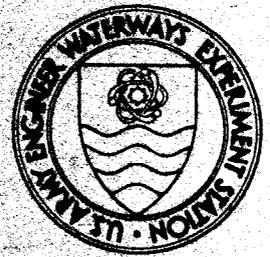


# DREDGED MATERIAL RESEARCH PROGRAM

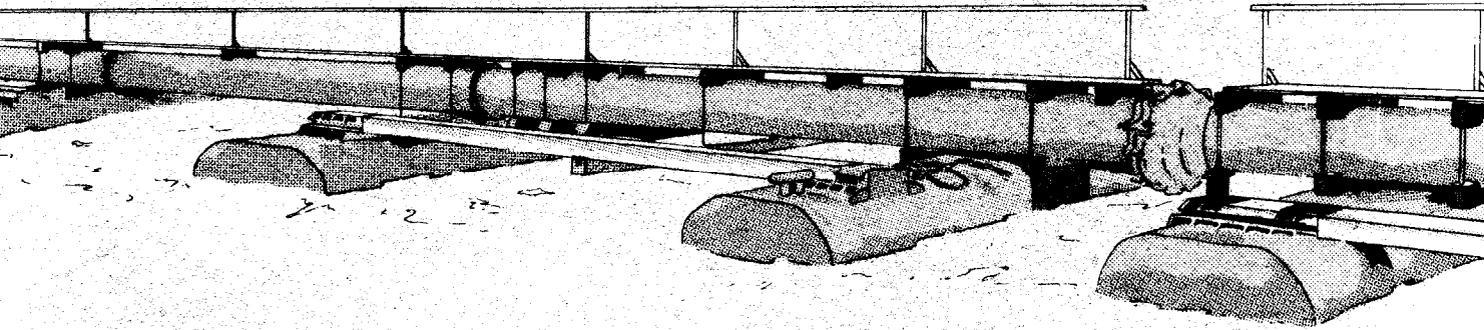


CONTRACT REPORT D-73-1

## FEASIBILITY STUDY OF HYDROCYCLONE SYSTEMS FOR DREDGE OPERATIONS

by

W. G. Tiederman, M. M. Reischman



July 1973

Sponsored by and Prepared for

**U. S. Army Engineer Waterways Experiment Station  
CORPS OF ENGINEERS  
Vicksburg, Mississippi**

Under Contract No. DACW 39-72-C-0050

By Office of Engineering Research, Oklahoma State University, Stillwater, Oklahoma

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED

**Destroy this report when no longer needed. Do not return  
it to the originator.**

**The findings in this report are not to be construed as an official  
Department of the Army position unless so designated  
by other authorized documents.**



DEPARTMENT OF THE ARMY  
WATERWAYS EXPERIMENT STATION, CORPS OF ENGINEERS  
P. O. BOX 631  
VICKSBURG, MISSISSIPPI 39180

IN REPLY REFER TO: WESVS

1 August 1973

SUBJECT: Transmittal of Contract Report D-73-1

TO: All Report Recipients

1. The contract report transmitted herewith represents the results of a feasibility study accomplished under the Corps of Engineers' Dredged Material Research Program. It was undertaken during the problem definition and assessment and research plan formulation phases of the program in order to better define the state-of-the-art and evaluate research needs in this particular subject area.
2. The use of hydrocyclonic devices for liquid-solid separation is well advanced in applications such as laboratory analytical procedures, waste treatment processes, and numerous industrial activities. However, application of the devices to any aspect of dredged material, whether it be for clarification, concentration, or separation, essentially has not been explored in the United States. Hydrocyclones are being used in Europe for separation of dredged sediments; however, their use has not been a high-priority research consideration in this country because of doubt about the economic feasibility of such treatment in terms of the tremendous volumes of material involved in most navigation project-related dredging and disposal activities.
3. The study reported on herein was an attempt to evaluate the efficiency of treatment for various types of dredged materials from differing environments. Six samples of dredged material from such diverse locations as the Pascagoula River (Mobile District), Hillsborough Bay (Jacksonville District), Savannah Harbor (Savannah District), Toledo Harbor (Detroit District), and the Calcasieu River (New Orleans District) were used in the tests. The experimental program was designed to evaluate the degree of clarification, concentration, and fine-coarse particle separation that could be achieved by either a single hydrocyclone or a series of them.
4. Evaluation of system efficiency was conceived as a first step in a possible series of research efforts leading to application of the system in actual field operations. Should the efficiency prove satisfactory,

WESVB

SUBJECT: Transmittal of Contract Report D-73-1

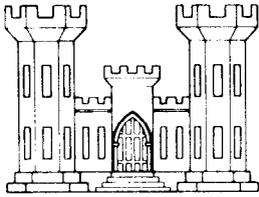
a next step would be investigation of system design and operation for one or more specific applications. These might include treatment of hopper dredge overflow to reduce turbidity, treatment to increase the solids content of material in the hoppers, and treatment of confined disposal area effluent to reduce turbidity.

5. Results of this feasibility study indicate that the clarification and concentration performance of the hydrocyclones was below average to poor on the samples of dredged material tested. There is no reason to suspect that the samples are atypical and that these results are invalid. Consequently, the state-of-the-art of hydrocyclonic separation does not appear to warrant further research aimed at system design for purposes such as those mentioned above. However, the performance of hydrocyclones in separating sand-size particles from finer particles in all samples tested was quite favorable.

6. A distinct possibility exists for the application of hydrocyclonic devices at dredged material disposal sites to classify materials for the recovery of sand or large-size particles which may have value for use as landfill or even construction material. From the standpoint that this could be applicable to Corps of Engineers dredged material disposal problems by extending the life expectancy of disposal areas, this aspect will be considered in further research to be accomplished under the Dredged Material Research Program.



G. H. HILT  
Colonel, Corps of Engineers  
Director



# DREDGED MATERIAL RESEARCH PROGRAM



CONTRACT REPORT D-73-1

## FEASIBILITY STUDY OF HYDROCYCLONE SYSTEMS FOR DREDGE OPERATIONS

by

W. G. Tiederman, M. M. Reischman

July 1973

Sponsored by and Prepared for

**U. S. Army Engineer Waterways Experiment Station  
CORPS OF ENGINEERS  
Vicksburg, Mississippi**

Under Contract No. DACW 39-72-C-0050

By Office of Engineering Research, Oklahoma State University, Stillwater, Oklahoma

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED

## FOREWORD

The work described in this report was performed under contract DACW 39-72-C-0050, titled "Research Study to Investigate the Feasibility of Utilizing Hydrocyclone Systems for Concentrating and Clarifying Dredge Spoil," dated 1 May 1972, between the U. S. Army Engineer Waterways Experiment Station (WES), Vicksburg, Mississippi, and Oklahoma State University. The research was sponsored by the Office, Chief of Engineers (DAEN-CWO-M) under the civil works research program, "Dredged Material Research Program."

This report is a summary of the results of a laboratory investigation whose purpose was to determine the feasibility of using hydrocyclones to clarify, concentrate, and classify dredge spoil.

The research was conducted under the supervision of Dr. W. G. Tiederman, Associate Professor, School of Mechanical and Aerospace Engineering. Mr. M. M. Reischman and Mr. L. A. Maciula assisted in the planning, execution, supervision, and analyses of the experimental program. Students who participated in the laboratory testing were Messrs. John Herod, C. T. Hairfield, Phil Burch, Steve Wegener, David Bogard, Charles Plumlee, David Oldaker, Bruce Fabert and Mike Schneider. Important contributions to the final report were made by L. A. Maciula, John Herod, Phil Burch, and David Oldaker.

The contract was managed by Messrs. R. L. Montgomery and G. N. Bigham under the general supervision of Mr. M. B. Boyd, Office of Dredged Material Research. Contracting Office was COL Ernest D. Peixotto, CE, Director, U. S. Army Engineer Waterways Experiment Station.

# CONTENTS

	Page
<u>FOREWORD</u> . . . . .	iii
<u>LIST OF TABLES</u> . . . . .	viii
<u>LIST OF ILLUSTRATIONS</u> . . . . .	x
<u>NOTATION</u> . . . . .	xiii
<u>SUMMARY</u> . . . . .	xvii
<u>PART I: INTRODUCTION</u> . . . . .	1
THE PROBLEM . . . . .	1
THE PURPOSE . . . . .	2
THE SCOPE . . . . .	3
GENERAL DESCRIPTION OF HYDROCYCLONES . . . . .	4
<u>PART II: CHARACTERIZATION OF DREDGE SPOIL SAMPLES AND CLAY SLURRIES</u> . . . . .	7
MATERIALS . . . . .	7
TEST APPARATUS AND PROCEDURES . . . . .	9
RESULTS . . . . .	21
<u>PART III: HYDROCYCLONE EXPERIMENTS</u> . . . . .	25
I <sub>c</sub> - II <sub>b</sub> HYDROCYCLONE SERIES . . . . .	25
HYDROCYCLONE DEVELOPMENT . . . . .	32
HYDROCYCLONE CLASSIFIER . . . . .	36
OVER-UNDER HYDROCYCLONE SERIES . . . . .	42
CHEMICAL TREATMENT . . . . .	45

## CONTENTS (Continued)

	Page
<u>PART IV: ANALYSIS OF RESULTS</u> . . . . .	49
EFFECT OF PARTICLE SIZE . . . . .	49
EFFECT OF SPECIFIC GRAVITY AND VISCOSITY . . . . .	53
EFFECT OF INLET SOLIDS CONCENTRATION . . . . .	55
EFFECT OF CHEMICAL TREATMENT . . . . .	58
EFFECT OF DRAG-REDUCING ADDITIVES . . . . .	59
<u>PART V: CONCLUSIONS AND RECOMMENDATIONS</u> . . . . .	61
HYDROCYCLONE CLARIFICATION . . . . .	61
HYDROCYCLONE CONCENTRATION . . . . .	62
HYDROCYCLONE CLASSIFICATION . . . . .	62
CHEMICAL TREATMENT . . . . .	63
CHARACTER OF SPOIL . . . . .	63
DRAG REDUCTION . . . . .	64
APPLICATION TO OPERATIONS . . . . .	64
<u>LITERATURE CITED</u> . . . . .	66
<u>ILLUSTRATIONS AND TABLES</u> . . . . .	68
<u>APPENDIX A</u> <u>TABULATION OF RESULTS</u> . . . . .	105
<u>APPENDIX B</u> <u>DETAILED DESCRIPTIONS</u> . . . . .	113
SPOIL LOCATION . . . . .	114
HYDROCYCLONE GEOMETRIES AND CONSTRUCTION . . . . .	121
SPECIFIC GRAVITY PROCEDURE . . . . .	125

## CONTENTS (Continued)

	Page
PARTICLE SIZE PROCEDURE . . . . .	128
HIAC DILUTION PROCEDURE . . . . .	132
<u>APPENDIX C</u> . . . . .	135
SINK-VORTEX CLARIFIER . . . . .	135
SUMMARY TABLES OF THICKENING TESTS . . . . .	141
<u>APPENDIX D THEORETICAL ANALYSES AND</u>	
<u>MATHEMATICAL DERIVATIONS</u> . . . . .	151
CORRECTION TO SUSPENDED SOLIDS MEASUREMENTS . . . . .	151
FLOW RATE CONVERSION . . . . .	153
VISCOMETER EQUATIONS . . . . .	154
DEFINITION OF DRAG REDUCTION . . . . .	157
<u>APPENDIX E DATA SHEET FOR HYDROMETER ANALYSIS</u> . . . . .	159
<u>APPENDIX F SAMPLE CALCULATIONS</u> . . . . .	163
DISSOLVED SOLIDS CORRECTIONS TO SUSPENDED	
SOLIDS DATA . . . . .	164
HYDROCYCLONE SERIES TEST RUN . . . . .	165
SPECIFIC GRAVITY . . . . .	169
PARTICLE SIZE . . . . .	170
VISCOSITY . . . . .	172
PIPE PRESSURE DROP, FLOW RATE AND DRAG	
REDUCTION . . . . .	174
CENTRIFUGE TESTS . . . . .	176

## LIST OF TABLES

Table	Title	Page
1	Solids Concentration, Specific Gravity, and Conductivity . . . . .	75
2	Summary of the Clarification Achieved with a Laboratory Centrifuge . . . . .	90
3	Performance Summary of the I <sub>c</sub> - II <sub>b</sub> Hydrocyclone Series . . . . .	94
4	Comparison of the Clarification Effectiveness of Hydrocyclones Operating on Dispersed and Non-Dispersed Clay Slurries . . . . .	95
5	Comparison of Hydrocyclone Performance on Mobile Spoil and PRC Slurries . . . . .	96
6	Summary of Results with the Hydrocyclone Classifier Model I <sub>f</sub> . . . . .	100
7	Summary of the Clarification and Concentration Effectiveness of the Over-Under Series . . . . .	102
8	Comparison of Hydrocyclone Performance with and Without Chemical Treatment . . . . .	104
A. 1	Separation Results for the I <sub>c</sub> - II <sub>b</sub> Hydrocyclone Series . . . . .	106
A. 2	Separation Results for Hydrocyclone Development . . . . .	107
A. 3	Separation Results for the Hydrocyclone Classifier . . . . .	110
A. 4	Separation Results for the Over-Under Series . . . . .	111
A. 5	Pipe Flow Data . . . . .	112
B. 1	Flow Dimensions of 10 GPM Hydrocyclone Separators . . . . .	122
C. 1	Thickening Test Results with Mobile Spoil . . . . .	141
C. 2	Thickening Test Results with 10% Mobile Spoil . . . . .	142
C. 3	Thickening Test Results with 5% Mobile Spoil . . . . .	143

LIST OF TABLES (Continued)

Table	Title	Page
C. 4	Thickening Test Results with Tampa Spoil . . . . .	144
C. 5	Thickening Test Results with Lake Charles Spoil . . . . .	145
C. 6	Thickening Test Results with Toledo OF Spoil . . . . .	147
C. 7	Thickening Test Results with Toledo DE Spoil . . . . .	148
C. 8	Thickening Test Results with Savannah Spoil . . . . .	149

LIST OF ILLUSTRATIONS

Fig.	Title	Page
1.	Open underflow hydrocyclone . . . . .	69
2.	Conventional series of hydrocyclones . . . . .	70
3.	Sample location map . . . . .	71
4.	Toledo DE debris . . . . .	72
5.	Schematic of conductivity apparatus . . . . .	72
6.	Comparison of spoils and clay slurries after one month of gravity clarification . . . . .	73
7.	Pipe flow apparatus . . . . .	74
8.	Particle size distribution of RMGC . . . . .	76
9.	Particle size distribution of PRC . . . . .	77
10.	Particle size distribution of Mobile spoil . . . . .	78
11.	Particle size distribution of Tampa spoil . . . . .	79
12.	Particle size distribution of Lake Charles spoil . . . . .	80
13.	Particle size distribution of Toledo OF spoil . . . . .	81
14.	Particle size distribution of Toledo DE spoil . . . . .	82
15.	Particle size distribution of Savannah spoil . . . . .	83
16.	Effect of shear rate and dilution on the viscosity of Mobile spoil . . . . .	84
17.	Effect of shear rate, dilution, and polymer additives on the viscosity of Savannah spoil . . . . .	85
18.	Effect of shear rate on the viscosity of Tampa and Lake Charles spoil . . . . .	86
19.	Effect of shear rate on the viscosity of Toledo OF and Toledo DE spoil . . . . .	87

LIST OF ILLUSTRATIONS (Continued)

Fig.	Title	Page
20.	Pipe flow results for Lake Charles spoil . . . . .	88
21.	Pipe flow and drag-reduction results for Savannah spoil . . . . .	89
22.	Schematic of the I <sub>c</sub> -II <sub>b</sub> hydrocyclone series test stand .	91
23.	I <sub>c</sub> -II <sub>b</sub> hydrocyclone series test stand . . . . .	92
24.	Internal view of the 90 gallon reservoir with mixer and baffles . . . . .	93
25.	Mixing of spoil prior to transfer from shipping barrel .	93
26.	Effect of RMGC inlet solids concentration upon C <sub>N</sub> for the I <sub>c</sub> and II <sub>b</sub> hydrocyclones . . . . .	97
27.	Effect of RMGC inlet solids concentration upon C <sub>I</sub> for the I <sub>c</sub> and II <sub>b</sub> hydrocyclones . . . . .	97
28.	Schematic of the classifier test stand . . . . .	98
29.	Effect of particle size upon the separation effectiveness of the I <sub>f</sub> classifier . . . . .	99
30.	Schematic of the "over-under" series test stand . . . . .	101
31.	Illustration of thickening test using RMGC . . . . .	103
B. 1	Mobile dredge spoil sample location . . . . .	116
B. 2	Tampa Bay dredge spoil sample location . . . . .	117
B. 3	Lake Charles dredge spoil sample location . . . . .	118
B. 4	Toledo dredge spoil sample locations . . . . .	119
B. 5	Savannah dredge spoil sample location . . . . .	120
B. 6	Detailed view of model I <sub>c</sub> hydrocyclone . . . . .	123
B. 7	Exploded view of model II <sub>b</sub> hydrocyclone . . . . .	124

LIST OF ILLUSTRATIONS (Continued)

Fig.	Title	Page
C.1	Schematic of sink-vortex clarifier test stand . . . . .	136
D.1	Fann viscometer concentric cylinder arrangement . . .	155

## NOTATION

### English

$C_N$	= clarification number
$C_I$	= concentration index
$D$	= diameter, inches
$d$	= particle diameter, micrometers
$d_{50}$	= particle size separated with 50% effectiveness, micrometers
$E$	= centrifugal efficiency
$G$	= gravimetric concentration, $g/l$
$G_s$	= specific gravity of solids
$G_T$	= specific gravity of distilled water
Hz	= Hertz (cycle per second)
$L$	= axial length of hydrocyclone, inches
$L_V$	= length of vortex finder, inches
$M$	= mass flow rate, $lb_m/min$
$P$	= pressure, psi
$\Delta P$	= pressure drop, psi or inches of water
$Q$	= volumetric flow rate, GPM
$r_H$	= hydrometer reading
$r_c$	= hydrometer control reading
$R, R_1, R_2$	= resistance, ohms
$R_H$	= $R_H = (r_H - r_c) \times 10^3$
$S$	= conductivity, $(ohm-cm^{-1})$
$T$	= temperature, $^{\circ}C$
$V$	= volume, $l$ or $ml$

$V_t$  = tangential velocity  
 $W_s$  = weight of solids, g

#### Greek

$\alpha$  = hydrocyclone conical section half angle, degrees  
 $\rho$  = density  
 $\mu$  = viscosity, centipoise  
 $\gamma_c$  = specific gravity of spoil supernate  
 $\mu m$  = micrometers  
 $\tau$  = shearing stress, psi

#### Subscripts

c = cylinder  
ds = dissolved solids  
i = inlet  
o = overflow  
s = system  
ss = suspended solids  
u = underflow

#### Abbreviations

ACFTD - AC Fine test dust  
ASTM - American Society for Testing & Materials  
GPM - gallons per minute  
HP - horsepower  
ID - internal diameter  
OD - outer diameter  
PRC - Permian Red Clay

PVC - polyvinyl chloride  
rcf - relative centrifugal force  
RMGC - Roger Mills Gray Clay  
RPM - revolutions per minute  
wppm - parts per million by weight

## SUMMARY

A major difficulty with dredge spoil is that in most dredging operations small suspended solids become well dispersed in the large volumes of water used to hydraulically transport the solids from the bottom of the waterway. Frequently it is not efficient to transport this entire volume of water to a disposal site and yet in many cases it is also undesirable to return the turbid water to the waterway. However, even when the entire volume of spoil is transported to a disposal site, an overflow of turbid water can occur from the disposal site, particularly when the site is small or almost full. Consequently, the development of processes which will clarify the water and concentrate the small suspended solids in dredge spoil would make transport of spoil more efficient, would make the use of smaller disposal sites possible and would decrease the environmental impact of dredge operations.

The purpose of this study was to experimentally determine the feasibility of using hydrocyclone separators for the concentration and clarification of dredge spoil. Since hydrocyclones are also well suited for the task of separating solids into fractions, the feasibility of using hydrocyclones for the recovery of sand and gravel while rejecting fine silt was also investigated.

The experimental program was conducted with hydrocyclones and hydrocyclone series designed for overflow flow rates of about 10 gallons per minute. Six dredge spoil samples (supplied by the Corps of Engineers), two clay slurries and one sand were used to determine the effect of particle size, viscosity of the fluid, and inlet solids concentration upon the effectiveness of the hydrocyclones. Attempts were

also made to increase performance by chemically flocculating the solids upstream of the separators.

While the clarification and concentration performance of the hydrocyclones was good on low solids content clay slurries, the performance ranged from below average to poor on the spoil samples. The poor capability of the separators to clarify and to concentrate these spoils was due to the combination of high solids content, small particle sizes and highly pseudoplastic (high viscosity) behavior of the spoils. Centrifugation and chemical treatment were not effective on the higher solids content (greater than 100 g/l) spoils either. Spoils with solids contents less than 100 g/l could be flocculated but the flocs were too fragile to survive in the hydrocyclones and neither clarification nor concentration was enhanced by the treatment. The high solids content affects clarification more than it does concentration and thus hydrocyclone concentrators were reasonably effective on all but the highest solids content spoils. Meanwhile, the hydrocyclone proved very successful at recovering sand from the full range of spoils. The hydrocyclone system is recommended for this application of classifying the solids in dredge spoil.

## PART I: INTRODUCTION

### THE PROBLEM

The vast majority of dredging operations in the United State are conducted with either a cutterhead or a hopper dredge. In both cases the solids are hydraulically transported from the bottom of the waterway to the dredge where they are either temporarily stored or pumped elsewhere. This mixture of suspended solids and water is called dredge spoil. It is typically about 10% by weight solids or on a volume basis about 95% water. The suspended solids vary in size from rather large rock, bricks, cans, tires, and steel cable to extremely small particles of clay. When given the opportunity, the larger material quickly settles out of the water but the smaller and lighter particles settle so slowly that the water usually remains turbid for some time. The basic concept of modern dredging is to remove the solids as efficiently as possible and with a minimum environmental impact from that portion of the waterway being dredged. The combination of fine grained suspended solids well dispersed in a rather large volume of water frequently impairs either the efficiency of the operation or the quality of the waterway. For example, in order to improve the efficiency of a hopper dredge as it transports dredge spoil from a dredging site to a disposal site, the hoppers are frequently overfilled and allowed to overflow. The result is a larger volume of the settleable solids in the hopper, but the overflow which is frequently turbid remains suspended in the waterway as it spreads and moves downstream. A similar situation can occur at a disposal site particularly if the site is small or almost filled. Namely, there is an insufficient

residence time for removal of the fine material and it overflows to the waterway. The situation is particularly difficult in urban areas where the spoil may be polluted and adequate disposal sites difficult to acquire. Consequently, there is a growing need to develop methods which will concentrate the dredge spoil solids and clarify the water.

It is anticipated that these additional efforts to protect and to improve the water quality will be expensive. Therefore it is particularly important to manage the spoil solids as a resource and to recover any of the material which has value. Unfortunately, the fine soil and organic matter in dredge spoil has little utility even as construction fill. Consequently, there is also a need for methods which can separate the dredge spoil solids into fractions that will allow recovery of valuable material such as sand and gravel.

## THE PURPOSE

The original and basic purpose of this study was to determine the extent to which a hydrocyclone system is feasible for concentrating the solids and clarifying the water in dredge spoil. However, an important secondary aspect of the study was to determine the feasibility of using hydrocyclones to classify the solids into fractions so that solid material of value such as sand and gravel could be recovered.

These basic objectives were to be achieved by executing the following sub-objectives:

1. Develop a two or three stage, bench-scale hydrocyclone system which reflects "state-of-the-art" capability in concentration and clarification.

2. Evaluate this system's capability to concentrate and to clarify dredge spoil samples, selected and provided by the Corps of Engineers, which reflect the range of spoils typically encountered.
3. To the extent possible, quantify the feasibility of a hydrocyclone system based upon the particle size distribution, the particle density, and the solids concentration and the viscosity of the slurry presented to the hydrocyclone system.
4. To the extent appropriate, determine the effect of flocculents on the concentrating and clarifying capabilities of a hydrocyclone or hydrocyclone system.
5. Evaluate a hydrocyclone's capability for selectively separating sand from dredge spoil.

## THE SCOPE

During this study, the performance of twenty open-underflow hydrocyclones was evaluated. These twenty geometries were derived from six basic designs based upon suggestions from Bradley<sup>1</sup> and the experience derived from previous studies<sup>2,3</sup> conducted at Oklahoma State University (OSU). The clarification and concentration capability of the separators were evaluated separately and in two different series arrangements. A single separator was evaluated in the classification operation. Two clay slurries were used extensively in the developmental portion of the study while six dredge spoil samples provided by the Corps of Engineers were used in the final evaluations. Over one hundred combinations of different chemicals were experimentally

screened in an effort to find chemical treatment which would be effective on the dredge spoil samples. The most effective treatment was then evaluated with the hydrocyclone system. All of these hydrocyclone experiments along with the chemical treatments are described in Part III of the report.

The physical character of the dredge spoil samples was so different from what was expected that a significant portion of the study was devoted to determining the physical characteristics of the spoil. In particular, the average specific gravity, the particle-size distribution, the dependence of the apparent viscosity upon shear rate, the salinity, the concentration of dissolved solids, and the concentration of suspended solids were determined for each spoil sample. In addition, the pressure drop characteristics of the spoil samples flowing in horizontal pipes and the capability of a laboratory centrifuge to clarify and to concentrate the spoil samples was determined. This characterization is described in Part II of the report. An analyses of how these spoil characteristics affected hydrocyclone performance is Part IV.

## GENERAL DESCRIPTION OF HYDROCYCLONES

Before proceeding to the main parts of the report a brief introduction to hydrocyclones and hydrocyclone series will be helpful. The hydrocyclone is an inertial separator in which solids that are heavier than water are separated by centrifugal forces. The devices are axisymmetric except for a single tangential inlet through which the contaminated fluid enters at a relatively high velocity (50-100 ft/sec). Centrifugal accelerations hold the solids near the outer wall as the fluid spirals downward into the conical section of the hydrocyclone

(see Figure 1). As the swirling flow proceeds into the converging conical section, a secondary flow builds up. This secondary flow carries fluid inward and then upward along the axis to the overflow outlet. As a result, the fluid which proceeds downward through the underflow orifice is the fluid from the wall region and there is a forced vortex along the axis in which the flow is upward. Since the rotational motion has an inward radial motion superimposed on it, the solids are subjected to two opposing forces. There is an outward radial force due to the centrifugal acceleration and an inward radial force due to the Stokes' drag from the inwardly moving fluid. The magnitude of these forces and, hence, the separation characteristics of the hydrocyclone are dependent upon the physical properties of the solids (size, shape, density) and the hydrocyclone geometry.

As shown in Figure 1, there is one inlet stream and two outlet streams for an open-underflow hydrocyclone. The underflow flow rate is normally 5 to 30% of the inlet flow rate with the balance of the fluid exiting in the overflow stream. The underflow stream contains the suspended solids which have been separated by the centrifugal accelerations and therefore, it is a relatively concentrated flow of solids. The concentration of solids in the overflow stream is lower than the inlet concentration but not necessarily zero. Particles which are sufficiently small or light are carried out the overflow by viscous drag forces. Consequently the overflow outlet stream of a hydrocyclone is frequently pumped to the inlet of a second hydrocyclone for further clarification. Such a conventional series of hydrocyclones which is depicted in Figure 2 was the basic series configuration evaluated in this study. There was also some testing of this conventional series when its inlet came from the underflow of a larger capacity

hydrocyclone. This so called "over-under" series will be more completely described later. Recommendations and conclusions concerning the applicability of hydrocyclones and hydrocyclone systems for concentrating, clarifying and classifying dredge spoils appear in Part V of this report.

PART II: CHARACTERIZATION OF DREDGE SPOIL  
SAMPLES AND CLAY SLURRIES

MATERIALS

Location and Collection of Spoil

The samples referred to in this report were collected and furnished by the Corps of Engineers. The general location of the sample sites is shown on Figure 3. Detailed location maps are included in Appendix B.

The first sample received was taken and forwarded by the Mobile District, Corps of Engineers. The sample was taken at 1100 hours on 10 September 1972 while dredging  $\frac{1}{2}$  mile south of the Pascagoula River mouth on the center line of the ship channel. Two 55 gallon drums were shipped to OSU for the tests reported herein. This sample is referred to as Mobile spoil in this report.

The Tampa Area Office of Corps of Engineers collected and forwarded to OSU two 55 gallon drums of spoil collected on 29 September 1972 from the East Bay turning basin leading into Hillsborough Bay. This sample is referred to as Tampa spoil in this report.

Two 55 gallon drums were taken from the Savannah Harbor on 2 November 1972 and 3 November 1972 by the Savannah District, Corps of Engineers and forwarded to OSU. This sample, hereafter referred to as Savannah spoil, was taken while the dredge was working in the Fig Island Turning Basin.

The Detroit District, Corps of Engineers collected and forwarded to OSU four 55 gallon drums from the Toledo Harbor area.

Two drums referred to herein as Toledo OF were taken at 0834-0855 hours 19 October 1972 from the overflow of the Hopper dredge while dredging load #197 between C. S. 200+00 and 218+00 as shown on detail map in Appendix B. Two drums referred to herein as Toledo DE were taken at 1020-1150 hours, 19 October 1972 from the discharge pipe while load #197 was being pumped out into disposal area Penn #7.

On 7 November 1972 at 1300 and 1330 two 55 gallon samples were taken from the Calcasieu River by the Government contractor at the direction of the New Orleans District, Lafayette Area Office, Corps of Engineers and forwarded to OSU. This sample is referred to as Lake Charles spoil in this report.

The assistance and cooperation of the Corps of Engineers in providing these samples is gratefully acknowledged.

At various times, some testing was conducted with diluted spoils. All dilutions were done with a mixture of tap water and salt that duplicated the spoil supernate in question. With regard to the Mobile spoil, a special terminology accompanied the diluted states of the spoil. The full strength Mobile spoil is termed 20% Mobile; the first dilution by one-half yielded 10% Mobile and the second dilution to 1/4 strength is denoted 5% Mobile.

The Toledo DE spoil was the only sample received at OSU which required modification before any testing could be conducted. This sample contained about 65 pounds of larger rock, shell, and wood which would not pass through our bench-scale apparatus. This debris which is shown in Figure 4 was screened out of the sample prior to its use as a test fluid.

## Clay, Sand and Test Dust

Two different clays were used in slurries that provided additional working fluids for hydrocyclone evaluation. The first clay is denoted Roger Mills Gray Clay (RMGC). RMGC is a highly plastic clay obtained in Roger Mills county in western Oklahoma. Permian Red Clay (PRC) is the second clay. It is a material of medium plasticity obtained from the Permian marine deposits which are abundant in central Oklahoma.

A single sand was utilized; that being Sapulpa sand. The sample is taken from a weathered limonitic yellow sandstone formation which outcrops four miles west of Sapulpa, Oklahoma. Sapulpa sand is a fine yellow sand and it was selected because of its medium particle size distribution.

The final material used as a suspended solid was AC fine test dust (ACFTD). This material is classified from natural Arizona dust by AC Spark Plug Division of General Motors Corporation. It is primarily silicon oxide and it is widely used in contamination testing.

## TEST APPARATUS AND PROCEDURES

### Mixing of Spoil Samples

The accuracy and repeatability of all subsequent tests is highly dependent upon the acquisition of a representative sample of spoil from the 55 gallon barrels. Consequently, a portable mixer and a portable baffle arrangement were constructed so that each barrel could be thoroughly mixed prior to the removal of any or all of the sample. The mixing is required because some gravity sedimentation

takes place in the shipping barrels. The mixer was also used to stir the reservoir of the main test stand and it will be described more thoroughly later. Here it is sufficient to note that when the mixer is in place the shaft of the mixer extends to the bottom of the drum. Affixed to the shaft are two sets of four flat blades. The action of the blades rotating past the baffles creates large mixing cells and the solid particles soon become suspended. The time required to thoroughly mix each slurry varies. However, each spoil was typically mixed for 1 to 2 hours before a sample was withdrawn.

#### Solids Concentration (Dissolved and Suspended)

The determination of the solids content, both dissolved and suspended is of major importance in a careful characterization of dredge spoil. All other properties of the spoil depend somewhat on the weight percent dissolved and suspended solids. It is also important to note that dissolved solids, such as salt, can introduce significant errors in analyses because evaporation is used in the solids determination. Evaporation of the water was used because the spoils can be filtered only with great difficulty. The purpose of the tests described here was to determine the solids content, both dissolved and suspended, of the dredge spoils. In addition, a general method was developed for correcting the suspended solids data when dissolved solids were present.

The measurement of solids content requires a balance capable of weighing to the nearest 0.1 milligram, a desiccator, an electric laboratory heater, a pipette for accurate sample volume determination and two evaporating dishes per sample. Any convenient volume can be evaporated - depending on time available and spoil nature -

and a corresponding pipette and evaporating dish volumes should be chosen.

The determination of solids contents, both dissolved and suspended, involves evaporating the liquid from a known volume of spoil or supernate. For the total solids determination, two separate 15 to 25 ml samples were drawn from the spoil and placed in clean, pre-weighed evaporating dishes. The known volumes are then placed on a heater. Care should be taken during heating to prohibit any boiling which would splash some liquid and the solids contained within that liquid from the evaporating dish. After the liquid contents were removed, the evaporating dishes were placed in a desiccator and allowed to cool to room temperature before weighing. After cooling the samples were weighed to the nearest 0.1 milligram (mg). The results for a specific sample were averaged and reduced to a grams per per liter notation. The procedure for dissolved solids determination is basically the same. The 15 to 25 ml sample is drawn from the spoil supernate, after the suspended solids have gravity settled to the bottom. In some cases, the fineness of the solids within a spoil necessitated use of a centrifuge to expedite the settling process.

In the cases where the dissolved solids content was greater than 2 g/l, a data correction equation was developed. The correction equation includes the effect of the suspended-solids volume and the dissolved solids. A detailed derivation of the correction equation is presented in Appendix D.

### Specific Gravity

Specific gravity of the suspended solids in all the dredge spoil samples and test slurries is needed so that the particle size of the

suspended solids can be determined from the hydrometer analysis. The method of test used a specific gravity pycnometer, a balance with  $\pm 0.01$  g accuracy, evaporating dishes, electric heaters, a pestle and mortar, distilled water, a desiccator and an oven. It was based on the methods described in ASTM D 854-58<sup>4</sup> and soil testing text books.<sup>5</sup> However, these reference methods were insufficient because the solids in this study were initially wet, not dry, and in some cases, dissolved solids were also present in the original slurry.

The recommended procedure is fully described in Appendix B. Here only its general outline will be given. The method was applied to all six dredge spoil samples, slurries of Sapulpa sand, and slurries of PRC. The accuracy and reproducibility of the method for salt-water slurries was verified with salt-water slurries of PRC.

The initial step in the specific gravity determination involves the acquisition of a suitable sample of dry soil. This begins with obtaining a representative sample from a well-mixed container of the spoil or slurry. If the spoil contained a significant amount of dissolved solids, the original sample was rinsed and washed with distilled water to remove essentially all of these dissolved solids. Here considerable care must be taken to avoid loss of the fine suspended solids. For this reason, the washing procedure requires time for either gravity settling of the solids to occur or centrifugation. Gravity settling of the concentrated spoil samples can be enhanced by diluting the original sample by a factor of 2 to 4 with distilled water and by using 1 liter cylinders. After about 24 hours of settling, the supernate is carefully removed and replaced by distilled water. After mixing the contents are again allowed to settle. It was found that three rinses of this type were sufficient to lower the effect

of the dissolved solids to a negligible level. The sample was then evaporated in large evaporating dishes placed upon electrical hot plates. Sufficient spoil was evaporated to yield at least 50 g of solids. The dried soil is then removed from the evaporating dishes and ground with a pestle and mortar into a powder. The powder is thoroughly dried in a 110°C oven for 12 hours and allowed to cool to room temperature in a desiccator. From this point on the procedure follows standard practice.

### Particle Size

An existing hydrometer method<sup>5</sup> was modified to allow particle size determination of dredge spoil and clay slurries. The hydrometer method depends on Stokes' equation for the terminal velocity of a falling sphere. Simply, this experimental technique and subsequent calculations relate the falling time for various size particles to the buoyancy of a hydrometer.

The concept of hydrometer testing for particle sizes is to measure the hydrometer level in spoil as the solids settle and to compare these readings to measurements made in the spoil supernate at the same temperature. This is most easily accomplished in two test cylinders; one filled with spoil and one filled with the spoil supernate. The hydrometer is a standard ASTM model 151H that is primarily used on soil colloids. It is also necessary to have equipment permitting a determination of solids content of the tested spoil.

Particle size analyses were done on the six spoils provided by the Corps of Engineers (Mobile, Tampa, Lake Charles, Toledo OF, Toledo DE, and Savannah) and on the two clays (PRC and RMGC) used in the hydrocyclone testing. Hydrometer tests were conducted

with these materials in both a dispersed and non-dispersed condition. The purpose of dispersing (deflocculating) the spoil was to break apart existing agglomerates and inhibit the formation of new ones. The non-dispersed samples had the original character of the spoil sample except for possible dilution.

The technique developed is most dependent on (1) the sample being representative, (2) the amount of suspended solids in the hydrometer sample, and (3) the temperature of the sample. Care was taken in obtaining the sample because slight variations (e.g., different barrels, or loads, etc.) can yield inconsistent results. The control mixture used was spoil supernate obtained from allowing the solids to settle or an equivalent salt water mixture. It is also important that the solids concentration be low enough to keep the hydrometer from "sticking" in the spoil. Sticking can be avoided by maintaining the solids concentration at approximately 25 grams/liter (no greater than 50 grams/liter in any case). The last requirement was satisfied since the temperature of the control cylinder liquid and the spoil cylinder contents were uniform and equal. The actual measurements are made in two groups. The first group of readings were made at 15, 30, 60 and 120 seconds after mixing without removing the hydrometer from the solution. A second set of readings were taken at intervals chosen by the experimenter (usually 2, 5, 10, 20 minutes, etc.) with the hydrometer being removed between readings and placed in the control solution. The data was recorded on the form shown in Appendix E. After the hydrometer test was complete the solid concentration of the spoil was determined in order to obtain the transformation equation necessary for data conversion. The solids concentration was then corrected for dissolved solids, if

necessary. A detailed procedure for hydrometer analysis is included in Appendix B.

The data analysis requires three items: first, the solid's specific gravity; second, the transformation equation for percentage finer calculations; and third, a nomograph for particle size distribution. The specific gravity was obtained as discussed earlier. The transformation equation converts the experimental readings and constants to a percentage of soil below a certain size. The nomograph allows determination of actual sizes present using specific gravity, temperature, measurement times and experimental readings. A detailed data analysis and sample calculations are included in Appendices B and F, respectively.

#### Viscosity

A well known method for characterizing a fluid is the relationship between the fluid's viscosity and shear rate. Couette type viscometers are often used to obtain viscosity data over a wide range of shear rates. These instruments measure the torque necessary to overcome the viscous drag on a cylinder rotating at constant speed while immersed in the fluid.

In order to obtain adequate coverage of a wide range of shear rates it was necessary to use two viscometers: a Brookfield Synchro-Electric Model LVF and a Fann Model V-G. The Brookfield was used with five spindle arrangements: the LV1, LV2, LV3, LV4 and the UL adapter. Private communication with Brookfield Engineering yielded the shear rates present at various speeds for only the UL adapter, LV1 and LV4 spindles. These are given in Appendix D. The Brookfield is a relatively low-shear device but the Fann V-G is a

high-shear viscometer. An equation for the conversion of measured angular deflection of the Fann dial reading to viscosity is derived in Appendix D. The shear rates for given speeds of the Fann are also given in Appendix D. The viscometric measurements of both the Fann and Brookfield span a range of shear rates of 1 to 1000  $\text{sec}^{-1}$  and give data suitable for characterization of the fluids.

Viscosity measurements were made as a function of shear rate for six spoils and one test clay slurry. Viscometric measurements of the Mobile spoil were made both over a period of time (3 weeks) and over a range of dilutions (full strength,  $\frac{1}{2}$  strength, and  $\frac{1}{4}$  strength). The Savannah spoil was measured in two states of dilution (full strength and  $\frac{1}{2}$  strength). The test clay slurry was a 20% mixture of PRC and tap water.

The experimental procedure is similar for both units and is outlined in detail in the operators manual for each viscometer. As it is necessary to maintain consistency in temperature, each sample was allowed to come to room temperature before measurements were taken. Also to maintain a consistent spoil solids concentration, care was taken to obtain a 500 ml sample that was representative of the entire spoil and the same sample was used in both the Brookfield and Fann viscometers. Two trials were made for each spoil or slurry on each viscometer and the results were averaged. The spoils or slurries were well mixed between trials. The data analysis can be accomplished using equations developed in Appendix D. Sample calculations are shown in Appendix F.

