EPA-670/2-75-011
April 1975

Environmental Protection Technology Series

PHYSICAL AND SETTLING CHARACTERISTICS OF PARTICULATES IN STORM AND SANITARY WASTEWATERS

National Environmental Research Center
Office of Research and Development
U.S. Environmental Protection Agency
Cincinnati, Ohio 45268

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PHYSICAL AND SETTLING CHARACTERISTICS OF PARTICULATES IN STORM AND SANITARY WASTEWATERS

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FOREWORD

Man and his environment must be protected from the adverse effects of pesticides, radiation, noise and other forms of pollution, and the unwise management of solid waste. Efforts to protect the environment require a focus that recognizes the interplay between the components of our physical environment – air, water, and land. The National Environmental Research Centers provide this multidisciplinary focus through programs engaged in

- studies on the effects of environmental contaminants on man and the biosphere, and
- a search for ways to prevent contamination and to recycle valuable resources

The studies by the American Public Works Association of the use of secondary motions for the separation of solids from liquid flow fields has required precise definition of settleable solids in stormwater, combined sewer overflows, and sanitary sewage. Solid characteristics such as particle shape, size, and settling velocity determine the design and efficiency of solids removal.

Information on solid characteristics has not been researched to an appreciable degree. There is need for better definition of solids to facilitate design of physical treatment methods.

This report by Beak Consultants, Limited, covers studies conducted for solids, and the search for solids which could be used in a hydraulic model to simulate sewage solids.

The wide range of information which has been reported highlights the need for studies of this type to more precisely define the solids in the various flows to be treated.

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ABSTRACT

An investigation was conducted, as part of model studies utilizing a swirl concentrator as a primary separator, helical combined sewer overflow regulator, and related studies, to characterize the properties of solids in sanitary sewage, combined sewer overflows, and stormwater runoff. To effectuate this study, material suitable for monitoring removal efficiencies in hydraulic models of the swirl concentrator unit has been developed.

The approach taken by Beak Consultants, Ltd., serving as a subcontractor to the American Public Works Association in the simulation sewage studies, was to match as closely as possible the settling characteristics of solids in three types of sewage and/or urban runoff with a well-defined, uniform artificial test material. An Amberlite anion exchange resin (IRA-93), when ground and sieved to between 74 and 149 microns, was found to closely simulate the settling characteristics of domestic sewage. This material is of uniform density and appears to react according to Stokes' law for spherical particles at this size range. Arizona Road Dust, between 10 and 20 microns, was found to exhibit a similar settling velocity distribution.

Importantly, as background information for the selection of synthesized solids, the settling characteristics (including size and specific gravity distribution) of a few samples of sanitary sewage, combined sewer overflow, and stormwater were determined. These values will be useful for future determinations of physical treatment process design and associated treatability.

This report on these studies recommends that either or both of these materials be used in the scale-model efficiency trials.

This report was submitted in partial fulfillment of Contract 68-03-0272 between the U.S. Environmental Protection Agency and the American Public Works Association.

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ACKNOWLEDGMENTS

The American Public Works Association is deeply indebted to the following persons and their organizations for the services they have rendered to the APWA Research Foundation in carrying out this study for the U.S. Environmental Protection Agency.

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SECTION I
OVERVIEW, FINDINGS AND RECOMMENDATIONS

The research study reported here has resulted in the identification of an artificial material which may be used to represent the settling velocity characteristics of raw sanitary sewage flows and combined sewer overflows. This material has generally proved suitable for monitoring the solids removal efficiency of a model swirl concentrator being evaluated under the current contract. The development and evaluation of this material is the principal result of an intensive search and study which has resulted in several significant laboratory determinations.

A literature review of the settling characteristics of combined sewer overflows provided little information as to settling velocities of the suspended matter to be expected. Settling column tests on primary sewage in Philadelphia, Pa., disclosed that the median settling velocity of the suspended solids was 0.054 cm/sec (0.106 ft/sec). Attention was then directed to the selection of artificial materials with settling velocities approaching this parameter. Settling column studies on a variety of solid particles indicated that Amberlite IRA-93, anion exchange resin with a specific gravity of 1.04, possessed lower settling velocities than all other materials evaluated. Amberlite IRA-93, in its commercially available state, still did not have sufficiently low settling velocities to accurately simulate the action of sewage solids. Therefore, the resin was pulverized, classified according to particle size, and further settling column tests were conducted. Settling velocities for that portion passing through 100-mesh and retained on 200-mesh (74-145μ) provided results compatible with the desired range.

FINDINGS AND RECOMMENDATIONS

Based on results of studies of simulated sewage solids materials, it is recommended that the hydraulics prototype studies being conducted at the LaSalle Hydraulics Laboratory to develop and determine swirl concentrator removal efficiency proceed with the use of the proper size range of Amberlite IRA-93, Anion Exchange Resin and Arizona Road Dust. Both of these materials exhibit settling velocities in the desired ranges. However, the high cost and reported unavailability of the Arizona Road Dust have resulted in the use of the IRA-93 in initial monitoring tests.

The apparent improvement in settling characteristics after storage due to agglomeration of small particles should be the subject of additional study to define the effects of storage on settling characteristics and to determine the overall feasibility of this form of pretreatment. In addition, combined sewer overflows should be tested to determine if there is a like improvement in settling characteristics after storage.

THE STUDY

This research study was performed by Beak Consultants Limited, as a subcontractor to the American Public Works Association, (APWA), in connection with U.S. Environmental Protection Agency (EPA) Contract No. 68-03-0272. This contract was dated April 26, 1973 and is entitled *Development of a Swirl Primary Separator and a Helical Combined Sewer Overflow Dual Functioning Regulator and Separator.* The overall objective of this contract is the development and evaluation of a solids separation device to provide primary treatment of combined sewer overflows and stormwater runoff. The swirl separator, in addition, has applicability as a primary clarification unit at a wastewater treatment plant for handling dry-weather sanitary sewage.

Importantly, as background informatior for the selection of synthesized solids, the settling characteristics (including size anc specified gravity distribution) of sanitary sewage, combined sewer overflow, an stormwater were determined. These value will be useful for future determinations o physical treatment process design and associated treatability.

APWA has conducted hydraulic and mathematical model studies to develop the basic design and determine the efficiency of the unit. In conjunction with the hydraulic studies, a mathematical model has been developed to predict particle flow in the swirl concentrator. To preclude the utilization of actual sewage particulates in hydraulic studies and to facilitate computer simulation, Beak Consultants conducted a study to select a commercially available material to simulate the solids fractions in sanitary sewage, stormwater runoff, and combined sewer overflows and subsequently to monitor the efficiency of the swirl concentrator in removing the suspended particulates represented by the chosen solids material.

The scope of study included a literature search to define the properties and concentration of solids by sizes in combined sewer overflows and sanitary sewage. Sampling and analysis of sanitary sewage provided further information regarding settling characteristics in relation to particle size. Having gained knowledge of the settling velocities of suspended sewage solids, an evaluation of artificial materials to simulate sewage solids was undertaken. This report presents findings of the literature search, data obtained from sewage sampling, and results of the tests conducted to select a material which would represent the range of settling velocities characteristic of sanitary sewage solids particles.

The final phase of Beak's study covered a monitoring program to measure suspended solids removal efficiency of the swirl concentrator model at LaSalle Hydraulic Laboratory. The detailed results of the monitoring program will be submitted with the report on the model development.

SECTION II
REVIEW OF PHYSICAL AND CHEMICAL CHARACTERISTICS OF SUSPENDED SOLIDS IN SANITARY SEWAGE, COMBINED SEWER OVERFLOWS, AND STORMWATER RUNOFF

The following section presents the results of the literature review conducted to characterize sanitary sewage, combined sewer overflows and stormwater runoff in terms of their suspended solids content and physical and chemical characteristics. In some cases, investigators reported very similar results, especially for sanitary sewage. However, the inconsistency and variability of solids properties from a study in one city to that in another was most obvious. For example, these flows cannot be characterized by single *average* concentrations of suspended solids and volatile content, or by a single particle size distribution. Rather, a wide range of individual physical and chemical parameters is required to realistically represent the solids contained in sanitary sewage, combined sewer overflows and stormwater runoff.

SANITARY SEWAGE

An evaluation of the literature covering the characterization of solids in sanitary sewage emphasizes the variability of the physical and chemical properties of these solids. These properties are influenced by such factors as range of flow rate, time of day and contribution of industrial wastes to the total flow. Variation of solids properties in sewage from one geographical location to another is also evident.

Particle Size Distribution and Density

Several investigators[1,2,3,4] separated the insoluble particulate solids in sewage into three classifications: (a) settleable; (b) supracolloidal; and (c) colloidal solids. Generally the separation technique involved: (a) a sedimentation or quiescent settling step to determine settleable solids; (b) a centrifugal step to determine supracolloidal solids; and (c) a candle filtration[3] high-pressure membrane filtration,[1,2] or supercentrifugation[4] to determine colloidal solids. Rickert and Hunter[4] report ideal size limits of >100 microns, 1 to 100 microns and 1 millimicron to 1 micron for, respectively, the settleable fraction, supracolloidal fraction and colloidal fraction. Work by Rudolfs and Balmat[5] confirmed that the limits had been attained for the first two fractions. However, electron microscopy studies on secondary effluent[4] indicated that the colloidal fraction was in the range 0.2 to 1.0 micron. Table 1, Particle Size Distribution of Suspended Solids in Sanitary Sewage, shows the results of these investigations in terms of percent of solids in each size range. It can be seen that the split is approximately 45 percent settleable, 35 percent supracolloidal and 20 percent colloidal. This figure of 45 percent settleable solids coincides quite closely with accepted primary treatment efficiency of 50 to 60 percent removal of total suspended solids, as reported in the Water Pollution Control Federation's *Sewage Treatment Plant Design, 1967.* This distribution is presented graphically in Figure 1, Particle Size Distributions of Some Waste Stream Solids. A straight line is drawn using only two data points. The dotted portion of the line represents an extrapolation.

A sieve analysis of particle size was carried out on raw sanitary sewage from Lancaster City, Pa., by Meridian Engineers of Philadelphia, Pa.[6] This analysis shown in Table 1, covered sizes greater than 149 microns, and showed that only 13 percent of the solids were greater than 149 microns in size. This result would seem to indicate that some sewages can contain a high percentage of fine solids if it is assumed that the remainder passed through the 149 micron sieve. Solids were retained on five sieves only, indicating a rather narrow particle size range.

In addition to the sieve analysis, specific gravity measurements of the suspended solids were carried out, using a mineralogical sink-float procedure in benzene-acetylene tetrabromide solution. This analysis showed a

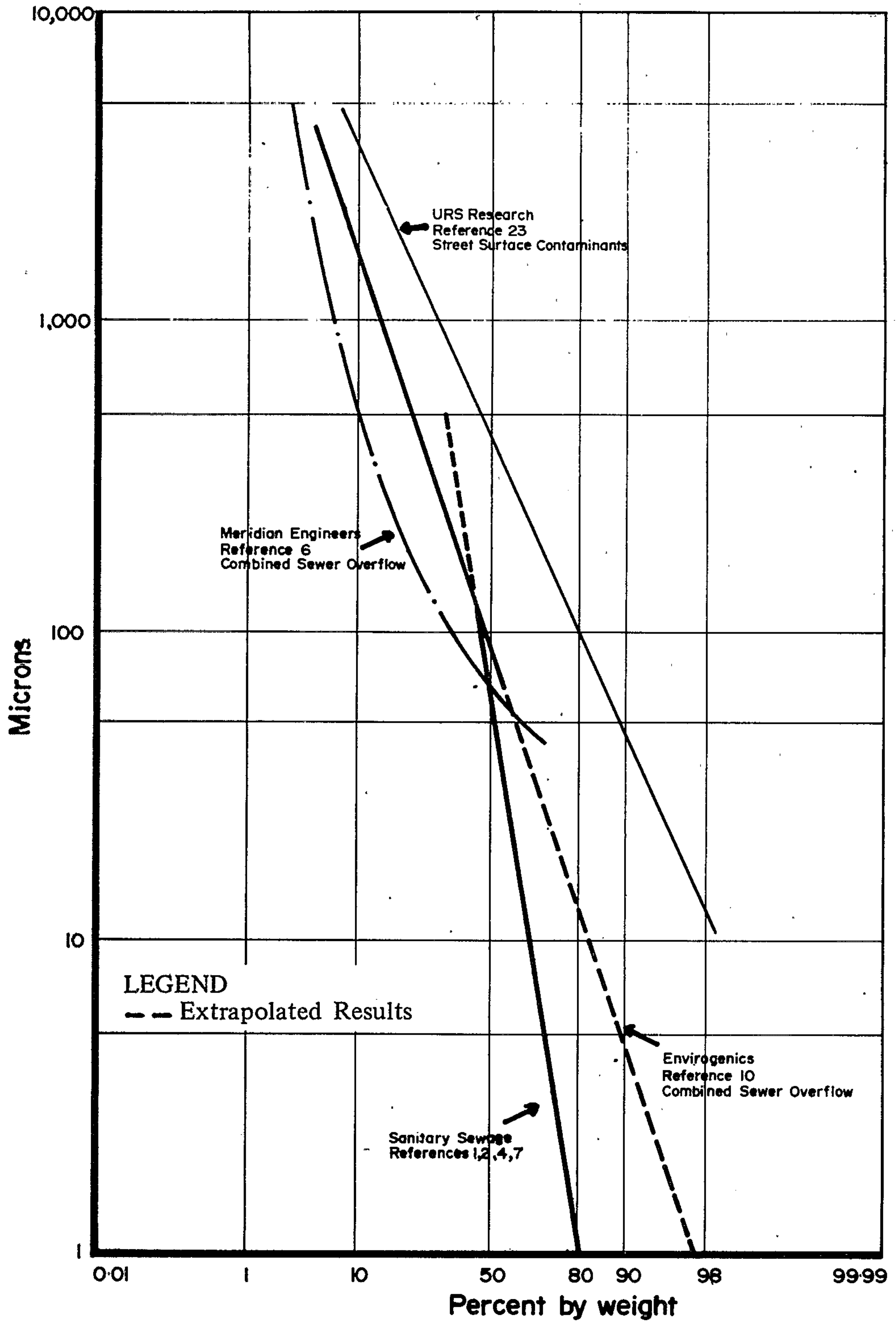

FIGURE 1 PARTICLE SIZE DISTRIBUTIONS OF SOME WASTE STREAM SOLIDS

TABLE 1
PARTICLE SIZE DISTRIBUTION OF SUSPENDED SOLIDS IN SANITARY SEWAGE

SOURCE OF FIGURES	PARTICLE SIZE RANGE (microns)	DISTRIBUTION (percent)
Hunter & Heukelekian[1] (average of two studies) a) Winter-Spring 1959 b) Fall-Winter 1959–1960	>100 (Settleable)	49.4
	1 – 100 (Supracolloidal)	31.4
	0.2 – 1.0 (Colloidal)	19.2
Heukelekian & Balmat[2]	>100	47.0
	1 – 100	34.0
	0.2 – 1.0	19.0
Meridian Engineers[6]*	>1,190 (0.047 in.)	4.42
	590 – 1,190	1.38
	420 – 590	3.46
	210 – 420	3.09
	< 149	86.9
Painter, Viney & Bywaters[7]	>100	37.1
	1 – 100	44.8
	0.2 – 1.0	18.1

* Note: Remainder passed No. 200 mesh

range of specific gravities from 0.80 to 1.60 percent were in the specific gravity range 0.80 to 1.25.

