for the test digester. This high variance was apparently induced by the overloading shock alone and could not be attributed to storm generated solids; the t-test for period #2 indicated gas production to be statistically equivalent (see Table 28).

This is not to suggest that the storm generated waste activated sludge was in all ways identical to the dry-weather waste activated sludge from the Kenosha waste treatment plant. The result of the t-test on both total gas produced and rate of methane produced during the period of waste activated sludge loading (period #3) indicated the dry-weather sludge produced statistically higher quantities of gas (averaging 0.6 l/day total gas, 0.4 l/day methane), yielded a 46% reduction of volatile solids versus 36% for the storm generated sludge, and contained 3% higher total volatile solids (Table 27). These data are consistent with previous combined sewage sludges studied in the laboratory (1) which were generally lower in total volatile solids than their dry-weather counterparts.

The role of metals in digester stability and their distribution in 33 U.S. waste treatment plants was studied by Salotto <u>et.al.,</u> (13), where the metals were found to have a log normal distribution. The results of their study are compared with the geometric means of the total metals concentration of the raw and digested sludge in this study and is summarized in Table 29. The raw Kenosha sludge (digester feed) was higher than the data cited (13) in zinc, copper, chromium and cadmium (whether dry-weather or storm) however, it was much lower in lead and mercury. In terms of percentile grouping for digester sludge, the control and the test digester sludges were equal for all metals except copper where the control was in the 75th percentile and the test digester was in the 90th percentile (2,100 mg/kg vs. 2,500 mg/kg) and chromium (control = 1090 mg/kg, test = 1,200). The digester sludge contained lower concentrations of mercury and lead than the geometric mean of the 33 plants studied (13). These data indicate that the accumulation of heavy metals as potentially toxic substances did not occur either in the control or the storm feed digester.

RESULTS OBTAINED USING RACINE, WISCONSIN - WET-WEATHER SLUDGE

An additional digestion study was performed using storm generated sludge from the Racine, Wisconsin CSO treatment facility. It was felt that this sludge, produced by physical/chemical treatment of combined sewer overflow, might have a greater effect on digestion than the Kenosha CSO sludge. Because of limited resources available for this extra digestion study, the monitoring parameters were limited to total gas production, pH, volatile

TABLE 29. DISTRIBUTION OF HEAVY METALS IN KENOSHA SLUDGE

Geometric Means (mg metal/kg dry solids)

Metal	Digester feed sludge			Digested sludge		
	Control	Wet-weather	EPA data(14)	Control	Wet-weather	EPA data(13)
Mercury	1.5	2.8	8.2	2.3	2.8	6.5
Lead	501	429	1,150	557	569	2,210
Zinc	3,260	3,330	1,740	4,100	4,240	2,900
Nickel	340	290	420	450	460	530
Copper	1,700	1,830	740	2,100	2,500	1,270
Chromium	830	960	940	1,090	1,200	1,050
Iron	73,300	79,000	--	82,100	83,800	--
Cadmium	34	43	27	43	46	43
Cd/Zn Ratio	1.04%	1.29%	1.55%	1.05%	1.08%	1.48%

Percentile Grouping Based on EPA Data*
(Percent of plants studied by EPA having similar or lower metal concentrations)

Mercury	25%	25%	50%
Lead	50%	50%	90%
Zinc	75%	75%	75%
Nickel	75%	75%	75%
Copper	75%	90%	75%
Chromium	50%	75%	50%
Iron	-	-	-
Cadmium	75%	75%	75%

* Reference 13

solids, volatile acids, and some heavy metals concentrations and a few alkalinity measurements.

Start-Up, Debugging and Initial Test Work with Dry-Weather Sludges

Because of construction work at the Racine sewage plant, the digesters were overloaded and performing poorly during the period of the laboratory digester work. Nevertheless, an attempt was made to start the laboratory digesters using digested sludge and maintain the digesters with Racine dry-weather sludge. After a 10 day period of operation, the gas volume produced remained at a very low level and the laboratory digesters were emptied. The laboratory digesters were re-started using digested sludge from the Milwaukee South Shore sewage treatment plant. A mixture of primary and waste activated sludges (40% primary/60% waste activated) from the South Shore plant was used as normal dry-weather feed. These sludges were obtained after several days dry-weather. The laboratory digesters were operated at a hydraulic retention time of 20 days and an organic loading of 1.39 kg volatile solids/m^3/day for a 20 day start-up period. During this time, leaks were located and repaired, but no operating data were obtained.

Digester Operation

After the start-up period, both digesters were operated another 21 days during which time gas production, pH, volatile acids, total solids and volatile solids were monitored. During this period, the normal variation between the two digesters was established. On the 22nd day, the wet-weather digester was fed a mixture of dry-weather sludge and CSO sludge at a loading similar to that which might occur if all the thickened CSO sludge from a 2.54 cm (1 in.) rain event were added in one day to the normal dry-weather sludge for digestion. For this one day, the volume fed to the wet-weather digester was increased from 900 ml to 1031 ml and the volatile solids loading increased from 1.39 to 1.73 kg/m3/day. On the same day, the amount of dry-weather sludge added to the control digester was increased so that the volatile solids loading to both digesters would be about the same. The volume of sludge added to the control digester increased from 900 ml to 1147 ml and the volatile solids loading was increased from 1.39 to 1.77 kg/m^3/day. The method of calculating the amounts of dry-weather and CSO sludges used are listed in Table D-7, Appendix D. On the 23rd day, both digesters were again fed dry-weather sludge at the normal rate (900 ml volume, 1.39 kg/m^3/day volatile solids loading). This continued until the end of the test.

A summary of the digester operation during the control period, the simulated wet-weather feeding and the period following the wet-weather feeding is listed in Table 30. All the data from the digester operation are listed in Table D-8, Appendix D.

Gas Production

During the control period the average gas production values for the control and variant digesters were 8.7 and 8.6 l/day, respectively. Daily gas pro-

TABLE 30. MONITORING PARAMETERS FOR CONTROL AND VARIANT LABORATORY DIGESTERS (RACINE WET-WEATHER SLUDGE)

	Control period		Wet-weather feed		Period following wet-weather feed	
Day from test start	1 to 21		22		23 to 28	
Digester*	C	W	C	W	C	W
Volatile solids loading (kg/day/m^3)	1.39	1.39	1.77	1.73	1.39	1.39
Gas production (l/day)						
average	8.7	8.6	9.6	9.8	9.0	8.3
Std deviation	0.6	0.5	-	-	1.1	1.0
m^3 gas/kg vol. sol. destroyed	0.88	0.91	-	-	1.02	1.05
Volatile solids						
feed sludge, %	64.6	64.6	64.6	57.6	64.6	64.6
digested sludge, %						
average	57.2	59.0	56.7	57.6	56.1	57.3
Std deviation	0.79	0.87	-	-	1.66	0.35
Average temperature, ^{o}C	32	35	34	36	32	35
Std deviation	0.7	0.7	-	-	0.8	0.2
Storm simulation rainfall - cm (in.)	None		2.54(1)		None	
Hydraulic retention time(days)	20	20	17.4	17.5	20	20
Volumetric loading, $l/m^3/day$	50	50	63.7	57.3	50	50

* C = control or dry-weather digester; W = variant or wet-weather digester

duction varied from 7.7 l/day to 9.5 l/day. The difference in daily gas production for the two digesters averaged 0.1 l/day with the control digester producing the most gas on 12 of the 20 days measured. The paired comparison t-test (15) showed that the difference in daily gas production between the two digesters could not be considered significant at the 95% confidence level. The ratio of the volume of gas produced to the weight of volatile solids destroyed for this period was similar for both digesters.

On the day of the simulated wet-weather feeding to the variant digester, the gas production increased for both digesters and remained high for four days. On the fifth day, however, the gas production from both digesters was markedly lower. The average difference in daily gas production between the two digesters after the simulated wet-weather feeding (including the data from the day of the wet-weather feeding) was 0.5 l/day. The control digester produced less gas on the day of the feeding but produced an average of 0.6 l/day more gas each of the days following the feeding. The paired comparison t-test showed that this difference in gas production was significant at the 95% confidence level but could not be considered significant at the 99% confidence level. The ratio of gas produced to volatile solids destroyed was similar for both digesters and slightly higher than for the control period.

pH, Volatile Solids, Volatile Acids and Alkalinity of the Digester Sludge

The pH value for both digesters remained stable through the entire test period. The pH of the sludges removed from the two digesters were within 0.1 unit each day. The pH values for both digesters were generally between 7.2 and 7.3.

The digesting sludge in the control digester consistently had a lower volatile solids concentration during the control period. The difference between the sludges was significant at the 95% confidence level using the paired t-test. After the simulated wet-weather feeding, the control digester sludge continued to have a lower volatile solids concentration on 5 of the 6 days measured. Although the reason for the difference in volatile solids concentrations in the two digesting sludges is not known, it may be related to the difference in temperature between the two digesters.

The volatile acid concentrations measured during these tests did not exceed 540 mg/l during the control period. After the simulated wet-weather feeding, the maximum volatile acid concentration measured was 440 mg/l and the volatile acid/alkalinity ratio was 0.13, well below the 0.3 to 0.4 ratio where the digester might be considered to be under stress (8).

Heavy Metals

Sludge removed from the digesters the week before the simulated wet-weather feeding was used to form composite samples for each digester. Heavy metals analyses (lead, zinc, nickel, copper, chromium, iron and cadmium) were performed on these composite samples, on the sludge added to each digester during the simulated wet-weather feeding, and digester sludge six days after the wet-weather feeding. The results of these analyses are listed in Table 31 in terms of weight of metal per weight of dry solids along with the geometric mean value for metals found by the EPA in 33 digested sludges (13). (Metal concentrations in terms of both wet and dry weights are listed in Appendix D-3, Table D-9). With the exception of lead, the simulated wet-weather feed sludge contained lower concentrations of metals than the dry-weather feed sludge (dry weight basis). The digested sludges (except lead) from both digesters before and after the simulated wet-weather feeding all contained similar concentrations of all heavy metals. In both digesters, the lead concentration decreased after the simulated wet-weather feeding. The digester sludge lead concentrations were well below the geometric mean value reported by the EPA (13). Zinc, nickel, and cadmium concentrations, however, were at least 150% greater than EPA mean values. The concentration of chromium was about 10 times higher than the EPA mean value. A review of the South Shore digester records from April to September 1976 show that the concentrations of metals in the laboratory digesting sludge were not unusual for this sludge. In spite of the high chromium concentration, the South Shore digesters were operating satisfactorily during this period.

TABLE 31. CONCENTRATION OF HEAVY METALS IN FEED, AND DIGESTER SLUDGES USING RACINE CSO SLUDGE FOR SIMULATED WET-WEATHER FEED. (CONCENTRATIONS IN MG METAL/KG DRY SOLIDS)

Sludge	Lead	Zinc	Nickel	Copper	Chromium	Iron	Cadmium
Feed sludges:							
Dry-weather	411	4560	690	1090	9840	30500	64
Simulated wet-weather	488	3090	508	894	6970	23400	32
Digester sludges:							
Control digester, before wet-weather feeding	521	-	903	1320	12400	36100	52
Control digester after wet-weather feeding	456	4360	980	1380	12000	35100	51
Wet-weather digester before wet-weather feeding	544	4740	912	1440	12600	34000	60
Wet-weather digester after wet-weather feeding	437	4830	909	1364	12300	33800	70
Geometric mean of EPA data*	2210	2900	530	1270	1050	-	43
Percent of plants studied by EPA having similar or lower values*	25	75	90	75	>95	-	75

* See Reference 13

SECTION XI

DESIGN CRITERIA AND ECONOMIC CONSIDERATIONS

It is important to note that it is difficult to make generalizations regarding the design criteria and economics associated with the thickening and centrifuge dewatering of CSO treatment residues. This section presents detailed criteria and economic evaluations for the specific individual sites investigated. The information presented may be used as guidelines and as first approximation of costs for applications which are similar to those investigated. However, if closer approximations are desired, then the specific site in question should be separately evaluated with respect to locale, rainfall patterns, type and location of CSO treatment systems, sludge volumes generated and their characteristics, etc.

Design criteria for the individual sites investigated were obtained from the discussions in Section IV of this report and from the associated Appendix data.

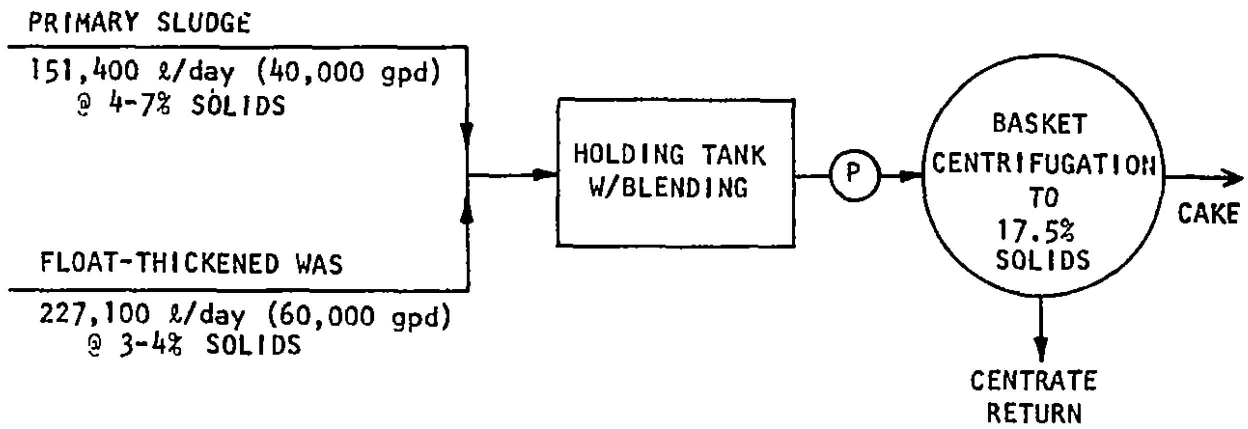
In providing cost estimates, equipment costs were obtained from manufacturer's estimates. Other costs, such as operation, maintenance, power and amortization were determined on a similar basis for all of the sites investigated. As much as possible, published cost data were utilized (16) after adjusting them to reflect June 1976 prices (17). Wherever similar unit processes were applied at different test sites, the same cost estimating structure was used. The discussion which follows, therefore, deals specifically, and in relatively great detail, with the design criteria used, design calculations, capital, operating, maintenance, power and amortization costs and the land requirements for the CSO sites investigated.

KENOSHA, WI

Dry-Weather Sludge

Kenosha dry-weather sludge consists of primary sludge and flotation thickened WAS. Currently, this sludge is anaerobically digested. If the sludge were to be dewatered as an alternative to digestion, the process schematic shown on the next page is suggested.

As shown in the schematic, the two sludges would be blended in a holding tank and pumped to the basket centrifuges for dewatering. The cake could be stabilized and landfilled, while the centrate would be returned to treatment.



Presented below are the basic dewatering design criteria:

1. Total daily sludge flow = 378,500 ℓ/day (100,000 gpd) at ≈ 5.0% solids

   378,500 ℓ/day x 50,000 mg/l x kg/10^6 mg = 18,925 kg/day (41,635 lb/day) of sludge to process.

2. From Section IV, Table 3, 144 kg/hr (317 lb/hr) of dry-weather solids can be processed.

3. Determine number of centrifuges required with 25% standby:

$$\frac{18{,}925 \text{ kg/day}}{144 \text{ kg/hr} \times 24} = 6 \text{ units} + 2 \text{ standby}$$

4. Check hydraulic flow:
   For a 5.0 percent feed, 113.6 ℓ/min (30 gpm) per machine should not be exceeded.

$$\frac{378{,}500 \text{ ℓ/day}}{6 \text{ machines} \times 1{,}440} = 43.8 \text{ ℓ/min}$$

Therefore six 121.9 x 76.2 cm (48" x 30") basket centrifuges would be required to process the dry-weather sludge. Two standby units are also recommended. The total annual cost for this system would be $219,000/year as summarized in Table 32. All of the data generated in Table 32 are based on the assumptions listed in Table 33.

<u>Wet-Weather Sludge</u>

The Kenosha wet-weather sludge generated from a 1.27 cm (0.5 in.) rainfall is 598 m^3/day (158,112 gpd) at 0.83 percent solids, assuming a sludge bleed/pump-back of 2 days. The thickening-dewatering schematic is shown in Figure 48. The biologically treated CSO sludge would be pumped to a flota-

TABLE 32. KENOSHA, WI - SUMMARY OF COST AND SPACE REQUIREMENTS

Equipment cost requirements	DRY-WEATHER SLUDGE Cost/unit($) based on handling 13,925 kg/day (41,635 lb/day) of dry solids	WET-WEATHER SLUDGE Cost/unit($) based on handling 4967 kg/day (10,937 lb/day) of dry solids	WET-WEATHER/DRY-WEATHER SLUDGE Cost/unit($) based on handling 23,892 kg/day (52,562 lb/day) of dry solids
Capital costs			
1. Sludge pumping to thickener	$ -	$180,000	$ 400,000
2. Flotation thickener	-	170,000	470,000
3. Sludge pumping to centrifuge	340,000	180,000	400,000
4. Centrifuge	780,000	420,000	920,000
Total capital cost	$1,120,000	$950,000	$2,190,000
Annual O&M Costs			
1. Operation			
pump to thickener	$ -	$ 1,600	$ 1,600
flotation thickener	-	2,000	2,000
pump to centrifuge	9,100	1,600	10,000
centrifuge	54,500	5,600	63,600
Subtotal	$ 63,600	$ 10,800	$ 77,720
2. Maintenance			
pump to thickener	$ -	$ 700	$ 700
flotation thickener	-	600	600
pump to centrifuge	4,000	700	4,300
centrifuge	8,600	900	10,000
Subtotal	$ 12,600	$ 2,900	$ 15,600
3. Electricity			
pump to thickener	$ -	$ 100	$ 100
flotation thickener	-	1,500	1,500
pump to centrifuge	500	100	600
centrifuge	12,400	900	14,500
Subtotal	$ 17,400	$ 2,600	$ 16,700
Total annual O&M cost	$ 93,600	$ 16,300	$ 109,500
Total annual cost[a, b] (@ 6%, 20 yr., zero salvage and 15% contingency)	$ 219,900/yr	$114,000/yr	$ 345,500/yr
Land requirements	158 m^2 (1700 ft^2)	204.4 m^2 (2200 ft^2)	390 m^2 (4200 ft^2)

[a] Total annual cost = [total capital cost +0.15 total cap. cost] x amor. factor (.08718) {6%, 20 yr}
+ [total annual O&M cost +0.15 total ann. O&M cost]

[b] The 15% contingency was added to include land cost and national cost variations

TABLE 33. ECONOMIC EVALUATION ASSUMPTIONS

GENERAL ASSUMPTIONS

1. All costs are based on 1976 prices.

2. The derived costs are a function of dry solids handling. Thus, individual costs per piece of equipment may vary from site to site.

3. The costs generated are for equipment only and are exclusive of required valving, holding tanks, flow distribution equipment, etc.

4. Costing information was obtained from Reference No. 16 and updated to 1976 dollars using a multiplier of 1.42 as listed in Reference No. 17

5. Land requirements have been estimated for the placement of equipment only. Land allocations include 9.29 sq m (100 sq ft) per pump, 9.29 sq m (100 sq ft) per chemical feed system, 18.59 sq m (200 sq ft) per centrifuge and a thickener and degritting surface area based on twice the required treatment area.

6. Assume polymer costs of $3.96/kg ($1.80/lb).

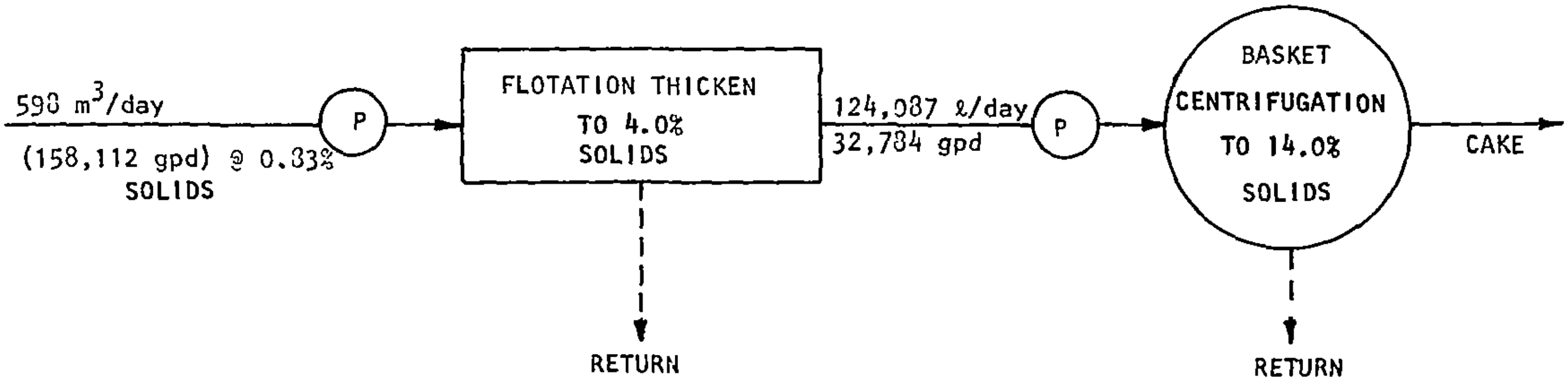
ASSUMPTIONS RELATED TO CSO GENERATED

1. Assume a 2-day bleed/pump-back of CSO sludge to the system.

2. Assume the waste volumes generated to be from a 1.27 cm (0.5 in.) rainfall over the entire CSO area.

3. Assume 50 CSO events/year. Assuming this and a 2-day bleed/pump-back of CSO sludge, equipment operation is estimated at 100 days/year.

4. The costs generated are independent of any costs required to expand the existing liquid handling facilities to treat the entire CSO area.



(Assuming a 2-day bleed/pump-back of CSO to the treatment site)

Figure 48. Thickening-dewatering schematic Kenosha CSO sludge.

tion thickener where the solids would be concentrated to 4.0 percent, resulting in a sludge reduction to 124,087 ℓ/day (32,784 gpd). The thickened sludge would then be dewatered to approximately 14.0 percent solids using basket centrifuges.

The design criteria are shown below.

1. Total daily sludge flow = 598 m^3/day (158,112 gpd) @ 0.83% solids 598,454 ℓ/day x 8,300 mg/l x kg/10^6 mg = 4,967 kg/day (10,937 lb/day) of sludge to process.