## Conductivity

In most cases the dissolved solids in a spoil supernate consist of salts, predominantly sodium chloride. Conductivity is a measure of the salinity of the supernate and an indicator of the amount of salt in the spoil supernate. Conductivity, in itself, has no meaning when applied to hydrocyclone operation, but it is a qualitative measure of dissolved solids. Thus, the conductivity of the spoils was measured.

The test apparatus consists of a modified wheatstone bridge circuit powered by an audio oscillator. Direct current is not ordinarily used in the tests due to electrolytic decomposition and polarization at the electrodes in the cell. These effects are minimized when an alternating current of about 1000 Hz is used. The equipment used for the conductivity tests was an audio signal generator, a standard resistance bridge, a set of headphones and a conductivity cell. The signal generator should have a range of 0 - 10,000 Hz.

The sample used for the conductivity measurements was always spoil supernate. The experimental procedure consists of nulling the resistance through the liquid between the plates of the conductivity cell with a resistance bridge. The experimental setup is shown in Figure 5. The audio signal oscillator is set to a frequency of about 1000 Hz, and the resistances  $R_1$  and  $R_2$  are set equal. The bridge resistance,  $R$  is then adjusted until a minimum level of tone is heard in the earphones. If the bridge has a nulling indicator (such as a meter or a light) the earphones need not be used.

The data analysis is accomplished by simply dividing the cell constant,  $K$  by the resistance value obtained above,  $R$ . That is,

$$S = \frac{K}{R}$$

where S is conductivity and has the units (ohm-cm)<sup>-1</sup>.

### Centrifugation

It was apparent that the Mobile spoil clarified very poorly under the influence of gravity alone. This is clearly illustrated in Figure 6 which shows the result of about one month of gravity settling. Consequently, these centrifugation tests were initiated as an attempt to get a better relative comparison of the potential for solid-liquid separation with the spoil samples. A Precision Scientific Universal centrifuge was used for these tests. It has the capability for centrifuging four 100 ml tubes simultaneously over a relative centrifugal force (rcf) range of 0 to 1000. (Most standard ASTM tests for settling are run at a rcf of 500 to 800.) It was necessary to know the rcf value for the speed settings on the centrifuge. Since this calibration was unknown a simple equation was used, as derived in ASTM Standard Method of Test D96-68<sup>6</sup>, which relates rotational speed to rcf. Thus in our case, the speed had to be measured and a magnetic pickup and electronic counter were used for this measurement. Other required apparatus is a timer accurate to the nearest second and ASTM standard 100 ml centrifuge tubes. It is convenient to use tubes that are clearly graduated for the entire length of the tube. The materials tested were the six dredge spoils supplied by the Corps of Engineers.

The testing procedure was begun by loading the centrifuge tubes with 100 ml of dredge spoil. The most efficient method of testing is to place a different spoil in each tube and simultaneously conduct four

tests. The four samples and holders were balanced and placed in the centrifuge. The centrifuge was then turned on and allowed to run for five minutes at the desired speed, and the speed was recorded. The samples were removed after five minutes and the amount of solids and supernate were measured and recorded. The samples were carefully replaced into the centrifuge and rotated at the same speed for five more minutes. The average speed for this five minute period is also recorded. The samples were then removed, measured, and recorded a second time. After the ten minutes of centrifuging, the samples were shaken until the solids were completely redistributed. The test described above was then repeated for another speed setting. A spread of 5-7 readings in the 0 to 1000 rcf range was suitable for data plotting and analysis.

The data analysis involves a single conversion of rotational speed (rpm) of the centrifuge to relative centrifugal force. This conversion was done by using an equation shown in Appendix F along with a sample calculation.

### Pipe Pressure Drop

The pressure drop and flow rate were measured for nine slurry flows in two pipes of different diameter (0.425 in and 0.835 in diameter). Figure 7 is a schematic diagram of the apparatus. The test apparatus includes a dilute polymer injection system which was used in one spoil run to determine the feasibility of reducing the viscous friction loss in a spoil pipe line. The dilute polymer solution is injected into the pipe line by air pressure while the spoils were pumped with centrifugal pumps. When polymer is injected, the test apparatus is configured so that none of the spoil mixed with polymer

can recirculate through the system. In this manner, the polymer concentration is known and maintained constant. However, during a normal spoil run the working fluid is recirculated so that a minimum volume of spoil is required to conduct the test.

The nine slurries tested were: (1) 5% Mobile, (2) 10% Mobile, (3) Tampa, (4) Lake Charles, (5) Toledo DE, (6) Toledo OF, (7) Savannah, (8)  $\frac{1}{2}$  strength Savannah and (9)  $\frac{1}{2}$  strength Savannah spoil with a dilute polymer injection of 100 weight parts per million of Dow Chemical Separan AP 273.

The transfer of each fluid to its respective test vessel must be accomplished carefully. The spoil was transferred by pumping directly from the 55 gallon barrel to the upstream tank or by filling a smaller container with spoil and carrying it to the upstream tank. On the other hand, the dilute polymer solution for drag-reduction tests was gravity fed into the polymer reservoir from the mixing container located above the reservoir. This was done to minimize mechanical degradation of polymer solution. For non-drag-reduction tests, 15 gallons of spoil were used. For the drag-reduction test, 35 gallons of spoil were required.

The specific gravity of each slurry was obtained before each test by weighing a sample of known volume. Flow rate was obtained by timing the collection of a sample at the exit of the recycle line. Pressure drop was read from the manometer in inches of slurry and later converted to inches of water for purposes of comparing the slurry data with the water reference data. The pressure drop reported for the 0.835-inch diameter pipe is the head loss in 113.5 inches of horizontal pipe. Similarly the pressure drop reported for the 0.425-inch diameter pipe is the head loss in 57 in. of horizontal pipe.

The same general procedure was followed for drag-reduction testing except that flow meters were used to determine how to adjust the flow rates. Each flow meter was calibrated before testing began to insure proper flow proportions of spoil and polymer. Spoil was maintained in the manometer throughout the drag-reduction test and manometer readings corrected as before.

## RESULTS

### Solids Concentration, Specific Gravity, and Conductivity

The results of the suspended solids, dissolved solids, specific gravity, and conductivity measurements are summarized in Table 1. Note that the spoil samples varied in suspended solids content from a low of 22 g/l for one of the Tampa barrels to a high of 209 g/l for the Toledo DE spoil. Two concentrations of suspended solids are listed for the Tampa spoil because the two barrels were significantly different. After noting the difference in solids content in the two Tampa barrels, all subsequent samples were mixed upon receipt. That is, the two barrels were mixed together so that the two barrel shipment was converted into an average for that site. The dissolved solids content of the spoils varied from 28 g/l (2.8%) to fresh water. This variation is also shown in the conductivity data. The specific gravity results for the spoils are relatively uniform. The Tampa spoil was the only sample whose specific gravity did not reflect a significant amount of organic material.

## Particle Size

The experimental results of the hydrometer measurement of spoil and clay slurry particle size distributions are shown in Figures 8 through 15. The experimental data shown here represents spoil and test clay samples that were both dispersed and non-dispersed. The non-dispersed data is for spoil at rest, with particles agglomerated according to their natural tendencies. The dispersed samples were mechanically mixed and chemically treated to break and to inhibit the formation of agglomerates. There are two general features of this data which are important. First it is apparent that in all cases the particles did agglomerate under quiescent settling conditions and that the resulting particle sizes are considerably larger than when the particles are dispersed. Secondly, all of the spoils have a very high percentage of their solids content in dispersed particle sizes between 3 and 10 micrometers.

## Viscosity

The results of the viscosity measurements are shown in Figures 16 through 19. Figure 16 shows a detailed analysis of the viscosity of the Mobile spoil. In this figure the effect of both solids concentration and storage time are compared to a 20% slurry of PRC. The viscosity of the Savannah spoil is shown on Figure 17. This figure shows not only the effect of percent solids content but also the effect of the addition of drag-reducing polymers. Figures 18 and 19 demonstrate the shear rate dependence of viscosity of the remaining spoils, Tampa, Lake Charles, Toledo OF and Toledo DE. In all cases the spoils "shear thin." In some cases such as the Mobile spoil, the apparent viscosity is very high at low shear rates. Although the

viscosity of Mobile spoil decreases, it is still large compared to the viscosity of water at the higher shear rates. As shown for the Mobile, Savannah, and Toledo spoils, the viscosity is strongly influenced by the solids concentration. Even the limiting viscosity at high shear rates increases as the solids content increases.

### Pressure Drop

Typical pressure drop results are summarized in Figures 20 and 21 while the complete data appears in Appendix A. The major feature of Figure 20 is the difference between a water flow and a spoil flow in a pipe line. The data presented represents pipe flow pressure drop for the Lake Charles spoil in two pipe sizes and at various flow rates. The shear thinning quality of the Lake Charles spoil is again evident. Figure 21 shows the effect of the addition of drag-reducing polymer additives in the pipe flow pressure drop of the Savannah spoil. These data are compared to water data in the same pipes. It is important to note that none of the spoils showed any drag-reducing capability by themselves. In fact, unless the spoil had been shear-thinned, the pressure drop was larger than that required for the same flow rate of water. The injection of the dilute polymer solution did reduce the viscous losses in the pipe flow. Drag reductions of about 45% were attained. That is, the pressure drop in the drag-reduced spoil was 45% lower than the pressure drop for an equal flow rate of water.

### Centrifugation

The results are shown in Table 2. The data remains in the rcf form for comparative purposes. This data representation is the most

meaningful one since the centrifuge tube takes up a major portion of the centrifuge radius - thus yielding widely different gravitational fields at various radial locations. For example, it could be stated that the settling characteristic of the spoil at the centrifuge tip for 200 rcf and 5 minutes of rotation is equivalent to a 1000 minute settling time in a 1 rcf environment. But the spoil is distributed over 7 inches in the radial direction and the calculation is meaningless when the whole tube is considered. The central feature of these results is the small amount of clarified liquid that can be achieved for the Lake Charles, Savannah, and Mobile spoils. Based upon the clarified volume acquired at the end of 10 minutes at a rcf of 400, the spoils rank in the following order in so far as potential for clarification is concerned: (easiest to clarify is listed first)

- (1) Toledo OF,
- (2) Tampa,
- (3) Toledo DE,
- (4) Savannah,
- (5) Lake Charles,
- (6) Mobile.

## PART III: HYDROCYCLONE EXPERIMENTS

The hydrocyclone experiments group into five distinct sets, all of which will be discussed here. These are:

- (1) tests of a conventional series composed of the  $I_c$  and  $II_b$  hydrocyclones,
- (2) developmental testing,
- (3) tests of a hydrocyclone classifier,
- (4) tests of a hydrocyclone series where the second separator attempts to clarify the underflow of the first, and
- (5) chemical treatment testing.

Since the experiments with the  $I_c$  -  $II_b$  hydrocyclone series were the central experimental feature of the project, these tests will be discussed first.

### $I_c$ - $II_b$ HYDROCYCLONE SERIES

#### Test Apparatus

The  $I_c$  -  $II_b$  hydrocyclone series is composed of two open underflow hydrocyclones connected in a series so that the overflow from the first unit (model  $I_c$ ) is pumped to the inlet of the second hydrocyclone (model  $II_b$ ). Hydrocyclone model  $I_c$  has a major cone diameter of about  $2\frac{1}{2}$  inches while the  $II_b$  has a major cone diameter of about  $2\frac{1}{4}$  inches. The internal axial lengths of the  $I_c$  and  $II_b$  are 18 and 16 inches, respectively. A complete listing of all the flow dimensions is given in Appendix B. These separators were sized for a series operation such that for an inlet flow of 12.1 GPM, approximately 1.5 GPM of concentrated spoil is rejected through the underflow of model  $I_c$ .

Approximately 0.6 GPM is rejected through the underflow of  $II_b$  and 10 GPM of clarified spoil is delivered at the overflow outlet of model  $II_b$ .

The test stand configuration for the  $I_c - II_b$  tests is shown in Figures 22 and 23. As shown in these Figures, the stand was basically designed for "once-through" operation. That is, during a test, none of the outlet streams were recirculated to the upstream reservoir. The two underflows and the single overflow were either directed to a drain or they were caught and held in containers during the run.

The upstream reservoir can hold and keep well mixed more than 90 gallons of spoil. The tank has three equally spaced internal baffles and the contents are stirred by an eight bladed mixer. Each baffle protrudes 3 inches from the walls and extends over the entire depth of the reservoir. Thus when the spoil is stirred by the flat bladed mixer which fits down the axis of the tank, large circulating cells with strong vertical mixing are established. The mixer is powered by a  $\frac{3}{4}$  HP, 3-phase Dayton motor which drives the shaft through a right-angle gear reducer. The rotational speed of the mixer is 72 RPM which is sufficient for excellent mixing without violent agitation. There are 2 sets of 4 mixing paddles. Each paddle is 7 inches long and the top set of paddles has a width of 3 inches while the bottom set is 4 inches wide. As shown in Figure 24, when the mixer is installed in the reservoir the bottom set of paddles is about 3 inches above the floor of the tank. Also clearly visible in the picture are the bottom supports for the vertical baffles and the fluid outlet. Note that the outlet is also about three inches above the floor. This position effectively prevents all material which can settle during the mixing from entering the hydrocyclones.

Two centrifugal pumps, each close-coupled to a  $1\frac{1}{2}$  HP single phase motor, were used to pump the spoil through the test stand. Flexible hose, polyvinyl chloride (PVC) pipe, and stainless steel tubing were used to plumb the stand. All of the piping was  $\frac{3}{4}$  inch diameter so that the flow would be turbulent and well mixed throughout. This consideration was most important near the sampling tees because the tees will yield representative samples only when the stream is well mixed. Sampling tees and pressure gages were located upstream and downstream of each hydrocyclone. The underflow streams were sampled directly at their outlets. A Fischer-Porter Rotameter was used to measure the overflow outlet flow rate while the mass flow rate of the underflow streams was measured by weighing the contents collected in a measured interval of time.

#### Materials

The  $I_c - II_b$  hydrocyclone series was evaluated with RMGC and PRC clay slurries, 5% Mobile, Tampa, Lake Charles, Toledo OF, Toledo DE, and Savannah dredge spoil. This was the only hydrocyclone system which was evaluated with all of the spoil samples.

#### Test Procedure

In preparation for a  $I_c - II_b$  separation test the spoil was transferred from the 55 gallon shipping barrels to the 90 gallon, test stand, reservoir. Prior to this transfer the mixer was removed from the test stand and placed, along with a second set of baffles, in the 55 gallon barrels of spoil. The barrel was then mixed (see Figure 25) until the spoil was homogeneous and all sedimentation had been redistributed in the spoil. After mixing, a centrifugal pump was used to transfer the spoil. If possible, the transfer took place while the 55 gallon drum

was continually being mixed. The pump inlet line contained a screen to keep large particles (small rocks, etc.) from going into the pump. The pump outflow was also screened (14 per inch). The only case in which the nature of the spoil was changed by those screens was the Toledo DE spoil. The transfer procedure was repeated for both barrels, until a 90 gallon homogeneous spoil sample was obtained. The mixer was then returned to the 90 gallon reservoir and used to mix the 90 gallon spoil sample until it was uniform. In the event that the separation run was to be done with a clay slurry, the transfer was not necessary since the proper amounts of contaminant can be added to an upstream tank of tap water.

At the beginning of the data run, flow rates and back pressures were adjusted to the predetermined level. In most cases maximum flow rate was desired and the pumping was unrestricted. After the original adjustment, the data run was divided into two segments. The first of these was sample collection. Samples (250 or 500 ml) were withdrawn from the sample tees and collected from the underflow streams. The valves on the tees were adjusted such that the flow from the tee was a small part ( $< 5\%$ ) of the total flow. It is believed that the tees provide a representable sample of the flow because samples taken upstream of the first hydrocyclone were always similar to the mixture in the 90 gallon reservoir. During the sample acquisition period, both pressures and flow rates were recorded. The final portion of the test was used for a flow rate determination. The sampling tees were closed and the two underflows were collected over a known period of time and the contents weighed. If the solids content was high enough to make the flowmeter reading inaccurate, the  $II_b$  overflow was also collected and weighed. Pressure readings were also recorded during the flow rate

determination. After collection of the flow-rate samples, the test was terminated. The remaining spoil or slurry (approximately 15 gallons) was then diluted and used to flush the system. If a spoil was the working fluid, the entire area was hosed down in an effort to minimize the health hazards. Immediately after the test, the sample bottles were capped, labeled and stored before determination of their solid contents.

The solids contents of the samples taken during the separation run was determined by evaporating the liquid from a known volume of the sample. Two volumes (15 or 25 ml) were drawn with a pipette from each sample bottle as it was being continuously stirred by a magnetic mixer. The known volumes were then placed in preweighed evaporating dishes and heated on an electric laboratory heater. Care was taken during the heating to prohibit any boiling which would splash liquid containing solids from the evaporating dish. After the liquid was evaporated, the evaporating dishes were placed in a desiccator and allowed to cool to room temperature before weighing. The dishes were weighed to the nearest 0.1 milligram with a digital balance and the two results for each sample bottle were averaged. The correction to the suspended solids content due to dissolved solids was done next. This correction is developed in Appendix D and a sample calculation is shown in Appendix F.

The final phase of the test procedure was the data analysis. The first step was to determine the validity of the sample acquisition, stirring, evaporation and weighing processes. This was done by computing a mass flow balance, using solids contents and flow rates, and by requiring the mass flow to balance within 10%. Experimental runs

which did not mass balance were repeated. Sample calculations for flow rates and mass flow balance are shown in Appendix F.

### Definitions of Hydrocyclone Performance Parameters

After experimental validity had been established, the separation trial was next characterized in terms of concentration index ( $C_I$ ), clarification number ( $C_N$ ), and centrifugal efficiency ( $E$ ). These quantities are defined by the following equations:

$$C_N = \frac{G_i - G_o}{G_i} ,$$

$$C_I = \frac{G_u - G_i}{G_i} ,$$

and

$$E = \frac{Q_o}{Q_i} C_N .$$

These three performance parameters were calculated for each separator in the series and also for the series as a whole. The definition of  $C_N$  and  $E$  for the series remains the same if one interprets  $G_i$  as the inlet gravimetric for the first separator and  $G_o$  as the outlet gravimetric for the last separator in the series.

The definition of  $C_I$  for a series requires additional definition because more than one underflow occurs. In this case, an average underflow gravimetric,  $(G_u)_s$  is defined by

$$(G_u)_s = \frac{\sum_{i=1}^n (G_u Q_u)_i}{\sum_{i=1}^n (Q_u)_i}$$

Then the concentration index for the series,  $(C_I)_s$ , becomes

$$(C_I)_s = \frac{(G_{us}) - G_i}{G_i}$$

where  $G_i$  is the inlet gravimetric of the first separator.

## Results

The results for the eleven  $I_c - II_b$  tests without chemical treatment are summarized in Table 3. The complete tabulation of the results is in Appendix A. The performance of this series on the various slurries and spoils falls into three groups. Reasonably good clarification and concentration was achieved with the clay slurries.  $C_N$  for the series varied from a high of 0.81 for a  $\frac{1}{2}\%$  by weight PRC slurry to 0.60 for a  $3\frac{1}{2}\%$  by weight RMGC slurry. Similarly,  $(C_I)_s$  was 4.06 for PRC and between 2.5 and 3.1 for RMGC. Thus the solids concentration of the combined underflow streams was 5 times the inlet concentration for PRC and  $3\frac{1}{2}$  to 4 times the inlet concentration for RMGC.

The performance of the series on the Tampa, Toledo OF, and Toledo DE spoils was only mediocre at best.  $C_N$  varied from a high of 0.40 for one Tampa run to 0.31 on Toledo DE. For these spoils  $(C_I)_s$  varied from 0.94 to 1.73.

Both clarification and concentration of the Mobile, Lake Charles, and Savannah spoils were poor.  $C_N$  was only about 0.15 for the Lake Charles and Savannah spoils. Although  $C_N$  was 0.25 for 5% Mobile spoil, one should remember that this spoil was diluted to  $\frac{1}{4}$  its original strength. With full strength Mobile spoil, it is estimated that  $C_N$  would be less than 0.15. The capability of the hydrocyclones to concentrate these spoils is also low.

## HYDROCYCLONE DEVELOPMENT

During the development of the I<sub>c</sub>-II<sub>b</sub> series and after the I<sub>c</sub>-II<sub>b</sub> tests were completed, several important discoveries were made. The purpose of this section is to report these miscellaneous results which had a direct influence on the conclusions and recommendations which will be made later.

### Test Apparatus

The test apparatus consisted of variations of the I<sub>c</sub>-II<sub>b</sub> test stand and hydrocyclones. Although the number of separators and the number of pumps in these tests varied between one and three, the basic configuration and capability of the test stand was always the same. At all times it was possible to sample upstream, downstream, and the underflow of each hydrocyclone. Similarly by using either flow meters or by weighing the contents caught in a given time, it was possible to determine the flow rates in and out of each separator. The only major mechanical difference was that during the early testing the upstream reservoir was stirred with a paddle. While this was physically difficult, the contents were kept well mixed throughout each run.

### Materials and Procedure

Most of the developmental runs were conducted with RMGC and PRC slurries. However, several tests were conducted with Mobile spoil and Calgon water softener was used with some of the clay slurries to disperse the clay particles. When the Calgon water softener was used, the Calgon and clay were mixed with water in a blender before they were added to the upstream reservoir. Thus, in these tests the clay particles were well dispersed. The remainder of the

test procedure and data analysis followed those outlined for the  $I_c - II_b$  series.

## Results

The initial hydrocyclone configurations (I, II, III) were designed to yield an underflow flow rate of about 2 to 3% of the inlet flow. With these relatively small underflow rates, these hydrocyclones produced the largest values of  $C_I$ . For example, model I has a  $C_I$  of about  $16 \frac{1}{2}$  for RMGC slurries. That is, the underflow is  $17 \frac{1}{2}$  times more concentrated with suspended solids than the inlet stream. It is worth noting that this result was achieved when the inlet concentrations were nominally  $\frac{1}{2}\%$  (Slur-11, see Appendix A) and  $2 \frac{1}{2}\%$  by weight (Slur-13). The underflow from model I in run Slur-13 was one of the more concentrated underflows measured during the entire program. With the gravimetric concentration of 456 g/l, the underflow was approximately 20 to 25% solids by volume. More will be reported about the effect of inlet solids concentration later.

The difference in inlet concentration from  $\frac{1}{2}\%$  to  $2 \frac{1}{2}\%$  did not effect the clarification number of model I either. It was constant at 0.46. However, of these initial, low-underflow-rate, configurations, model II was the best clarifier. On RMGC it produced  $C_N$  values of 0.55. This performance compares favorably with those reported in the experimental optimization of similar 4 GPM hydrocyclones.<sup>7</sup>

Most of the modifications which were made to these initial hydrocyclone configurations were attempts to improve the clarification capability. The basic concept which worked to some degree was to increase the underflow flow rate. Model 4DM was probably the best hydrocyclone clarifier which we tested when it was operating with an

inlet flow of 19 GPM and an underflow flow rate of about  $9\frac{1}{2}$  GPM. Under these conditions the 4DM had clarification numbers of 0.84 on PRC (Slur-31) and 0.69 on RMGC (Slur-18). However, due to the increased underflow the solids concentration of the underflow decreased substantially and  $C_I$  decreased to values on the order of 0.8 for PRC and 0.7 for RMGC.

The model  $I_c$  and  $II_b$  hydrocyclones were designed as an attempt to achieve the relatively good clarification of the 4DM and the good concentration of model II in single units. The attempt was relatively successful. The model  $I_c$  has  $C_N$  values of 0.79 and 0.64 on  $\frac{1}{2}\%$  PRC and  $\frac{1}{2}\%$  RMGC slurries, respectively (see Slur-54 and Slur-56). This good clarification was accomplished along with  $C_I$  values of 5.0 and 3.1 for the same slurries.

As shown above there are substantial differences in hydrocyclone performance as the suspended solids change from RMGC to PRC. The results summarized in Table 4 clearly indicate that there is also a substantial change in the separation effectiveness of a hydrocyclone when either clay is in a dispersed condition. Apparently the agglomerates which form in a fresh-water clay slurry are strong enough to withstand the shear rates inside the hydrocyclone. Thus, the effective particle diameter is somewhat larger than the diameter of individual dispersed particles. Since larger particles are easier to separate than small particles, the effectiveness of the hydrocyclones is much better when the clay slurries are allowed to form their natural agglomerates.

Run Slur-33 (see Appendix A) illustrates an important feature of hydrocyclones when they are arranged in a series. In this run the 4DM was the first separator in a series of three. Model I was the second unit and model II the third. The working fluid was  $\frac{1}{2}\%$  RMGC.

Since the first hydrocyclone in the series removes the large particles, the separation task for the succeeding units becomes increasingly difficult. Consequently,  $C_N$  for model I drops to 0.06 and  $C_N$  for model II is only 0.009. This result is characteristic of all the conventional series of three hydrocyclones. Since the third unit contributed so little to the clarity of the final overflow, the decision was made to limit all clarification operation to a series of two separators.

Several hydrocyclones were used in attempts to clarify the Mobile spoil. The performance of these individual units is summarized in Table 5. When possible the spoil performance is contrasted with the performance of the same separator on PRC. As indicated by the data, the performance increases as the spoil is diluted; however, in no case is the separation effectiveness nearly as good for Mobile spoil as it is for PRC. Model M8A was a configuration designed especially for higher viscosity fluids.

As shown in Part II, dilution of the Mobile spoil not only decreases the solids concentration but it also lowers the apparent viscosity of the spoil. Since it is not clear whether the increased effectiveness of the  $I_c$  and  $II_b$  is due to the lower viscosity or the lower solids concentration, a series of tests was conducted with various concentrations of RMGC. RMGC slurries were chosen because the viscosity of 7% and 15% by weight slurries of RMGC is constant at about 1.5 centipoise over a wide range of shear rate. The effect of inlet solids concentration upon  $C_N$  for the  $I_c$  and the  $II_b$  is shown in Figure 26. The effect upon  $C_I$  is shown in Figure 27. The inlet flow rate for these tests was relatively constant at 9 GPM for the  $II_b$  and  $10\frac{1}{2}$  GPM for the  $I_c$ . Obviously increasing the inlet solids concentration has a very deleterious effect upon the clarification performance of

these units. For example,  $C_N$  decreases from 0.56 at an inlet concentration of 15.8 g/l to 0.23 at an inlet concentration of 122.4 g/l.

It is interesting to note that  $C_I$  for the  $I_c$  does not decrease significantly over the range of inlet concentrations tested. At the highest inlet loading the solids concentration in the  $I_c$  underflow stream was 387 g/l. This is significant because  $C_I$  for the  $II_b$  does decrease and the first indication of this decrease occurs at an inlet concentration of 48 g/l and a corresponding underflow solids concentration of 369 g/l. In other words this limited data indicates that  $C_I$  begins to fall when the underflow concentration of RMGC exceeds about 350-400 g/l. The maximum underflow solids concentration during the entire program was achieved during this test series with the  $II_b$ . At an inlet concentration of 125 g/l, the underflow had 719 g/l of RMGC solids.

As a last attempt to improve the effectiveness of a hydrocyclone operating on dredge spoil, the  $I_c$  was tested with Toledo OF spoil at an inlet flow rate of 23 GPM. The purpose was to determine if a higher pressure drop and a higher inlet velocity would yield a stronger vortex motion which would overcome this deleterious effect of the high inlet solids concentration. Unfortunately, the value for  $C_N$  (see Spoil-28, Appendix A) was 0.31 which is essentially the same as the value of 0.30 obtained in run Spoil-18.

## HYDROCYCLONE CLASSIFIER

The function of a hydrocyclone classifier is to separate suspended particles into two groups; those which are smaller than a given size and those which are larger than that size. The smaller particles are carried out the overflow outlet while the larger particles are

rejected with the underflow fluid. The object of these tests with a classifier was to determine the feasibility of classifying spoil solids into two groups; an overflow of fines and an underflow of coarser material which would have value as either a fill material or aggregate.

### Test Apparatus

The classifier used to demonstrate the potential of hydrocyclones in this application was a modification of the model  $I_c$  clarifier. The unit is called the model  $I_f$  and it differs geometrically from the  $I_c$  by having a smaller overflow outlet, a smaller underflow outlet and a short vortex finder. It also differs in that it is nominally an 8 GPM unit. A complete tabulation of the flow dimensions is given in Appendix B.

A schematic of the test stand used to evaluate the performance of model  $I_f$  is presented in Figure 28. The upstream reservoir has a capacity of about 30 gallons. The contents were continuously and violently mixed during each test by a hand-held water jet powered by one of the two pumps. This jet stirred the tank from the top. In addition, the primary pump was equipped with a bypass which was always partially open and this stream re-entered and was directed horizontally across the bottom of the tank. The same  $1\frac{1}{2}$  HP motors and centrifugal pumps used in the  $I_c$ -II<sub>b</sub> test stand were also used here. Again,  $\frac{3}{4}$  inch flexible hose, PVC pipe, and stainless steel tubing were used to transport the fluid. There were sampling tees and pressure gages both upstream and downstream of the hydrocyclone. The underflow stream and the overflow stream were both either caught and contained during the run or directed to a drain. In either case samples could be withdrawn from these outlet streams. Specifically, the underflow

could be sampled as it exited the hydrocyclone and the overflow piping had a free-fall as it entered the downstream reservoir where it could be sampled directly.

In addition to the gravimetric analysis of the bottle samples, a "HIAC" particle counter was used to evaluate the effect of particle size on separation effectiveness. This counter senses the projected area of the particle or particles which are in the sensing cell at any one time. This projected area is then electronically converted into the diameter of the sphere which has an equal projected area. In a pre-set interval of time, each particle is counted and the count is registered on one of five displays. The size range covered by each display is adjustable within limits; however, the sensor has a lower size limit of 5 micrometers and an upper size limit of 120 micrometers.

#### Materials

ACFTD which is primarily silicon-oxide was the material used in the particle-count test. This commercially available test dust has the following size distribution:

<u>Size</u> <u>(micrometers)</u>	<u>Weight % smaller than</u> <u>indicated size</u>
80	100
40	91
20	73
10	57
5	39

Gravimetric analysis was performed on test runs using RMGC, PRC, 5% Mobile, Toledo OF and Savannah spoil. In addition tests were conducted with each of the above materials mixed with Sapulpa sand. Sapulpa sand has the following size distribution:<sup>8</sup>

<u>Size (micrometers)</u>	<u>Weight % smaller than indicated size</u>
450	100
300	60
200	18
100	2

## Test Procedures

Chronologically the particle-size tests were conducted first because knowledge was needed about the particle sizes which would be rejected in the underflow stream. Recall that the purpose is not to reject all particle sizes, but only those below a given size. To obtain accurate particle-count results, great care must be taken to insure that only the desired suspended particles are present in the water. Consequently, prior to the test runs the test stand was thoroughly cleaned. In addition to extensive flushing with filtered water and detergent, the stand was partially disassembled and cavities where dirt had collected were cleaned. When samples drawn from the sampling tees no longer showed evidence of residual contamination, the upstream reservoir was filled with 30 gallons of filtered tap water and 12 g of ACFTD was mixed with this water to form a 100 mg/l mixture. The flow rate was set by using the pressure drop across the hydrocyclone and a previously established calibration of flow rate through the separator as a function of pressure drop. After the stand reached a steady state condition, 500 ml sample bottles were filled from the upstream and downstream sampling tees. These bottles were then diluted following the procedure described in Appendix B and the suspended solids in the diluted bottles were counted with the HIAC automatic particle counter.

Two particle-size tests were conducted, one at an inlet flow rate of 10 GPM and one at 8 GPM. For the analysis of the 10 GPM tests the HIAC registers were set to count particles in the following size ranges: 6 to 8; 8 to 14; 14 to 20; 20 to 30; and 30 to the maximum size of 80 micrometers. The percent separation was then calculated in each size range by subtracting the downstream count from the upstream count and dividing the difference by the upstream count. The result was then plotted at the mid-point in the size range except for the last register which counted the largest particles. Here the result was plotted at 40 micrometers because in any range there are always more small particles than large. Thus, using the mid-point in the small ranges is a conservative estimate of the separation effectiveness. For the 8 GPM analysis the HIAC registers were adjusted to count particles in the following ranges: 10 to 15, 15 to 20, 20 to 25, 25 to 30, and 30 to 80 micrometers.

The procedure for conducting the gravimetric tests was considerably simpler to execute because the high solids content of the test fluids made the extensive cleaning procedure unnecessary. For these runs sufficient cleaning between each material was accomplished by simply flushing the stand with filtered water. When the stand was clean, the upstream reservoir was filled with either 30 gallons of filtered water and 7 pounds 11  $\frac{1}{2}$  ounces of clay or 30 gallons of dredge spoil. Both pumps were started and with the by-pass full open the contents of the upstream reservoir were thoroughly mixed for several minutes before the by-pass was closed and the flow rate adjusted to 8 GPM. When steady state was reached, samples were taken from the upstream reservoir, the upstream sampling tee, the underflow outlet, and the overflow outlet. All of this could be done and the flow through

the test stand stopped with 15 gallons of slurry or spoil remaining in the reservoir. At this point, 5 pounds 5 ounces of Sapulpa sand was added to the reservoir and the contents thoroughly mixed with both pumps. The by-pass was then closed and the second part of the run started. The flow rate was again set at 8 GPM using the pressure drop across the hydrocyclone as the flow meter and sample bottles were filled from the upstream reservoir, upstream sampling tee, underflow outlet and overflow outlet line. The test run was then completed by flushing the system. Two features of this testing procedure have not been specifically mentioned. They are the pre-mixing of spoil prior to its removal from its 55 gallon shipping drum and the continuous mixing of the upstream reservoir during each run. Both of these are necessary before representative samples can be obtained.

## Results

The results of the particle-size test runs are shown in Figure 29. Quite obviously the separation or classification is not perfect. Some large particles are not separated and some small particles are separated. This is characteristic of all hydrocyclones and one must regard separation as a statistical phenomenon and not a deterministic one. Notice that the classification becomes much sharper, that is, the separation curve is steeper, as the particle size separated with 50% effectiveness,  $d_{50}$ , increases. This is also a typical result and as shown here, it is relatively easy to derate a hydrocyclone's performance and to move the  $d_{50}$  point to higher values.

The gravimetric results summarized in Table 6 are arranged so that a comparison can be easily made between the results with and without Sapulpa sand. Note that in all cases, the addition of relatively

large amounts of Sapulpa sand to the upstream reservoir had relatively little effect upon the overflow gravimetric. As expected from the particle size results essentially all of the sand was rejected in the underflow stream while the finer material in the clay slurries and the spoil samples was carried over in the overflow stream. However, as indicated by the results without Sapulpa sand, the underflow did contain spoil and clay solids. This was quite apparent from a visual inspection of the sample bottles. The particles in the underflow bottle would rapidly settle so that the bottom layer of sand was covered by a layer of clay or spoil. After a short time, the supernate in these underflow bottles was relatively clear. In contrast, the overflow bottles showed no evidence of sand and the fines remained suspended in the supernate for some time. Note that the underflow gravimetrics were on the order of 300 mg/l or about 15% by volume solids. Consequently, the underflow stream could not be classified as dry. However, with the fines removed, the water does drain from these underflow samples rather well.

#### OVER-UNDER HYDROCYCLONE SERIES

As explained in the previous section, the purpose of a hydrocyclone classifier is to reject large particles with the underflow stream and to carry over the small fine particles with the overflow stream. With the fines removed the underflow stream should thus be considerably easy to clarify. This concept led to the testing of an "over-under" series of hydrocyclones. The basic configuration of the series is shown in Figure 30. The first hydrocyclone in the series acts as a classifier. The overflow from this unit contains small particles and

would require further processing in an actual application. In these tests it was simply sampled and run to a drain. The underflow stream from this initial classifier should contain larger particles and it was pumped to either a second hydrocyclone or a conventional series of two hydrocyclones for clarification and concentration. That is, the overflow from this second or third hydrocyclone should be relatively clear while the underflow, especially from the second hydrocyclone, should be very concentrated.

### Test Apparatus

As shown in Figure 30, the test stand was basically a reconfiguration of the I<sub>c</sub>-II<sub>b</sub> test stand. There were pressure gages, sampling tees, and flow meters located so that the pressure, flow rate and solids content could be measured or calculated upstream and downstream of each hydrocyclone. The contents of the upstream 90 gallon reservoir were kept well mixed during each run and they made a single pass through each unit before being directed to a drain.

The first hydrocyclone in this "over-under" series was either the model 4DM or a modification of that configuration. The inlet flow rate to this unit was 19 to 20 GPM. The ratio of overflow to underflow flow rate was varied somewhat depending upon the choice of hydrocyclone used to clarify the underflow. In most of the tests these underflow units were 10 GPM designs so the underflow from the first unit was typically 10 GPM to match the design inlet flow rate of these units.

### Materials and Procedure

All testing of this over-under series concept was done with either ACFTD or a clay slurry. The solids in the clay slurries were either

PRC, RMGC, chemically dispersed RMGC, or chemically coagulated PRC. The basic procedures for conducting a test with these slurries were the same as those described earlier.

## Results

There are two important features of the results summarized in Table 7. (See Appendix A for a complete tabulation of the results.) In all cases the clarification numbers of the system were less than the clarification number of the first hydrocyclone in the series. In other words the overflow from the first hydrocyclone contained fewer solids than the overflow from the second or third hydrocyclone in the series. While the over-under series did not work better than a single unit as a clarifier, it did work extremely well as a concentrator. The underflow of the second unit was particularly concentrated when compared to the solids content of the inlet stream. In Table 7, this is indicated by the values of  $(C_I)_{\max}$ .  $(C_I)_{\max}$  is defined by

$$(C_I)_{\max} = \frac{(G_u)_2}{(G_i)_1} - 1$$

where  $(G_u)_2$  is the underflow gravimetric concentration of the first underflow hydrocyclone (second unit) and  $(G_i)_1$  is the gravimetric concentration of the inlet stream to the first hydrocyclone. Note that both deflocculation and coagulation of the solids in the upstream reservoir had about the same effect here as they did with conventional series. Deflocculation yielded lower values for  $C_N$  and a less concentrated underflow from the second unit. However, even so this over-under series did a good job of concentrating the dispersed solids. Coagulation seems to have had little effect upon either the clarification or concentration.

## CHEMICAL TREATMENT

The motivation for combining chemical coagulation of the suspended solids with hydrocyclone treatment is easily understood with reference to Figure 29. Quite simply any hydrocyclone can separate the larger particles with greater effectiveness than it can smaller particles. The purpose of chemical treatment is to coagulate the small particles into large flocs. There are two difficulties in executing this scheme. First, there is no published method for a priori determining which chemicals at what concentrations will successfully coagulate the suspended solids. Consequently, screening tests are required to determine the most effective chemicals and their concentrations. Secondly, the agglomerated particles or flocs which form are usually not resistant to high shear rates. That is, the flocs are generally broken if the solution is vigorously handled. Unfortunately, the shear rates in a hydrocyclone are large. Consequently, for application with a hydrocyclone there is the additional constraint that the flocculated particles must be resistant to high shear rates.

The chemical treatment experiments can be divided into two groups. First, there were a large number of screening tests conducted in one liter cylinders. These were used to determine the chemicals and concentrations which were effective. The most effective chemicals were used to treat spoil samples and clay slurries which were pumped through the hydrocyclones. Both test series will be described here starting with the screening experiments.

## Screening Experiments

The only apparatus required to conduct the screening test are one liter graduated cylinders, pipettes, 100 ml graduated cylinders, and a clock. The type of test used is called a thickening test. It is recommended by chemical manufacturers for slurries which have a suspended solids content greater than 2% by weight.<sup>9</sup> The procedure consists of (1) filling the graduated one liter cylinder with the sample, (2) distributing the solids evenly by inverting the cylinder several times, (3) adding the inorganic coagulants such as alum and mixing the contents, (4) adding the organic flocculent in three equal steps with each step followed by inverting the cylinder three times in about one-half minute to mix the contents, (5) setting the graduated cylinder upright and recording the level of the solids/liquid interface at various times. Figure 31 illustrates step 5 by comparing the settling of treated and untreated RMGC.

The inorganic coagulants used in these tests were alum and ferric sulfate. The organic flocculents were obtained from three manufacturers and included non-ionic, anionic, and cationic polymers.

Those used at least once included:

<u>Manufacturer</u>	<u>Manufacturer's Name or Designation</u>
American Cyanamid	Magnifloc 835A
American Cyanamid	Magnifloc 905N
Dow Chemical	AP273
Dow Chemical	MG200
Dow Chemical	XD1612
Dow Chemical	N17
Calgon	2690

<u>Manufacturer</u>	<u>Manufacturer's Name or Designation</u>
Calgon	WT2630
Calgon	WT2600

As will be discussed later, some of the spoils were difficult to coagulate and consequently sand was also added to some of the thickening tests conducted with the Lake Charles and Savannah spoils. Screening tests were conducted with all six dredge spoils plus two dilutions of Mobile spoil.