It is reasonable to postulate that particle size can be affected by two main factors: flow rate and industrial wastewater contribution. High flow rates in sewer lines can cause agglomerates to break up, thus producing more fine solids. Industrial wastes can provide a variety of particle sizes, dependent on types of waste involved.

Total and Settleable Suspended Solids

Table 2, Solids Classification by Concentrations in Sanitary Sewage, shows actual solids concentrations found in the various studies reviewed. Settleable solids range from 37 percent to 65 percent of the suspended solids concentration.

No correlation was found between concentrations of settleable, solids in *milliliters per liter (ml/l)* and *milligrams per liter (mg/l)*. Settleable solids are measured volumetrically, percentagewise, by quiescent settling of a one liter sample for one hour in an Imhoff cone. The cone is graduated in milliliters and, after one hour, the volume of settled solids is recorded to give settleable solids in *ml/l*. A sample of at least one liter is settled quiescently in a cylindrical glass container for one hour. Suspended solids in the supernatant liquor are determined before and after to determine settleable solids gravimetrically (in mg/l). See Appendix A.

Actual levels of suspended and settleable solids can be affected by time of day at which the sample was obtained, by the contribution of industrial flows, and the amount of inflow, infiltration or sand among other factors. Peak flow periods of the day such as morning (preparation for work) and late afternoon (cleaning up after work) are characterized by high solids loads. Large input flows of an industrial effluent containing high solids levels also will result in increased solids concentrations.

Insoluble Oil Fraction

The insoluble oil fraction or total grease in sewage was reported by several sources. Hunter and Heukelekian[1] found that approximately 25 mg/l of grease were contributed by the particulate matter to the raw sewage. The settleable solids fraction

TABLE 2
SOLIDS CLASSIFICATION BY CONCENTRATIONS IN SANITARY SEWAGE

Sources of Figures (Reference No.)	Settleable Solids Volumetric ml/l			Settleable Solids mg/l	Total Suspended Solids mg/l			Volatile Suspended Solids mg/l		
	Avg.	Max.	Min.	Avg.	Avg.	Max.	Min.	Avg.	Max.	Min.
Hunter and Heukelekian[1]										
a) Winter-Spring 1959	3.3	6.1	1.8	69	145	258	83	120	208	62
b) Fall-Winter 1959-1960	6.7	10.6	2.4	75	146	236	58	125	174	54
Rickert and Hunter[4] Spring 1967				74	162			125		
Meridian Engineers[6] Lancaster, Pa.					188					
Painter, Viney & Bywaters[7]				240	647					
Imhoff, Muller & Thistlethwayte[8]				310	480			340		
Fair, Geyer, Okun[9]				140	235			170		
Portland, Oregon[14]	4.8	7.0	2.5		129	244	50			
Roy F. Weston, Inc.[15] Washington, D.C.				95	176	260	90	161	230	88
Engineering-Science, Inc. San Francisco[16]										
a) Selby Street					209			148		
b) Laguna Street					194			162		
City of Los Angeles Hyperion Treatment Plant	13.2				255			[illegible]		
City of Philadelphia Northeast Water Pollution Control Plant	8.9				272			212		
City of New Orleans	3.0				186			130		
City of Phoenix					255					
Fair and Geyer, 1954[31]				180	295					

contributed the most to this total. The City of Los Angeles reported a total grease concentration of 52 mg/l at its Hyperion Treatment Plant. Grease and floatables concentrations in dry-weather flow at two locations in San Francisco[16] averaged 45 mg/l and 2.9 mg/l respectively.

Organic Content as a Function of Particle Size

It can be determined from the data in Table 2 that the organic content of the suspended solids in sewage, measured as volatile suspended solids, ranges from 70 to 85 percent of the suspended solids (ss) concentration. In terms of particle size fractions, approximately the same distribution occurs as for total ss. Several sources[1,2,3,4] reported that of the total volatile ss, approximate contributions by the settleable, supracolloidal and colloidal fractions are respectively 50, 30 and 20 percent. The results are shown in Table 3, Particle Size Distribution of Volatile Suspended Solids in Sanitary Sewage.

COMBINED SEWER OVERFLOWS

As was found for sanitary sewage, a similar variability of solids properties was observed in different combined sewer overflows investigated. In addition to those solids normally found in sanitary sewage, combined sewer overflows contain solids washed into the sewer system from urban roadway and land areas. Since overflows occur as a result of elevated flow rate, scouring of solids deposits in lines may take place. Scouring loosens and mixes the solids which may accumulate between storm events and contributes additional grit and sand to the solids load. A *first flush* phenomenon may

TABLE 3
PARTICLE SIZE DISTRIBUTION OF VOLATILE SUSPENDED SOLIDS IN SANITARY SEWAGE

Source of Figures	>100 Microns % Settleable	1 – 100 Microns % Supracolloidal	0.2 – 1.0 Micron % Colloidal
Hunter & Heukelekian[1]			
a) Winter-Spring 1959	46.5	35.0	18.5
b) Fall-Winter 1959-1960	53.0	30.2	16.8
Heukelekian & Balmat[2]	45	35	20
Painter & Viney[3]	48	31	21
Rickert & Hunter[4]	48	35	17

occur. This results in increased contaminant concentration levels during the initial stages of a storm event. An intense, widespread storm and smaller drainage area increases the possibility of a *first flush* occurrence. As the storm continues, contaminant concentrations tend to decrease. This solids level at the end of a storm and after *first flush* may be lower than dry-weather flow solids concentrations.

Particle Size Distribution and Density

The Envirogenics Company[10] carried out an extensive study of the physical and chemical properties of combined sewer overflow solids collected in San Francisco from April 1969 to May 1970 using a screening technique. The samples obtained represented several storms and in all cases the overflow was sampled as close to the beginning of the storm as possible and at specific time intervals thereafter. A total of 60 combined sewage composite samples were analyzed for a number of parameters, including a qualitative description of physical appearance.

In addition to fecal material, paper, food particles and cigarette butts contributed by sanitary sewage; leaves, twigs, string, rags and plastic-materials, most coming from street washings; were observed. Particle size distribution analyses were successfully accomplished for 47 samples. Overall average results are reported in Table 4, Particle Size Distribution of Suspended Solids in Combined Sewer Overflows. The cumulative particle size distribution of the samples is presented graphically in Figure 1. The sanitary sewage graph is included for purpose of comparison. For the combined sewer overflows, 27.0 percent of the solids are greater than 100 microns in size, which is comparable to the character of sanitary sewage solids.

An extrapolation of the combined sewer overflow graph is shown by the dotted portion. There is an indication that a greater percentage of ss in range 1 to 100 microns was found in combined sewer overflows than in sanitary sewage – 50 percent compared with 35 percent respectively. It must be

TABLE 4
PARTICLE SIZE DISTRIBUTION OF SUSPENDED SOLIDS IN COMBINED SEWER OVERFLOWS

Source of Figures	Size Range (microns)	Distribution (percent)
Envirogenics Co.[10]	>3,327	5.1
San Francisco, Cal.	991-3,327	8.8
	295-991	15.9
	74-295	21.8
	<74	48.3
Meridian Engineers[6]*	>9,525	1.77
Lancaster, Pa.	4,760-9,525	1.06
	2,000-4,760	1.40
	1,190-2,000	1.88
	590-1,190	3.10
	420-590	2.78
	210-420	7.01
	149-210	5.19
	74-149	20.1
	44-74	23.8
	<44**	31.91

* The material tested represents those solids retained in a catch basin. Sampling took place the week following the storm event. Thus, results are not directly applicable to all solids in combined sewer overflows. The particle sizes could be higher than in the actual flow as some fractions of the smaller size ranges could have been carried through the basin.

** Not measured

pointed out, however, that the method of analysis was not designed to provide an accurate distribution below 74 microns, which was the smallest mesh sieve used. For the same reason, no reliable comparison of the fraction less than one micron can be made.

Meridian Engineers [6] carried out particle size analysis and density measurements of solids in catch basins. Since sampling occurred after the storm event, the solids collected are considered to have been hydraulically classified. Therefore, the size classification is not representative of the total combined sewer overflow. The results of this analysis are shown in Table 4, and graphically in Figure 1. A total of 68.1 percent of the suspended material was retained on a sieve size as small as 44 microns. It must be assumed that the remaining 31.9 percent of the solids was less than 44 microns in size.

A much larger range of discrete sizes of particles was obtained from the combined sewer overflow than for raw sanitary sewage in the Meridian study (compare the entries on Table 4 with those on Table 1).

The specific weight of the combined overflow solids was measured using the same procedure as Meridian used for the raw sanitary sewage solids. A relatively wide range of specific weights was reported ranging from less than 0.80 g/cc to 2.60 g/cc. In the size range of 2,000 microns and higher, all particle specific weights were in the range 1.05 g/cc to 1.25 g/cc. However, as size range decreased to 149 microns, the full range of specific weights was encountered, with by far the greatest percentage being in the range 1.25 g/cc to 2.60 g/cc. This would tend to indicate that the particles of moderate size (149-2,000 microns) have the highest specific weight. This particle size lies within the range of some silica-sands grit. Since a similar analysis on raw sanitary sewage indicated a complete lack of solids in the specific weight range of 1.60 g/cc to 2.60 g/cc, it could be reasonably concluded that these denser particles were washed into the system from urban roadways, land areas, and by infiltration. The overall implication of the analyses of particle size and density is that combined sewer overflows contain larger amounts of solids of various sizes and densities than those found in sanitary sewage.

Additional estimates of particle size range of combined sewer overflows can be extracted from studies of treatment methods involving screening or filtration through specific size mesh screens. A study [11] reported ss removal efficiencies of 36± 16 percent for *first flushes* and 27 ± 5 percent for extended overflows in Milwaukee, Wisconsin, using a screen of mesh size 50 (297 micron openings). Such higher removal for *first flushes* probably results from the formation of a solids mat on the screen due to the presence of initial high ss. However, for extended overflows, the indication is that roughly 27 percent of the solids is larger than 297 microns in size. This compares favorably with the particle size distribution previously cited.[12] The drum screen consisted of a rotating straining element enveloped with replaceable wire mesh plates. Rotating on its horizontal axis, the straining element accepted incoming gravity flow while partially submerged inside an open chamber. As the drum turned, a jet spray washed off debris trapped on the mesh screen into a waste collector above the fluid level. Two sizes of screen were used – 841 micron openings (20 mesh) and 420 micron openings (40 mesh). Removal of ss averaged 19 percent for the larger screen and 25 percent for the smaller screen. These results were also comparable to some of the particle size distributions reported in Figure 1. This study was extended to include monitoring of settleable solids removal by the two screen sizes. Removal by both screens was in the order of 55 to 60 percent. Thus it can be assumed that a large portion of settleable solids was smaller than 420 microns in size.

