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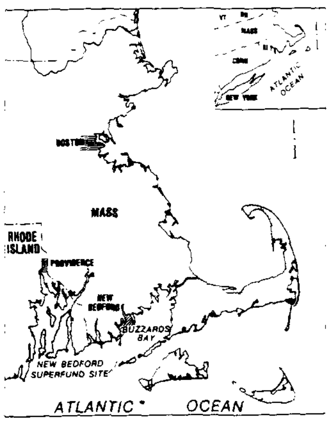
TECHNICAL REPORT HL-89-11

DEPOSITION AND EROSION TESTING ON THE COMPOSITE DREDGED MATERIAL SEDIMENT SAMPLE FROM NEW BEDFORD HARBOR, MASSACHUSETTS



by

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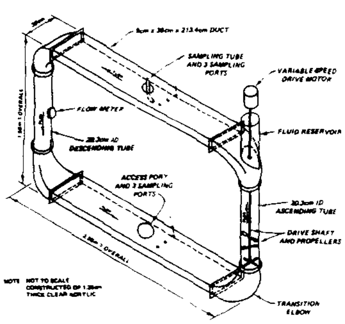

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Contaminated fine-grained sediments from upper New Bedford Harbor were tested to determine erosion, deposition, and settling characteristics. The study was performed to support an Engineering Feasibility Study (EFS) of dredging and disposal of contaminated harbor sediments. An important issue addressed by the EFS was the possible hydraulic dispersion of contaminated sediment material out of the upper harbor during dredging and disposal operations. Sediment transport characteristics were required to perform mathematical modeling and make predictions. Erosion was determined for newly deposited sediments. Deposition and erosion results indicated that the sediment material was composed of three fractions. The most easily eroded sediment fraction was also the slowest to deposit, and was by far the most mobile sediment fraction. This fraction comprised 29 percent of the sediment fines, or 40 percent of the bulk sediment composite, and was composed of

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sediments less than 14 μm. The critical bed shear stress which initiated erosion was 0.06 N/sq m, and the critical shear stress below which deposition occurred was 0.043 N/sq m for the finest fraction. Suspended sediment settling velocities were found to increase as the four-thirds power of suspension concentration at concentrations above 75 mg/ℓ, and were found to be constant below 75 mg/ℓ at about 0.006 mm/sec.

A special closed-conduit sediment water tunnel was developed to safely test contaminated sediments. The rectangular-shaped water tunnel was constructed so that a uniform cross-sectional area was maintained. Other details, including safety precautions and test limitations, are noted in the report. The results of the settling and resuspension tests conducted in the water tunnel provided data for statistical and other analysis.

PREFACE

This study was conducted as one element of Task 4 of the Upper Acushnet River Estuary Engineering Feasibility Study of Alternatives for Dredging and Dredged Material Disposal, which is sponsored by Region I of the US Environmental Protection Agency (USEPA). The purpose of this task was to evaluate contaminant migration associated with dredge- and disposal-resuspended sediments. Project Manager for USEPA was Mr. Frank Ciavattieri. Coordination and management support was provided by the US Army Engineer District, Omaha. The study was conducted in cooperation with the US Army Engineer Division, New England. The US Army Corps of Engineers Water Resources Support Center, Dredging Division, contributed technical support and guidance for the study. Funding for this report was provided by the Improvement of Operations and Maintenance Techniques (IOMT) research program sponsored by the Headquarters, US Army Corps of Engineers (USACE), because of the direct association with Work Unit No. 31765, "Fine-Grained Shoaling in Navigation Channels."

Task 4 was performed by personnel of the Hydraulics Laboratory (HL) of the US Army Engineer Waterways Experiment Station (WES). This study was conducted during the period May-July 1987 under the general supervision of Messrs. Frank A. Herrmann and Richard A. Sager, Chief and Assistant Chief, respectively, of HL; William H. McAnally, Jr., Chief, Estuaries Division; George M. Fisackerly, Chief, Estuarine Processes Branch; and E. C. McNair and R. F. Athow, Estuaries Division, former and present IOMT Program Managers, respectively. Messrs. James L. Gottesman and Charles Hummer were USACE Technical Monitors. The study was conducted and the report written by Mr. Allen M. Teeter, Estuarine Processes Branch. Mr. Walter Pankow, Estuarine Processes Branch, assisted in the preparation of this report. Mr. Larry Caviness, Estuarine Processes Branch, the lead technician for the work, operated the testing apparatus, performed sampling, and conducted sample analysis. The testing apparatus was constructed by the Engineering and Construction Services Division, WES. Parts of the testing apparatus were based on a design developed for a pump suction inlet by the Structures Division, HL. The shear stress sensor used in this study was developed and calibrated by the University of South Florida at Tampa under contract to HL. This report was reviewed by Mr. David T. Williams, Math Modeling Group, Waterways Division, HL, and edited by Mrs. Marsha C. Gay, Information Technology Laboratory, WES.

This study was monitored by Messrs. Norman R. Francingues and Daniel E. Averett of the Environmental Laboratory, WES.

COL Dwayne G. Lee, EN, is Commander and Director of WES. Dr. Robert W. Whalin is the Technical Director.

APPENDIX A: NOTATION

A	Depositional area of the water tunnel
$A1$	Constant
C	Suspended sediment concentration; concentration just above the bed
C_f	Friction coefficient
C_o	Initial concentration
D	Deposition
E	Particle resuspension
h	Height of suspension above the sampling point; effective depth V/A
i	Subscript indicating a sediment fraction
k	Number of sediment fractions
M	Erosion rate constant
n	Enhanced-settling exponent
P	Probability that an aggregate which has reached the bed will remain there
R^2	Coefficient of determination
t	Sampling time or time
t^*	Time at which half the fraction was deposited
$\bar{U}$	Mean velocity
V	Suspension volume
W_s	Settling rate or velocity
W_{s_g}	Geometric mean of settling velocity
ρ	Fluid density
σ_g	Geometric standard deviation
τ_b	Bed shear stress
τ_c	Critical erosion shear stress
τ_{cd}	Critical shear stress for deposition

CONTENTS

DEPOSITION AND EROSION TESTING ON THE COMPOSITE DREDGED MATERIAL SEDIMENT SAMPLE FROM NEW BEDFORD HARBOR, MASSACHUSETTS

PART I: INTRODUCTION

Background

1. Because the sediments of the upper New Bedford Harbor were found to be highly contaminated, the site was selected for an Engineering Feasibility Study (EFS), performed by the US Army Corps of Engineers for a possible Superfund cleanup by dredging and disposal of sediments contaminated with polychlorinated biphenyls (PCB's) in upper New Bedford Harbor, Massachusetts (Figure 1). Task 4 of the EFS evaluated contaminant migration associated with dredge- and disposal-resuspended sediments. Elements within Task 4 include evaluation of controls for dredging, hydraulic characterization of New Bedford Harbor, testing for contaminant release from sediments, sediment deposition and erosion testing, and contaminant migration analysis. Most contaminants are associated with bed sediments, and the migration of contaminated sediments out of the upper harbor during cleanup is an issue being addressed by the EFS.

2. Potential sources for resuspended sediments considered in the EFS include the dredging operation, effluent from confined disposal at a diked facility (CDF), and effluent from confined aquatic disposal (CAD) beneath the harbor bed. Migration of resuspended sediments from the upper harbor depends on their settling and depositional characteristics and, to some extent, erosion characteristics. CAD dredged material will be subjected to tidal currents and possible erosion prior to capping; therefore, the erosion characteristics of dredged material deposited in the CAD must be known. Unsteady tidal hydraulics make cyclic deposition/erosion another possible mode of transport for fine sediment material to escape the upper harbor. Therefore, both deposition and erosion information are needed to evaluate sediment-associated contaminant migration.

3. Depositional and erosional characteristics of fine-grained sediments vary greatly, and are critical to the prediction of sediment and contaminant migration. Direct testing on sediments from the study area was therefore necessary. Testing was complicated by the nature of the sediments, which were highly contaminated with PCB's, heavy metals, and aromatic hydrocarbons.

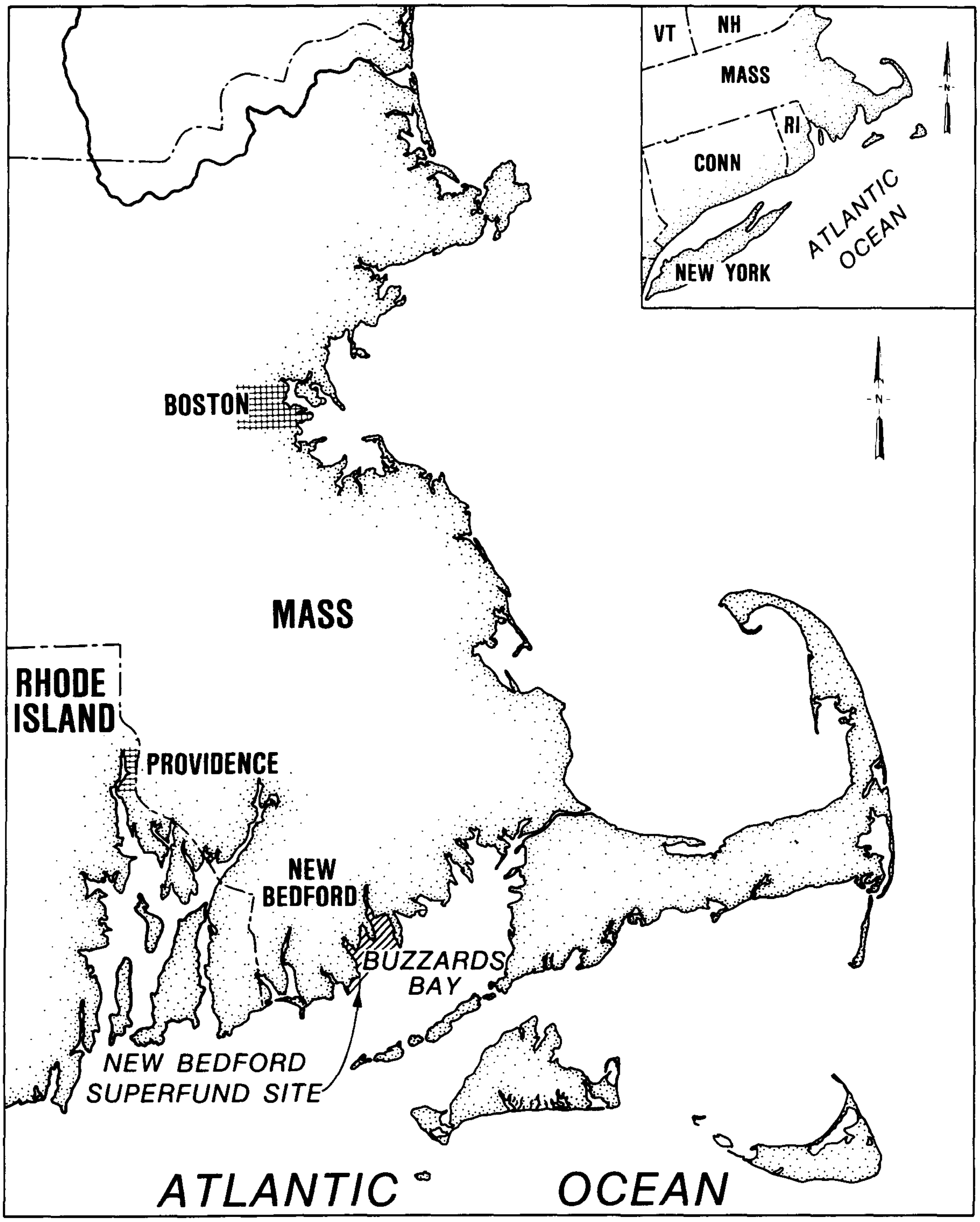


Figure 1. Location of New Bedford, MA

Purpose

4. This report presents findings of laboratory studies on deposition and erosion of New Bedford Harbor bottom sediments and presents new testing procedures in this field of study. Information developed in this study was intended to meet requirements for numerical sediment-associated contaminant migration predictions, and for planning and controlling dredging and disposal operations.

Scope

5. A total of twelve tests in four test series were performed on sediments from New Bedford Harbor. All tests included a deposition test phase and at least one erosion test phase. Ten tests included settling test phases. Process description, materials and equipment, test procedures, data analysis, results, discussion of results, and conclusions follow.

PART II: PROCESS DESCRIPTION

6. Sediment released into suspension by dredging and disposal operations represents some specific fraction of the bed material in the upper harbor. Sediment is physically sorted or fractionated during dredging and disposal operations and during subsequent suspended transport. The objective of the deposition and erosion tests was to characterize the more mobile, fine-grained New Bedford Harbor sediment smaller than 74 μm (silts and clays) and larger than 0.45 μm (colloids). Fine-grained sediments are hydraulically transported almost entirely in suspension rather than as bed load. Because of the differences in cohesion, settling characteristics, etc., for silts (4-72 μm) and clays (0.45-4 μm), fine-grained sediment was characterized for these tests as a sum of several fractions or components. The fine-grained material can also contain an organic fraction, which behaves similar to cohesive sediments.

7. Fine-grained sediments exhibit some degree of cohesion; thus clay and organic solid particles aggregate under normal estuarine conditions. The state or degree of aggregation affects deposition, erosion, and settling processes to be described later, and depends on sediment concentration, salinity, turbulence in the flow, pH, temperature, etc.

Settling

8. Settling is that component of suspended particle or aggregate motion caused by the balance between gravity and viscous drag forces. Settling rates are therefore defined in quiescent native fluid. Settling characteristics affect rates of deposition and the vertical distribution of suspended material.

9. Aggregation is very important to cohesive sediment settling rates, and is responsible for clay deposition in estuaries and marine environments. Aggregation of a particular sediment particle suspension depends primarily on suspended sediment concentration, current shear or velocity gradients, and salinity. Current shear and salinity effects on New Bedford sediments have not been studied. However, previous experiments on the effects of current shear on settling found impacts at shear rates above those encountered within most natural flows (Hunt 1982). Salinity effects on aggregation are greatest between 0- and 4-ppt concentration, and are not an important factor in

New Bedford Harbor, which is almost entirely above this range.

10. Three ranges of concentration-dependent settling usually occur. At low concentrations, aggregate and particle interaction is minimal, and settling is independent of concentration. At intermediate concentrations, settling is enhanced by concentration because of increased aggregation and particle interaction. At high concentrations, aggregate and particle interaction hinders settling.

11. Resuspended sediment concentrations from dredging and disposal operations are expected initially to be in the enhanced-settling range. The dependence of settling velocity in the enhanced-settling concentration range has the functional form (Ariathurai, MacArthur, and Krone 1977):

$$W_s = A1C^n \tag{1}$$

where

W_s = settling rate or velocity*

$A1$ = constant

C = suspended sediment concentration

n = enhanced-settling exponent

The exponent n is usually found to be close to 1.33. The concentration range over which Equation 1 applies varies with the cohesive properties of the sediment. Generally the lower bound is in the range of 10-200 mg/ℓ, and the upper bound is in the range 2,000-75,000 mg/ℓ.

12. Fine-grained sediment suspensions usually have a range or distribution of W_s. Clay and fine silt fractions aggregate to form a relatively uniform settling aggregate. Medium and coarse silt fractions settle at higher rates, and are less dependent on concentration than the clay fraction. The objective of the settling tests was to determine the magnitude and distribution of W_s at various suspended sediment concentrations for the finer fractions of the material.