2. Determine area of thickening required:
   From Section VII, a CSO sludge concentration of 4.0 percent can be obtained at a mass loading of 53.8 kg/m^2/day (11 lb/ft^2/day). Therefore, required area for thickening would be:

$$\frac{4{,}967 \text{ kg/day of sludge to process}}{53.8 \text{ kg/m}^2\text{/day}} = 92.3 \text{ m}^2 \ (993.5 \text{ ft}^2)$$

3. Check thickener hydraulic flow:
   Underflow rate = $\frac{598{,}454 \text{ ℓ/day}}{92.3 \text{ m}^2}$ = 6,484 ℓ/m^2/day (159 gal./ft^2/day)

4. From Section IV, Table 3, the processing rate to the basket centrifuges would be 103 kg/hr (227 lb/hr).

5. Determine number of centrifuges required with 25% standby:

$$\frac{4{,}967 \text{ kg/day of sludge to process}}{103 \text{ kg/hr x } 24} = 2 \text{ units} + 1 \text{ standby}$$

6. Check hydraulic flow:
   For a 4.0 percent feed, 113.6 ℓ/min. (30 gpm) per machine should not be exceeded.

$$\frac{124{,}087 \text{ ℓ/day}}{2 \text{ machines x } 1{,}440} = 43.1 \text{ ℓ/min.}$$

Therefore, 3 - 121.9 x 76.2 cm (48" x 30") basket centrifuges are required. Two machines would be on-line during wet-weather with one additional unit acting as a standby.

The wet-weather system annual costs as summarized in Table 32 would be $114,000/year.

Wet-Weather/Dry-Weather Sludge Combination

In this process train, CSO sludge generated from a 1.27 cm (0.5 in.) rainfall and flotation thickened to 4.0 percent solids would be blended in a holding tank with dry-weather primary and thickened WAS. The expected flow to the dewatering equipment would be 502,600 ℓ/day (132,800 gpd) assuming a two-day bleedback of CSO sludge. The expected sludge concentration would be 4.0 percent. The schematic flow diagram is presented in Figure 49.

Shown below are dewatering design criteria:

1. Total daily sludge flow = 502,600 ℓ/day (132,800 gpd) @ ≈ 4.7% solids 502,600 ℓ/day x 47,500 mg/l x kg/10^6 mg = 23,892 kg/day (52,562 lb/day) of sludge to process.

2. From Section IV, Table 3, 99 kg/hr (218 lb/hr) of wet-weather/dry-weather sludge can be processed assuming no polymer addition.

3. The required area for thickening as discussed in the wet-weather sludge design criteria would be 92.3 m^2 (993.5 ft^2).

4. Determine number of centrifuges required with 25% standby:

$$\frac{23{,}892 \text{ kg/day to process}}{99 \text{ kg/hr x } 24} = 10 \text{ units + 3 standby}$$

5. Check hydraulic flow:
For a 4.7 percent feed, 113.6 ℓ/min. (30 gpm) per machine should not be exceeded.

$$\frac{502{,}600 \text{ ℓ/day}}{10 \text{ machines x } 1{,}440} = 34.9 \text{ ℓ/min.}$$

Thus, to process the wet-weather/dry-weather sludge, 13 basket centrifuges 121.9 x 76.2 cm (48" x 30") would be required. Three of the units would act as standby machines. The total annual cost for this system is $345,500 as presented in Table 32.

MILWAUKEE, WI

Dry-Weather Sludge

Milwaukee South Shore dry-weather primary sludge is currently generated at an average rate of 868,658 ℓ/day (229,500 gpd) at 5.7 percent solids. This sludge is presently fed directly to the anaerobic digesters for stabilization. One alternative to this would be direct dewatering of the primary sludge by centrifugation using a decanter-type centrifuge. The schematic diagram illustrating this process is shown on the following page.

Based on the dewatering data presented in Section VIII, 15-20 percent haulable cakes can consistently be produced. The dewatering design criteria would be as follows:

1. Total daily sludge flow = 868,658 ℓ/day (229,500 gpd) @ 5.7% solids

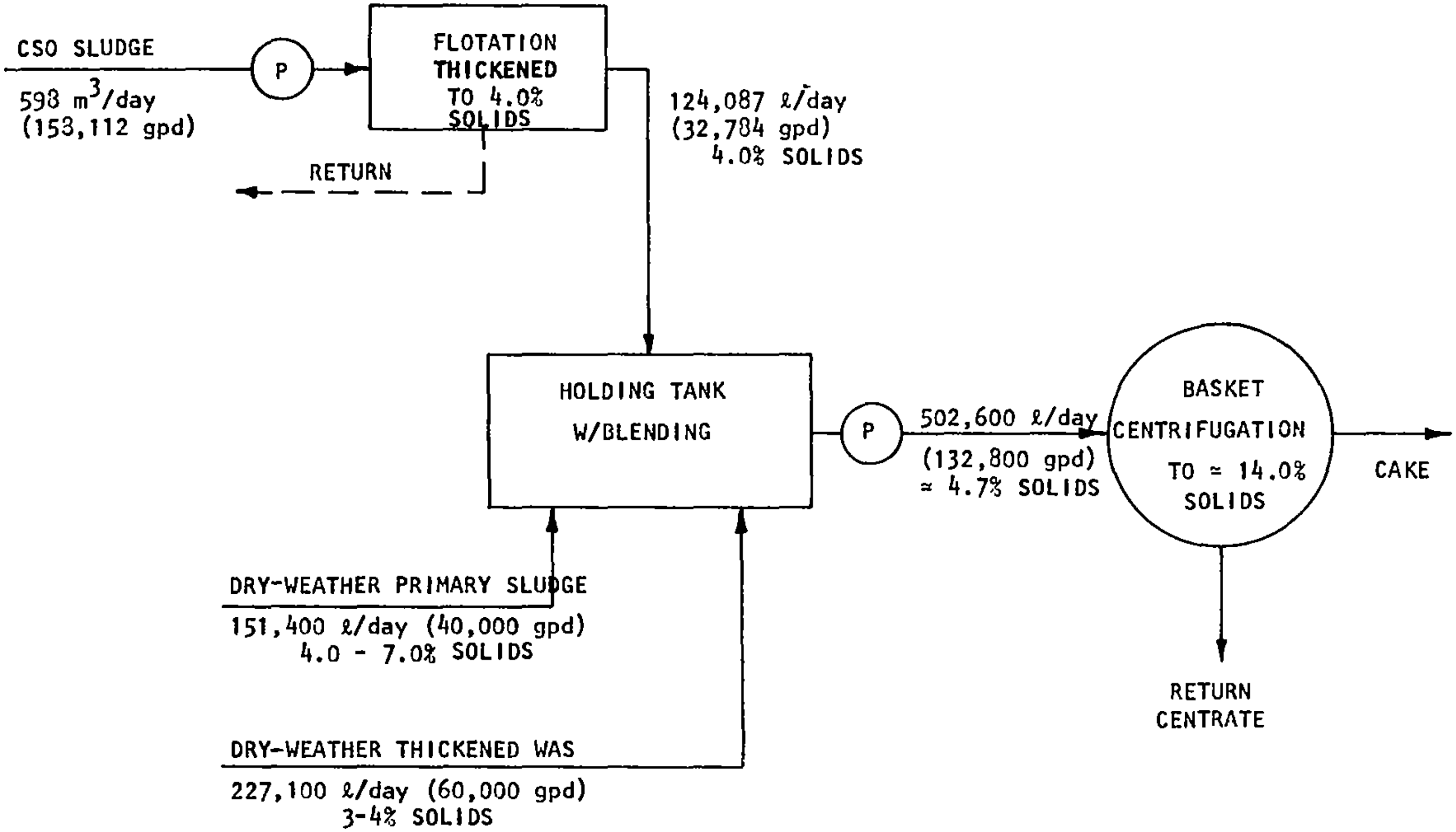
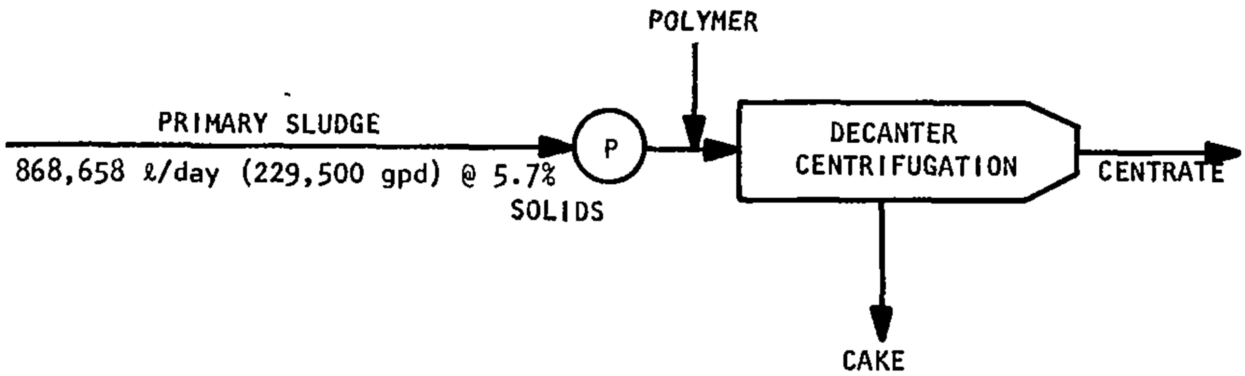


Figure 49. Solids dewatering schematic
Kenosha wet-weather/dry-weather sludge combination.



868,658 ℓ/day x 57,000 mg/l x kg/10^6 mg = 49,514 kg/day (108,930 lb/day) of sludge to process.

2. From Section IV, optimal conditions were obtained at feed rates of 118-203 kg/hr (260-450 lb/hr) for a 35.56 cm diameter x 86.36 cm long rotor (14" x 34") decanter centrifuge. This is equivalent to a throughput of 394-682 kg/hr (867-1500 lb/hr) for a 50.8 cm diameter x 199.4 cm long rotor (20" x 78.5") decanter centrifuge.

3. Determine number of centrifuges required with 25% standby:

$$\frac{49{,}514 \text{ kg/day}}{394 \text{ kg/hr} \times 24} = 6 \text{ units} + 2 \text{ standby}$$

4. Check hydraulic flow rate:
At optimal feed rates, flows of 37.9-68 ℓ/min (10-18 gpm) were maintained. This is equivalent to a not-to-exceed flow rate of 190-340 ℓ/min (50-90 gpm) for the 50.8 x 199.4 cm (20" x 78.5") decanter centrifuge.

$$\frac{868{,}658 \text{ ℓ/day}}{6 \text{ machines} \times 1{,}440} = 100.5 \text{ ℓ/min (26.5 gpm)}$$

5. Estimate polymer requirements:
For the optimal conditions discussed in Section IV, polymer dosages of 0.88-1.24 kg/metric ton (1.76-2.48 lb/ton) would be required.

$$\frac{49{,}514 \text{ kg sludge/day}}{1000 \text{ kg/metric ton}} \times 0.88 \text{ kg polymer/metric ton} =$$

43.57 kg (95.85 lb) polymer/day required.

Therefore, six 50.8 x 199.4 cm (20" x 78.5") decanter centrifuges would be required. Two additional units would be available for standby. Polymer requirements for this system would be 43.57 kg/day (95.85 lb/day). It should be noted that this design is based on sizing the units at the lower optimal dry solids dewatering rate, and therefore stresses optimum solids recovery. If optimum cake solids are limiting, the design should be based on the higher optimum feed rate values shown.

The total annual cost as shown in Table 34 is estimated at \$488,400/year. All of the data generated in Table 34 are subject to the assumptions listed previously in Table 33.

Wet-Weather Sludge

The Milwaukee wet-weather sludge gravity settles to 0.015-0.14 percent solids without chemical addition as discussed in Section VIII. Since this sludge concentration is too dilute for economical full-scale dewatering, the addition of chemical would be required. This step combined with gravity settling would increase solids to approximately 1.74 percent as reported in Phase I (1). Based on the results discussed in Section IV, it is anticipated that this sludge could then be dewatered to a 10 percent cake. An allowance for grit removal would also have to be included. One possible method of degritting would be the application of a swirl concentrator in lieu of conventional equipment. The concentrator would precede the dewatering step to degrit the settled sludge. Since this process has had only limited exposure, its actual application would require an in-depth preliminary study. The proposed wet-weather sludge process schematic is presented in Figure 50.

The Milwaukee wet-weather criteria for design are discussed below:

1. Determine size of grit chamber required (assume conventional design)

   Design Parameters
   Grit removal size = 65 mesh (.24 mm) (.01 in.)
   V_s = settling velocity to remove grit on a No. 65 mesh = 112.8 cm/min (3.7 fpm) (18)

   Depth/width = D/W = 1

   V_f = flow through velocity = 30.5 cm/sec (1.0 fps)

   $Q = 1{,}860{,}523\ \ell/\text{day} = 1{,}862\ m^3/\text{day}\ (0.492\ \text{mgd})$

   $Q = AV_f = DWV_f$

   $$D^2 = Q/V_f = \frac{1{,}862\ m^3/\text{day} \times 100\ \text{cm/m}}{30.5\ \text{cm/sec} \times 86{,}400} = .07\ m^2 \quad (.76\ ft^2)$$

   D = .27 m (.89 ft)

   Assume a Safety Factor = 2, then
   D = 0.54 m (1.78 ft); Say 0.61 m (2.0 ft)

   W = .27 m (.89 ft); Say 0.31 m (1.0 ft)

TABLE 34. MILWAUKEE, WI - SUMMARY OF COST AND SPACE REQUIREMENTS

Equipment cost requirements	DRY-WEATHER SLUDGE cost/unit($) based on handling 49,514 kg/day (54.5 ton/day) of dry solids	WET-WEATHER SLUDGE cost/unit($) based on handling 32,373 kg/day (35.6 ton/day) of dry solids
Capital costs		
1. Sludge pumping	$ 540,000	$ 426,000
2. Sedimentation	-	732,700[a]
3. Chemical feed	60,000	573,000[b]
4. Centrifuge	1,349,000	1,051,000
5. Degritting	-	33,000
Total capital cost	$1,903,000	$2,915,700
Annual O&M costs		
1. Operation		
pumping	$ 13,200	$ 3,100
sedimentation	-	6,600
chemical feed	6,000[c]	67,300[c]
centrifuge	118,100	22,400
degritting	-	700
Subtotal	$ 137,300	$ 100,100
2. Maintenance		
pumping	$ 5,700	$ 1,400
sedimentation	-	3,700
chemical feed	c	c
centrifuge	19,500	3,700
degritting	-	500
Subtotal	$ 25,200	$ 9,300
3. Electricity		
pumping	$ 1,300	$ 200
sedimentation	-	300
chemical feed	c	c
centrifuge	32,000	5,700
degritting	-	100
Subtotal	$ 33,300	$ 6,300
4. Chemical	$ 63,000	$ 203,400[b,d]
Total annual O&M cost	$ 258,800	$ 319,100
Total annual cost[e, f] (@ 6%, 20yr, zero salvage and 15% contingency)	$ 488,400/yr	$ 659,300/yr
Land requirements	288 sq m (3100 ft^2)	573 sq m (6200 ft^2)

[a] Capital expenditure required to convert storage basin into sedimentation basin. From Phase I, updated to 1976 dollars (1)

[b] Costed to include both ferric chloride and polymer addition to system

[c] Annual cost assumed to be 10% of capital expenditure

[d] Assume required ferric chloride dosage = 25 mg/l (1) and a cost of $17.60/KG ($8.00/lb)

[e] Total annual cost = [tot. cap. cost + 0.15 tot. cap. cost] x amor. factor (.08718) (6%, 20 yr) + [tot. ann. O&M cost + 0.15 tot. O&M ann. cost]

[f] The 15% contingency was added to include land cost and national cost variations

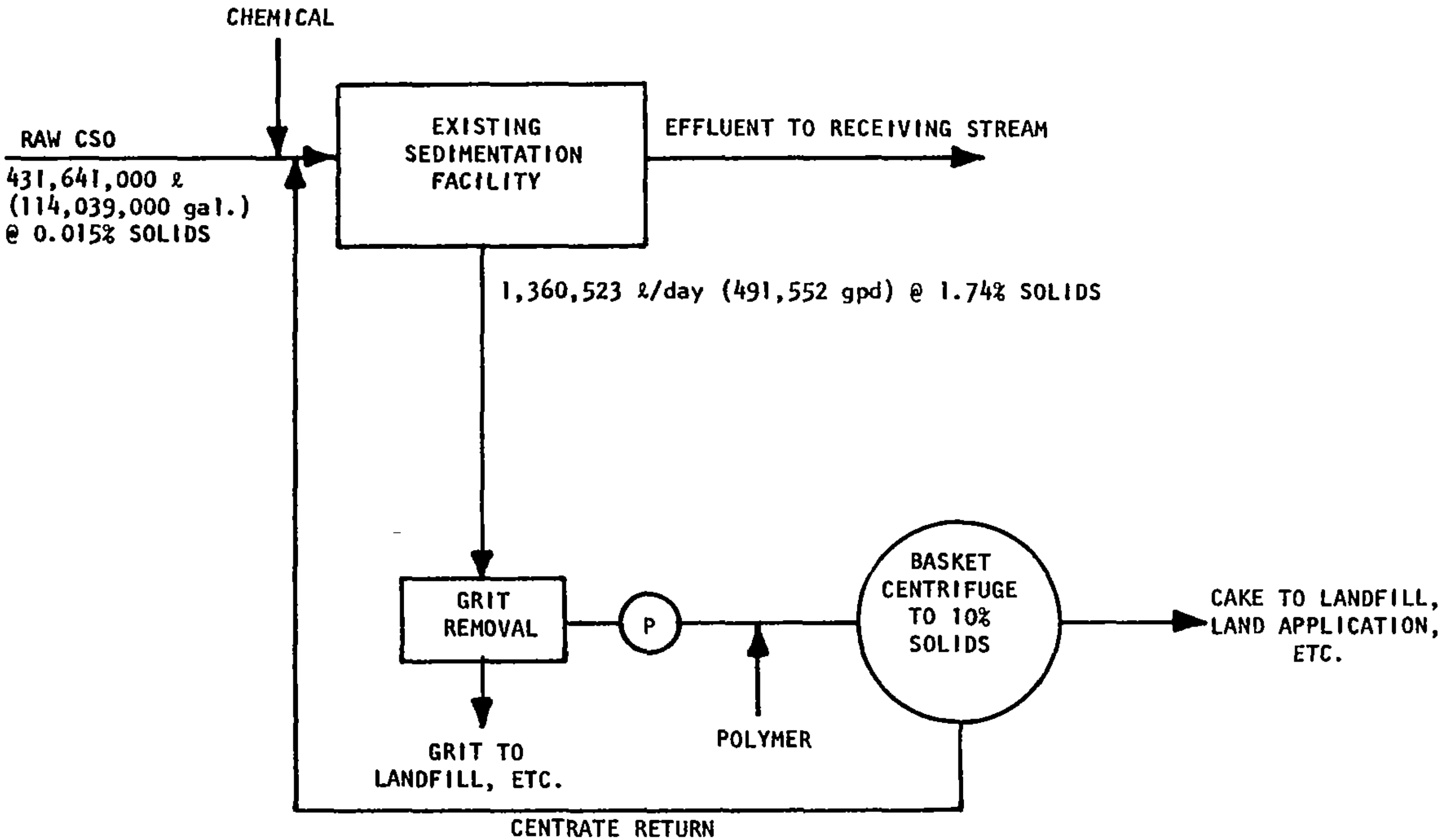


Figure 50. Dewatering schematic Milwaukee CSO sludge.

Determine L:

$$D/V_s = \frac{0.61 \text{ m} \times 100 \text{ cm/m}}{112.8 \text{ cm/min}} = 0.54 \text{ min flow time}$$

0.54 min x 30.5 cm/sec x 0.6 = 9.9 m (32.5 ft)

Assume a 0.31m (1 ft) free board, then:

Use 1 chamber: D = 0.92 m (3.0 ft)
W = 0.31 m (1.0 ft)
L = 9.9 m (32.5 ft)

2. Total daily sludge flow = 1.860,523 ℓ/day (491,552 gpd) @ 1.74% solids.
1,860,523 ℓ/day x 17,400 mg/l x kg/10^6 mg = 32,373 kg/day (71,221 lb/day) of sludge to process.

3. For sizing purposes, assume an average dewatering feed rate of 94.6 liters/min (25 gpm).

$$94.6 \text{ ℓ/min} \times \frac{60 \text{ min}}{\text{hr}} \times 17{,}400 \text{ mg/l} \times \text{kg}/10^6 \text{ mg} = 98.8 \text{ kg/hr}$$

(217 lb/hr) of process sludge.

4. Determine number of centrifuges required with 25% standby:

$$\frac{32{,}373 \text{ kg/day}}{98.8 \text{ kg/hr} \times 24} = 14 \text{ units} + 4 \text{ standby}$$

5. Verify hydraulic flow:
For a 1.8% sludge, 151.4 ℓ/min (40 gpm) should be exceeded.

$$\frac{1{,}860{,}523 \text{ ℓ/day}}{14 \text{ machines} \times 1{,}440} = 92.3 \text{ ℓ/min}$$

6. Estimate polymer requirements:
From Section VIII, a polymer dosage of 1.05 kg/metric ton (2.1 lb/ton) was required.

$$\frac{32{,}373 \text{ kg sludge/day}}{1{,}000 \text{ kg/metric ton}} \times \frac{1.05 \text{ kg polymer}}{\text{metric ton}} = 34 \text{ kg } (74.8 \text{ lb})$$

polymer/day required.

The design criteria indicate that eighteen 121.9 x 76.2 (48" x 30") basket centrifuges are required to dewater the wet-weather sludge generated by a 1.27 cm (0.5 in.) rainfall over the entire Milwaukee CSO area. Four of these centrifuges would act as standby units. Polymer requirements are estimated at 34 kg/day (74.8 lb/day).