Total and Settleable Suspended Solids

Table 5, Solids Concentrations in Combined Sewer Overflows, shows total suspended and settleable solids concentrations found in the various combined sewer overflows from different geographical locations. Just as was found for sanitary sewage, settleable solids in combined overflows range quite widely in terms of portion of suspended solids; from 37 to 87 percent based on mean values. For the most

TABLE 5
SOLIDS CONCENTRATIONS IN COMBINED SEWER OVERFLOWS

Source of Figures (Reference No.)	Settleable Solids ml/l			Settleable Solids mg/l			Total Suspended Solids mg/l			Volatile Suspended Solids mg/l		
	Avg.	Max.	Min.	Avg.	Max.	Min	Avg.	Max.	Min.	Avg.	Max.	Min.
Envirogenics Company[10]	2.58	14	0.05				67.6	426	4	52.2	373	4
Rex Chainbelt, Inc.[11]												
a) Extended overflows							166 ±26			14 ±90		
b) First flushes (95% confidence level for a & b)							522 ±150			308 ±83		
Hydrotechnic Corporation[12]												
a) Spring Storms (1971)	6.98	14.0	1.5				411	976	177			
b) Summer and Fall Storms (1970)	5.26	19.0	0.2				234	1,560	28			
Envirogenics Company[13] Winter 1968-1969												
a) Start of Storm				178.2	488	28	230.5	502	56	166.2	311	51
b) 3 hrs. after start				77.3	142	0	106.3	186	47	91.7	186	26
c) 12-18 hrs. after start				112.2	210	28	145.5	241	30	99.5	221	26
Symposium on Storm and Combined Sewer Overflows[14]												
Portland, Oregon	3.1	5.0	1.5				146	325	70	90	166	57
Milwaukee, Wisconsin												
a) Extended overflows							133-174			58-87		
b) First flushes (95% confidence level)							330-848			221-495		
Detroit, Michigan												
a) 1968 Avg. of daily grab samples - 59 Loc.								1,350	53			
b) 1969 Avg. of daily grab samples - 59 Loc.								1,005	70			
Bucyrus, Ohio - 3 sewer locations[14]							533	2,440	20	182	440	70
							430	990	90	238	570	80
							477	1,050	120	228	640	70
Engineering Science, Inc.[16]												
San Francisco, Selby St.		145	<0.3		1,067	27		1,260	24		886	4
Laguna St.		40	2.0					483	53		264	28
Benzie and Courchaine[18]												
Detroit, Michigan (1964)							150	1,398	23			
Burm et al[19]												
Detroit, Michigan (1965)				238	656		274	804		117	452	
Dunbar and Henry[20]												
Buffalo, New York								1,220	172			
Buffalo, New York								544	158			
Buffalo, New York								436	126			
Detroit, Michigan							250					
Toronto, Ontario								930	130			
Toronto, Ontario								580	17			
Welland, Ontario								426	168			
Weibel et al[21]												
Cincinnati, Ohio (1962-1963)							210	1,200	5	53	290	1

part, however, combined sewer overflows contain a greater percentage of settleable solids than does sanitary sewage. For values found, total suspended solids concentrations range from 4 mg/l to 2,400 mg/l and settleable solids from zero to 1,380 mg/l. These minima and maxima values do not necessarily correspond to the same samples.

The type of storm that causes the overflow can affect solids concentrations greatly. De Filippi and Shih[17] found that post peak ss concentrations in overflows from long, intense storms are reduced to approximately one-third of the comparable values for a short, intense storm. They concluded that solids characteristics of overflows from consecutive storms are probably similar to those from long-duration, low-intensity storms. In the case of their study, they found that the quantity of waste materials contributed by the initial *first flush* of a storm is proportional to the dry-weather period between storms. Dry-weather flow and quality characteristics were reported to be similar in both combined sewer systems and sanitary sewage systems during dry weather. However, the quantity of waste materials contributed by the iitial *first flush* of a storm is affected by several factors including antecedent dry period, intensity of storm, sewer system configuration, soil characteristics in the area, street cleaning practices and land use in the drainage area.

Insoluble Oil Fraction

Several investigators report results of oil and grease analysis of combined sewer overflow samples. Engineering Science Inc.[16] performed studies on combined sewer overflows at two locations in San Francisco resulting from several storms. Samples were obtained throughout the course of each overflow at time periods ranging from ten minutes to almost three hours between samples. Sampling was most frequent (i.e. – smaller time periods between samples) during the first few hours of the overflow. Combined results from the two locations showed a range of 0.4 to 120.5 mg/l of grease, using liquid–liquid extraction with hexane as the solvent following acidification and gentle heating of the sample. Floatable solids were also collected, using a Teflon-coated Flotation Funnel following mixing to create a homogeneous sample. Concentration ranged from 0.4 to 44.6 mg/l.

Extensive analysis of combined sewer overflows for parameters including oil and grease was undertaken by the Detroit Metro Water Department[14] (Section 6). Daily grab samples from 59 different locations were analyzed. The average oil and grease concentration of these daily grab samples ranged from 11 to 2,775 mg/l for the various locations in 1968, and from 13 to 689 mg/l in 1969.

Organic Content

Table 5, shows the volatile ss concentrations in several combined sewer overflows. A relatively wide range of organic content is portrayed. Actual average concentrations range from 51 mg/l to 495 mg/l, which is similar to sanitary sewer flows with an average range of 1:10 and the maximum twice the average. Minimum and maximum values reported are 1 mg/l and 1,280 mg/l, respectively. There is also evidence of a wide range of organic content in terms of percentage of total ss. Using average concentrations as a basis, the content ranges from 25 percent[21] to 86 percent.[13] Unfortunately, none of the investigators reported analysis of size range fractions for organic content. Thus, an estimate of organic content as a function of particle size cannot be made.

However, volatile content of settleable solids was reported by some observers. Burm et.al.[19] reported that volatile settleable solids ranged from 30 to 50 percent of total settleable solids. Engineering Science, Inc.[16] reported a wider range – from 15 to 70 percent. Most results however are well below 50 percent.

URBAN STORMWATER

Urban stormwater includes either overland sheet flow or storm flow in the separate storm sewered or unsewered drainage system. In most cases, separate storm-sewer flows are quite large over a short period of time and are not tributary to wastewater treatment system. As a result, large quantities of relatively heavily contaminated wastewater are diverted to natural watercourses with no form of treatment to reduce the pollution load. In this respect, and in some others, urban stormwater and untreated combined sewer overflows may be similar. However, a close examination of physical and chemical properties reveals important differences, especially with respect to ss with which this report is primarily concerned.

Several investigators previously cited have conducted studies of separate stormwater concurrently with combined sewer overflow investigations, so that a comparison between the two discharges could be made. The results of these comparisons will be discussed.

Particle Size Distribution

The URS Corporation[23] conducted an extensive investigation of street surface contaminants which are washed into both combined and separate sewers during a storm event. Sections of streets in several cities were washed down with water. The washings were collected and analyzed. Solid materials were extracted and dry-sieved for particle size distribution covering ten individual ranges from less than 4 microns to greater than 4,800 microns. The results are shown in Table 6, Particle Size Distribution of Solids – Selected City Composites. The percentage in each size range was averaged for the five cities under investigation to produce an overall distribution. This provides a very rough estimate. The average distribution is presented graphically in Figure 1. It is somewhat different from those for combined sewer overflows and indicates that solids particle sizes are larger in separate storm runoff.

Total and Settleable Suspended Solids

De Fillipi and Shih[17] observed that total suspended solids and settleable solids concentrations were much higher in stormwater runoff than in combined sewer overflows during their study in Washington, D. C. Suspended solids ranged from 130 to 11,280 mg/l, with an average concentration of 1,697 mg/l. Settleable solids ranged from zero to 7,640 mg/l, with an average of 687 mg/l. Volatile ss concentrations, however, were lower in stormwater runoff than in combined sewer overflows.

Benzie and Courchaine[18] and Burm et.al.[19] also observed higher ss concentrations in stormwater runoff. Both of these studies compared combined sewer overflows in Detroit, Michigan, with stormwater runoff in Ann Arbor, Michigan. The latter study[19] showed that stormwater runoff was higher in all solids parameters studied: ss, volatile ss, settleable solids and volatile settleable solids.

TABLE 6
PARTICLE SIZE DISTRIBUTION OF SOLIDS
– SELECTED CITY COMPOSITES –

PARTICLE SIZE RANGE (microns)	DISTRIBUTION (PERCENT BY WEIGHT)				
	Milwaukee	Bucyrus	Baltimore	Atlanta	Tulsa
>4,800	12.0	–	17.4	–	–
2,000-4,800	12.1	10.1	4.6	14.8	37.1
840-2,000	40.8	7.3	6.0	6.6	9.4
246-840	20.8	20.9	22.3	30.9	16.7
104-246	5.5	15.5	20.3	29.5	17.1
43-104	1.3	20.3	11.5	10.1	12.0
30-43	4.2	13.3	10.1	5.1	3.7
14-30	2.0	7.9	4.4	1.8	3.0
4-14	1.2	4.7	2.6	0.9	0.9
<4	0.5	–	0.9	0.3	0.1

Source: URS Research Company (23)

Average concentrations for the four parameters were 2,080, 218, 1,590, and 140 mg/l, respectively. In physical appearance, the stormwater runoff was brownish and muddy while the combined sewer overflow was less turbid and darker in color. Geomorphological differences between the two study areas were the primary cause of the differences. Ann Arbor has a more rolling topography and is subject to a higher degree of scouring and erosion. The soil has a much looser texture than the primarily clay soil found in Detroit. The settleable solids ranged from 70 to 90 percent of the total ss in both cases.

Wiebel et al.[21] investigated urban land runoff in Cincinnati, Ohio. Their results were much different than other studies. Average ss ranged from 5 to 1,200 mg/l, with a weighted average of 210 mg/l. Volatile content was approximately 25 percent of the ss concentration. Settling for 20 minutes reduced ss 27 to 53 percent and volatile ss 17 and 50 percent. Soderlund and Lehtinen[22] reported similar low ss (129 mg/l[3] average) and volatile ss (51 mg/l average) in urban stormwater runoff from Stockholm, Sweden.

A study[24] in Tulsa, Oklahoma, showed that stormwater runoff in this location contained an average ss concentration of 367 mg/l. Concentrations ranged from 84 to 2,052 mg/l. These results fall between the high levels first cited and the low levels just described.

An overview of these investigations indicates that there is a wide variety in the solids characteristics of separate stormwater runoff. These properties are primarily a function of land use, along with soil and topographical features.

SETTLING VELOCITY

Specific information concerning settling velocities of solids in sanitary sewage, stormwater and combined sewer overflows was not available in the literature. However, general design specifications for conventional primary clarifiers supplied some basic data. These clarifiers are designed to remove virtually 100 percent of settleable solids while operating with overflow rates that may range from 600-900 gal/sq ft/day. This range of overflow rates is equivalent to a settling velocity range of 0.028 to 0.043 cm/sec (0.0009 to 0.0014 ft/sec). Thus, the settling velocities of settleable solids should be larger than these figures. In practice 37 to 65 percent of the total ss are settleable and should be removed by primary clarification. Arrangements were made to conduct settling column tests of sanitary sewage and combined sewer overflow in Philadelphia to confirm settling velocities.

Settling Velocities of Erosion Solids

As previously stated, the types of solids to be found in stormwater runoff are affected by the type of soil found in the area that is tributary to the storm-sewer system. The erosion of land areas can be the prime contributor of solids to stormwater. As mentioned in an APWA publication, Hazen[25] reported that settling velocities of soil materials can range from 0.015 cm/sec (0.0005 ft/sec) for silt 10 microns in size, to 0.33 ft/sec for coarse sand, 1,000 microns in size. The relatively large range of settling velocities indicates that the effectiveness of a solids separation device for treatment of stormwater will be dependent on the type of particles in the waste stream. If the runoff contains fine and coarse sand, 40 microns and greater in size, separation should be efficiently accomplished. However, silt and clay materials present a much more difficult separation problem.

SECTION III
SETTLING VELOCITY RELATIONSHIPS OF SANITARY SEWAGE AND STORMWATER RUNOFF

The review of solids characteristics (Section II) provided minimal information regarding the settling characteristics of the ss fraction in the waste streams studied. Settling velocity is an important factor in determining performance of a swirl concentrator as a solids separation device. The purpose of this study, to establish settling velocity relationships for sanitary sewage, stormwater, and combined sewer overflows was two-fold. Initially, the laboratory settling column tests provided an indication of the settling characteristics to be expected. Secondly, particle settling velocities provided a target for selection of a material to simulate the sewage ss.

At the time of the preparation of this report a suitable sample of combined sewer overflows has not been available for settling column analysis. The stormwater runoff sample obtained in Toronto, Canada, at the Sherwood Park Storm Sewer Outfall, contained a low concentration of ss compared to reported averages from other sources. More important, however, was the low settleable solids portion of the ss in the sample. The results of settling column studies on this sample are reported.

SANITARY SEWAGE

Sanitary sewage sampling was conducted by Beak personnel at the Northeast Water Pollution Control Plant in Philadelphia, Pa. Three samples of sewage were collected at different times during the day following grit removal, and settling column tests were performed on each sample. Although the three samples contained different concentrations of ss and percent settleable solids, their settling characteristics were found to be sufficiently comparable so that the results for each could be combined. The ss and percent settleable solids in the samples after one hour of settling were as follows:

Sample No. 1 – 495 mg/l; 84% settleable
Sample No. 2 – 220 mg/l; 64% settleable
Sample No. 3 – 437 mg/l; 63% settleable

The range of settling velocities observed in sanitary sewage tested is presented graphically in Figure 2, Settling Velocity Distribution of Solids in Sanitary Sewage. The median settling velocity observed was 0.054 cm/sec (0.0017 ft/sec). The next section of the report indicates that the type of simulated solids used by previous researchers had settling velocities significantly greater than sanitary sewage, and hence would not be suited to this study.

URBAN STORMWATER

The settling column test procedure is described in detail in Appendix 1, together with all other test procedures used by Beak Laboratory staff.

The stormwater runoff sample was collected in late afternoon and stored overnight at 4° C (39° F) to ensure a minimum of biological activity. The following morning settling column tests were performed on a portion of the sample; the other portion remained in storage for future testing. The first test is referred to as Run 1. The initial ss concentration was 337 mg/l and settleable solids after one hour were 20 percent of this value. Complete results are presented graphically in Figure 3, Settling Velocity Distribution by weight of Solids in Stormwater Runoff. Figure 3 shows that settling velocities were approximately an order of magnitude below those observed in sanitary sewage. In fact, in Run 1, 78 percent of the solids in the stormwater have settling velocities less than 0.01 cm/sec (0.00033 ft/sec) compared with only 31 percent for sanitary sewage. This indicates that the solids in the sample were probably coarse clays and silt and perhaps not representative of many soil types.

