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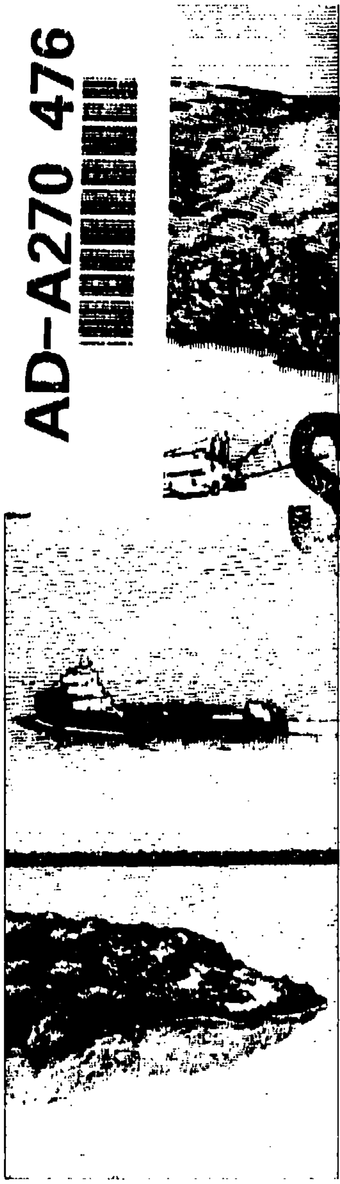

DREDGING RESEARCH PROGRAM

TECHNICAL REPORT DRP-93-1

DEVELOPMENT AND VERIFICATION OF NUMERICAL MODELS FOR PREDICTING THE INITIAL FATE OF DREDGED MATERIAL DISPOSED IN OPEN WATER

Report 1

PHYSICAL MODEL TESTS OF DREDGED MATERIAL DISPOSAL FROM A SPLIT-HULL BARGE AND A MULTIPLE BIN VESSEL

by

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Darla C. McVan, Mike J. Trawle

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May 1993

Report 1 of a Series

Prepared for DEPARTMENT OF THE ARMY
U.S. Army Corps of Engineers
Washington, DC 20314-1000

Under Work Unit No. 32465

The Dredging Research Program (DRP) is a seven-year program of the US Army Corps of Engineers. DRP research is managed in these five technical areas:

Area 1 - Analysis of Dredged Material Placed in Open Water

Area 2 - Material Properties Related to Navigation and Dredging

Area 3 - Dredge Plant Equipment and Systems Processes

Area 4 - Vessel Positioning, Survey Controls, and Dredge Monitoring Systems

Area 5 - Management of Dredging Projects

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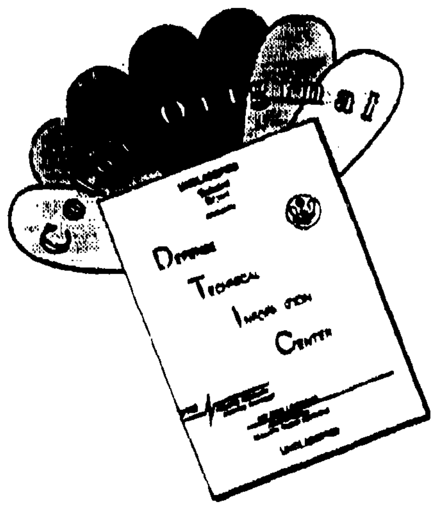