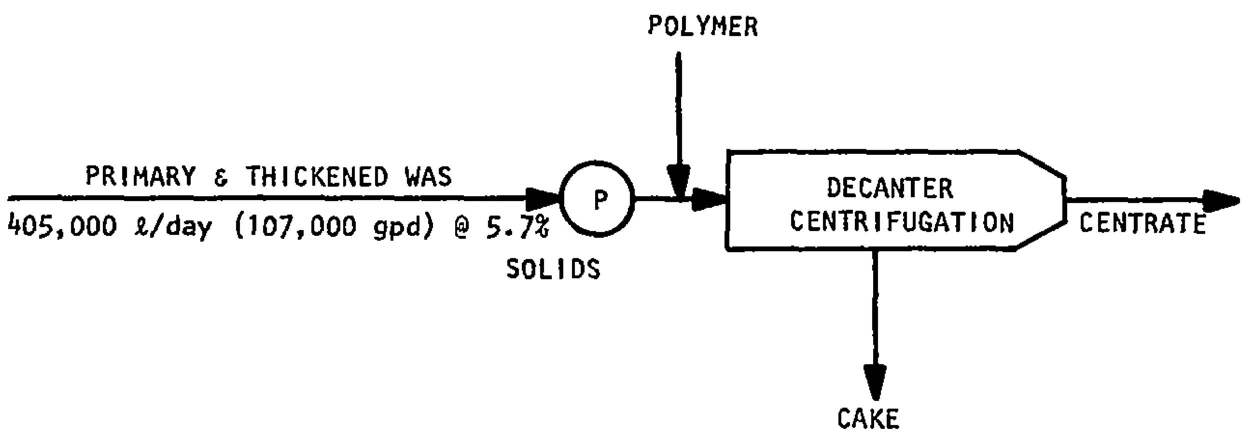
The expected cost to operate this wet-weather facility is $659,300/yr as identified in Table 34 and derived according to the assumptions of Table 33.

RACINE, WI

Dry-Weather Sludge

The dry-weather sludge produced at the Racine Water Pollution Control Plant consists of primary plus waste activated sludge. The WAS is returned to the primary settling basins for thickening. The combined sludges are then anaerobically digested. As discussed in Section IX, the undigested sludge mixture was dewatered using a decanter centrifuge. During 1976, the Racine Water Pollution Control Plant pumped an average of 405,000 ℓ/day (107,000 gpd) of sludge at a concentration of 8.9 percent solids.

The alternative process flow diagram utilizing centrifuge dewatering is shown below:



Design criteria for the centrifuge dewatering of Racine dry-weather sludge are shown below:

1. Total sludge flow = 405,000 ℓ/day (107,000 gpd) @ 8.9% solids. 405,000 ℓ/day x 89,000 mg/l x kg/10^6 mg = 36,045 kg/day (79,300 lb/day) of sludge to process.

2. From Section IV, optimal dewatering conditions were maintained at a feed rate of 336 kg/hr (740 lb/hr). These results were obtained using the 35.56 x 86.36 cm (14" x 34") decanter centrifuge. If the

larger 50.8 x 199.4 cm (20" x 78.5") decanter centrifuges were utilized, the equivalent throughput would be 1,120 kg/hr (2,424 lb/hr) of dry solids.

3. Determine number of centrifuges required assuming 25% standby:

$$\frac{36,045 \text{ kg/day}}{1,120 \text{ kg/hr} \times 24} = 2 \text{ units} + 1 \text{ standby.}$$

4. Check hydraulic flow rate:
For optimal dewatering, a flow rate of 57.5 ℓ/min (15.2 gpm) was maintained. An equivalent flow rate for the 50.8 x 199.4 cm (20" x 78.5") decanter centrifuge is 287.5 ℓ/min (76 gpm).

$$\frac{405,000 \text{ ℓ/day}}{2 \text{ machines} \times 1,440} = 140.6 \text{ ℓ/min} \quad (37.2 \text{ gpm})$$

5. Estimate polymer requirements:
As discussed in Section IV, polymer dosages of 1.2 kg/metric ton (2.4 lb/ton) would be required for optimal conditions.

$$\frac{36,045 \text{ kg sludge/day}}{1,000 \text{ kg/metric ton}} \times 1.2 \text{ kg polymer/metric ton} = 43.25 \text{ kg}$$

(95.2 lb) polymer/day required.

Thus, to dewater the Racine dry-weather primary plus thickened WAS, three decanter centrifuges - 50.8 x 199.4 cm (20" x 78.5") are required. One of these units would be standby. The polymer requirements for the system would be 43.25 kg (95.2 lb) per day. The costs generated in Table 35 for this system are estimated at an annual cost of $408,900/yr assuming the criteria developed in Table 33 apply.

Wet-Weather Sludge

The Racine wet-weather sludge produced from a 1.27 cm (0.5 in.) rain over the CSO area is 433,000 ℓ/day (114,400 gpd) for a two day bleedback. The average solids concentration is 0.84 percent. A proposed thickening/dewatering process train is shown in Figure 51. The treatment scheme includes grit removal of the screening backwash water prior to its introduction into the sludge holding tank. The physical-chemical sludge resulting from treatment can be gravity thickened to an estimated 14.0 percent solids as shown in the bench scale thickening results of Section IX. This would result in a thickened sludge volume of 51,945 liters (13,724 gal.) to be dewatered over two days. It is expected that the dewatered cake would be approximately 32 percent dry solids, which makes it very acceptable for hauling.

The design criteria are discussed below.

TABLE 35. RACINE, WI - SUMMARY OF COST AND SPACE REQUIREMENTS

Equipment cost requirements	DRY-WEATHER SLUDGE cost/unit($) based on handling 36,045 kg/day (39.7 ton/day) of dry solids	WET-WEATHER SLUDGE cost/unit($) based on handling 3,637 kg/day (4.0 ton/day) of dry solids
Capital costs		
1. Sludge pumping	$ 469,000	$ 40,000
2. Thickening	-	60,000
3. Chemical feed	30,000	10,000
4. Centrifuge	1,136,000	125,000
5. Degritting	-	71,000
Total capital cost	$1,635,000	$306,000
Annual O&M costs		
1. Operation		
pumping	$ 11,800	$ 1,400
thickening	-	600
chemical feed	3,000[a]	1,000[a]
centrifuge	90,900	4,700
degritting	-	400
Subtotal	$ 105,700	$ 8,100
2. Maintenance		
pumping	$ 5,200	$ 600
thickening	-	500
chemical feed	a	a
centrifuge	15,000	800
degritting	-	300
Subtotal	$ 20,200	$ 2,200
3. Electricity		
pumping	$ 1,000	$ 50
thickening	-	50
chemical feed	a	a
centrifuge	25,600	800
degritting	-	100
Subtotal	$ 26,600	$ 1,000
4. Chemical	$ 60,600	$ 5,100
Total annual O&M cost	$ 213,100	$ 16,400
Total annual cost[b, c] (@ 6%, 20 yr, zero salvage and 15% contingency)	$408,900/yr	$ 49,500/yr
Land requirements	93 sq m (1000 ft^2)	135 sq m (1,450 ft^2)

[a] Annual cost assumed to be 10% of capital expenditure

[b] Total annual cost = [tot. cap. cost +0.15 tot. cap. cost] x amor. factor (0.08718) (6%, 20 yr) + [tot. ann. O&M cost + 0.15 tot. ann. O&M cost]

[c] The 15% contingency was added to include land cost and national cost variations

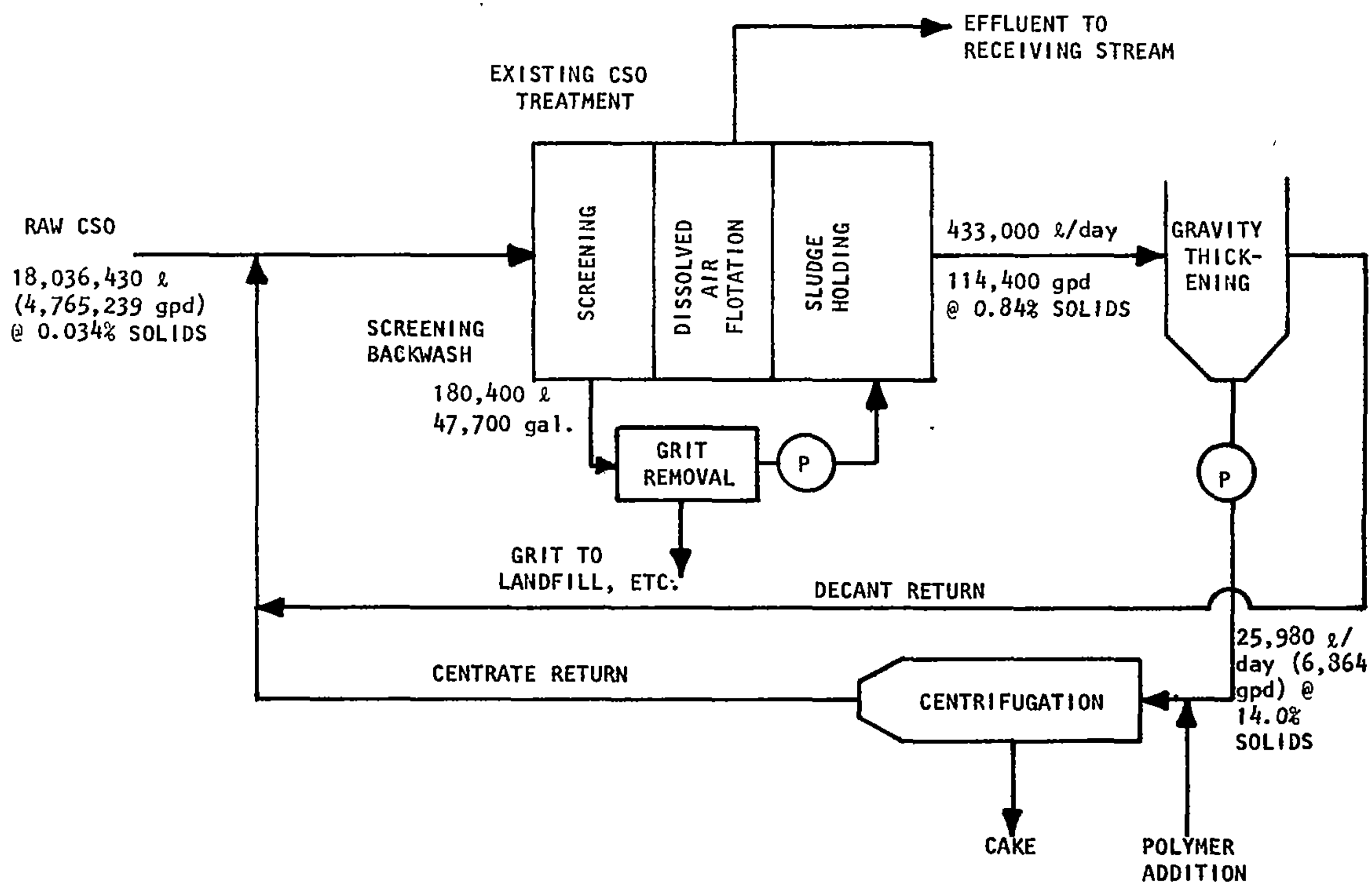


Figure 51. Dewatering schematic Racine CSO sludge.

1. Total daily sludge flow = 433,000 ℓ/day (114,400 gpd) at 0.84% solids. 433,000 ℓ/day x 8,400 mg/l x kg/10^6 mg = 3,637 kg/day (8,002 lb/day) of sludge to process

2. Determine area of thickening required:
The mass loadings obtained in Section IX appear excessive and will not be used. For typical gravity thickener design, a mass loading of 122 kg/m^2/day (25 lb/ft^2/day) is suggested (18). Then, the re-required area for thickening would be:

$$\frac{3{,}637 \text{ kg/day of sludge to process}}{122 \text{ kg/m}^2\text{/day}} = 29.8 \text{ m}^2 \ (321 \text{ ft}^2)$$

3. Check thickener hydraulic flow:
Overflow rate = $\frac{433{,}000 \ \ell\text{/day}}{29.8 \text{ m}^2}$ = 14,530 ℓ/m^2/day (356 gal./ft^2/day)

4. Determine size of grit chamber required (Assume conventional design):

Design Parameters
Grit removal size = 65 mesh (.24 mm) (.01 in.)

V_s = settling velocity to remove grit on a No. 65 mesh = 112.8 cm/min (3.7 gpm) (18)

Depth/width = D/W = 0.25

V_f = flow through velocity = 30.5 cm/sec (1.0 fps)

Q = 180,400 ℓ/day = 180 m^3/day (0.48 mgd)

$$Q = AV_f = DWV_f = D \cdot 4D \cdot V_f$$

$$4D^2 = Q/V_f = \frac{180 \text{ m}^3\text{/day x } 100 \text{ cm/m}}{30.5 \text{ cm/sec x } 86{,}400} = 0.007 \text{ m}^2 \ (0.076 \text{ ft}^2)$$

D = 0.04 m (0.14 ft)

Assume Safety Factor = 2, then
D = 0.1 m (0.3 ft)
W = 0.2 m (0.7 ft)

Determine L:

$$W/V_s = \frac{0.2 \text{ m x } 100 \text{ cm/m}}{112.8 \text{ cm/min}} = 0.2 \text{ min Flow Time}$$

0.2 min x 30.5 cm/sec x 0.6 = 3.7 m (12 ft)

Assume a 0.31 m (1 ft) free board, then:

Use 1 chamber: L = 3.7 m (12 ft)
D = 0.41 m (1.4 ft)
W = 0.2 m (0.7 ft)

5. From Section IV, Table 4, the processing rate to the decanter centrifuge was 18.0 kg/hr (39.6 lb/hr). The reason for the low loading rate was due to the diluteness of the sludge. With proper gravity thickening, the expected sludge feed rate is estimated at 250 kg/hr/machine (550 lb/hr/machine) using the 35.56 x 86.36 cm (14" x 34") decanter centrifuge.

6. Determine number of centrifuges required:

$$\frac{\text{3,637 kg/day of sludge to process}}{\text{250 kg/hr} \times 24} = \text{1 unit + 1 standby}$$

7. Check hydraulic flow:
For a 35.56 x 86.36 cm (14" x 34") decanter centrifuge, flows of 90.8 ℓ/min (24 gpm) should not be exceeded.

$$\frac{25{,}980\ \ell\text{/day}}{1\ \text{machine} \times 1{,}440} = 18\ \ell\text{/min (4.7 gpm)}$$

8. Estimate polymer requirements:
From Section IV, Table 4, an estimated polymer dosage of 0.96 kg/metric ton (1.92 lb/ton) will be required.

$$\frac{\text{3,637 kg sludge/day}}{\text{1000 kg/metric ton}} \times \text{0.96 kg polymer/metric ton}$$

= 3.5 kg (7.7 lb) polymer/day required.

In conclusion, the Racine wet-weather sludge can be dewatered using one 35.56 x 86.36 cm (14" x 34") decanter centrifuge. One additional centrifuge is recommended as a backup unit. Polymer requirements to aid the dewatering process are estimated at 3.5 kg (7.7 lb) per day of operation. As shown in Table 35, the total annual cost for this system would be $49,500/year using the assumptions developed in Table 33.

SECTION XII

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SECTION XIII

APPENDICES

APPENDIX A - KENOSHA, WISCONSIN CENTRIFUGE TEST DATA

TABLE A-1. 30.5 CM (12 IN.) CENTRIFUGE BASKET TESTS - RUN NO. 1

Centrifuge Basket Used - 30.5 cm (12 in.)
Run No. 1
Date: August 7, 1975
Sludge Tested: Flotation-Thickened Dry-Weather WAS

PROCEDURE

Sludge was fed to the 30.5 cm (12 in.) basket centrifuge (producing 1300 G's at the basket wall) at a constant rate of 2.43 l/min. (0.64 gpm) until an abrupt decrease in the centrate quality was observed. A feed sample was taken for analyses prior to centrifugation and subsequent centrate samples were taken during centrifugation. A skimmings sample and two cake samples were taken at the end of the run for total solids analysis. The reported cake value is the average of the two samples. No polymer was utilized.

RESULTS

		Volume		mg/l SS	Solids
	Time	liters	gal.	or % TS	Recovery (%)
Feed	for 7.5 min.	18.2	4.8	3.86%	--
Centrate	@ 5 min.	--	--	1,540 mg/l	96.0
Centrate	@ 6.5 min.	--	--	2.50%	35.7
Skimmings	--	0.50	0.13	2.65%	--
Cakes	--	5.18	1.37	10.60% (11.98 & 9.22)	--

NOTES

1. Dissolved solids were approximately 475 mg/l.
2. Cake collapsed from the wall of the basket.
3. Volume reduction was 3.51 (feed volume/cake volume).

TABLE A-2. 30.5 CM (12 IN.) CENTRIFUGE BASKET TESTS - RUN No. 2

Centrifuge Basket Used - 30.5 cm (12 in.)
Run No. 2
Date: August 7, 1975
Sludge Tested: Flotation-Thickened Dry-Weather WAS

PROCEDURE

Same as for Run No. 1, except sludge was fed at a constant rate of 1.14 l/min (0.30 gpm). No polymer was utilized.

RESULTS

	Time	Volume liters	Volume gal.	mg/l SS or % TS	Solids Recovery (%)
Feed	for 11.5 min.	13.1	3.5	3.84%	--
Centrate	@ 7 min.	--	--	1,245 mg/l	96.7
Centrate	@ 10 min.	--	--	1,385 mg/l	96.3
Centrate	@ 10.5 min.	--	--	2.32%	40.2
Skimmings	--	0.16	0.04	4.13%	--
Cake	--	5.52	1.46	11.46% (12.97&9.96)	--

NOTES

1. Dissolved solids were approximately 570 mg/l.
2. Cake fell from upper half of basket.
3. Volume reduction was 2.37.

TABLE A-3. 30.5 CM (12 IN.) CENTRIFUGE BASKET TESTS - RUN NO. 3

Centrifuge Basket Used - 30.5 cm (12 in.)
Run No. 3
Date: August 7, 1975
Sludge Tested: Flotation-Thickened Dry-Weather WAS

PROCEDURE

Same as for Run No. 1, except sludge was fed at a constant rate of 0.73 l/min (0.19 gpm). No polymer was utilized.

RESULTS

	Time	Volume liters	Volume gal.	mg/l SS or % TS	Solids Recovery (%)
Feed	for 20.2 min.	14.7	3.9	3.72%	--
Centrate	@ 10 min.	--	--	1,393 mg/l	96.2
Centrate	@ 13 min.	--	--	1,384 mg/l	96.2
Centrate	@ 16 min.	--	--	1,363 mg/l	96.3
Centrate	@ 19.5 min.	--	--	1.61%	57.5
Skimmings	--	0.23	0.06	4.74%	--
Cake	--	5.45	1.44	11.36% (12.79 & 9.93)	--

NOTES

1. Dissolved solids were approximately 505 mg/l
2. Cake fell from upper third of basket
3. Volume reduction was 2.70

TABLE A-4. 30.5 CM (12 IN.) CENTRIFUGE BASKET TESTS - RUN NO. 4

Centrifuge Basket Used - 30.5 cm (12 in.)
Run No. 4
Date: August 8, 1975
Sludge Tested: Mixture of Dry-Weather Flotation-Thickened WAS and Dry-Weather Primary Sludge

PROCEDURE

Mixture was 37.85 l (10 gal.) of primary sludge mixed with 52.99 l (14 gal.) of thickened WAS. Procedure was then the same as for Run No. 1, except sludge was fed at a constant rate of 1.70 l/min. (0.45 gpm). No polymer was utilized.

RESULTS

	Time	Volume liters	Volume gal.	mg/l SS or % TS	Solids Recovery (%)
Feed	for 8.0 min.	13.6	3.6	4.17%	--
Centrate	@ 5 min.	--	--	2,250 mg/l	94.4
Centrate	@ 7 min.	--	--	6,425 mg/l	84.1
Skimmings	--	0.70	0.18	2.86%	--
Cake	--	4.98	1.32	14.09% (17.08 & 12.81)	--

NOTES

1. Dissolved solids were approximately 1,194 mg/l
2. Cake fell from upper two-thirds of basket
3. Volume reduction was 2.73

TABLE A-5. 30.5 CM (12 IN.) CENTRIFUGE BASKET TESTS - RUN NO. 5

Centrifuge Basket Used - 30.5 cm (12 in.)
Run No. 5
Date: August 8, 1976
Sludge Tested: Mixture of Dry-Weather, Flotation-Thickened WAS and Dry-Weather Primary Sludge

PROCEDURE

Mixture was 37.85 l (10 gal.) of primary sludge mixed with 52.99 (14 gal.) of thickened WAS. Procedure and then the same as for Run No. 1, except sludge was fed at a constant rate of 0.95 l/min. (0.25 gpm). No polymer was utilized.

RESULTS

	Time	Volume liters	Volume gal.	mg/l SS or % TS	Solids Recovery (%)
Feed	for 18.0 min.	17.1	4.5	4.23%	--
Centrate	@ 8 min.	--	--	2,210 mg/l	94.6
Centrate	@ 11 min.	--	--	2,325 mg/l	94.3
Centrate	@ 14 min.	--	--	3,000 mg/l	92.7
Centrate	@ 17 min.	--	--	11,275 mg/l	72.6
Skimmings	--	0.30	0.08	4.26%	--
Cake	--	5.38	1.42	13.44% (14.07 & 12.81)	--

NOTES

1. Dissolved solids were approximately 1,166 mg/l
2. Cake fell from upper half of basket
3. Volume reduction was 3.18

TABLE A-6. 30.5 CM (12 IN.) CENTRIFUGE BASKET TESTS - RUN NO. 6

Centrifuge Basket Used - 30.5 cm (12 in.)
Run No. 6
Date: August 8, 1975
Sludge Tested: Mixture of Dry-Weather, Flotation-Thickened WAS and Dry-Weather Primary Sludge

PROCEDURE

Mixture was 37.85 l (10 gal.) of primary sludge mixed with 52.99 l (14 gal.) of thickened WAS. Procedure was then the same as for Run No. 1, except sludge was fed at a constant rate of 0.55 l/min. (0.15 gpm). No polymer was utilized.

RESULTS

	Time	Volume liters	Volume gal.	mg/l SS or % TS	Solids Recovery (%)
Feed	for 33.0 min.	18.2	4.8	4.05%	--
Centrate	@ 14 min.	--	--	1,425 mg/l	96.3
Centrate	@ 18 min.	--	--	1,294 mg/l	96.7
Centrate	@ 22 min.	--	--	1,435 mg/l	96.3
Centrate	@ 26 min.	--	--	1,850 mg/l	95.2
Centrate	@ 30 min.	--	--	2,475 mg/l	93.6
Skimmings	--	0.20	0.06	6.28%	--
Cake	--	5.46	1.44	14.46% (15.48 & 13.45)	--

NOTES

1. Dissolved solids were approximately 1,562 mg/l
2. Cake fell from upper third of basket
3. Volume reduction was 3.33

TABLE A-7. 30.5 CM (12 IN.) CENTRIFUGE BASKET TESTS - RUN NO. 7

Centrifuge Basket Used - 30.5 cm (12 in.)
Run No. 7
Date: August 12, 1975
Sludge Tested: Flotation-Thickened, Dry-Weather WAS with Polymer

PROCEDURE

Same as for Run No. 1, except sludge was fed at a constant rate of 1.27 l/min. (0.34 gpm). A 0.05% solution of Percol 728 (a high molecular weight cationic polymer) was fed at 1.15 g/kg (2.31 lb/ton) (116.1 ml/min.) (.03 gpm).