The remaining portion of stormwater runoff was kept at 4° C (39° F) for six days and then tested with the settling column so that the effect of storage could be determined. The testing of this sample is referred to as Run 2. The initial suspended

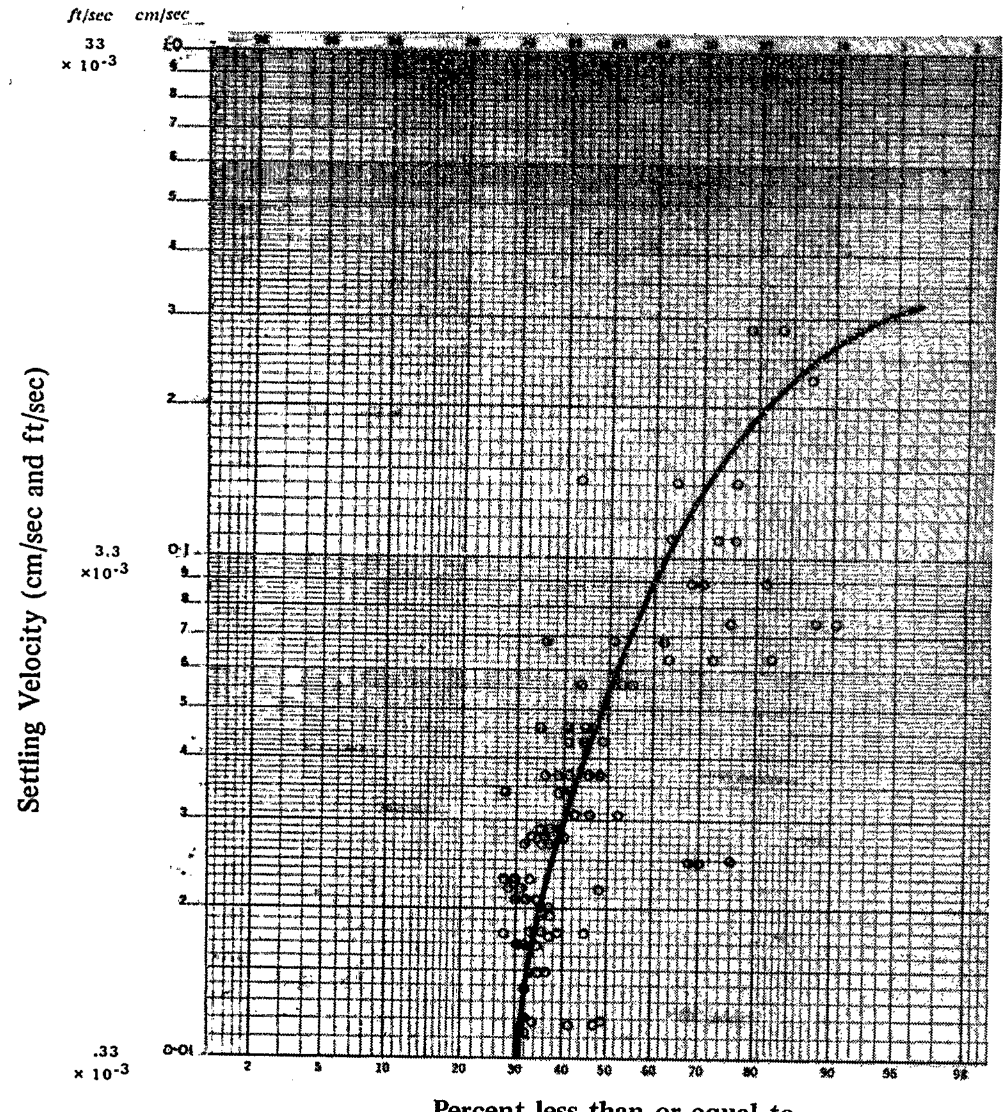

FIGURE 2 SETTLING VELOCITY DISTRIBUTION OF SOLIDS IN SANITARY SEWAGE

solids concentration was 323 mg/l, similar to that in Run 1. However, settleable solids after one hour were only 13 percent of the initial. Surprisingly, as the results for Run 2 indicate in Figure 3, the settling characteristics were improved by *aging* in storage. In Run 2 only 57 percent of the solids in the stormwater had settling velocities less than 0.01 cm/sec (0.00033 ft/sec).

This observation would seem to indicate an error in the measurement of settleable solids for Run 2 since with improved settling characteristics more solids should settle in one hour. The test could not be repeated due to exhaustion of the sample. For both Runs 1 and 2, the sample was tested at its storage temperature. During the test period the temperature rose from 5° C to 12° C (41° F to 54° F). As the samples were obtained in March, a winter month, it was decided to run the test at a low temperature rather than at an indoor ambient temperature.

The improvement in settling characteristics after storage is apparently due

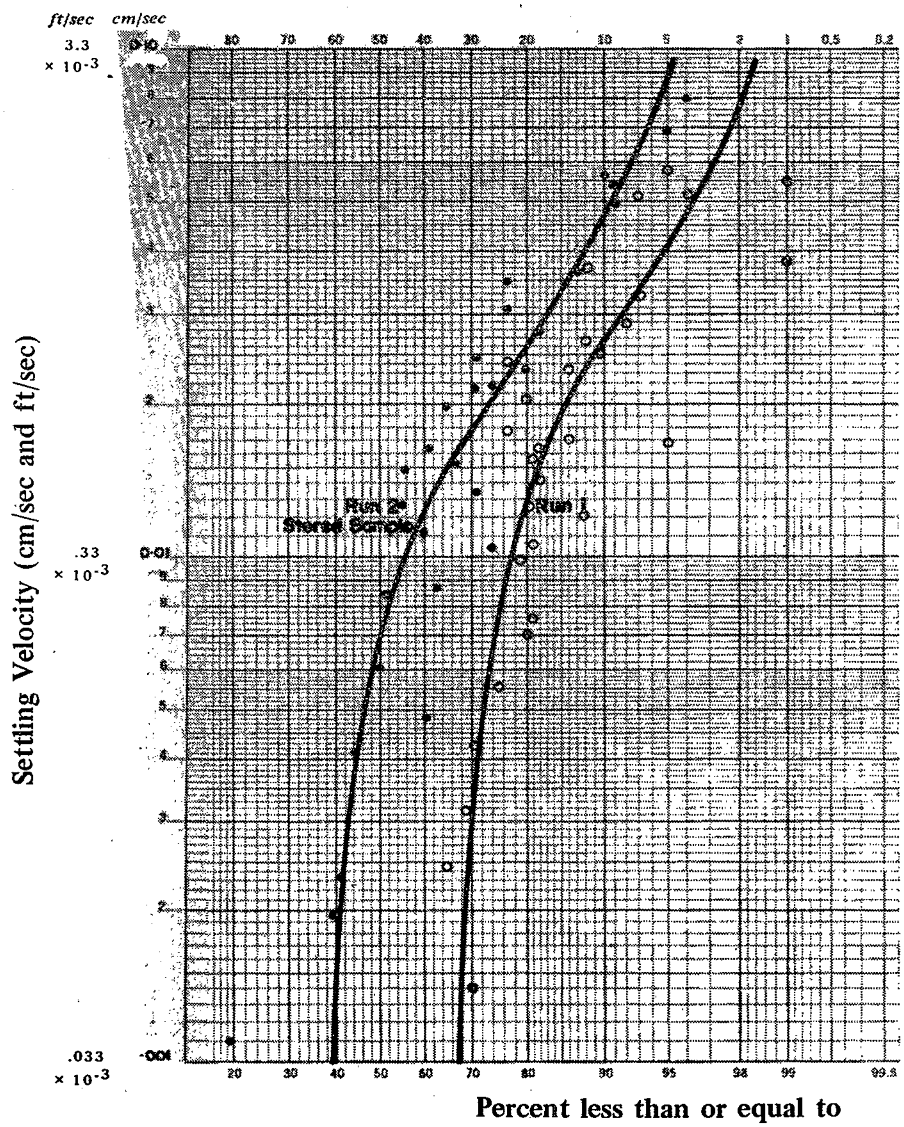

FIGURE 3 SETTLING VELOCITY DISTRIBUTION BY WEIGHT OF SOLIDS IN STORMWATER RUNOFF

to agglomeration of small particles since the agglomeration phenomenon was also observed during one-hour tube settling tests. This observation, although based only on a few settling column tests, does suggest that storage prior to sedimentation may increase the removal rate and hence decrease the concentration of ss in stormwater runoff. Further study appears warranted to precisely define the effects of storage on settling characteristics and to determine the overall feasibility of this form of pretreatment and to determine if inprovement also occurs with combined sewer overflows.

SECTION IV
SIMULATED SEWAGE

MATERIALS USED IN PREVIOUS STUDIES

Several different materials have been used in the past to simulate the ss contained in sewage flows. Investigators have generally used mixtures of different materials in an attempt to simulate grit, fine and coarse ss, bed material and floating or surface solids separately. The properties of these different fractions differ in terms of settling characteristics. The theoretical settling velocity of a material in an aqueous medium is a function of the specific weight of the particles as well as of their size and shape. This function is the familiar Stokes' law relationship, which is shown below for spherical particles. Stokes' law is valid only for particles when the Reynolds number is less than 1.

$$V_s = \frac{D^2 (\gamma_s - \gamma_w)}{18\mu}$$

where:

V_s = fall velocity
D = sphere diameter
γ_s = specific weight of sphere
γ_w = specific weight of fluid
μ = fluid viscosity

In previous studies of simulated materials for use with swirl separators, the size and specific weight of the specific fraction of solids in sewage was estimated and the settling velocity calculated. Then the scale factor of the model that was being tested was applied to determine the required size and specific weight of the test materials to be used to simulate the sewage solids. From this size and specific weight, a settling velocity was calculated. Knowing the size and specific weight desired enabled researchers to select a material with properties close to those required. As will be discussed later, Beak chose to approach the simulation problem from a different point of view.

Smisson[26] used a specifically prepared mixture of hardwood sawdust for the ss, and perspex filings for the floatables. The mixture had a specific gravity of 1.19, with individual particles being fibrous in shape. Equivalent sphere sizes ranged from 200 to 600 microns, with theoretical settling velocities ranging from 0.25 to 0.75 cm/sec (0.1 to 0.3 in/sec). Prus-Chacinski and Wielgorski[27] also used perspex shavings to simulate the surface or floatable material. However, a mixture of graduated coal dust (100 to 1,000-micron particle size range) and polystyrene 0.16 to 0.32 cm (1/16 to 1/8-inch) diameter and average relative density 1.05 was used to simulate, respectively, the bed material and suspended load.

Ackers, Harrison and Brewer[28] likewise used a mixture of three materials to represent grit, coarse ss and floating solids. Bakelite particles of specific gravity 1.42 and about 500 microns diameter were used to simulate grit. The size and specific gravity of the coarser fraction of solids were assumed to be 2.54 cm (one inch) in diameter and 1.005. respectively. Particles of this size and specific gravity were determined to have a settling velocity of 6.1 cm/sec (0.2 ft/sec). The model scale was applied and the desirable settling velocity of the test material was determined to be 1.77 cm/sec (0.058 ft/sec). Polystyrene particles 1,250 microns in size, with a settling velocity of 1.98 cm/sec (0.065 ft/sec), were used. Following a similar method of assumption, the desirable rise velocity of the floatables in the model work was calculated to be 1.77 cm/sec (0.058 ft/sec). Polythene particles 2,000 microns in size, with a calculated rise velocity of 2.13 cm/sec (0.07 ft/sec) were selected for use in that study.

Other materials which have been used to simulate the solids fraction of sewage include repulped newspaper, nylon thread, asbestos fibers, calcium carbonate floc, river silts, coarse clays, polyethylene beads and size-classified road dust. Beak examined many of these materials for their applicability as simulated sewage solids, but only polystyrene beads, a shredded polyethylene material and size-classified road dust (Arizona Road Dust) were selected for further study.

DESCRIPTION AND RESULTS OF STUDY

Settling velocity data from Beak's Philadelphia study of raw sanitary sewage provided the basis for consideration of simulated sewage materials. The median settling velocity of primary sewage was determined to be 0.054 cm/sec (.002 ft/sec). Before the settling velocities determined could be applied to the selection of a material to simulate the solids load, the scale factor of the swirl concentrator model developed by LaSalle Hydraulic Laboratory had to be taken into consideration. The model work was done with Froude number scaling, and as a result, settling velocity of sewage must be reduced by the square root of the model scale factor. In this way, removal efficiencies in the one-twelfth scale model should be comparable to removal efficiencies using actual sewage in the full-scale prototype.