Deposition

13. Deposition D, or flux of sediment material to the bed, is the

* For convenience, symbols and abbreviations are listed in the Notation (Appendix A).

sum over a number of fractions of settling flux times deposition probability (Mehta et al. 1986):

$$D = \sum_{i=1}^{k} P_i W_{s_i} C_i \tag{2}$$

where

k = number of sediment fractions

P = probability that an aggregate which has reached the bed will remain there

C = concentration just above the bed

and the subscript i indicates a sediment fraction. P varies linearly from 0 at a bed shear stress equal to the critical shear stress for deposition, $\tau_b = \tau_{cd}$, to 1 at zero bed shear stress, $\tau_b = 0$. The functional form $1 - (\tau_b/\tau_{cd})$ where $\tau_b < \tau_{cd}$ is used for P (Krone 1962). The objective of the deposition testing was to determine τ_{cd} and the magnitude of the product PW_s for each sediment fraction identified.

14. A suspension of uniform material in a steady, uniform flow will either deposit completely or remain entirely suspended depending on whether τ_b is below or above τ_{cd}, according to Equation 2. The consequence of the presence of multiple sediment fractions in a suspension is that, under a given flow condition, some sediment fractions may deposit while others may remain in suspension. The suspension may therefore transport an equilibrium concentration (some fraction of the source concentration) indefinitely.

15. The values for W_s referred from deposition tests are smaller than those obtained from quiescent settling tube tests. The cause for this is not known. However, shear in the flow is greatest just above the bed, and could cause disaggregation and/or produce lift forces counteracting settling at this point.

Resuspension

16. The mode of resuspension (used synonymously with erosion) considered important to potential contaminant migration at New Bedford Harbor is particle erosion. At τ_b above a critical value, particles or clusters of

particles are individually dislodged from the sediment bed as interaggregate bonds are broken. Particle resuspension E is related to the shear stress in excess of a critical value, and to an erosion rate constant M , thus:

$$E = M\left(\frac{\tau_b}{\tau_c} - 1\right), \quad \tau_b > \tau_c \tag{3}$$

where τ_c is the critical erosion shear stress (Ariathurai, MacArthur, and Krone 1977). Observed erosion does not follow Equation 3 indefinitely. Suspension concentrations above experimental eroding beds often reach equilibrium values which depend on the bed shear stress and character of the bed. Equilibrium suspensions form as erosion rates decrease with time to zero, while the flow remains constant. Equilibrium suspensions have been found to be related not to the transport capacity of the flow (as for sand), but to vertical differences or nonhomogeneity in the bed (either particle characteristics or bed density) or to armoring by selective erosion at the bed surface. The purpose of the resuspension tests was to determine the magnitude of M and τ_c for representative sediment fractions, and to detect the formation and nature of equilibrium suspensions.

PART III: MATERIALS AND EQUIPMENT

Test Materials

17. The test material consisted of sediment from the composite sample collected as Task 5 of the EFS. The composite sample was made from individual samples taken from a number of locations in the upper harbor, and is representative of moderately contaminated (in a relative sense) sediments. The composite sample has been used for a number of laboratory tests in the EFS. The grain size distribution of the composite sample is shown in Figure 2. The solids concentration, total exchangeable cations, and oil and grease content of the composite sample are given in the following tabulation.

Composite Sample	Replicate 1	Replicate 2	Replicate 3
Total solids, percent	35.8	35.6	36.1
Total exchangeable cations, ppm	220	248	212
Oil and grease, ppm	28,000	27,000	30,000

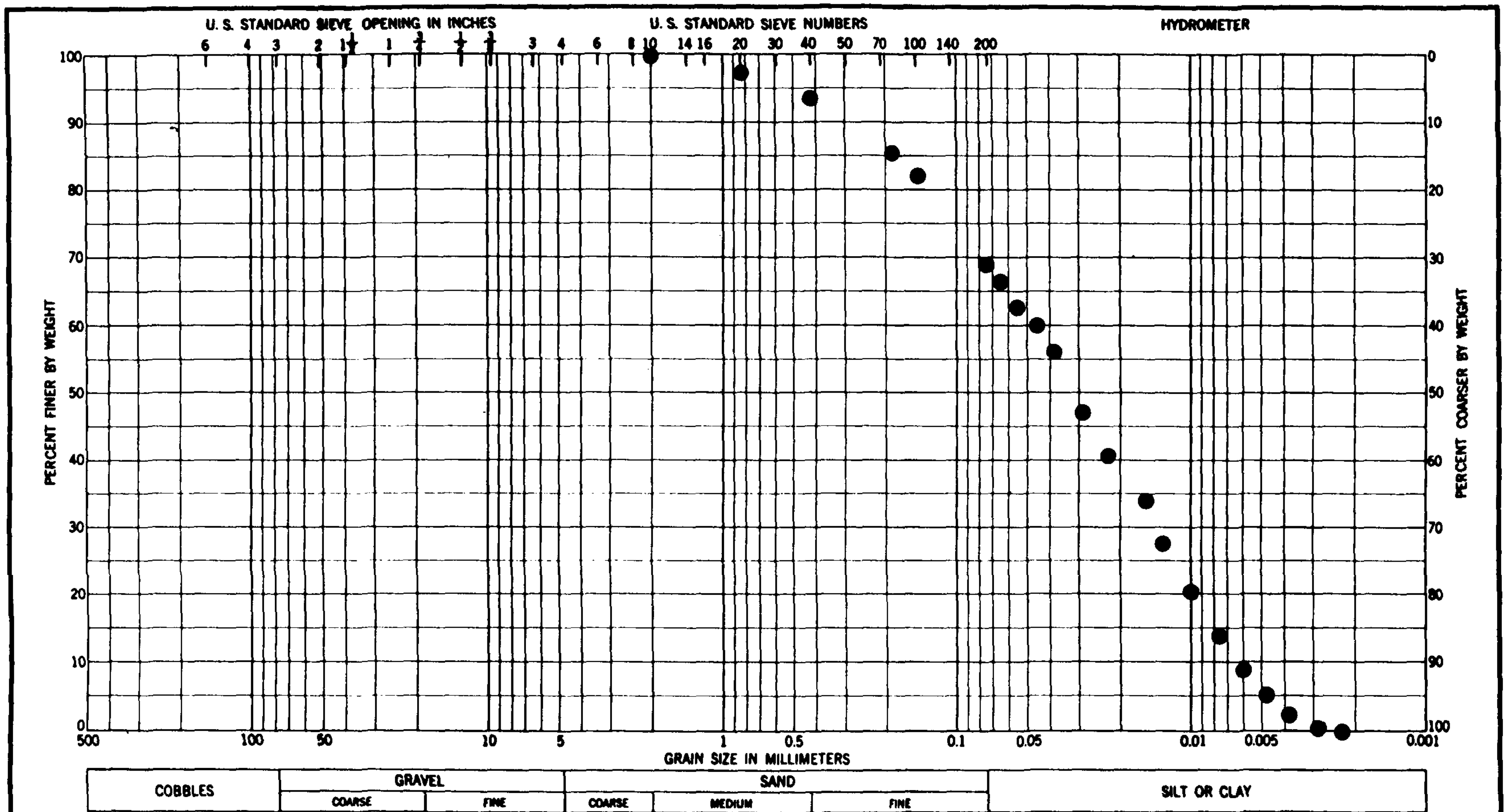
The principal mineral groups for New Bedford sediments have been reported to be chlorite and mica by Ellis et al. (1977).

18. The composite sample was prepared for erosion and deposition testing by passing it through a US Standard No. 200 sieve, with a screen opening of 74 μm. Figure 3 shows the grain size distribution for the sieved composite sample reconstructed from Figure 2. About 32 percent of the composite sample was coarser than 74 μm. Seawater was used in the sieving operation, and reduced the bulk density or concentration of the material to 1.17 g/cu cm or 250 g/ℓ, respectively.

19. Tests were performed as a sequence of sediment additions to a closed system, the sediment water tunnel, as described later. Sediments resuspended from the bed of the sediment water tunnel at the beginning of each test became incorporated into the test material. In some cases only resuspended material was tested. This resulted in the test material being different from, and finer than, the original sieved composite sample.

Description of Sediment Water Tunnel

20. A special testing device was developed for this study to safely



Sample No.	Elev or Depth	Classification	Nat w %	LL	PL	PI	
27		dark gray-sandy organic SILT (OH)					Project New Bedford Harbor, Mass.
							Area Composite
							Boring No. Lab ser no 100-452-27
GRADATION CURVES							Date 29 Jan 87

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Figure 2. Grain size distribution of the composite sample

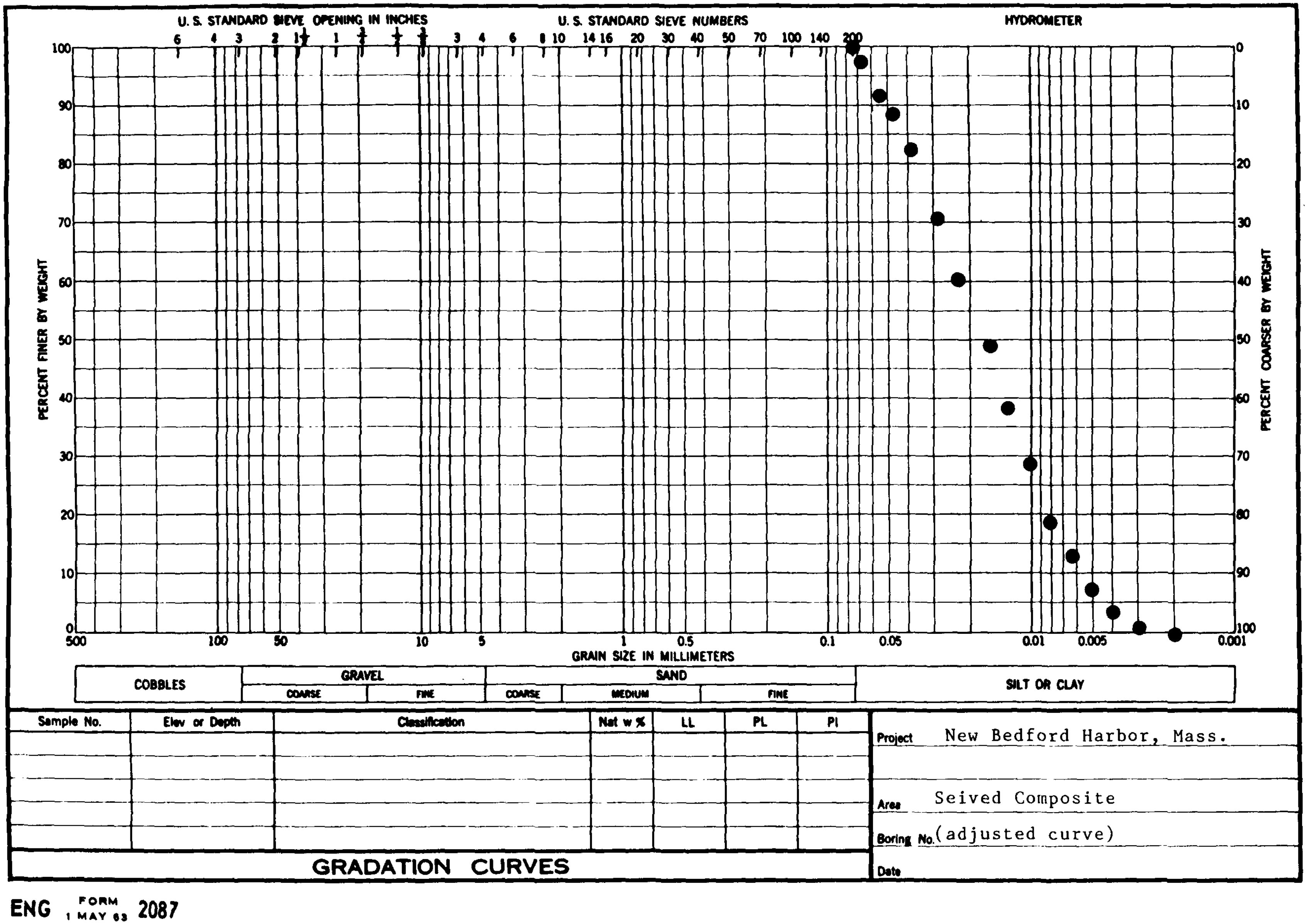

Figure 3. Adjusted grain size distribution for the sieved composite sample

test contaminated sediments. The testing device was a closed-conduit sediment water tunnel, open to the air only at a small expansion chamber. The water tunnel had a uniform cross-section area, which changed from rectangular in the horizontal deposition/resuspension sections to circular in the vertical settling and pumping sections. The configuration of the sediment water tunnel is shown in Figures 4 and 5. The sediment water tunnel was constructed of clear acrylic. The transition shapes or elbows were based on a design developed for a pump suction inlet.

21. The volume of the water tunnel was 280 ℓ, and the area for deposition and resuspension was 1.64 sq m. Flow in the sediment water tunnel was driven by a tandem pair of Minnkota ER-3 two-bladed, skewed propellers, and by a variable-speed induction motor. Propeller speed was determined by monitoring 10 reflective spots on a 23-cm-diam flywheel with a photoelectric tachometer.

22. The water tunnel was calibrated so that propeller speed could be related to average velocity and bed shear stress as shown in the following tabulation:

Propeller Speed rpm	Average Current Speed cm/sec	Bed Shear Stress N/m^2
150	6.0	0.015
200	10.2	0.030
240	13.6	0.056
280	17.5	0.077
320	21.3	0.164
440	35.1	0.591

Calibration curves were developed using the tachometer, a flowmeter, and a hot-film shear stress sensor. Flow was measured with a Data Industrial Series 900 Flowmeter with a Model 228 impeller sensor. The shear stress sensor was developed and calibrated by the University of South Florida at Tampa (Gust and Weatherly 1985 and Gust, in preparation). The shear stress sensor operated on the hot-film principle, and was monitored using a Thermal Systems Incorporated Model 1050 constant-temperature anemometer. Bed shear stress was also calculated as