RESULTS

	Time	Volume liters	Volume gal.	mg/l SS or % TS	Solids Recovery (%)
Feed	for 10.0 min.	12.7	3.4	3.95%	--
Centrate	@ 6 min.	--	--	436 mg/l	98.9
Centrate	@ 9 min.	--	--	1.16%	71.7
Skimmings	--	0.06	0.02	3.87%	--
Cake	--	5.62	1.48	9.70% (9.74 & 9.67)	--

NOTES

1. Dissolved solids were approximately 604 mg/l
2. Cake only slumped slightly at the top
3. Volume reduction was 2.26

TABLE A-8. 30.5 CM (12 IN.) CENTRIFUGE BASKET TESTS - RUN NO. 8

Centrifuge Basket Unit - 30.5 cm (12 in.)
Run No. 8
Date: August 12, 1975
Sludge Tested: Flotation-Thickened, Dry-Weather WAS with Polymer

PROCEDURE

Same as for Run No. 1, except sludge was fed at a constant rate of 1.26 l/min. (0.33 gpm). A 0.1% solution of Percol 728 (a high molecular weight cationic polymer) was fed at 2.29 g/kg (4.57 lb/ton) (116.1 ml min.) (.03 gpm).

RESULTS

	Time	Volume liters	Volume gal.	mg/l SS or % TS	Solids Recovery (%)
Feed	for 10.5 min.	13.2	3.5	4.03%	--
Centrate	@ 6 min.	--	--	303 mg/l	99.2
Centrate	@ 8 min.	--	--	233 mg/l	99.4
Centrate	@ 10 min.	--	--	2.10%	48.7
Skimmings	--	0.06	0.02	2.78%	--
Cake	--	5.62	1.48	10.22% (10.61 & 9.82)	--

NOTES

1. Dissolved solids were approximately 682 mg/l
2. Cake slumped only slightly at the top
3. Volume reduction was 2.35

TABLE A-9. 30.5 CM (12 IN.) CENTRIFUGE BASKET TESTS - RUN NO. 9

Centrifuge Basket Used - 30.5 cm (12 in.)
Run No. 9
Date: August 12, 1975
Sludge Tested: Flotation-Thickened, Dry-Weather WAS with Polymer

PROCEDURE

Same as for Run No. 1, except sludge was fed at a constant rate of 1.20 l/min. (0.32 gpm). A 0.1% solution of Percol 728 (a high molecular weight cationic polymer) was fed at 3.83 g/kg (7.66 lb/ton) (191.1 ml/min.) (0.5 gpm).

RESULTS

	Time	Volume		mg/l SS or % TS	Solids Recovery (%)
		liters	gal.		
Feed	for 11.5 min.	13.8	3.6	4.16%	--
Centrate	@ 6 min.	--	--	184 mg/l	99.6
Centrate	@ 8 min.	--	--	172 mg/l	99.6
Centrate	@ 11 min.	--	--	19,950 mg/l	51.3
Skimmings	--	0	0	--	--
Cake	--	5.68	1.50	9.94% (10.37 & 9.52)	--

NOTES

1. Dissolved solids were approximately 593 mg/l
2. Cake stood firmly
3. Volume reduction was 2.43

TABLE A-10. 30.5 CM (12 IN.) CENTRIFUGE BASKET TESTS - RUN NO. 10

Centrifuge Basket Used - 30.5 cm (12 in.)
Run No. 10
Date: August 12, 1975
Sludge Tested: Flotation-Thickened, Dry-Weather WAS with Polymer

PROCEDURE

Same as for Run No. 1, except sludge was fed at a constant rate of 0.72 l/min. (0.19 gpm). A 0.05% solution of Percol 728 (a high molecular weight cationic polymer) was fed at 0.93 g/kg (1.87 lb/ton) (55.4 ml/min.) (.015 gpm).

RESULTS

	Time	Volume liters	Volume gal.	mg/l SS or % TS	Solids Recovery (%)
Feed	for 19.0 min.	13.7	3.6	4.12%	--
Centrate	@ 9 min.	--	--	583 mg/l	98.6
Centrate	@ 12 min.	--	--	715 mg/l	98.2
Centrate	@ 15 min.	--	--	555 mg/l	98.6
Centrate	@ 18 min.	--	--	2.00%	52.6
Skimmings	--	0	0	--	--
Cake	--	5.68	1.50	10.32% (10.55 & 10.10)	--

NOTES

1. Dissolved solids were approximately 869 mg/l
2. Cake stood firmly
3. Volume reduction was 2.41

TABLE A-11. 30.5 CM (12 IN.) CENTRIFUGE BASKET TESTS - RUN NO. 11

Centrifuge Basket Used - 30.5 cm (12 in.)
Run No. 11
Date: August 13, 1975
Sludge Tested: Mixture of Dry-Weather, Flotation-Thickened WAS and Dry-Weather Primary Sludge With Polymer

PROCEDURE

Mixture was 37.85 l (10 gal.) of primary sludge mixed with 52.99 l (14 gal.) of thickened WAS. Procedure was then the same as for Run No. 1, except sludge was fed at a constant rate of 1.62 l/min. (0.43 gpm). A 0.05% solution of Percol 728 (a high molecular weight cationic polymer) was fed at 0.84 g/kg (1.67 lb/ton) (130.0 ml/min) (.034 gpm).

RESULTS

	Time	Volume liters	Volume gal.	mg/l SS or % TS	Solids Recovery (%)
Feed	for 10.0 min.	16.2	4.3	4.79%	--
Centrate	@ 5 min.	--	--	955 mg/l	98.0
Centrate	@ 8 min.	--	--	856 mg/l	98.2
Skimmings	--	0	0	--	--
Cake	--	5.68	1.50	13.48% (14.69 & 12.28)	--

NOTES

1. Dissolved solids were approximately 844 mg/l
2. Cake stood firmly
3. Volume reduction was 2.85

TABLE A-12. 30.5 CM (12 IN.) CENTRIFUGE BASKET TESTS - RUN NO. 12

Centrifuge Basket Unit - 30.5 cm (12 in.)
Run No. 12
Date: August 13, 1975
Sludge Tested: Mixture of Dry-Weather, Flotation-Thickened WAS and Dry-Weather Primary Sludge with Polymer

PROCEDURE

Mixture was 37.85 l (10 gal.) of primary sludge mixed with 52.99 l (14 gal.) of thickened WAS. Procedure was then the same as for Run No. 1, except sludge was fed at a constant rate of 1.62 l/min. (0.43 gpm). A 0.1% solution of Percol 728 (a high molecular weight cationic polymer) was fed at 1.73 g/kg (3.45 lb/ton) (130 ml/min.) (.034 gpm).

RESULTS

	Time	Volume liters	Volume gal.	mg/l SS or % TS	Solids Recovery (%)
Feed	for 9.0 min.	14.6	3.9	4.64%	--
Centrate	@ 5 min.	--	--	749 mg/l	98.4
Centrate	@ 8 min.	--	--	1,140 mg/l	97.5
Skimmings	--	0.10	0.03	1.81%	--
Cake	--	5.58	1.47	13.41% (15.26 & 11.56)	--

NOTES

1. Dissolved solids were approximately 704 mg/l
2. Cake stood firmly
3. Volume reduction was 2.62

TABLE A-13. 30.5 CM (12 IN.) CENTRIFUGE BASKET TESTS - RUN NO. 13

Centrifuge Basket Used - 30.5 cm (12 in.)
Run No. 13
Date: August 13, 1975
Sludge Tested: Mixture of Dry-Weather, Flotation-Thickened WAS and Dry-Weather Primary Sludge with Polymer

PROCEDURE

Mixture was 37.85 l (10 gal.) of primary sludge mixed with 52.99 l (14 gal.) of thickened WAS. Procedure was then the same as for Run No. 1, except sludge was fed at a constant rate of 1.66 l/min. (0.44 gpm). A 0.1% solution of Percol 728 (a high molecular weight cationic polymer) was fed at 2.37 g/kg (4.74 lb/ton) (183.5 ml/min) (.05 gpm).

RESULTS

	Time	Volume liters	Volume gal.	mg/l SS or % TS	Solids Recovery (%)
Feed	for 10.0 min.	16.6	4.4	4.66	--
Centrate	@ 5 min.	--	--	593 mg/l	98.7
Centrate	@ 8 min.	--	--	1,900 mg/l	95.9
Skimmings	--	0.11	0.03	0.73%	--
Cake	--	5.57	1.47	14.14% (16.02 & 12.25)	--

NOTES

1. Dissolved solids were approximately 543 mg/l
2. Cake stood firmly
3. Volume reduction was 2.98

TABLE A-14. 122 cm BASKET CENTRIFUGE TEST, KENOSHA - RUN NO. 1

Location: Kenosha WPCP	G Force: 1300
Date: November 11, 1975	Feed Rate: 95 l/min (25.1 gpm)
Run No.: 1	Centrate Breakover: 4.8 min
Sludge Type: Thickened WAS CSO Sludge	Length of Run: 12 min
Basket Size: 122 cm (48 in.)	Volume of Skimmings: 276 l (73 gal.)
Basket Speed: 1375 rpm	

Sample	Time of sample, min	Percent total solids	SS, mg/l
Feed 1	0	3.03	29,600
Feed 2	6	3.58	35,100
Centrate 1	5	0.264	1,910
Centrate 2	7.5	0.937	8,640
Centrate 3	11	2.04	19,700
Centrate 4	12.5	2.10	20,300
Skimmings 1		4.00	39,200
Skimmings 2		4.78	47,100
Cake 1		6.58	
Cake 2		8.20	
Cake 3		31.82	
Cake 4		47.40	

TABLE A-15. 122 cm BASKET CENTRIFUGE TEST, KENOSHA - RUN NO. 2

Location: Kenosha WPCP	G Force: 1300
Date: November 11, 1975	Feed Rate: 54 l/min (14.3 gpm)
Run No.: 2	Centrate Breakover: 8.4 min
Sludge Type: Thickened WAS CSO Sludge	Length of Run: 35 min
Basket Size: 122 cm (48 in.)	Volume of Skimmings: 189 l (50 gal.)
Basket Speed: 1375 rpm	

Sample	Time of sample, min	Percent total solids	SS, mg/l
Feed 1	10	0.83	7,600
Feed 2	13	1.51	14,400
Feed 3	25.5	3.37	33,000
Centrate 1	10	0.155	823
Centrate 2	13	0.151	790
Centrate 3	18	0.163	900
Centrate 4	22.5	0.178	1,060
Centrate 5	27.5	0.195	1,230
Centrate 6	32.5	0.899	8,260
Centrate 7	35.5	1.03	9,590
Skimmings		4.50	44,300
Cake 1		7.02	
Cake 2		19.07	
Cake 3		31.00	
Cake 4		26.54	

TABLE A-16. 122 cm BASKET CENTRIFUGE TEST, KENOSHA - RUN NO. 3

Location: Kenosha WPCP	G Force: 1300
Date: November 11, 1975	Feed Rate: 111 l/min (29.4 gpm)
Run No.: 3	Centrate Breakover: 4.1 min
Sludge Type: Thickened WAS CSO Sludge	Length of Run: 9 min
Basket Size: 122 cm (48 in.)	Volume of Skimmings: 276 l (73 gal.)
Basket Speed: 1375 rpm	

Sample	Time of sample, min	Percent total solids	SS, mg/l
Feed 1	5	3.58	35,000
Feed 2	10	3.60	35,300
Centrate 1	5	1.26	11,800
Centrate 2	7	1.56	14,900
Centrate 3	9	1.86	17,900
Centrate 4	10	2.10	15,900
Skimmings 1		3.41	33,400
Skimmings 2		3.73	36,600
Cake 1		8.51	
Cake 2		17.50	
Cake 3		27.10	

TABLE A-17. 122 cm BASKET CENTRIFUGE TEST, KENOSHA - RUN NO. 4

Location: Kenosha WPCP	G Force: 1300
Date: November 11, 1975	Feed Rate: 60 l/min (15.8 gpm)
Run No.: 4	Centrate Breakover: 7.6 min
Sludge Type: Thickened WAS CSO Sludge	Length of Run: 15 min
Basket Size: 122 cm (48 in.)	Volume of Skimmings: 189 l (50 gal.)
Basket Speed: 1375 rpm	

Sample	Time of sample, min	Percent total solids	SS, mg/l
Feed 1	10	3.38	33,000
Feed 2	17	3.10	30,300
Centrate 1	10	0.328	2,560
Centrate 2	15	1.63	15,600
Centrate 3	17	1.59	15,200
Skimmings		3.67	36,000
Cake 1		7.18	
Cake 2		16.3	
Cake 3		28.7	
Cake 4		37.9	

TABLE A-18. 122 cm BASKET CENTRIFUGE TEST, KENOSHA - RUN NO. 5

Location: Kenosha WPCP

Date: November 12, 1975

Run No.: 5

Sludge Type: Thickened WAS CSO Sludge

Basket Size: 122 cm (48 in.)

Basket Speed: 1375 rpm

G Force: 1300

Feed Rate: 69 l/min (18.1 gpm)

Centrate Breakover: 6.6 min

Length of Run: 14 min

Volume of Skimmings: 276 l (73 gal.)

Sample	Time of sample, min	Percent total solids	SS, mg/l
Feed 1	5	2.90	28,300
Feed 2	12	4.14	40,700
Centrate 1	8	0.339	2,670
Centrate 2	10	0.307	2,340
Centrate 3	12	0.316	2,430
Centrate 4	14	0.436	3,630
Centrate 5	15	0.821	7,480
Skimmings 1		2.74	26,600
Skimmings 2		3.48	34,000
Cake 1		6.75	
Cake 2		23.2	
Cake 3		32.3	

TABLE A-19. 122 cm BASKET CENTRIFUGE TEST, KENOSHA - RUN NO. 6

Location: Kenosha WPCP	G Force: 1300
Date: November 12, 1975	Feed Rate: 40 l/min (10.6 gpm)
Run No.: 6	Centrate Breakover: 11.3 min
Sludge Type: Thickened WAS CSO Sludge	Length of Run: 16 min
Basket Size: 122 cm (48 in.)	Volume of Skimmings: 170 l (45 gal.)
Basket Speed: 1375 rpm	

Sample	Time of sample, min	Percent total solids	SS, mg/l
Feed 1	1	2.36	22,800
Feed 2	17	2.93	28,600
Centrate 1	13	0.332	2,590
Centrate 2	16	0.326	2,540
Centrate 3	17	1.47	13,900
Skimmings		3.25	31,700
Cake 1		5.85	
Cake 2		12.1	
Cake 3		33.7	

TABLE A-20. 122 cm BASKET CENTRIFUGE TEST, KENOSHA, RUN NO. 7

Location: Kenosha WPCP	G Force: 1300
Date: November 17, 1975	Feed Rate: 88 l/min (23.2 gpm)
Run No.: 7	Centrate Breakover: 5.2 min
Sludge Type: Combined Dry-Weather*	Length of Run: 10 min
Basket Size: 122 cm (48 in.)	Volume of Skimmings: 322 l (85 gal.)
Basket Speed: 1375 rpm	

Sample	Time of sample, min	Percent total solids	SS, mg/l
Feed 1	3	4.06	39,210
Feed 2	10	4.14	40,060
Centrate 1	6	0.919	7,840
Centrate 2	8	0.463	3,280
Centrate 3	10	0.586	4,513
Skimmings 1		2.09	19,590
Skimmings 2		4.56	44,240
Cake 1		12.4	
Cake 2		18.0	
Cake 3		18.0	

* Combined dry-weather sludge consisted of a 1:1 volumetric mixture of thickened WAS and primary sludge.

TABLE A-21. 122 cm BASKET CENTRIFUGE TEST, KENOSHA, RUN NO. 8

Location: Kenosha WPCP	G Force: 1300
Date: November 17, 1975	Feed Rate: 54 l/min (14.2 gpm)
Run No.: 8	Centrate Breakover: 8.5 min
Sludge Type: Combined Dry-Weather*	Length of Run: 14 min
Basket Size: 122 cm (48 in.)	Volume of Skimmings: 276 l (73 gal.)
Basket Speed: 1375 rpm	

Sample	Time of sample, min	Percent total solids	SS, mg/l
Feed 1	3	4.03	38,990
Feed 2	14	4.09	39,560
Centrate 1	10	0.713	5,781
Centrate 2	13	0.461	3,261
Centrate 3	14	1.21	10,710
Centrate 4	15	0.835	6,992
Skimmings 1		1.76	16,270
Skimmings 2		4.52	43,850
Cake 1		9.74	
Cake 2		17.2	
Cake 3		23.0	

* Combined dry-weather sludge consisted of a 1:1 volumetric mixture of thickened WAS and primary sludge.

TABLE A-22. 122 cm BASKET CENTRIFUGE TEST, KENOSHA - RUN NO. 9

Location: Kenosha WPCP	G Force: 1300
Date: November 17, 1975	Feed Rate: 39 l/min (10.2 gpm)
Run No.: 9	Centrate Breakover: 11.8 min
Sludge Type: Combined Dry-Weather*	Length of Run: **
Basket Size: 122 cm (48 in.)	Volume of Skimmings: 265 l (70 gal.)
Basket Speed: 1375 rpm	

Sample	Time of sample, min	Percent total solids	SS, mg/l
Feed 1	3	4.11	39,790
Feed 2	14	3.84	37,090
Centrate 1	12	1.49	13,550
Centrate 2	14	0.804	6,688
Skimmings 1		3.71	35,730
Skimmings 2		3.44	33,000
Cake 1		19.5	
Cake 2		23.8	
Cake 3		23.5	

* Combined dry-weather sludge consisted of a 1:1 volumetric mixture of thickened WAS and primary sludge.

** Automatic shutoff due to excessive vibration.

TABLE A-23. 122 cm BASKET CENTRIFUGE TEST, KENOSHA - RUN NO. 10

Location: Kenosha WPCP	G Force: 1300
Date: November 18, 1975	Feed Rate: 35 l/min (9.32 gpm)
Run No.: 10	Centrate Breakover: 12.9 min
Sludge Type: Combined Dry-Weather*	Length of Run: 76 min
Basket Size: 122 cm (48 in.)	Volume of Skimmings: 151 l (40 gal.)
Basket Speed: 1375 rpm	

Sample	Time of sample, min	Percent total solids	SS, mg/l
Feed 1	2	1.57	14,320
Feed 2	15	2.09	19,540
Feed 3	23	0.75	6,150
Feed 4	29	0.37	2,380
Feed 5	43	1.03	8,130
Feed 6	72	2.95	28,130
Centrate 1	16	0.280	1,453
Centrate 2	24	0.223	879
Centrate 3	40	0.203	677
Centrate 4	50	0.232	968
Centrate 5	60	0.241	1,063
Centrate 6	70	0.267	1,322
Centrate 7	76	1.23	10,970
Skimmings		3.82	36,890
Cake 1		12.2	
Cake 2		27.9	

* Combined dry-weather sludge consisted of a 1:1 volumetric mixture of thickened WAS and primary sludge.

TABLE A-24. 122 cm BASKET CENTRIFUGE TEST, KENOSHA - RUN NO. 11

Location: Kenosha WPCP	G Force: 1300
Date: November 18, 1975	Feed Rate: 38 l/min (10.1 gpm)
Run No.: 11	Centrate Breakover: 11.8 min
Sludge Type: Combined Dry-Weather*	Length of Run: 26 min
Basket Size: 122 cm (48 in.)	Volume of Skimmings: 106 l (28 gal.)
Basket Speed: 1375 rpm	

Sample	Time of sample, min	Percent total solids	SS, mg/l
Feed 1	3	3.18	30,450
Feed 2	15	3.31	31,750
Centrate 1	13	0.334	1,987
Centrate 2	17	0.286	1,513
Centrate 3	21	0.298	1,632
Centrate 4	25	0.358	2,224
Centrate 5	27	1.22	10,800
Skimmings		0.247	1,117
Cake 1		9.03	
Cake 2		23.5	

* Combined dry-weather sludge consisted of a 1:1 volumetric mixture of thickened WAS and primary sludge.

TABLE A-25. 122 cm BASKET CENTRIFUGE TEST, KENOSHA - RUN NO. 12

Location: Kenosha WPCP	G Force: 1300
Date: November 19, 1975	Feed Rate: 58 l/min (15.4 gpm)
Run No.: 12	Centrate Breakover: 7.8 min
Sludge Type: Combined Dry-Weather*	Length of Run: 11 min
Basket Size: 122 cm (48 in.)	Volume of Skimmings: 140 l (37 gal.)
Basket Speed: 1375 rpm	

Sample	Time of sample, min	Percent total solids	SS, mg/l
Feed 1	3	5.34	52,060
Feed 2	11	6.56	64,220
Centrate 1	9	2.18	20,470
Centrate 2	11	3.09	29,570
Centrate 3	12	3.06	29,290
Skimmings		3.45	
Cake 1		5.23	
Cake 2		9.76	
Cake 3		37.5	

* Combined dry-weather sludge consisted of a 1:1 volumetric mixture of thickened WAS and primary sludge.

TABLE A-26. 122 cm BASKET CENTRIFUGE TEST, KENOSHA - RUN NO. 13

Location: Kenosha WPCP	G Force: 1300
Date: September 10, 1976	Feed Rate: 54.1 l/min (14.3 gpm)
Run No.: 13	Centrate Breakover: 8.4 min
Sludge Type: Wet-weather/dry-weather ratio*	Length of Run: 25 min
Basket Size: 122 cm (48 in.)	Volume of Skimmings: 155 ℓ (41 gal.)
Basket Speed: 1375 RPM	Polymer Addition: None

Sample	Time of sample, min	Percent TS	Percent TVS	SS, mg/l	VSS, mg/l
Feed 1	15	3.63	2.24	34,840	21,630
Feed 2	25	3.64	2.26	34,940	21,880
Centrate 1	15	0.26	0.19	1,170	1,000
Centrate 2	25	1.20	0.90	11,080	8,540
Skimmings		2.72	1.74	25,200	16,210
Cake 1		14.55	7.95		
Cake 2		11.90	7.00		

* Wet-weather/dry-weather sludge consisted of a 1.2:1.2:1.0 volumetric mixture of dry-weather primary, dry-weather thickened WAS and wet-weather thickened WAS.

TABLE A-27. 122 cm BASKET CENTRIFUGE TEST, KENOSHA - RUN NO. 14

Location: Kenosha WPCP

Date: September 14, 1976

Run No.: 14

Sludge Type: Wet-weather/dry-weather ratio*

Basket Size: 122 cm (48 in.)