The distribution of settling velocities was altered by multiplying the settling velocity at each percentage by $1/\sqrt{12}$, since the scale factor of the model is 12. This new frequency distribution, shown in Figure 4, Settling Velocity Distribution of Solids in Sanitary Sewage After Application of Model Scale Factor, represents the desired settling velocity distribution of the *ideal* test material. It was

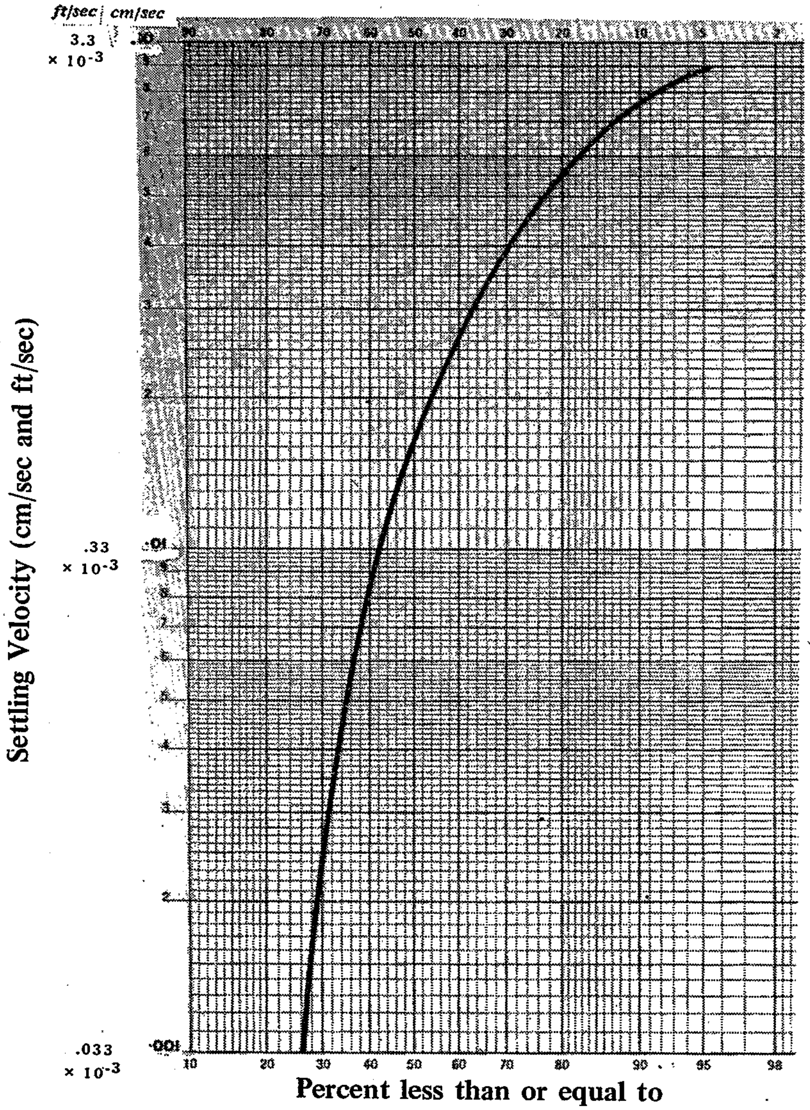

FIGURE 4 SETTLING VELOCITY DISTRIBUTION OF SOLIDS IN SANITARY SEWAGE AFTER APPLICATION OF MODEL SCALE FACTOR

observed that the required median settling velocity range is 0.016 – 0.02 cm/sec (.0005-.0007 ft/sec).

Having established this range of settling velocity, numerous materials were evaluated for suitability as simulated sewage solids with terminal settling velocities in the desired range. Where particle size permitted, each simulated sewage material was examined for the relationship between settling velocity and particle size by the use of tube settling tests. In this test, individual particles were sized and settling time over a known tube depth was measured. These screening tests, when performed in replicate, provided a basis for the selection of the particle size range required for each prospective simulated solid. Other factors considered during selection of solid materials included cost, availability and uniformity of particle characteristics.

Table 7, Physical Characteristics of Simulated Sewage Materials, presents information regarding materials given consideration as simulated sewage solids. Several materials, including IRA-93, IRA-401, XAD-2, DOWEX 21K resins and shredded Petrothene were examined as they were received by Beak, i.e. in large particle sizes. The IRA-401 and DOWEX 21K are gel-type resins and are easily broken into irregularly shaped pieces. Particle uniformity was one of the selection factors and due to this physical instability, these resins were eliminated from further consideration. The remaining resins, IRA-93 and XAD-2, are macro-reticular-type resins which are physically more stable. IRA-93 resin is a polystyrene based copolymer which is extremely stable both chemically and physically. The manufacturer states that in aqueous medium the resin is

TABLE 7
PHYSICAL CHARACTERISTICS OF SIMULATED SEWAGE MATERIALS

Material	Manufacturer	Type	Specific Gravity	Size Range (Microns)	Settling Velocity Range (cm/sec)
Amberlite Anion Exchange Resin	Rohm and Haas	IRA-93	1.04	200-1,000	0.15-1.5
				149-297	<0.02:2% 0.02-0.1:42% > 0.1:56%
				74-149	<0.01:24% 0.01-0.05:53% >0.05:23%
				38-74	>0.01:68% 0.01-0.05 :30% >0.05:2%
		IRA-401	1.06	300-1,400	0.2-2.4
Non-ionic Resin	Rohm and Haas	XAD-2	1.03	200-1,000	0.1-1.0
Dowex Anion Exchange Resin	Dow Chemical	21K	1.06	200-1,000	0.15-2.0
Arizona Road Dust	Donaldson Co.,Inc. Minneapolis, Mn.		2.65	10-20	<0.01:18% 0.01-0.05 :77% > 0.05:5%
Petrothene X101	U.S. Industrial Chemicals	Shredded	1.01	700-3,000	0.3-1.7
		Dust	1.01	100-1,000	< 0.01 :11% 0.01-0.05 :20% > 0.05 :69%

electrically neutral and therefore should not be electrically attracted to the swirl concentrator model construction material. The resin absorbs moisture from the dry to the wet state rapidly. Laboratory tests have indicated an immeasurable amount of swelling as the resin becomes wet. In addition, swelling due to ion exchange should be negligible at the neutral pH of the hydraulic model test water. Swelling of about 20 percent maximum may occur within five minutes.

Figure 5, Settling Velocity vs. Particle Size for IRA-93 Exchange Resin and Figure 6, Settling Velocity vs Particle Size for XAD-2 Non-Ionic Resin, show the results of tube settling tests of individual particles.

Both resins were tested in their commercially available particle size range. The shredded Petrothene, also physically stable, was likewise tested for settling rate as a function of particle size. The results are shown in Figure 7, Settling Velocity vs.