For record purposes, a complete summary of all the thickening test results appears in Appendix C. Here only the general nature of the results and those results which influenced the subsequent hydrocyclone testing will be discussed. Generally the results can be classified into two groups. No success was achieved in our attempts to chemically hasten the settling of Mobile, 10% Mobile, Lake Charles, Toledo DE, or Savannah spoil. Meanwhile, chemical treatment was successful with 5% Mobile, Tampa, and Toledo OF spoils. The most dramatic positive feature was the greatly enhanced settling of Tampa spoil when it was treated with 10 mg/l of Magnifloc 835A and 10 mg/l alum. Magnifloc 835A at 15 mg/l and 10 mg/l of alum was also effective treatment of the Toledo OF spoil. It is probably significant that these spoils and 5% Mobile spoil contained appreciably less suspended solids than any of the other spoils.

#### Hydrocyclone Tests with Chemical Treatment

The capability of hydrocyclones to concentrate and to clarify chemically treated PRC slurries was evaluated for conventional series of hydrocyclones, and for the over-under series arrangement. Only

the conventional series and its individual separators were evaluated with dredge spoil and only Tampa spoil was used. No attempt was made to develop hydrocyclones specifically for this task. The purpose was to determine whether or not the performance of the conventional models could be enhanced by first chemically coagulating the solids.

The only modification to either the procedures or the test stands described earlier was the addition of the chemicals to the upstream reservoir. These chemicals were slowly and uniformly poured onto the surface of the mixing 90-gallon reservoir of test fluid. The inorganic coagulants were added first and allowed to mix with the contents of the tank before the polymeric flocculent was added. After a few minutes of mixing, the test run began and proceeded as before. The chemical treatment for the PRC slurries was established in a previous study<sup>3</sup> while the treatment for the Tampa spoil was based on the thickening tests.

Table 8 summarizes and compares the effectiveness of chemical treatment for conventional hydrocyclone series and for individual separators. The over-under series result is given in Table 7. Obviously there is no significant improvement due to chemical treatment. The particles of spoil and clay do flocculate in the upstream reservoir. However, the shear stresses in the hydrocyclones are apparently too large and the flocs break up in the hydrocyclones. Consequently, from the view point of the hydrocyclone, the particle size is not increased and no improvement occurs in either separation or concentration.

## PART IV: ANALYSIS OF RESULTS

The capability of a given hydrocyclone is probably best understood and analyzed in terms of the effect of particle size, fluid viscosity, specific gravity of the solids, and inlet solids concentration upon the separation effectiveness. In a dredge spoil sample all of these effects are not independent. For example, as the weight percent solids increases so does the pseudoplastic behavior and the apparent viscosity of the spoil. However, in so far as possible, the effects of these four parameters will be considered independently. Chemical treatment and drag reduction will also be discussed in this Part.

### EFFECT OF PARTICLE SIZE

The basic effect of particle size upon the separation effectiveness is graphically demonstrated in Figure 29. All hydrocyclones perform with this general characteristic. That is, larger particles are separated with a high degree of effectiveness and as the size decreases, so does the separation effectiveness. The configuration of the hydrocyclone affects both the steepness of the separation curve and its location. Specifically,  $d_{50}$  and the ratio of the size separated with 95% effectiveness to  $d_{50}$  are strongly influenced by the geometry. Although particle-size-separation curves were not measured for the model I<sub>c</sub> and II<sub>b</sub>, it is possible to make some rather good estimates of what these characteristics are. Previously<sup>2</sup> both the particle-size-separation curves and the centrifugal efficiency was measured for nine 4 GPM hydrocyclones. For example, one 4 GPM hydrocyclone had a centrifugal efficiency of 51.5% and  $d_{50}$  was  $7\frac{1}{2}$  micrometers.

The results are relevant here because the geometry of the separators is similar and the working fluid was a RMGC slurry. Using the results from these nine separators an approximate correlation can be developed which relates  $d_{50}$  to the centrifugal efficiency and which allows estimates to be made for the  $d_{50}$  of the  $I_c$  and  $II_b$  hydrocyclones when the solids are RMGC. With centrifugal efficiencies of  $55\frac{1}{2}\%$  for RMGC these units should have a  $d_{50}$  of about 7 micrometers.

Knowledge of the particle-size-separation curves for a hydrocyclone is important because with it and an appropriate particle-size analysis of the solids in a spoil, one could rather accurately estimate the effectiveness of that hydrocyclone on that spoil when the effects of viscosity and inlet solids are negligible. The difficulty is that the appropriate particle size distribution is apparently difficult and perhaps impossible to obtain. Particle-size curves are reported in Figures 8 through 15 for both the naturally agglomerated particles and the dispersed particles in each spoil and clay slurry. However, neither of these curves accurately reflect the relevant particle sizes inside the hydrocyclone. The following example will demonstrate the difficulty. The centrifugal efficiency of the model  $I_c$  on PRC slurries is about 66% (see Slur-54). However, using the naturally agglomerated size distribution shown in Figure 9 and the estimated value of  $d_{50} = 7\mu m$ , one would estimate a centrifugal efficiency of at least 90%. On the other hand, if the dispersed particle size distribution is used a centrifugal efficiency of about 45% would be predicted. Thus it seems clear that the effective particle-size distribution inside the hydrocyclone falls somewhere in between the two distributions which can be measured. This also means that there is a strong coupling between the

shearing stresses inside a hydrocyclone and the particle sizes inside a hydrocyclone. From the example just cited, it is clear that the shearing stresses inside the hydrocyclone must break up some of the naturally occurring agglomerates. However, it is equally clear from the example and from the results reported in Table 4 that not all of the clay agglomerates are destroyed in a hydrocyclone. When the particles are initially chemically and mechanically dispersed, the clarification numbers are considerably lower. The only logical explanation for this decrease with chemical deflocculation is that there are agglomerates which are strong enough to survive inside a hydrocyclone if they have not been previously dispersed chemically. For the relatively dilute clay slurries, this result is very clear because there is no additional effect due to changes in either viscosity or inlet solids concentration.

As shown above, it is not possible to use either the dispersed or the non-dispersed particle-size curves for the clay solids to predict the exact effectiveness of a hydrocyclone acting on slurries of these materials. However, it does appear possible to at least rank and perhaps correlate the performance with the dispersed particle sizes. For example, as the weight percent of the material larger than 7 micrometers increases so does  $C_N$ . The following table illustrates this for the model  $I_c$  hydrocyclone.

<u>Clay slurry</u>	<u>Weight percent larger than 7 <math>\mu</math>m</u>	<u><math>C_N</math> for the <math>I_c</math></u>
RMGC	24	0.64
PRC	44	0.79

Unfortunately, the same type of ranking does not hold for all of the dredge spoils. In fact one major difference between the above discussion for clay slurries and the performance of hydrocyclones on

dredge spoil is that  $C_N$  is never significantly greater than the weight percent of particles larger than 7 micrometers. This is surprising because the particle-size measurements indicate that the spoil particles do agglomerate. It is not known if these spoil agglomerates are too weak to withstand the shear rates in the hydrocyclones or if some other effect is solely responsible for the decrease in performance. Nevertheless, as shown in the following table

<u>Spoil</u>	<u>Weight percent larger than 7 <math>\mu</math> m</u>	<u><math>C_N</math> for the <math>I_c</math></u>
Mobile	18	0.11
Lake Charles	13	0.14
Tampa	33	0.34
Toledo DE	33	0.29
Savannah	50	0.19
Toledo OF	79	0.30

$C_N$  for the Mobile, Lake Charles, Tampa, and the Toledo DE spoil correlates rather well with the weight percent larger than 7 micrometers. However, the Savannah and Toledo OF spoils simply do not separate nearly as well as one would expect based upon their particle-size distributions. These anomalies with Savannah and Toledo OF spoil are quite important because they force us to look at other characteristics of the spoil for an explanation.

Before leaving the particle-size discussion, a few additional comments should be made about the applicability and the validity of the hydrometer method for this application. Since the hydrocyclone can be considered a dynamic settling basin in which fluid rotation effectively increases gravity, the hydrometer method appears to be well suited. Namely, the solids settle and separate under the

influence of similar forces in the hydrocyclone and in the hydrometer test. However, there are two difficulties. First, in a dredge spoil, the suspended solids do not have a single specific gravity and they do not necessarily all have the same characteristic shape. In this study an average specific gravity was measured for all the solids in a given spoil and the sizes were calculated with this value. Further, no attempt was made to either determine or correct for different shape materials. It is not known how accurate these approximations are, but it is believed that the method should still yield distributions which are correct relative to each other. The second difficulty is that some of the spoils are so viscous at 50 g/ℓ (typical recommended concentration for hydrometer analysis) that the hydrometer will stick. Consequently, lower concentrations (15 to 30 g/ℓ) were used for the spoil analyses. In all cases, hindered settling which is typical for a hydrometer test was observed but the solids concentration did vary from spoil to spoil. The effect of this is not known.

#### EFFECT OF SPECIFIC GRAVITY AND VISCOSITY

As mentioned in Part I, there are two radial forces on a particle inside a hydrocyclone. These are a centrifugal force which tends to separate the solids and to concentrate them in the underflow stream, and a Stokes' drag force which tends to carry the solids inward to the overflow stream. Stokes' law is frequently used to predict and correlate the separation performance of a hydrocyclone. In these analyses<sup>1</sup> the terminal velocity of the particle is equated to the inward radial velocity of the fluid and the body force acting on the particle is set equal to the particles' mass times  $V_t^2/R$ .  $V_t$  is the tangential

velocity and  $R$  is the radial location of the particle. For a specified hydrocyclone geometry, the equation which results from these analyses predicts that

$$d_{50} = K \sqrt{\frac{\mu}{\rho_p - \rho}}$$

Here  $K$  is a constant,  $\mu$  is the fluid viscosity,  $\rho_p$  is the density of the solid particle and  $\rho$  is the fluid density.

The first item to note is that the term  $(\rho_p - \rho)$  does not vary widely from spoil to spoil. In fact for all the spoils except Tampa, the difference between the average specific gravity of the fluid is effectively constant at  $1.64 \text{ g/cm}^3$ . The Tampa solids had a higher specific gravity and the difference was about  $1.76 \text{ g/cm}^3$ . At most, this higher difference in specific gravities for the Tampa spoil would yield a 3% decrease in  $d_{50}$ . It is doubtful that this decrease would yield a significant increase in  $C_N$  and  $C_I$ .

There were much larger variations in the viscosity and the viscous behavior of the spoils. In most cases, these viscous effects are clearly correlated with separation performance. Recall that all spoils were shear thinning fluids. That is, the apparent viscosity decreases as the shear rate increases. This variation in viscosity makes interpretation somewhat difficult because there are a wide range of shear rates and thus a wide range in the viscosity of a spoil inside a hydrocyclone. For example, the shear rates at the inlet and at the apex of the cone are extremely high, on the order of  $10^4 \text{ sec}^{-1}$ . However, the shear rates in the so called "short circuit" flow across the top of the cylindrical section are much lower. Consequently, there is no single value of viscosity which will completely characterize the fluid and which could be used to predict variations in  $d_{50}$  using the equation

based on Stokes' law. However, it is clear that the high viscosity of the Mobile, Lake Charles, and Savannah spoils will be quite deleterious to the separation performance of a hydrocyclone. While it is not sufficient to use only one value of viscosity to characterize a spoil, a single value was chosen in the following table to illustrate the good correlation between high viscosity and relatively poor separation and concentration performance.

<u>Spoil</u>	<u>Viscosity @ 1000 sec<sup>-1</sup> (centipoise)</u>	<u>C<sub>N</sub> for the I<sub>c</sub></u>	<u>C<sub>I</sub> for the I<sub>c</sub></u>
Mobile	16.0	0.11	0.46
Lake Charles	11.0	0.14	0.65
Savannah	9.0	0.19	0.34
10% Mobile	4.1	0.20	1.28
Toledo DE	3.2	0.29	1.46
5% Mobile	1.5	0.24	1.61
Tampa	1.4	0.34	2.25
Toledo OF	1.2	0.30	1.98

#### EFFECT OF INLET SOLIDS CONCENTRATION

A high concentration of small particles at the inlet of the hydrocyclone is detrimental in at least three respects. First, it is the presence of many small particles which makes a slurry a shear thinning, pseudoplastic fluid. (The effect of the resulting high viscosities at the lower shear rates was just discussed.) However, even when the size distribution of the small particles is such that the fluid behaves in a Newtonian manner, C<sub>N</sub> decreases as the inlet solids concentration increases. This behavior which was discussed in Part III and shown

in Figure 26 is believed to be the result of (1) hindered settling in the hydrocyclone and (2) a decrease in flow rate capacity. Here hindered settling or hindrance simply means that the separation of a particle into the underflow stream is hindered by the presence of other particles. In this study, these latter two phenomena occurred at the same time, but this is not believed to be either typical or necessary.

The decrease in flow rate capacity and an increase in the percent of underflow occurred as the weight percent of RMGC solids in the inlet increased (see Slur-67 thru 76). Quite simply this behavior is the result of the higher unit weight and increased inertia of the fluid. The tests were conducted at a constant pressure drop and therefore, as the solids content and unit weight of the fluid increased the amount of acceleration in the inlet orifice decreased. This leads directly to a decrease in the vortex strength and a higher percentage of underflow as well as a decrease in flow rate capacity. The underflow percentage increases as the vortex strength decreases because the strength of the secondary flow in which the downward moving fluid moves inward and then upward depends upon the amount of fluid rotation.

The conditions or limits above which hindrance becomes important is undoubtedly strongly dependent upon the particle-size distribution of the solids. For example, increasing the inlet solids concentration of the  $I_f$  classifier with Sapulpa sand did not yield a decrease in  $C_N$  while increasing the inlet solids concentration of the  $I_c$  with RMGC did. This is reasonable when you consider the surface area of a given weight of particles. The surface area and hence the fluid drag on the particle increases dramatically as the particle size decreases. Thus the practical limits for inlet solids content and underflow solids content will depend upon the particle-size distribution of the solids.

One should also recall that Figures 26 and 27 demonstrate that hindered settling effects  $C_N$  at lower inlet solid concentrations than it does  $C_I$ . Hence, a practical upper limit on inlet solids will also depend upon the function of the hydrocyclone. Based upon the clay and spoil data in this study, it would appear that the clarification capability of a hydrocyclone begins to decrease significantly when the inlet solids concentration reaches 20 g/ℓ while  $C_I$  does not fall until underflow concentrations of about 400 g/ℓ are reached. A practical upper limit for underflow concentration appears to be about 800 g/ℓ. It should be emphasized that these values apply only to the fine grained spoils and clays tested. Bradley<sup>1</sup> reports much higher limits on both inlet solids concentration and underflow concentration. The difference is believed to be due to differences in the particle-size distribution of the solids. For example, underflow concentrations of 1250 g/ℓ have been reported (see Bradley<sup>1</sup>) for hydrocyclones designed for the recovery of fine sand. These underflows of sand were 73% solids on a weight basis and 46% solid on a volume basis (assuming a specific gravity of 2.7 g/cm<sup>3</sup>). Although a complete understanding of hindered settling is still lacking, it is clear that the clarification of fine grained clay and spoil is seriously impaired at inlet concentrations above 20 g/ℓ.

As seen in the above discussions, the effects of particle size, viscosity and inlet solids concentration are coupled. Unfortunately, in the dredge spoil samples tested here the coupling was generally detrimental to performance. Namely the spoil solids were typically small (all spoil samples had the bulk of their weight in particle sizes

smaller than 15 micrometers\*), the slurries had high viscosities at low shear rates and the solids concentrations exceeded the upper limit for reasonable clarification performance.

It is also this coupling of all three effects which contributes to the very poor gravity settling characteristics of the spoils. Mobile, Lake Charles, Toledo DE, and Savannah spoils, in particular, clarify slowly and poorly under quiescent gravitational conditions. Further, as shown in Part II, centrifugation does not accelerate the settling process as much as would be desirable.

### EFFECT OF CHEMICAL TREATMENT

While the above discussions about particle size, viscosity, and inlet solids concentration are based on rather complete data, the following discussion about chemical treatment should be considered as more preliminary. The reason is that there are so many variables and possible combinations in chemical treatment that this study was only a beginning.

Two significant, general results were achieved. All of the chemical treatments which were found to be effective on the spoil samples produced rather fragile flocs. These were broken in the hydrocyclones and performance was not improved. Secondly, in the thickening tests chemical treatment was much more successful with the spoils which have a relative low solids content. Both results seem to be

---

\*This is not precisely true for the Toledo DE spoil which contained some large material which was removed with screens before testing.

typical of, and consistent with the state-of-the-art in chemical coagulation.

The result that is needed to make chemical treatment increase hydrocyclone performance is a highly shear resistant agglomerate. The floc need not be as large as those required for gravity clarification, but it does need to be more shear resistant. Since the number of chemicals which are effective increases significantly as the solids content goes down, the probability of finding treatment which will yield the desired result is much higher for dilute spoils. Consequently, future efforts should first be conducted with rather dilute spoils.

#### EFFECT OF DRAG-REDUCING ADDITIVES

In a preliminary test using  $\frac{1}{2}$  strength Savannah spoil and 100 wppm of AP273, the frictional head loss in a pipe was decreased 45% at constant flow rate. At this time it is not known how general this result is or how it would scale up to a full-scale flow of spoil in a pipe. However, it is very illuminating to consider what effect a 45% decrease in frictional head loss would have on the pump-out unloading of a hopper dredge. For this example calculation, the pump-out process of the HOFFMAN which we observed on July 13, 1972 was taken as the model. At that time the dredge was working in Calumet harbor, Chicago, Illinois.

The HOFFMAN has a 410 HP pump which was being used to unload the spoil through a 12-inch pipe. The line was about 1500 feet long and there was an elevation increase of about 14 feet between the pump and the pipe discharge. For this calculation it was assumed that the pump efficiency was 80% and that the mechanical efficiency of

the drive was 95%. Thus it was assumed that 310 HP was supplied to the fluid. It was further assumed that the system of pump and pipe line would operate such that the product of flow rate and pressure drop would be constant at this value of 310 HP. Under these conditions and with a bulk spoil specific gravity of 1.4, a 45% decrease in the friction losses in the pipe will result in approximately a 60% increase in flow rate. Although the assumptions make this estimate somewhat rough, the potential is obvious.

Such an increase in flow rate would be of great benefit in operations such as that of the HOFFMAN because a large percentage of the total dredge cycle was required for pump out. The problem was particularly severe because the pumping capacity was so marginal that the flow rates were low and solids were settling and plugging the line. Hence, a large amount of dilution was required to remove all of the solids from the hoppers. Higher flow rates would keep more of the solids in suspension and reduce the volume of extra water required to transport the solids. Thus pump-out time would be reduced by more than 60%.

There are many features of this drag-reduction phenomenon which are not known yet. In particular, it is not known how the amount of drag reduction would vary as the character of the spoil changes and it is not known how the phenomenon would scale up. Since the potential for improving the operation of existing equipment is significant, a program to more precisely determine the operational limits and feasibility is recommended.

## PART V: CONCLUSIONS AND RECOMMENDATIONS

The results of this study support a number of conclusions about the feasibility of using hydrocyclones for clarifying, concentrating and classifying dredge spoil. Conclusions and recommendations can also be made about the difficulty of clarifying spoil and about the potential for significantly reducing the frictional head loss in pipe flows of dredge spoil.

### HYDROCYCLONE CLARIFICATION

Quite obviously the clarification performance of hydrocyclones on the dredge spoil samples was not good. The high solids content of the spoil and the spoil's high viscosity at low shear rates are the primary contributors to the poor performance. It is believed that the hydrocyclones are capable of better clarification based on the particle size distributions. Thus, it is concluded that for highly pseudoplastic, high solid content spoils the hydrocyclone by itself is not a feasible clarifier. Undoubtedly there are sandy spoils with little organic content for which this conclusion should be modified. Similarly, there may be clarification processes involving several unit operations in which hydrocyclones could contribute. However, by itself a hydrocyclone or a hydrocyclone series will not clarify the spoil typical of the Southeastern United States.

## HYDROCYCLONE CONCENTRATION

A hydrocyclone operating on the underflow of an upstream hydrocyclone can very effectively concentrate dilute clay slurries. It is believed that this result will also apply to dilute (inlet concentrations less than 10 g/ℓ) dredge spoils. However, it is estimated that the practical maximum underflow concentration of dredge spoil will be about 800 g/ℓ. In general, the high inlet solids and pseudoplastic behavior of the spoils is not as detrimental to the concentration effectiveness of a hydrocyclone as it is to clarification. Therefore, a hydrocyclone or a hydrocyclone series is a feasible concentrator of dredge spoil when the inlet solids concentration of the spoil is 100 g/ℓ or less. The overflow from this concentrator will not be clear; it will probably require further processing before it can be returned to a waterway.

## HYDROCYCLONE CLASSIFICATION

The capability of a hydrocyclone to recover medium size sand from a dredge spoil sample containing a large percentage of fine silt is excellent. A hydrocyclone designed to yield a cut size of 20 to 30 micrometers is recommended for this operation. The underflow slurry from such a classifier will be about 50% or more water on a volume basis. However, with the fines removed from this slurry the water should drain from the solids rather easily and the water will be relatively clear. Further study about the clarification of the water in the underflow of such a classifier is recommended.

## CHEMICAL TREATMENT

The conclusions about the results with chemically treated dredge spoil must be considered as preliminary because there are so many possibilities which have not yet been studied. However, at this time it appears that coagulation of the spoils with solids concentrations above 50 g/l will be difficult and will require rather large dosages of chemicals. The flocs which formed in the treatment which was effective in the thickening tests did not withstand the shear forces inside the hydrocyclones and the performance of the hydrocyclones was not enhanced by that chemical treatment. However, there may be more effective chemical treatment and further study is recommended. A highly shear resistance floc is needed to improve hydrocyclone performance. However, this floc need not be nearly as large as those required for gravity settling. It is estimated that a 100 to 200 micrometer floc would be sufficient for hydrocyclone separation if it were sufficiently strong. Another approach which has merit is the development of low-shear, low-residence-time clarifiers for use with chemically treated spoil.

## CHARACTER OF SPOIL

Three of the spoils (Mobile, Lake Charles, and Savannah) are very difficult to clarify and concentrate. Hydrocyclones, centrifuges, and chemical treatment were all only marginally effective at best. This is due to the fact that (1) the bulk of the material has a particle size less than 15 micrometers, (2) the spoils are pseudoplastic with very high viscosities at low shear rates, and (3) the suspended solids

concentration is high (greater than 100 g/ℓ). Elaborate processes will be required to clarify and consolidate spoils of this type. Hydrocyclones may be useful in reducing the solids content prior to further treatment and chemical treatment may be effective if the spoils are diluted. The effectiveness of all the methods used in this study increases as the solid concentration decreases. The difficulty in clarifying and concentrating spoils of this type should not be minimized.

### DRAG REDUCTION

The pipe-flow tests showed that none of the spoils are drag-reducing fluids. However, a preliminary test showed that viscous pipe-flow losses could be reduced 45% by the injection of a 100 wppm polymer solution. This phenomenon could be of significant benefit in the transport of spoil in pipe lines and during the pump-out process of a hopper dredge. Consequently, it is recommended that further study be conducted to determine (1) the amount of drag reduction possible with various spoils and (2) a procedure for scaling up laboratory results.

### APPLICATION TO OPERATIONS

Due to the poor clarification capability of the hydrocyclones when operating on dredge spoil, the application of hydrocyclones to clarify hopper dredge overflow is not recommended. On a turbidity basis, the hydrocyclone overflow will be quite similar to the present hopper overflow. The equipment necessary to clarify this water will

be expensive and complex. Therefore, the application of hydrocyclones for the clarification of hopper dredge overflow does not appear to be feasible.

The most likely place where hydrocyclones can be used in dredging operations is at a disposal site. This is particularly true if the site is being managed as a relatively permanent installation from which both consolidated solids and clarified water are continuously removed. At a disposal site hydrocyclone classifiers are recommended for the selective recovery of sand and gravel. Hydrocyclone concentrators could be used as part of a dewatering scheme and hydrocyclone clarifiers could be effective as part of a larger clarification process. The possibility of chemically treating the diluted overflow of a hydrocyclone in a low-residence time clarifier should be investigated further.

## LITERATURE CITED

1. Bradley, D. The Hydrocyclone, Pergamon Press, Oxford, 1965.
2. Kincannon, D. F. and Tiederman, W. G. "Development of Hydrocyclones for Clarification in Physical Chemical Waste Water Treatment Systems," Final Progress Report to U. S. Army Medical Research and Development Command, November, 1972.
3. Kincannon, D. F. and Tiederman, W. G. "Water Reclamation for Ground Water Recharge," Final Report, Oklahoma A-034, Office of Water Resources Research, United States Department of the Interior, July, 1972.
4. ASTM D 854-58, "Standard Method of Test for Specific Gravity of Soils," Annual Book of ASTM Standards, Part 11, 1972.
5. Lambe, T. W. Soil Testing for Engineers, John Wiley, New York, 1951.
6. ASTM D 96-68. "Standard Methods of Test for Water and Sediment in Crude Oils," Annual Book of ASTM Standards, Part 18, 1972.
7. Tiederman, W. G., Kincannon, D. F. and Bowen, J. G. "Experimental Design of 4 GPM Hydrocyclones for the Clarification of Waste Water," Presented at the ASME Symposium on Air and Water Pollution, Atlanta, Georgia, June 20-22, 1973.
8. Moore, R. K. and Haliburton, T. A. "Subgrade Moisture Variations Interim Report IV: Suggested Nuclear Depth Gage Calibration Procedures," Civil Engineering Research Report No. 29, School of Civil Engineering, Oklahoma State University, Stillwater, Oklahoma, January, 1969.

9. SEPARAN Polymers Settle Process Problems, The Dow Chemical Company, 1971.
10. Van Wazer, J. R., Lyons, J. W., Kim, K. Y. and Colwell, R. E. Viscosity and Flow Measurement, Interscience, New York, 1963.

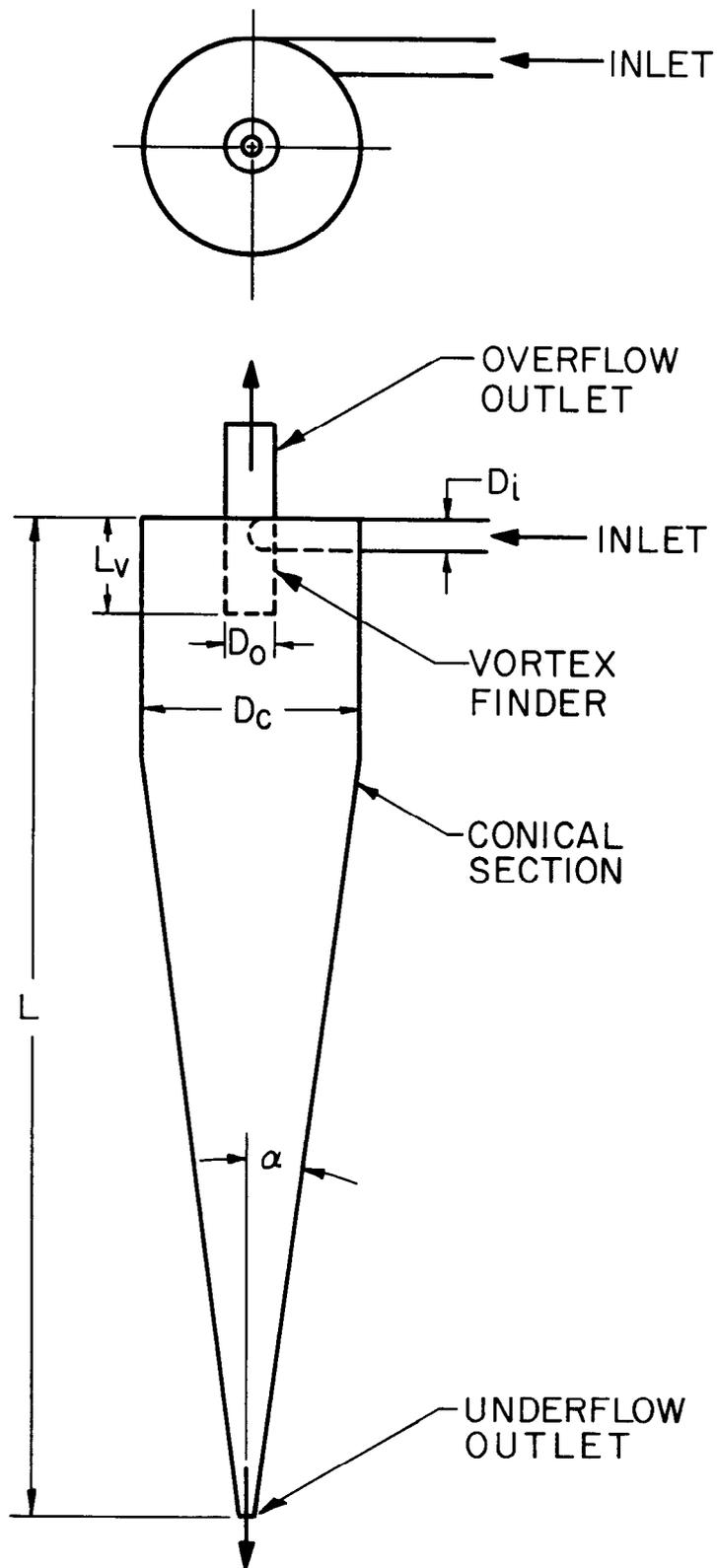


Fig. 1. Open underflow hydrocyclone

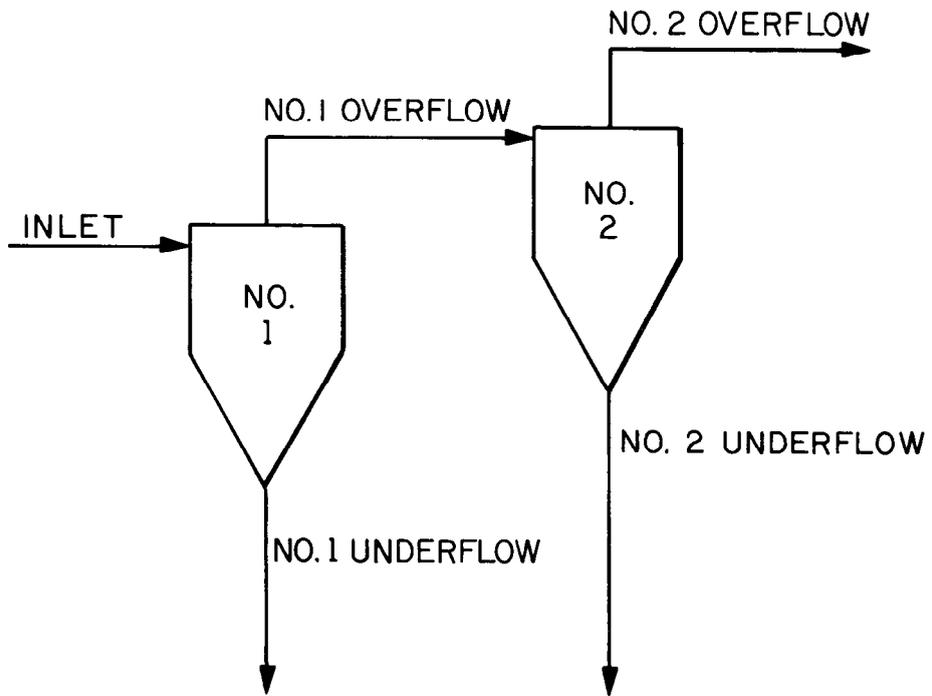


Fig. 2. Conventional series of hydrocyclones

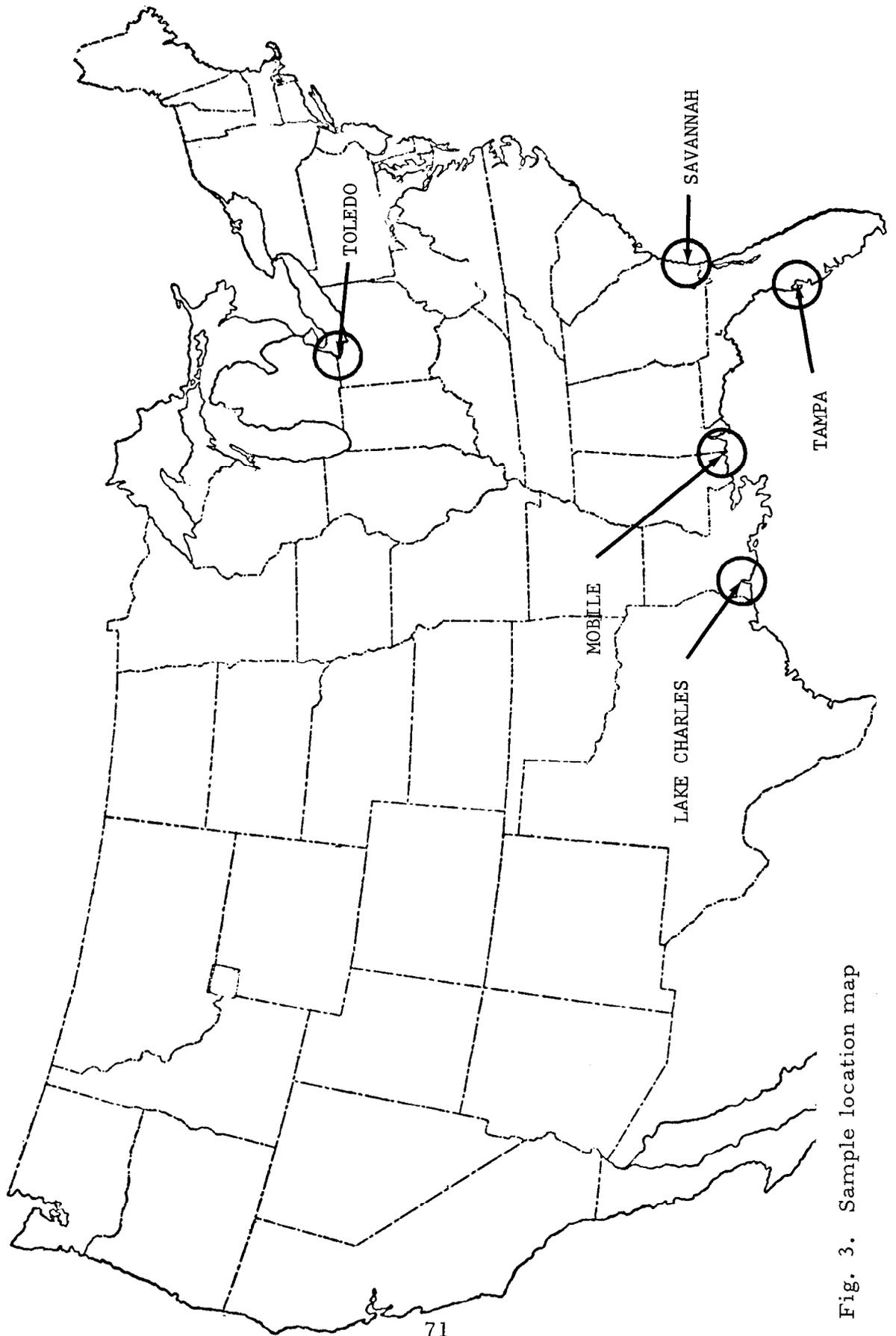


Fig. 3. Sample location map



Fig. 4. Toledo DE debris

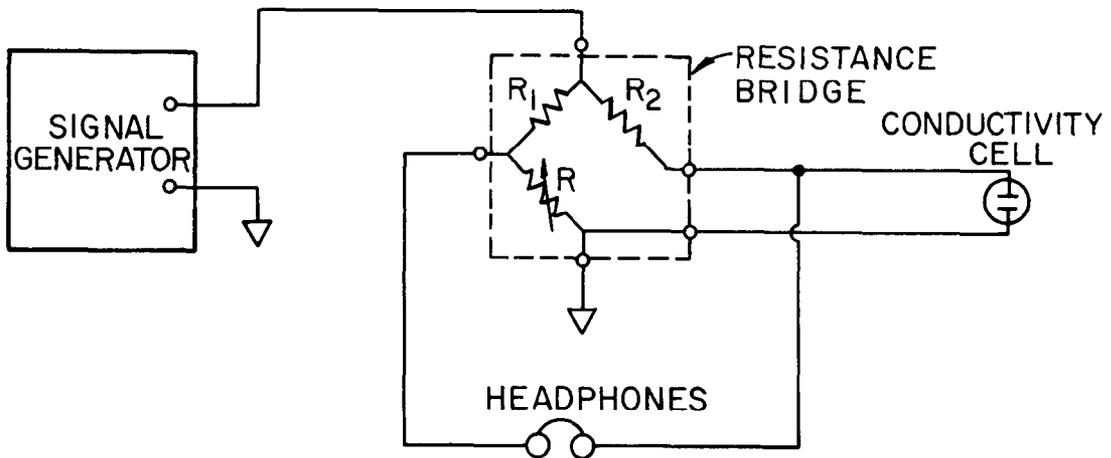


Fig. 5. Schematic of conductivity apparatus

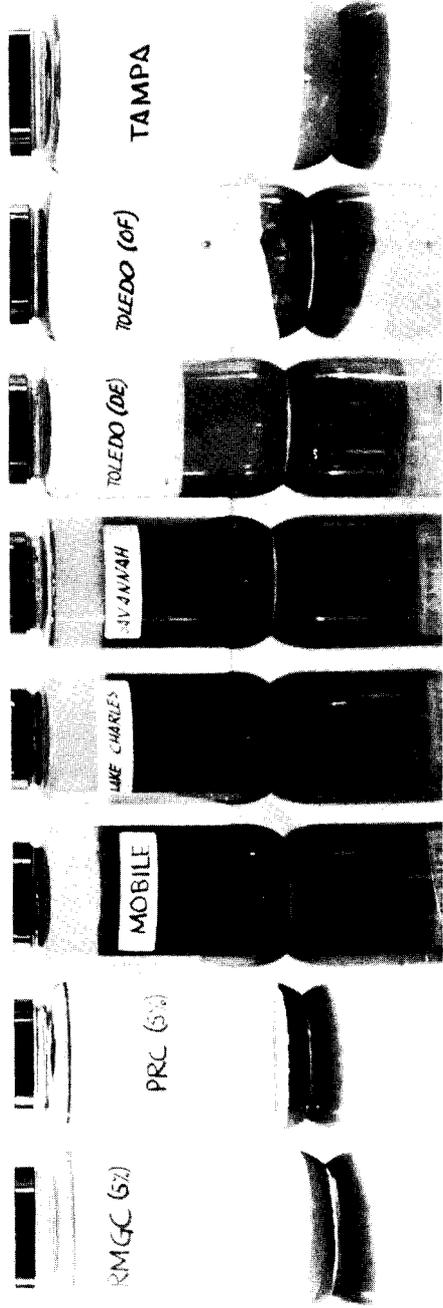


Fig. 6. Comparison of spoils and clay slurries after one month of gravity clarification