Basket Speed: 1375 RPM

G Force: 1300

Feed Rate: 94.6 l/min (25.0 gpm)

Centrate Breakover: 4.8 min

Length of Run: 17 min

Volume of Skimmings: 208 ℓ (55 gal.)

Polymer Addition: None

Sample	Time of sample, min	Percent TS	Percent TVS	SS, mg/l	VSS, mg/l
Feed 1	10	1.46	0.85	12,570	7,410
Feed 2	17	2.25	1.34	20,470	12,310
Centrate 1	10	0.56	0.40	3,790	2,960
Centrate 2	17	0.59	0.40	4,140	3,000
Skimmings		3.60	2.17	34,400	20,660
Cake 1		46.5	27.8		
Cake 2		43.6	27.0		

* Wet-weather/dry-weather sludge consisted of a 1.2:1.2:1.0 volumetric mixture of dry-weather primary, dry-weather thickened WAS and wet-weather thickened WAS.

TABLE A-28. 122 cm BASKET CENTRIFUGE TESTS, KENOSHA - RUN NO. 15

Location: Kenosha WPCP

Date : September 14, 1976

Run No.: 15

Sludge Type: Wet-weather/dry-weather ratio*

Basket Size: 122 cm (48 in.)

Basket Speed: 1375 RPM

G Force: 1300

Feed Rate: 37.9 l/min (10.0 gpm)

Centrate Breakover: 5.1 min

Length of Run: 23 min

Volume of Skimmings: 189 ℓ (50 gal.)

Polymer Addition: None

Sample	Time of sample, min	Percent TS	Percent TVS	SS, mg/l	VSS, mg/l
Feed 1	13	4.17	2.38	39,470	22,530
Feed 2	18	5.19	2.88	49,670	27,530
Feed 3	23	5.70	3.27	54,770	31,430
Centrate 1	13	0.69	0.52	4,970	4,080
Centrate 2	18	0.96	0.70	7,590	5,830
Centrate 3	23	1.04	0.79	8,280	6,600
Skimmings		3.34	2.38	31,600	22,630
Cake 1		38.7	11.8		
Cake 2		24.4	11.3		

* Wet-weather/dry-weather sludge consisted of a 1.2:1.2:1.0 volumetric mixture of dry-weather primary, dry-weather thickened WAS and wet-weather thickened WAS.

TABLE A-29. 122 cm BASKET CENTRIFUGE TEST, KENOSHA - RUN NO. 16

Location: Kenosha WPCP

Date: September 14, 1976

Run No.: 16

Sludge Type: Wet-weather/dry-weather ratio*

Basket Size: 122 cm (48 in.)

Basket Speed: 1375 RPM

G Force: 1300

Feed Rate: 70.0 l/min (18.5 gpm)

Centrate Breakover: 6.5 min

Length of Run: 19 min

Volume of Skimmings: 189 ℓ (50 gal.)

Polymer Addition: None

Sample	Time of sample, min	Percent TS	Percent TVS	SS, mg/l	VSS, mg/l
Feed 1	9	1.87	1.15	14,790	8,530
Feed 2	14	1.78	1.08	13,890	7,830
Feed 3	19	1.90	1.16	15,090	8,630
Feed 4	24	1.88	1.13	14,890	8,330
Centrate 1	9	0.59	0.42	3,950	3,160
Centrate 2	14	0.61	0.44	4,110	3,070
Centrate 3	19	0.59	0.42	3,900	3,120
Centrate 4	24	0.56	0.41	4,330	3,010
Skimmings		1.35	0.92	11,470	8,070
Cake 1		35.7	9.50		
Cake 2		21.0	9.43		

* Wet-weather/dry-weather sludge consisted of a 1.2:1.2:1.0 volumetric mixture of dry-weather primary, dry-weather thickened WAS and wet-weather thickened WAS.

TABLE A-30. 122 cm BASKET CENTRIFUGE TEST, KENOSHA - RUN NO. 17

Location: Kenosha WPCP

Date: September 14, 1976

Run No.: 17

Sludge Type: Wet-weather/dry-weather ratio*

Basket Size: 122 cm (48 in.)

Basket Speed: 1375 RPM

G Force: 1300

Feed Rate: 109.0 l/min (28.8 gpm)

Centrate Breakover: 4.2 min

Length of Run: 15 min

Volume of Skimmings: 189 ℓ (50 gal.)

Polymer Addition: None

Sample	Time of sample, min	Percent TS	Percent TVS	SS, mg/l	VSS, mg/l
Feed 1	9	3.30	1.88	30,870	17,610
Feed 2	12	3.81	2.22	35,970	21,010
Feed 3	15	3.88	2.23	36,670	21,110
Centrate 1	9	1.01	0.74	8,090	6,340
Centrate 2	12	1.81	1.31	16,090	12,000
Centrate 3	15	1.92	1.40	17,350	12,900
Skimmings		4.00	2.61	37,680	24,880
Cake 1		28.7	10.0		
Cake 2		16.5	7.77		

* Wet-weather/dry-weather sludge consisted of a 1.2:1.2:1.0 volumetric mixture of dry-weather primary, dry-weather thickened WAS and wet-weather thickened WAS.

TABLE A-31. 122 cm BASKET CENTRIFUGE TEST, KENOSHA - RUN NO. 18

Location: Kenosha WPCP

Date: September 13, 1976

Run No.: 18

Sludge Type: Wet-weather/dry-weather ratio*

Basket Size: 122 cm (48 in.)

Basket Speed: 1375 RPM

G Force: 1300

Feed Rate: 44.3 l/min (11.7 gpm)

Centrate Breakover: 10.3 min

Length of Run: 20 min

Volume of Skimmings: 189 ℓ (50 gal.)

Polymer Addition: 2.76 kg/metric ton (5.51 lb/ton)

Sample	Time of sample, min	Percent TS	Percent TVS	SS, mg/l	VSS, mg/l
Feed 1	10.5	2.38	1.45	21,580	13,280
Feed 2	15	2.42	1.46	21,980	13,380
Feed 3	20	2.45	1.48	22,280	13,580
Centrate 1	10.5	0.33	0.21	1,350	1,060
Centrate 2	15	0.38	0.26	1,850	1,460
Centrate 3	20	0.37	0.26	1,690	1,380
Skimmings		2.50	1.40	23,020	12,920
Cake 1		23.5	11.5		
Cake 2		24.6	14.3		

* Wet-weather/dry-weather sludge consisted of a 1.2:1.2:1.0 volumetric mixture of dry-weather primary, dry-weather thickened WAS and wet-weather thickened WAS.

TABLE A-32. 122 cm BASKET CENTRIFUGE TEST, KENOSHA - RUN NO. 19

Location: Kenosha WPCP

Date: September 13, 1976

Run No.: 19

Sludge Type: Wet-weather/dry-weather ratio*

Basket Size: 122 cm (48 in.)

Basket Speed: 1375 RPM

G Force: 1300

Feed Rate: 44.3 l/min (11.7 gpm)

Centrate Breakover: 10.3 min

Length of Run: 25 min

Volume of Skimmings: 189 ℓ (50 gal.)

Polymer Addition: 1.92 kg/metric ton (3.84 lb/ton)

Sample	Time of sample, min	Percent TS	Percent TVS	SS, mg/l	VSS, mg/l
Feed 1	11	2.42	1.46	21,980	13,440
Feed 2	20	2.50	1.52	22,780	14,040
Feed 3	25	2.48	1.48	22,580	13,640
Centrate 1	11	0.28	0.18	1,270	1,010
Centrate 2	20	0.30	0.20	1,530	1,240
Centrate 3	25	0.29	0.19	1,440	1,160
Skimmings		6.14	3.45	59,020	33,130
Cake 1		20.3	10.8		
Cake 2		31.5	11.5		

* Wet-weather/dry-weather sludge consisted of a 1.2:1.2:1.0 volumetric mixture of dry-weather primary, dry-weather thickened WAS and wet-weather thickened WAS.

TABLE A-33. 122 cm BASKET CENTRIFUGE TEST, KENOSHA - RUN NO. 20

Location: Kenosha WPCP

Date: September 15, 1976

Run No.: 20

Sludge Type: Wet-weather/dry-weather ratio*

Basket Size: 122 cm (48 in.)

Basket Speed: 1000 RPM

G Force: 700

Feed Rate: 60.6 l/min (16.0 gpm)

Centrate Breakover: 7.5 min

Length of Run: 22 min

Volume of Skimmings: 132 ℓ (35 gal.)

Polymer Addition: 1.40 kg/metric ton (2.81 lb/ton)

Sample	Time of sample, min	Percent TS	Percent TVS	SS, mg/l	VSS, mg/l
Feed 1	10	4.92	2.49	46,710	23,460
Feed 2	15	4.31	2.48	40,610	23,360
Feed 3	20	3.82	2.28	35,710	21,360
Feed 4	22	4.04	2.32	37,910	21,760
Centrate 1	10	0.35	0.24	1,250	1,070
Centrate 2	15	0.32	0.22	950	830
Centrate 3	20	0.30	0.21	780	730
Centrate 4	22	0.45	0.32	2,290	1,870
Skimmings		4.57	2.94	43,460	28,080
Cake 1		19.3	9.14		
Cake 2		21.0	10.1		

* Wet-weather/dry-weather sludge consisted of a 1.2:1.2:1.0 volumetric mixture of dry-weather primary, dry-weather thickened WAS and wet-weather thickened WAS.

TABLE A-34. 122 cm BASKET CENTRIFUGE TEST, KENOSHA - RUN NO. 21

Location: Kenosha WPCP

Date: September 15, 1976

Run No.: 21

Sludge Type: Wet-weather/dry-weather ratio*

Basket Size: 122 cm (48 in.)

Basket Speed: 1000 RPM

G Force: 700

Feed Rate: 81.4 l/min (21.5 gpm)

Centrate Breakover: 5.6 min

Length of Run: 11 min

Volume of Skimmings: 140 ℓ (37 gal.)

Polymer Addition: 0.78 kg/metric ton (1.56 lb/ton)

Sample	Time of sample, min	Percent TS	Percent TVS	SS, mg/l	VSS, mg/l
Feed 1	8	5.42	3.16	51,720	30,190
Feed 2	11	5.65	3.24	54,020	30,990
Centrate 1	8	0.75	0.57	5,600	4,470
Centrate 2	11	3.67	2.76	34,800	26,350
Skimmings		4.18	2.73	39,550	25,950
Cake 1		20.1	9.53		
Cake 2		16.2	8.59		

* Wet-weather/dry-weather sludge consisted of a 1.2:1.2:1.0 volumetric mixture of dry-weather primary, dry-weather thickened WAS and wet-weather thickened WAS.

APPENDIX B - MILWAUKEE, WISCONSIN CENTRIFUGE TEST DATA

TABLE B-1. 122 cm BASKET CENTRIFUGE TEST - RUN NO. 1

Location: Humboldt Avenue Detention Tank

Date: May 10, 1976

Run No.: 1

Sludge Type: Gravity Thickened CSO Sludge

Basket Size: 122 cm (48 in.)

Basket Speed: 1375 RPM

G Force: 1300

Feed Rate: 223 liter/min (59 gpm)

Centrate Breakover: 2.03 min

Length of Run: 73 min

Volume of Skimmings: -

Polymer Addition: None

Sample	Time of sample, min	Percent TS	Percent TVS	SS, mg/l
Feed 1	3	0.07	0.02	297
Feed 2	7	0.07	0.03	270
Feed 3	17	0.05	0.02	131
Feed 4	50	0.13	0.05	933
Feed 5	65	0.14	0.05	964
Centrate 1	3	0.05	0.02	81
Centrate 2	7	0.04	0.02	14
Centrate 3	17	0.04	0.02	34
Centrate 4	50	0.04	0.02	18
Centrate 5	65	0.05	0.02	66
Cake		0.13	0.05	
Cake		0.14	0.05	

TABLE B-2. 30.5 cm (12 in.) CENTRIFUGE BASKET TESTS - RUN NO. 1

Centrifuge Basket Used - 30.5 cm (12 in.)
Run No. 1
Date: June 8, 1976
Sludge Tested: Gravity Thickened CSO Sludge

PROCEDURE

Sludge was fed to the 30.5 cm (12 in.) basket centrifuge (producing 1300 G's at the basket wall) at a constant rate of 10.22 l/min (2.7 gpm) for 240 minutes. A feed sample was taken for analyses prior to centrifugation and subsequent centrate samples were taken during centrifugation. A skimmings sample and one cake sample was taken at the end of the run for total solids analysis. No polymer was utilized.

RESULTS

	Time	Volume liters	Volume gal.	mg/l SS or % TS	Solids recovery, %
Feed	for 240 min	2453	648	.062%	-
Centrate	@ 30 min			19	76.6
Centrate	@ 60 min			20	
Centrate	@ 90 min			18	
Centrate	@ 120 min			17	
Centrate	@ 150 min			17	
Centrate	@ 180 min			11	
Centrate	@ 210 min			7	
Centrate	@ 240 min			7	
Skimmings	-			.0008%	
Cake	-			18.3%	

TABLE B-3. 30.5 cm (12 in.) CENTRIFUGE BASKET TESTS - RUN NO. 2

Centrifuge Basket Used - 30.5 cm (12 in.)
Run No. 2
Date: June 9, 1976
Sludge Tested: Gravity Thickened CSO Sludge

PROCEDURE

Same as for Run No. 1, except a 0.1% polymer (Percol 728) solution was fed at a constant rate of 0.014 ℓ/min (0.0037 gpm).

RESULTS

	Time	Volume liters	Volume gal.	mg/l SS or % TS	Solids recovery, %
Feed	for 240 min	2453	648	.069%	-
Centrate	@ 30 min			22	82.1%
Centrate	@ 60 min			10	
Centrate	@ 90 min			8	
Centrate	@ 120 min			28	
Centrate	@ 150 min			22	
Centrate	@ 180 min			22	
Centrate	@ 210 min			22	
Centrate	@ 240 min			17	
Skimmings	-			.0655%	
Cake	-			28.4%	

TABLE B-4. AVNX 314 DECANTER CENTRIFUGE TESTS

Location: Milwaukee South Shore WPCP | Bowl Speed: 2700 RPM
Date: May 25, 1976 | Pool Radius: 103 mm
Run No.: 1 | Differential Speed: Δn = 15 RPM
Sludge Type: Dry-Weather Primary | Polymer Addition: None
Feed Rate: 105.6 liters/min (27.9 gpm) | Recovery: 41%

Sample	Percent total solids	Percent total volatile solids	SS, mg/l	VSS, mg/l
Feed 1	5.92	3.23	54,600	29,840
Feed 2	5.65	3.48	51,970	32,420
Centrate 1	3.83	2.63	34,370	23,900
Centrate 2	3.88	2.63	34,210	23,890
Cake 1	27.0	12.3		
Cake 2	25.3	12.0		

TABLE B-5. AVNX 314 DECANTER CENTRIFUGE TESTS

Location: Milwaukee South Shore WPCP | Bowl Speed: 2700 RPM
Date: May 25, 1976 | Pool Radius: 103 mm
Run No.: 2 | Differential Speed: Δn = 23 RPM
Sludge Type: Dry-Weather Primary | Polymer Addition: None
Feed Rate: 105.6 liters/min (27.9 gpm) | Recovery: 47%

Sample	Percent total solids	Percent total volatile solids	SS, mg/l	VSS, mg/l
Feed 1	5.61	3.42	51,570	31,790
Feed 2	5.71	3.51	52,550	32,680
Feed 3	5.63	3.36	51,710	31,130
Centrate 1	3.61	2.46	31,560	22,160
Centrate 2	3.84	2.56	33,790	23,180
Centrate 3	3.36	2.30	29,030	20,540
Cake 1	19.95	9.80		
Cake 2	21.28	10.42		
Cake 3	18.38	9.22		

TABLE B-6. AVNX 314 DECANTER CENTRIFUGE TESTS

Location: Milwaukee South Shore WPCP	Bowl Speed: 2700 RPM
Date: May 25, 1976	Pool Radius: 103 mm
Run No.: 3	Differential Speed: Δn = 23 RPM
Sludge Type: Dry-Weather Primary	Polymer Addition: None
Feed Rate: 36.3 liters/min (9.6 gpm)	Recovery: 50%

Sample	Percent total solids	Percent total volatile solids	SS, mg/l	VSS, mg/l
Feed 1	5.76	3.59	53,030	33,460
Feed 2	5.51	3.35	50,530	31,040
Centrate 1	3.53	2.35	30,730	21,060
Centrate 2	3.49	2.43	30,310	21,870
Cake 1	17.5	8.8		
Cake 2	17.1	8.7		

TABLE B-7. AVNX 314 DECANTER CENTRIFUGE TESTS

Location: Milwaukee South Shore WPCP	Bowl Speed: 2700 RPM
Date: May 25, 1976	Pool Radius: 103 mm
Run No.: 4	Differential Speed: Δn = 15 RPM
Sludge Type: Dry-Weather Primary	Polymer Addition: None
Feed Rate: 36.3 liters/min (9.6 gpm)	Recovery: 52%

Sample	Percent total solids	Percent total volatile solids	SS, mg/l	VSS, mg/l
Feed 1	5.58	3.38	51,260	31,420
Feed 2	5.47	3.19	50,130	29,500
Feed 3	5.59	3.43	51,330	31,890
Centrate 1	3.43	2.36	29,660	21,170
Centrate 2	3.33	2.29	28,700	20,460
Centrate 3	3.28	2.28	28,190	20,350
Cake 1	16.8	8.9		
Cake 2	17.4	9.1		
Cake 3	16.6	8.7		

TABLE B-8. AVNX 314 DECANTER CENTRIFUGE TESTS

Location: Milwaukee South Shore WPCP
Date: May 25, 1976
Run No.: 5
Sludge Type: Dry-Weather Primary
Feed Rate: 67.8 liters/min (17.9 gpm)

Bowl Speed: 2700 RPM
Pool Radius: 103 mm
Differential Speed: Δn = 15 RPM
Polymer Addition: None
Recovery: 41%

Sample	Percent total solids	Percent total volatile solids	SS, mg/l	VSS, mg/l
Feed 1	5.74	3.49	52,810	32,430
Feed 2	5.63	3.78	51,730	35,370
Feed 3	5.84	3.24	51,260	29,970
Centrate 1	3.86	2.62	34,010	23,820
Centrate 2	3.85	2.53	33,890	22,920
Centrate 3	3.89			
Cake 1	21.8			
Cake 2	20.9			
Cake 3	22.5			

TABLE B-9. AVNX 314 DECANTER CENTRIFUGE TESTS

Location: Milwaukee South Shore WPCP

Date: May 26, 1976

Run No.: 6

Sludge Type: Dry-Weather Primary

Feed Rate: 37.5 liters/min (9.9 gpm)

Bowl Speed: 2700 RPM

Pool Radius: 103 mm

Differential Speed: Δn = 10 RPM

Polymer Addition: None

Recovery: 47%

Sample	Percent total solids	Percent total volatile solids	SS, mg/l	VSS, mg/l
Feed 1	5.62	3.52	52,440	33,300
Feed 2	5.64	3.29	52,610	31,050
Feed 3	5.63	3.36	52,470	31,720
Centrate 1	3.55	2.47	31,740	22,860
Centrate 2	3.54	2.46	31,630	22,690
Centrate 3	3.55	2.37	31,700	21,860
Cake 1	20.6	10.9		
Cake 2	19.8	10.3		
Cake 3	19.8	10.4		

TABLE B-10. AVNX 314 DECANTER CENTRIFUGE TESTS

Location: Milwaukee South Shore WPCP
Date: May 26, 1976
Run No.: 7
Sludge Type: Dry-Weather Primary
Feed Rate: 37.5 liters/min (9.9 gpm)

Bowl Speed: 2700 RPM
Pool Radius: 101 mm
Differential Speed: Δn = 23 RPM
Polymer Addition: None
Recovery: 53%

Sample	Percent total solids	Percent total volatile solids	SS, mg/l	VSS, mg/l
Feed 1	5.64	3.37	52,610	31,870
Feed 2	5.59	3.37	52,080	31,850
Feed 3	5.37	3.23	49,920	30,520
Centrate 1	3.33	2.33	29,450	21,450
Centrate 2	3.24	2.25	28,550	20,570
Centrate 3	3.25	2.23	28,680	20,460
Cake 1	16.7	8.3		
Cake 2	16.8	8.9		
Cake 3	16.7	8.6		

TABLE B-11. AVNX 314 DECANTER CENTRIFUGE TESTS

Location: Milwaukee South Shore WPCP

Date: May 27, 1976

Run No.: 8

Sludge Type: Dry-Weather Primary

Feed Rate: 37.5 liters/min (9.9 gpm)

Bowl Speed: 2700 RPM

Pool Radius: 101 mm

Differential Speed: Δn = 15 RPM

Polymer Addition: 0.88 kg/metric ton (1.76 lb/ton)

Recovery: 90%

Sample	Percent total solids	Percent total volatile solids	SS, mg/l	VSS, mg/l
Feed 1	5.63	3.50	52,480	33,130
Feed 2	5.70	3.46	53,250	32,690
Feed 3	5.53	3.37	51,540	31,810
Centrate 1	1.65	1.14	12,660	9,540
Centrate 2	0.91	0.61	5,260	4,260
Centrate 3	0.81	0.54	4,320	3,500
Cake 1	14.7	9.0		
Cake 2	14.4	9.1		
Cake 3	14.4	8.8		

TABLE B-12. AVNX 314 DECANTER CENTRIFUGE TESTS

Location: Milwaukee South Shore WPCP

Date: May 27, 1976

Run No.: 9

Sludge Type: Dry-Weather Primary

Feed Rate: 37.5 liters/min (9.9 gpm)

Bowl Speed: 2700 RPM

Pool Radius: 101 mm

Differential Speed: Δn = 15 RPM

Polymer Addition: 1.33 kg/metric ton (2.68 lb/mon)

Recovery: 95%

Sample	Percent total solids	Percent total volatile solids	SS, mg/l	VSS, mg/l
Feed 1	5.63	3.37	52,460	31,750
Feed 2	5.36	3.34	49,840	31,520
Feed 3	5.55	3.47	51,740	32,820
Centrate 1	0.75	0.48	3,650	2,930
Centrate 2	0.83	0.55	4,630	3,650
Centrate 3	0.64	0.40	2,600	2,130
Cake 1	15.5	9.5		
Cake 2	15.4	9.5		
Cake 3	15.3	9.1		

TABLE B-13. AVNX 314 DECANTER CENTRIFUGE TESTS

Location: Milwaukee South Shore WPCP

Date: May 27, 1976

Run No.: 10

Sludge Type: Dry-Weather Primary

Feed Rate: 66.6 liters/min (17.6 gpm)

Bowl Speed: 2700 RPM

Pool Radius: 103 mm

Differential Speed: Δn = 20 RPM

Polymer Addition: 1.5 kg/metric ton (3.0 lb/ton)