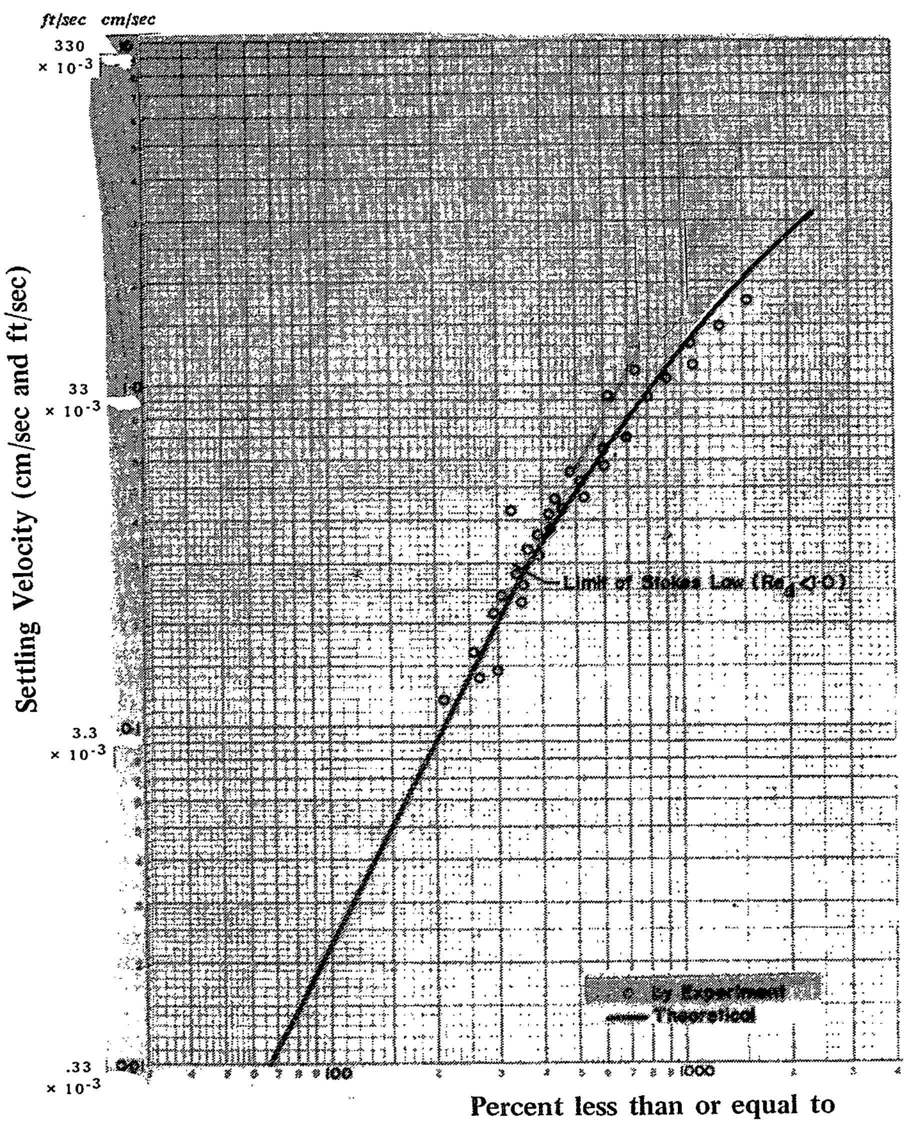

FIGURE 5 SETTLING VELOCITY VS PARTICLE SIZE FOR IRA-93 ANION EXCHANGE RESIN

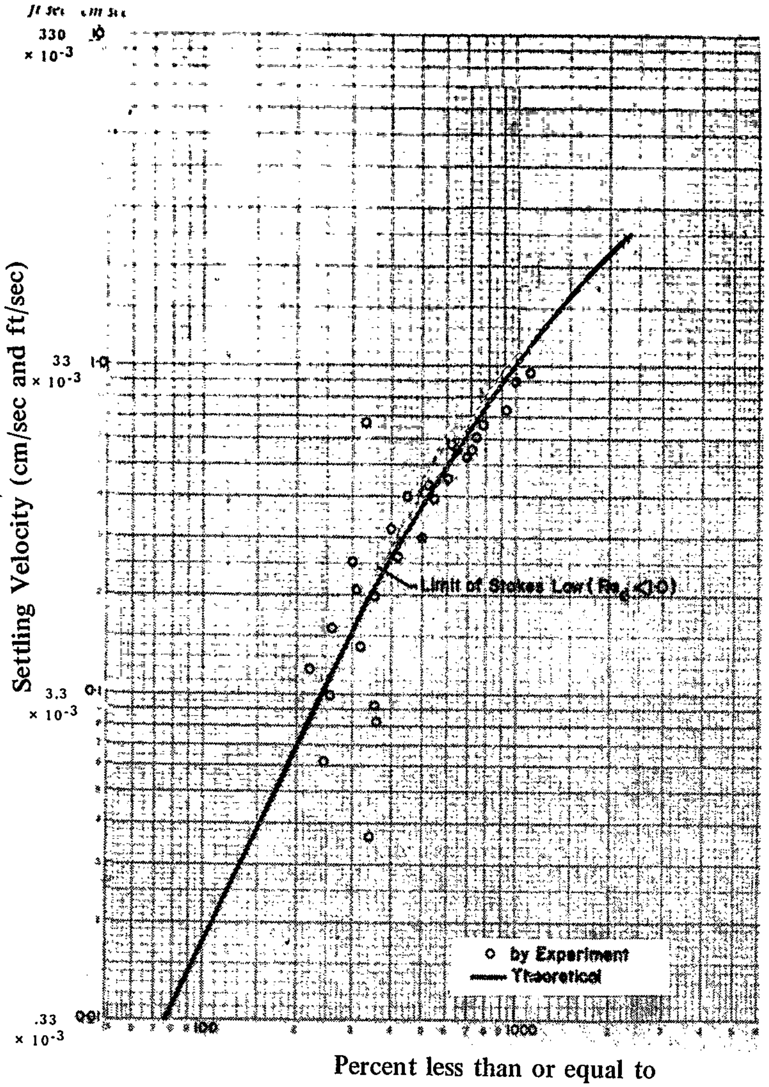

FIGURE 6 SETTLING VELOCITY VS PARTICLE SIZE FOR XAD-1 NON-IONIC RESIN

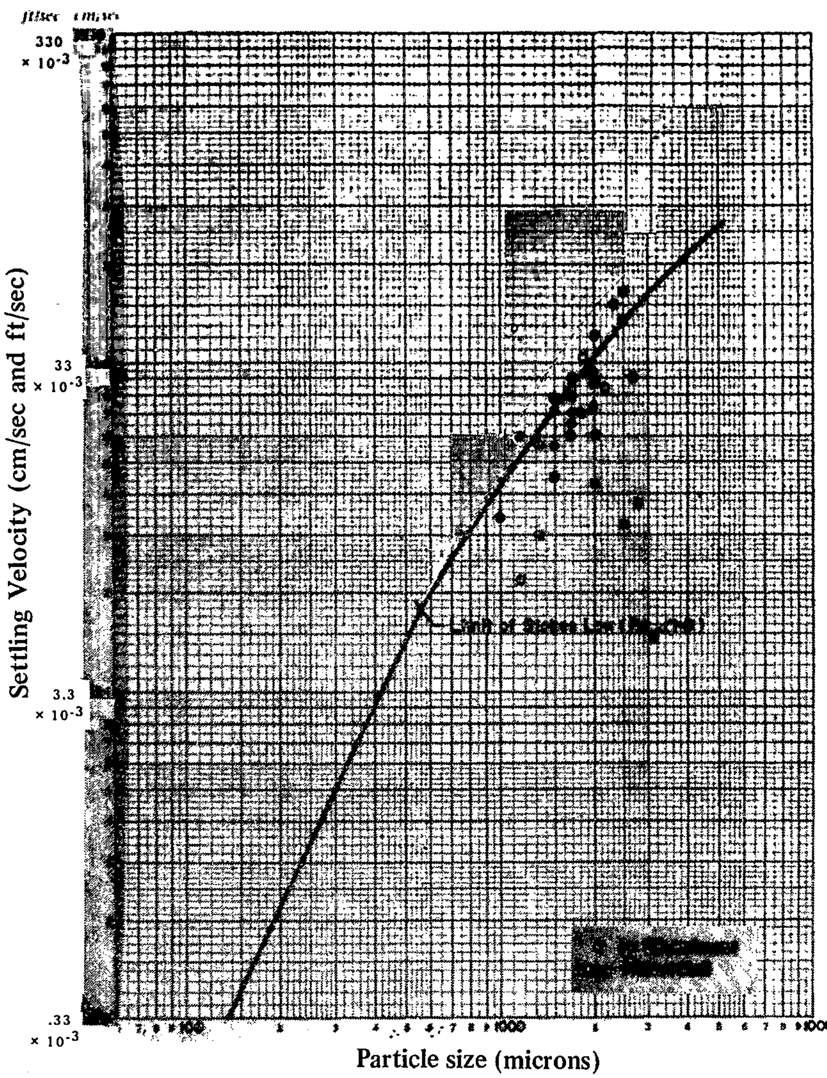

FIGURE 7 SETTLING VELOCITY VS PARTICLE SIZE FOR SHREDDED PETROTHENE X-101

Particle Size for Shredded Petrothene – X-101. In each figure, the ideal Stokes' law relationship between particle size and settling velocity for spherical shaped particles is included. For the spherically shaped resins, the experimental points are in close agreement with theory. However, there is more scatter and less agreement for shredded Petrothene. Experimental settling velocities are less than those predicted by theory. This is due to the irregular shape of the shredded particles, which results in an increased drag force. It was obvious from these figures that a much smaller particle size was necessary to obtain settling velocities in the desired range.

This posed the problem of determining a method of reducing the size of the particulates. At this point it was necessary to rule out further study with XAD-2 non-ionic resin. Amberlite IRA-93 was selected for particle size reduction due to the results of tube settling tests presented in Figure 5 and its cost advantage over XAD-2. IRA-93 costs \$85 per cubic foot wheres XAD-2 costs \$92 per cubic foot. Extrapolation of the ideal Stokes' law line shown in Figure 5 indicated that the particle size range required to give settling velocities in the range 0.016-0.02 cm/sec(0.04-0.05 in/sec) was 80-100 microns. Pulverization of the IRA-93 resin was established as the practical means of obtaining the desired particle sizes. The resin was pulverized with a rotary mill pulverizer by a Toronto laboratory. It was decided to test the pulverized resin in three size ranges – 50-100 mesh (149-297 microns); 100-200 mesh (74-149 microns); and 200-400 mesh (38-74 microns) – so that the theoretical range would be well bracketed to allow for possible non-ideal behavior. As a result of pulverization, the particles in these three size ranges are non-spherical in shape.

Pulverizing could not be used for Petrothene, however, since the heat evolved in the pulverizing step is sufficient to melt the plastic material. Fortunately, a by-product of the shredding operation was available for use. Petrothene is commercially available in approximately 4 mm cubical pieces. LaSalle Hydraulic Laboratories had this larger material shredded to obtain the smaller size shredded Petrothene. The Petrothene dust, a by-product of shredding, has much smaller particles than the shredded fraction.

The ideal Stokes' law line shown in Figure 7 predicted that particle sizes in the range 170 to 200 microns would be required for settling velocities in the range 0.016 to 0.02 cm/sec (0.04-0.05 in/sec).

However, indications were that the irregular shape of the Petrothene dust particles resulted in lower settling velocities than theory predicted. This meant that the ideal theoretical size range might have provided lower settling velocities than those desired. Thus it was decided to continue settling studies on Petrothene dust in a mixture of several size ranges below 1,000 microns in particle size to provide, as for IRA-93, a large bracketing for non-ideal behavior.

A third material in the desired settling velocity range was obtained. This was the specially size-classified Arizona Road Dust. Settling velocity distributions for each size fraction were available from a member of the project team, General Electric in Philadelphia, Pa. From these curves, a size range 10 to 20 microns was selected for study by Beak. This material is very expensive at \$100 per pound and therefore only the one size range was studied.

SETTLING COLUMN STUDIES

As a result of screening tests, three materials were selected for further settling velocity analysis. These were the ground IRA-93 in three size ranges; the Petrothene dust; and the 10-20 micron-size Arizona Road Dust. The settling column tests were used because tube settling of individual particles was not practical at the small sizes involved. All materials tested in the settling column were tested at an initial concentration of approximately 200 mg/l.

Amberlite, IRA-93

A settling velocity distribution curve for each size range tested was prepared. Figure 8, Settling Velocity Distribution for 50-100 Mesh IRA-93, 149-297 microns, indicates that this size range is too small. The median settling velocity is 0.1 cm/sec (.003 ft/sec), which is greater than that required for simulation. These results are also in close agreement with theory.

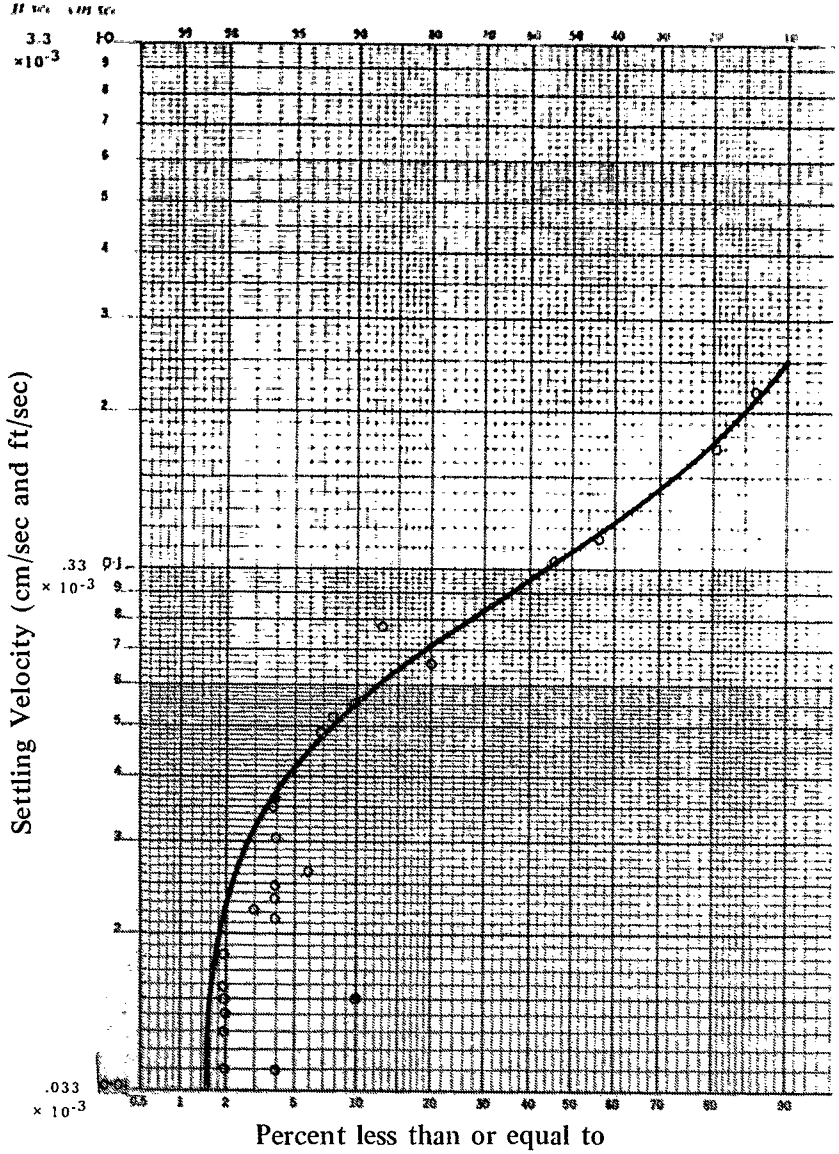

FIGURE 8 SETTLING VELOCITY DISTRIBUTION FOR 50-100 MESH IRA-93, 149-297 MICRONS

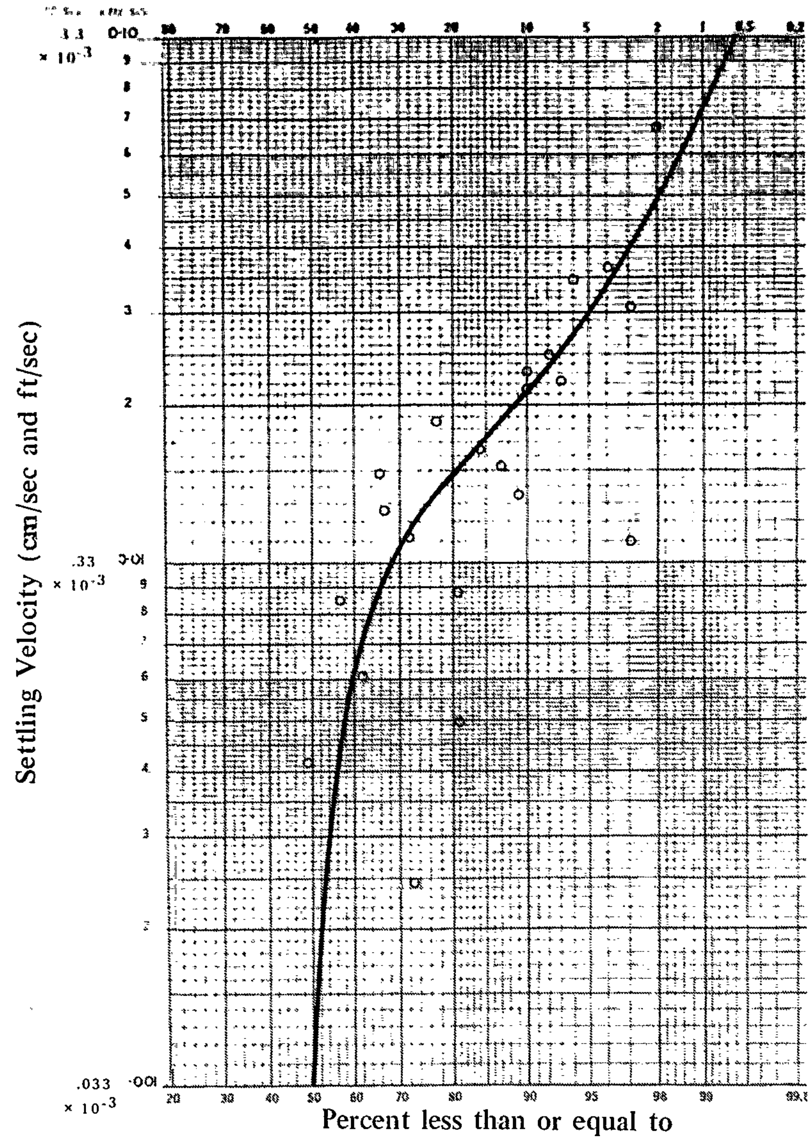

FIGURE 9 SETTLING VELOCITY DISTRIBUTION FOR 200-400 MESH IRA-93, 38-74 MICRONS

Figure 9, Settling Velocity Distribution for 200-400 Mesh IRA-93, 38-74 microns, indicates that this size range is too small. The median settling velocity is 0.001 cm/sec (0.0004 in/sec), which is lower than that required for simulation. These results are also in close agreement with theory.

Figure 10, Settling Velocity Distribution for 100-200 Mesh IRA-93, 74-149 microns, indicated that this material was in the desired range. The median settling velocity for the three runs varied from 0.0215 to 0.037 cm/sec (.0007-.0012 ft/sec), which was slightly higher than the ideal requirement of 0.016 cm/sec (.0005 ft/sec). The range of settling velocities observed was in close agreement with that predicted by Stokes' law for spherical particles of 1.04 specific gravity. This theoretical range is 0.012 to 0.05 cm/sec (.0004-.002 ft/sec). The pulverized IRA-93 resin appeared to behave according to Stokes' law and therefore would lend itself readily to mathematical modeling of the settling characteristics of the swirl separator.

The difference between the three batches was due to the fact that the material tested in each case was the product of a different sieving and pulverizing batch. The sieving was done manually. This indicated the need to regulate the pulverizing and sieving procedure so that the same material could be obtained in each batch.

A procedure for pulverizing and sieving the IRA-93 resin was developed in order to produce a consistently uniform sample. A detailed description of this procedure is included in Appendix B.

The study of simulated sewage solids resulted in the selection of Amberlite IRA-93 resin, 100-200 mesh particle size range, as the material with which to monitor the efficiency of the swirl concentrator model developed by the LaSalle Hydraulic Laboratory. Figure 11, Efficiency Monitoring Material, IRA-93, 74-149 Microns; and 12, Efficiency Monitoring Material, IRA-93, 74-149 Microns, Wet Sieved; present settling velocity distribution curves for two typical samples of IRA-93 used in the swirl concentrator monitoring program. The sample shown in Figure 12 was wet sieved to provide a comparison to the dry-sieving procedure previously mentioned. The median settling velocity for the wet-sieved resin is slightly higher than for the dry-sieved material, indicating that wet sieving may have removed a higher percentage of the very fine particles.