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Dredging Research Program

Technical Report DRP-93-1
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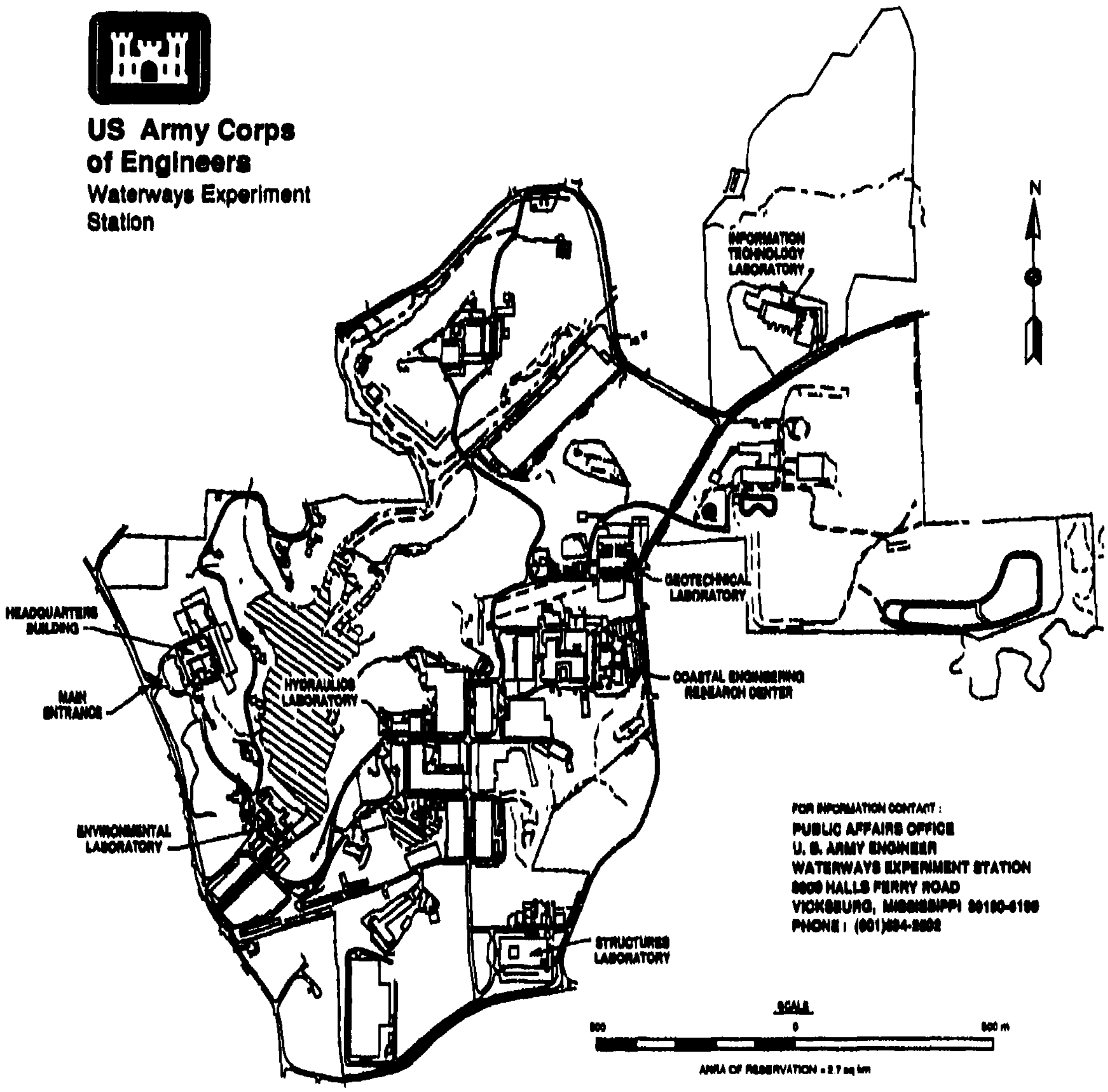

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Dredging Research Program Report Summary

Development and Verification of Numerical Models for Predicting the Initial Fate of Dredged Material Disposed in Open Water; Report 1, Physical Model Tests of Dredged Material Disposal from a Split-Hull Barge and a Multiple Bin Vessel(TR DRP-93-1)

ISSUE: Numerical models for predicting the initial fate of material disposed in open water are required for the following activities:

- Address environmental concerns related to the disposal of dredged material
- Provide input for long-term sediment transport models used in disposal site management

RESEARCH: Dredged material disposal models were developed under the Dredged Material Research Program (DMRP), 1973-1978. Under the Dredging Research Program (DRP), additional developments to the earlier models have resulted in the numerical disposal model called STFATE (Short-Term FATE) for application to split-hull barge and hopper dredge disposal operations. These developments have been guided by both field data and data from large-scale laboratory tests. In addition to guiding model developments, data from the laboratory tests are being used in model validation efforts.

SUMMARY: Large-scale laboratory tests of disposal operations used a model split-hull barge and a multiple bin disposal vessel. The tests were conducted in water depths up to 6 ft with the maximum horizontal dimensions of the test facility being 32 ft by 41 ft. Both stationary and moving disposal operations were simulated with materials ranging from essentially pure clay to fine coal. Data collected consisted of bottom disposition depths, suspended sediment samples, and video taping through side-viewing windows. Results from the individual testsand an analysis of those results are presented in the report.