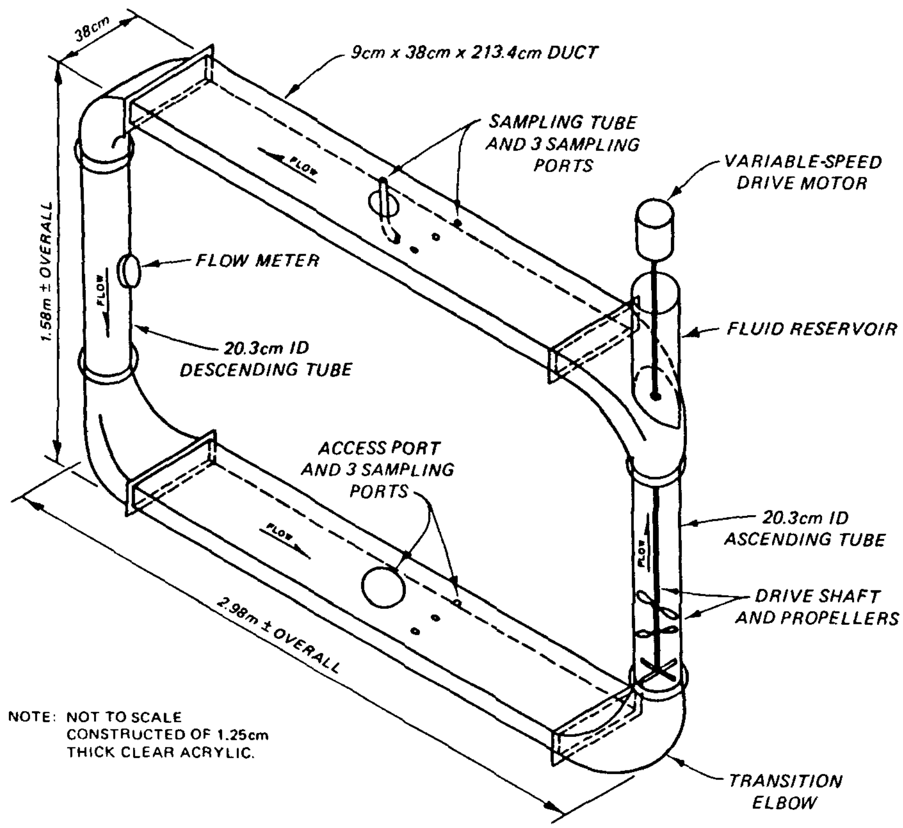

Figure 4. Isometric view of sediment water tunnel

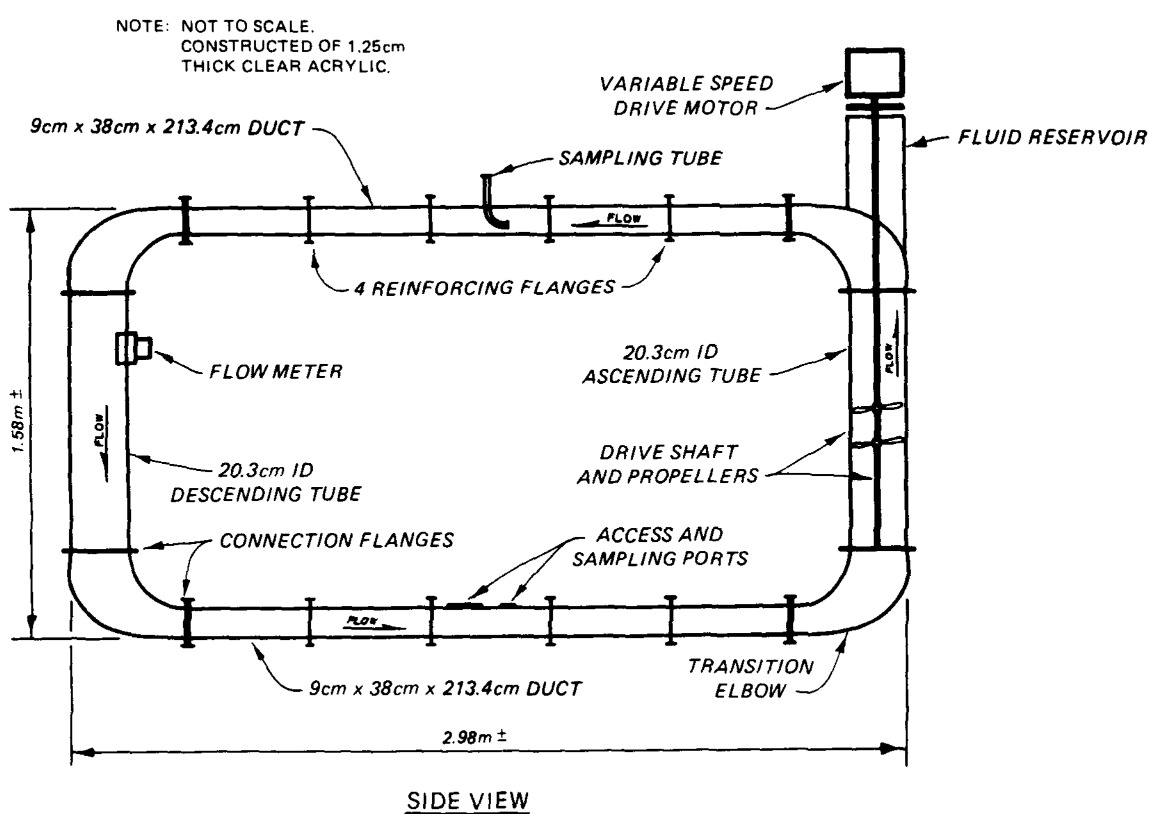

Figure 5. Side view of sediment water tunnel

$$\tau_b = \rho \left(\frac{C_f}{2} \right)^{1/2} \bar{U}^2 \qquad (4)$$

where

ρ = fluid density

C_f = friction coefficients from Reynolds (1974)

U = mean velocity

Calculated and measured values were in agreement up to a shear stress of about 0.2 N/sq m. Higher values disagreed, probably because elbow frictional losses were ignored in the calculations and because of distortion of velocity profiles.

23. Secondary flows and other flow irregularities were examined in the water tunnel using flow visualization. Flow was made visible by adding a rheoscopic compound to the water and by special illumination. Overall the flow patterns appeared to be smooth and turbulence structure uniform, except for a small area near the propeller. The propeller wake appeared to be completely contained within the ascending tube. No flow features were observed that would adversely affect testing results.

24. The seawater used for the tests was reconstituted from Instant Ocean salt mix. The salinity was 25.8 ppt. Sixty cubic centimetres of 30 percent formaldehyde solution was added to the water tunnel to inhibit microbial growth. Water temperature for the tests was between 22.2° and 22.6° C, and varied less than 0.3° C during any individual test. The temperature for the tests was controlled as carefully as possible, and monitored often with a calibrated thermistor.

PART IV: TEST PROCEDURES

25. Four test series (designated I through IV) were performed to provide deposition and resuspension data over ranges of conditions and to allow estimation of the coefficients described in Part II. Three tests were performed in each series, and each test had combinations of erosional, depositional, and settling test phases. An initial water tunnel sediment bed was established by the addition of 75 g of sediment during two preliminary deposition periods. Tests were performed by additions of sediment to the water tunnel without removal of material from previous tests. Table 1 shows the chronology for all tests.

Test Chronology

26. Series I tests began with two 30-min resuspension periods. The flow for the resuspension periods was at least as great as for deposition periods. The sediment water tunnel was then operated at high flow speed (0.6 N/sq m). Sediment material was injected into the sediment water tunnel and allowed to mix for an additional 30 min. About 25 g of sediment was introduced in Test I-1, and about 12.5 g was introduced in Tests I-2 and I-3. The flow speed was then reduced to a depositional speed for 90 min while samples were taken. The flow during the deposition phase was varied for the three tests in the series. After the deposition phase, the flow was stopped and a settling test was performed for 300 min, during which samples were taken as described later.

27. Series II tests began with two 30-min resuspension periods. The flow during the first resuspension period was less than during the second. The resuspension flows were generally increased for subsequent tests in the series. No additional sediment material was added during Series II tests. After the second resuspension period, the flow was reduced and deposition observed for 90 min, during which samples were taken. Flow was then terminated, and a 300-min settling test phase performed.

28. Series III tests began with two resuspension periods. Flow during the first period was the same for all tests in Series III (0.6 N/sq m). Flow in the sediment water tunnel during the second resuspension period was decreased during the test series. Sediment material (about 8.3 g) was injected

into the sediment water tunnel and allowed to mix at high flow (0.6 N/sq m) for an additional 30 min. The flow speed was reduced to the depositional speed for 90 min. The flow during the deposition phase varied for the three tests in the series. After the deposition phase, the flow was terminated and a 300-min settling test performed.

29. Sediments (about 50 g) were added during the first test of Series IV. After a 30-min mixing period at high flow, the flow was terminated and a settling test performed. The three tests in series IV consisted of deposition test phases, preceded by high-flow (0.6-N/sq m) resuspension periods. Depositional flows were decreased during the test Series. The final deposition test of the series was extended to 150 min.

Test Sampling

30. The following paragraphs detail the procedures followed for individual test phases. Samples from the sediment water tunnel were analyzed for total nonfilterable solids by a standard method. Sample volumes were 50 cu cm, and were processed immediately. Nuclepore polycarbonate filters with 0.4 μm pore size were used in the analysis of suspended material.

Settling

31. Settling tests were performed in the descending tube, as shown in Figure 5, with the flow in the sediment water tunnel stopped. Samples were withdrawn from the water tunnel at 0, 8, 15, 30, 45, 60, 90, 120, 180, 240, and 300 min using a syringe with an 18-gage needle. The samples were drawn about 2.5 cm from the wall of the water tunnel. The height of the sediment/water suspension above the sampling port was 1,067 mm.

Deposition

32. After establishment of the deposition test speed, samples were taken at 0, 2, 4, 6, 10, 15, 20, 30, 45, 60, and 90 min. Samples were drawn from a 3.2-cm depth in the center of the upper rectangular tunnel section by syringe.

Resuspension

33. Resuspension of deposited sediment was studied in the water tunnel by subjecting deposits to a range of current shear stresses. Resuspension periods were observed and sampled at the beginning of each test. After the flow was established, samples were taken after 30 min at the same location as

the deposition samples. Some samples were also taken at 15 and/or 22.5 min.

Safety Procedures

34. The sediment was sieved at a special Environmental Laboratory facility at the US Army Engineer Waterways Experiment Station equipped with full environmental suits, self-contained air supplies, and special venting. Full-length disposable suits, neoprene gloves, respirators, and safety glasses were worn by personnel during sediment additions to the water tunnel. The water tunnel was located in one chamber of a portable laboratory remote from other activities. The water tunnel laboratory was kept closed, and a constant air exhaust from the chamber to the outside was maintained during testing. The exhaust port was located about 0.6 m from the expansion chamber of the water tunnel. The water tunnel was situated above a spill pan capable of holding the entire water tunnel volume. Two Norelco Clean Air Machine II air cleaners with charcoal filters were located near the water tunnel. During the sediment tests, all personnel wore respirators in the water tunnel chamber. Tests were performed by no more than two persons. Neoprene gloves were worn while sampling, and at any time of possible contact.

35. Suspended samples were analyzed immediately by vacuum filtration and gravimetric methods. The exhaust from the vacuum pump was vented to the outside. Filtrate was recycled back into the water tunnel at the end of the tests. Filters were oven-dried in an open-air shelter.

PART V: DATA ANALYSIS

Settling

36. Settling velocities were calculated from settling test data using a method similar to the pipette method. The change in concentration (amount removed) at the sampling depth was equal to the fraction of material settling at a greater rate than h/t , where h is the height of the suspension above the sampling point and t is the sampling time. The settling test data were transformed into percent removed and natural log of sampling time. A second-order polynomial was fit through the data by least squares regression. Settling velocity distributions were reconstructed from the regression coefficients.

37. In addition to cumulative distributions, some statistical parameters were calculated that are descriptive of the settling velocity distributions similar to those used to characterize grain size distributions (Inman 1963). The geometric mean, standard deviation, skewness, and kurtosis were calculated as follows:

<u>Geometric mean</u>

$$W_{s_g} = \left(W_{s_{16}} W_{s_{84}}\right)^{1/2} \tag{5}$$

<u>Geometric standard deviation</u>

$$\sigma_g = \left(\frac{W_{s_{84}}}{W_{s_{16}}}\right)^{1/2} \tag{6}$$

<u>Skewness</u>

$$\frac{\log\left(\frac{W_{s_g}}{W_{s_{50}}}\right)}{\log \sigma_g} \tag{7}$$

Kurtosis

$$\frac{\left(\frac{W_{s_{95}}}{W_{s_5}}\right)^{1/2} - \sigma_g}{\sigma_g} \tag{8}$$

where the subscripts refer to percentile values of the cumulative percent-greater-than distribution. The geometric mean is a better descriptor of the central tendency of the distribution than the simple average, which was also calculated. The median $W_{s_{50}}$ is a commonly used descriptor of central tendency. The geometric standard deviation is a dimensionless indicator of the spread of the distribution. Skewness indicates the symmetry and direction of distribution shift. Kurtosis indicates the peakedness of the distribution.

Deposition

38. Deposition was determined by monitoring suspended sediment concentration of a steady flow. The equation expressing mass balance for the water tunnel suspension is

$$\frac{\partial(CV)}{\partial t} = -APW_sC \tag{9}$$

where

C = average suspended concentration

V = suspension volume

A = depositional area of the water tunnel

39. Two solutions to Equation 9 were used in the data analysis. Assuming that W_s is constant and independent of C , then the solution is

$$\log_e\left(\frac{C}{C_o}\right) \approx -PW_s\frac{t}{h} \tag{10}$$

where C_o is the initial concentration and h is the effective depth V/A .

Assuming that W_s depends on a power of C, as expressed by Equation 1, then another solution to Equation 9 is

$$C^{-n} - C_o^{-n} = nAlP \frac{t}{h} \tag{11}$$

Al is expected to have a different (smaller) value for the deposition tests than for the settling tests. The power n was assumed to have the value 4/3 based on the results of settling tests and previous experience with other sediments. Equations 10 and 11 were rearranged and used as regression equations to determine W_s, P, and AlP, respectively, from the raw data.

40. Deposition data were further analyzed as the superposition of a number of fractions, as in Equation 2. Plots of $C^{-4/3}$ versus t/h were used to differentiate the test data into three depositional components or fractions, as indicated by straight-line segments and inflections. The magnitudes of these fractions and the time at which half the fraction was deposited t^* were estimated from the data. The slopes for the deposition fractions were then estimated from

$$\frac{4}{3} Al_i P_i = \frac{h}{t^*} \left[\left(\frac{C_{o_i}}{2} \right)^{-4/3} - C_{o_i}^{-4/3} \right] \tag{12}$$

By plotting the left side of Equation 12 versus τ_b, τ_{cd} was estimated for each fraction. Al was then calculated for each fraction.

Resuspension

41. Resuspension was determined by monitoring the suspension concentration in a steady flow. The constancy of E was determined visually and by inspection of concentration/time data. The magnitudes of equilibrium suspension concentrations and of the fraction of total mass in suspension were compared to bed shear stress.

Limitations of Tests

42. There are no standard methods for testing deposition and resuspension. The methods described herein were designed by the author in light of the most recent research and understanding of fine sediment behavior. The sediment tests were conducted in physical models and included bed shear stresses, concentrations, and important sediment characteristics equivalent to prototype conditions. The water chemistry in the water tunnel was somewhat different from normal prototype conditions in that very little reaeration was possible. Oxygen demand may have reduced or depleted dissolved oxygen levels in the sediment water tunnel, although no measurements were made. Dissolved oxygen in the water column near dredging and dredged material disposal operations would be reduced only slightly. The effect of low or zero dissolved oxygen concentrations on sediment behavior is not known.

PART VI: RESULTS

43. Test Series I was carried out 19-21 May; Series II, 27-29 May; Series III, 9-11 June; and Series IV, 26-27 June 1987. Equilibrium suspensions, an important feature of the tests, were formed during both deposition and erosion phases of certain tests. Suspension concentrations changed, then became constant. The formation of equilibrium suspension was caused by non-uniform sediment characteristics.

44. The sediment water tunnel functioned well, although some propeller speed drift occurred, especially at low speed. The larger organic fractions present in the suspension added to the variability in the suspended material analysis and to the scatter in the data. While apparent data scatter varied between tests, it was never severe, and only a small number of data points were rejected as spurious.

Settling

45. Table 2 shows individual settling test results and composite results for Series II and III. Composites were calculated by averaging the percent-removed curves from the test series. This was done only when results indicated that analytical variation (sampling and sample analysis) was probably larger than the true variation between the tests (based on test procedures).

46. Example raw data plots are shown in Figure 6 for representative tests. Generally between 70 and 85 percent of the suspended material was removed by settling during the 300 min of the settling test phases. Most of the regression fits to the data had coefficients of determination R^2 of about 0.99. The lowest R^2 was 0.92.