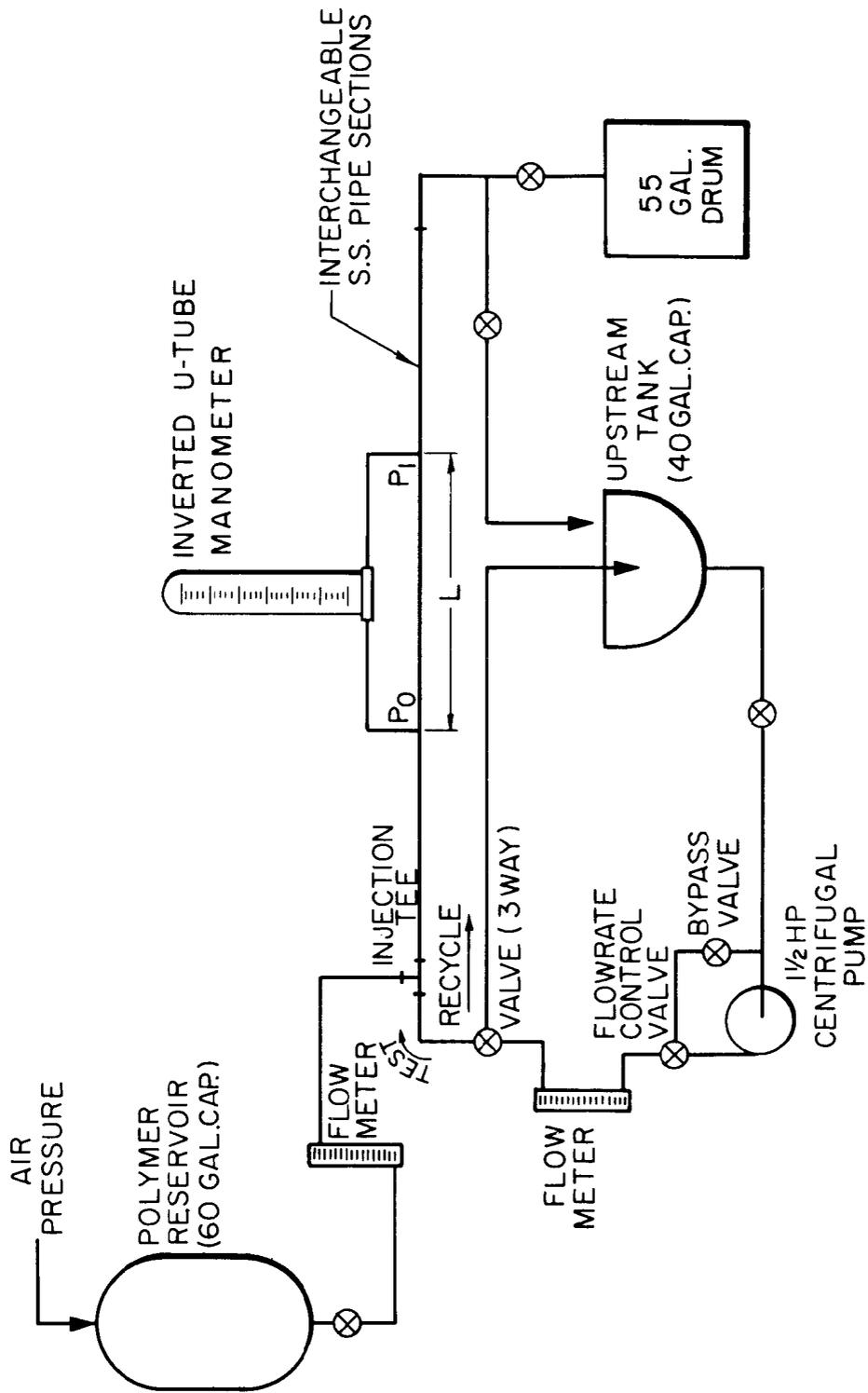


Fig. 7. Pipe flow apparatus

TABLE 1  
SOLIDS CONCENTRATION, SPECIFIC GRAVITY, AND CONDUCTIVITY

Material	Suspended Solids (g/l)	Dissolved Solids (g/l)	Conductivity (ohm-cm) <sup>-1</sup>	Specific Gravity
RMGC				2.73
PRC				2.77
Sapulpa Sand				2.66
Mobile Spoil	183	28.5	0.0476	2.68
Tampa Spoil	45	27.8	0.0455	2.79
Tampa Spoil	22	27.8	0.0455	2.79
Lake Charles Spoil	174	20.3	0.0286	2.66
Toledo OF Spoil	53	1.6	0.000692	2.64
Toledo DE Spoil	209	0.8	0.000825	2.64
Savannah Spoil	113	4.9	0.00746	2.66

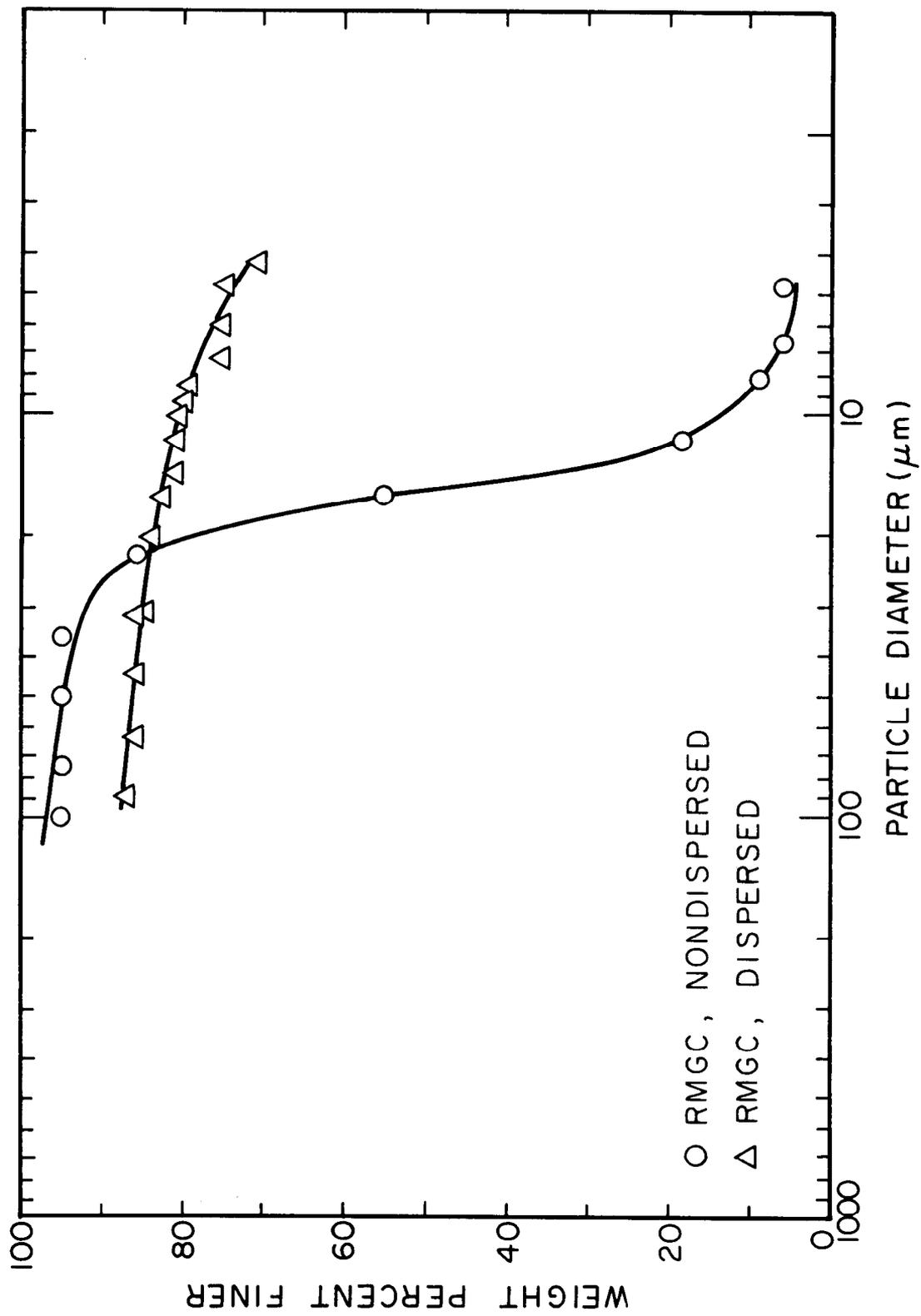


Fig. 8. Particle size distribution of RMGC

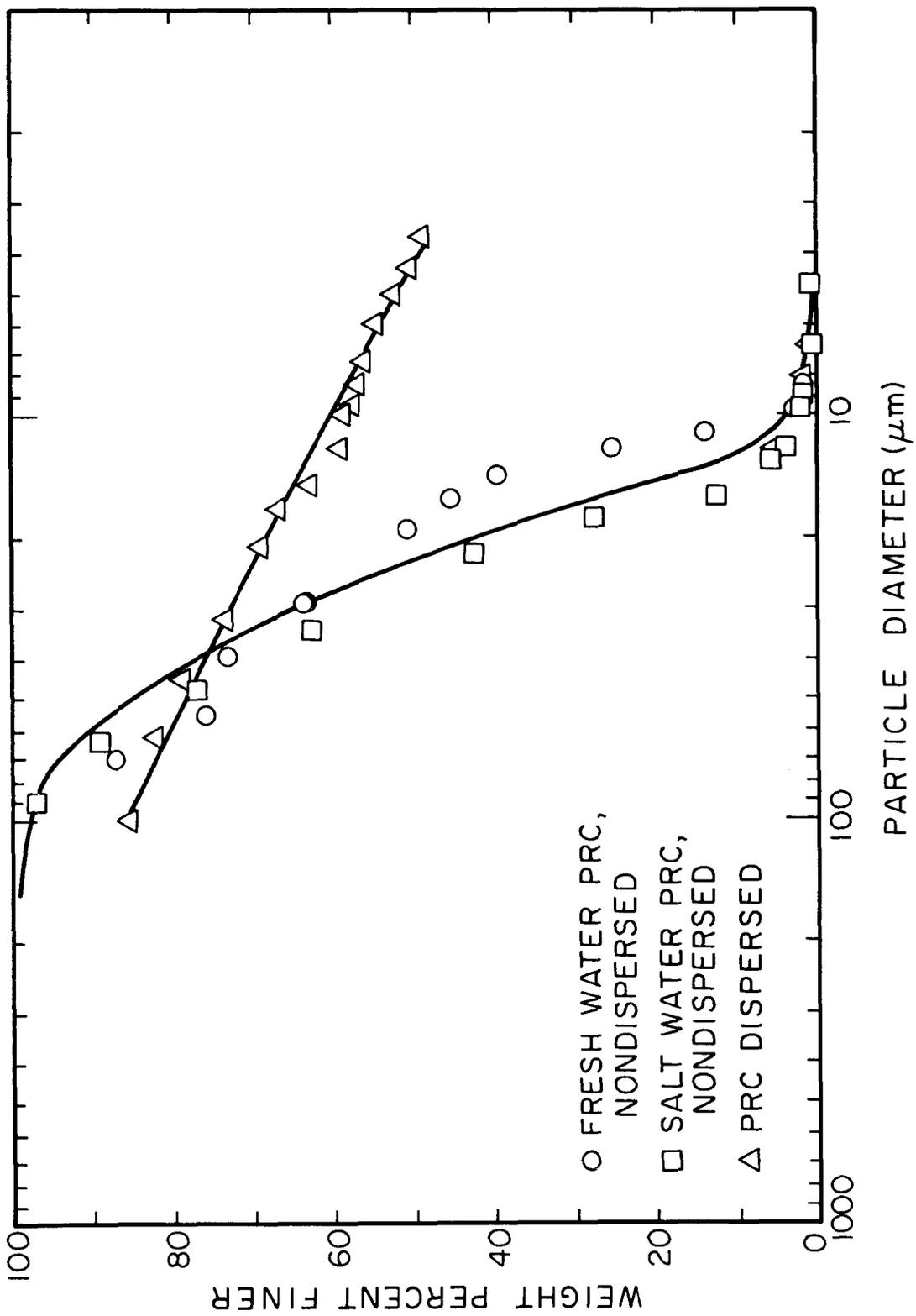


Fig. 9. Particle size distribution of PRC

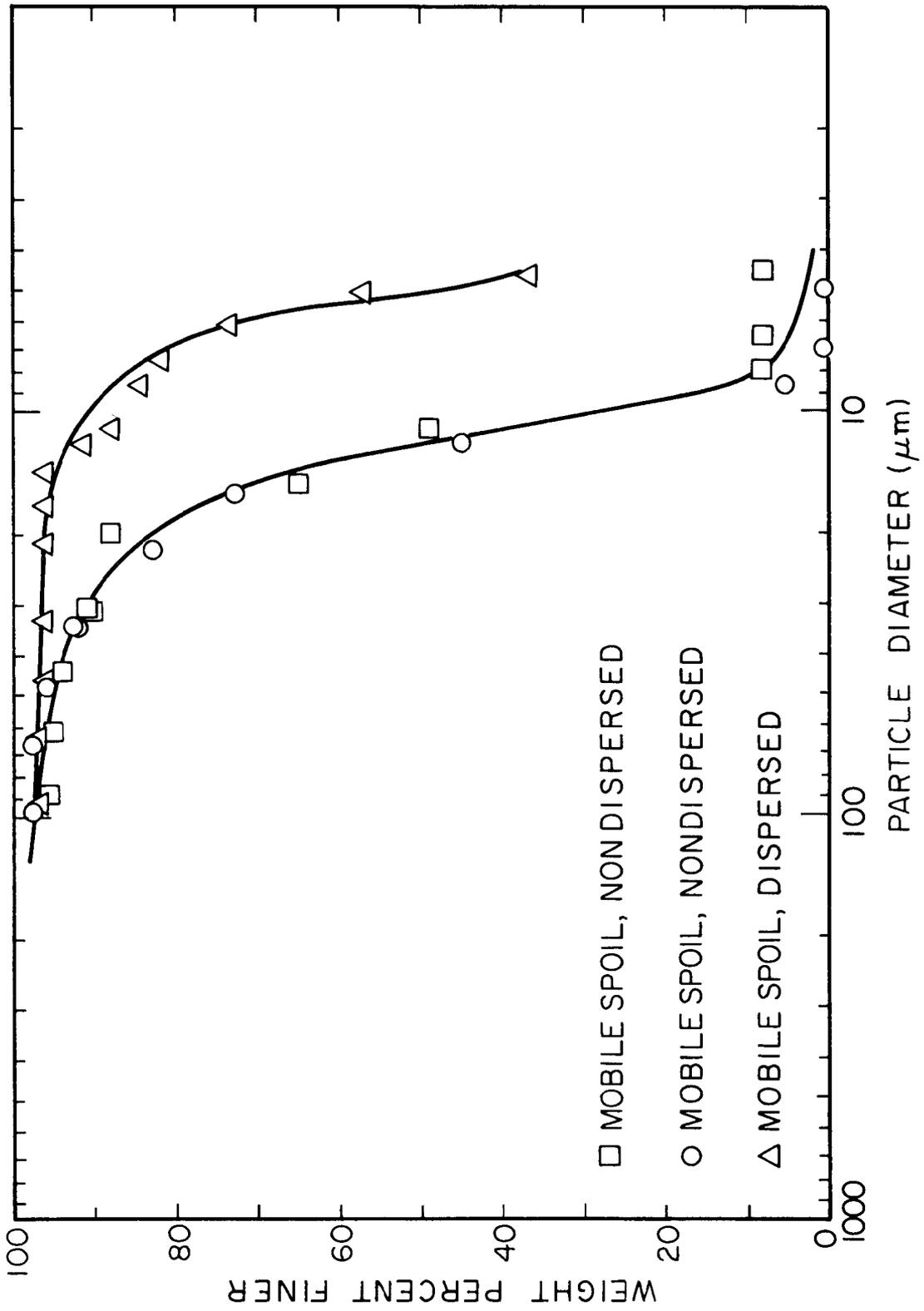


Fig. 10. Particle size distribution of Mobile spoil

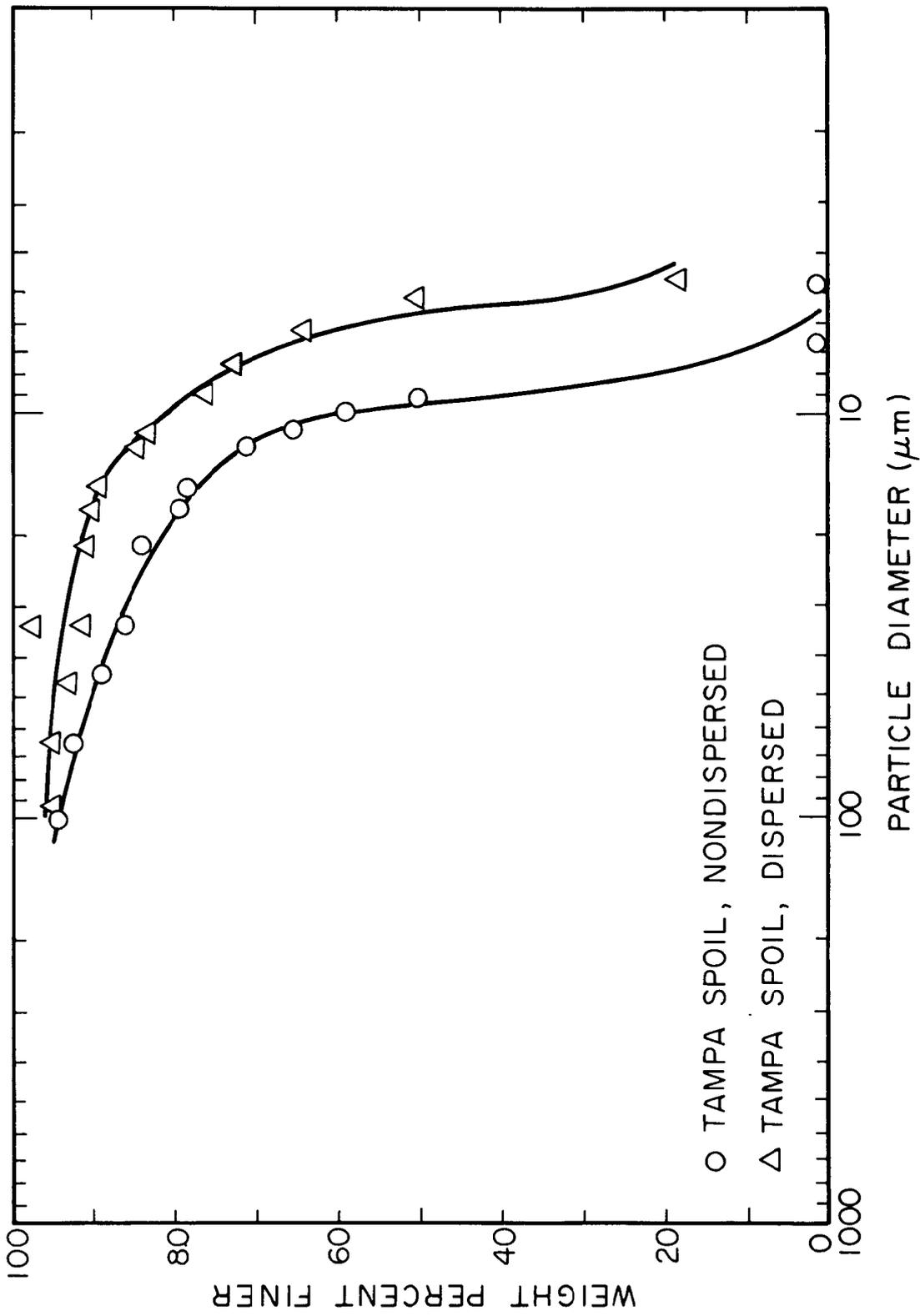


Fig. 11. Particle size distribution of Tampa spoil

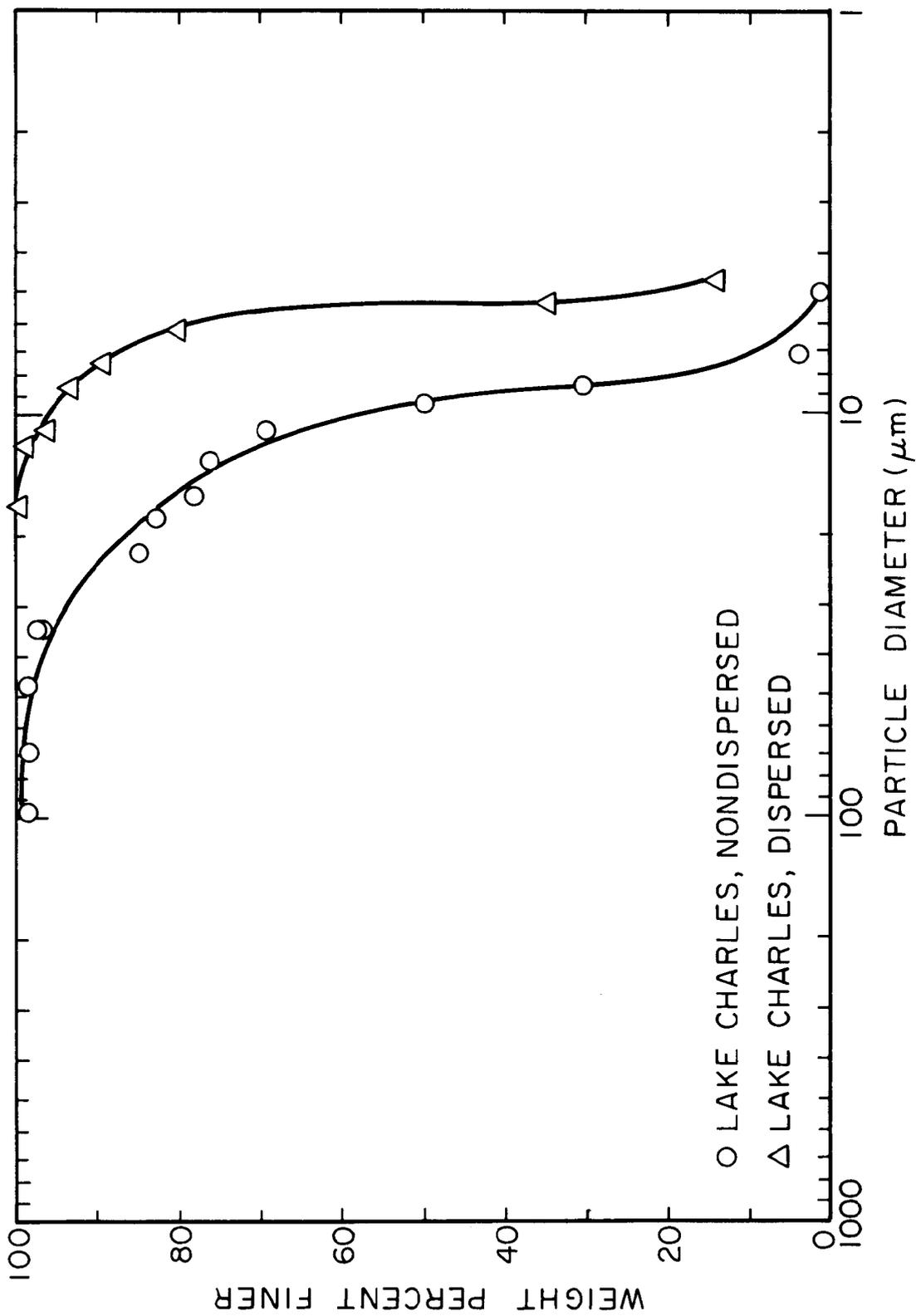


Fig. 12. Particle size distribution of Lake Charles spoil

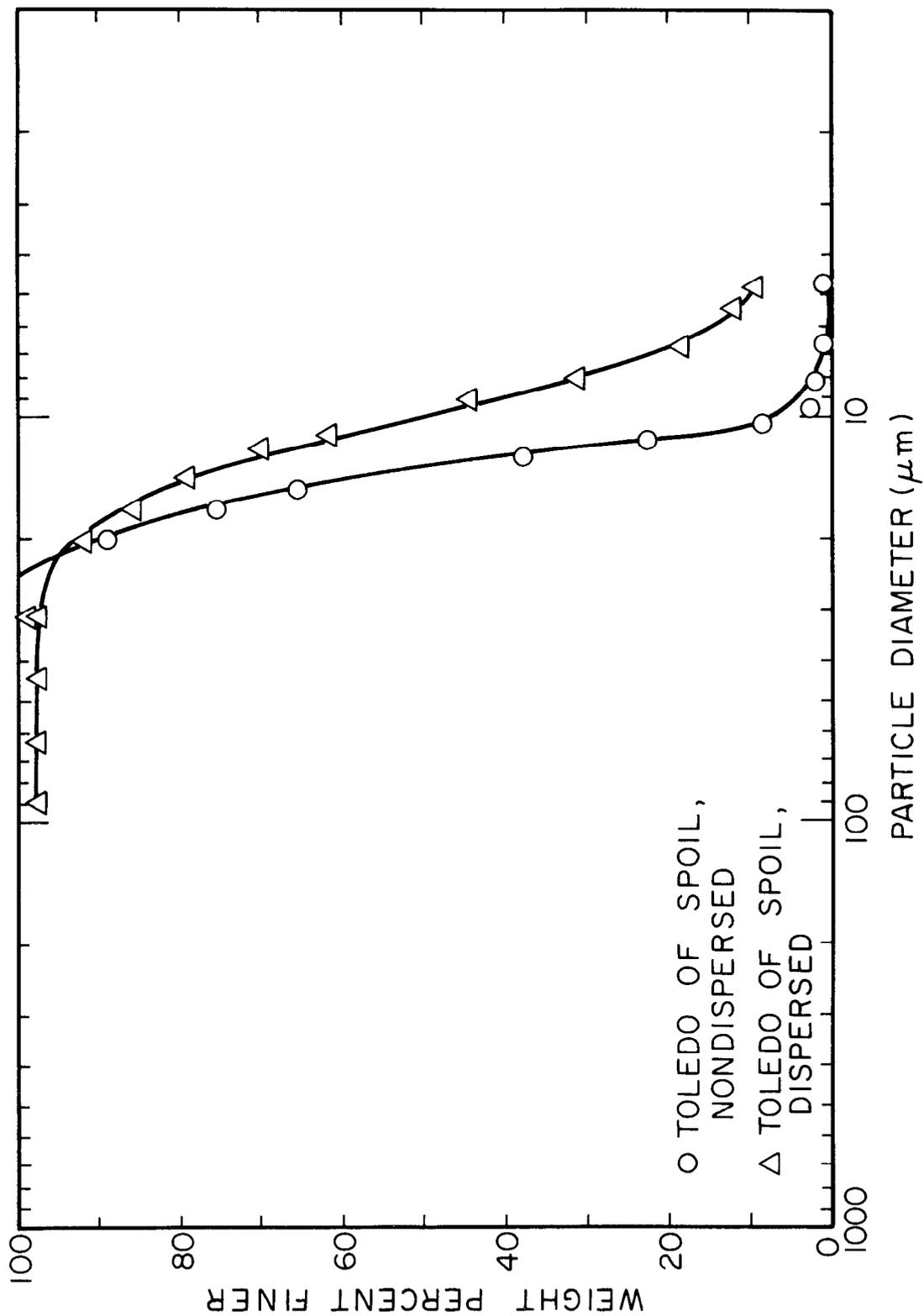


Fig. 13. Particle size distribution of Toledo OF spoil

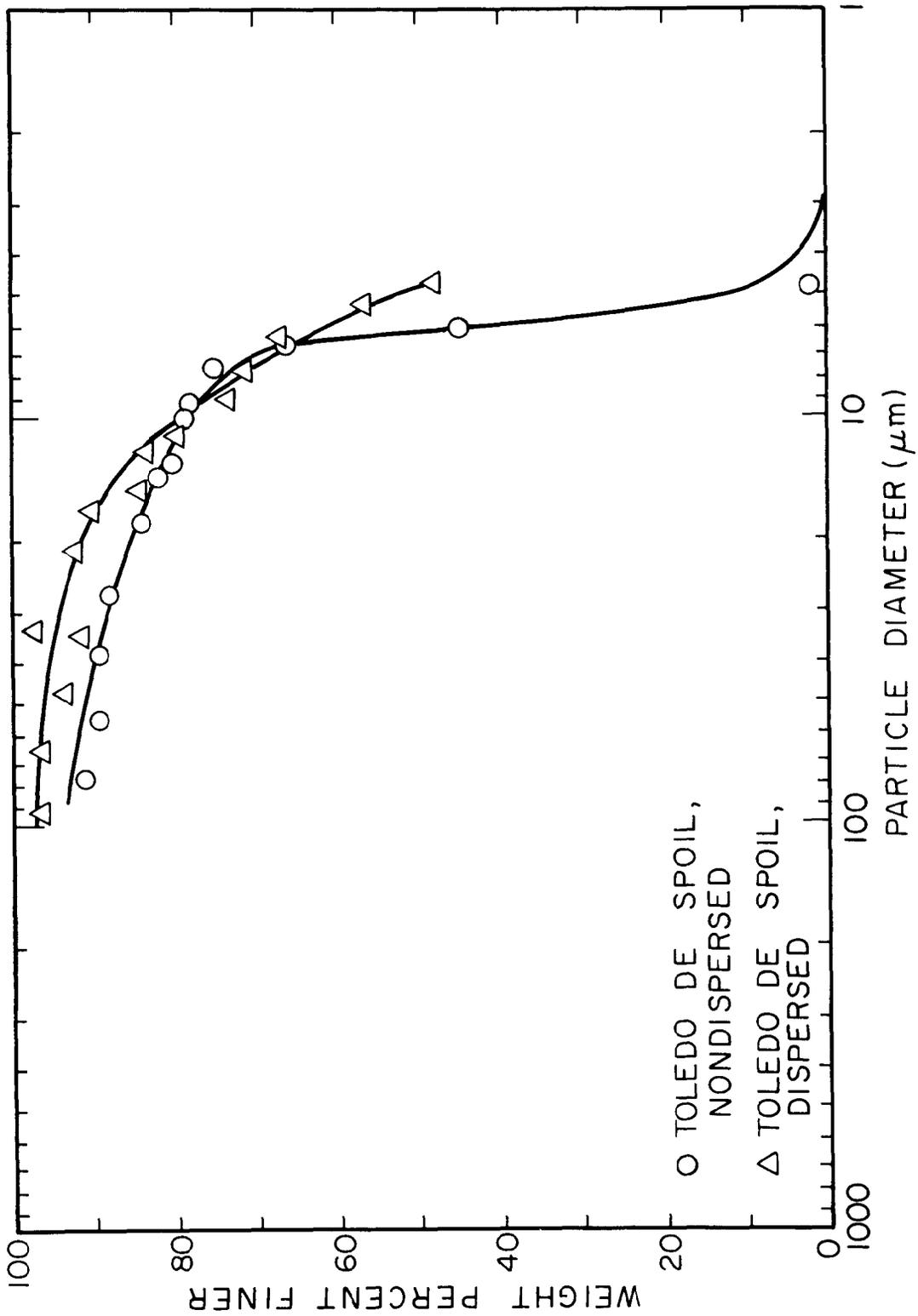


Fig. 14. Particle size distribution of Toledo DE spoil

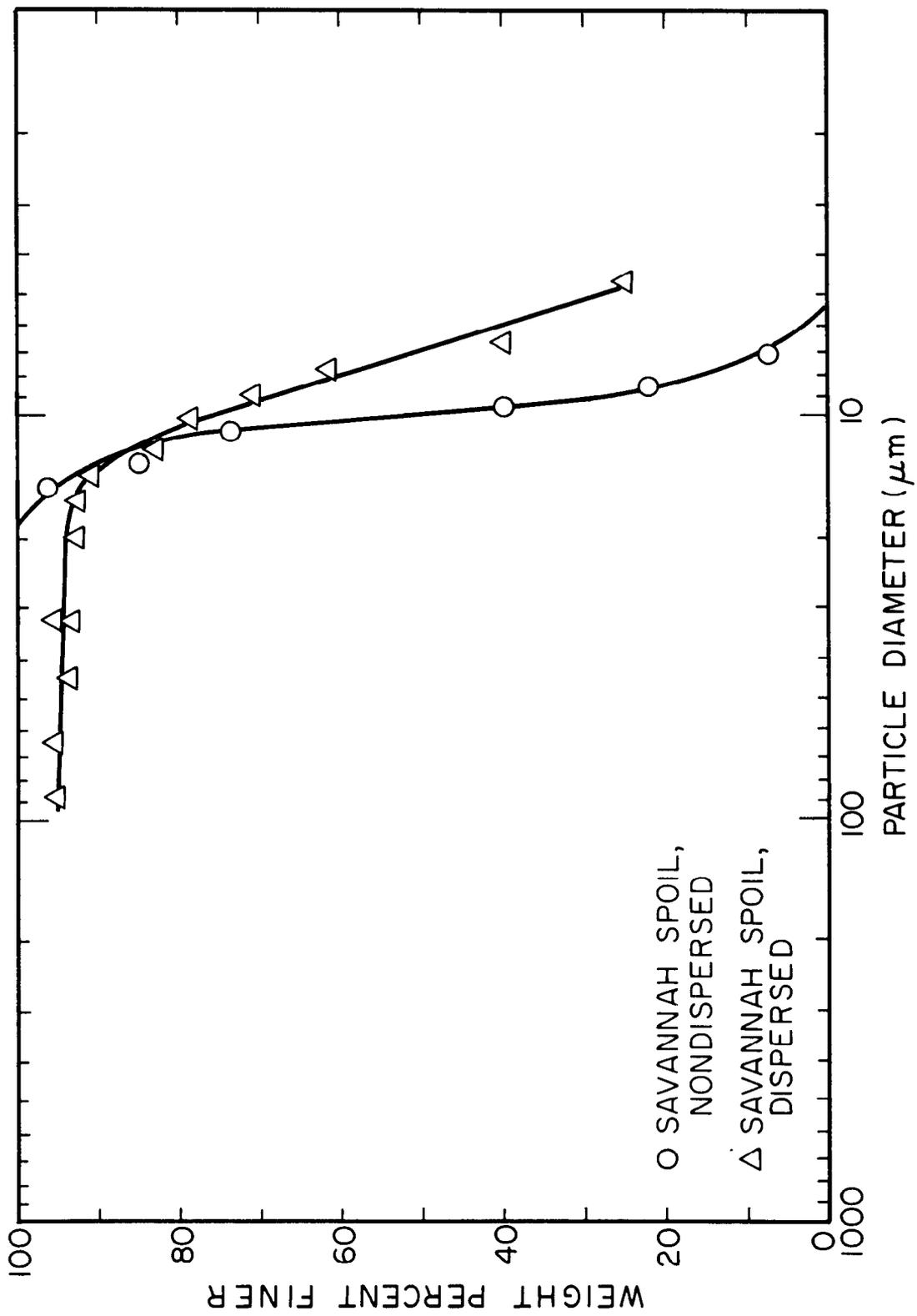


Fig. 15. Particle size distribution of Savannah spoil

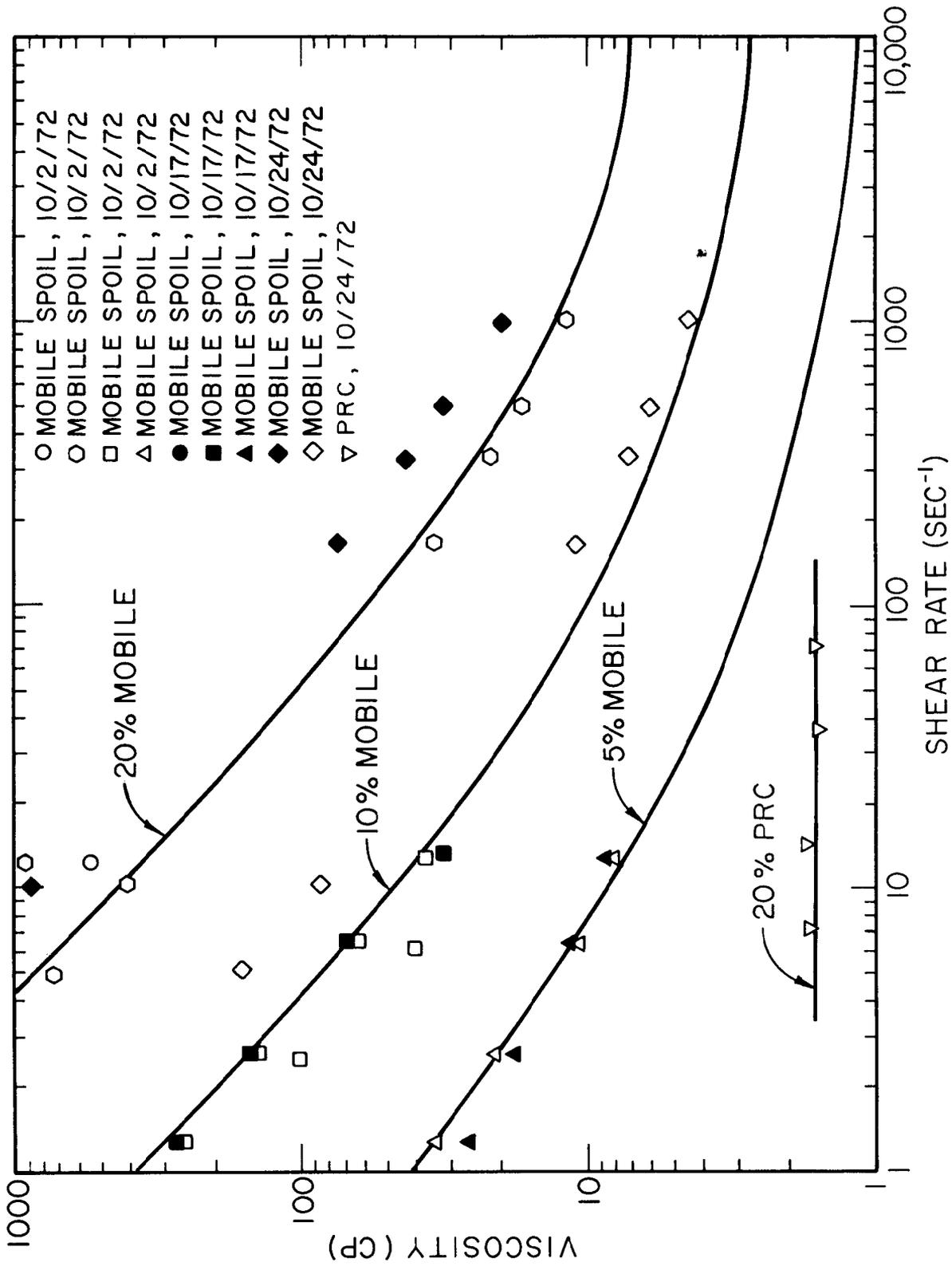


Fig. 16. Effect of shear rate and dilution on the viscosity of Mobile spoil

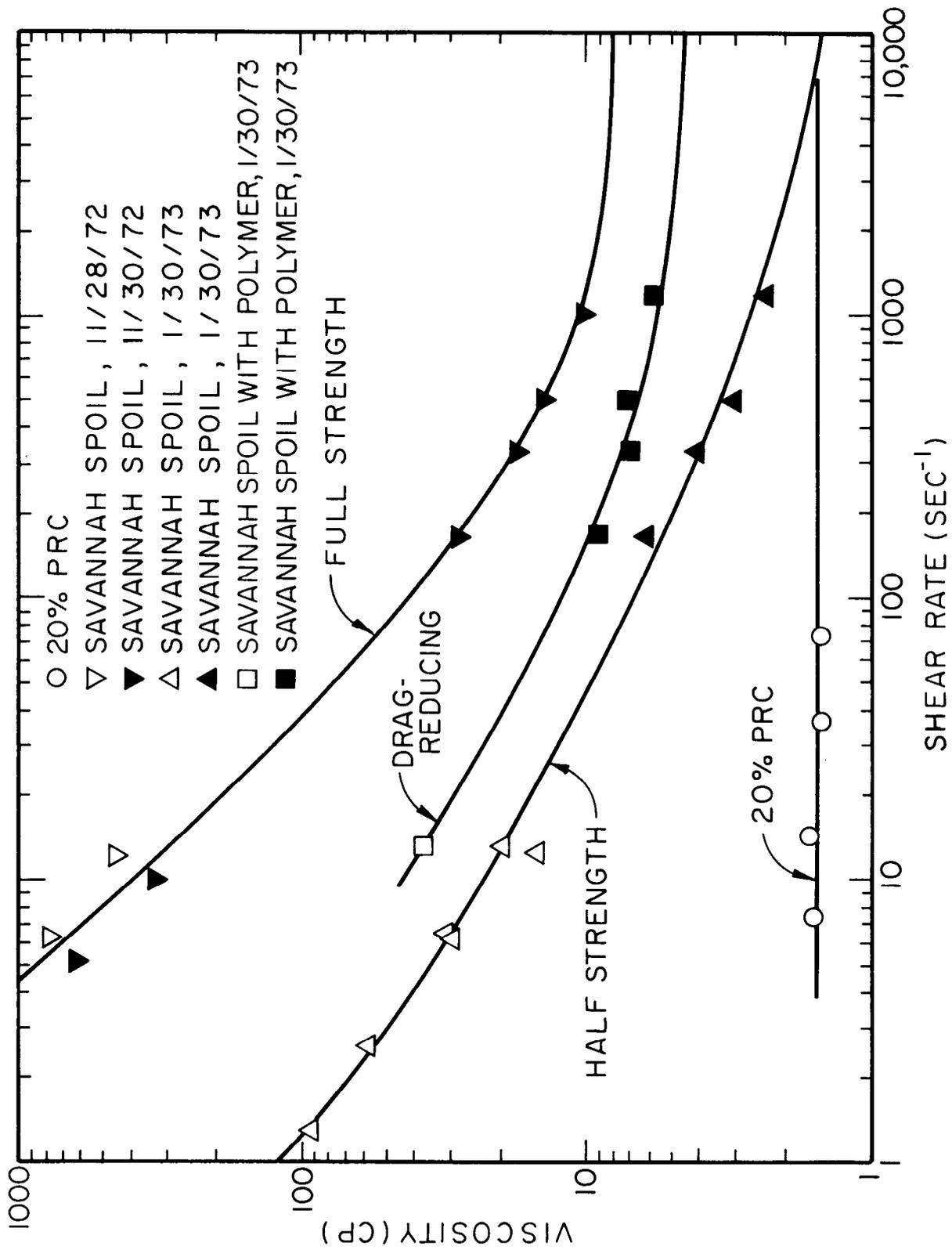


Fig. 17. Effect of shear rate, dilution, and polymer additives on the viscosity of Savannah spoil