AVAILABILITY OF REPORT: The report is available through the Interlibrary Loan Service from the US Army Engineer Waterways Experiment Station (WES) Library, telephone number (601) 634-2355. National Technical Information Service (NTIS) report numbers may be requested from WES Librarians.

To purchase a copy of the report, call NTIS at (703) 487-4780.

About the Authors: Dr. Billy H. Johnson, WES Hydraulics Laboratory, was Principal Investigator for this work unit and is now Technical Area 1 Manager. The other authors are also members of the Hydraulics Laboratory staff.

Point of Contact: Dr. Johnson.

For information about the DRP, contact Mr. E. Clark McNair, Jr., Manager, DRP, at (601) 634-2070.

PREFACE

This study was authorized as part of the Dredging Research Program (DRP) of Headquarters, US Army Corps of Engineers (HQUSACE), and was performed under the "Numerical Simulation Techniques for Evaluation of Short-Term Fate and Stabilization of Dredged Material Disposal in Open Waters" Work Unit 32465. This work unit is part of DRP Technical Area 1 (TA1), Analysis of Dredged Material Placed in Open Water. Messrs. Robert Campbell and Glenn R. Drummond were DRP Chief and TA1 Technical Monitors from HQUSACE, respectively. Mr. E. Clark McNair, Jr., Coastal Engineering Research Center (CERC), US Army Engineer Waterways Experiment Station (WES), was DRP Program Manager (PM) and Dr. Lyndell Z. Hales, CERC, was Assistant PM. Dr. Nicholas C. Kraus, Senior Scientist, CERC, was Technical Manager for DRP TA1. Dr. Billy H. Johnson, Waterways Division (WD), Hydraulics Laboratory (HL), WES, was the Principal Investigator for Work Unit 32465.

The physical model facility described herein was constructed during September-December 1988. Mr. Robert W. McCarley, Math Modeling Branch, WD, designed the test facility and model disposal vessels. The test facility design generally followed guidelines offered by Soldate, Pagenkopf, and Morton of Tetra Tech in their investigation of scaling laws.

The physical model disposal tests described herein and the preparation of this report were conducted during April 1989 - March 1992 by Dr. Billy H. Johnson, WD; Ms. Dinah McComas, Math Modeling Branch, WD; Ms. Darla McVan, Prototype Measurements Branch, Hydraulics Structures Division (HS); and Mr. Mike Trawle, Chief, Math Modeling Branch, WD. General administrative supervision was provided by Mr. Frank Herrmann, Chief HL, and Messrs. M. B. Boyd, Chief WD, and Glenn Pickering, Chief HS, and Dr. Bobby Brown, Chief Prototype Measurements Branch, HS.

Within the framework of the existing numerical disposal model, modifications to allow for the observed behavior of real disposal operations are being planned. Details concerning the modified model results from application to the data presented in this report, as well as field data, will be published in a separate report.

Dr. Robert W. Whalin was Director of WES during publication of this report. COL Leonard G. Hassel, EN, was Commander and Deputy Director.

Additional information can be obtained from Mr. E. Clark McNair, Jr., Program Manager, at (601) 634-2070 or Dr Billy H. Johnson, Principal Investigator, at (601) 634-3425.

CONTENTS

CONVERSION FACTORS, NON-SI TO SI (METRIC)
UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
cubic feet	0.02831	cubic meters
cubic yards	0.7645549	cubic meters
feet	0.3048	meters
feet per second	0.3048	meters per second
gallons	0.003785412	cubic meters
knots	0.5144444	meters per second
square feet	0.09290304	square meters

DEVELOPMENT AND VERIFICATION OF NUMERICAL MODELS FOR PREDICTING THE INITIAL FATE OF DREDGED MATERIAL DISPOSED IN OPEN WATER

PHYSICAL MODEL TESTS OF DREDGED MATERIAL DISPOSAL FROM A SPLIT-HULL BARGE AND A MULTIPLE BIN VESSEL

PART I: INTRODUCTION

Background

1. An integral part of the problem of managing a dredged material disposal site is the ability to determine the physical fate of material immediately after an individual disposal operation and ultimately the long-term movement and/or accumulation of the material deposited initially within the site. The ability to determine the short-term fate of dredged material disposal in open water also is an integral part of assessing the water column environmental impact of disposal operations.