47. A plot of the power law settling function (Equation 1) is shown in Figure 7.

Deposition

48. Deposition was fairly uniform over the bed surface of the water tunnel. Heavy silts formed scattered small mounds of higher deposition about 2 cm across. Mounding has been observed in previous deposition tests with

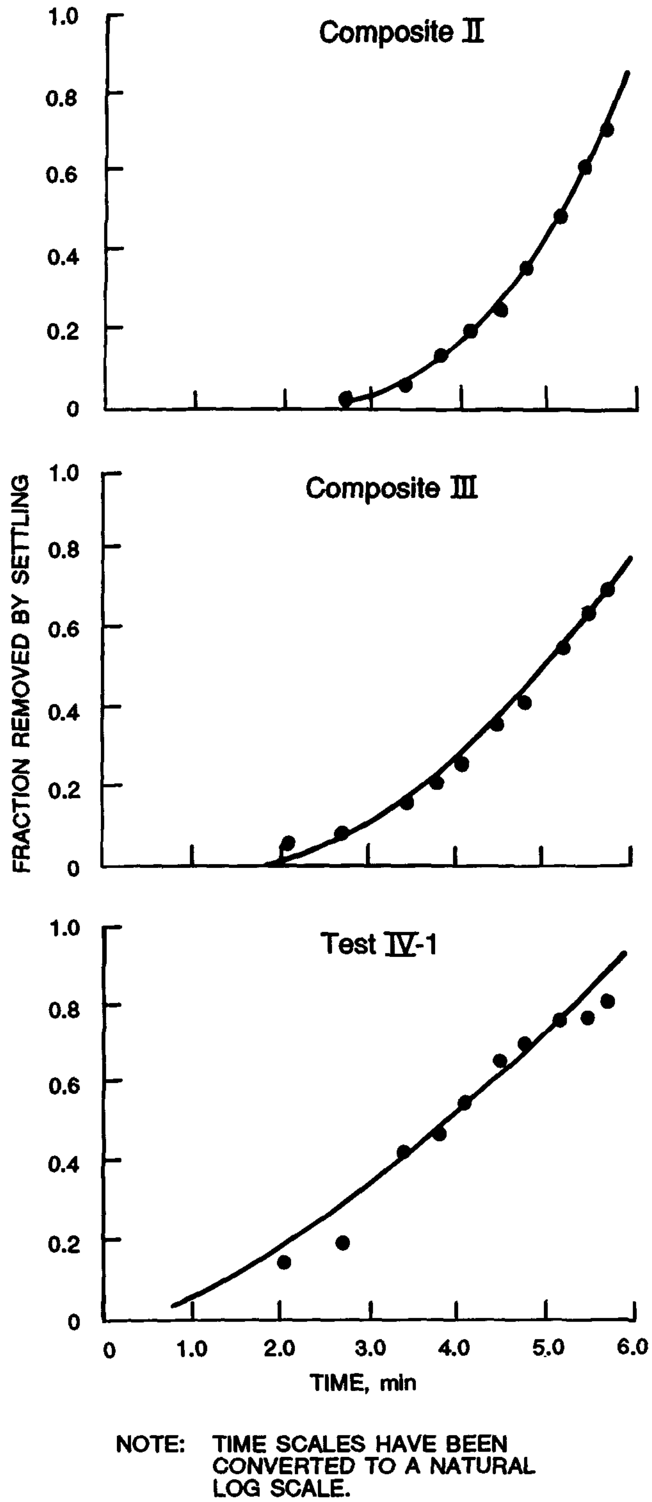

Figure 6. Example settling test phase data and regression curves

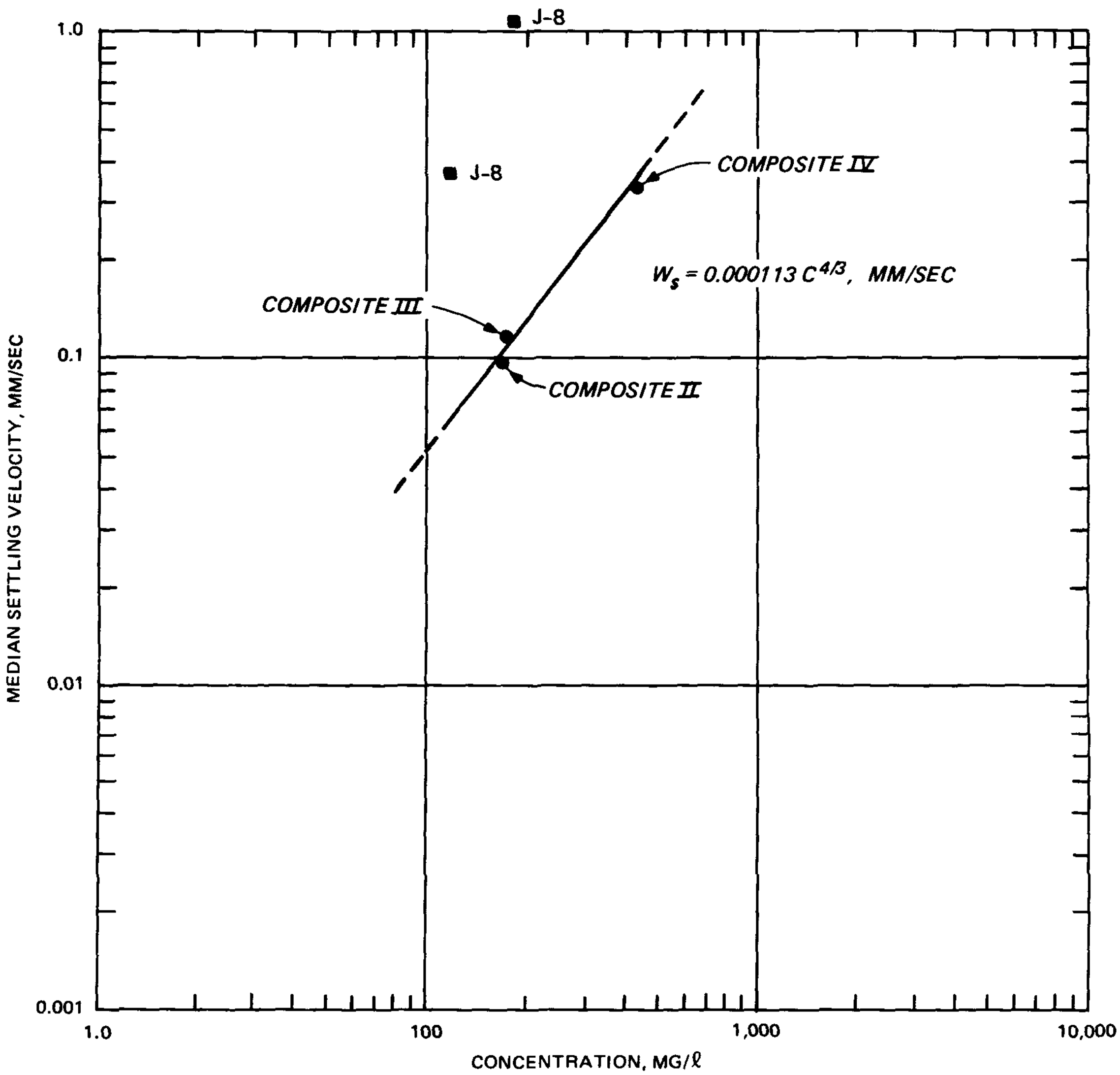

Figure 7. Median settling velocity/concentration relationship for settling test phases and previous field samples at grid cell J-8

sediment containing a high percentage of silt. Suspensions appeared to remain turbulent and vertically well mixed in the horizontal sections of the water tunnel during all tests.

49. Data from the 12 deposition test phases are shown in Plates 1-12, along with synthesized results to be described later.

50. Regression analyses were applied to depositional test data using Equations 10 and 11 as regression models, assuming $n = 4/3$ and that the material was uniform (a single fraction). The overall correlation coefficient between $C^{-4/3}$ and t/h (Equation 11) was 0.84, and between $\log_e (C/C_o)$ and t/h (Equation 10) was -0.83. Equation 11 fit the data slightly better

than Equation 10. However, the coefficients and constants produced by both regression models were not consistent between tests and in many cases not physically realistic. This was caused by the equilibrium suspensions of many tests. The depositional test data therefore indicated that the material was not uniform enough to be considered a single component or fraction.

51. Analysis of the $C^{-4/3}$ versus t/h plots suggested that the test material could be described by the superposition of three components or fractions. A uniform sediment fraction obeying Equations 1 and 11 would plot as a straight line. Data that fell along a curve could be subdivided using straight-line sections. However, data from many deposition tests fell along relatively consistent straight-line sections. This suggested that the test sediment could not only be treated as a composite of three fractions, but that the material did in fact contain three dominant fractions. Figure 8 shows two examples of deposition test data plotted as $C^{-4/3}$ versus t/h .

52. Not all tests displayed all three fractions, due to variations in the composition of the test material and to sorting. Weight percentages found for the three depositional fractions are given in Table 3 for the various tests and the sieved composite. The method used to determine the weight fractions will be described later in this section. The values for τ_{cd} and A1 developed from the analysis of the data for the deposition fractions using Equation 12 are given in Table 4.

Resuspension

53. Resuspension rates were not constant for test periods, and equilibrium suspensions occurred. Erosion was rapid during the first few minutes after the application or increase in bed shear stress. Sediments were picked up by the flow as small clouds, which formed windrows above the bed like blowing snow on a frozen lake. Erosion decreased rapidly as the tests progressed, and suspended concentrations reached an equilibrium value. Thus Equation 3 applied only to the beginning of the resuspension test phases.

54. The fraction of material eroded from the bed was found to be within a narrow range (37 to 64 percent) for the entire shear stress range. A number of test results at the lower end of this range represented an easily erodible fraction.

55. The total fraction of resuspended material in the water tunnel was

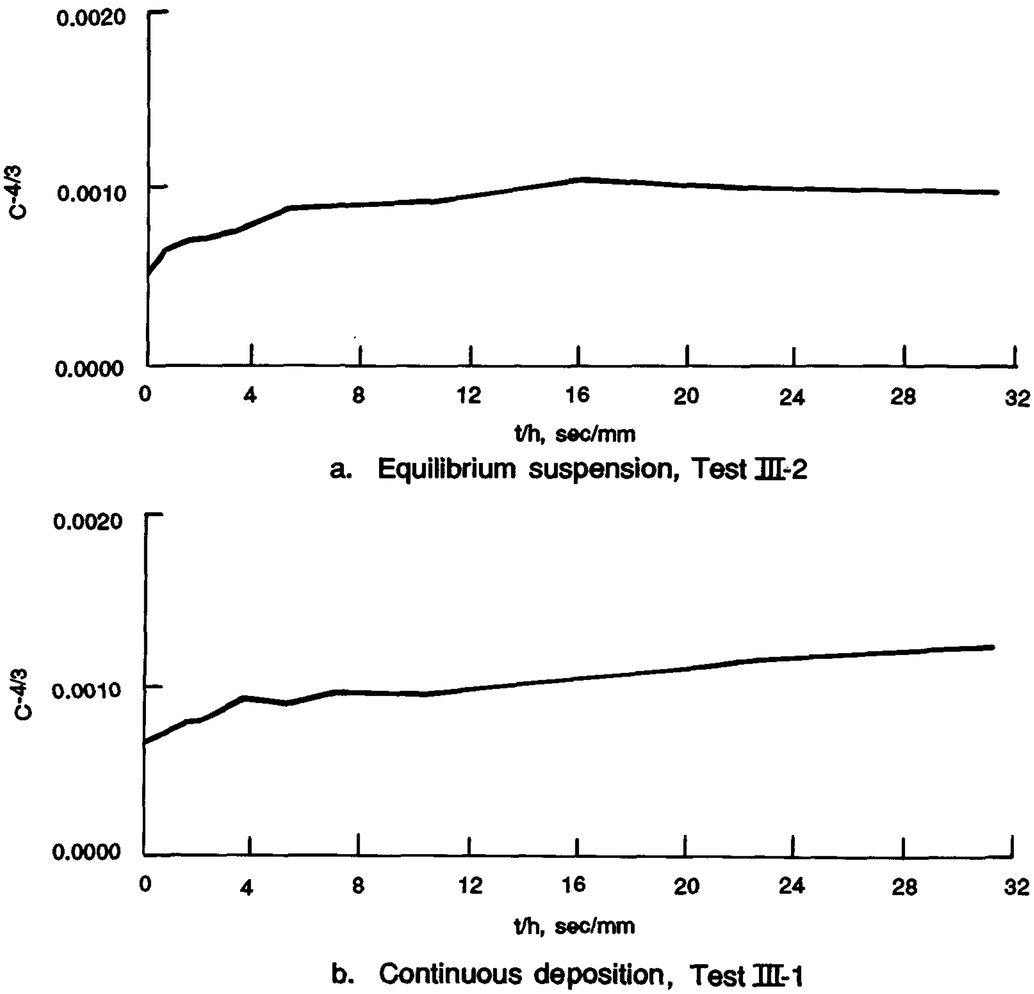

Figure 8. Deposition phase plots of $C^{-4/3}$ versus t/h

nearly constant for a given shear stress over all tests. This indicated that resuspension was source limited. Resuspension stopped after the sediment supplied from the bed was exhausted.

56. The percent of the total deposit composing the most erodible fraction was estimated by averaging the percent eroded during resuspension phases in Tests II-1, II-2, II-3, III-2, and III-3. These seven resuspension phases had τ_b values between 0.03 and 0.077 N/sq m. The average percent eroded was 39, with a standard deviation of 1.8 percent.

57. Resuspension test results identified the characteristics of the most easily eroded fraction of sediment, as given in Table 4. A listing of

resuspension test data including τ_b, concentrations, and fraction of sediment resuspended is given in Table 5.

Fraction Quantification

58. Sediment fractions were designated 1, 2, and 3 based on their erosion and deposition characteristics. The fractional composition of material in the depositional tests, resuspension tests, and the sediment additions to the water tunnel was estimated using the following approach. The most easily eroded fraction (fraction 3) was first identified as 39 percent of the total sediment deposit. At the end of resuspension test phases, 39 percent of the total material in the sediment water tunnel was suspended in fraction 3, as discussed in paragraph 56. The remainder of the material resuspended was assumed to be in fraction 2. This procedure quantified sediment fractions for resuspension test phases, and for Series II and IV deposition tests.

59. Series I and III deposition tests were preceded by sediment additions, and also had resuspended bed material incorporated into test suspensions. The resuspended material was fractionated as described in the previous paragraph. The depositional test material contained in fractions 2 and 3 was determined by evaluating the $C^{-4/3}$ versus t/h curves as discussed in paragraph 51. Fraction 3 could also be assumed to be the same percentage of the depositional test material and sediment additions as for the resuspended material, 39 percent. Fraction 1 was identified as the most rapidly depositing fraction from $C^{-4/3}$ versus t/h curves.

60. The fractional makeup of the sediment material added to the water tunnel during test Series I and III was determined by subtracting the concentration of resuspended fractions from the deposition test fraction concentrations and normalizing the results. Series I tests had the largest sediment additions, and produced the most consistent added-material fraction composition. The average fraction composition of the added material (the sieved composite sample) was determined. Fraction 3 averaged 41 percent of the added material, confirming the magnitude of this fraction. Considering all results, the approximate composition of the sieved composite sample was 30, 30, and 40 percent for fractions 1, 2, and 3, respectively, as shown in Table 3.

PART VII: DISCUSSION OF RESULTS

61. The equilibrium suspensions formed during resuspension and deposition test phases and the variability in deposition results between resuspended and directly added sediments indicated the presence of multiple sediment fractions and their importance on sediment behavior. Table 4 shows that τ_{cd} and τ_c varied about an order of magnitude between sediment fractions. W_s and Al varied by greater than an order of magnitude.