Arizona Road Dust

Figure 13, Settling Velocity Distribution for Arizona Road Dust, 10-20 microns, indicates that this material has a median settling velocity of 0.023 cm/sec (0.06 in/sec), which is close to the desired range. This material is also considered to be an excellent material for use as simulated sewage solids but its high cost, $100 per pound, in comparison to that of IRA-93, $85 per cu ft or about $12 per pound, reduces its practical application to the monitoring program in which larger quantities will be required.

Petrothene Dust

Figure 14, Settling Velocity Distribution for Petrothene Dust (<1,000 microns), indicates that settling velocities obtained were not in the desired range. Problems were encountered in wetting the surface of particles of this size so that they would not float on the surface of the water. The smaller the particles, the more difficult this procedure. This test indicated that much smaller particles would be required to obtain the required settling velocities. Particle size analysis of the dust showed that less than 15 percent of the dust would be suitable. This dust is difficult to obtain in quantity, so further work with Petrothene was abandoned.

The overall summary of the study of simulated sewage is presented in Table 7. This table presents results of screening tests and settling column tests conducted on simulated sewage solids.

In addition to the development of a material to simulate sewage solids. Beak designed a program by which solids removal efficiency could be studied on the hydraulic model of the swirl concentrator as a primary settling device. The procedure is described in Appendix C.

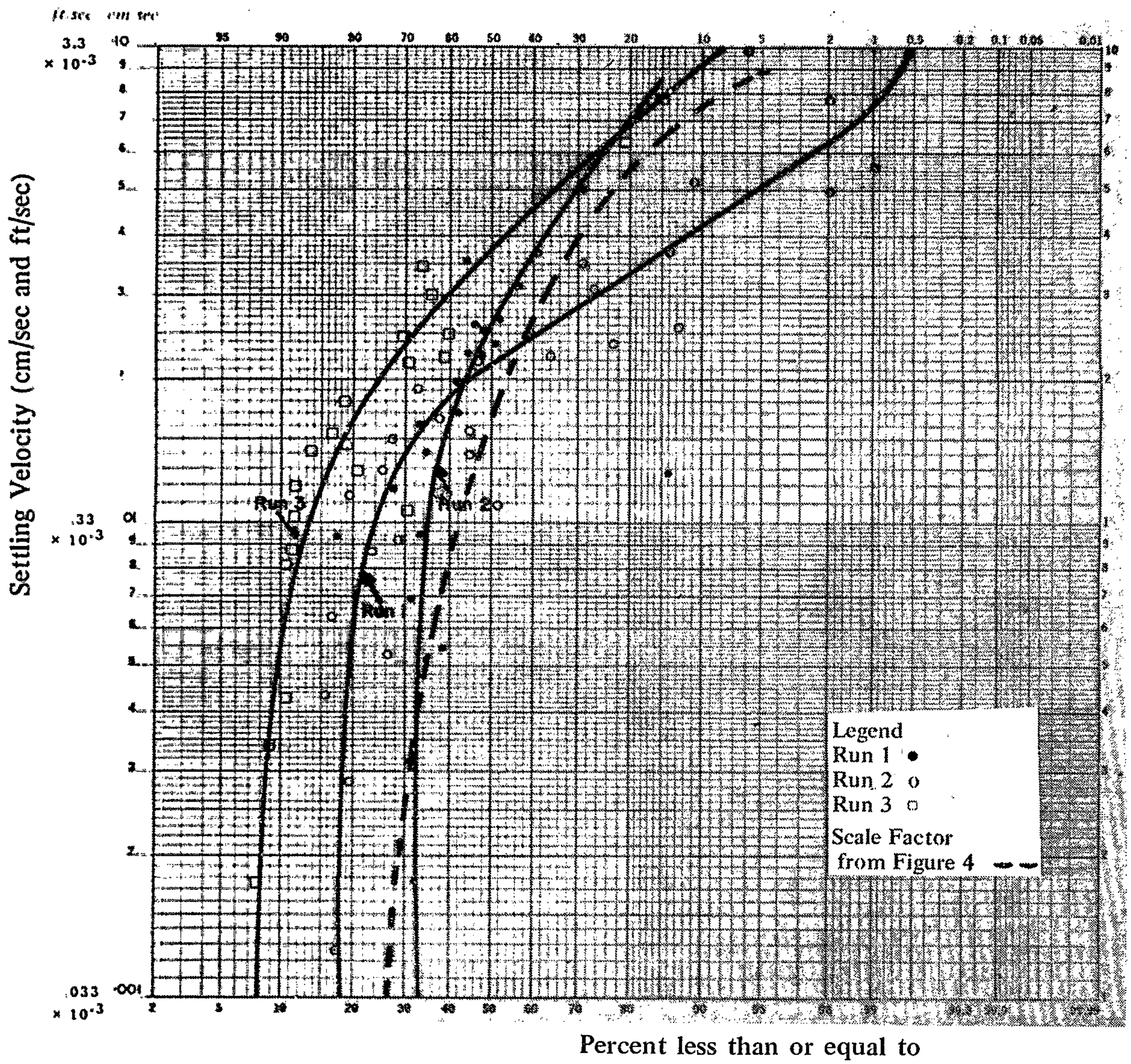

FIGURE 10 SETTLING VELOCITY DISTRIBUTION FOR 50-100 MESH IRA-93, 74-149 MICRONS AND COMPARISON WITH SANITARY SEWAGE (after application of model scale factor)

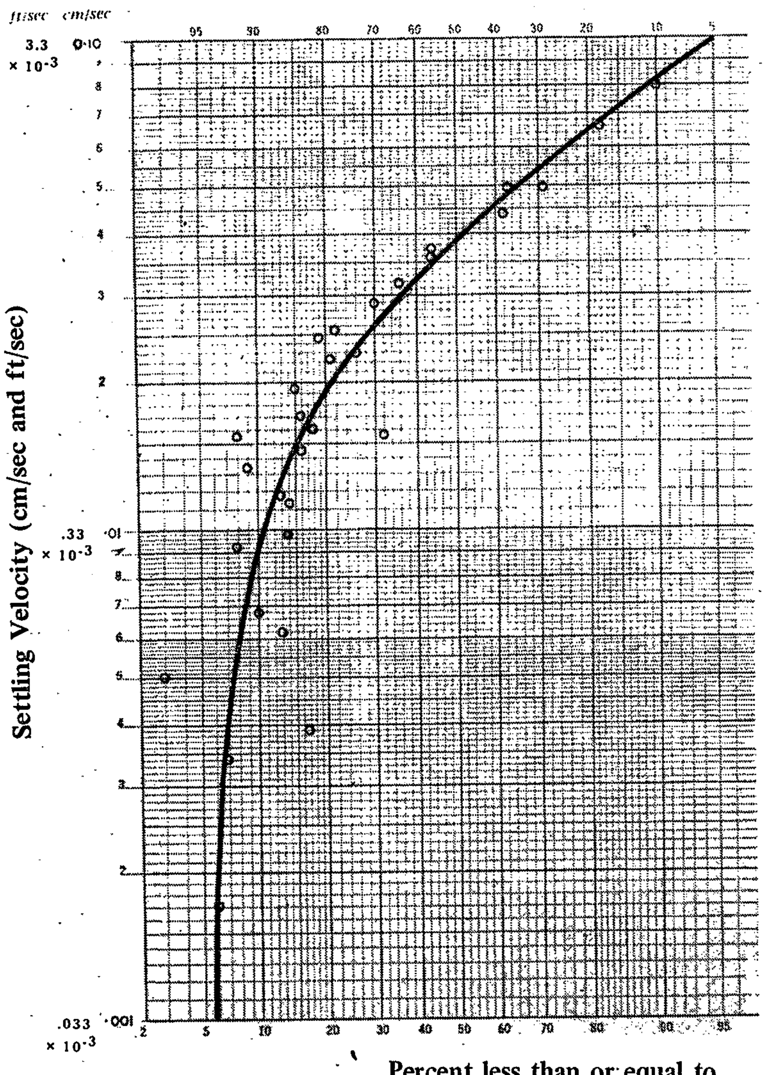

FIGURE 11 EFFICIENCY MONITORING MATERIAL IRA-93, 74-149 MICRONS, Temperatures 24°C to 25.5°C, Sample obtained May 8, 1974

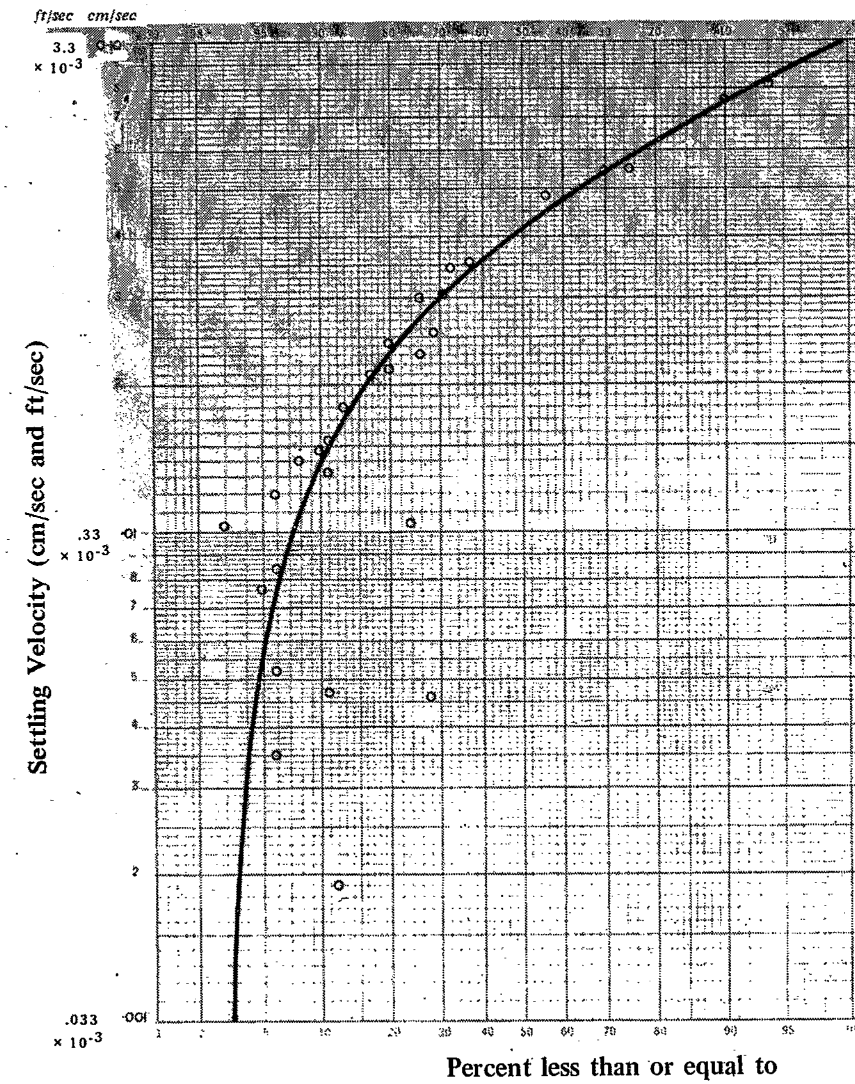

FIGURE 12 EFFICIENCY MONITORING MATERIAL IRA-93, 74-149 MICRONS (Wet Sieved) Temperature 21°C, Sample obtained May 24, 1974

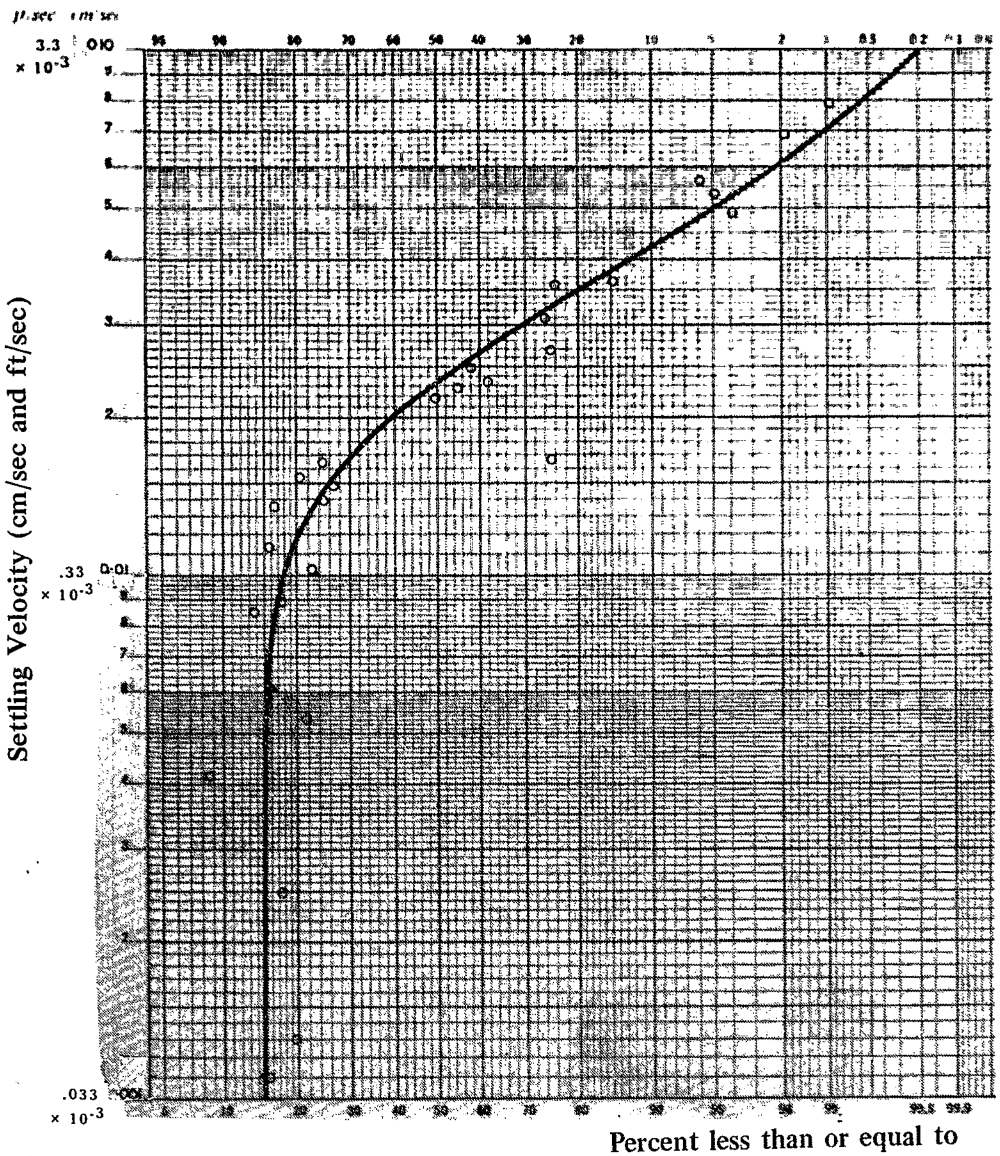

FIGURE 13 SETTLING VELOCITY DISTRIBUTION FOR ARIZONA ROAD DUST (10-20MICRONS)