2. Field evaluations by Bokuniewicz et al. (1978) have shown that the placement of dredged material generally follows a three-step process: (a) convective descent during which the material falls under the influence of gravity, (b) dynamic collapse, occurring when the descending cloud or jet either impacts the bottom or arrives at a level of neutral buoyancy, in which case the descent is retarded and horizontal spreading dominates, and (c) passive transport-dispersion, commencing when the material transport and spreading are determined more by ambient currents and turbulence than by the dynamics of the disposal operation. Mathematical models for predicting the short-term fate of material from individual disposal operations that consider these three phases have been developed, e.g., Koh and Chang (1973), Brandsma and Divoky (1976), Johnson (1990).

3. A common deficiency of these numerical models is the lack of data for verification and the inadequacy of their representation of the convective descent and collapse phases in real disposal operations. For example, the models developed by Koh and Chang and subsequently modified by Brandsma and Divoky and by Johnson treat the disposal from a split-hull barge as a single hemispherical cloud descending through the water column.

Such an assumption prohibits the accurate simulation of water column concentrations of suspended sediments.

Purpose

4. Although field observations were made at several disposal sites by Bokuniewicz et al. (1978) and provided useful data in qualitatively better understanding the placement processes, detailed data sets are required for quantitative verification and to guide model modifications for an accurate representation of the actual disposal from split-hull barges and hopper dredges. Field data are being collected under the Dredging Research Program (DRP) for this purpose. However, to visually observe the processes involved in a disposal operation, relatively large-scale laboratory disposal tests are required.

Scope

5. As part of the DRP, physical model disposal tests have been conducted at the US Army Engineer Waterways Experiment Station (WES). These tests involved the disposal of various types of material from physical replicates of a split-hull barge and a hopper dredge in a deep basin. Disposals were made in water depths ranging from 2.0 to 6.0 ft.* At a model scale of 1:50, these tests simulated disposal volumes of 4,000 cu yd from a split-hull barge and 8,000 cu yd from a hopper dredge in water depths of 100 to 300 ft. As discussed by Soldate, Pagenkopf, and Morton (1988), results from the convective descent and collapse phases can be approximately scaled to the prototype as long as flow conditions generated by the disposal are in the turbulent range.

6. Results from eight stationary and seven moving disposals from the model split-hull barge and two stationary and three moving disposals from the hopper vessel are presented. These results consist of information on the short-term dynamics, e.g., average descent and bottom surge speeds, suspended sediment concentrations immediately after disposal, and bottom deposition. The results are being used at WES to guide numerical model developments and to provide data for model verification.

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* A table of factors for converting non-SI units of measurement to SI (metric) units is presented on page 4.

PART II: SCALING CONSIDERATIONS

7. A detailed investigation of scaling laws for the physical modeling of dredged material disposal is given by Soldate, Pagenkopf, and Morton (1988). A brief summary is presented below. Only undistorted models are considered because distorted models have inherent disadvantages. As summarized by Graf (1971), among these are that "velocities are not necessarily correctly reproduced in magnitude and direction," and that "there is an unfavorable psychological effect on the observer who views distorted models."

Processes

8. As previously stated the physical processes which occur in the discharge of dredged material are commonly divided into three phases: convective descent, dynamic collapse, and passive diffusion. During convective descent, which begins immediately on discharge, the descent of the discharge is caused by its negative buoyancy and discharge conditions. As the discharge descends, it entrains receiving water and as a result the bulk density of the discharge mixture decreases. If the water depth is sufficiently large and the receiving water density stratification is sufficiently strong, the bulk density of the discharge may equal the density of the receiving water at a depth called the neutral buoyancy depth. If this occurs, then the discharge tends to stabilize near this depth and collapse. If the water depth is not great enough, the discharge mixture will impact the bottom and surge laterally. The collapse of the discharge mixture either in the water column or on the bottom is termed the dynamic collapse phase. This phase ends when the energy of the discharge is spent. Thereafter (i.e., during the passive diffusion phase), the motion of material remaining in the water column is caused by processes independent of the method of discharge. Processes occurring during passive diffusion will not be discussed further. Placement processes for the case of bottom encounter are illustrated in Figure 1.