Settling

62. Measured settling velocities were representative of the finer sediment fractions, because the test material was sieved and further sorted by other test phases. Series I, II, and III settling test phases were performed after deposition phases. Test IV-1 was conducted after mixing and before deposition testing to initiate the test at a high concentration. Settling Test IV-1 also contained fractions of silt that were not present in other settling test phases.

63. The relationship between median settling velocity and concentration from Figure 7 appears to follow a power law relationship similar to Equation 1. The slope of the power law relationship approximated the 4/3 value found by Krone (1962). The proportionality constant was 1.13E-4. However, the presence of a coarser fraction in Test IV-1 also increased the median of that test by an unknown amount.

64. Previous New Bedford settling tests were reported in Teeter (1987).* Field suspended samples were taken in the proximity of a coring operation in the field and tested as part of the EFS. Previous results for median W_s were higher by a factor of 5 to 10 than the results presented here, and are shown in Figure 7. Those earlier tests may be more representative of bulk sediments from the upper harbor, while the present tests represent the finer, more slowly depositing fraction of the sediment.

65. The range of the tests was not sufficient to directly determine a lower limit of enhanced concentration-dependent settling. An indirect method

* A. M. Teeter. 1987 (Jan). "Sediment and Contaminant Release During Composite Sampling, New Bedford, MA," Memorandum for Record, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

using the settling velocity distributions was used to estimate the lower limit for the application of Equation 1. A uniform sediment material which exhibits concentration-dependent settling rates will also exhibit an apparent W_s distribution when tested because concentration decreases during testing. The concentration dependence can be identified by plotting the W_s from the distribution against a concentration equal to the initial concentration times twice the corresponding percent exceeded. The 50^{th} percentile (5^{th} dectile) W_s therefore plots at the initial concentration.

66. Figure 9 shows the W_s distributions obtained from composite II and Test IV-1 plotted as concentration dependence relative to their initial

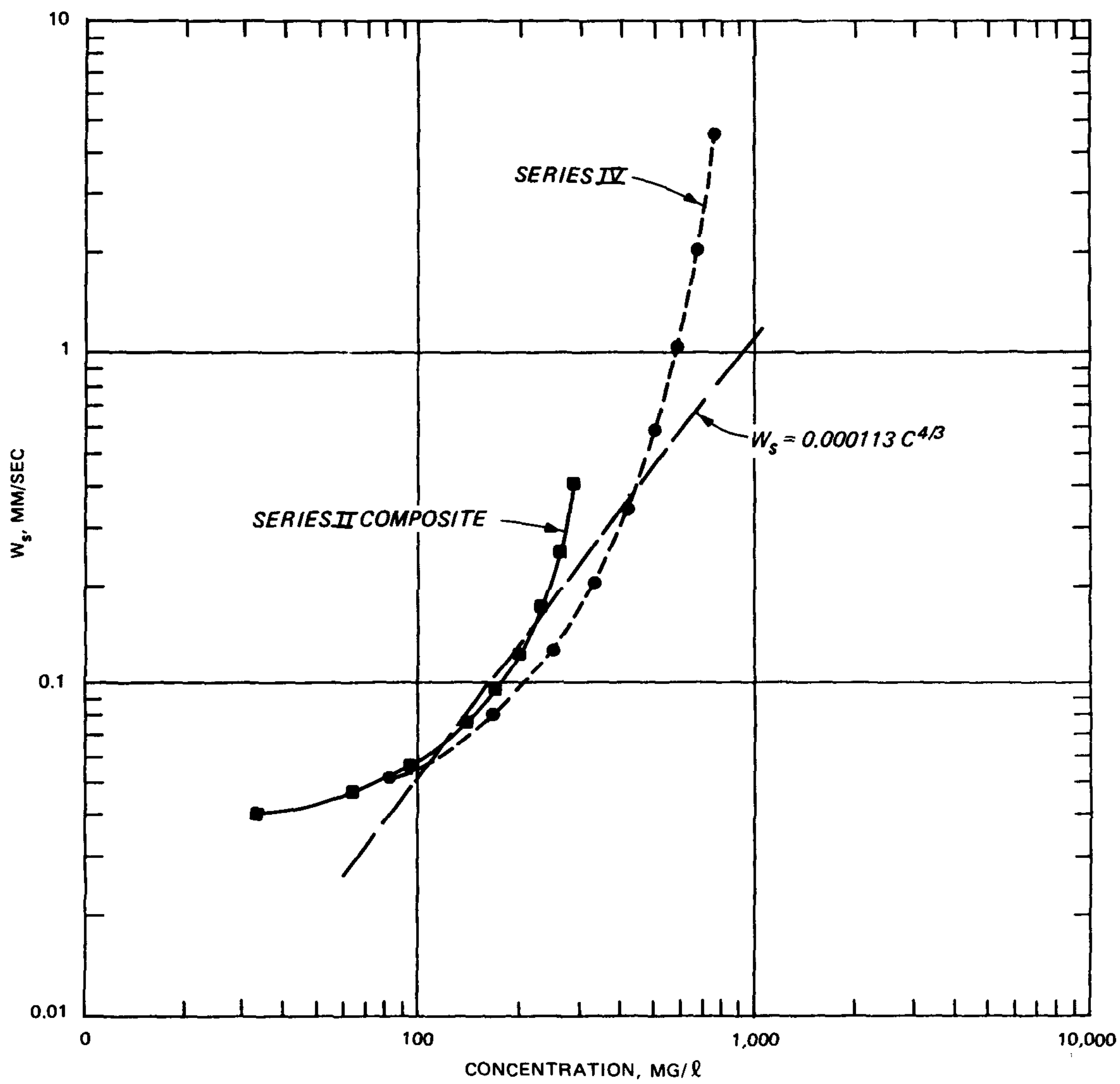

Figure 9. Settling velocity distributions from 1 to 9 dectiles plotted as concentration dependence

concentration. Both tests show that the settling distributions diverge from the enhanced settling curve at about 100 mg/ℓ. The lowest W_s values are equivalent to about 75 mg/ℓ on the enhanced settling curve. Thus 75 mg/ℓ is a reasonable lower limit of application of Equation 1 and the coefficients obtained from the settling and deposition tests.

Deposition

67. Results for τ_{cd} for the slowest deposition fraction (fraction 3, τ_{cd} = 0.043 N/sq m) were about 25 percent lower than Krone's (1962) result for San Francisco Bay sediments, and in the general reported range of 0 to 0.15 N/sq m (O'Connor and Tuxford 1980).

68. The coefficient A1 determined for deposition fraction 3 was about an order of magnitude smaller than the A1 determined from the settling tests. Krone (1962) also found that the settling velocity based on deposition tests was much smaller (one-sixth) than the value obtained from quiescent settling tests. Shear rates at the bed for these tests ranged from 14 to 152 per second, which could have caused disaggregation or particle lift near the bed.

69. Results from the deposition tests were used to mathematically synthesize the experiments, and in this way check the overall consistency of the results. Equation 11 was rearranged into a predictor for the total suspension concentration

$$C(t) = \sum_{i=1}^{k} C_i = \sum_{i=1}^{k} \left(\frac{4}{3} A1_i \, P_i \, \frac{t}{h} + C_{o_i}^{-4/3} \right)^{-3/4} \qquad (13)$$

The initial weight fractions for the experiments given in Table 3 and the coefficients given in Table 4 were used to evaluate Equation 13. Plots of the synthesized results, along with the experimental data, are given in Plates 1-12.

70. The synthesized results generally agreed with the experimental results. The average error was less than 0.1 mg/ℓ, and the standard deviation for the error was 9.0 mg/ℓ.

71. Equations 13 and 1 apply to the enhanced concentration-dependent

settling concentration range above 75 mg/ℓ as indicated earlier in this section. At concentrations below 75 mg/ℓ, Equation 10 and a constant W_s should be used to calculate deposition. Appropriate W_s values are shown in Table 4 for the three sediment fractions.

Resuspension

72. Test II-1 indicated that τ_c was less than 0.03 N/sq m. However, when the flow was first increased to 0.056 N/sq m and then decreased to 0.03 N/sq m, definite deposition occurred (Plate 4). The best explanation for this inconsistency is that the propeller oversped the flow slightly during the speed adjustment. During Test II-2, sediment material was resuspended, and only a very small amount redeposited (Plate 5). Therefore, τ_c for the most erodible fraction was taken as 0.06 N/sq m.

73. The most easily eroded fraction is the same fraction identified as the slowest to deposit (fraction 3). Both were about 40 percent of the sieved composite. τ_{cd} for this fraction was 0.043 N/sq m, while τ_c was 0.06 N/sq m. The two critical shear stresses for fraction 3 were therefore similar.

74. Only about an additional 15 percent of the total bed material, or half of fraction 2, eroded between 0.06 and 0.6 N/sq m, and the remainder of the material had critical shear stresses greater than 0.6 N/sq m. Figure 10 shows resuspension concentrations and concentrations as a fraction of bed material for tests with τ_b of 0.6 N/sq m. The percent of bed material eroded was relatively uniform for these tests.

75. Resuspension tests were performed after a range of bed consolidation times from 1 hour to 2 weeks. Results were similar. The implication was that bed sediment consolidation and/or hardening was very slow for New Bedford sediments, and would not affect application of these experimental results to similar time periods in the prototype.

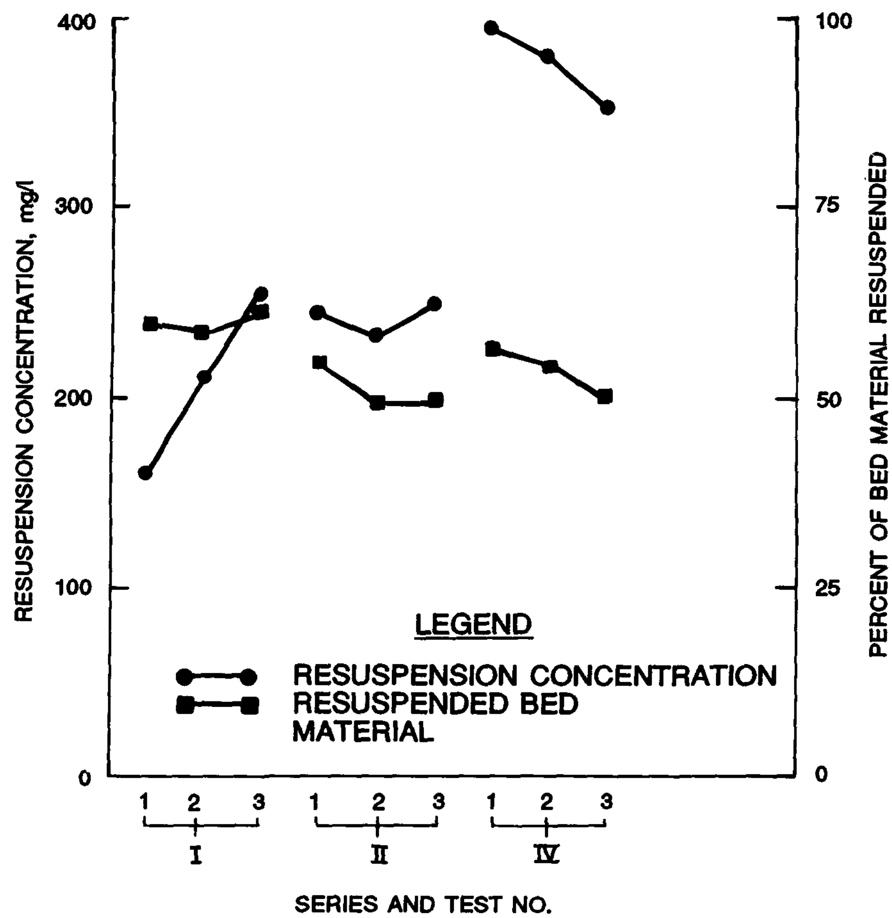

Figure 10. Equilibrium resuspended suspension concentrations and percent of bed material for τ_b = 0.6 N/sq m

PART VIII: CONCLUSIONS AND RECOMMENDATIONS

76. Tests on the settling, deposition, and erosion characteristics of the fine-grained fraction of upper New Bedford Harbor composite sediments were performed in a sediment water tunnel developed for this study. Results were interpreted as the superposition of three sediment fractions. The depositional and resuspension characteristics of the three fractions varied by an order of magnitude or so. The fraction of sediment identified as the slowest to settle and deposit and easiest to erode is of the greatest concern to the migration of contaminants from dredging and disposal activities in upper New Bedford Harbor.

77. The main results are presented in Table 4, and can be used to estimate the escape of resuspended material around possible dredging and disposal operations and from the upper harbor. Results indicate that only the slowest fraction to deposit will be highly mobile.

78. Calculation of deposition at concentrations greater than 75 mg/ℓ should use Equation 1 and coefficients presented in Table 4 to evaluate an effective settling velocity. At concentrations below 75 mg/ℓ, the constant effective W_s in Table 4 should be used.

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Table 1

Chronology of Bed Shear Stress Application During Tests

Test	Bed Shear Stress, N/sq m: Resuspension Phases (30 min each) 1	2	Mixing Period (30 min)	Depositional Phases (90 min)	Settling Phase (300 min)
I-1	0.164	0.60	0.60	0.164	X
I-2	0.164	0.60	0.60	0.077	X
I-3	0.077	0.164	0.60	0.030	X
II-1	0.030	0.056		0.030	X
II-2	0.056	0.077		0.056	X
II-3	0.077	0.164		0.077	X
III-1	0.60	0.164	0.60	0.164	X
III-2	0.60	0.077	0.60	0.077	X
III-3	0.60	0.030	0.60	0.030	X
IV-1	0.60		0.60	0.077	X*
IV-2	0.60			0.030	
IV-3	0.60			0.015**	

* Settling phase after mixing and before resuspension and depositional test phase.