Recovery: 66%

Sample	Percent total solids	Percent total volatile solids	SS, mg/l	VSS, mg/l
Feed 1	5.28	3.24	49,000	30,520
Feed 2	5.37	3.26	49,890	30,720
Centrate 1	2.50	1.66	21,980	14,710
Centrate 2	2.51	1.67	21,380	14,870
Cake 1	15.9	9.2		
Cake 2	16.1	9.6		

TABLE B-14. AVNX 314 DECANTER CENTRIFUGE TESTS

Location: Milwaukee South Shore WPCP

Date: May 27, 1976

Run No.: 11

Sludge Type: Dry-Weather Primary

Feed Rate: 66.6 liters/min (17.6 gpm)

Bowl Speed: 2700 RPM

Pool Radius: 103 mm

Differential Speed: Δn = 25 RPM

Polymer Addition: 1.48 kg/metric ton (2.96 lb/ton)

Recovery: 71%

Sample	Percent total solids	Percent total volatile solids	SS, mg/l	VSS, mg/l
Feed 1	5.38	3.30	50,030	31,140
Feed 2	5.45	3.40	50,710	32,200
Feed 3	5.44	3.29	50,600	31,050
Centrate 1	2.49	1.66	21,100	14,760
Centrate 2	2.45	1.63	20,730	14,410
Centrate 3	2.03	1.36	16,490	11,710
Cake 1	14.8	8.5		
Cake 2	14.9	9.1		

TABLE B-15. AVNX 314 DECANTER CENTRIFUGE TESTS

Location: Milwaukee South Shore WPCP

Date: May 27, 1976

Run No.: 12

Sludge Type: Dry-Weather Primary

Feed Rate: 54.5 liters/min (14.4 gpm)

Bowl Speed: 2700 RPM

Pool Radius: 103 mm

Differential Speed: Δn = 20 RPM

Polymer Addition: 1.85 kg/metric ton (3.69 lb/ton)

Recovery: 61%

Sample	Percent total solids	Percent total volatile solids	SS, mg/l	VSS, mg/l
Feed 1	5.02	3.10	46,380	29,130
Feed 2	5.45	3.25	50,700	30,640
Feed 3	5.35	3.23	49,700	30,490
Centrate 1	2.27	1.53	18,940	13,420
Centrate 2	2.47	1.68	20,890	14,990
Centrate 3	3.37	2.32	29,910	21,360
Cake 1	16.1	9.7		
Cake 2	15.6	8.7		
Cake 3	16.6	8.8		

TABLE B-16. AVNX 314 DECANTER CENTRIFUGE TESTS

Location: Milwaukee South Shore WPCP

Date: June 1, 1976

Run No.: 13

Sludge Type: Dry-Weather Primary

Feed Rate: 58.3 liters/min (15.9 gpm)

Bowl Speed: 2700 RPM

Pool Radius: 103 mm

Differential Speed: Δn = 23 RPM

Polymer Addition: 3.22 kg/metric ton (6.43 lb/ton)

Recovery: 98%

Sample	Percent total solids	Percent total volatile solids	SS, mg/l	VSS, mg/l
Feed 1	5.35	3.64	50,530	34;980
Feed 2	4.93	3.16	46,330	30,160
Feed 3	2.45	1.62	21,440	14,810
Centrate 1	0.48	0.28	1,780	1,450
Centrate 2	0.41	0.22	1,080	840
Centrate 3	0.40	0.21	880	680
Cake 1	11.6	8.9		
Cake 2	15.3	10.0		
Cake 3	12.7	8.6		

TABLE B-17. AVNX 314 DECANTER CENTRIFUGE TESTS

Location: Milwaukee South Shore WPCP

Date: June 1, 1976

Run No.: 14

Sludge Type: Dry-Weather Primary

Feed Rate: 58.3 liters/min (15.4 gpm)

Bowl Speed: 2700 RPM

Pool Radius: 103 mm

Differential Speed: Δn = 18 RPM

Polymer Addition: 2.7 kg/metric ton (5.39 lb/ton)

Recovery: 95%

Sample	Percent total solids	Percent total volatile solids	SS, mg/l	VSS, mg/l
Feed 1	5.07	3.30	47,730	31,590
Feed 2	4.98	3.31	46,800	31,710
Feed 3	5.14	3.50	48,380	33,570
Centrate 1	0.59	0.38	2,930	2,370
Centrate 2	0.73	0.48	4,340	3,350
Centrate 3	0.47	0.27	1,660	1,320
Cake 1	17.1	11.7		
Cake 2	17.4	11.3		
Cake 3	17.6	11.0		

TABLE B-18. AVNX 314 DECANTER CENTRIFUGE TESTS

Location: Milwaukee South Shore WPCP
Date: June 1, 1976
Run No.: 15
Sludge Type: Dry-Weather Primary
Feed Rate: 58.3 liters/min (15.4 gpm)

Bowl Speed: 2700 RPM
Pool Radius: 103 mm
Differential Speed: Δn = 13 RPM
Polymer Addition: 2.17 kg/metric ton (4.33 lb/ton)
Recovery: 90%

Sample	Percent total solids	Percent total volatile solids	SS, mg/l	VSS, mg/l
Feed 1	4.76	3.05	44,570	29,130
Feed 2	4.76	3.03	44,570	28,920
Feed 3	4.65	2.94	43,480	27,970
Centrate 1	0.95	0.68	6,520	5,430
Centrate 2	0.98	0.67	6,780	5,310
Centrate 3	0.75	0.50	4,510	3,570
Cake 1	15.7	10.6		
Cake 2	18.4	12.0		
Cake 3	18.1	11.5		

TABLE B-19. AVNX 314 DECANTER CENTRIFUGE TESTS

Location: Milwaukee South Shore WPCP

Date: June 2, 1976

Run No.: 16

Sludge Type: Dry-Weather Primary

Feed Rate: 57.9 liters/min (15.3 gpm)

Bowl Speed: 2700 RPM

Pool Radius: 103 mm

Differential Speed: Δn = 15 RPM

Polymer Addition: 2.03 kg/metric ton (4.07 lb/ton)

Recovery: 82%

Sample	Percent total solids	Percent total volatile solids	SS, mg/l	VSS, mg/l
Feed 1	5.13	3.36	48,740	32,390
Feed 2	4.73	3.18	44,810	30,640
Feed 3	4.20	2.67	39,410	25,500
Centrate 1	1.63	1.30	13,760	11,820
Centrate 2	1.77	0.94	9,690	8,210
Centrate 3	0.96	0.75	7,030	6,310
Cake 1	16.8	10.5		
Cake 2	17.2	11.0		
Cake 3	17.0	10.1		

TABLE B-20. AVNX 314 DECANTER CENTRIFUGE TESTS

Location: Milwaukee South Shore WPCP

Date: June 2, 1976

Run No.: 17

Sludge Type: Dry-Weather Primary

Feed Rate: 57.9 liters/min (15.3 gpm)

Bowl Speed: 2700 RPM

Pool Radius: 103 mm

Differential Speed: Δn = 15 RPM

Polymer Addition: 1.54 kg/metric ton (3.08 lb/ton)

Recovery: 81%

Sample	Percent total solids	Percent total volatile solids	SS, mg/l	VSS, mg/l
Feed 1	4.65	3.05	43,970	29,340
Feed 2	5.00	3.39	47,440	32,690
Feed 3	4.36	2.89	41,090	27,730
Centrate 1	0.76	0.51	4,470	3,930
Centrate 2	1.19	0.96	9,380	8,460
Centrate 3	1.90	1.58	12,270	14,640
Cake 1	15.6	9.5		
Cake 2	16.4	10.1		
Cake 3	16.6	10.7		

TABLE B-21. AVNX 314 DECANTER CENTRIFUGE TESTS

Location: Milwaukee South Shore WPCP

Date: June 3, 1976

Run No.: 18

Sludge Type: Dry-Weather Primary

Feed Rate: 66.6 liters/min (17.6 gpm)

Bowl Speed: 2700 RPM

Pool Radius: 103 mm

Differential Speed: Δn = 15 RPM

Polymer Addition: 4.46 kg/metric ton (8.93 lb/ton)

Recovery: 87%

Sample	Percent total solids	Percent total volatile solids	SS, mg/l	VSS, mg/l
Feed 1	2.75	1.75	24,670	16,180
Centrate 1	0.63	0.44	3,530	3,040
Cake 1	17.8	11.3		

TABLE B-22. AVNX 314 DECANTER CENTRIFUGE TESTS

Location: Milwaukee South Shore WPCP
Date: June 3, 1976
Run No.: 19
Sludge Type: Dry-Weather Primary
Feed Rate: 66.6 liters/min (17.6 gpm)

Bowl Speed: 2700 RPM
Pool Radius: 103 mm
Differential Speed: Δn = 23 RPM
Polymer Addition: 2.29 kg/metric ton (4.58 lb/ton)
Recovery: 96%

Sample	Percent total solids	Percent total volatile solids	SS, mg/l	VSS, mg/l
Feed 1	5.40	3.53	51,190	33,970
Feed 2	5.27	3.21	49,860	30,750
Feed 3	5.40	3.25	51,200	31,150
Centrate 1	0.81	0.58	5,330	4,470
Centrate 2	0.43	0.26	1,540	1,240
Centrate 3	0.46	0.28	1,830	1,510
Cake 1	16.2	9.9		
Cake 2	16.3	9.8		
Cake 3	16.5	10.5		

TABLE B-23. AVNX 314 DECANTER CENTRIFUGE TESTS

Location: Milwaukee South Shore WPCP
Date: June 3, 1976
Run No.: 20
Sludge Type: Dry-Weather Primary
Feed Rate: 66.6 liters/min (17.6 gpm)

Bowl Speed: 2700 RPM
Pool Radius: 103 mm
Differential Speed: Δn = 11 RPM
Polymer Addition: 2.53 kg/metric ton (5.05 lb/ton)
Recovery: 81%

Sample	Percent total solids	Percent total volatile solids	SS, mg/l	VSS, mg/l
Feed 1	5.45	3.33	51,660	32,000
Feed 2	5.31	3.34	50,300	31,100
Feed 3	3.83	2.35	35,490	22,220
Centrate 1	1.97	1.43	16,930	12,990
Centrate 2	1.61	1.15	13,280	10,210
Centrate 3	0.47	0.29	1,940	1,620
Cake 1	20.6	12.0		
Cake 2	20.7	11.9		
Cake 3	19.0	11.4		

TABLE B-24. AVNX 314 DECANTER CENTRIFUGE TESTS

Location: Milwaukee South Shore WPCP

Date: June 3, 1976

Run No.: 21

Sludge Type: Dry-Weather Primary

Feed Rate: 66.6 liters/min (17.6 gpm)

Bowl Speed: 2700 RPM

Pool Radius: 103 mm

Differential Speed: Δn = 15 RPM

Polymer Addition: 2.28 kg/metric ton (4.56 lb/ton)

Recovery: 80%

Sample	Percent total solids	Percent total volatile solids	SS, mg/l	VSS, mg/l
Feed 1	5.25	3.45	49,680	33,090
Feed 2	5.30	3.29	50,230	31,550
Feed 3	5.58	3.54	53,020	34,100
Centrate 1	2.37	1.73	20,740	15,970
Centrate 2	1.35	0.99	10,610	8,660
Centrate 3	1.19	0.84	9,040	7,110
Cake 1	17.8	10.8		
Cake 2	15.4	9.5		
Cake 3	16.1	9.7		

APPENDIX C - RACINE, WISCONSIN CENTRIFUGE TEST DATA

TABLE C-1. AVNX 314 DECANTER CENTRIFUGE TESTS

Location: Racine WPCP	Bowl Speed: 2700 RPM
Date: August 2, 1976	Pool Radius: 103 mm
Run No.: 1	Differential Speed: Δn = 28 RPM
Sludge Type: Dry-Weather Primary + WAS	Polymer Addition: None
Feed Rate: 38.2 l/min (10.1 gpm)	Recovery: 67.1%

Sample	Percent total solids	Percent total volatile solids	SS, mg/l	VSS, mg/l
Feed 1	9.00	3.87	87,390	37,290
Centrate 1	4.09	2.69	34,600	22,760
Cake 1	34.8	11.2		

TABLE C-2. AVNX 314 DECANTER CENTRIFUGE TESTS

Location: Racine WPCP	Bowl Speed: 2700 RPM
Date: August 2, 1976	Pool Radius: 103 mm
Run No.: 2	Differential Speed: Δn = 26 RPM
Sludge Type: Dry-Weather Primary + WAS	Polymer Addition: None
Feed Rate: 25.4 l/min (6.7 gpm)	Recovery: 71.5%

Sample	Percent total solids	Percent total volatile solids	SS, mg/l	VSS, mg/l
Feed 1	13.90	6.0	135,300	57,810
Centrate 1	5.42	3.54	51,700	33,900
Cake 1	38.1	10.7		

TABLE C-3. AVNX 314 DECANTER CENTRIFUGE TESTS

Location: Racine WPCP

Date: August 2, 1976

Run No.: 3

Sludge Type: Dry-Weather Primary + WAS

Feed Rate: 76.8 l/min (20.3 gpm)

Bowl Speed: 2700 RPM

Pool Radius: 103 mm

Differential Speed: Δn = 5 RPM

Polymer Addition: 1 kg/metric ton (2 lb/ton)

Recovery: 72.0%

Sample	Percent total solids	Percent total volatile solids	SS, mg/l	VSS, mg/l
Feed 1	3.88	2.31	37,700	22,500
Centrate 1	1.30	0.76	11,900	7,340
Cake 1	24.05	14.45		

TABLE C-4. AVNX 314 DECANTER CENTRIFUGE TESTS

Location: Racine WPCP

Date: August 2, 1976

Run No.: 4

Sludge Type: Dry-Weather Primary + WAS

Feed Rate: 78.7 l/min (20.8 gpm)

Bowl Speed: 2700 RPM

Pool Radius: 103 mm

Differential Speed: Δn = 15 RPM

Polymer Addition: 3.55 kg/metric ton (7.1 lb/ton)

Recovery: 87.4%

Sample	Percent total solids	Percent total volatile solids	SS, mg/l	VSS, mg/l
Feed 1	0.64	0.41	5,330	3,680
Feed 2	0.51	0.34	4,080	2,920
Centrate 1	0.14	0.07	640	530
Centrate 2	0.13	0.07	570	440
Cake 1	16.80	10.46		
Cake 2	29.24	19.51		

TABLE C-7. AVNX 314 DECANTER CENTRIFUGE TESTS

Location: Racine WPCP
Date: August 2, 1976
Run No.: 7
Sludge Type: Dry-Weather Primary + WAS
Feed Rate: 78.7 l/min (20.8 gpm)

Bowl Speed: 2700 RPM
Pool Radius: 103 mm
Differential Speed: Δn = 10 RPM
Polymer Addition: 0.7 kg/metric ton (1.4 lb/ton)
Recovery: 87.1%

Sample	Percent total solids	Percent total volatile solids	SS, mg/l	VSS, mg/l
Feed 1	2.10	1.34	19,920	12,980
Feed 2	3.21	2.00	31,020	19,580
Centrate 1	0.28	0.17	1,860	1,480
Centrate 2	0.64	0.41	5,380	3,600
Cake 1	24.36	15.98		
Cake 2	24.17	14.60		

TABLE C-8. AVNX 314 DECANTER CENTRIFUGE TESTS

Location: Racine WPCP
Date: August 2, 1976
Run No.: 8
Sludge Type: Dry-Weather Primary + WAS
Feed Rate: 78.7 l/min (20.8 gpm)

Bowl Speed: 2700 RPM
Pool Radius: 103 mm
Differential Speed: Δn = 10 RPM
Polymer Addition: 0.9 kg/metric ton (1.8 lb/ton)
Recovery: 97.4%

Sample	Percent total solids	Percent total volatile solids	SS, mg/l	VSS, mg/l
Feed 1	5.15	2.30	50,500	28,500
Centrate 1	0.29	0.21	1,620	1,400
Cake 1	26.28	15.59		

TABLE C-9. AVNX 314 DECANTER CENTRIFUGE TESTS

Location: Racine WPCP
Date: August 5, 1976
Run No.: 9
Sludge Type: Dry-Weather Primary + WAS
Feed Rate: 72.3 l/min (19.1 gpm)

Bowl Speed: 2700 RPM
Pool Radius: 103 mm
Differential Speed: Δn = 5 RPM
Polymer Addition: 1.3 kg/metric ton (2.6 lb/ton)
Recovery: 86.2%

Sample	Percent total solids	Percent total volatile solids	SS, mg/l	VSS, mg/l
Feed 1	1.78	0.88	16,230	8,070
Feed 2	3.97	1.83	38,130	17,570
Centrate 1	0.25	0.14	1,380	830
Centrate 2	0.93	0.57	6,740	4,240
Cake 1	29.4	13.2		
Cake 2	32.1	13.9		

TABLE C-10. AVNX 314 DECANTER CENTRIFUGE TESTS

Location: Racine WPCP
Date: August 5, 1976
Run No.: 10
Sludge Type: Dry-Weather Primary + WAS
Feed Rate: 57.5 l/min (15.2 gpm)

Bowl Speed: 2700 RPM
Pool Radius: 103 mm
Differential Speed: Δn = 15 RPM
Polymer Addition: 1.3 kg/metric ton (2.5 lb/ton)
Recovery: 96.3%

Sample	Percent total solids	Percent total volatile solids	SS, mg/l	VSS, mg/l
Feed 1	5.17	2.33	50,130	22,570
Feed 2	6.01	2.72	58,530	26,470
Centrate 1	0.33	0.21	1,380	1,120
Centrate 2	0.55	0.36	3,520	2,480
Cake 1	26.0	11.6		
Cake 2	28.8	10.8		

TABLE C-13. AVNX 314 DECANTER CENTRIFUGE TESTS

Location: Racine WPCP

Date: August 5, 1976

Run No.: 13

Sludge Type: Dry-Weather Primary + WAS

Feed Rate: 76.8 l/min (20.3 gpm)

Bowl Speed: 2700 RPM

Pool Radius: 103 mm

Differential Speed: Δn = 23 RPM

Polymer Addition: 3.9 kg/metric ton (7.9 lb/ton)

Recovery: 96.1%

Sample	Percent total solids	Percent total volatile solids	SS, mg/l	VSS, mg/l
Feed 1	0.73	0.44	6,500	4,140
Feed 2	1.20	0.77	11,160	7,380
Centrate 1	0.11	0.05	430	320
Centrate 2	0.12	0.07	290	190
Cake 1	21.61	13.26		
Cake 2	19.57	12.03		

TABLE C-14. AVNX 314 DECANTER CENTRIFUGE TESTS

Location: Racine WPCP

Date: August 6, 1976

Run No.: 14

Sludge Type: Dry-Weather Primary + WAS

Feed Rate: 57.9 l/min (15.3 gpm)

Bowl Speed: 2700 RPM

Pool Radius: 103 mm

Differential Speed: Δn = 15 RPM

Polymer Addition: 1.4 kg/metric ton (2.8 lb/ton)

Recovery: 84.9%

Sample	Percent total solids	Percent total volatile solids	SS, mg/l	VSS, mg/l
Feed 1	12.24	5.24	119,380	50,990
Feed 2	13.57	5.80	132,680	56,590
Centrate 1	3.81	2.21	34,270	20,570
Centrate 2	2.88	1.73	25,520	15,500
Cake 1	29.4	12.2		
Cake 2	29.4	11.8		

TABLE C-15. AVNX 314 DECANTER CENTRIFUGE TESTS

Location: Racine WPCP	Bowl Speed: 2700 RPM
Date: August 6, 1976	Pool Radius: 103 mm
Run No.: 15	Differential Speed: Δn = 15 RPM
Sludge Type: Dry-Weather Primary + WAS	Polymer Addition: 1.8 kg/metric ton (3.6 lb/ton)
Feed Rate: 45.4 l/min (12.0 gpm)	Recovery: 92.0%

Sample	Percent total solids	Percent total volatile solids	SS, mg/l	VSS, mg/l
Feed 1	12.56	5.34	122,670	51,950
Feed 2	12.99	5.70	126,970	55,550
Centrate 1	0.96	0.64	6,730	4,630
Centrate 2	3.04	1.84	26,630	16,230
Cake 1	28.6	12.2		
Cake 2	28.4	12.4		

TABLE C-16. AVNX 314 DECANTER CENTRIFUGE TESTS

Location: Racine WPCP	Bowl Speed: 2700 RPM
Date: August 6, 1976	Pool Radius: 103 mm
Run No.: 16	Differential Speed: Δn = 26 RPM
Sludge Type: Dry-Weather Primary + WAS	Polymer Addition: 1.8 kg/metric ton (3.6 lb/ton)
Feed Rate: 47.3 l/min (12.5 gpm)	Recovery: 99.5%

Sample	Percent total solids	Percent total volatile solids	SS, mg/l	VSS, mg/l
Feed 1	12.40	5.33	121,110	51,920
Centrate 1	0.32	0.19	1,070	830
Cake 1	28.0	12.3		

TABLE C-17. AVNX 314 DECANTER CENTRIFUGE TESTS

Location: Racine WPCP

Date: August 6, 1976

Run No.: 17

Sludge Type: Dry-Weather Primary + WAS

Feed Rate: 47.3 l/min (12.5 gpm)

Bowl Speed: 2700 RPM

Pool Radius: 103 mm

Differential Speed: Δn = 22 RPM

Polymer Addition: 1.6 kg/metric ton (3.2 lb/ton)

Recovery: 93.3%

Sample	Percent total solids	Percent total volatile solids	SS, mg/l	VSS, mg/l
Feed 1	13.85	5.93	135,610	57,920
Centrate 1	1.87	1.15	16,270	10,530
Cake 1	28.6	11.4		

TABLE C-18. AVNX 314 DECANTER CENTRIFUGE TESTS

Location: Racine WPCP

Date: August 9, 1976

Run No.: 18

Sludge Type: Dry-Weather Primary + WAS

Feed Rate: 25.4 l/min (6.7 gpm)

Bowl Speed: 2700 RPM

Pool Radius: 103 mm

Differential Speed: Δn = 15 RPM

Polymer Addition: 2.5 kg/metric ton (5.9 lb/ton)

Recovery: 99.4%

Sample	Percent total solids	Percent total volatile solids	SS, mg/l	VSS, mg/l
Feed 1	13.7	6.0	133,270	57,810
Centrate 1	0.37	0.20	1,360	640
Cake 1	29.0	13.2		

TABLE C-19. AVNX 314 DECANTER CENTRIFUGE TESTS

Location: Racine WPCP

Date: August 9, 1976

Run No.: 19

Sludge Type: Dry-Weather Primary + WAS

Feed Rate: 25.4 l/min (6.7 gpm)