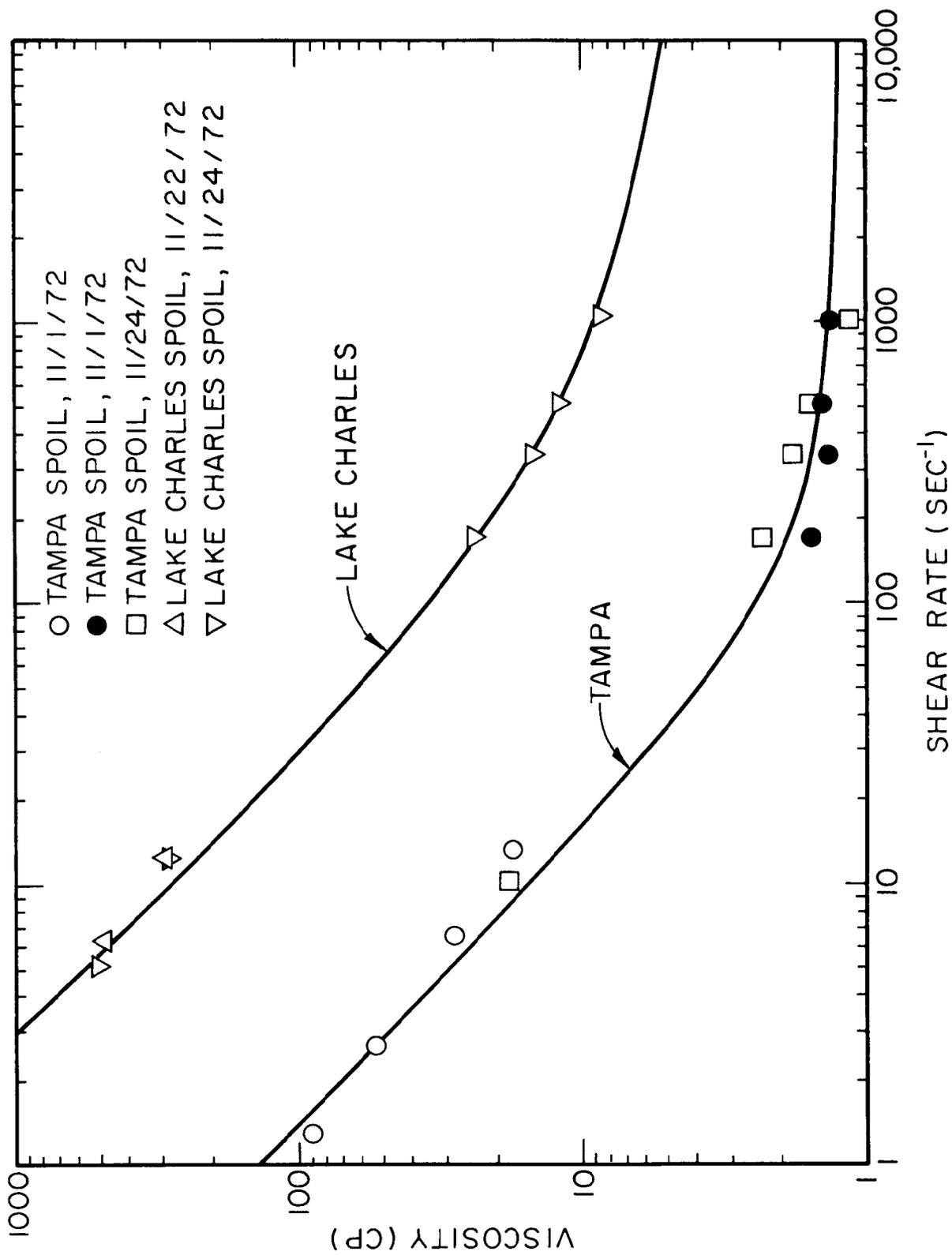


Fig. 18. Effect of shear rate on the viscosity of Tampa and Lake Charles spoil

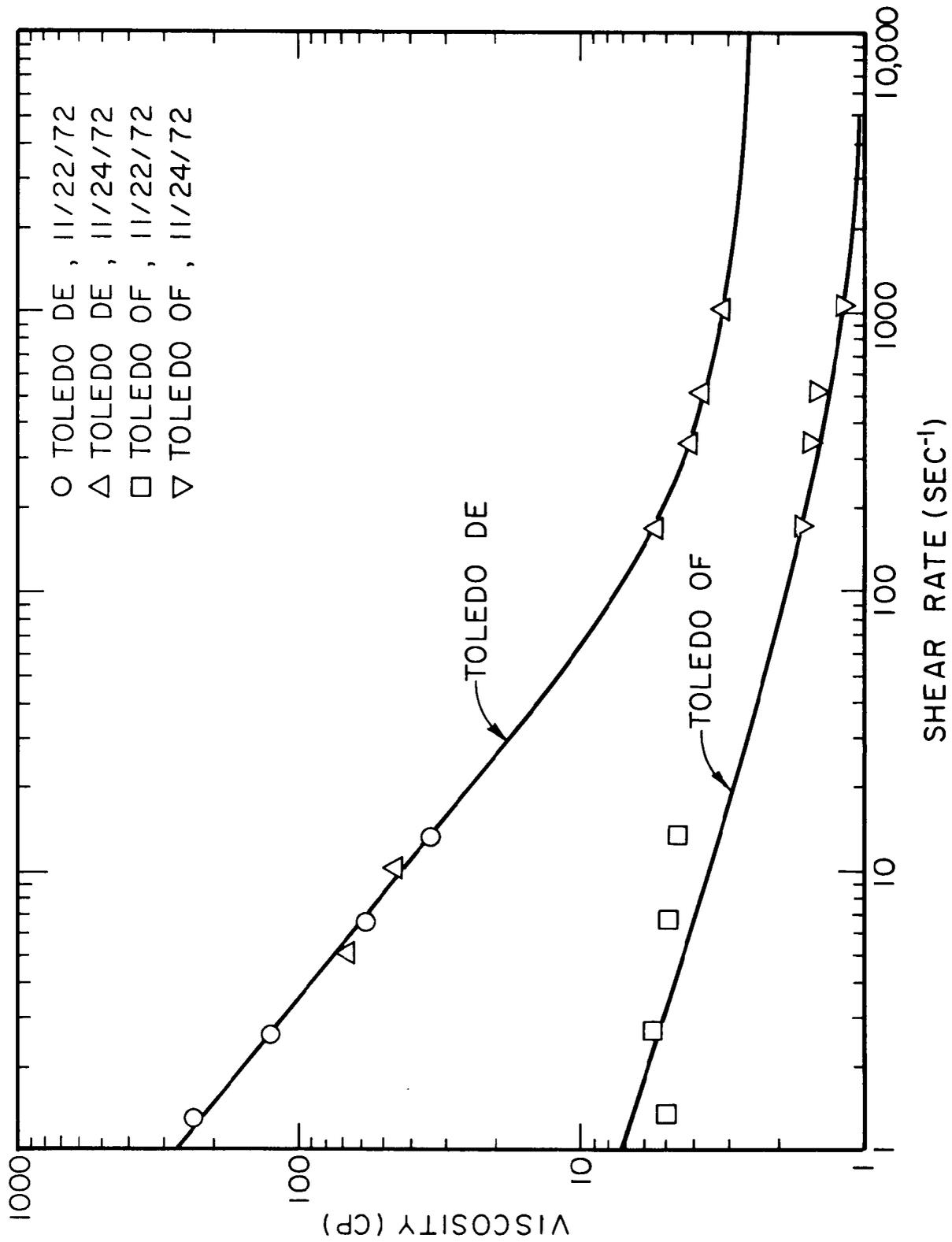


Fig. 19. Effect of shear rate on the viscosity of Toledo OF and Toledo DE spoil

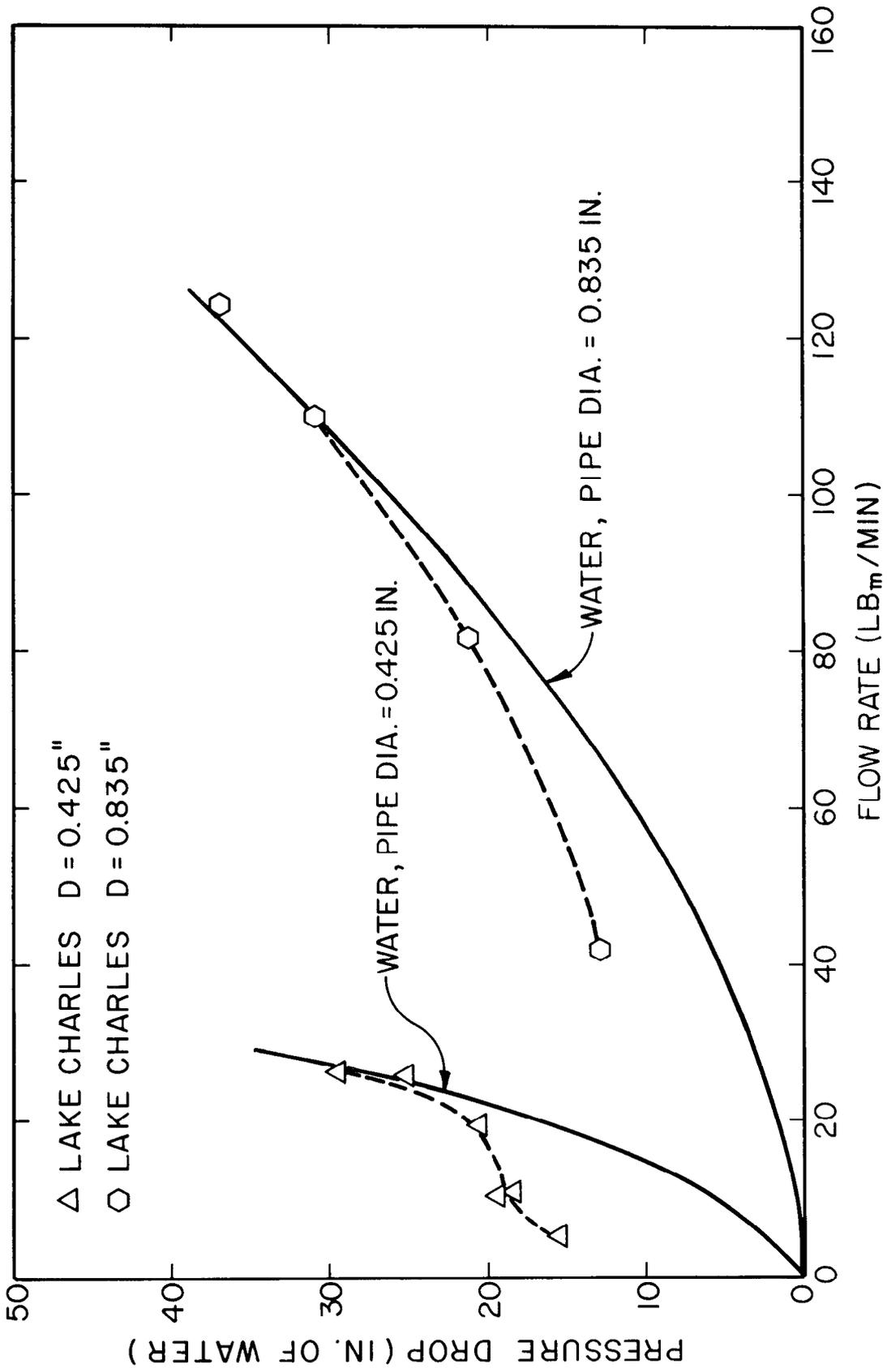


Fig. 20. Pipe flow results for Lake Charles spoil

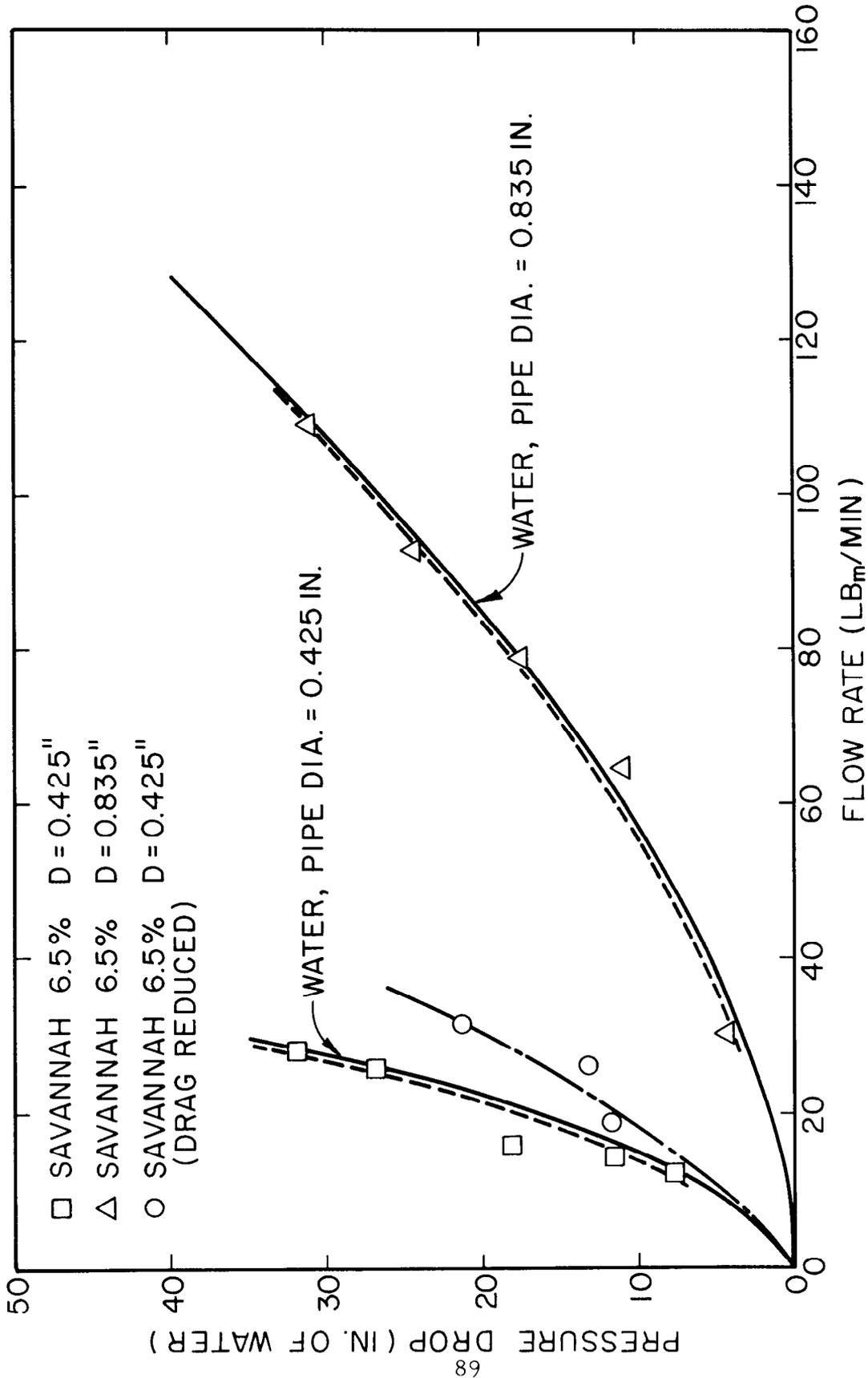


Fig. 21. Pipe flow and drag-reduction results for Savannah spoil

TABLE 2

SUMMARY OF THE CLARIFICATION ACHIEVED WITH A LABORATORY CENTRIFUGE

Spoil	Elapsed Time in Centrifuge (min.)	Volume of Clarified Supernate in 100 ml Tubes (ml/100 ml)		
		rcf		
		200	400	800
Mobile	5	4	7	-
Mobile	10	10	16	-
Mobile	20	-	-	40
Mobile	40	-	-	55
Mobile	60	-	-	60
Tampa	5	45	59	72
Tampa	10	65	74	82
Lake Charles	5	2	8	14
Lake Charles	10	6	21	33
Toledo OF	5	85	88	90
Toledo OF	10	87	90	92
Toledo DE	5	11	22	32
Toledo DE	10	36	49	61
Savannah	5	7	17	28
Savannah	10	17	28	40

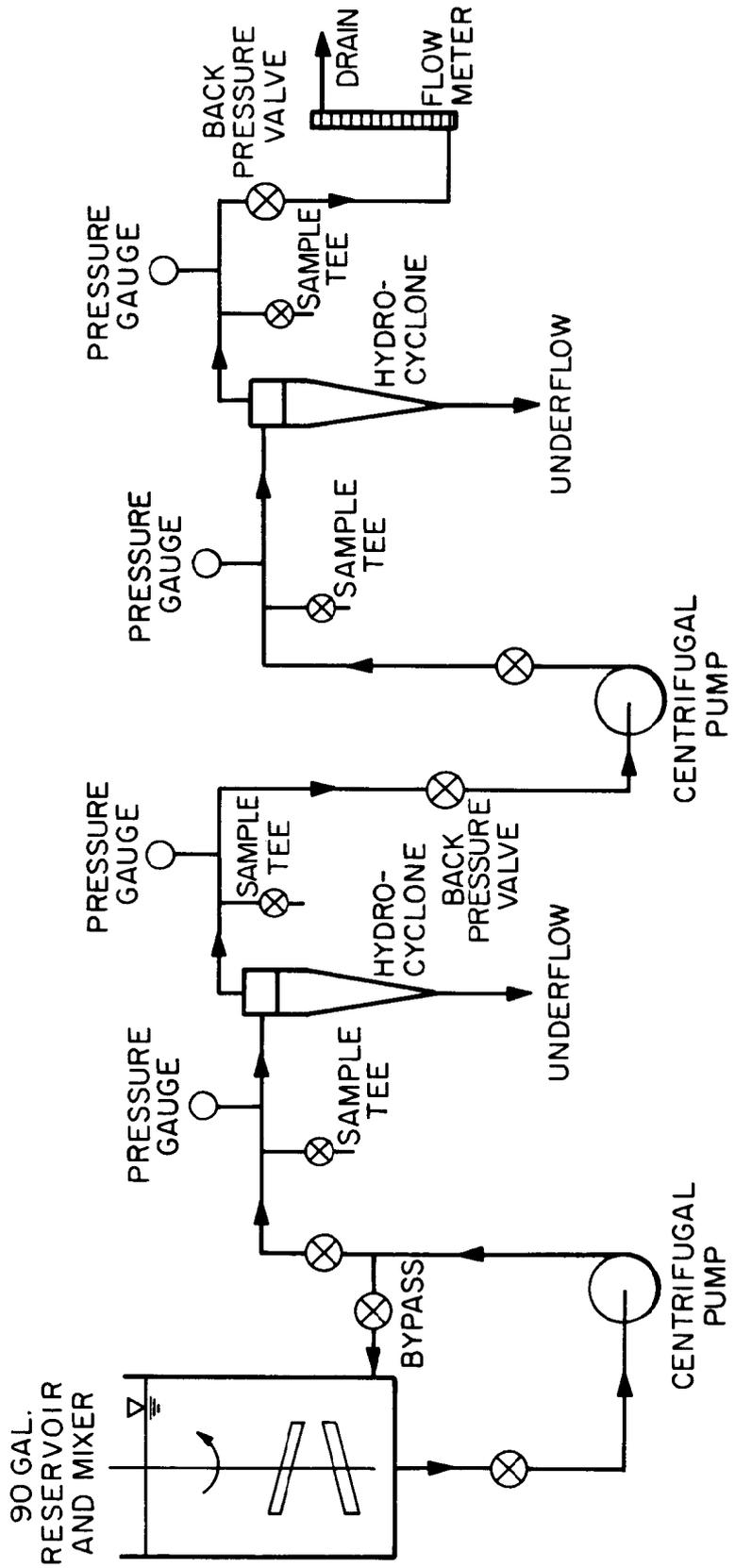


Fig. 22. Schematic of the I<sub>c</sub> - II<sub>b</sub> hydrocyclone series test stand

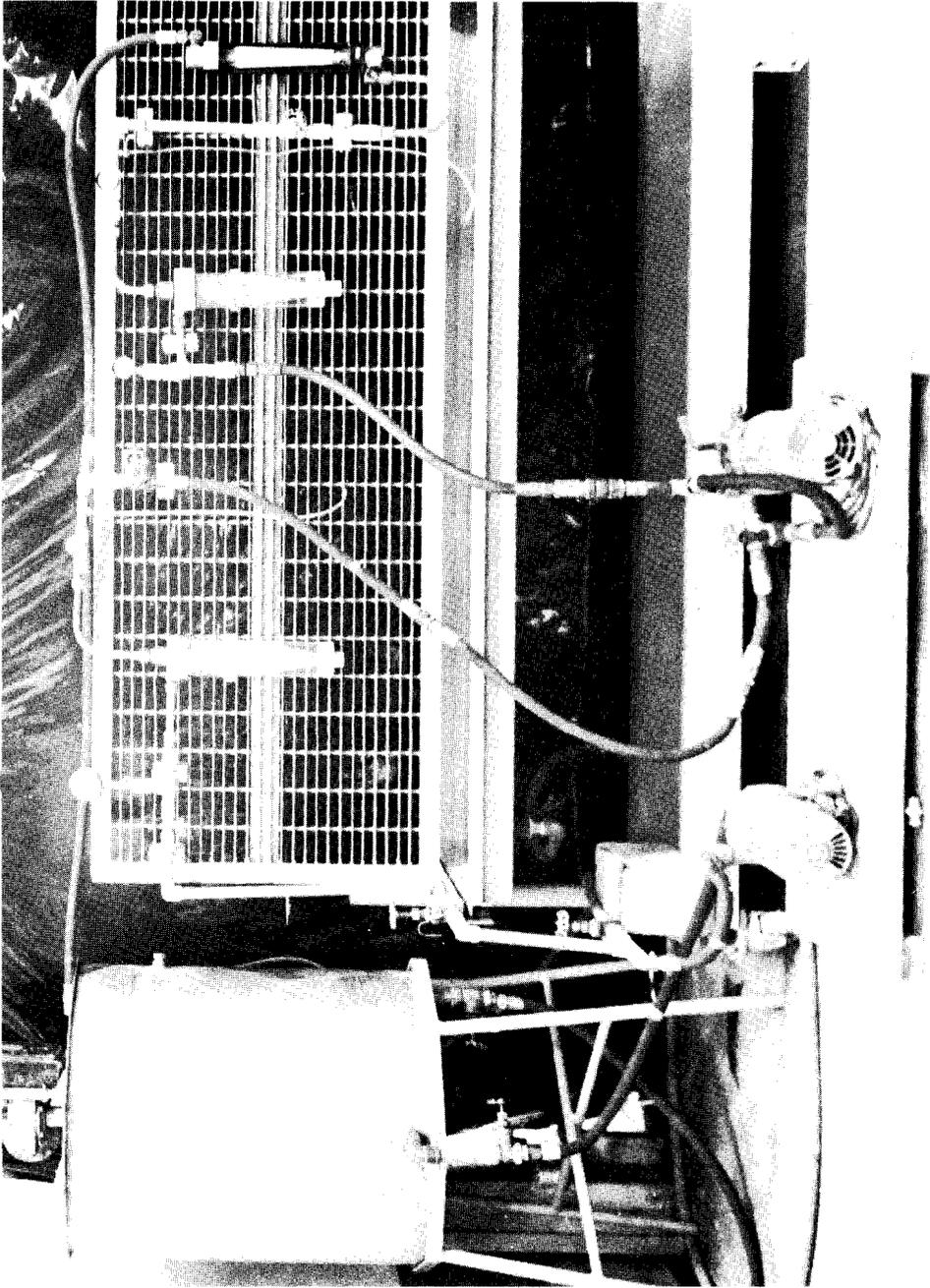


Fig. 23. I - II<sub>c</sub> hydrocyclone series test stand



Fig. 24. Internal view of the 90 gallon reservoir with mixer & baffles

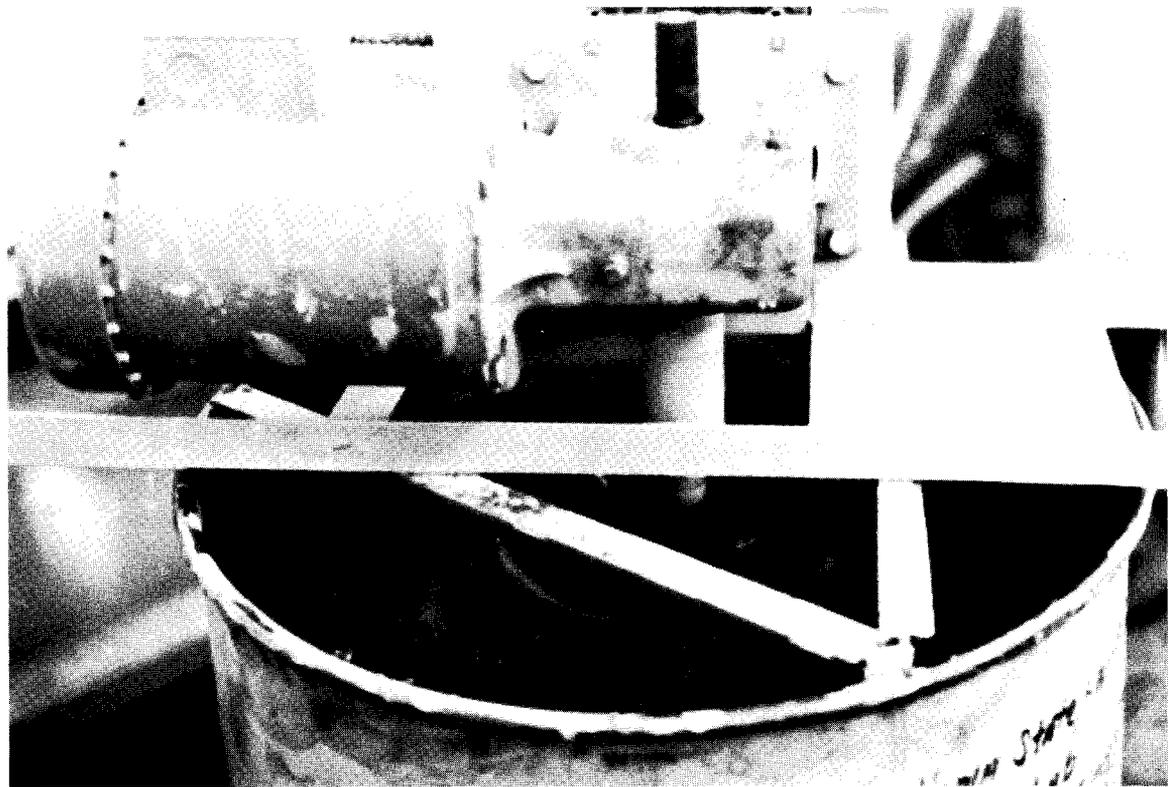


Fig. 25. Mixing of spoil prior to transfer from shipping barrel

TABLE 3  
PERFORMANCE SUMMARY OF THE I<sub>c</sub>-II<sub>b</sub> HYDROCYCLONE SERIES

Working Fluid	I <sub>c</sub> Inlet Flow Rate (GPM)	I <sub>c</sub> Inlet Gravimetric (g/ℓ)	II <sub>b</sub> Overflow Gravimetric (g/ℓ)	Clarification Number (C <sub>N</sub> 'S)	Concentration Index (C <sub>I</sub> 'S)
RMGC	13.3	4.5	1.5	0.67	2.54
RMGC	13.0	35.5	14.3	0.60	3.14
PRC	13.4	4.3	0.82	0.81	4.06
5% Mobile	11.6	43.0	32.1	0.25	1.06
Tampa	12.5	42.4	26.4	0.38	1.73
Tampa	12.9	21.1	12.7	0.40	1.23
Lake Charles	11.6	174.1	148.9	0.14	0.57
Toledo OF	12.8	53.1	36.2	0.32	1.54
Toledo DE	-	215.5	143.5	0.33	1.32
Toledo DE	10.8	208.6	144.6	0.31	0.94
Savannah	10.8	113.4	95.9	0.16	0.24

TABLE 4

COMPARISON OF THE CLARIFICATION EFFECTIVENESS  
OF HYDROCYCLONES OPERATING ON DISPERSED  
AND NON-DISPERSED CLAY SLURRIES

Run Number	Unit	Working Fluid	$G_i$ (g/l)	$C_N$
Slur-13	I	RMGC	25.7	.46
Slur-14	I	RMGC (dispersed)	14.6	.32
Slur-18	4DM	RMGC	5.0	.69
Slur-23	4DM	RMGC (dispersed)	5.1	.29
Slur-31	4DM	PRC	4.8	.84
Slur-32	4DM	PRC (dispersed)	5.0	.45

TABLE 5

COMPARISON OF HYDROCYCLONE PERFORMANCE  
ON MOBILE SPOIL AND PRC SLURRIES

Unit	Working Fluid	Inlet Flow Rate (GPM)	Overflow Flow Rate (GPM)	Clarification Number $C_N$
4CM	$\frac{1}{2}$ % PRC	11.8	10.0	0.77
4CM	20% Mobile	14.0	9.1	0.04
4CM	10% Mobile	15.4	11.7	0.20
4CM	5% Mobile	15.4	12.0	0.18
$I_c$	$\frac{1}{2}$ % PRC	13.4	11.2	0.79
$I_c$	20% Mobile	13.1	10.6	0.11
$I_c$	10% Mobile	12.5	11.1	0.18
$I_c$	5% Mobile	13.0	11.2	0.24
$II_b$	10% Mobile	10.7	10.0	0.15
$II_b$	5% Mobile	10.7	10.0	0.22
M8A	20% Mobile	7.8	6.8	0.06

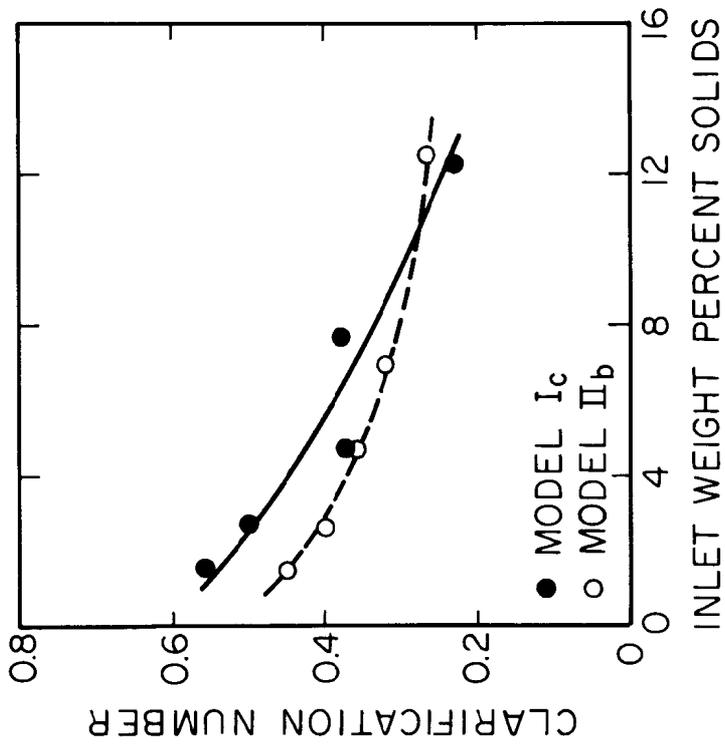


Fig. 26. Effect of RMGC inlet solids concentration upon  $C_N$  for the  $I_c$  and  $II_b$  hydrocyclones

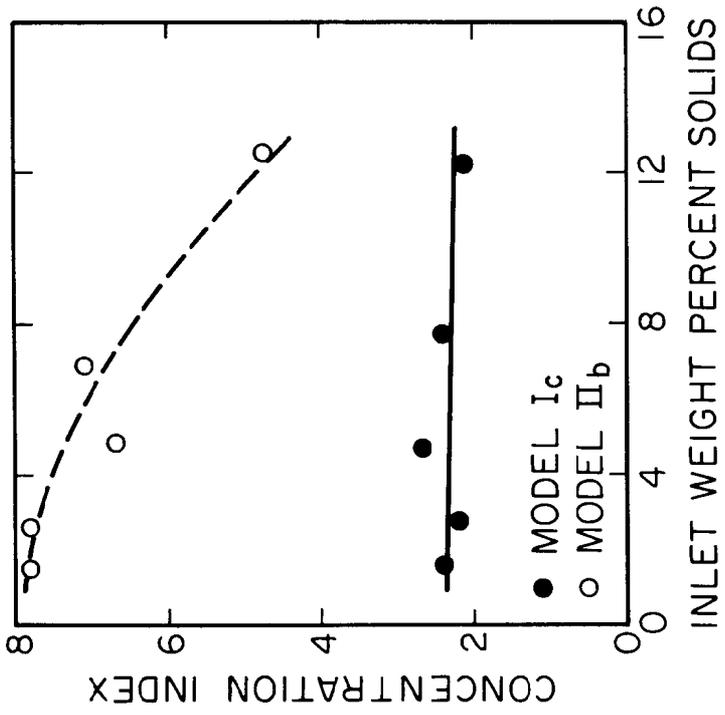


Fig. 27. Effect of RMGC inlet solids concentration upon  $C_I$  for the  $I_c$  and  $II_b$  hydrocyclones

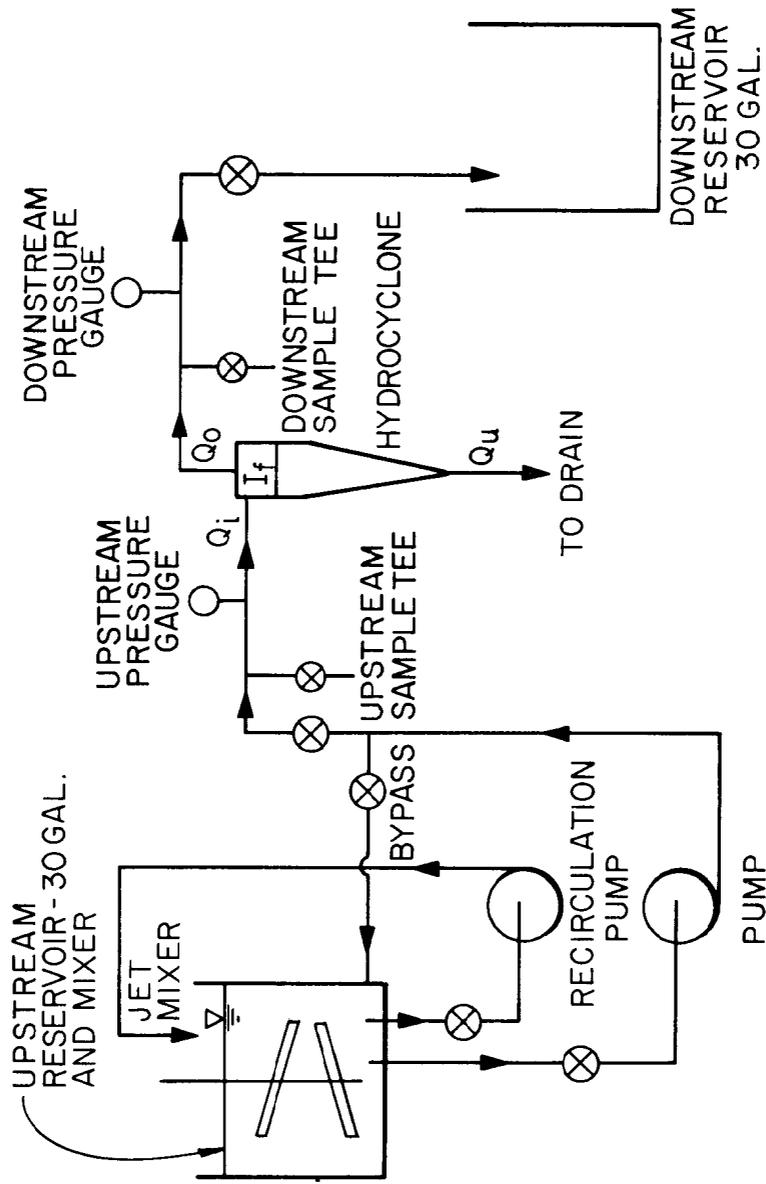


Fig. 28. Schematic of the classifier test stand

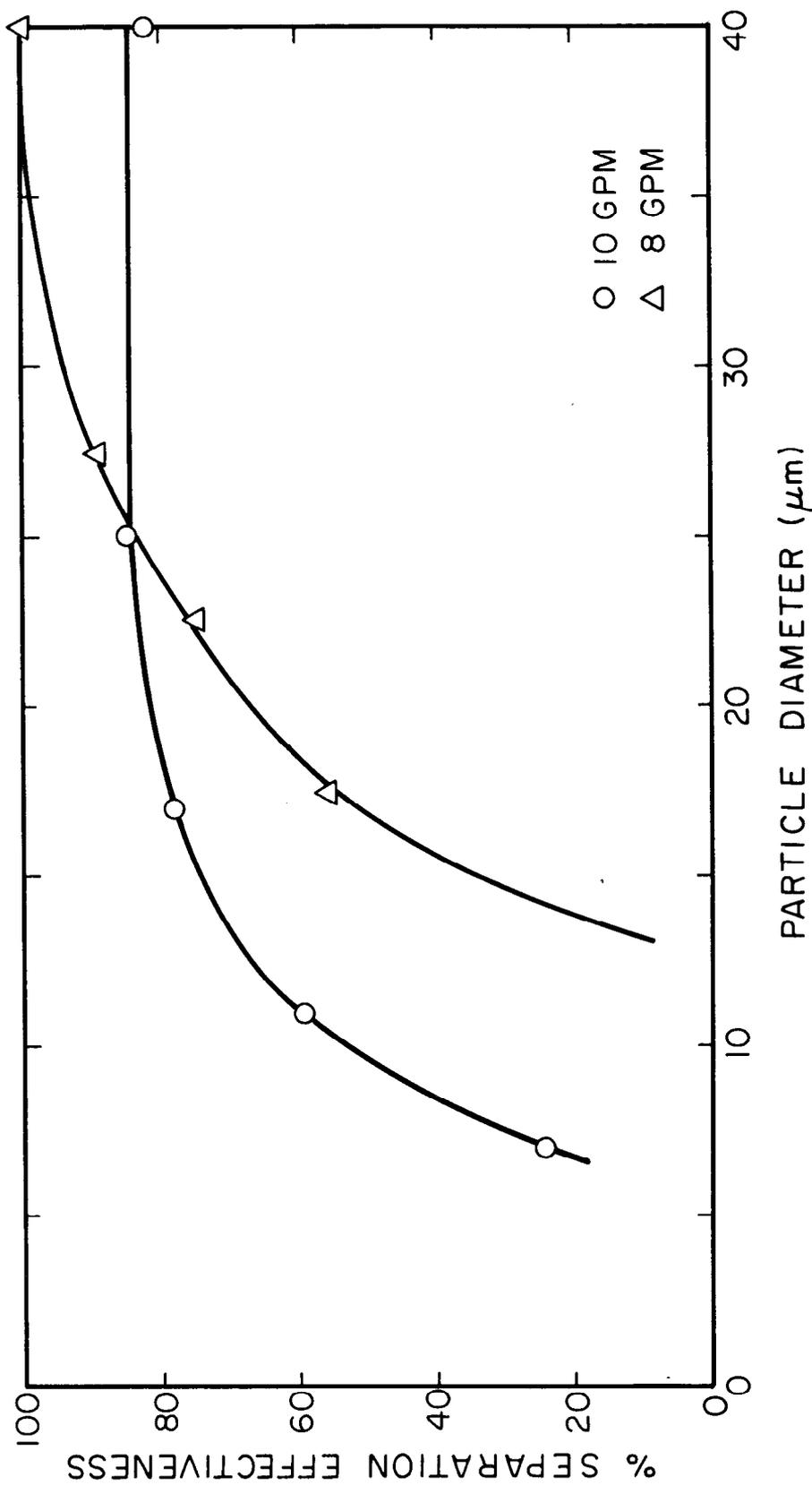


Fig. 29. Effect of particle size upon the separation effectiveness of the  $I_f$  classifier

TABLE 6

SUMMARY OF RESULTS WITH THE HYDROCYCLONE CLASSIFIER MODEL I<sub>f</sub>

Working Fluid	Inlet Gravimetric (g/ℓ)	Overflow Gravimetric (g/ℓ)	Underflow Gravimetric (g/ℓ)	Clarification Number C <sub>N</sub>	Concentration Index C <sub>I</sub>
RMGC	29.0	16.1	73.7	0.45	1.54
RMGC and Sapulpa sand	51.4	19.8	182.7	0.61	2.56
PRC	24.2	9.2	85.5	0.62	2.53
PRC and Sapulpa sand	59.6	11.4	254.7	0.81	3.28
5% Mobile	45.8	35.5	82.5	0.22	0.80
5% Mobile and Sapulpa sand	71.8	32.5	262.6	0.55	2.66
Toledo OF	60.0	42.6	135.4	0.29	1.26
Toledo OF and Sapulpa sand	75.8	44.2	298.4	0.42	2.94
Savannah	113.8	99.3	182.5	0.13	0.60
Savannah and Sapulpa sand	141.9	102.3	300.7	0.28	1.12



TABLE 7

SUMMARY OF THE CLARIFICATION AND CONCENTRATION  
EFFECTIVENESS OF THE OVER-UNDER SERIES

First Unit	Underflow Unit(s)	Working Fluid	$G_i$ of First Unit (g/l)	$C_N$ of First Unit	$(C_N)_S$	$(C_I)_{max}$
4DM	I	RMGC	4.4	0.69	0.13	23.0
4DM	T6	RMGC	3.8	0.65	-0.02	4.6
9M	I-II	RMGC	4.0	0.65	0.28	23.5
9M	I-II	PRC	4.3	0.83	0.59	39.7
9M	I-II	ACFTD	4.6	0.73	0.58	20.5
4DM	I-II	RMGC <sup>1</sup>	5.1	0.29	0.15	11.2
10M	I <sub>a</sub> -II	PRC	4.5	0.82	0.68	10.7
9AM	I <sub>a</sub> -II	PRC <sup>2</sup>	4.6	0.90	0.61	10.7

<sup>1</sup>Dispersed with Calgon water softener.