** Depositional test phase extended to 150 min.

Table 2

Settling Velocity Distributions

Initial Concentration mg/ℓ	Average Settling Velocity mm/sec	Geometric Mean Settling Velocity mm/sec	Standard Deviation	Skewness	Kurtosis	Cumulative Percent Greater than Settling Velocity	Cumulative Settling Velocity mm/sec
				Test I-1			
160	0.327	0.131	4.6	0.18	0.44	10	9.758E-01
						20	4.596E-01
						30	2.551E-01
						40	1.548E-01
						50	9.946E-02
						60	6.662E-02
						70	4.605E-02
						80	3.264E-02
						90	2.362E-02
				Test I-2			
172	0.304	0.145	3.4	0.17	0.41	10	6.926E-01
						20	3.952E-01
						30	2.503E-01
						40	1.686E-01
						50	1.184E-01
						60	8.580E-02
						70	6.366E-02
						80	4.815E-02
						90	3.701E-02
				Test I-3			
184	0.359	0.170	3.7	0.17	0.42	10	9.375E-01
						20	5.003E-01
						30	3.033E-01
						40	1.975E-01
						50	1.349E-01
						60	9.538E-02
						70	6.926E-02
						80	5.137E-02
						90	3.877E-02
				Test II-1			
158	0.169	0.117	2.2	0.19	0.46	10	3.445E-01
						20	2.271E-01
						30	1.655E-01
						40	1.269E-01
						50	1.005E-01
						60	8.136E-02
						70	6.703E-02
						80	5.598E-02
						90	4.727E-02

(Continued)

Table 2 (Continued)

Initial Concentration mg/ℓ	Average Settling Velocity mm/sec	Geometric Mean Settling Velocity mm/sec	Standard Deviation	Skewness	Kurtosis	Cumulative: Percent Greater than Settling Velocity	Cumulative: Settling Velocity mm/sec
			Test II-2				
168	0.255	0.118	3.2	0.19	0.47	10	5.607E-01
						20	3.066E-01
						30	1.942E-01
						40	1.324E-01
						50	9.453E-02
						60	6.976E-02
						70	5.278E-02
						80	4.071E-02
						90	3.191E-02
			Test II-3				
176	0.168	0.116	2.5	0.19	0.45	10	3.973E-01
						20	2.481E-01
						30	1.728E-01
						40	1.274E-01
						50	9.737E-02
						60	7.637E-02
						70	6.107E-02
						80	4.961E-02
						90	4.080E-02
			Composite II				
167	0.165	0.117	2.6	0.20	0.48	10	4.198E-01
						20	2.535E-01
						30	1.741E-01
						40	1.273E-01
						50	9.679E-02
						60	7.561E-02
						70	6.029E-02
						80	4.886E-02
						90	4.011E-02
			Test III-1				
164	0.307	0.137	3.7	0.17	0.42	10	7.427E-01
						20	4.014E-01
						30	2.448E-01
						40	1.600E-01
						50	1.096E-01
						60	7.761E-02
						70	5.643E-02
						80	4.189E-02
						90	3.165E-02

(Continued)

Table 2 (Concluded)

Initial Concentration mg/ℓ	Average Settling Velocity mm/sec	Geometric Mean Settling Velocity mm/sec	Standard Deviation	Skewness	Kurtosis	Cumulative Percent Greater than Settling Velocity	Cumulative Settling Velocity mm/sec
			Test III-2				
190	0.364	0.164	4.1	0.18	0.43	10	1.048E-00
						20	5.258E-01
						30	3.050E-01
						40	1.917E-01
						50	1.270E-01
						60	8.739E-02
						70	6.191E-02
						80	4.489E-02
						90	3.317E-02
			Test III-3				
174	0.356	0.153	4.5	0.18	0.44	10	1.092E-00
						20	5.194E-01
						30	2.914E-01
						40	1.785E-01
						50	1.158E-01
						60	7.824E-02
						70	5.453E-02
						80	3.895E-02
						90	2.839E-02
			Composite III				
176	0.337	0.147	4.1	0.18	0.43	10	9.240E-01
						20	4.662E-01
						30	2.720E-01
						40	1.719E-01
						50	1.144E-01
						60	7.906E-02
						70	5.624E-02
						80	4.093E-02
						90	3.036E-02
			Test IV-1				
426	0.509	0.444	6.4	0.15	0.38	10	4.607E+00
						20	2.089E+00
						30	1.064E+00
						40	5.843E-01
						50	3.391E-01
						60	2.053E-01
						70	1.286E-01
						80	8.276E-02
						90	5.453E-02

(Sheet 3 of 3)

Table 3

Weight Percentages of Test Material

Test	Percent by Weight for Fraction		
	1	2	3
I-1	18	24	58
I-2	18	24	58
I-3	18	24	58
II-1	0	0	100
II-2	0	0	100
II-3	0	11	89
III-1	18	24	58
III-2	18	24	58
III-3	18	24	58
IV-1	0	28	72
IV-2	0	28	72
IV-3	0	21	79
Seived composite	30	30	40

Table 4

Summary of Erosion and Deposition Test Coefficients

Variables	Fraction		
	1	2	3
Deposition			
τ_{cd} , N/sq m	0.42	0.33	0.043
Al	6.4E-3	1.2E-3	0.95E-5
W_s , mm/sec	2.02	1.04	0.006
Erosion			
τ_c , N/sq m	>0.6	0.6-0.16	0.060
M , g/sq m/min	--	--	0.25

Table 5

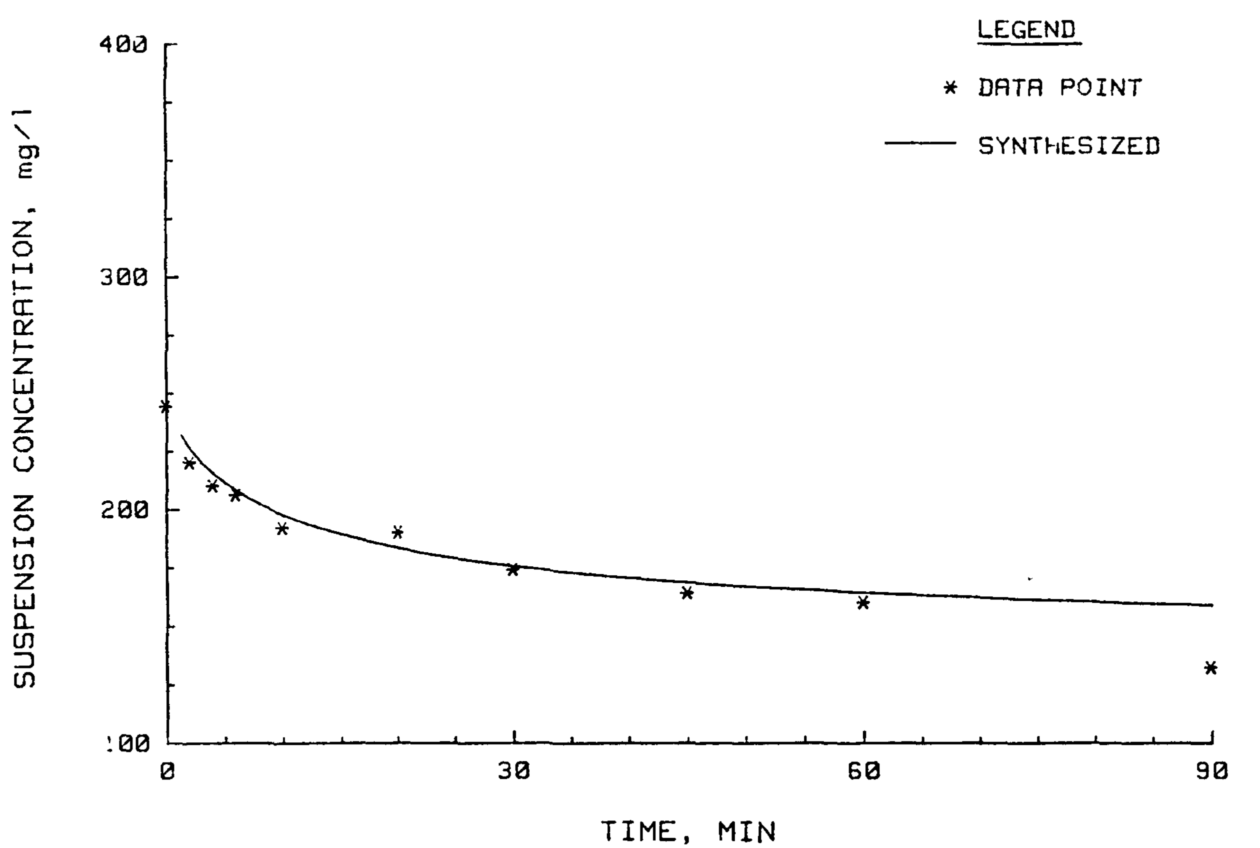
Erosion Test Concentrations

Test	τ_b N/sq m	Elapsed Time min	Concentration mg/ℓ	Resuspended Fraction as Percent of Total Deposit
I-2	0.164	30	172	48
	0.59	30	210	58
I-3	0.077	30	180	45
	0.164	30	194	48
	0.59	30	256	64
II-1	0.030	15	172	39
		30	170	38
	0.056	15	184	41
		30	178	40
II-2	0.056	15	178	40
		30	196	44
	0.077	15	166	37
		30	174	39
II-3	0.077	15	174	39
		30	194	44
	0.164	15	198	45
		30	192	43
III-1	0.59	22.5	214	48
		30	248	55
	0.164	15	186	42
		22.5	166	37
		30	170	38
III-2	0.59	15	218	46
		30	232	49
	0.077	15	202	43
		30	180	39
III-3	0.59	15	224	45
		30	250	50
	0.077	15	192	38
		30	170	34

(Continued)

Table 5 (Concluded)

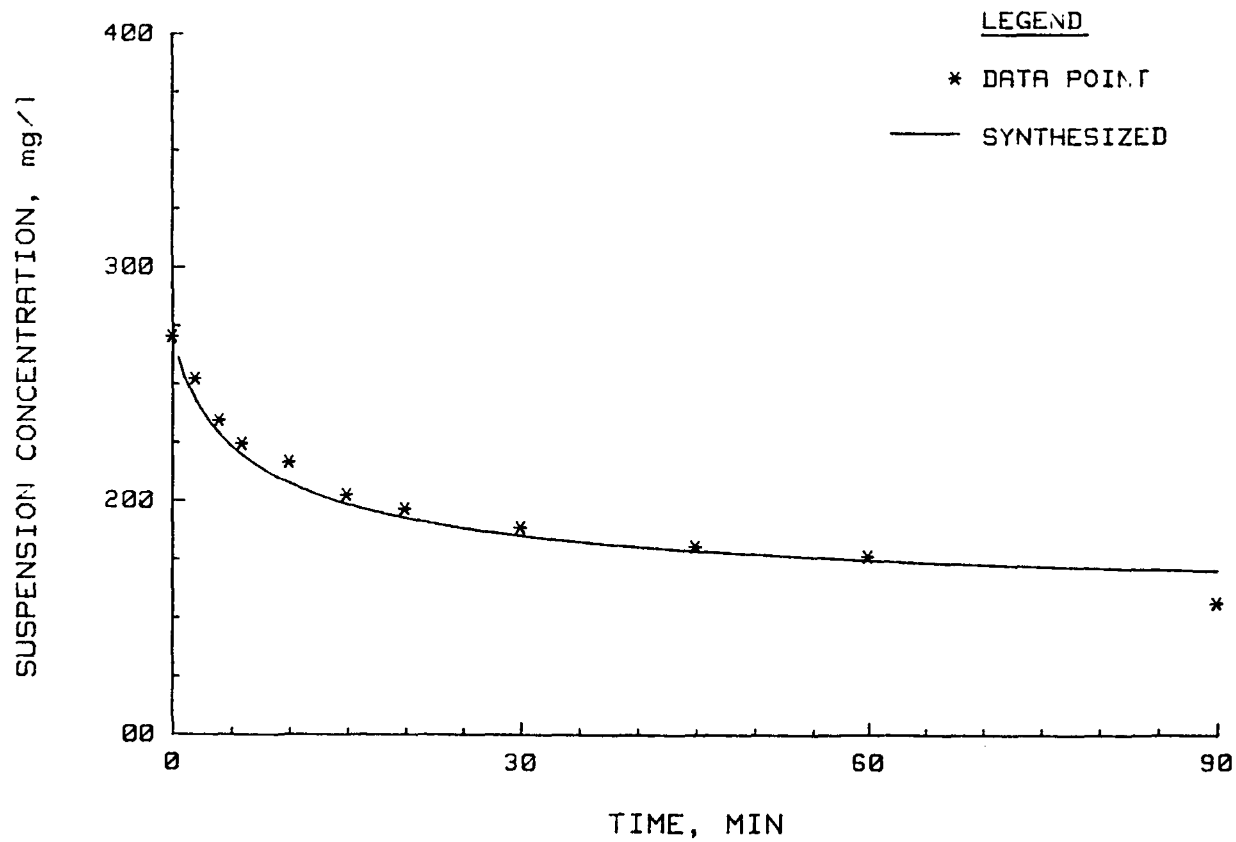
Test	τ_b N/sq m	Elapsed Time min	Concentration mg/ℓ	Resuspended Fraction as Percent of Total Deposit
IV-1	0.59	15	376	53
		22.5	398	56
		30	396	56
IV-2	0.59	15	388	55
		22.5	378	54
		30	380	54
IV-3	0.59	15	356	50
		22.5	358	51
		30	354	50



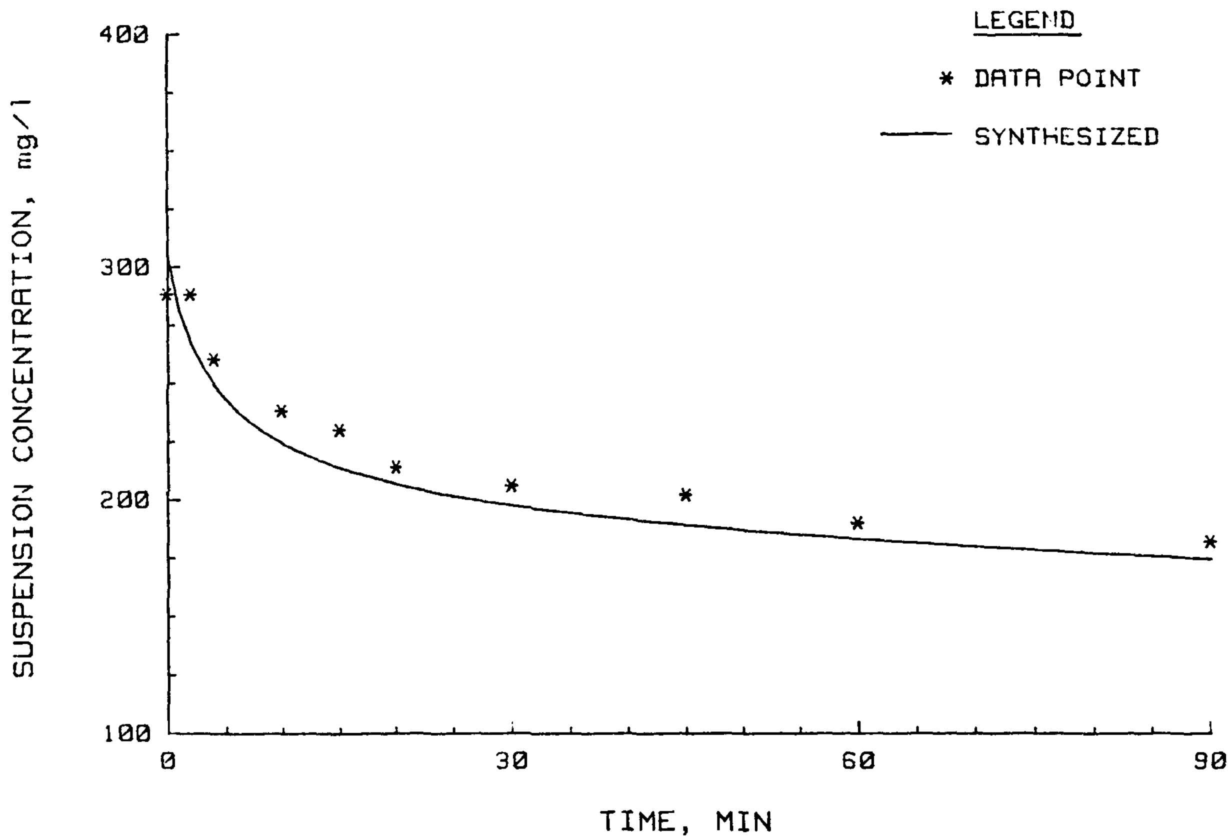
DEPOSITION TIME-HISTORY
SERIES I
TEST 1
BED SHEAR STRESS 0.164 N/sq m