Bowl Speed: 2700 RPM

Pool Radius: 103 mm

Differential Speed: Δn ≈ 15 RPM

Polymer Addition: 0.9 kg/metric ton (1.7 lb/ton)

Recovery: 98.7%

Sample	Percent total solids	Percent total volatile solids	SS, mg/l	VSS, mg/l
Feed 1	13.5	5.9	131,320	56,810
Centrate 1	0.54	0.35	3,040	2,060
Cake 1	29.2	11.7		

TABLE C-20. AVNX 314 DECANTER CENTRIFUGE TESTS

Location: Racine WPCP

Date: August 9, 1976

Run No.: 20

Sludge Type: Dry-Weather Primary + WAS

Feed Rate: 25.4 l/min (6.7 gpm)

Bowl Speed: 2700 RPM

Pool Radius: 103 mm

Differential Speed: Δn = 23 RPM

Polymer Addition: 1.8 kg/metric ton (3.5 lb/ton)

Recovery: 98.7%

Sample	Percent total solids	Percent total volatile solids	SS, mg/l	VSS, mg/l
Feed 1	13.7	5.9	133,320	56,810
Centrate 1	0.61	0.40	3,500	2,500
Cake 1	25.6	10.6		

TABLE C-23. AVNX 314 DECANTER CENTRIFUGE TESTS

Location: Racine WPCP	Bowl Speed: 2700 RPM
Date: August 9, 1976	Pool Radius: 103 mm
Run No.: 23	Differential Speed: Δn = 7 RPM
Sludge Type: Dry-Weather Primary + WAS	Polymer Addition: 2.6 kg/metric ton (5.1 lb/ton)
Feed Rate: 25.4 l/min (6.7 gpm)	Recovery: 90.7%

Sample	Percent total solids	Percent total volatile solids	SS, mg/l	VSS, mg/l
Feed 1	13.7	6.0	133,320	57,740
Centrate 1	2.13	1.33	18,900	11,800
Cake 1	35.1	13.6		

TABLE C-24. AVNX 314 DECANTER CENTRIFUGE TESTS

Location: Racine WPCP	Bowl Speed: 2700 RPM
Date: August 9, 1976	Pool Radius: 103 mm
Run No.: 24	Differential Speed: Δn = 26 RPM
Sludge Type: Dry-Weather Primary + WAS	Polymer Addition: 2.6 kg/metric ton (5.1 lb/ton)
Feed Rate: 25.4 l/min (6.7 gpm)	Recovery: 99.1%

Sample	Percent total solids	Percent total volatile solids	SS, mg/l	VSS, mg/l
Feed 1	13.7	6.0	133,320	57,740
Centrate 1	0.45	0.26	2,350	1,000
Cake 1	26.2	11.5		

TABLE C-25. AVNX 314 DECANTER CENTRIFUGE TESTS

Location: Racine WPCP

Date: August 9, 1976

Run No.: 25

Sludge Type: Dry-Weather Primary + WAS

Feed Rate: 25.4 l/min (6.7 gpm)

Bowl Speed: 2700 RPM

Pool Radius: 103 mm

Differential Speed: Δn = 15 RPM

Polymer Addition: 2.5 kg/metric ton (5.0 lb/ton)

Recovery: 98.3%

Sample	Percent total solids	Percent total volatile solids	SS, mg/l	VSS, mg/l
Feed 1	13.9	6.1	135,330	58,810
Centrate 1	0.67	0.43	4,200	2,830
Cake 1	30.1	12.5		

TABLE C-26. AVNX 314 DECANTER CENTRIFUGE TESTS

Location: Racine WPCP

Date: August 9, 1976

Run No.: 26

Sludge Type: Dry-Weather Primary + WAS

Feed Rate: 76.8 l/min (20.3 gpm)

Bowl Speed: 2700 RPM

Pool Radius: 103 mm

Differential Speed: Δn = 10 RPM

Polymer Addition: 2.1 kg/metric ton (4.2 lb/ton)

Recovery: 96.6%

Sample	Percent total solids	Percent total volatile solids	SS, mg/l	VSS, mg/l
Feed 1	1.22	0.76	11,400	7,440
Feed 2	2.38	1.46	22,800	14,160
Centrate 1	0.14	0.07	340	280
Centrate 2	1.77	1.04	1,040	810
Cake 1	19.84	12.16		
Cake 2	22.14	13.36		

TABLE C-27. AVNX 314 DECANTER CENTRIFUGE TESTS

Location: Racine WPCP

Date: August 9, 1976

Run No.: 27

Sludge Type: Dry-Weather Primary + WAS

Feed Rate: 72.3 l/min (19.1 gpm)

Bowl Speed: 2700 RPM

Pool Radius: 103 mm

Differential Speed: Δn = 10 RPM

Polymer Addition: 3.8 kg/metric ton (7.6 lb/ton)

Recovery: 67.4%

Sample	Percent total solids	Percent total volatile solids	SS, mg/l	VSS, mg/l
Feed 1	0.74	0.37	6,090	2,970
Feed 2	0.79	0.39	6,590	3,170
Centrate 1	0.20	0.11	450	250
Centrate 2	0.20	0.11	500	300
Cake 1	23.1	11.6		
Cake 2	23.5	12.0		

TABLE C-28. AVNX 314 DECANTER CENTRIFUGE TESTS

Location: Racine Wet-Weather Site No. 1

Date: August 11, 1976

Run No.: 1

Sludge Type: Thickened S/DAF CSO Sludge

Feed Rate: 51.1 l/min (13.5 gpm)

Bowl Speed: 2700 RPM

Pool Radius: 103 mm

Differential Speed: Δn = 15 RPM

Polymer Addition: None

Recovery: 69.0%

Sample	Percent total solids	Percent total volatile solids	SS, mg/l	VSS, mg/l
Feed 1	0.24	0.11	1,840	780
Centrate 1	0.13	0.07	570	260
Cake 1	18.6	11.1		

TABLE C-29. AVNX 314 DECANTER CENTRIFUGE TESTS

Location: Racine Wet-Weather Site No. 1	Bowl Speed: 2700 RPM
Date: August 18, 1976	Pool Radius: 103 mm
Run No.: 2	Differential Speed: Δn = 15 RPM
Sludge Type: Thickened S/DAF CSO Sludge	Polymer Addition: None
Feed Rate: 48.5 l/min (12.8 gpm)	Recovery: 63.4%

Sample	Percent total solids	Percent total volatile solids	SS, mg/l	VSS, mg/l
Feed 1	0.58	0.30	5,230	2,720
Centrate 1	0.22	0.13	1,230	820
Cake 1	25.9	9.4		

TABLE C-30. AVNX 314 DECANTER CENTRIFUGE TESTS

Location: Racine Wet-Weather Site No. 1	Bowl Speed: 2700 RPM
Date: August 11, 1976	Pool Radius: 103 mm
Run No.: 3	Differential Speed: Δn = 15 RPM
Sludge Type: Thickened S/DAF CSO Sludge	Polymer Addition: None
Feed Rate: 68.1 l/min (18 gpm)	Recovery: 52.4%

Sample	Percent total solids	Percent total volatile solids	SS, mg/l	VSS, mg/l
Feed 1	.0528	.0213	110	100
Centrate 1	.0503	.0205	50	35
Cake 1	30.8	17.4		

TABLE C-31. AVNX 314 DECANTER CENTRIFUGE TESTS

Location: Racine Wet-Weather Site No. 1	Bowl Speed: 2700 RPM
Date: August 18, 1976	Pool Radius: 103 mm
Run No.: 4	Differential Speed: Δn = 15 RPM
Sludge Type: Thickened S/DAF CSO Sludge	Polymer Addition: None
Feed Rate: 126 l/min (33.3 gpm)	Recovery: 99.4%

Sample	Percent total solids	Percent total volatile solids	SS, mg/l	VSS, mg/l
Feed 1	0.090	0.038	490	300
Centrate 1	0.062	0.025	190	110
Cake 1	33.7	17.0		

TABLE C-32. AVNX 314 DECANTER CENTRIFUGE TESTS

Location: Racine Wet-Weather Site No. 1	Bowl Speed: 2700 RPM
Date: August 11, 1976	Pool Radius: 103 mm
Run No.: 5	Differential Speed: Δn = 6 RPM
Sludge Type: Thickened S/DAF CSO Sludge	Polymer Addition: 2.58 kg/metric ton (5.16 lb/ton)
Feed Rate: 48.5 l/min (12.8 gpm)	Recovery: 91.3%

Sample	Percent total solids	Percent total volatile solids	SS, mg/l	VSS, mg/l
Feed 1	0.23	0.13	1,740	980
Centrate 1	0.07	0.04	150	130
Cake 1	30.1	14.2		

TABLE C-33. AVNX 314 DECANTER CENTRIFUGE TESTS

Location: Racine Wet-Weather Site No. 1
Date: August 11, 1976
Run No.: 6
Sludge Type: Thickened S/DAF CSO Sludge
Feed Rate: 65.1 l/min (17.2 gpm)

Bowl Speed; 2700 RPM
Pool Radius: 103 mm
Differential Speed: Δn = 6 RPM
Polymer Addition: 0.96 kg/metric ton (1.92 lb/ton)
Recovery: 92.4%

Sample	Percent total solids	Percent total volatile solids	SS, mg/l	VSS, mg/l
Feed 1	0.46	0.24	4,040	2,080
Centrate 1	0.09	0.05	310	240
Cake 1	32.1	14.9		

TABLE C-34. AVNX 314 DECANTER CENTRIFUGE TESTS

Location: Racine Wet-Weather Site No. 1
Date: August 11, 1976
Run No.: 7
Sludge Type: Thickened S/DAF CSO Sludge
Feed Rate: 65.1 l/min (17.2 gpm)

Bowl Speed: 2700 RPM
Pool Radius: 103 mm
Differential Speed: Δn = 10 RPM
Polymer Addition: 2.33 kg/metric ton (4.65 lb/ton)
Recovery: 89.9%

Sample	Percent total solids	Percent total volatile solids	SS, mg/l	VSS, mg/l
Feed 1	0.19	0.09	1,480	800
Centrate 1	0.07	0.03	150	80
Cake 1	30.8	14.2		

TABLE C-35. AVNX 314 DECANTER CENTRIFUGE TESTS

Location: Racine Wet-Weather Site No. 1	Bowl Speed: 2700 RPM
Date: August 11, 1976	Pool Radius: 103 mm
Run No.: 8	Differential Speed: Δn = 15 RPM
Sludge Type: Thickened S/DAF CSO Sludge	Polymer Addition: 3.16 kg/metric ton (6.31 lb/ton)
Feed Rate: 60.1 l/min (17.2 gpm)	Recovery: 89.9%

Sample	Percent total solids	Percent total volatile solids	SS, mg/l	VSS, mg/l
Feed 1	0.14	0.07	980	600
Centrate 1	0.07	0.32	100	90
Cake 1	23.4	11.2		

TABLE C-36. AVNX 314 DECANTER CENTRIFUGE TESTS

Location: Racine Wet-Weather Site No. 1	Bowl Speed: 2700 RPM
Date: August 11, 1976	Pool Radius: 103 mm
Run No.: 9	Differential Speed: Δn = 15 RPM
Sludge Type: Thickened S/DAF CSO Sludge	Polymer Addition: 1.35 kg/metric ton (2.69 lb/ton)
Feed Rate: 126 l/min (33.3 gpm)	Recovery: 89.8%

Sample	Percent total solids	Percent total volatile solids	SS, mg/l	VSS, mg/l
Feed 1	0.17	0.09	1,280	760
Centrate 1	0.07	0.03	130	120
Cake 1	25.5	13.7		

TABLE C-37. AVNX 314 DECANTER CENTRIFUGE TESTS

Location: Racine Wet-Weather Site No. 1
Date: August 11, 1976
Run No.: 10
Sludge Type: Thickened S/DAF CSO Sludge
Feed Rate: 126 l/min (33.3 gpm)

Bowl Speed: 2700 RPM
Pool Radius: 103 mm
Differential Speed: Δn = 10 RPM
Polymer Addition: 3.17 kg/metric ton (6.34 lb/ton)
Recovery: 71.4%

Sample	Percent total solids	Percent total volatile solids	SS, mg/l	VSS, mg/l
Feed 1	0.07	0.27	310	200
Centrate 1	0.05	0.15	90	70
Cake 1	30.5	14.8		

TABLE C-38. AVNX 314 DECANTER CENTRIFUGE TESTS

Location: Racine Wet-Weather Site No, 1
Date: August 18, 1976
Run No.: 11
Sludge Type: Thickened S/DAF CSO Sludge
Feed Rate: 48.5 l/min (12.8 gpm)

Bowl Speed: 2700 RPM
Pool Radius: 103 mm
Differential Speed: Δn = 15 RPM
Polymer Addition: 1.52 kg/metric ton (3.04 lb/ton)
Recovery: 92.5%

Sample	Percent total solids	Percent total volatile solids	SS, mg/l	VSS, mg/l
Feed 1	0.39	0.20	3,340	1,680
Centrate 1	0.09	0.05	260	210
Cake 1	26.2	11.9		

TABLE C-39. AVNX 314 DECANTER CENTRIFUGE TESTS

Location: Racine Wet-Weather Site No. 1

Date: August 11, 1976

Run No.: 12

Sludge Type: Thickened S/DAF CSO Sludge

Feed Rate: 48.5 l/min (12.8 gpm)

Bowl Speed: 2700 RPM

Pool Radius: 103 mm

Differential Speed: Δn = 10 RPM

Polymer Addition: 1.70 kg/metric ton (3.39 lb/ton)

Recovery: 63.0%

Sample	Percent total solids	Percent total volatile solids	SS, mg/l	VSS, mg/l
Feed 1	0.35	0.19	2,940	1,580
Centrate 1	0.17	0.08	1,100	560
Cake 1	26.4	11.8		

APPENDIX D - BENCH SCALE ANAEROBIC DIGESTION TEST DATA AND CALCULATIONS

TABLE D-1. RAW DATA DURING START-UP PERIOD, KENOSHA ANAEROBIC DIGESTION STUDY

Date	Diges-ter	Temper-ature, °C	Total gas production l/day[a]	pH	Vola-tile acids, mg/l	Comments
9/2/75	C	--	7.5	7.10	130	
	W	--	6.0	7.15	130	
9/5/75	C	--	--	7.13	130	Leak in mixer shaft
	W	--	--	7.15	120	guides
9/8/75	C	32	8.0	7.20	--	Adjusted sludge vol.
	W	37	7.3	7.20	--	
9/9/75	C	28	8.4	7.30	--	Adjusted temperature
	W	30	8.9	7.35	--	controller
9/10/75	C	29	7.3	7.30	130	
	W	31	8.1	7.30	130	
9/11/75	C	29	8.0	7.55	--	Adjusted water bath
	W	32	8.0	7.55	--	level
9/12/75	C	33	--	7.30	--	Daily adjustments
	W	35	--	7.25	--	started to balance digester temps.
9/13/75	C	34	--	7.15	--	
	W	35	--	7.20	--	
9/14/75	C	35	--	7.20	--	
	W	38	--	7.21	--	
9/15/75	C	35	--	7.25	--	Power off-used 1/2
	W	30	--	7.50	--	normal feed vol.
9/16/75	C	36	--	7.30	--	Return to normal
	W	38	--	7.35	--	feed volume
9/17/75	C	33	8.5	7.20	--	
	W	36	8.1	7.25	--	
9/18/75	C	--	--	7.30	--	
	W	--	--	7.20	--	
9/19/75	C	33	8.1	7.30	130	Volatile solids re-
	W	38	8.6	7.30	130	duction = 27.5%
9/20/75[c]	C	34	--	7.30	--	
	W	37	--	7.40	--	

a. l/day at 760 min Hg and 20°C

b. Measured as acetic acid.

c. From Sept. 21 to Nov. 7 bath digesters were fed regularly to maintain the cultures. Monitoring resumed on Nov. 7, 1975.

TABLE D-2. DETERMINATION OF VOLUMES OF WET-WEATHER SLUDGE GENERATED FROM KENOSHA STORM EVENTS

1. Combined sewer area (Kenosha, Wisconsin) = 539 hectares (1331 acres).

2. CSO sludge volume produced (1% solids) per volume of CSO treated = 0.035.

3. Example: For 2.54 cm (1 inch) of total rainfall and a runoff coefficient of 0.5,

   a. CSO volume treated - 68.5×10^6 liters (18.1×10^6 gal.)

   b. CSO sludge volume produced at 1% solids = 2.4×10^6 liters (632,477 gal.)

   c. Thickened CSO sludge volume at 4% solids = 598,454 liters (158,112 gal.)

   d. Digester hydraulic loadings at various feed addition times.

Addition to full-scale digesters for periods of	2.54 cm (1") rain		1.27 cm (0.5") rain		0.63 cm (0.25") rain	
	liters/day	gpd	liters/day	gpd	liters/day	gpd
12 hours	1.2×10^6	316,224	0.6×10^6	158,112	0.3×10^6	79,056
24 hours	0.6×10^6	158,112	0.3×10^6	79,056	0.15×10^6	39,528
48 hours	0.3×10^6	79,056	0.15×10^6	39,528	0.07×10^6	19,764
74 hours	0.2×10^6	52,704	0.1×10^6	26,352	0.05×10^6	13,176
96 hours	0.15×10^6	39,528	0.07×10^6	19,764	0.03×10^6	9,882

TABLE D-3. CALCULATION OF DIGESTER SLUDGE LOADINGS FOR A SIMULATED STORM EVENT [1.27 cm (0.5") rain] - KENOSHA, WISCONSIN

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1. Given: a. 0.5" total rainfall storm event

   b. Two day CSO sludge bleed into digester

2. CSO sludge generated = 0.15×10^6 liters/day = 39,528 gpd (from Table D-1)

3. Dry-weather sludge feed to digesters

   a. Primary sludge = 0.16×10^6 liters/day (41,100 gpd)

   b. Thickened WAS = 0.22×10^6 liters/day (57,700 gpd)

   c. Total dry-weather feed = 0.37×10^6 liters/day (98,800 gpd)

4. Total feed to digesters (CSO + dry-weather sludges)

   0.53×10^6 liters/day (138,328 gpd) for two days

5. Hydraulic loading increase

   (138,328 - 98,800) / 98,800 = 40%

TABLE D-4. RAW DATA FROM KENOSHA BENCH SCALE DIGESTION STUDY
(C = Control digester; W = Wet-weather digester)

	Feed Sludge					Gas Production				Digesting Sludge					
Day	TS, %	TVS, %	pH	Alkalinity mg/l as $CaCO_3$	WAS/primary %	Total production 1/24 hr (STP)	CO_2 %	CH_4 %	CO_2/CH_4	Total solids	TVS, %	pH	Alkalinity mg/l as $CaCO_3$	Volatile acids mg/l as acetic	Volatile acids/alkalinity
	3.6	58	6.78	1,050	58.3/41.7	6.9				3.0	49	7.49	3,900	186	0.05
						3.8				2.9	49	7.57	3,900	186	0.05
						6.8				2.9	49	7.51	4,000	186	0.05
						4.4				2.9	50	7.60	4,000	232	0.06
1 C						5.9				3.0	49	7.51	3,900	210	0.05
W						5.2				3.0	51	7.58	4,000	200	0.05
2 C	3.7	58	6.81	1,100		6.3	31	64	48	2.9	48	7.56	4,000	140	0.04
W						6.9	30	67	45	2.9	49	7.62	4,000	140	0.04
3 C						6.2	29	62	47	3.0	47	7.65	4,000	140	0.04
W						6.7	28	63	44	2.9	48	7.68	4,000	140	0.04
4 C	3.6	59	6.76	1,000		6.6	31	65	48	2.9	48	7.63	4,000	115	0.03
W						5.5	30	66	45	3.0	50	7.72	4,100	115	0.03
5 C						6.4	30	66	45	2.9	48	7.61	4,000	140	0.04
W						6.2	30	67	45	3.0	50	7.65	3,900	140	0.04
6 C						6.5	30	67	45	2.9	49	7.68	4,000	186	0.05
W						5.7	31	67	46	3.0	51	7.69	4,000	140	0.04
7 C	3.8	61	6.94	1,100		6.9	30	69	43	2.9	48	7.45	4,000	115	0.03
W						6.1	33	66	50	3.1	50	7.48	3,900	115	0.03
8 C						6.9	34	64	53	2.9	49	7.46	4,000	115	0.03
W						6.4	35	62	56	3.1	49	7.50	3,900	115	0.03
9 C						6.2	29	70	43	3.0	48	7.49	4,000		
W						6.4	30	70	41	3.0	49	7.52	4,000		
10C						6.0	33	67	49	3.0	49	7.46	4,000		
W						6.3	33	67	49	2.9	48	7.49	4,000		
11C						5.7	32	67	48	3.0	49	7.69	4,000	162	0.04
W						6.2	30	69	43	3.0	49	7.63	4,000	139	0.03
12C	4.2	60	6.82	1,100	58.3/41.7	5.1	32	67	48	3.0	48	7.64	4,000		
W						6.9	32	67	48	3.0	49	7.61	4,000		
13C						6.6	34	65	52	2.9	49	7.58	4,000		
W						6.6	33	66	50	3.0	49	7.53	4,000		
14C	3.9	60	6.67	1,400	71/29	9.6	31	68	46	2.9	48	7.50	4,000	115	0.03
W	3.7	60	6.73	1,350	29/29	10.0	31	68	46	3.1	50	7.52	3,900	115	0.03

continued

TABLE D-4. (continued)