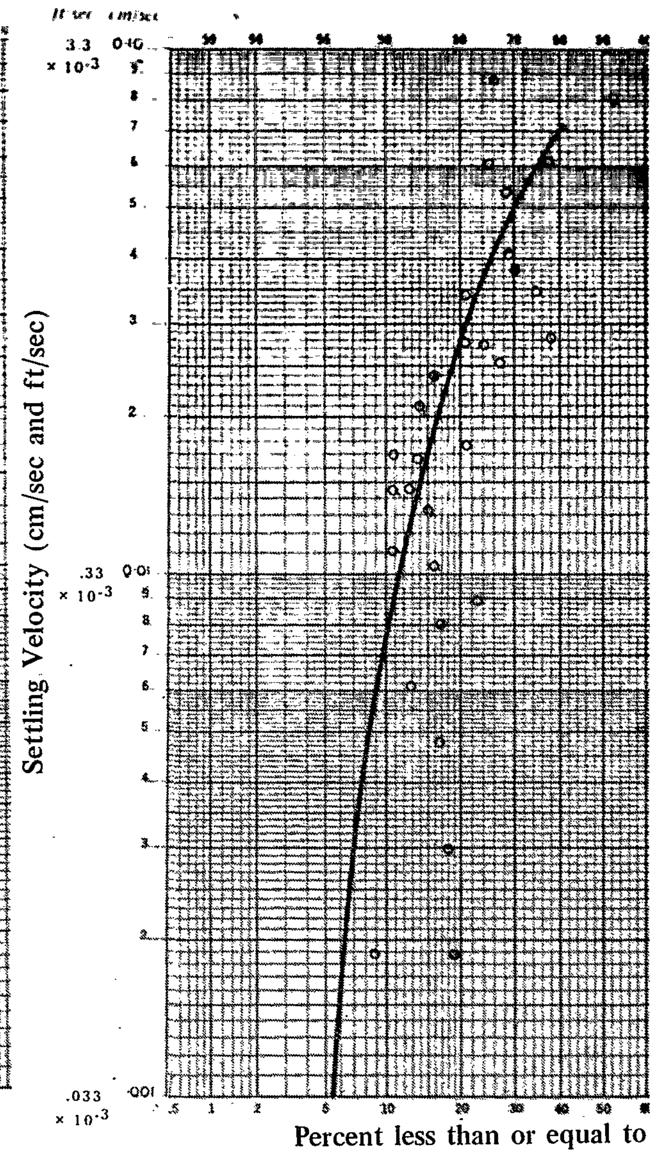

FIGURE 14 SETTLING VELOCITY DISTRIBUTION FOR PETROTHENE DUST (<1000 MICRONS)

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SECTION VI
APPENDIX A
LABORATORY METHODS USED BY BEAK PERSONNEL

SETTLING COLUMN TEST

Procedure

The test column consists of a 6-foot, 8-inch diameter, Plexiglas® cylinder with sampling ports at 1-foot increments. The bottom of the cylinder is fitted with a watertight base, 12-inch diameter, to give a stable base during the test run.

A 15-gallon sample was collected and the settling test run immediately to prevent any changes in the sample. The most important variable was temperature and, where possible, the test should be performed before any great change occurs. In most cases it is not practical (or meaningful) to attempt to adjust the sample temperature to that of the ambient temperature where the test is being performed. The temperature of the sample in the column was recorded at the start and the finish of the test run. The samples were mixed thoroughly and dumped into the test column as quickly as possible. To assure thorough mixing in the column, a handmade plunger was used to agitate the contents throughout the depth of the column. The timer is then started and the column is sampled in sequence within 30 seconds at each port. Starting from the top of the column, the ports sampled are at the 0.305, 0.61, 0.91, 1.22, 1.52. and 1:67 meter levels. (1,2,3,4,5, and 5.5 foot)

These *time zero* samples are averaged to provide the initial ss of the sample in the column. The column is then sampled from each port at convenient time intervals. The time intervals were: 10, 20, 40, 60, 80, and 120 minutes.

The samples withdrawn from each sample port (except the bottom one) were collected in small containers (approximately 500 ml) to be analyzed for ss. Care must be taken to flush out each sample port before the sample is taken. The filter paper used for this analysis was Whitman GF-C® or equivalent.

The depth of liquid in the column should be recorded initially and after each set of samples has been removed. It is more convenient to measure all depths from the top of the column.

The percent settleable solids was determined on the large sample collected for the settling test. This was done by filling a graduated cylinder (1,000 ml) with the sample and allowing the sample to stand for one hour. After 60 minutes a sample is withdrawn from the center of the cylinder for ss determination.

Interpretation of Results

Using the ss results from the above procedure, the percent of initial ss is calculated for each sample. Each sample is associated with a specific port, time and liquid level. The quantity z/t is calculated where z is the distance down the column from the surface of the sample and t is the time at which the sample was taken. This quantity is converted to a settling velocity in cm/sec. Percent of initial ss is then plotted against z/t resulting in a distribution of settling velocities of the ss in the sample. When interpreted by a slightly different method, the percent removal of ss can be evaluated as a function of overflow rate and detention time. This is used for the design of a primary clarifier.

SETTLEABLE SOLIDS (BY WEIGHT)

The settleable solids after one hour quiescent settling analysis was conducted according to Standard Methods, Edition 13,[29] with one change. The glass vessel used had a diameter of 6 cm (2.4 in.) as opposed to the required 9 cm (3.5 in.). The minimum settling depth of 20 cm (7.8 in.) was observed. In all other respects Beak's method was identical to that in Standard Methods.

A study by Happel and Byrne[30] has indicated that wall effects are negligible for settling in columns 6-9 cm (2.4-3.5 in.). The wall effect is given by the expression:

$$\frac{V_D}{V_\infty} = \left[1 - \left(\frac{d}{D}\right)^2\right] \left[1 - 1/2\left(\frac{d}{D}\right)^2\right]^{1/2}$$

where:

V_D = the settling velocity in column of diameter D

V_∞ = the settling velocity in an infinite diameter medium

d = the particle size

For the size of material we investigated it is apparent that $\frac{d}{D}$ is infinitely small and $\frac{V_D}{V}$ is unity when D equals 6 cm.

APPENDIX B
PREPARATION OF AMBERLITE IRA-93 SOLID PARTICLES

Amberlite IRA-93 is an anion exchange resin manufactured by Rohm and Haas, Philadelphia, Pa. IRA-93 is a macroreticular exchange resin that is a crosslinked copolymer based on polystyrene. Preparation of the resin for use in solids removal efficiency evaluations was as follows:

1. The resin was pulverized utilizing an IRL Bleuler R-28 Rotary Mill. This unit is a ring pulverizer with a 125 ml ring container. Tests revealed that a grind time of 1.5 minutes resulted in the greatest quantity of particles in the desired size range.
2. After being pulverized, the resin particles were size classified using U.S. standard sieves and a mechanical shaker. The sieve series employed was 30, 50, 100 and 200 mesh sieves. Sieving time used was 20 minutes. Material retained on 200 mesh was then wet sieved by placing the 200 mesh screen under a flowing water tap for 15 minutes. The purpose of the wet-sieving was to remove the extremely fine particles. The resin solids were then dried and considered ready for use.

APPENDIX C
MONITORING PROCEDURE FOR EFFICIENCY TRIALS

BEAK established a monitoring program to determine the efficiency of the swirl concentrator model in removing suspended solids material. The program was based on the principle of monitoring the steady-state condition. The monitoring of the efficiency trials was performed in the following manner.

1. A premeasured quantity of prepared resin was added to the inlet at specific time intervals depending on the flowrate through the model. The intervals were considered to be short compared to the detention time of the system hence representative of a continuous injection. The samples were added by a premeasured leveled spoon.
2. In order to permit steady-state conditions to develop in the swirl concentrator, a period of time equal to 4 detention times was permitted to lapse before outlet samples were collected. It was determined experimentally that after 4 detention times the overflow concentration approached 98 percent of the final steady state concentrations.
3. The overflow sample was a composite sample of 10 subsamples taken at equal intervals during the steady-state period.
4. The concentration of suspended solids of the overflow composite was measured and compared to the average suspended solids concentration of the inlet after correction for background concentration of the water supply.

The overall program is described in Table 8, Efficiency Trials Monitoring Program Conditions. The percent removal efficiency was calculated as:

$$\% \text{ Removal} = 100\left(1 - \frac{\text{Conc. out}}{\text{Conc. added} - \text{Conc. background}}\right)$$

TABLE 8
EFFICIENCY PROGRAM MONITORING PROGRAM CONDITIONS

Flow Q (1*/sec)	Detention Time t (min)	4 t (min)	Inject One Spoon Every Sec	Sampling Period (min)	Take Sample Every Sec	Amount of Sample (ml)	Number of Samples	Total Sample Volume (ml)
0.1	37.5	150	300	150-240	600	100	10	1,000
0.3	12.5	50	100	50-80	200	100	10	1,000
0.5	7.5	30	60	30-48	120	100	10	1,000
0.75	5.0	20	40	20-32	80	100	10	1,000
1.0	3.75	15	30	15-24	60	100	10	1,000

* 1 spoon of resin weighs 1.13 grams

TECHNICAL REPORT DATA

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1. REPORT NO. EPA-670/2-75-011	2.	3. RECIPIENT'S ACCESSION NO.
4. TITLE AND SUBTITLE PHYSICAL AND SETTLING CHARACTERISTICS OF PARTICULATES IN STORM AND SANITARY WASTEWATERS		5. REPORT DATE April 1975; Issuing Date 6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Robert J. Dalrymple, Stephen L. Hodd, David C. Morin		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS AMERICAN PUBLIC WORKS ASSOCIATION 1313 East 60th Street Chicago, Illinois 60637		10. PROGRAM ELEMENT NO. 1BB034; ROAP 21-ASY; Task 107 11. CONTRACT/~~GRANT~~ NO. 68-03-0272
12. SPONSORING AGENCY NAME AND ADDRESS National Environmental Research Center Office of Research Development U.S. Environmental Protection Agency Cincinnati, Ohio 45268		13. TYPE OF REPORT AND PERIOD COVERED Final 14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

16. ABSTRACT

An investigation was conducted, as part of model studies utilizing a swirl concentrator as a primary separator, helical combined sewer overflow regulator, and related studies, to characterize the properties of solids in sanitary sewage, combined sewer overflows, and stormwater runoff. To effectuate this study, material suitable for monitoring removal efficiencies in hydraulic models of the swirl concentrator unit has been developed.

The approach taken by Beak Consultants, Ltd., serving as a subcontractor to the American Public Works Association in the simulation sewage studies, was to match as closely as possible the settling characteristics of solids in three types of sewage and/or urban runoff with a well-defined, uniform artificial test material. An Amberlite Anion Exchange Resin (IRA-93), when ground and sieved to between 74 and 149 microns, was found to closely simulate the settling characteristics of domestic sewage. This material is of uniform density and appears to react according to Stokes' law for spherical particles at this size range. Arizona Road Dust, between 10 and 20 microns, was found to exhibit a similar settling velocity distribution to that of the colloidal (or semi-colloidal) components of sanitary sewage flow.

Importantly, as background information for the selection of synthesized solids, the settling characteristics (including size and specific gravity distribution) of sanitary sewage, combined sewer overflow and stormwater were determined. These values will be useful for future determinations of physical treatment process design and associated treatability.

This report on these studies recommends that either or both of these materials be used in the scale-model efficiency trials.

This report was submitted in partial fulfillment of Contract 68-03-0272 between the U.S. Environmental Protection Agency and the American Public Works Association entitled *Development of a Swirl Primary Separator and a Helical Combined Sewer Overflow Dual Functioning Regulator and Separator.*

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Regulations Overflows Hydraulic models Combined sewers Waste treatment	Solids separation Overflow quality Particulate size Particulate density Settling velocity	13B

18. DISTRIBUTION STATEMENT RELEASE TO PUBLIC	19. SECURITY CLASS *(This Report)* UNCLASSIFIED	21. NO. OF PAGES 41
	20. SECURITY CLASS *(This page)* UNCLASSIFIED	22. PRICE

☆ U.S. GOVERNMENT PRINTING OFFICE: 1978— 757-140/1385

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