PLATE 1

PLATE 2



DEPOSITION TIME-HISTORY
SERIES I
TEST 2
BED SHEAR STRESS 0.077 N/sq m



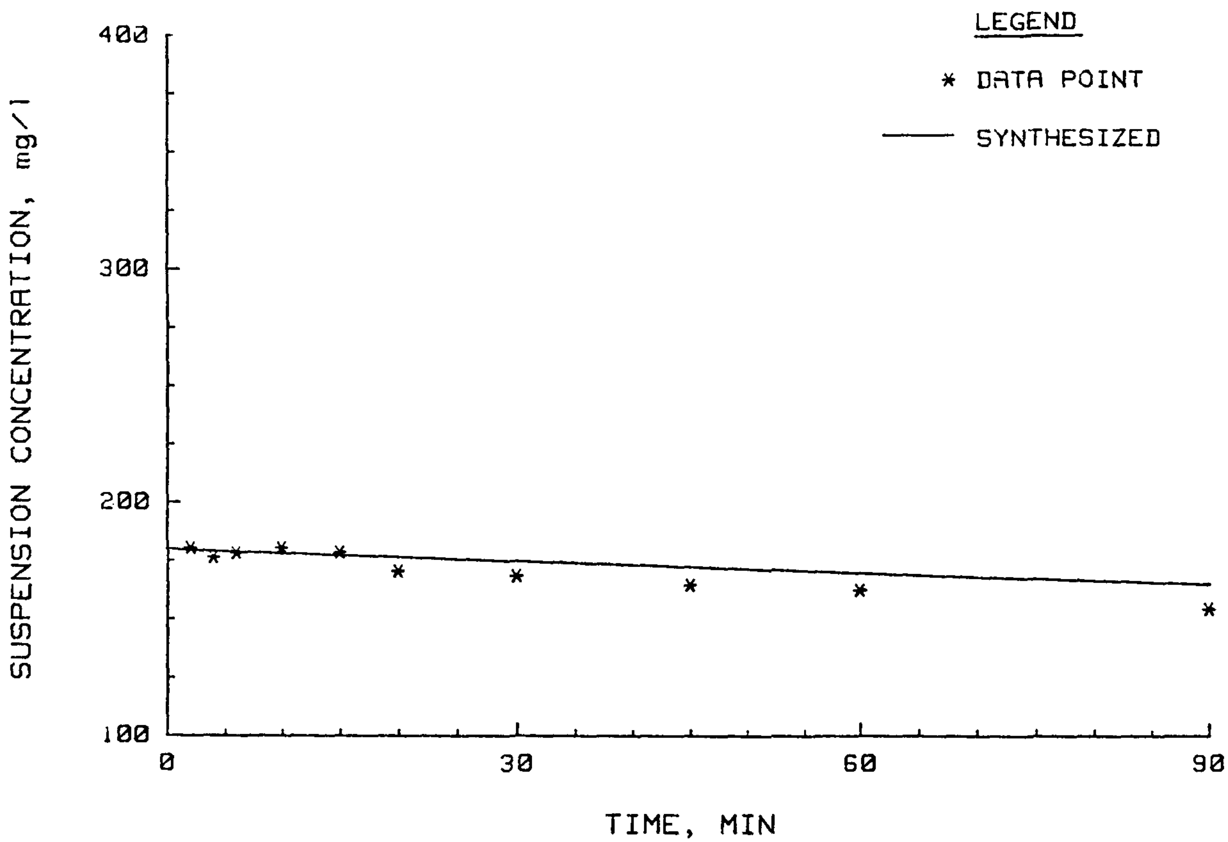
DEPOSITION TIME-HISTORY

SERIES I

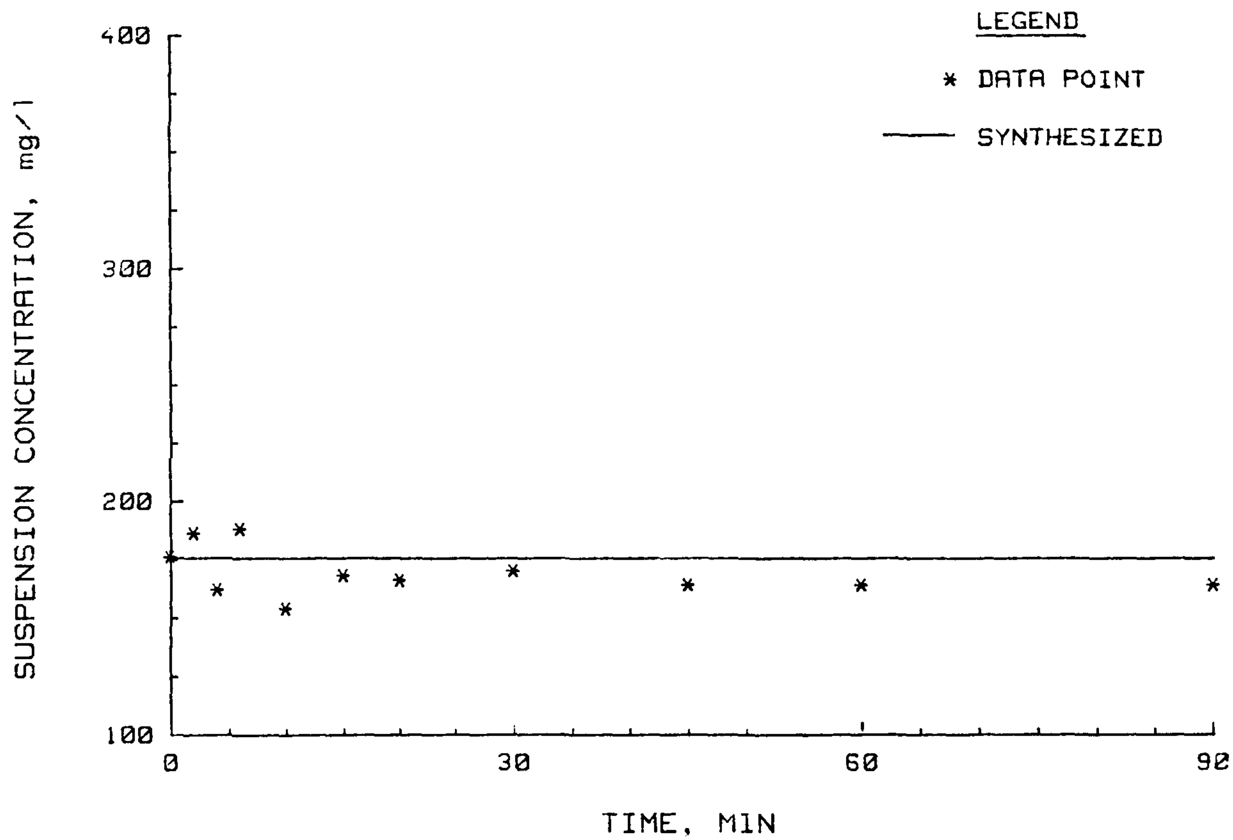
TEST 3

BED SHEAR STRESS 0.03 N/sq m

PLATE 4

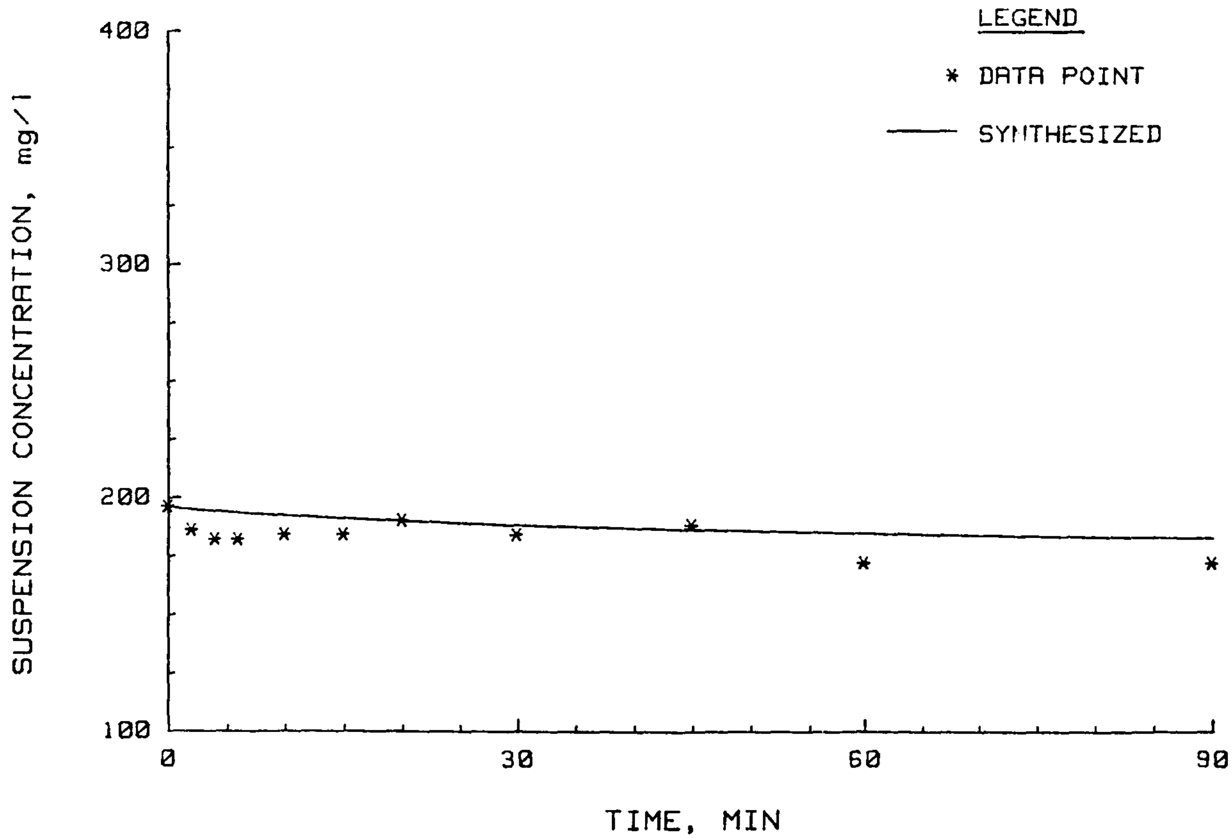


DEPOSITION TIME-HISTORY
SERIES II
TEST 1
BED SHEAR STRESS 0.03 N/sq m



DEPOSITION TIME-HISTORY
SERIES II
TEST 2
BED SHEAR STRESS 0.056 N/sq m

PLATE 6

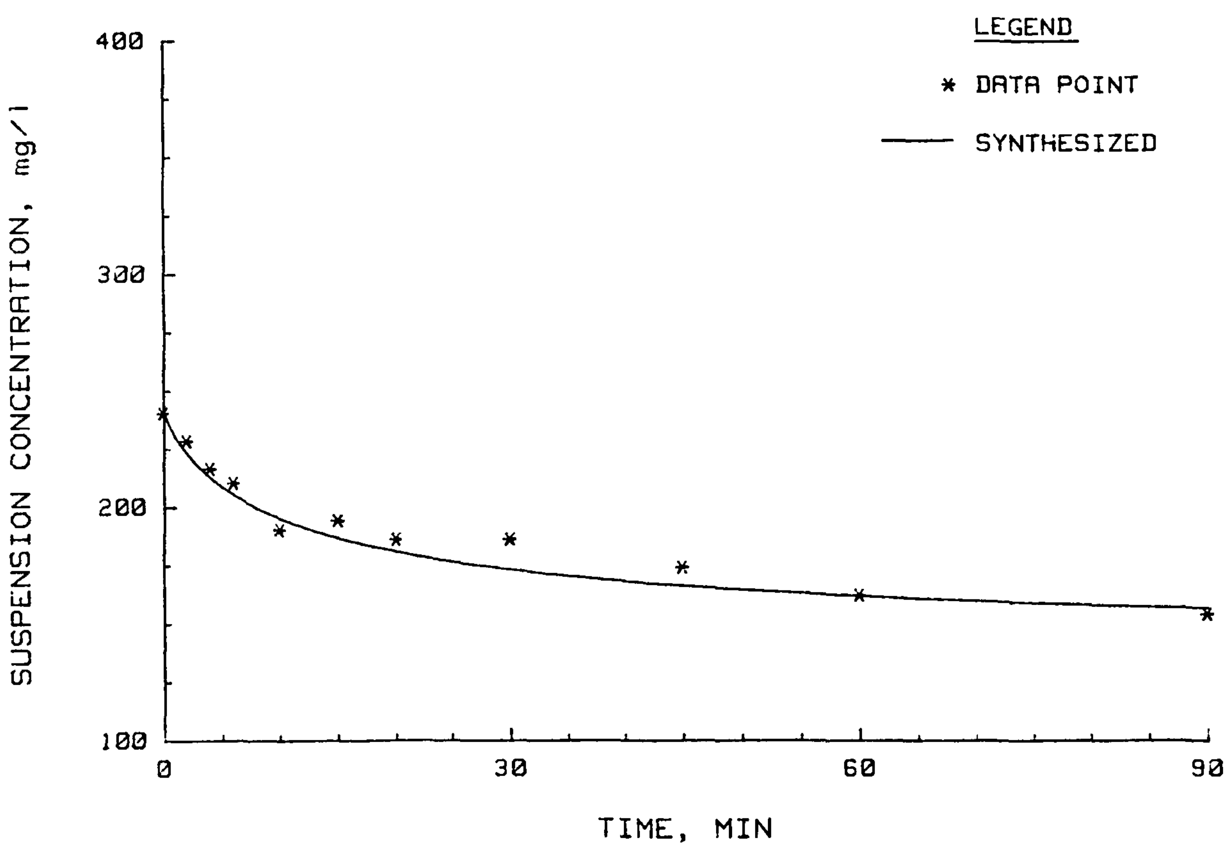


DEPOSITION TIME-HISTORY

SERIES II

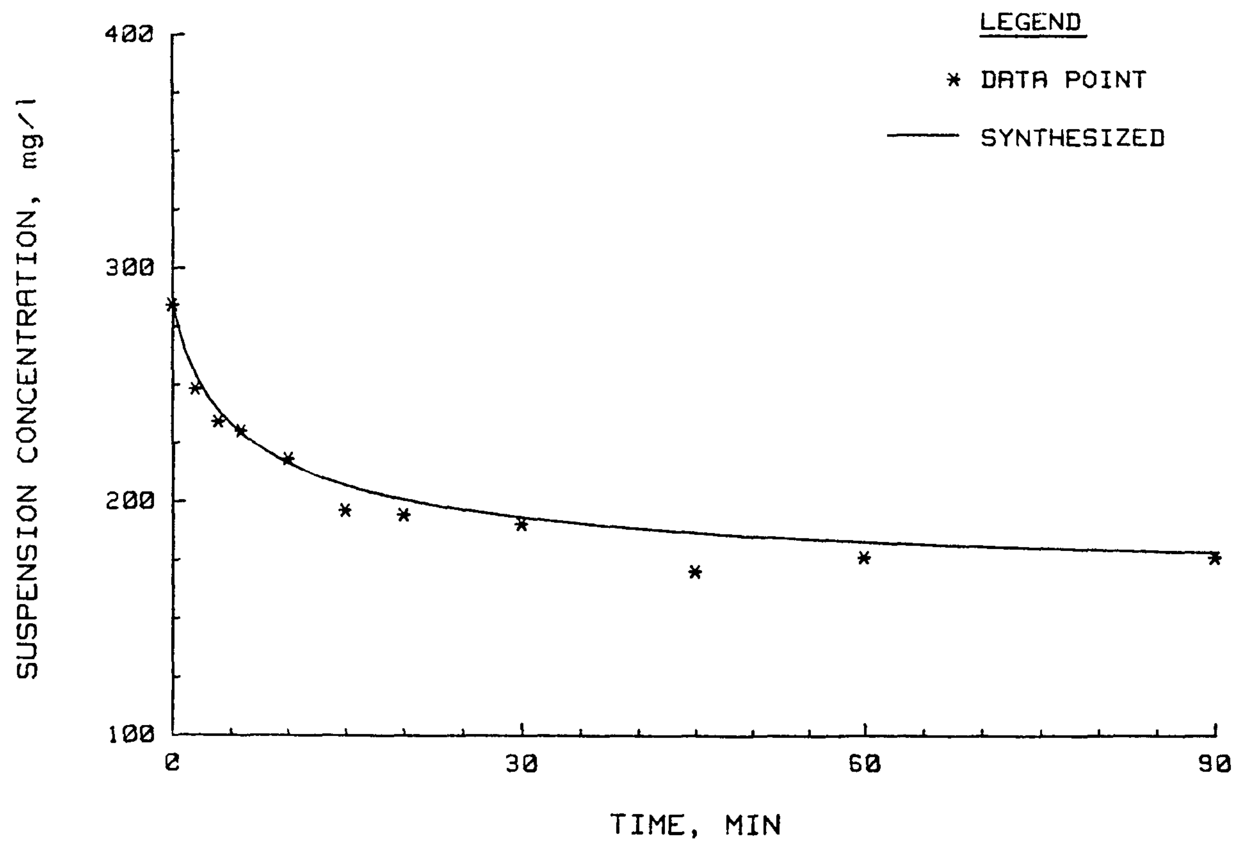
TEST 3

BED SHEAR STRESS 0.077 N/sq m