	Feed Sludge					Gas Production				Digesting Sludge					
Day	TS, %	TVS, %	pH	Alka-linity mg/l as $CaCo_3$	WAS/ primary %	Total produc-tion 1/24 hr (STP)	CO_2 %	CH_4 %	CO_2/ CH_4	Total solids	TVS, %	pH	Alka-linity mg/l as $CaCO_3$	Vol-atile acids mg/l as ascetic	Volatile acids/ alka-linity
15 C	3.8	60	6.64	1,400	71/29	8.9	33	66	50	2.9	48	7.50	4,000	115	0.03
W	3.7	59	6.72	1,400	42/29	9.2	32	67	48	3.1	50	7.52	3,900	115	0.03
16 C					58.3/41.7	6.2	31	68	45	2.7	51.8	7.85	4,050		
W					58.3/41.7	7.4	31	69	44	2.9	48	7.88	4,000		
17 C					58.3/41.7	7.8	31	67	46			7.54			
W						6.6	32	68	47			7.69			
18CC	3.8	60	6.65	1,500	58.3/41.7	7.8	32	67	48	2.8	50				
W					58.3/41.7	7.0	31	67	46	2.9	49				
19 C					58.3/41.7	7.4	30	69	43	2.85	48	7.45	5,500	95	
W					58.3/41.7	6.7	29	68	43	3.00	50	7.40	5,950	118	
20 C					58.3/41.7	7.1	31	68	46	2.90	47	7.45			
W					58.3/41.7	7.0	31	68	46	2.92	49	7.42			
21 C					58.3/41.7	8.2	28	67	42	2.8	49	7.75	4,300		
W					58.3/41.7	7.1	31	68	45	2.9	50	7.69	4,200		
22 C	3.98	60			58.3/41.7	6.8				2.8	49	7.74	4,250	160[a]	
W					58.3/41.7	6.7				2.9	50	7.77	4,150	141	
23 C						6.9	30	69	43	2.8	50	7.91	4,300		
W						6.8	30	68	44	2.9	49	7.76	4,100		
24 C						6.4	31	68	46	2.7	47	7.83	4,350		
W						7.1	29	65	44	2.7	49	7.94	4,160		
25 C	3.61	61.0	7.2	500		10.4	34	64	53			7.72	4,150	233	
W	3.47	59.4	7.12	1,300		10.5	34/31	64/68	53/46			7.65	4,050	210	
26 C						8.5	31	68	45	2.90	47.1	7.73	4,000		
W						8.2	30	69	43	2.84	48.0	7.69	4,100		
27 C						7.5	30	70	43	3.02	49				
W						8.0	29	71	41	2.98	48.9				
28 C	3.82	60.1	7.20	1,100		9.9	33	66	50	3.06	47.9	7.72	4,000		
W						10.3	32	67	48	3.03	49.3	7.63	4,100		
29 C						8.2	35	67	52	3.01	47.9	7.67	4,300		
W						9.6	33	66	50	3.20	48.2	7.67	4,150		
30 C						7.6	31	68	45	2.99	47.4				
W						9.3	32	68	47	2.80	48.2				

continued

TABLE D-4. (continued)

	Feed Sludge					Gas Production				Digesting Sludge					
Day	TS, %	TVS, %	pH	Alkalinity mg/l as $CaCO_3$	WAS/ primary %	Total production 1/24 hr (STP)	CO_2 %	CH_4 %	CO_2/ CH_4	Total solids	TVS %	pH	Alkalinity mg/l as $CaCO_3$	Volatile acids mg/l as ascetic	Volatile acids/ Alkalinity
31 C			6.65	1,000		8.9	33	64	52	2.92	46			162.9	
W						8.1	32	68	47	2.94	47.6			116.0	
32 C	3.12	63	7.2	326		8.0	32	66	48						
W	3.22	60.2	7.15	1,848		9.3	31	65	48						
33 C	3.22	60.2	7.15	1,848		7.8	30	66	45	2.90	46.7	7.63	4,000		
W	3.22	60.2	7.15	1,848		7.0	30	66	45	2.99	47.9	7.68	3,900		
34 C	3.22	60.2	7.15	1,848		6.0	29	69	42	2.89	47				
W	3.22	60.2	7.15	1,848		5.6	28	68	41	2.95	45				
35 C	3.22	60.2	7.15	1,848		6.0	29	68	43	2.8	47.8	7.81	4,400	163.2	
W	3.22	60.2	7.15	1,848		5.5	30	66	45	2.86	49.3	7.8	4,200	140	
36 C	3.22	60.2	7.15	1,848		5.9	27	68	40	2.78	47.1	7.69	4,350		
W	3.22	60.2	7.15	1,848		5.5	26	69	38	2.95	48.4	7.87	4,300		
37 C	3.22	60.2	7.15	1,848		5.6	28	69	41	2.86	47.9	7.67	4,300		
W	3.22	60.2	7.15	1,848		4.7	27	70	39	2.97	49.1	7.66	4,200		
38 C	3.22	60.2	7.15	1,848		5.2	27	69	39	2.84	48.9				
W	3.22	60.2	7.15	1,848		4.4	25	66	36	2.96	50.3				
39 C	3.22	60.2	7.15	1,848		6.1	29	68	43			7.77	4,450	140	
W	3.22	60.2	7.15	1,848		5.3	26	65	40	2.9	54	7.75	4,300	140	
40CC	3.22	60.2	7.15	1,848		5.5	26	63	41						
W	3.22	60.2	7.15	1,848		4.6	29	68	43						
41 C	3.22	60.2	7.15	1,848		5.3				2.81	47.2	7.69	4,200		
W	3.22	60.2	7.15	1,848		4.5				2.90	49.3	7.72	4,200		
42 C	3.14	63.1	7.19	500		5.1				2.76	47.3	7.63	4,200	163	
W	3.23	59.8	7.09	2,000		4.3				2.82	48.5	7.69	4,300	163	
43 C						5.4	25	69	36	2.72	47.7	7.68	4,000		
W						4.9	25	70	36	2.78	48.8	7.75	4,200		

TABLE D-5. TOTAL HEAVY METAL ANALYSES FOR THE BENCH SCALE DIGESTION TESTS - KENOSHA, WISCONSIN
(All analyses in mg metal/kg)

Test day	Test period	Sludge sampled	Mercury, wet	Mercury, dry	Lead, wet	Lead, dry	Zinc, wet	Zinc, dry	Nickel, wet	Nickel, dry	Copper, wet	Copper, dry	Chromium, wet	Chromium, dry	Iron, wet	Iron, dry	Cadmium, wet	Cadmium, dry
		Feed	0.052	1.43	15	420	140	3,800	10	300	86	2,400	31	900	3,100	84,500	1.1	40
13	Control	Dig. Sl. (C)	0.052	1.77	17	560	160	5,600	10	400	88	3,000	34	1,100	2,800	100,000	1.8	51
		Dig. Sl. (W)	0.067	2.30	16	550	160	5,500	10	500	86	2,900	34	1,200	2,700	92,500	1.9	51
		Feed (C)			14	400	100	2,900	10	400	81	2,300	32	900	2,700	77,000	0.9	30
16	#1	Feed (W)	0.059	2.30	10	400	90	3,300	10	400	50	1,900	24	920	2,200	83,000	1.0	40
		Dig. Sl. (C)			16	560	97	3,500	20	600	56	2,000	36	[illegible]	2,400	85,000	1.8	60
		Dig. Sl. (W)	0.086	3.05	17	620	130	4,700	20	600	85	3,000	34	1,200	2,400	94,000	1.8	60
		Feed (C)	0.046	1.70	16	590	86	3,100	10	400	42	1,500	23	820	2,100	77,000	1.0	37
25	#2	Feed (W)	0.078	2.70	13	460	91	3,200	9	300	54	1,900	28	990	2,300	79,200	1.5	51
		Dig. Sl (C)			15	530	100	3,600	10	400	57	2,000	25	890	2,200	76,000	1.2	42
		Dig. Sl. (W)			15	510	100	3,700	10	400	84	2,900	32	1,100	2,300	78,000	1.2	42
		Feed	0.067	1.80	22	590	130	3,620	10	300	63	1,700	28	750	2,300	63,000	1.2	31
28	#2	Dig. Sl (C)			16	510	110	3,500	10	400	58	1,900	26	838	2,200	71,000	1.2	40
		Dig. Sl. (W)			17	550	120	3,900	10	400	70	2,300	30	1,000	2,400	80,000	1.3	42
		Feed (C)	0.036	1.20	17	540	94	3,000	9	300	55	1,100	25	800	2,100	67,000	1.1	30
35	#3	Feed (W)	0.061	1.90	14	430	110	3,500	7	200	55	1,700	31	960	2,400	75,000	1.4	40
		Dig. Sl. (C)	0.063	2.30	16	570	110	3,900	10	40	54	1,900	25	890	2,200	76,400	1.2	42
		Dig. Sl. (W)	0.079	2.30	16	570	120	4,300	10	400	71	2,500	31	1,100	2,300	82,000	1.2	43
43	#3	Dig. Sl. (C)	0.078	2.90	17	620	134	4,900	14	530	50	1,900	50	1,800	2,300	85,000	1.0	40
		Dig. Sl. (W)	0.069	2.50	17	600	130	4,700	15	550	60	2,100	48	1,700	2,400	87,000	1.0	40

Note: C = Control digester
W = Wet-weather digester

TABLE D-6. SOLUBLE HEAVY METAL ANALYSES FOR THE BENCH SCALE DIGESTION TESTS - KENOSHA, WISCONSIN
(All concentrations in mg/l)

Test day	Test period	Sludge sampled	Lead	Zinc	Nickel	Copper	Chromium	Iron	Cadmium
11-13	Control	Dig. Sludge (C)	<0.05	0.58	<0.1	0.93	0.05	0.39	<0.01
		Dig. Sludge (W)	0.08	0.43	<0.1	0.76	0.04	0.34	<0.01
35	#3	Feed (W)	0.08	0.31	<0.1	0.10	0.03	0.38	<0.01
		Feed (C)	0.07	0.33	<0.1	0.07	0.02	0.59	<0.01
		Dig. Sludge (C)	0.06	0.62	<0.1	0.16	0.07	0.40	<0.01
		Dig. Sludge (W)	<0.05	0.52	<0.1	0.21	0.04	0.23	<0.01

TABLE D-7. CALCULATION OF DIGESTER SLUDGE LOADINGS FOR A SIMULATED STORM EVENT OF 2.54 cm (1 inch) RAIN USING RACINE CSO SLUDGE

1. Average dry weather sludge feed to Racine digesters is 404995 l/day (107,000 gpd) at 8.9% total solids, 36044 kg (79422 lb) solids are added daily.

2. For a 2.54 cm (1 inch) rain event, the following amounts of CSO sludge are expected:

   1,731,500 ℓ (457,464 gal.) sludge at 0.84% total solids.

   After thickening, this would be equivalent to:

   121,407 ℓ (32,076 gal.) at 11.98% total solids or 14,567 kg (32,048 lb) dry solids.

3. If the sludge from a 2.54 cm (1 inch) rain were added to the digesters in one day, the ratio of CSO solids to dry-weather solids added to the Racine digesters would be 14,567 kg/36,044 kg = 0.404.

4. To feed our laboratory digesters at a ratio of 0.404 parts CSO solids per part of dry-weather solids, we need 0.404 x 4.30/11.98 = 0.145 volume of CSO sludge per volume of dry-weather sludge. Amounts added to the wet-weather digester are:

	Normal Dry-Weather Sludge	CSO Sludge	Total Wet-Weather Feed*
Volume, ml	900 ml	131 ml	1031 ml
Volumetric loading, ℓ/m^3/day	50	7.3	57.3
Hydraulic retention time, days	-	-	17.5
Total solids, conce., %	4.30	11.98	5.28
Total solids loading, kg/m^3/day	2.15	0.87	3.02
Volatile solids conc., %	2.77	5.24	3.08
Volatile solids loading, kg/m^3/day	1.39	0.38	1.77

* Calculated values.

5. To feed the control digester at the same volatile solids loading (1.77 kg/m^3/day) using dry-weather sludge only, 900 ml x 1.77/1.39 = 1147 ml sludge is needed. This would result in a total solids loading of 2.74 kg/m^3/day and a volumetric loading of 63.7 ℓ/m^3/day or an equivalent hydraulic retention time of 17.4 days for the wet-weather feed day.

TABLE D-8. RAW DATA FROM BENCH SCALE DIGESTION STUDY USING RACINE CSO SLUDGE FOR WET-WEATHER SIMULATION

Day	Date	Digester	Gas Production ℓ/day(STP)	Total Solids %	Volatile Solids %	pH	Alkalinity mg/l as $CaCO_3$	Volatile Acids mg/l as Acetic
1	8/23	C	9.5	2.76	57.6	-	-	-
		W	9.3	2.86	59.8	-	-	-
2	8/24	C	9.4	2.86	58.4	7.4	-	140
		W	8.8	2.91	60.1	7.5	-	540
3	8/25	C	9.0	2.82	58.2	7.3	-	40
		W	8.8	2.86	60.1	7.2	-	50
4	8/26	C	9.0	2.88	58.0	7.2	-	-
		W	8.8	2.90	59.6	7.3	-	-
5	8/27	C	8.4	2.87	57.8	-	-	-
		W	7.8	2.79	58.8	-	-	-
6	8/28	C	8.1	2.83	58.3	7.2	-	95
		W	8.3	2.84	59.5	7.2	-	85
7	8/29	C	8.2	2.85	58.2	7.2	-	-
		W	8.6	2.83	59.4	7.2	-	-
8	8/30	C	7.8	2.83	57.2	7.2	-	210
		W	8.2	2.80	59.6	7.2	-	470
9	8/31	C	7.7	2.86	-	7.2	-	-
		W	8.2	2.86	56.6	7.3	-	-
10	9/1	C	8.9	2.97	57.9	7.2	-	260
		W	8.2	2.97	60.6	7.2	-	390

continued

TABLE D-8. (continued)

Day	Date	Digester	Gas Production ℓ/day (STP)	Total Solids %	Volatile Solids %	pH	Alkalinity mg/l as $CaCO_3$	Volatile Acids mg/l as Acetic
11	9/2	C	9.2	2.90	56.5	7.2	-	-
		W	9.0	2.86	58.7	7.2	-	-
12	9/3	C	9.4	2.89	56.7	7.2	-	10
		W	9.2	2.82	58.9	7.2	-	10
13	9/4	C	8.4	2.86	56.6	7.2	-	-
		W	8.4	2.80	58.9	7.2	-	-
14	9/5	C	8.2	2.93	56.3	7.2	-	50
		W	8.4	2.86	59.1	7.2	-	80
15	9/6	C	8.4	3.01	57.5	7.2	-	-
		W	8.5	2.89	58.8	7.2	-	-
16	9/7	C	9.5	2.96	56.7	7.2	-	90
		W	9.5	2.92	58.9	7.2	-	15
17	9/8	C	9.3	2.90	56.6	7.2	-	<10
		W	9.1	2.86	58.4	7.2	-	<10
18	9/9	C	8.3	2.92	56.2	7.1	-	30
		W	8.0	2.87	58.2	7.2	-	270
19	9/10	C	8.6	2.87	56.4	7.2	-	<10
		W	8.6	2.89	58.8	7.2	-	170
20	9/11	C	8.6	2.88	56.2	7.2	-	<10
		W	8.0	2.88	58.0	7.2	-	340

continued

TABLE D-8. (continued)

Day	Date	Digester	Gas Production ℓ/day (STP)	Total Solids %	Volatile Solids %	pH	Alkalinity mg/l as $CaCO_3$	Volatile Acids mg/l as Acetic
21	9/12	C	-	2.95	56.6	7.2	-	140
		W	-	2.92	58.2	7.2	-	300
22*	9/13	C	9.6	2.98	56.7	7.3	-	20
		W	9.8	2.95	57.6	7.3	-	20
23	9/14	C	9.9	2.95	58.6	7.3	2800	50
		W	9.1	3.00	57.0	7.2	2400	<10
24	9/15	C	9.2	3.00	54.0	7.3	-	30
		W	8.3	2.93	57.3	7.3	-	30
25	9/16	C	10.0	-	-	7.2	-	220
		W	9.4	-	-	7.3	-	70
26	9/17	C	7.3	3.26	55.8	7.2	3350	210
		W	6.7	2.93	57.3	7.2	3350	440
27	9/18	C	-	2.91	55.7	-	-	-
		W	-	2.87	57.8	-	-	-
28	9/19	C	8.5	2.94	56.5	7.2	-	-
		W	8.2	2.88	56.9	7.2	-	-

Note: C = control digester; W = wet-weather digester

continued

TABLE D-8. (continued)

<u>Feed Sludge Concentrations:</u>

Day 1 and 2 - 4.36% total solids, 65.1% volatile solids, 6.6 pH

Day 3 to day 11 - 4.29% total solids, 64.6% voaltile solids, 6.65 pH

Day 12 to day 12 - 4.31% total solids, 64.6% volatile solids, 6.75 pH

Day 23 to day 28 - 4.42% total solids, 63.5% volatile solids

Day 22 - Control digester - 4.42% total solids, 63.5% volatile solids

Day 22 - Wet-weather digester - 5.23% total solids, 57.6% volatile solids

* Simulated wet-weather sludge feed day. Mixture of Racine CSO sludge and dry-weather sludge added to wet-weather digester at loading of 1.73 kg volatile solids/m^3/day. Dry-weather sludge added to control digester at loading of 1.77 kg/m^3/day.

TABLE D-9. TOTAL HEAVY METAL ANALYSIS FOR THE BENCH SCALE DIGESTION TESTS - RACINE, WISCONSIN
(All analyses in mg metal/kg)

Test Day	Sample description	Digester	Lead		Zinc		Nickel		Copper		Chromium		Iron		Cadmium		Manganese	
			wet	dry	wet	dry	wet	dry	wet	dry	wet	dry	wet	dry	wet	dry	wet	dry
15/21	Composite samples of dig. sludge during control period	C	15	521	-	-	26	903	38	1320	358	12400	1040	36100	1.5	52	8.9	309
		W	15.5	544	135	4740	26	912	41	1440	360	12600	970	34000	1.7	60	8.4	295
22	Feed to digesters during wet-weather simulation	C	15.5	411	172	4560	26	690	41	1090	371	9840	1150	30500	2.4	64	10.4	276
		W	24	488	152	3090	25	508	44	894	343	6970	1150	23400	1.6	32	11.5	234
28	Dig. sludge after wet-weather simulation	C	13.5	456	129	4360	29	980	41	1380	355	12000	1040	35100	1.5	51	8.9	300
		W	12.5	437	138	4830	26	909	39	1364	352	12300	968	33800	2.0	70	8.3	290

Note: C = Control digester
W = Wet-weather digester

TABLE E-1. GLOSSARY

Anaerobic Digestion -	The process by which organic matter in sludge is decomposed by bacteria in the absence of free oxygen. This process usually takes place under elevated temperatures in an enclosed tank. A major by-product is methane gas.
Basket Centrifuge -	A centrifuge equipped with either an imperforate or perforated cylindrical bowl, mounted vertically and driven by means of a vertical spindle. These types of machines operate in a batch type mode and are normally equipped for complete automatic operation.
Bowl Speed -	Rotational speed of the centrifuge bowl normally expressed in rpm's.
Cake -	The solid phase achieved after centrifugation of the solid-liquid slurry.
Centrate -	The liquid phase achieved after centrifugation of the solid-liquid slurry.
Centrifugation -	The act of separating a mixture of solids and liquids into a solid phase and a liquid phase through centrifugal force.
Centrifuge -	A mechanical device utilizing centrifugal force to achieve solids - liquid separation of a solid-liquid mixture.
Combined Sewer -	A sewer which carries both sanitary sewage and storm water run-off.
Combined Sewer Overflow (CSO) -	The flow in a combined sewer which is in excess of the sewage system capacity. This excess flow is commonly diverted to a water body without treatment.

continued

TABLE E-1. (continued)

CSO Sludge -	The precipitated solid matter resulting from the treatment of combined sewer overflows.
Decanter Centrifuge -	A centrifuge equipped with a horizontal rotating conveyor mounted within an indepently rotating bowl. These machines operate in a continuous mode and are normally equipped for complete automatic operation.
Dewatering -	Any unit operation used to reduce the moisture content of sludge so that it can be handled and processed as a semisolid material instead of a liquid. As it refers to this report - the separation of a mixture of solids and liquids into a solids phase (normally called cake) and a liquid phase (normally called centrate or clarified liquor).
Differential Speed -	Relative speed between centrifuge bowl and solids conveyor. (Applies to decanter centrifuge only).
Dry-Weather Sludge -	The precipitated solid matter resulting from the treatment of sewage which has not had its characteristics altered by rainfall, snow melts etc.
Feed -	Solids-liquid slurry pumped into the centrifuge.
Feed Rate -	Rate of slurry flow pumped into the centrifuge, expressed either as lpm (gpm) or kg (lbs) of dry solids per hour.
Polymer -	Organic chemical conditioner or coagulant used for conditioning sludge prior to centrifugation.

continued

TABLE E-1. (continued)

Pool Radius -	The distance between the center of the rotating bowl and the surface of the liquid retained within the rotating bowl). (Applies to decanter centrifuge only).
Scrollability -	A characteristic measure of the cake solids deposited on the centrifuge bowl. (Applies to decanter centrifuge only).
Skimmings -	Semi-dewatered solids removed from the accumulated cake in a basket type centrifuge.
Sludge -	The accumulated solids removed from any liquid processing stream.
Sludge Treatment -	Any unit operation which dewaters or thickens the precipitated solids resulting from the treatment of sewage.
Sludge Disposal -	The ultimate placement, distribution or partial destruction of sludge. Common methods of sludge disposal include landfilling, land application, ocean dumping and incineration.
Solids Recovery -	A measure of centrifuge performance expressed in percent suspended solids. $N = \frac{\text{weight of solids in solid phase (cake)}}{\text{weight of solids in feed slurry}} \times 100$
Suspended Solids (SS) -	Solids physically suspended in sewage which can be removed by proper laboratory filtering.

continued

Thickening -	Any physical and/or chemical process which results in the concentration or compaction of the solid phase of sewage sludges. Generally, a liquid layer containing relatively low solids is removed during the thickening process.
Total Solids (TS) -	The total amount of solids in solution and suspension.
Waste Activated Sludge (WAS) -	That portion of sludge from the secondary clarifier in the activated sludge process that is wasted to avoid a buildup of solids in the system.
Wet-Weather Sludge -	See CSO sludge.

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16. ABSTRACT

This report documents the results of a project initiated to evaluate the handling and disposal of combined sewer overflow (CSO) treatment residuals. Bench scale thickening and pilot and full-scale centrifugation dewatering tests were performed at dry-weather and CSO treatment sites in Kenosha, Racine and Milwaukee, WI. In addition, bench scale anaerobic digestion studies were conducted to determine the effect of CSO sludges on the anaerobic digestion stabilization process.

The results indicated that the dewatering of CSO sludges appears feasible when the sludges are first degritted, where required, and thickened prior to centrifugation. Under optimum centrifuge operating conditions, thickened sludges were dewatered to cake concentrations varying from 14.0% to 32% with solids recoveries ranging from 80% to 99%. Similarly, the dry-weather sludges for the test sites dewatered to haulable cakes. The bench scale anaerobic digestion studies showed that no significant adverse effect was realized by adding CSO generated sludges to dry-weather digesters.

Preliminary economic estimates indicate that first investment capital costs for thickening-centrifiguation of CSO sludges ranged from 0.31 to 2.92 million dollars with annual costs of $49,500 to $659,300 per year when handling 4.0 to 36.5 tons dry sludge per day, respectively.

17. KEY WORDS AND DOCUMENT ANALYSIS		
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