<sup>2</sup>Chemically coagulated with 1 mg/l Calgon 2690, 10 mg/l alum, 10 mg/l ferric sulfate.

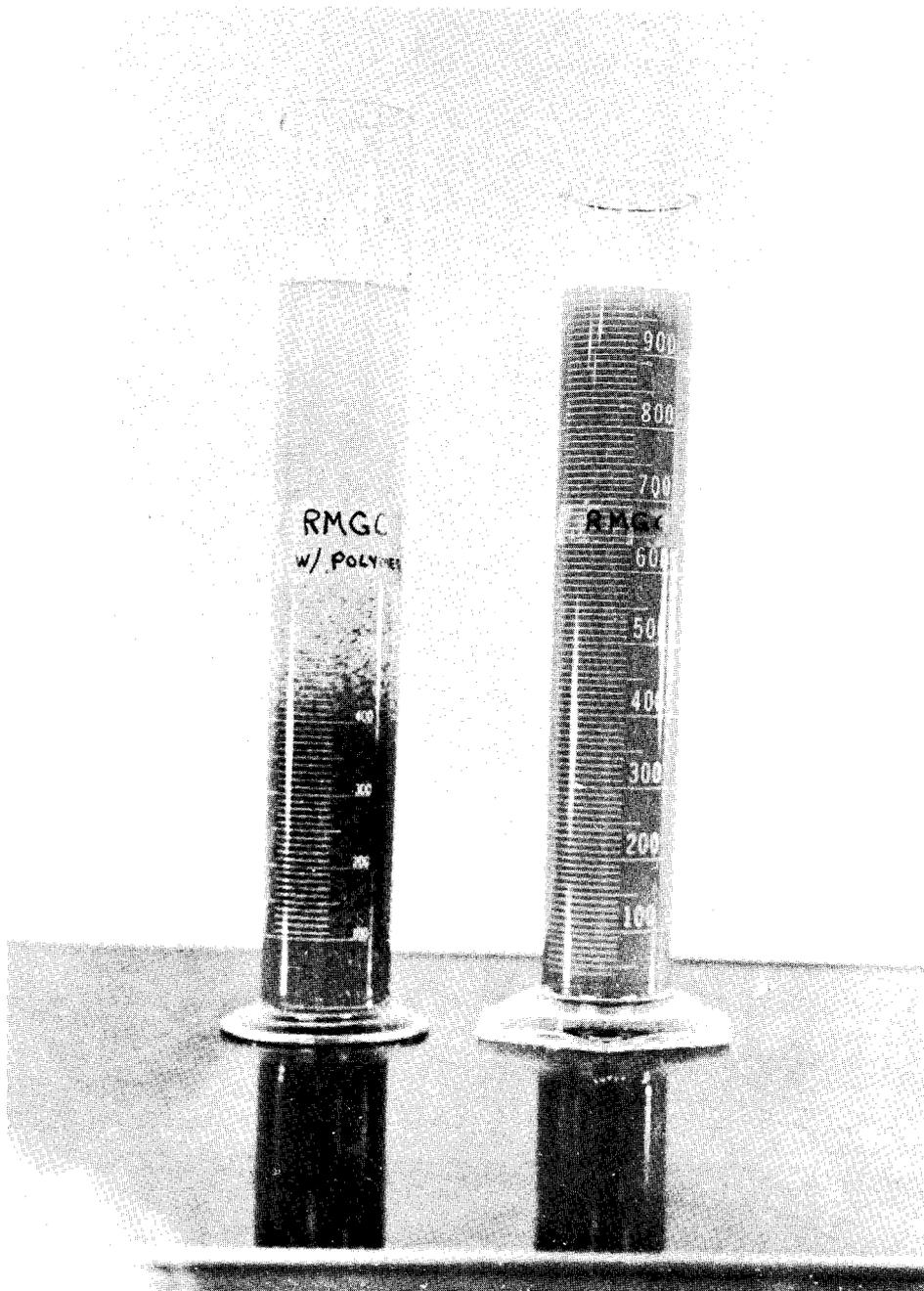


Fig. 31. Illustrations of thickening test using RMGC

TABLE 8

COMPARISON OF HYDROCYCLONE PERFORMANCE  
WITH AND WITHOUT CHEMICAL TREATMENT

Run Number	Hydrocyclone Units	C <sub>N</sub> for the individual units	(C <sub>N</sub> ) <sup>2</sup>	C <sub>I</sub> for the individual units	Working Fluid
Slur-38	4DM/I <sub>a</sub> /II	.84/.20/ -	0.87	1.4/1.3/1.3	PRC <sup>1</sup>
Slur-31	4DM/I/II	.84/.15/.06	0.86	.8/3.3/1.2	PRC
Slur-52	I <sub>b</sub> /II <sub>b</sub>	.79/.17	0.82	8.1/2.6	PRC <sup>1</sup>
Slur-51	I <sub>b</sub> /II <sub>b</sub>	.76/.13	0.79	8.5/2.7	PRC
Slur-55	I <sub>c</sub> /II <sub>b</sub>	.80/.07	0.81	5.1/2.3	PRC <sup>1</sup>
Slur-54	I <sub>c</sub> /II <sub>b</sub>	.79/.09	0.81	5.0/2.0	PRC
Spoil-14	I <sub>c</sub> /II <sub>b</sub>	.34/.07	0.39	2.4/0.5	Tampa <sup>2</sup>
Spoil-12	I <sub>c</sub> /II <sub>b</sub>	.34/.06	0.38	2.3/0.6	Tampa
Spoil-16	I <sub>c</sub> /II <sub>b</sub>	.23/.20	0.38	1.4/0.6	Tampa <sup>3</sup>
Spoil-15	I <sub>c</sub> /II <sub>b</sub>	.36/.06	0.40	1.6/0.7	Tampa

<sup>1</sup> 1 mg/ℓ Calgon 2690, 10 mg/ℓ alum, and 10 mg/ℓ ferric sulfate.

<sup>2</sup> 10 mg/ℓ Magnifloc 835A and 10 mg/ℓ ferric sulfate.

<sup>3</sup> 10 mg/ℓ Magnifloc 835A, 10 mg/ℓ alum, and 10 mg/ℓ ferric sulfate.

## APPENDIX A

### TABULATIONS OF RESULTS

This appendix contains four tables which give all of the hydrocyclone separation results and one table which contains the pipe flow data. A brief explanation about how to read Tables A. 1 through A. 4 is in order. When a hydrocyclone series run is listed there are two or three numbers separated by slashes listed under each heading. The first number is the value for the first hydrocyclone in the series, the second number is the value for the second hydrocyclone, etc. For example in Table A. 1, run Spoil-10, the inlet gravimetric concentration of model I<sub>c</sub> was 43.0 g/ℓ and the inlet gravimetric concentration of the model II<sub>b</sub> was 32.6 g/ℓ. Double slashes were used to separate the values for the first hydrocyclone in the "over-under" series from the values listed for the underflow hydrocyclones. However, as before if there were two underflow hydrocyclones they are listed in their respective order in the table and the values are separated by a single slash. For example in Table A. 4, run Slur-27, the inlet flow rate of the first hydrocyclone in the series, model 9M was 19.5 GPM. In this case, there were two underflow hydrocyclones, model I and model II in that order. The model I had an inlet flow rate of 10.5 GPM while the inlet flow rate of model II was 9.9 GPM.

TABLE A.1

SEPARATION RESULTS FOR THE I<sub>c</sub>-II<sub>b</sub> HYDROCYCLONE SERIES

Test	Units	ΔP (psi)	P <sub>o</sub> (psi)	C <sub>1</sub> (GPM)	Q <sub>o</sub> (GPM)	Q <sub>u</sub> (GPM)	Q <sub>u</sub> /Q <sub>i</sub> (%)	G <sub>1</sub> (g/l)	G <sub>o</sub> (g/l)	G <sub>u</sub> (g/l)	C <sub>N</sub>	C <sub>I</sub>	E	(C <sub>N</sub> ) <sup>1</sup> /S	(C <sub>I</sub> ) <sup>1</sup> /S	Working Fluid
Slur-54	I <sub>c</sub> /II <sub>b</sub>	39/43	12/8	13.36/11.2	11.2 / 10.2	2.16/.46	16.2/4.3	4.25/ .90	.90/ .82	25.47/ 2.74	.79/ .09	5.00/2.05	.66/.08	0.81	4.07	0.5% PRC
Slur-55	I <sub>c</sub> /II <sub>b</sub>	38/43	12/8	13.39/11.3	11.3 / 10.2	2.09/.46	15.6/4.3	4.27/ .87	.87/ .81	26.13/ 2.91	.80/ .07	5.12/2.34	.67/.07	0.81	4.13	0.5% PRC <sup>1</sup>
Slur-56	I <sub>c</sub> /II <sub>b</sub>	39/43	12/8	13.26/11.1	11.1 / 10.1	2.16/.46	16.3/4.4	4.5 / 1.6	1.6 / 1.5	18.56/ 3.5	.64/ .06	3.12/1.19	.54/.06	0.67	2.54	0.5% RMGC
Slur-57	I <sub>c</sub> /II <sub>b</sub>	36/42	10/7	13.03/11.0	11.0 / 10.1	2.03/.47	15.6/4.5	35.5 / 15.1	15.1 / 14.3	173 / 32.4	.58/ .05	3.88/1.15	.48/.05	0.60	3.14	4.0% RMGC
Spoil-10	I <sub>c</sub> /II <sub>b</sub>	32/37	4/0	11.64/ 9.90	9.90 / 9.28	1.74/.62	14.8/6.3	43.0 / 32.6	32.6 / 32.1	100.8 / 53.7	.24/ .02	1.34/ .65	.20/.01	.25	1.06	Mobile 5%
Spoil-11	I <sub>c</sub> /II <sub>b</sub>	40/34	2/0	11.45/ 9.83	9.83 / 9.21	1.62/.62	14.1/6.7	40.5 / 34.8	34.8 / 33.2	104.8 / 51.2	.14/ .04	1.59/ .47	.12/.04	.18	1.24	Mobile 5%
Spoil-12	I <sub>c</sub> /II <sub>b</sub>	35/39	6/0	12.48/10.26	10.26 / 9.57	2.22/.69	17.8/6.7	42.44/ 27.91	27.91/ 26.36	137.97/ 44.74	.34/ .06	2.25/ .60	.28/.05	.38	1.73	Tampa
Spoil-14	I <sub>c</sub> /II <sub>b</sub>	35/40	6/0	12.53/10.28	10.28 / 9.56	2.25/.72	17.9/7.0	44.53/ 29.32	29.32/ 27.20	151.23/ 43.26	.34/ .07	2.40/ .47	.28/.07	.39	1.81	Tampa <sup>2</sup>
Spoil-15	I <sub>c</sub> /II <sub>b</sub>	32/40	9/-	12.90/10.44	10.44 / 9.70	2.46/.74	19.1/7.1	21.14/ 13.47	13.47/ 12.66	54.17/ 23.87	.36/ .06	1.56/ .77	.29/.06	.40	1.23	Tampa
Spoil-16	I <sub>c</sub> /II <sub>b</sub>	35/40	10/-	12.91/10.44	10.44 / 9.70	2.47/.74	19.1/7.1	19.32/ 14.95	14.95/ 11.95	46.69/ 23.47	.23/ .20	1.42/ .57	.18/.19	.38	1.14	Tampa <sup>3</sup>
Spoil-17	I <sub>c</sub> /II <sub>b</sub>	40/41	2/0	11.65/ 8.95	8.95 / 8.36	2.70/.59	23.2/6.6	174.1 / 149.2	149.2 / 148.9	288.0 / 203.3	.14/ .00	.65/ .36	.11/.00	.14	.57	Lake Charles
Spoil-18	I <sub>c</sub> /II <sub>b</sub>	39/41	4/0	12.75/10.79	10.79/10.11	1.96/.68	15.4/6.3	53.1 / 37.1	37.1 / 36.2	158.5 / 66.9	.30/ .02	1.98/ .80	.26/.02	.32	1.54	Toledo OF
Spoil-19	I <sub>c</sub> /II <sub>b</sub>	24/30	2/0	10.76/ 8.93	8.93 / 8.13	1.83/.80	17.0/9.0	113.45/ 92.3	92.3 / 95.93	152.32/112.9	.19/ .04	.34/ .22	.16/-	.16	.24	Savannah
Spoil-20	I <sub>c</sub> /II <sub>b</sub>	27/31	0/0	- / 7.61	7.61 / 7.05	- / .56	- / 7.3	215.5 / 150.5	150.5 / 143.5	577.5 / 250.5	.30/ .05	1.68/ .66	.25/.04	.33	1.32	Toledo DE
Spoil-21	I <sub>c</sub> /II <sub>b</sub>	39/34	1/0	10.76/ 8.95	8.95 / 8.37	1.81/.57	16.9/6.4	208.6 / 150.0	150.0 / 144.6	465.9 / 209.4	.28/ .04	1.23/ .40	.23/.03	.31	.94	Toledo DE

<sup>1</sup>Chemically treated with 1 mg/l of Calgon 2690, 10 mg/l of alum, 10 mg/l of ferric sulfate.<sup>2</sup>Chemically treated with 10 mg/l Magnifloc 835A, 10 mg/l of ferric sulfate.<sup>3</sup>Chemically treated with 10 mg/l Magnifloc 835A, 10 mg/l of alum, 10 mg/l of ferric sulfate.

TABLE A.2  
SEPARATION RESULTS FOR HYDROCYCLONE DEVELOPMENT

Test	Units	2 P (psi)	P <sub>0</sub> (psi)	Q <sub>1</sub> (GPM)	Q <sub>0</sub> (GPM)	Q <sub>u</sub> (GPM)	Q <sub>u</sub> /Q <sub>1</sub> (%)	G <sub>1</sub> (g/2)	G <sub>0</sub> (g/2)	G <sub>u</sub> (g/2)	C <sub>N</sub>	C <sub>1</sub>	E	(C <sub>N</sub> ) <sub>1</sub> / (C <sub>1</sub> ) <sub>1</sub>	Working Fluid
Slur-2	III	50	0	8.04	7.80	0.24	3.1	23.3	14.2	-	0.39	-	-	-	0.5% RMGC
Slur-3	III	70	0	8.77	8.95	0.22	2.5	3.32	1.63	-	0.51	-	0.50	-	0.5% RMGC
Slur-4	II	53	7	9.66	9.4	0.26	2.7	3.36	1.52	-	0.55	-	0.54	-	0.5% RMGC
Slur-5	II	53	7	9.66	-	0.26	2.7	1.44	1.41	-	0.02	-	0.02	-	0.5% RMGC
Slur-6	I	39	8	10.31	10	0.31	2.96	2.94	1.48	-	0.50	-	0.48	-	0.5% RMGC
Slur-7	I	42	9	10.31	10	0.31	2.96	1.45	1.36	-	0.06	-	0.06	-	0.5% RMGC
Slur-8	III	88	8	10.24	10	0.24	2.4	3.31	1.71	-	0.48	-	0.47	-	0.5% RMGC
Slur-9	III	92	8	10.24	10	0.24	2.4	1.67	1.52	-	0.09	-	0.09	-	0.5% RMGC
Slur-10	I	42	20	10.50	10	0.50	4.8	3.65	2.00	31.56	0.45	7.64	0.43	-	0.5% RMGC
Slur-11	I	38	15	10.36	10	0.36	3.5	3.72	2.02	64.63	0.46	16.41	0.44	-	0.5% RMGC
Slur-12	I	40	25	10.64	10	0.64	6.0	3.46	1.86	37.22	0.46	9.76	0.43	-	0.5% RMGC
Slur-13	I/II	35/45	10/5	10.09/9.78	9.78/9.60	.31/.18	3.1/1.8	25.69/13.81	13.81/13.18	456/54.7	.46/.05	16.77/2.95	.45/.04	11.01	1.0% RMGC
Slur-14	I/II	-	-	9.97/9.67	9.67/9.50	.30/.17	3.0/1.8	14.63/9.96	9.96/9.23	173/39.8	.32/.07	10.82/2.99	.31/.06	7.53	1.5% RMGC <sup>1</sup>
Slur-15	4DM	42	16	16.95	15	1.95	11.5	4.01	1.59	22.78	0.60	4.68	0.54	-	0.5% RMGC
Slur-16	4DM	45	40	16.74	13.1	3.64	21.7	5.57	1.84	16.19	0.67	1.91	0.53	-	0.5% RMGC
Slur-17	4DM	43	9	7.9	11.9	6.0	33.5	4.91	1.69	11.97	0.66	1.44	0.44	-	0.5% RMGC
Slur-18	4DM	52	21	8.9	9.2	9.7	51.3	4.98	1.56	8.41	0.69	0.69	0.35	-	0.5% RMGC
Slur-19	4DM	44	16	7.1	9.2	7.9	46.2	4.44	1.56	8.21	0.65	0.85	0.36	-	0.5% RMGC
Slur-20	4DM	32	24	5.0	4.7	10.3	68.7	4.70	1.91	6.15	0.59	0.31	0.19	-	0.5% RMGC
Slur-23	4DM	50	20	18.85	9.1	9.75	51.7	5.13	3.63	6.94	0.29	0.35	0.14	-	0.5% RMGC <sup>1</sup>
Slur-24	4DM	45	15	18.04	9.8	8.23	45.7	5.47	3.68	7.21	0.33	0.32	0.18	-	0.5% RMGC <sup>1</sup>
Slur-25	4DM	40	12	18.54	12	6.54	35.4	5.30	3.73	6.49	0.30	0.22	0.19	-	0.5% RMGC <sup>1</sup>
Slur-31	4DM/I /II	40/36/48	18/22/12	19.1/10.1 / 9.6	10.1/ 9.6 / 9.4	8.95/0.5 / 0.2	4.7 / 5.1 / 2.5	4.82/ .78 / .67	.78/ .67 / .62	8.79/3.37/1.50	.84/.15/ .06	.83/3.3 / 1.2	.44/.14/.06	0.86	0.5% PBC

TABLE A.2 (Continued)

Test	Units	$\Delta P$ (psi)	$P_o$ (psi)	$Q_1$ (GPM)	$Q_o$ (GPM)	$Q_u$ (GPM)	$Q_u/Q_i$ (%)	$C_i$ (g/l)	$G_o$ (g/l)	$C_u$ (g/l)	$C_N$	$C_i$	E	$\{C_N\}$ (C/S)	$\{C_i\}$ (C/S)	Working Fluid
Slur-32	4DM/1/II	52/38/50	26/27/16	19.4/10.5 / 9.9	10.5/ 9.9 / 9.7	8.9 / 8.9 / 8.9	45.3/ 5.7 / 2.1	5.03/2.76/2.75	2.76/2.75/2.66	10.4 / 4.79/3.85	.45/ .00/ .05	1.07/ .73/ .40	.24/ .00/ .03	0.47	-	0.5% PRC
Slur-33	4DM/1/II	51/40/49	29/30/18	19.5/11.2 / 10.2	11.2/10.2 / 9.9	8.5 / 0.86/0.3	43.5/ 7.8 / 2.5	3.95/1.45/1.37	1.43/1.37/1.35	7.49/3.95/2.49	.63/ .06/ .01	.89/1.7 / .82	.36/ .05/ .01	0.56	-	0.5% RMGC
Slur-34	4FM/1/II	51/39/47	14/12/ 6	19.3/10.1 / 9.0	10.1/ 9.0 / 8.9	9.3 / 1.14/0.1	47.7/11.3 / 1.1	4.10/ .75/ .62	.73/ .62/ .60	8.38/1.6 / 1.3	.82/ .17/ .03	1.04/1.1 / 1.1	.43/ .15/ .03	0.85	-	0.5% PRC
Slur-35	4FM/1/II	53/38/47	14/13/ 6	19.0/10.1 / 9.1	10.1/ 9.1 / 8.9	8.3 / 1.05/ .2	46.8/10.4 / 2.2	4.40/1.52/1.45	1.52/1.45/1.43	8.14/2.5 / 2.1	.63/ .05/ .01	.85/ .65/ .45	.33/ .05/ .01	0.68	-	0.5% RMGC
Slur-38	4DM/1/II	40/31/41	10/ 9/ 5	18.8/ 9.91/ 9.15	9.9/ 9.15/ 8.9	8.9 / .76/ .25	47.3/ 7.86/ 2.76	4.4 / .69/ .55	.69/ .55/ .58	10.58/1.58/1.27	.84/ .20/ -.05	1.41/1.29/1.31	.44/ .19/ .05	0.87	-	0.5% PRC
Slur-39	I <sub>a</sub> /II	28/40	4/ 4	9.1 / 8.4	8.4 / 8.2	.68/ .19	7.5/2.3	4.42/ 1.08	1.08/ .97	38.11/ 6.01	.76/ .10	7.64/4.54	.70/ .10	0.78	-	0.5% PRC
Slur-40	I <sub>a</sub> /I	37	13	10.59	9.60	.99	9.4	4.63	1.33	34.52	.72	6.46	.65	-	-	0.5% PRC
Slur-41	I <sub>a</sub> /I	39	13	11.16	10.00	1.16	10.4	4.45	.88	33.68	.80	6.57	.72	-	-	0.5% PRC
Slur-42	I <sub>a</sub> /I	47	5	9.62	9.2	.42	4.4	4.79	1.12	84.8	.77	16.72	.73	-	-	0.5% PRC
Slur-43	II J <sub>a</sub>	35	5	9.62	9.1	.52	5.4	4.73	1.13	64.06	.78	12.56	.74	-	-	0.5% PRC
Slur-44	I <sub>a</sub>	28	5	9.06	8.4	.66	7.3	4.33	1.09	50.33	.75	10.63	.69	-	-	0.5% PRC
Slur-45	I <sub>a</sub> /I	27	6	9.11	8.4	.71	7.9	4.44	1.03	38.99	.77	7.78	.71	-	-	0.5% PRC
Slur-46	4CM/II <sub>a</sub>	35/42	13/ 8	16.2 / 11.9	11.9 / 10.4	4.3 / 1.0	26.5/8.7	4.32/ .94	.94/ .85	14.47/ 2.44	.78/ .10	2.35/1.60	.57/ .09	0.80	-	0.5% PRC
Slur-47	4CM/II <sub>b</sub>	44/47	20/10	17.9 / 12	12 / 10.5	5.9 / .47	32.9/4.3	4.54/ .97	.97/ .85	11.34/ 3.37	.79/ .13	1.50/2.47	.53/ .12	0.81	-	0.5% PRC
Slur-48	4CM	19	5	11.81	10.0	1.81	15.3	4.11	.95	16.65	.77	3.05	.65	-	-	0.5% PRC
Slur-49	4CM	29	8	15.0	12.2	2.8	18.9	4.11	.90	17.10	.78	3.15	.63	-	-	0.5% PRC
Slur-50	4CM	12	5	10.2	8.2	2.0	19.9	4.28	.91	17.67	.79	3.13	.63	-	-	0.5% PRC
Slur-51	I <sub>b</sub> /II <sub>b</sub>	28/39	7/ 7	11.2 / 10.2	10.2 / 9.3	1.0 / .43	8.93/4.4	4.39/ 1.05	1.05/ .91	41.82/ 3.88	.76/ .13	8.52/2.69	.69/ .13	.79	-	0.5% PRC
Slur-52	I <sub>b</sub> /II <sub>b</sub>	30/39	7/ 7	10.99/10.0	10.0 / 9.3	.99/ .43	9.1 / 4.5	4.57/ .98	.98/ .81	41.88/ 3.55	.79/ .17	8.07/2.62	.72/ .17	.82	-	0.5% PRC
Slur-53	I <sub>b</sub> /II <sub>b</sub>	33/43	10/ 7	12.51/11.3	11.3 / 10.6	1.21/ .45	9.7 / 4.1	4.30/ 1.00	1.00/ .99	34.94/ 3.12	.77/ .01	7.06/2.12	.69/ .01	.77	-	0.5% PRC

TABLE A. 2 (Continued)

Test	Units	ΔP (psi)	P <sub>o</sub> (psi)	Q <sub>1</sub> (GPM)	Q <sub>2</sub> (GPM)	Q <sub>3</sub> (GPM)	Q <sub>4</sub> /Q <sub>1</sub> (%)	G <sub>1</sub> (lb/l)	G <sub>2</sub> (lb/l)	G <sub>3</sub> (lb/l)	G <sub>4</sub> (lb/l)	C <sub>N</sub>	C <sub>1</sub>	E	(C.N.S.) (C.I.S)	Working Fluid
Slur-67	I <sub>c</sub>	29	0	9.86	7.57	2.29	30.2	122.4	94.0	387.1		.23	2.16	.18	-	RMGC
Slur-68	II <sub>b</sub>	31	0	8.51	7.68	0.83	9.75	125.0	91.6	719.0		.27	4.75	.24	-	RMGC
Slur-69	II <sub>b</sub>	31	0	8.98	8.28	0.70	7.80	98.9	46.7	560.3		.32	7.13	.29	-	RMGC
Slur-70	I <sub>c</sub>	29	0	10.57	8.39	2.18	20.6	77.0	47.6	263.1		.38	2.41	.30	-	RMGC
Slur-71	I <sub>c</sub>	29	0	10.76	8.58	2.18	20.2	47.3	29.7	174.3		.37	2.68	.29	-	RMGC
Slur-72	II <sub>b</sub>	31	0	9.12	8.40	0.72	7.90	48.1	30.9	369.0		.36	6.67	.33	-	RMGC
Slur-73	II <sub>b</sub>	31	0	9.36	8.77	0.59	6.30	26.1	15.6	231.3		.40	7.87	.37	-	RMGC
Slur-74	I <sub>c</sub>	28	0	10.46	8.39	2.07	19.8	27.6	13.8	88.6		.50	2.20	.40	-	RMGC
Slur-75	I <sub>c</sub>	28	0	10.42	8.38	2.04	19.5	15.8	7.2	53.9		.56	2.41	.45	-	RMGC
Slur-76	II <sub>b</sub>	31	0	9.27	8.56	0.71	7.66	15.0	8.2	132.6		.45	7.84	.42	-	RMGC
Spoil-1	4CM	26	5	14.0	9.08	4.92	35.2	175.2	167.8	213.4		.04	.22	.03	-	20% Mobile
Spoil-2	I <sub>c</sub>	34	7	13.10	10.62	2.48	18.9	185.0	162.2	266.6		.11	.46	.09	-	20% Mobile
Spoil-3	MBA	44	5	7.84	6.77	1.07	13.6	173.3	163.7	266.1		.06	.54	.05	-	20% Mobile
Spoil-4	4CM	30	8	15.4	11.71	3.70	24.0	84.6	68.1	147.3		.20	.74	.16	-	10% Mobile
Spoil-5	I <sub>c</sub>	35	7	12.53	11.06	1.47	11.7	84.2	69.4	191.6		.18	1.28	.15	-	10% Mobile
Spoil-6	II <sub>b</sub>	42	5	10.67	9.95	0.72	6.7	77.5	65.6	337.1		.15	3.35	.14	-	10% Mobile
Spoil-7	I <sub>c</sub>	36	7	13.03	11.15	1.88	14.4	42.2	32.2	110.1		.24	1.61	.20	-	5% Mobile
Spoil-8	II <sub>b</sub>	41	6	10.66	10.02	0.64	6.0	42.0	32.9	201.2		.22	3.79	.20	-	5% Mobile
Spoil-9	4CM	29	8	15.42	12.05	3.37	21.9	39.6	32.4	80.1		.18	1.02	.14	-	5% Mobile
Spoil-13	II <sub>b</sub>	43	0	10.67	9.82	0.85	8.0	43.77	30.43	272.45		.30	5.22	.28	-	Tampa
Spoil-28	I <sub>c</sub>	-	0	23.0	20.0	3.0	13.0	65.2	45.3	239.0		.31	2.66	.27	-	Tuldo Of

<sup>1</sup> Dispersed with Calgon water softener.

<sup>2</sup> Chemically treated with 1 mg/l of Calgon 2690, 10 mg/l of alum and 10 mg/l of ferric sulfate.

TABLE A. 3

## SEPARATION RESULTS FOR THE HYDROCYCLONE CLASSIFIER

Test	Units	$\Delta P$ (psi)	$P_o$ (psi)	$Q_i$ (GPM)	$Q_o$ (GPM)	$Q_u$ (GPM)	$Q_u/Q_i$ (%)	$G_i$ (g/l)	$G_o$ (g/l)	$G_u$ (g/l)	$C_N$	$C_I$	E (%)	Working Fluid
Slur 63	I <sub>F</sub>	25	5	7.94	6.51	1.43	18	29.0	16.07	73.7	.45	1.54	.37	3% RMGC
Slur 64	I <sub>F</sub>	25	5	7.94	6.51	1.43	18	51.38	19.84	182.74	.61	2.56	.50	3% RMGC 3% Sapulpa Sand
Slur 65	I <sub>F</sub>	25	5	7.94	6.51	1.43	18	24.2	9.19	85.5	.62	2.53	.51	3% PRC
Slur 66	I <sub>F</sub>	25	5	7.94	6.51	1.43	18	59.55	11.41	254.70	.81	3.28	.66	3% PRC 3% Sapulpa Sand
Spoil 22	I <sub>F</sub>	25	5	7.94	6.51	1.43	18	45.79	35.52	82.48	.22	.80	.18	5% Mobile
Spoil 23R	I <sub>F</sub>	25	5	7.94	6.51	1.43	18	71.75	32.49	262.62	.55	2.66	.45	5% Mobile 3% Sapulpa Sand
Spoil 24	I <sub>F</sub>	25	5	7.94	6.51	1.43	18	60.0	42.60	135.40	.29	1.26	.24	Toledo OF
Spoil 25	I <sub>F</sub>	25	5	7.94	6.51	1.43	18	75.8	44.20	298.40	.42	2.94	.34	Toledo OF 3% Sapulpa Sand
Spoil 26	I <sub>F</sub>	25	5	7.94	6.51	1.43	18	113.8	99.30	182.50	.13	.60	.10	Savannah
Spoil 27	I <sub>F</sub>	25	5	7.94	6.51	1.43	18	141.6	102.30	300.70	.28	1.12	.23	Savannah 3% Sapulpa Sand

Flow rates are nominal since heavy concentrations of solids in flow should require correction - but no correction is applied to flow rates here.

TABLE A.4  
SEPARATION RESULTS FOR THE "OVER-UNDER" SERIES RUNS

Test	Units	$\Delta P$ (psi)	$P_0$ (psi)	$Q_1$ (GPM)	$Q_0$ (GPM)	$Q_2$ (GPM)	$Q_3$ (GPM)	$Q_4/Q_3$ (%)	$C_1$ (g/l)	$C_0$ (g/l)	$\sigma_1$ ( $\mu$ /l)	$C_N$	$C_I$	E	( $C_N$ ) (%)	( $C_I$ ) (%)	Working Fluid
Slur 21	4DM// I	32/34	10/6	19.4/10.3	9.1/10.2	10.2/10.1	53.1/30.5	.98	4.35/7.34	1.33/3.77	7.34/104.7	.69/49	.69/13.3	.32/4.49	.13	.91	.5% RMGC
Slur 22	4DM//T6	43/77	34/6	19.1/7.27	11.8/5.1	7.27/2.25	38.1/30.5		3.802/8.594	1.33/3.86	8.59/21.3	.65/35	1.26/1.48	.40/3.8	-.02	2.05	.5% RMGC
Slur 26	9M// I/II	32/42/57	34/27/7	20.5/11.4/10.4	9.1/10.4/10.2	11.4/1.0/0.2	55.6/8.8/1.9		3.76/6.25/2.68	1.43/2.63/2.52	6.25/81.7/12.5	.62/57/06	.65/12.1/3.6	.28/3.52/1.06	.29	2.28	.5% RMGC
Slur 27	9M// I/II	35/37/51	25/20/7	19.5/10.5/9.9	9.1/9.9/9.7	10.5/0.6/0.2	53.6/5.9/2.1		4.0/6.75/3.9	1.39/3.00/2.87	6.75/97.9/11.8	.65/56/04	.68/13.5/2.9	.30/3.53/1.04	.28	1.92	.5% RMGC
Slur 28	9M// I/II	27/40/50	47/23/30	19.2/10.2/9.7	9.1/10.2/9.8	10.2/0.5/0.2	52.6/4.9/2.1		4.33/8.25/2.00	0.75/2.00/1.77	8.25/176/10.4	.83/76/12	.91/20.3/4.2	.39/3.72/1.12	.59	2.69	.5% PRC
Slur 29	4DM// I/II	42/77	36/6	20.7/11.7/10.2	9.1/10.2/9.8	11.7/1.5/0.4	56.4/12.8/3.9		4.61/7.82/2.12	1.26/2.12/1.91	7.82/99.0/13.1	.73/73/10	.70/11.7/5.1	.32/3.64/1.10	.58	2.00	.5% ACTFD
Slur 30	4DM// I/II	37/40/48	22/16/6	19.8/10.8/9.7	9.1/9.7/9.4	10.8/1.07/0.34	54/9.9/3.5		5.11/6.25/4.57	3.65/4.57/4.16	6.25/62.8/11.6	.29/27/05	.22/9.0/1.5	.13/3.24/1.05	.15	1.22	.5% RMGC <sup>1</sup>
Slur 36	10M// I/II	30/32/40	4/8/5	18.5/9.8/9.0	8.9/9.0/8.8	9.8/1.3/0.2	53.1/12.5/2.2		4.49/7.92/1.54	.76/1.54/1.46	7.92/52.6/6.87	.82/81/05	.76/5.63/3.46	.38/3.71/1.05	.68	1.84	.5% PRC
Slur 37	9AM// I/II	30/32/40	4/8/5	18.5/9.8/9.0	8.9/9.0/8.8	9.8/1.3/0.2	51.8/8.60/0.9		4.59/7.92/1.82	.46/1.82/1.64	7.92/53.9/7.81	.90/77/10	.73/5.82/3.30	.43/3.71/1.10	.61	1.50	.5% PRC <sup>2</sup>

<sup>1</sup> Dispersed with Calgon water softener.

<sup>2</sup> Chemically treated with 1 mg/l Calgon 2640, 10 mg/l alum, 10 mg/l of ferric sulfate.

TABLE A. 5  
PIPE FLOW DATA

Pipe Diameter	Mobile 5%		Mobile 10%		Tampa		Lake Charles		Toledo DE		Toledo OF		Savannah		Strength Savannah	
	$\Delta P$ (in H <sub>2</sub> O)	Q (lb <sub>m</sub> /min)	$\Delta P$ (in H <sub>2</sub> O)	Q (lb <sub>m</sub> /min)	$\Delta P$ (in H <sub>2</sub> O)	Q (lb <sub>m</sub> /min)	$\Delta P$ (in H <sub>2</sub> O)	Q (lb <sub>m</sub> /min)	$\Delta P$ (in H <sub>2</sub> O)	Q (lb <sub>m</sub> /min)	$\Delta P$ (in H <sub>2</sub> O)	Q (lb <sub>m</sub> /min)	$\Delta P$ (in H <sub>2</sub> O)	Q (lb <sub>m</sub> /min)	$\Delta P$ (in H <sub>2</sub> O)	Q (lb <sub>m</sub> /min)
0.425"	19.37	13.55	5.90	3.39	2.20	5.50	15.40	4.75	8.47	12.00	6.60	11.50	15.60	17.00	7.65	12.00
0.425"	10.38	16.45	7.00	10.00	4.80	7.50	18.40	7.75	10.27	13.00	12.50	17.00	20.70	23.00	11.65	14.50
0.425"	11.80	13.75	7.25	5.65	6.20	10.37	19.30	7.25	17.30	19.00	17.45	19.50	28.60	28.00	18.20	16.00
0.425"	13.90	18.05	7.55	10.00	10.10	14.80	20.70	11.75	24.60	22.50	25.1	27.00	33.20	24.00	26.80	26.00
0.425"	14.65	18.95	8.00	14.00	12.70	16.00	24.90	15.00	35.40	29.50	34.5	30.00			31.90	28.00
0.425"	16.18	19.30	9.70	14.90	18.00	19.75	29.30	15.25								
0.425"	17.80	19.25			24.4	23.50	37.70	17.25								
0.425"	23.20	22.50			30.3	26.75										
0.425"	30.10	26.25														
0.835"	2.70	24.65	4.20	28.00	2.40	29.00	4.70	19.50	6.48	32.50	5.48	43.50	19.60	47.50	4.03	25.50
0.835"	2.90	27.25	6.60	46.60	4.10	36.75	12.90	42.00	13.30	67.00	8.94	57.50	21.60	60.00	11.05	65.00
0.835"	3.15	7.31	11.70	62.25	7.20	50.00	21.30	81.66	20.90	89.00	13.70	74.00	25.60	91.00	17.45	79.00
0.835"	3.50	26.60	16.10	67.55	10.10	59.50	29.30	110.00	25.70	101.00	24.10	94.00	27.90	94.00	24.40	93.00
0.835"	3.60	25.10	18.60	70.00	13.10	70.00	34.90	124.16	32.80	110.00	31.40	113.00	32.30	114.00	31.10	109.00
0.835"	5.15	35.25	21.50	87.50	17.90	83.33										
0.835"	6.20	42.00	23.70	88.30	24.80	97.50										
0.835"	10.35	58.40	27.30	112.10	30.50	106.25										
0.835"	11.80	61.60	30.30	100.80												
0.835"	17.90	80.00														
0.835"	24.0	96.30														
0.835"	30.6	112.16														

## APPENDIX B

### DETAILED DESCRIPTIONS

This appendix contains detailed descriptions of:

- (1) spoil location;
- (2) hydrocyclone geometries and construction;
- (3) specific gravity procedure;
- (4) particle size procedure;
- (5) "HIAC" dilution procedure.

## SPOIL LOCATION

Figure B.1 is a detailed map showing the location of the Mobile spoil sample site. This sample was collected on 10 September 1972 at 110 hour while dredging  $\frac{1}{2}$  mile south of the Pascagoula River mouth on the centerline of the channel. The sample was collected by pulling a 5 gallon bucket up through the discharge jet.

The location of the Tampa spoil collection site is shown in Figure B.2. This sample was collected on 29 September 1972 from the East Bay turning basin. The sample was taken from the discharge pipe extending into disposal area D/A 15C.

The Lake Charles spoil was collected on 7 November 1972 at 1300 and 1330 hours from the Calcasieu River at approximately mile 27.1 (Station 1440 + 00). The location is shown in Figure B.3. The sample was taken from a two inch valve welded to the lower one third of a 24 inch floating line. A fire hose was connected to the valve to obtain the sample. Sample was taken only when a heavy cut on channel edge was encountered to obtain a representative sample.

The Toledo samples were collected on 19 October 1972 at intervals between 0834 - 0855 and 1020 - 1150 hours from the Toledo harbor area while dredging load #197 between C.S. 200 + 00 and 218 + 00 as indicated on Figure B.4. The OF sample was taken by holding a 2 gallon bucket to the lip of the overboard discharge and then transferring the contents to sample drums. The DE sample was taken by holding a 2 gallon bucket to the discharge pipe and then transferring to sample drums while load #197 was being pumped out into disposal area Penn #7.

Figure B. 5 shows the collection location of the Savannah spoil. The two barrels were taken separately, one on 2 November 1972 and one on 3 November 1972 while working in the Fig Island Turning basin. The samples were collected on the U. S. Dredge Henry Bacon by connecting a 1-inch hose to a sample port located at the midpoint (top to bottom) of the discharge line immediately behind the pump.