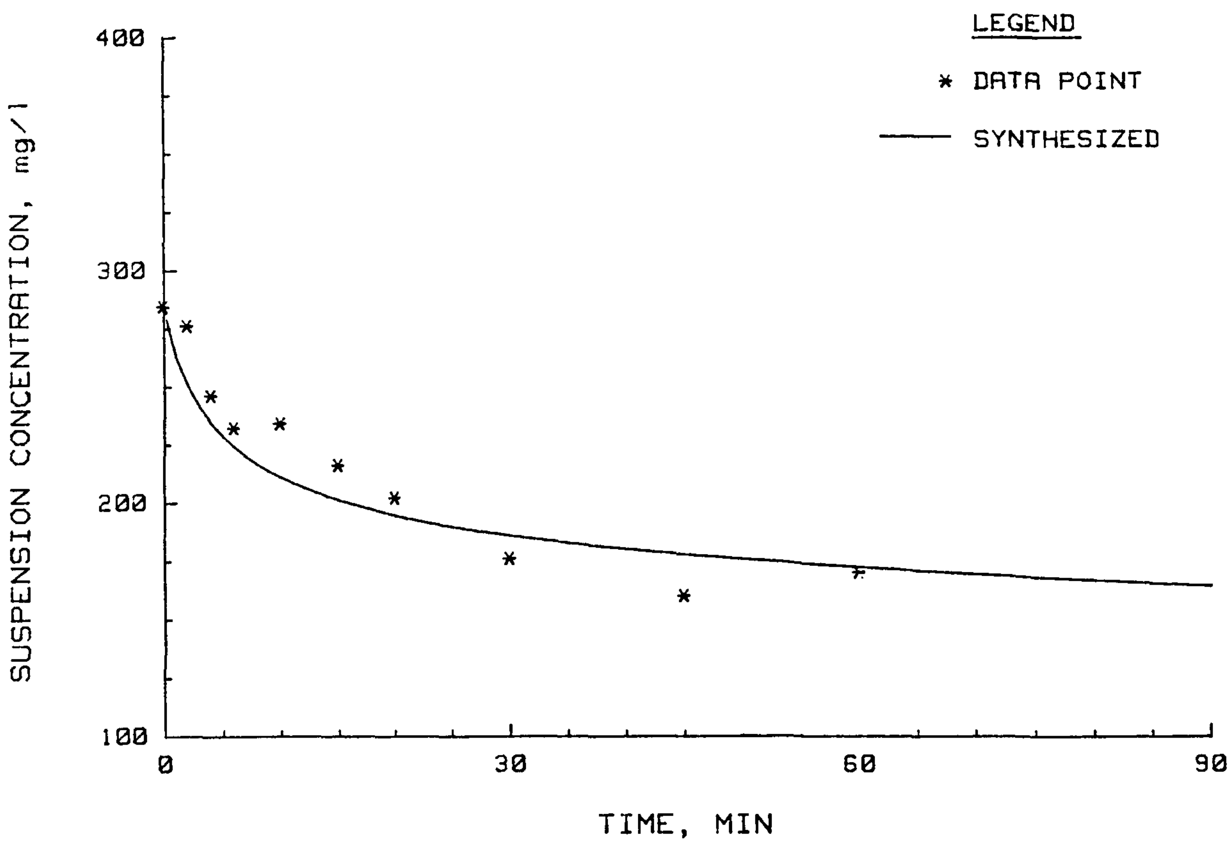


DEPOSITION TIME-HISTORY
SERIES III
TEST 1
BED SHEAR STRESS 0.164 N/sq m

PLATE 8

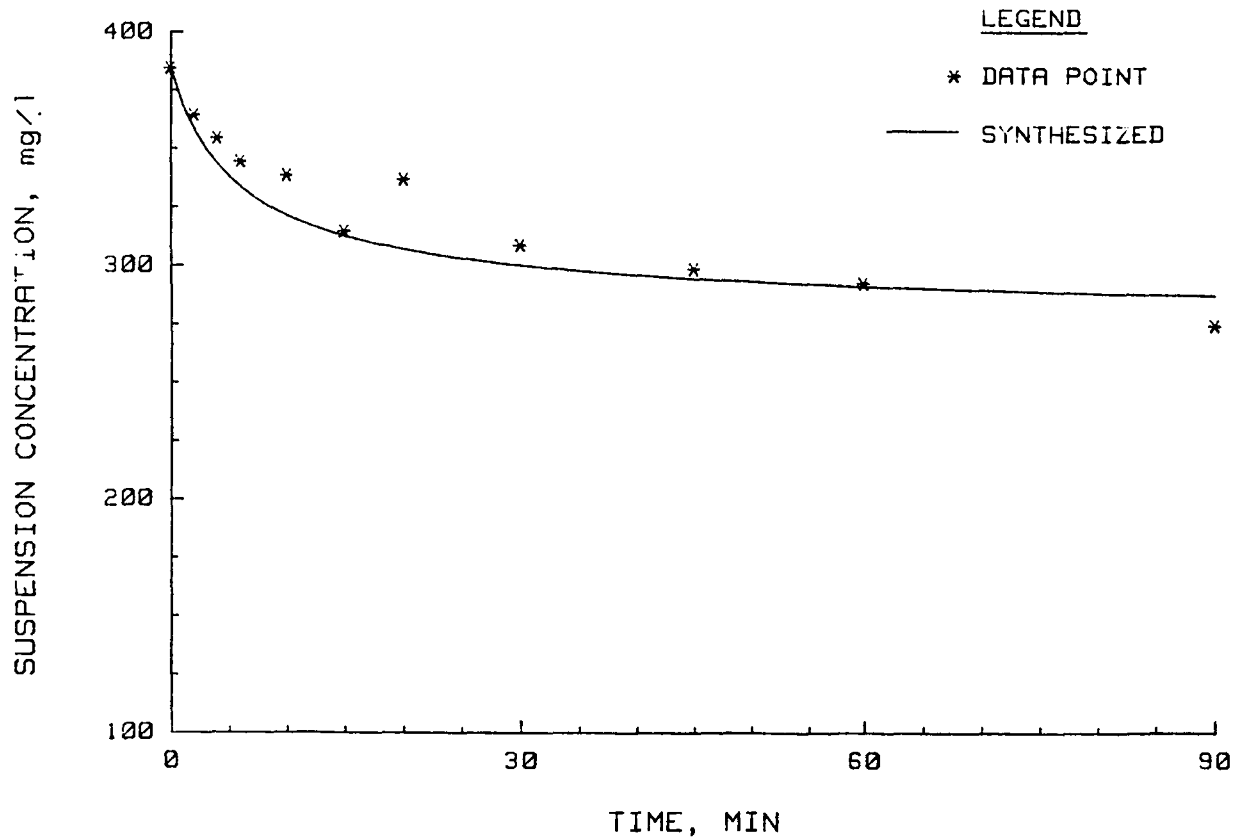


DEPOSITION TIME-HISTORY
SERIES III
TEST 2
BED SHEAR STRESS 0.077 N/sq m

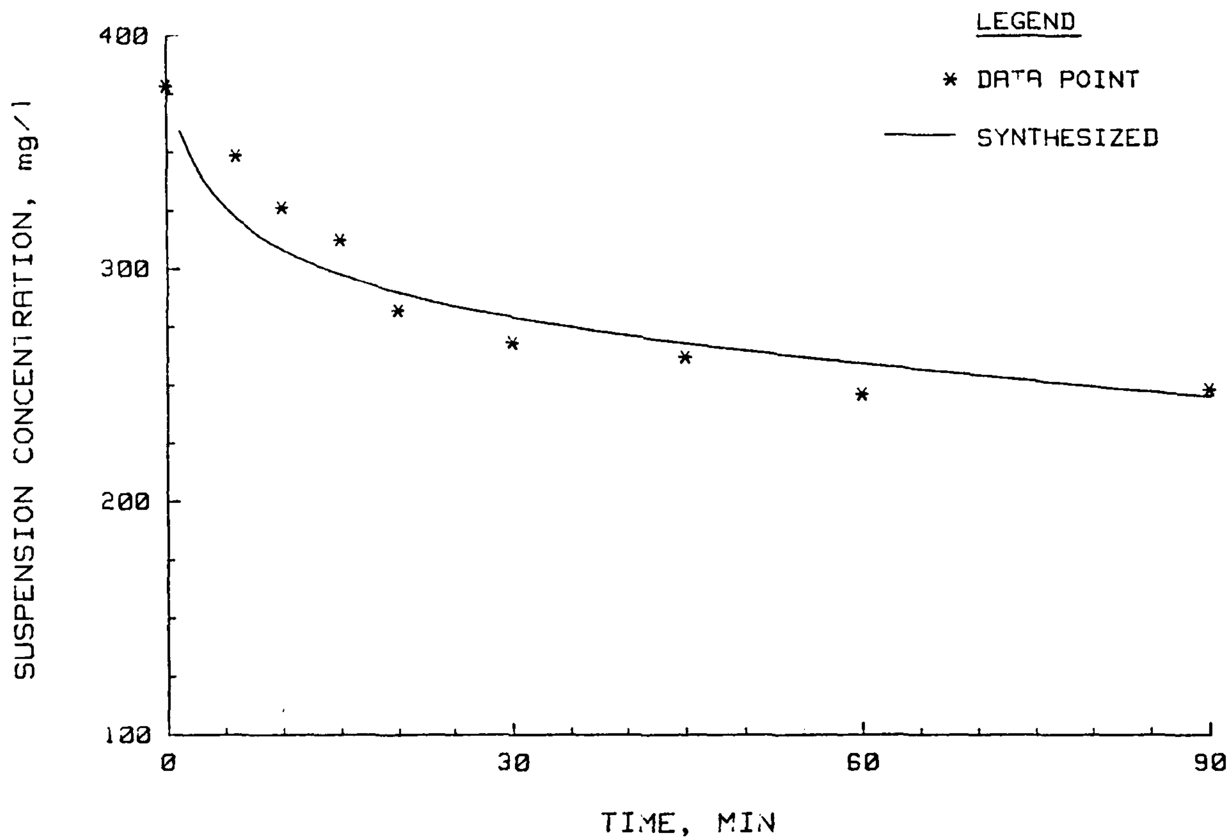


DEPOSITION TIME-HISTORY
SERIES III
TEST 3
BED SHEAR STRESS 0.03 N/sq m

PLATE 10

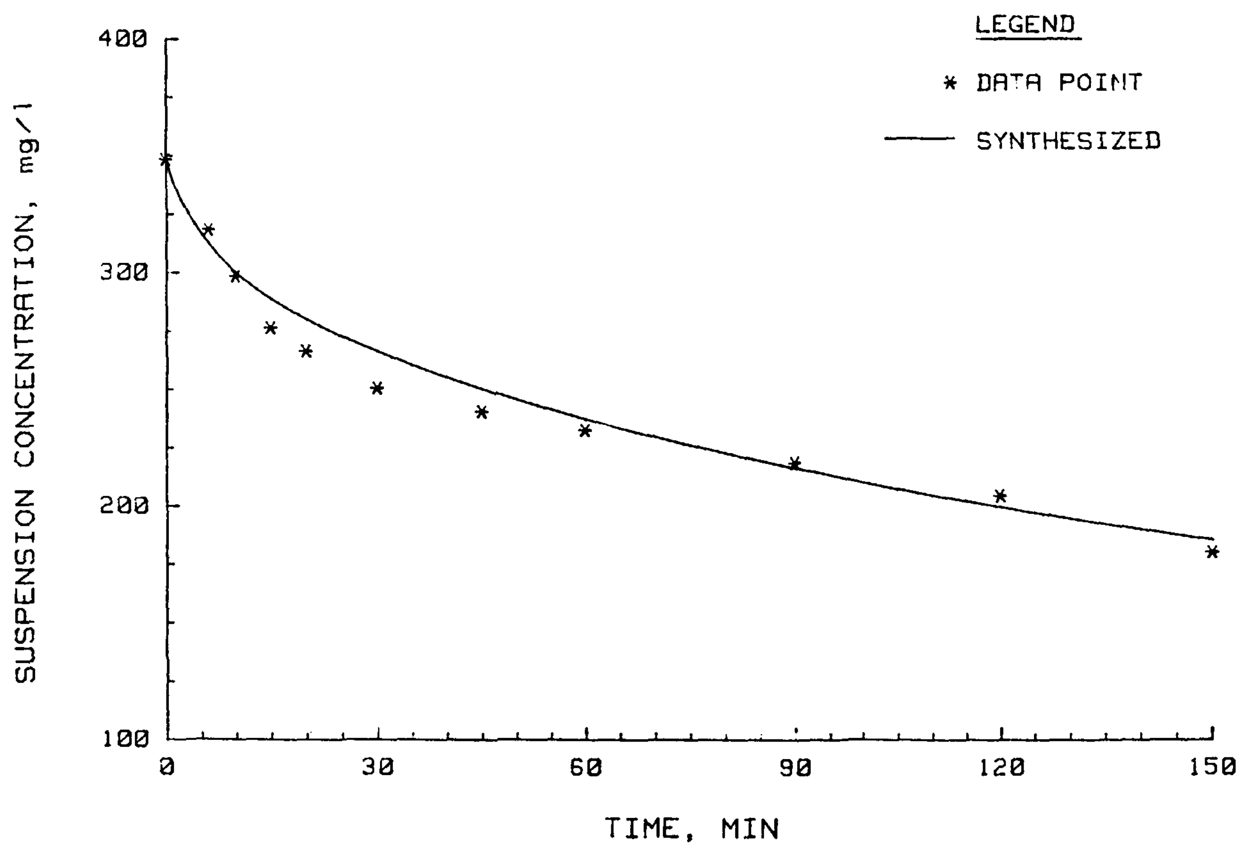


DEPOSITION TIME-HISTORY
SERIES IV
TEST 1
BED SHEAR STRESS 0.077 N/sq m



DEPOSITION TIME-HISTORY
SERIES IV
TEST 2
BED SHEAR STRESS 0.23 N/sq m

PLATE 12



DEPOSITION TIME-HISTORY
SERIES IV
TEST 3
BED SHEAR STRESS 0.015 N/sq m