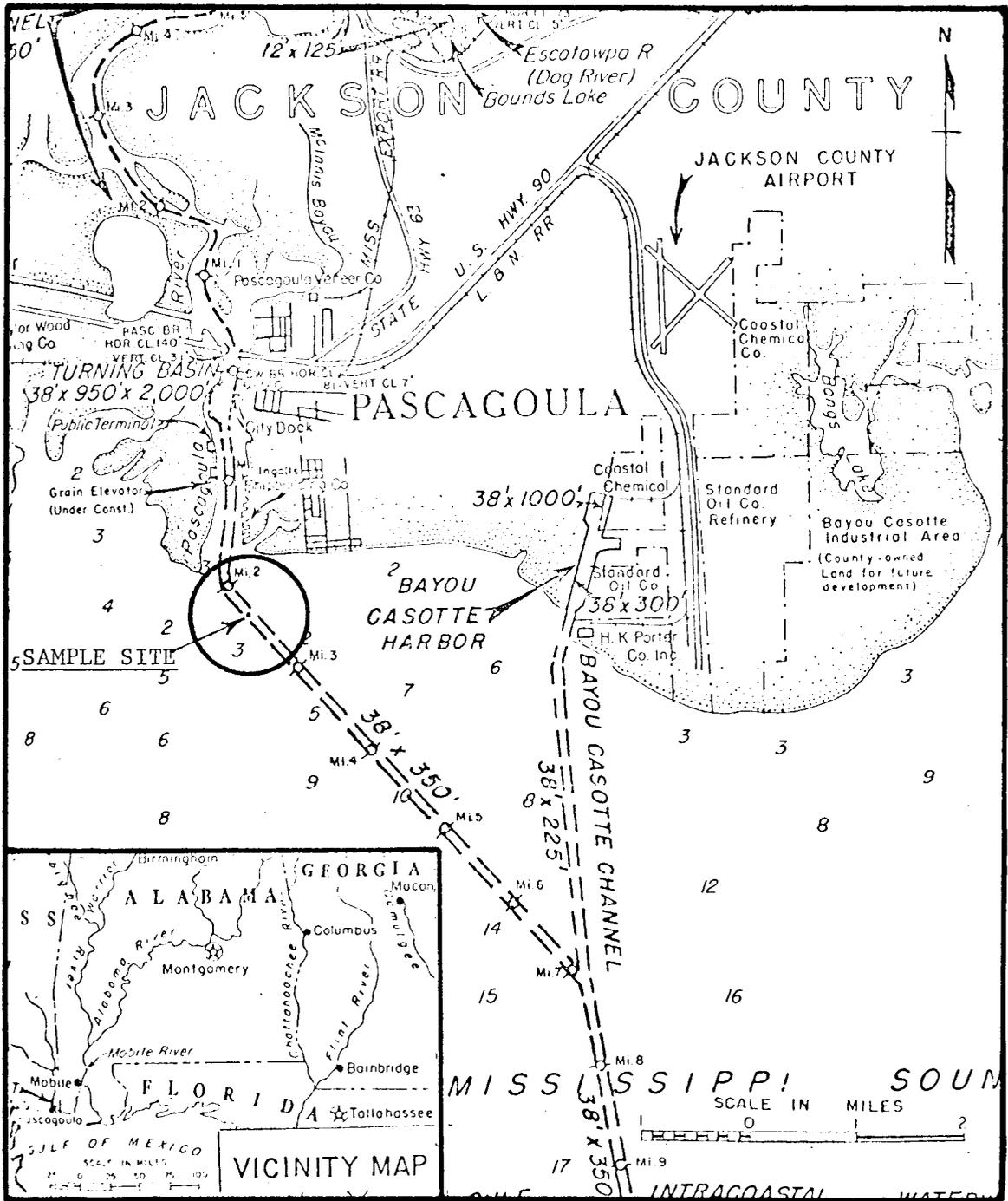


Fig. B.1. Mobile dredge spoil sample location

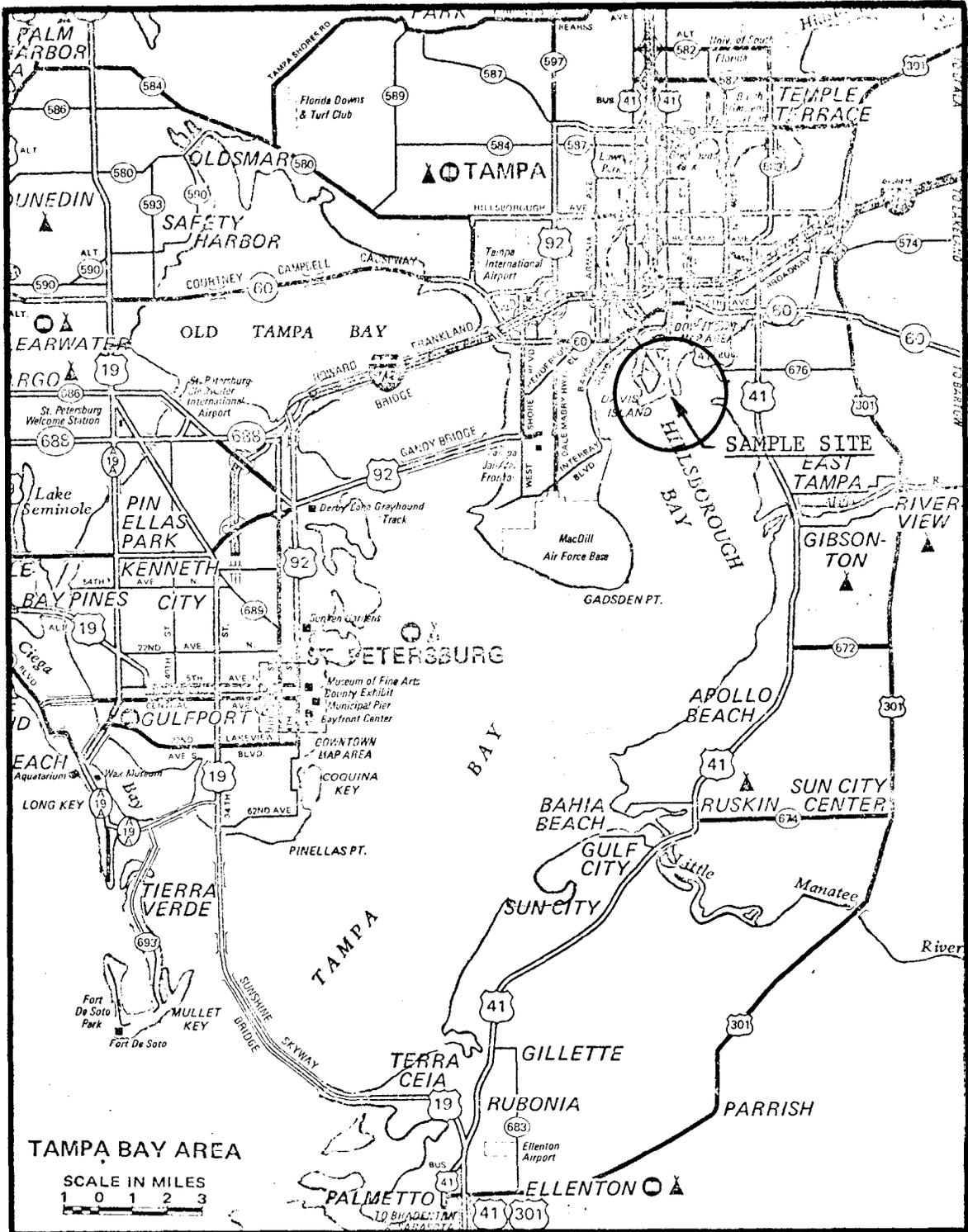


Fig. B.2. Tampa Bay dredge spoil sample location

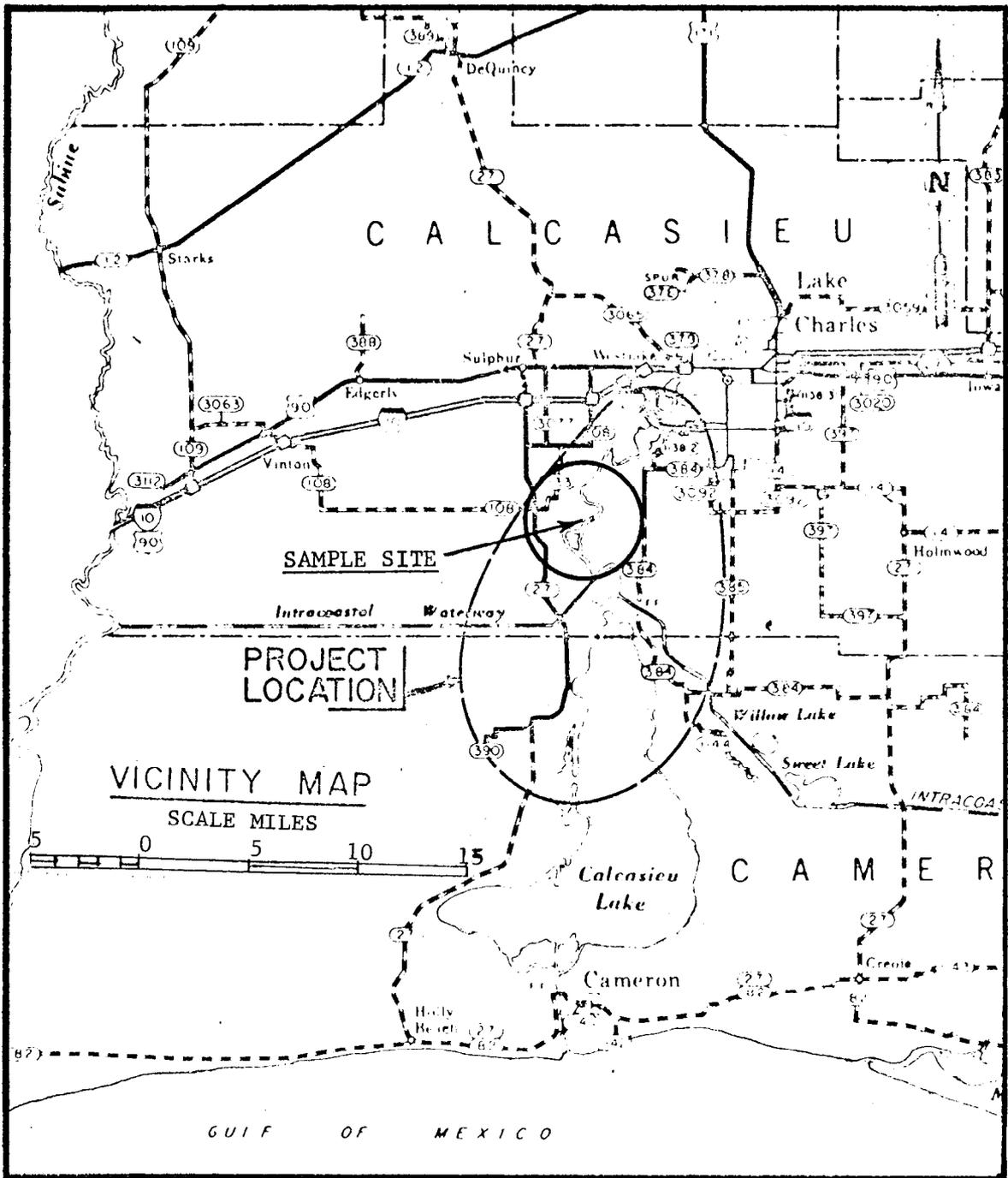


Fig. B.3. Lake Charles dredge spoil sample location

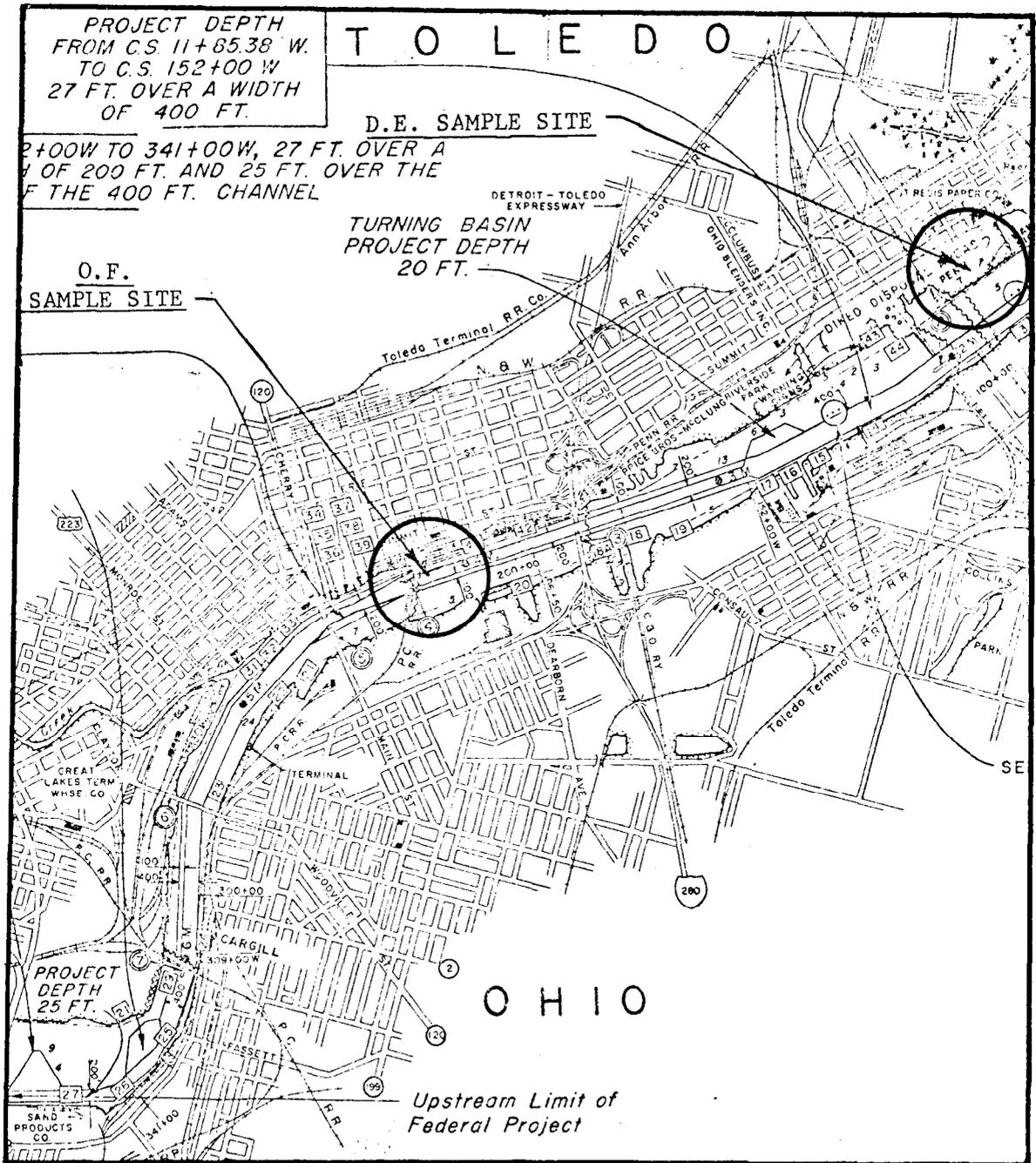


Fig. B.4. Toledo dredge spoil sample locations

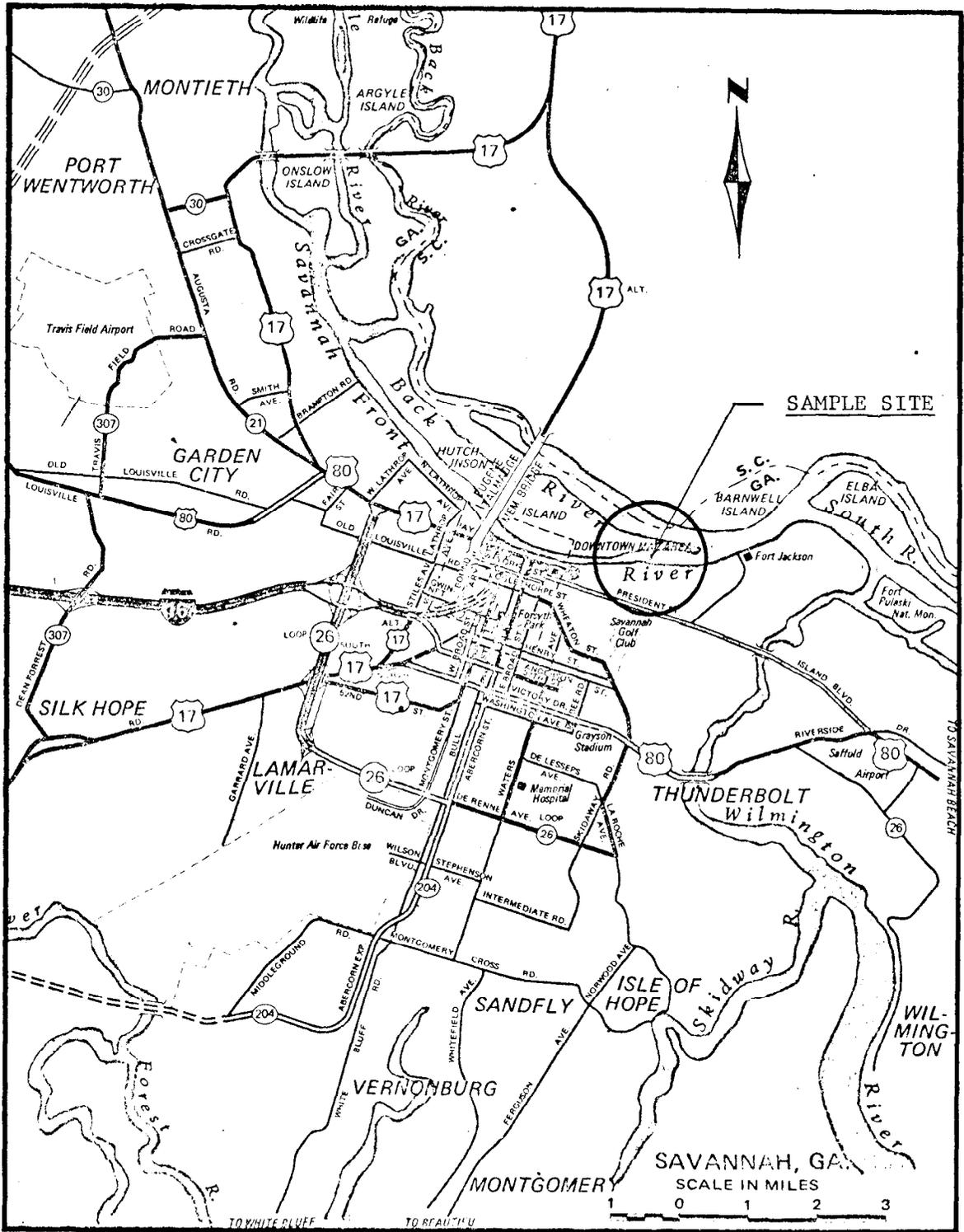


Fig. B. 5. Savannah dredge spoil sample location

## HYDROCYCLONE GEOMETRIES AND CONSTRUCTION

The pertinent flow dimensions of the 10 GPM hydrocyclone configurations used in this study are listed in Table B.1. A detailed view of the model I<sub>c</sub> hydrocyclone installed on the test stand is shown in Figure B.6 and an exploded view of the model II<sub>b</sub> appears in Figure B.7. The "inlet-overflow outlet head" was machined out of brass. The inlet orifice was drilled in this head and an AN fitting connected the inlet to the inlet pipe. As shown in Figure B.7, the vortex finder was a separate piece which also screwed into the head. The vortex finder was threaded for the outlet fitting. Although a portion of the cylindrical length is contained in the head, the major portion of the cylindrical length was plastic. Most of the cone was also plastic. However, due to the severe abrasion which takes place in the underflow region, the lower portion of the cone including the underflow itself, was made from a piece of nylon which was threaded to screw into the plastic part of the cone. Thus the I<sub>c</sub> and II<sub>b</sub> hydrocyclones consisted of five separate pieces, a head, a vortex finder, a cylindrical section, a cone, and an underflow section.

As indicated in Table B.1, some of the earlier configurations had underflow sections which included a subcone. The subcone was simply a conical expansion starting at the underflow diameter which controlled to some extent the expansion of the underflow stream after it passed downwards through the underflow orifice. These subcones were an integral part of the underflow section and they were typically one inch long with an included angle of 34°.

TABLE B.1

## FLOW DIMENSIONS OF 10 GPM HYDROCYCLONE SEPARATORS

Model	Diameter of Cone		Diameter of Inlet $D_i$ (in.)	Diameter of Overflow		Axial Length $L$ (in.)	Length of Vortex Finder		Diameter of Underflow		Type of Underflow
	$D_c$ (in.)	$D_o$ (in.)		$D_o$ (in.)	$D_o$ (in.)		$L_v$ (in.)	$L_v$ (in.)	$D_u$ (in.)	$D_u$ (in.)	
I	2.543	0.364	0.364	0.509	12.715	1.517	1.517	0.170	0.170	Subcone	
I <sub>a</sub>	2.543	0.364	0.364	0.509	12.715	1.517	1.517	0.254	0.254	Subcone	
I <sub>1a</sub>	2.543	0.364	0.364	0.509	12.715	1.517	1.517	0.254	0.254	No-Subcone	
I <sub>b</sub>	2.543	0.364	0.364	0.509	17.801	1.517	1.517	0.254	0.254	No-Subcone	
I <sub>c</sub>	2.543	0.364	0.364	0.509	17.801	1.517	1.517	0.296	0.296	No-Subcone	
I <sub>d</sub>	2.543	0.364	0.364	0.363	17.801	1.271	1.271	0.296	0.296	No-Subcone	
I <sub>f</sub>	2.543	0.364	0.364	0.363	17.801	1.271	1.271	0.192	0.192	Subcone	
II	2.298	0.328	0.328	0.460	11.49	1.419	1.419	0.153	0.153	Subcone	
II <sub>a</sub>	2.298	0.328	0.328	0.460	11.49	1.419	1.419	0.192	0.192	Subcone	
II <sub>L</sub>	2.298	0.328	0.328	0.460	16.086	1.419	1.419	0.192	0.192	Subcone	
II <sub>b</sub>	2.298	0.328	0.328	0.460	16.086	1.419	1.419	0.192	0.192	No-Subcone	
III	2.022	0.289	0.289	0.404	10.11	1.309	1.309	0.135	0.135	Subcone	

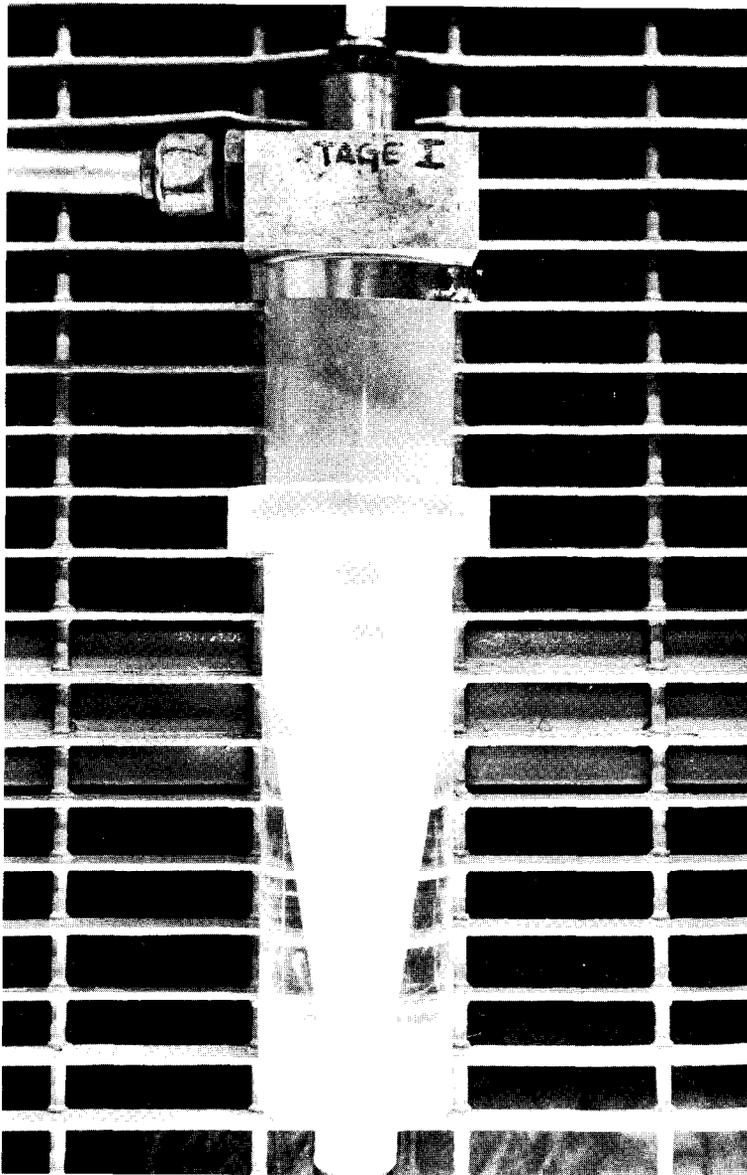


Fig. B.6. Detailed view of model I<sub>c</sub> hydrocyclone

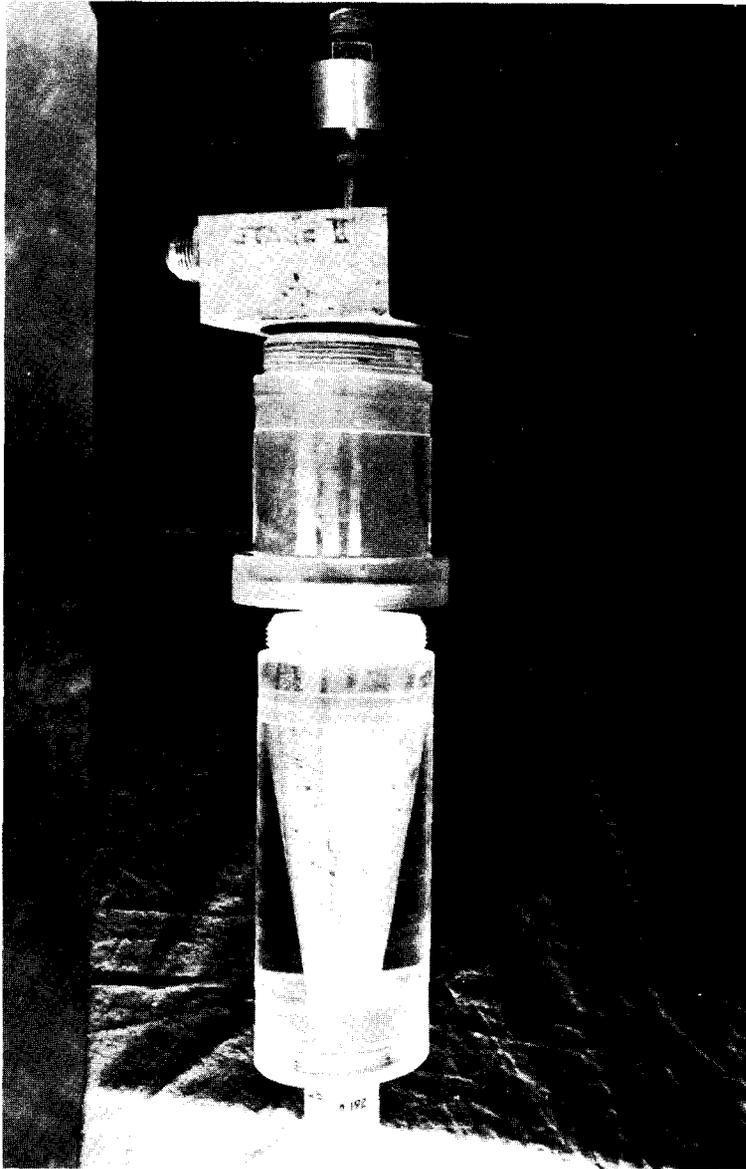


Fig. B. 7. Exploded view of model II<sub>b</sub> hydrocyclone

## SPECIFIC GRAVITY PROCEDURE

### Purpose

The objective of this procedure is to determine the specific gravity of the suspended solids in a dredge spoil sample. Steps are included which will allow accurate determinations when there are significant amounts of dissolved solids in the sample.

### Equipment

The required equipment includes: a specific gravity pycnometer or volumetric flask; balance with  $\pm 0.01$  g accuracy and capability to weigh the pycnometer or flask when they are filled with water and soil; a reference table or graph showing the variation of the specific gravity of water as a function of temperature; an oven; three 250 ml evaporating dishes; a hot plate or bunsen burner; distilled water; a pestle and mortar; a desiccator; and several 1 liter cylinders.

### Procedure

1. Fill clean, dry pycnometer to its maximum level with distilled water.
2. Deair the water by heating to a light boil for 10 minutes. Bring the level of the bottom of the meniscus to the maximum reading of the pycnometer.
3. Dry the outside of the pycnometer and the inside to the level of the water, place stopper in pycnometer.
4. Weigh pycnometer and water to  $\pm 0.01$  g. This weight is referred to as  $W_2$ .
5. Record the temperature of water, T.

(All 5 of the above steps can be replaced by calibration of the pycnometer's weight variation with temperature.)

6. If there are dissolved solids in the spoil sample, the spoil should be "washed" with distilled water to remove these dissolved solids. This is accomplished as follows. Obtain a clear supernate in the spoil sample by either gravity clarification or centrifugation. Carefully pour off this supernate and replace the volume with distilled water. Mix the sample and repeat this process of clarification and washing with distilled water two more times. Extreme care is needed to avoid loss of suspended solids when the supernate is being removed.
7. Evaporate a large quantity of spoil sample, resulting in a dry soil sample of over 50 g. Grind this into powder form to enable easy mixing. Place the ground soil sample into a 110°C oven for 12 hours to thoroughly dry.
8. Cool the soil sample to room temperature in a desiccator.
9. Weigh out an exact portion of solids on removal from oven ( $\pm 0.01$  g). For pycnometers with a capacity of 250 to 500 ml, 50.00 g is an adequate amount. This weight is referred to as  $W_S$ .
10. Pour soil into pycnometer half filled with deaired, distilled water, making sure all the soil enters the liquid. Soak for 12 hours and then deair this solution as in step 2.
11. Add deaired, distilled water to bring the bottom of the meniscus to the maximum pycnometer reading (the exact level reached in step 2).

12. Bring solution to T (found in step 5) or if you have a calibration for pycnometer, cool to uniform T which is measured and recorded.
13. Dry the outside of the pycnometer and the inside to the level of the water.
14. Weigh to  $\pm 0.01$  g. Recheck the temperature to make sure it equals T. This weight is referred to as  $W_1$ .
15. From the reference, find the specific weight of distilled water at T. This is  $G_T$ .
16. Find the specific gravity of the soil sample,  $G_s$ , using the following relationship

$$G_s = \frac{W_s G_T}{W_s - W_1 + W_2}$$

$W_s$  = dry weight of soil

$W_1$  = weight of cylinder, soil, and water

$W_2$  = weight of cylinder and water

$G_T$  = specific gravity of distilled water at T.

## PARTICLE SIZE PROCEDURE

### Purpose

The objective of this procedure is to determine the particle size distribution of the suspended solids in a dredge spoil sample using a hydrometer.

### Equipment

The required equipment includes: two 1 liter cylinders with the 1 liter level clearly marked, 1 ASTM type 151H hydrometer, defloculating agent (Calgon water conditioner), a mixer, evaporating dishes and heater, drying oven, balance, desiccator, and a timer.

### Procedure

1. Draw a one liter sample of the spoil supernate from a well-settled container of spoil. This is to be used as the control.
2. Mix dredge spoil thoroughly. Collect a one liter sample of spoil from the well-mixed container. Transfer both control and spoil to the liter cylinders. (If dispersion of the spoil sample is desired, two ml of a 10% by weight of Calgon water conditioner is added to one liter of spoil sample. The mixture is then mixed vigorously for 10 to 15 minutes. The mixing may be accomplished with a blender).
3. Mix the one liter cylinder of spoil by placing the palm of the hand over the opening and turning the cylinder end for end rapidly. Continue mixing until spoil mixture is uniform. Place the hydrometer in the cylinder to see if reading is on hydrometer scale. If not, dilute spoil until an on-scale reading is obtained

- and the hydrometer will "bob" when tapped and return to a consistent reading. The dilution is done with spoil supernate or an equivalent salt solution of tap water. (If the solids concentration of the spoil is known beforehand, it is simpler to dilute the spoil immediately to an approximate 25 grams/liter concentration before checking for on-scale reading and "bobbing".)
4. Check the temperature of the two cylinders; they must be equal and uniform to the nearest one °C. If temperatures are unequal, heating or cooling the control solution should be done.
  5. Record temperature and control hydrometer reading ( $r_c$ ) on data sheet.
  6. Mix spoil solution (as in step 3) for 30 seconds. Place the hydrometer in the spoil cylinder and take readings at 15, 30, 60 and 120 seconds from the time mixing was ended; the hydrometer should not be removed between readings. Record the readings on the data sheet ( $r_H$ ).
  7. Recheck and record control reading ( $r_c$ ) and temperature.
  8. Mix spoil solution (as in step 3) for 30 seconds. Take hydrometer readings at 2, 5, 7.5, 10, 15, 20, 30, 40, 60 and 120 minutes from the end of the mixing process. Record the readings ( $r_H$ ) on the data sheet. The hydrometer should be slowly placed in the spoil cylinder just below each reading and slowly removed to prevent disturbing the settling process. At all other times the hydrometer should be placed in the control solution, and readings (both temperature and hydrometer) taken at convenient intervals. Record these control readings on the data sheet.
  9. It is necessary to know the solids concentration of the spoil tested. This may be accomplished by evaporating two

representative samples of the spoil used. These samples should be accurately measured 15 to 25 ml samples. However, rapid settling of larger particles in the spoil can cause difficulties in obtaining a typical sample. In this case, it is best to evaporate the entire spoil cylinder contents thus insuring an accurate solids concentration determination. Regardless of the method used, it is necessary to correct the solids concentration for the presence of dissolved solid. This correction is outlined in Appendix D.

### Data Analysis

1. Determine  $R_H$ .  $R_H$  is the difference between the spoil and control readings times a constant

$$R_H = (r_H - r_c) \times 10^3$$

2. Determine particle sizes,  $d$ .  $d$  is found with the use of a Nomographic Chart for the Solution of Stokes' Law.<sup>5</sup>
3. Determine the percentage finer,  $W_d^2$ , from the transformation equation

$$W_d^2 = \frac{G_s}{G_s - 1} \left[ \frac{V \gamma_c 10^{-3}}{W_s} \right] 100 R_H$$

where

$G_s$  = specific gravity of solids

$W_s$  = solids contained in volume  $V$  (grams)

$V$  = volume of tested spoil (usually one liter)

$\gamma_c$  = specific gravity of supernate control liquid at the temperature of hydrometer readings

$R_H$  =  $(r_H - r_c) 10^3$

4. A plot of  $W_d^2$  (ordinate) versus  $D$  (abscissa) will give a graph of particle size distribution. The most informative graph is a result of a semilog plot (linear in  $W_d^2$  and logarithmic in  $D$ ). A detailed sample calculation is shown in Appendix F.

## HIAC DILUTION PROCEDURE

### Purpose

Both visual particle size techniques and automatic particle counters are accurate only when the sample is dilute and each particle is individually discernable. Generally this means that the suspended solids concentration must be about 2 mg/l or less. This procedure describes a method for accurately diluting a 100 mg/l sample for analysis with a HIAC particle counter.

### Equipment

The required equipment includes: one 10 ml pipet, tee-stopcock valve, 9 super-clean 500 ml bottles, one super-clean 500 ml graduated cylinder, 3.6 liters of water which has been triple filtered with 0.45 $\mu$  Millipore filters, a vacuum source, magnetic mixer.

### Procedure

1. Assemble the pipet and stopcock and rinse this assembly with triple-filtered water.
2. Place the magnetic mixer under the pipet assembly.
3. Shake the bottle of sample to be analyzed vigorously by hand, then insert the magnet into the bottle, place it on the magnetic mixer and allow it to mix vigorously for at least 5 minutes.
4. Then, insert the pipet tip in the bottle approximately 1  $\frac{1}{2}$  inch from the bottom of the bottle and centered.
5. Turn the dial on the magnetic mixer down until it just stirs smoothly.

6. Using the stopcock valve, draw 10 ml into the pipet with the vacuum source.  
Note: (This control is extremely sensitive so open it slowly.)  
Note: If more than 10 ml is drawn into the pipet, do not keep this sample. Discard it, flush the pipet with tri-filtered water, then repeat the test.
7. Remove the sample bottle quickly and drain the pipet into a super super-clean 500 ml test bottle.
8. Insert the tip of the triple filtered water bottle into the open tee of the stopcock and flush the pipet completely into the test bottle. Complete filling the test bottle with triple-filtered water.
9. Remove the nozzle and blow into the tee to make sure all water is forced from the pipet.
10. Repeat steps 3 thru 9 for the other samples.

#### Comment

When using an automatic particle counter to analyze the diluted bottle samples, be certain to adequately clean and flush the counting equipment prior to recording the counts.

## APPENDIX C

### SINK-VORTEX CLARIFIER

#### Introduction

The chemical coagulation tests showed that some of the dredge spoils will coagulate and settle. However, it was also discovered that the chemically flocculated particles would not stay coagulated inside the hydrocyclone. Consequently, the effectiveness of the hydrocyclones was not enhanced by chemically coagulating the solids in the upstream reservoir. In an effort to provide a low-shear, low-residence-time clarifier for chemically treated spoil, the sink-vortex clarifier was originated. The object is to provide a long residence time in the gentle swirling motion of a bath-tub vortex for particles which do not readily settle to the floor of the tank. The concept is to get clarified water from a short stand pipe located at the center of the tank while the solids are drained from the tank floor. The slurry enters the apparatus tangentially at its outer wall.

#### Test Apparatus

The test stand and a schematic drawing of the sink-vortex clarifier are shown in Figure C.1. The clarification tank in which the sink-vortex flow was created is a 4 foot diameter stock tank. The slurry enters the tank tangentially through a flexible hose whose outlet was on the floor of the tank. Polymer flocculants were injected into this inlet stream before it entered the tank. The height of the axial overflow pipe was adjustable so that the amount of water in the tank was also adjustable.

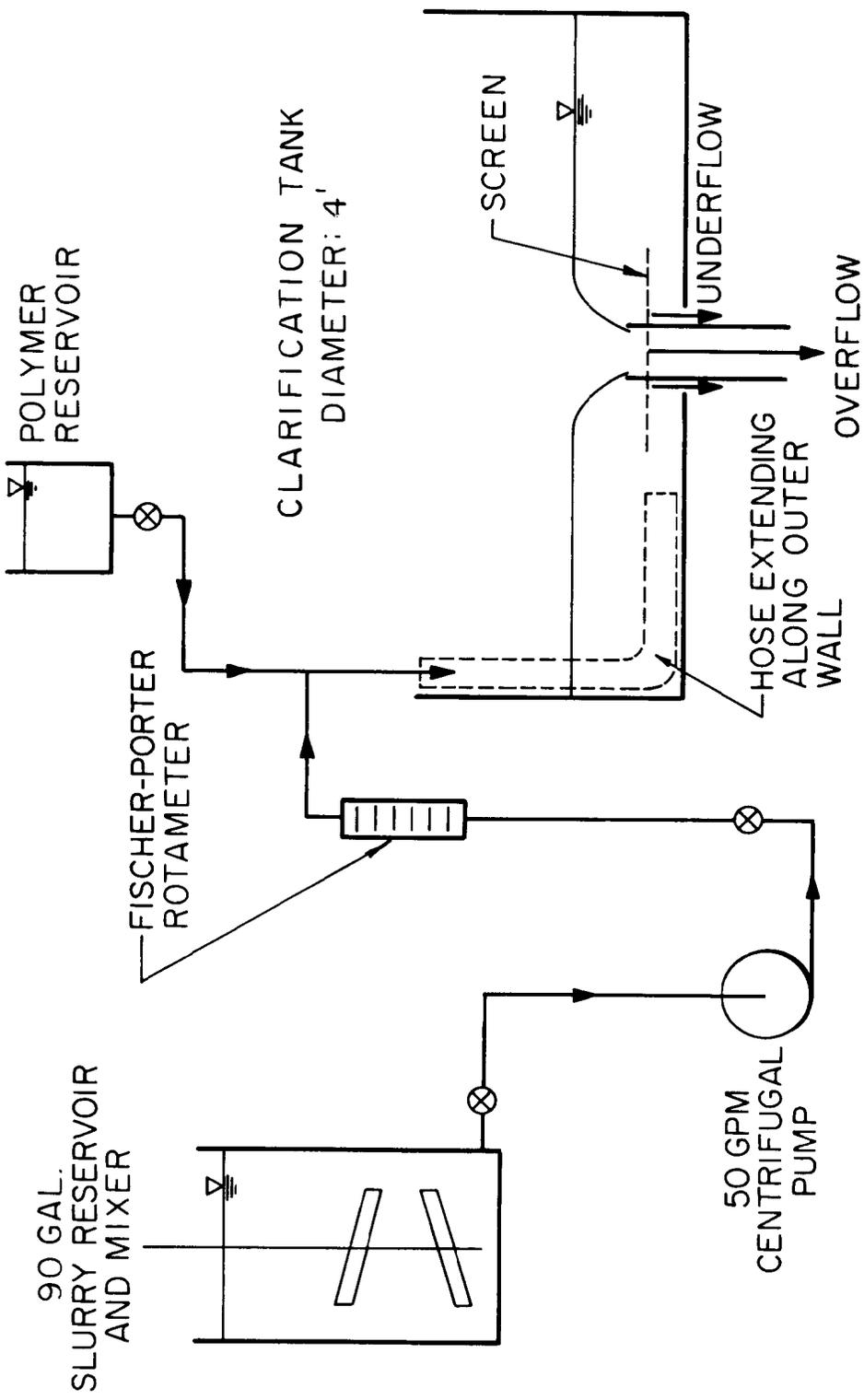


Fig. C.1. Schematic of sink-vortex clarifier test stand

In these preliminary tests the following three outlets were tested:

(1) A piece of 3-inch ID PVC pipe extended 2.8 inches upward through the center of the tank floor to give a 20 gallon capacity (a 2 minute residence time). A 1 foot square piece of screen (16 per inch) surrounded the overflow pipe at a height of 1.25" from the floor. The purpose of the screen was to collect the flocced particles and allow clean water to pass through. In this case, there was a single outlet stream and the solids were retained in the tank.

(2) Two pieces of PVC pipe, 2-inch and 3-inch internal diameter were used in a concentric arrangement to separate an underflow of flocced particles and an overflow of clarified water. The 2-inch pipe outlet was raised above the tank floor while the annular outlet for the underflow was flush with the floor. Rings were placed in the underflow annulus to restrict the flow area and to allow flow area adjustments.

(3) One piece of 3-inch internal diameter PVC pipe was extended upward through the floor of the tank. Thirty-six 1/16-inch diameter holes were drilled at a radius of 4 inches from the center of the tank floor. These holes provided an outlet for the flow laden with flocced particles.

#### Materials

RMGC slurries (.5% by weight) were used as the working fluid. Sand, dye, and oil soak were used to provide visualization of flow patterns inside the tank. Two chemicals were added which caused the flocculation. Alum, at a concentration of 10 mg/l was added to the

upstream reservoir. Magnifloc 835A, at 1 mg/l concentration, was the flocculant. It is a product of American Cyanamid.

### Test Procedure

Prior to conducting a test, 4.18 lbs. of RMGC was added to the upstream reservoir. The reservoir contained 100 gallons of fluid and was mixed continuously. A 100 mg/l solution of Magnifloc 835A was mixed and placed in the polymer reservoir. After the RMGC slurry had mixed for 15 minutes, alum was added to the 100 gallon reservoir and the test began.

During a test, the flow was adjusted to 10 GPM. Polymer was gravity fed into the inlet line at .631 mg/sec. This results in a 1 wppm solution. The overflow pipe was capped until the tank flow was at the proper level and then the outlet was opened and the timer was started.

Samples from the underflow and the overflow were taken at times of 5, 7, and 9 minutes. Flow rates out of the tank were determined by collecting the overflow and underflow over a period of time and weighing the amounts collected. After the test was completed the samples were analyzed for suspended solids contents.

### Results

The quantitative results are summarized below.

Flow Rates (gpm)			Solids Concentration (g/ℓ)			Clarification Number, $C_N$	Outlet Configuration
$Q_i$	$Q_o$	$Q_u$	$G_i$	$G_o$	$G_u$		
10	10	0	5.00	0.69		.862	with screen
9.47	7.78	1.69	5.00	2.58	3.74	.483	concentric pipes
9.70	6.84	2.86	5.00	1.58	2.80	.684	holes drilled in tank floor

Two important qualitative observations were also made. The chemical treatment was successful in that the flow field was gentle enough to prevent excessive destruction of agglomerates. However, the vortex action near the outlet was strong particularly with the 2-inch pipe. Future designs should employ at least a 3-inch outlet for the clarified flow. Most of the overflow and the underflow fluid came from the floor area.

#### Analysis of Results

The clarification number for the screen arrangement is considerably larger than any achieved with a hydrocyclone. Fundamentally, this is because the chemical treatment successfully increased the particle sizes of the solids so that they would gravity settle. The screen outlet was more effective than the other outlets because the overflow fluid comes upward from the floor region near the center stand pipe before overflowing. Thus some of the settled particles are pulled up from the floor and into the overflow. The screen caught many of these particles.

#### Conclusions and Recommendations

Obviously the sink-vortex clarifier concept works only when chemical treatment is successful. However, when chemical

treatment is feasible a hydrocyclone series followed by a clarification tank could be quite successful. The object of the hydrocyclones would be to remove as many solids as possible to minimize the amount of chemicals required. Chemicals would be injected downstream of the hydrocyclones and upstream of the clarification tank. The flocculated solids would be separated in the sink-vortex clarifier and relatively clear water would leave through the overflow.

For the spoils that can be chemically flocculated, the sink-vortex tank possess considerable potential as a low-residence time clarifier. However, additional testing is required before the full feasibility of the sink-vortex clarifier is known. Particularly important parameters requiring additional study are the geometry of the outlet and the flow rate split between the overflow and underflow. It is also highly recommended that bench-scale testing be conducted with dredge spoil samples.

SUMMARY TABLES OF THICKENING TESTS

TABLE C.1

THICKENING TEST RESULTS WITH MOBILE SPOIL

Chemicals (concentration)	ml of Supernate in 1 liter	
	Settling Time - 24 hrs	
<u>Anionic</u>		
Magnifloc 835A (10/100/100)*	20	
Dow AP273 (10/100/100)	10	
Dow MG200 (10/100/100)	20	
<u>Nonionic</u>		
Magnifloc 905N (10/100/100)	15	
Calgon 2690 ( 1/ 10/ 10)	20	
Calgon 2690 ( 1/ 10/ 5)	20	
Calgon 2690 ( 1/ 10/ 15)	20	
Calgon 2690 ( 1/ 5/ 10)	20	
Calgon 2690 ( 1/ 15/ 10)	20	
Calgon 2690 (10/100/100)	20	
<u>Untreated</u>		
Natural Settling ( 0/ 0/ 0)	15	

\*Parenthetical numbers denote:

$$\frac{\text{mg}}{\ell} \text{ polymer} / \frac{\text{mg}}{\ell} \text{ alum} / \frac{\text{mg}}{\ell} \text{ ferric sulfate} .$$

TABLE C.2

## THICKENING TEST RESULTS WITH 10% MOBILE SPOIL

Chemicals (concentration)	ml of Supernate in 1 liter			
	Settling Time			
	2 min	10 min	30 min	19 hrs
<u>Cationic</u>				
Calgon WT2630 ( 1/10/10)*	0	15	15	180
Calgon WT2630 (10/10/10)	0	5	15	220
Dow XD1612 ( 1/10/10)	0	10	40	280
Dow XD1612 (10/10/10)	0	10	10	190

\*Parenthetical numbers denote:

$\frac{\text{mg}}{\ell}$  polymer /  $\frac{\text{mg}}{\ell}$  alum /  $\frac{\text{mg}}{\ell}$  ferric sulfate .

TABLE C.3

## THICKENING TEST RESULTS WITH 5% MOBILE SPOIL

Chemicals (concentration)	ml of Supernate in 1 liter		
	Settling Time		
	2 min	10 min	30 min
<u>Anionic</u>			
Magnifloc 835A ( 10/ 10/10)*	10	30	280
Dow MG200 ( 10/ 10/10)	70	390	550
<u>Cationic</u>			
Calgon WT2630 ( 10/ 10/10)	0	10	20
Calgon WT2630 ( 10/100/10)	0	10	25
Calgon WT2630 ( 1/ 10/10)	0	1	10
Calgon WT2630 ( 1/100/10)	0	1	10
Calgon WT2630 (150/ 10/10)	0	20	40
Calgon WT2600 ( 10/ 10/10)	0	2	4
Calgon WT2600 ( 10/100/10)	0	2	4
Calgon WT2600 ( 1/ 10/10)	0	2	4
Calgon WT2600 ( 1/100/10)	0	2	4
Dow XD1612 ( 10/ 10/10)	0	1	10
Dow XD1612 ( 1/ 10/10)	0	1	10
Dow XD1612 ( 1/100/10)	0	1	5
Dow XD1612 ( 10/100/10)	0	1	5
Dow N17 ( 1/ 10/10)	0	1	10
Dow N17 ( 10/ 10/10)	0	1	10
Dow N17 ( 1/100/10)	0	1	10
Dow N17 ( 10/100/10)	0	1	10
<u>Untreated</u>			
Natural Settling ( 0/ 0/ 0)	0	5	15

\*Parenthetical numbers denote:

$$\frac{\text{mg}}{\ell} \text{ polymer} / \frac{\text{mg}}{\ell} \text{ alum} / \frac{\text{mg}}{\ell} \text{ ferric sulfate} .$$

TABLE C.4

## THICKENING TEST RESULTS WITH TAMPA SPOIL

Chemicals (concentration)	ml of Supernate in 1 liter		
	Settling Time		
	2 min	10 min	30 min
<u>Anionic</u>			
Magnifloc 835A ( 1/ 0/10)*	0	3	5
Magnifloc 835A ( 5/ 0/10)	0	10	15
Magnifloc 835A (10/ 0/10)	30	150	400
Magnifloc 835A (10/10/10)	760	810	840
Dow AP273 ( 1/ 0/10)	5	10	10
Dow AP273 ( 5/ 0/10)	5	10	15
Dow AP273 (10/ 0/10)	5	15	20
Dow MG200 ( 1/ 0/10)	1	10	50
Dow MG200 ( 5/ 0/10)	5	30	180
Dow MG200 (10/ 0/10)	15	35	360
<u>Nonionic</u>			
Magnifloc 905N ( 1/ 0/10)	0	10	105
Magnifloc 905N ( 5/ 0/10)	1	35	165
Magnifloc 905N (10/ 0/10)	10	140	420
Calgon WT2690 ( 1/ 0/10)	0	0	30
Calgon WT2690 ( 5/ 0/10)	0	7.5	20
Calgon WT2690 (10/ 0/10)	0	10	20
<u>Untreated</u>			
Natural Settling ( 0/ 0/ 0)	10	20	140

\*Parenthetical numbers denote:

$$\frac{\text{mg}}{\ell} \text{ polymer} / \frac{\text{mg}}{\ell} \text{ alum} / \frac{\text{mg}}{\ell} \text{ ferric sulfate} .$$

TABLE C.5

## THICKENING TEST RESULTS WITH LAKE CHARLES SPOIL

Chemicals (concentration)	ml of Supernate in 1 liter					
	Full Strength Spoil			Spoil with Sand**		
	Settling Time			Settling Time		
	2 min	10 min	30 min	2 min	10 min	30 min
<u>Anionic</u>						
Magnifloc 835A ( 1.5/ 10)*	0	0	0	0	0	0
Magnifloc 835A ( 1.5/ 50)	0	0	0	0	0	0
Magnifloc 835A ( 6 / 40)	0	0	0	-	-	-
Magnifloc 835A ( 6 /200)	0	5	5	-	-	-
Magnifloc 835A (15 / 10)	0	0	0	0	0	0
Magnifloc 835A (15 / 50)	0	0	0	0	0	0
Magnifloc 835A (60 / 40)	0	5	5	-	-	-
Magnifloc 835A (60 /200)	5	10	10	-	-	-
<u>Cationic</u>						
Calgon WT2630 ( 1.5/ 10)	0	0	0	0	0	0
Calgon WT2630 ( 1.5/ 50)	0	0	0	0	0	0
Calgon WT2630 ( 6 / 40)	0	0	0	-	-	-
Calgon WT2630 ( 6 /200)	0	0	0	-	-	-
Calgon WT2630 (15 / 10)	0	0	0	0	0	0
Calgon WT2630 (15 / 50)	0	0	0	0	0	0
Calgon WT2630 (60 / 40)	0	0	0	-	-	-
Calgon WT2630 (60 /200)	0	0	0	-	-	-

TABLE C. 5 (Continued)

Chemicals (concentration)	ml of Supernate in 1 liter					
	Full Strength Spoil			Spoil with Sand**		
	Settling Time			Settling Time		
	2 min	10 min	30 min	2 min	10 min	30 min
<u>Nonionic</u>						
Magnifloc 905N ( 1.5/ 10)	-	-	-	0	0	0
Magnifloc 905N ( 1.5/ 50)	-	-	-	0	0	0
Magnifloc 905N ( 3 / 20)	0	0	0	-	-	-
Magnifloc 905N ( 3 /100)	0	0	0	-	-	-
Magnifloc 905N (15 / 10)	-	-	-	0	0	0
Magnifloc 905N (15 / 50)	-	-	-	0	0	0
Magnifloc 905N (30 / 20)	0	0	0	-	-	-
Magnifloc 905N (30 /100)	0	0	0	-	-	-

\*Parenthetical numbers denote:

$$\frac{\text{mg}}{\ell} \text{ polymer} / \frac{\text{mg}}{\ell} \text{ alum} .$$

\*\*10 grams/ℓ of Sapulpa sand were added to the spoil.

TABLE C.6

## THICKENING TEST RESULTS WITH TOLEDO OF SPOIL

Chemicals (concentration)	ml of Supernate in 1 liter		
	Settling Time		
	2 min	10 min	30 min
<u>Anionic</u>			
Magnifloc 835A ( 1.5/10)*	20	140	440
Magnifloc 835A ( 1.5/50)	10	130	430
Magnifloc 835A (15 /10)	680	740	760
Magnifloc 835A (15 /50)	680	740	760
<u>Cationic</u>			
Calgon WT2630 ( 1.5/10)	10	80	260
Calgon WT2630 ( 1.5/50)	10	75	230
Calgon WT2630 (15 /10)	10	75	310
Calgon WT2630 (15 /50)	10	70	305
<u>Nonionic</u>			
Magnifloc 905N ( 1.5/10)	10	130	410
Magnifloc 905N ( 1.5/50)	10	140	440
Magnifloc 905N (15 /10)	25	205	465
Magnifloc 905N (15 /50)	45	280	515
<u>Untreated</u>			
Natural Settling ( 0 / 0)	10	85	260

\*Parenthetical numbers denote:

$$\frac{\text{mg}}{\ell} \text{ polymer} / \frac{\text{mg}}{\ell} \text{ alum} .$$

TABLE C.7

## THICKENING TEST RESULTS WITH TOLEDO DE SPOIL

Chemicals (concentration)	ml of Supernate in 1 liter		
	Settling Time		
	2 min	10 min	30 min
<u>Anionic</u>			
Magnifloc 835A ( 1.5/10)*	0	5	10
Magnifloc 835A ( 1.5/50)	0	5	10
Magnifloc 835A (15 /10)	0	5	10
Magnifloc 835A (15 /50)	0	5	10
<u>Cationic</u>			
Calgon WT2630 ( 1.5/10)	0	5	10
Calgon WT2630 ( 1.5/50)	0	5	10
Calgon WT2630 (15 /10)	0	0	10
Calgon WT2630 (15 /50)	0	5	10
<u>Nonionic</u>			
Magnifloc 905N ( 1.5/10)	0	5	10
Magnifloc 905N ( 1.5/50)	0	5	10
Magnifloc 905N (15 /10)	0	5	10
Magnifloc 905N (15 /50)	5	10	10

\*Parentetical numbers denote:

$$\frac{\text{mg}}{\ell} \text{ polymer} / \frac{\text{mg}}{\ell} \text{ alum} .$$

TABLE C. 8

## THICKENING TEST RESULTS WITH SAVANNAH SPOIL

Chemicals (concentration)	ml of Supernate in 1 liter					
	Full Strength Spoil			Spoil with Sand**		
	Settling Time			Settling Time		
	2 min	10 min	30 min	2 min	10 min	30 min
<u>Anionic</u>						
Magnifloc 835A ( 1.5/10)*	0	0	0	0	5	5
Magnifloc 835A ( 1.5/50)	0	0	0	0	0	0
Magnifloc 835A (15 /10)	0	5	5	0	5	5
Magnifloc 835A (15 /50)	0	5	5	0	5	5
<u>Cationic</u>						
Calgon WT2630 ( 1.5/10)	0	0	5	0	0	3
Calgon WT2630 ( 1.5/50)	0	0	5	0	0	0
Calgon WT2630 (15 /10)	0	0	5	0	0	0
Calgon WT2630 (15 /50)	0	0	5	0	0	0
<u>Nonionic</u>						
Magnifloc 905N ( 1.5/10)	0	0	0	0	0	0
Magnifloc 905N ( 1.5/50)	0	0	0	0	0	0
Magnifloc 905N (15 /10)	0	5	5	0	0	0
Magnifloc 905N (15 /50)	0	0	0	0	5	5

\*Parenthetical numbers denote:

$$\frac{\text{mg}}{\ell} \text{ polymer} / \frac{\text{mg}}{\ell} \text{ alum} .$$

\*\*10 grams/ $\ell$  of Sapulpa sand were added to spoil.

APPENDIX D

THEORETICAL ANALYSES AND MATHEMATICAL DERIVATIONS

CORRECTION TO SUSPENDED SOLIDS MEASUREMENTS

The purpose of this derivation is to develop an equation to correct the experimentally determined solids concentration of spoil when dissolved solids are present. This correction is based on the fact that

$$G_{ss} = \frac{W_{ss}}{V_t} = \frac{W_{ts}}{V_t} - \frac{W_{ds}}{V_{sn}} \frac{V_{sn}}{V_t}$$

or

$$G_{ss} = G_{ts} - A G_{ds} \tag{D-1}$$

where

$$A = V_{sn} / V_t$$

Here  $G$  is the gravimetric concentration ( $g/\ell$ ) and  $W$  is a weight ( $g$ ). The subscripts  $ds$ ,  $ss$ , and  $ts$  refer to dissolved solids, suspended solids and total solids, respectively.  $V_t$  is the total volume of the sample in liters and  $V_{sn}$  is the volume occupied by the supernate liquid.  $A$  may also be expressed in terms of  $G_{ss}$  and the specific gravity of the solids,  $G_s$ , because

$$A = 1 - \frac{V_{ss}}{V_t}$$

or

$$A = 1 - \frac{G_{ss}}{G_s V_t}$$

Then for a total volume of 1 liter

$$A = 1 - \frac{G_{ss}}{1000 G_s} \quad (D-2)$$

because  $G_s$  has units of g/ml.

Substituting Equation D-2 into Equation D-1 and solving for  $G_{ss}$  yields

$$G_{ss} = \frac{G_{ts} - G_{ds}}{\left(1 - \frac{G_{ds}}{1000 G_s}\right)} \quad (D-3)$$

Equation D-3 was used for all determinations of suspended solids concentrations when the dissolved solids content of the spoil was significant.

## FLOW RATE CONVERSION

Since the volume samples which are collected and weighed for flow rate determinations were frequently heavily laden with solids, the slurry weight per gallon was required to convert the mass flow rate measurements to volume flow rates. This was done as follows.

$$\begin{aligned} \text{weight of spoil/gallon} &= \text{weight of solids/gallon} \\ &+ \text{weight of water/gallon} \end{aligned}$$

Therefore,

$$\begin{aligned} W_{\text{spoil}}/\text{gallon (lb/gal)} &= G_{\text{ss}} (\text{g}/\ell) \times 2.21 \times 10^{-3} (\text{lb/g}) \\ &\times 3.78 (\ell/\text{gal}) + 8.34 (\text{lb/gal}) \end{aligned}$$

or

$$W_{\text{spoil}}/\text{gallon (lb/gal)} = 0.00834 G_{\text{ss}} + 8.34$$

## VISCOMETER EQUATIONS

The Fann and Brookfield viscometers are Couette type viscometers. Their readout must be converted to units of viscosity and shear rate. Thus equations must be developed that converts angular indication of torque into centipoise and rotational speed into shear rate.

For the Fann viscometer<sup>10</sup> the shearing stress may be calculated from

$$\tau = \frac{k_s \beta}{2\pi R_B^2} \left[ h_1 + \frac{h_2}{3 \cos \alpha} \right]^{-1}$$

The significance of  $h_1$  and  $h_2$  are shown in Figure D.1. The other factors have the following values for the Model V-G:

- $k_s$  = spring constant = 387 dyne-cm/degree
- $R_B$  = radius of inner stationary cylinder = 1.725 cm
- $h_1$  = height of inner stationary cylinder = 3.80 cm
- $h_2$  = height of conical section = 0.70 cm
- $\cos \alpha$  = 0.376
- $\beta$  = dial indication (degrees)
- $\tau$  = shearing stress (dyne/cm<sup>2</sup>)

Thus

$$\tau = 4.66 \frac{\text{dyne}}{\text{cm}^2\text{-degree}}$$

Viscosity is related to shearing stress through the rate of shear, as defined by

$$\tau = \mu \frac{dU}{dy}$$

where

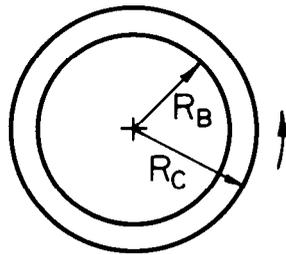
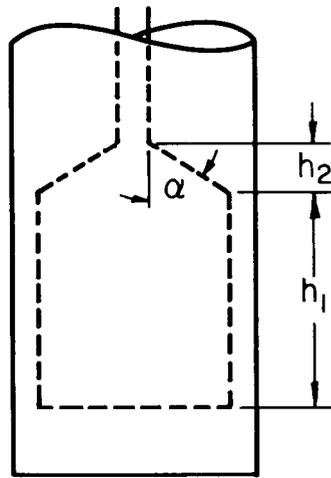


Fig. D.1. Fann viscometer concentric cylinder arrangement

$\mu$  = viscosity (centipoise)

$\frac{dU}{dy}$  = shear rate ( $\text{sec}^{-1}$ )

It can be shown that<sup>10</sup>

$$\text{Shear Rate } \left(\frac{1}{\text{sec}}\right) = 1.703 \times \text{Cylinder Speed (rpm)}.$$

Thus, for the Fann V-G viscometer the following table may be constructed.

<u>Speed (rpm)</u>	<u>Shear Rate (<math>\text{sec}^{-1}</math>)</u>	<u>Viscosity (centipoise)</u>
3	5.11	91.2 $\beta$
6	10.22	45.6 $\beta$
100	170.2	27.4 $\beta$
200	340.4	13.7 $\beta$
300	511.0	9.1 $\beta$
600	1022.0	4.6 $\beta$

Using this table, viscosity may be calculated directly from the Fann viscometer dial reading of  $\beta$ .

For the Brookfield Synchro-Electric viscometer, the equations applicable to the calculation of shear rates were obtained from a private communication with Brookfield Engineering. Equations valid only for the LV1, LV4, and UL adapter spindles were available. The results of computations with those equations are shown below

<u>Speed (rpm)</u>	<u>Shear Rate (<math>\text{sec}^{-1}</math>)</u>		
	<u>LV1</u>	<u>LV4</u>	<u>UL Adapter</u>
6	1.32	1.25	7.35
12	2.64	2.51	14.71
30	6.60	6.27	36.71
60	13.20	12.54	73.42

The values of viscosity are calculated by multiplying the dial reading by multiplication factors supplied by Brookfield.

## DEFINITION OF DRAG REDUCTION

The percent drag reduction is defined as a comparison between pressure drop in a length of pipe under normal conditions and the pressure drop in the same distance when drag reduction is occurring. Flow rate must be constant for this comparison. Thus

$$\%DR \equiv \left[ \frac{\Delta P - (\Delta P)_{DR}}{\Delta P} \right] 100 \quad ,$$

where  $(\Delta P)_{DR}$  is the pressure drop of the drag-reduced flow.

APPENDIX E

DATA SHEET FOR HYDROMETER ANALYSIS



## APPENDIX F

### SAMPLE CALCULATIONS

This appendix contains sample calculations for

- (1) dissolved solids corrections to suspended solids measurements,
- (2) hydrocyclone test run,
- (3) specific gravity,
- (4) particle size,
- (5) viscosity characterization,
- (6) pipe pressure drop flowrate and drag reduction,
- (7) centrifuge tests.

## DISSOLVED SOLIDS CORRECTIONS TO SUSPENDED SOLIDS DATA

When evaporation is used as the experimental procedure for the determination of suspended solids, a correction must be applied to the resultant data if the supernate contains dissolved solids. This typically occurs when a salt water spoil is encountered. In Appendix D the correction equation was derived;

$$G = \frac{G_{ts} - G_{ds}}{1 - \frac{G_{ds}}{1000G_s}}$$

For the Lake Charles spoil, see Table 1

$$G = 1.008 G_{ts} - 20.3$$

For a total solids content of 100 grams/liter, the actual suspended solid present is

$$G_{ss} = 80.5 \text{ g/l.}$$

All gravimetric data was corrected in this manner.

## HYDROCYCLONE SERIES TEST RUN

Here sample calculations for the complete data reduction of run Spoil-21 with Toledo DE spoil will be presented. After the test run, lab work and appropriate corrections for dissolved solids, the following information is known:

- (1) weight of  $I_c$  underflow collected = 9 lb. 1.5 oz. = 9.09 lb.
- (2) weight of  $II_b$  underflow collected = 2 lb. 6 oz. = 2.37 lb.
- (3) weight of  $II_b$  overflow collected = 32 lb. 12.5 oz. = 32.78 lb.
- (4) time of collection of (1), (2), and (3) =  $\Delta T = 0.41$  min.
- (5) solids concentration:

$$\begin{aligned}
 I_c: \quad & \text{upstream} - G_i = 208.6 \text{ g/}\ell \\
 & \text{underflow} - G_u = 465.9 \text{ g/}\ell \\
 II_b: \quad & \text{upstream} - G_i = 150.0 \text{ g/}\ell \\
 & \text{underflow} - G_u = 209.4 \text{ g/}\ell \\
 & \text{overflow} - G_o = 144.6 \text{ g/}\ell
 \end{aligned}$$

With this information available, the unit weight  $U_w$  of collected samples may be computed. For the  $I_c$  unit

$$(U_w)_u = 0.00834 (465.9) + 8.34 = 12.22 \text{ lb/gal}$$

and for the  $II_b$  unit

$$(U_w)_u = 0.00834 (209.4) + 8.34 = 10.09 \text{ lb/gal}$$

and

$$(U_w)_o = 0.00834 (144.6) + 8.34 = 9.55 \text{ lb/gal}$$

The flow rates may now be calculated from the following equation

$$Q = \frac{\text{wt. collected (lb)}}{\Delta T(\text{min}) W(\text{lb/gal})} = Q \text{ (gal/min)}$$

Thus, for the  $II_b$

$$Q_o = \frac{(32.78)}{(0.41)(9.55)} = 8.37 \text{ GPM} ,$$

$$Q_u = \frac{(2.37)}{(0.41)(10.09)} = 0.57 \text{ GPM} ,$$

and

$$Q_i = 8.37 + .57 = 8.94 \text{ GPM} ;$$

for the  $I_c$

$$Q_o = 8.94 \text{ GPM}$$

$$Q_u = \frac{(9.09)}{(0.41)(12.22)} = 1.81 \text{ GPM} ,$$

and

$$Q_i = 8.94 + 1.81 = 10.75 \text{ GPM} .$$

A mass flow balance may now be performed to check the experimental validity of the test procedure. The mass flow,  $M$ , has the units grams per minute and is calculated from

$$M \text{ (g/min)} = \frac{G \text{ (g/}\ell) Q \text{ (gal/min)}}{.264 \text{ (gal/}\ell)} .$$

For the  $I_c$  hydrocyclone,

$$M_i = \frac{(208.6)(10.75)}{(.264)} = 8500 \text{ g/min} ,$$

$$M_u = \frac{(465.9)(1.81)}{.264} = 3202 \text{ g/min}$$

and

$$M_o = \frac{(150.0)(8.94)}{.264} = 5086 \text{ g/min.}$$

The addition of  $M_o$  and  $M_u$  yield 8288 g/min and compares to  $M_i$  within 2.5%. Thus the balance is verified. For the  $II_b$  unit,

$$M_i = 5086 \text{ g/min} ,$$

$$M_u = \frac{(209.4)(0.57)}{.264} = 455 \text{ g/min}$$

and

$$M_o = \frac{(144.6)(8.37)}{.264} = 4588 \text{ g/min}$$

The combined mass flows for the underflow and overflow for the II<sub>b</sub> are within 1% of the inlet mass flow. When the mass flow balances were complete and verified, it was concluded that the separation test was experimentally valid and contained no significant random or systematic errors.

The parameters used to characterize separation tests are outlined and defined in Part III. For this example, the I<sub>c</sub> unit has the following separation performance

$$C_N = \frac{208.6 - 150.0}{208.6} = 0.281$$

$$C_I = \frac{(465.9 - 150.0)}{150.0} = 1.233$$

and

$$E = \left( \frac{8.94}{10.75} \right) 0.281 = 0.226$$

The II<sub>b</sub> may be described by

$$C_N = \frac{150.0 - 144.6}{150.0} = 0.036$$

$$C_I = \frac{209.4 - 150.0}{150.0} = 0.396$$

and

$$E = \left( \frac{8.37}{8.95} \right) 0.036 = 0.034$$

For the two unit series

$$(C_N)_s = \frac{208.6 - 144.6}{208.6} = 0.307$$

and

$$(C_{I_s}) = \frac{404.4 - 208.6}{208.6} = 0.939 \text{ .}$$

## SPECIFIC GRAVITY

Specific gravity is simply a ratio of the weight of a substance to the weight of the amount of water displaced by that substance and its calculation follows from the equation and definition presented in Appendix B. For example, in the experimental procedure (outlined in Appendix B) for the determination of  $G_s$  for the Savannah spoil, the following experimental values were found.

$$W_1 = 731.25 \text{ g}$$

$$W_2 = 697.97 \text{ g}$$

$$W_s = 53.32 \text{ g}$$

$$T = 20^\circ\text{C}$$

From tabulated data

$$G_T = .998$$

Thus, the general form results in

$$G_s = \frac{(53.32)(0.998)}{53.32 - 731.25 + 697.97}$$

and

$$G_s = 2.66$$

## PARTICLE SIZE

A transformation equation is used to convert hydrometer readings to weight percentage finer calculations. The general equation is

$$W_d^2 = \frac{G_s}{G_s - 1} \left[ \frac{V \gamma_c 10^{-3}}{W_s} \right] 100 R_H$$

For example, for the Tampa spoil, the hydrometer test yielded the following constants,

$$G_s = 2.79 = \text{solids specific gravity,}$$

$$W_s = 26.90 \text{ grams} = \text{weight of solids in hydrometer test,}$$

$$V = 1000 \text{ ml} = \text{volume of spoil tested,}$$

$$\gamma_c = 1.016 = \text{specific gravity of Tampa supernate (3\% salt) at test temperature (20}^\circ\text{C),}$$

$$T = 20^\circ\text{C} = \text{temperature,}$$

$$W_d^2 = \frac{2.79}{1.79} \left[ \frac{(1000)(1.016)(10^{-3})}{26.90} \right] 100 R_H = 5.887 R_H.$$

Thus for each hydrometer reading,  $r_H$ , a weight percentage finer,  $W_d^2$ , may be calculated. The experimental data above is also used in a nomographic determination of particle sizes,  $d$ . An appropriate nomograph and description can be found in Reference 5.

As a specific example, for an elapsed time of 120 sec.,  $r_H$  was 1035.0, the control reading,  $r_c$ , was 1020.3, and

$$R_H = (r_H - r_c) 10^3 = 14.7$$

The weight percentage finer is

$$W_d^2 = 5.887 R_H = 86.5\%$$

From the nomograph, the particle size,  $d$ , is found to be 0.033 mm or 33 micrometers.

## VISCOSITY

Calculations of viscosity must be made from the dial readings on both the Fann Model V-G and the Brookfield Synchro-Electric. The Brookfield uses a set of multiplication factors (MF) to obtain viscosity units from dial readings. The MF are multiplied by the dial readings to obtain viscosity in centipoise, that is

$$(\text{cp}) = \text{MF} \times \text{Dial Readings}$$

The shear rates as a function of RPM are given only for the LV1, LV4 and UL Adapter spindles. As an example, for the Lake Charles spoil, the computations for the LV4 spindle are

### SPINDLE LV4

<u>Shear Rate</u> (1/sec)	<u>rpm</u>	<u>MF</u>	<u>Dial</u> <u>Reading</u>	<u>Viscosity</u>
1.25	6	1000	1.50	1500
2.51	12	500	2.25	1125
6.27	30	200	2.50	500
12.54	60	100	3.00	300

The equations used in conversion of the dial readings of the Fann V-G viscometer were derived and shown in Appendix D. They are restated here for convenience,

$$\tau = 4.66 \beta \frac{\text{dyne}}{\text{cm}^2\text{-degree}} ,$$

$$\text{Shear rate (1/sec)} = 1.703 \times \text{spindle speed (RPM)}$$

and

$$\mu (\text{cp}) = \tau \left( \frac{\text{dyne}}{\text{cm}^2} \right) / \text{shear rate (1/sec)}$$

Using these equations and the data generated by two trials, as described in the procedure, a table of calculated values may be

constructed. For the Lake Charles spoil such a table appears as

Speed (rpm)	Dial Reading			$\tau$ (dyne/cm <sup>2</sup> )	Shear Rate (1/sec)	Viscosity (centipoise)
	Trial		Average			
	1 (degree)	2 (degree)				
3	5.5	6.0	5.75	26.74	5.11	523.2
6	6.0	6.25	6.12	28.46	10.22	278.5
100	9.0	9.0	9.0	41.85	170.2	24.59
200	11.25	11.25	11.25	52.31	340.4	15.37
300	13.50	13.25	13.37	62.17	511.0	12.17
600	19.50	19.0	19.25	89.51	1027.0	8.76

The data thus generated can be plotted on log-log paper where viscosity appears as the ordinate and shear rate the abscissa.

## PIPE PRESSURE DROP, FLOW RATE AND DRAG REDUCTION

The data presented in Table A. 5 reflects calculations made from experimental pipe pressure drop-flow rate measurements for both a conventional spoil and drag-reduced spoil. It is the purpose of this section to demonstrate those calculations. To insure the broadest scope possible, the experimental data from the Savannah experiments (both with and without drag-reducing additives) is used. Due to the spoils solids content the pressure drop in the pipe as measured with a manometer (inches of spoil) must be converted into standard units (inches of water). This conversion requires knowledge of the spoil's unit weight in lb/ft<sup>3</sup>. For the Savannah  $\frac{1}{2}$  strength spoil

$$\text{unit weight of spoil} = 64.5 \text{ lb/ft}^3$$

and

$$G_s = \frac{\text{unit weight spoil}}{\text{unit weight water}} = \frac{64.5}{62.4} = 1.032$$

Furthermore, it is known that

$$\Delta P \text{ (in. of water)} = \Delta P \text{ (in. of spoil)} \times G_s$$

Flow rate may be calculated from

$$Q \text{ (lb/min)} = \frac{\text{collected spoil weight (lb)}}{\text{collection time (min)}}$$

Consider the pipe with an internal diameter of 0.835" (area of  $38 \times 10^{-4} \text{ ft}^2$ ) and a length of 113.5 inches. A typical data point computation would start with the experimental values,

$$\Delta P \text{ (in of spoil)} = 23.6 \text{ inches}$$

$$\text{collection time} = .25 \text{ min}$$

and

collected spoil weight =  $23\frac{1}{4}$  lb

Thus,

$$\Delta P \text{ (in. of water)} = 24.4 \text{ inches}$$

$$M = 93.0 \text{ lb/min}$$

A series of points such as this one may be computed for both the spoil and drag-reduced spoil pipe flows, and curves such as those seen in Figure 21 can be plotted. The amount of friction reduction for a specific flow rate may now be computed. Percent drag reduction is defined as

$$\%DR \equiv \left[ \frac{\Delta P - (\Delta P)_{DR}}{\Delta P} \right] 100$$

for constant  $M$ , where the subscript  $(\Delta P)_{DR}$  denotes the pressure drop during the friction-reducing pipe flow. As a sample, assume  $M = 31.5$  lb/min for the 0.425" ID pipe, whose length is 57". From Figure 21,  $\Delta P = 40$  in. of water and  $\Delta P_{DR} = 21.4$  in. of water; thus

$$\%DR = \left[ \frac{40 - 21.4}{40} \right] 100 = 46.5\%$$

## CENTRIFUGE TESTS

In an effort to make data for the settling tests more meaningful on a comparative basis, it was decided to use rcf as the primary independent variable. From the ASTM D76-68 Standard Method of Test, it is known that

$$\text{RPM} = 265 \left[ \frac{\text{rcf}}{\delta} \right]^{\frac{1}{2}}$$

where

RPM = centrifuge speed (RPM)

$\delta$  = tip to tip diameter of centrifuge tubes when fully extended.

For the work reported here,  $\delta = 18.75$  inches. Solving for rcf yields

$$\text{rcf} = 2.68 \times 10^{-4} (\text{RPM})^2$$

For the Savannah spoil, the following calculations were made for the five minute centrifuge run.

<u>RPM</u>	<u>rcf</u>	<u>Clarified Supernate Volume (ml)</u>
572	87.7	2
914	223.9	8
1200	385.9	15
1563	654.7	23
1957	1026.4	28

Unclassified  
Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Office of Engineering Research Oklahoma State University Stillwater, Oklahoma		2a. REPORT SECURITY CLASSIFICATION Unclassified	
		2b. GROUP	
3. REPORT TITLE FEASIBILITY STUDY OF HYDROCYCLONE SYSTEMS FOR DREDGE OPERATIONS			
4. DESCRIPTIVE NOTES (Type of report and inclusive dates) Final report			
5. AUTHOR(S) (First name, middle initial, last name) W. G. Fiedeman M. W. Reisman			
6. REPORT DATE July 1973		7a. TOTAL NO. OF PAGES 133	7b. NO. OF REFS 10
8a. CONTRACT OR GRANT NO. DAGW 39-72-C-0050		9a. ORIGINATOR'S REPORT NUMBER(S)	
b. PROJECT NO.			
c.		9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report) U. S. Army Engineer Waterways Experiment Station Contract Report D-73-1	
d.			
10. DISTRIBUTION STATEMENT Approved for public release; distribution unlimited.			
11. SUPPLEMENTARY NOTES Prepared under contract for U. S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi.		12. SPONSORING MILITARY ACTIVITY U. S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi	
13. ABSTRACT A major difficulty with dredge spoil is that in most dredging operations small suspended solids become well dispersed in the large volumes of water used to hydraulically transport the solids from the bottom of the waterway. Frequently it is not efficient to transport this entire volume of water to a disposal site and yet in many cases it is also undesirable to return the turbid water to the waterway. However, even when the entire volume of spoil is transported to a disposal site, an overflow of turbid water can occur from the disposal site, particularly when the site is small or almost full. Consequently, the development of processes which will clarify the water and concentrate the small suspended solids in dredge spoil would make transport of spoil more efficient, would make the use of smaller disposal sites possible and would decrease the environmental impact of dredge operations. The purpose of this study was to experimentally determine the feasibility of using hydrocyclone separators for the concentration and clarification of dredge spoil. Since hydrocyclones are also well suited for the task of separating solids into fractions, the feasibility of using hydrocyclones for the recovery of sand and gravel while rejecting fine silt was also investigated. The experimental program was conducted with hydrocyclones and hydrocyclone series designed for overflow flow rates of about 10 gallons per minute. Six dredge spoil samples (supplied by the Corps of Engineers), two clay slurries and one sand were used to determine the effect of particle size, viscosity of the fluid, and inlet solids concentration upon the effectiveness of the hydrocyclones. Attempts were also made to increase performance by chemically flocculating the solids upstream of the separators. While the clarification and concentration performance of the hydrocyclones was good on low solids content clay slurries, the performance ranged from below average to poor on the spoil samples. The poor capability of the separators to clarify and to concentrate these spoils was due to the combination of high solids content, small particle sizes and highly pseudoplastic (high viscosity) behavior of the spoils. Centrifugation and chemical treatment were not effective on the higher solids content (greater than 100 g/l) spoils either. Spoils with solids contents less than 100 g/l could be flocculated but the flocs were too fragile to survive in the hydrocyclones and neither clarification nor concentration was enhanced by the treatment. The high solids content affects clarification more than it does concentration and thus hydrocyclone concentrators were reasonably effective on all but the highest solids content spoils. Meanwhile, the hydrocyclone proved very successful at recovering sand from the full range of spoils. The hydrocyclone system is recommended for this application of classifying the solids in dredge spoil.			

DD FORM 1473 REPLACES DD FORM 1473, 1 JAN 64, WHICH IS OBSOLETE FOR ARMY USE.

Unclassified  
Security Classification

Unclassified

Security Classification

14.	KEY WORDS	LINK A		LINK B		LINK C	
		ROLE	WT	ROLE	WT	ROLE	WT
	Dredge spoil Gravel Hydrocyclones Sands Suspended sediments Turbidity						

Unclassified

Security Classification