Dredged Material Disposal Characteristics

9. The characteristics of dredged material vary substantially. The material ranges from gravel to clays with particle size distributions

depending on the site. Sediment-particle densities usually range from 2.6 to 2.7 gm/cc. In situ bulk densities commonly range from 1.3 to 1.7 gm/cc or more. Clamshell dredging tends not to disturb the in situ properties of the dredged material. In contrast, hydraulic dredging tends to destroy the in situ properties of the material and mixes the sediments with water, lowering the bulk density of the water-sediment mixture. The particle fall velocities of sand and gravel particles are usually assumed to obey Stokes Law. Clay and silt particles are usually cohesive, and, as such, particle velocity is a function of sediment concentration. Commonly, fall velocities for dilute clay-silt mixtures are dependent on the concentration to a power, usually 4/3. If the particles are bound together in clumps, then the fall velocity of the clump is calculable as a noncohesive particle. The volume of dredged material discharged instantaneously from barges typically ranges from around 500 to 4,000 cu yd. The speed of the barge during discharge operations usually does not exceed 4 knots.

Convective Descent Phase

10. In the dynamic descent phase, the motion of the descending discharge cloud is assumed to be primarily dependent on bulk parameters, and only weakly on individual particle types. The nine initial parameters of importance are the radius of the disposal cloud at the time of release, b_o ; the initial fall velocity of the disposal cloud, W_o ; the initial bulk density, ρ_o ; the barge speed, U_B ; the receiving water velocity, u ; the receiving water density, ρ_a ; the acceleration of gravity, g ; the Brunt-Vaisala frequency or buoyancy, N ; and the kinematic viscosity, ν .

11. As derived by Soldate, Pagenkopf, and Morton (1988), there are six dimensionless parameters that must be the same in the model and the prototype for complete similitude. For this study, the receiving water was quiescent and unstratified. Thus, for similar conditions in the prototype these six parameters reduce to the following three:

$$\frac{g\left(\frac{\rho_o - \rho_a}{\rho_a}\right)b_o}{W_o^2} , \quad \frac{b_o W_o}{\nu} , \quad \frac{U_B}{W_o} \qquad (1)$$

If one uses a length scale $L_R = L_m/L_p$ to scale all lengths, the time scale $T_R = t_m/t_p$ is determined from the first relation to be

$$T_R = \sqrt{L_R \frac{\Delta\rho_p}{\Delta\rho_m}} \qquad (2)$$

and thus the descent velocity scales as

$$W_m = \frac{L_R W_p}{T_R} \qquad (3)$$

For the case of a stationary disposal (i.e., $U_B = o$), the final requirement for similitude is that the Reynolds number $R_e = \frac{b_o W_o}{\nu}$ be the same in the model and the prototype. Since ν is essentially the same in the model and the prototype, if b and W are scaled by L_R and L_R/T_R, respectively, the model Reynolds number is a factor L_R^2/T_R too small. For typical disposal operations, the prototype Reynolds number will be in excess of 10^6. For the case of purely sand dumps and a length scale of 1:50, the model Reynolds number will be about $3x10^3$. For a lighter material such as crushed coal or a dilute slurry of silt, the model Reynold's number might be reduced further by a factor of two or three. However, even though the similitude of the Reynolds number cannot be achieved, as long as the model Reynolds number is greater than about 10^3 the drag coefficient will be approximately the same in the model and the prototype. The behavior of the drag coefficient for a solid sphere as a function of R_e is illustrated in Figure 2. Thus, for a length scale of 1:50, model results concerning bulk behavior of the convective descent phase should be approximately scalable to the prototype.

12. Theoretically, the dimensionless particle fall velocities W_j/W_o should be the same in the model and the prototype. This effectively places a restriction on model particle diameters and/or density. Soldate, Pagenkopf, and Morton (1988) show that for noncohesive material the model particle diameter should satisfy

$$D_m^2 = \frac{\left(\frac{\rho_{s_p} - \rho_p}{\rho_p}\right)}{\left(\frac{\rho_{s_m} - \rho_m}{\rho_m}\right)} \frac{\nu_m}{\nu_p} \frac{D_p^2 L_R}{T_R} \qquad (4)$$

Thus, since $\nu_m = \nu_p$, if the particle density in the model and prototype are the same, the model particle diameter should be

$$D_m = D_p (L_R)^{1/4} \qquad (5)$$

13. Achieving invariance of the ratio W_j/W_o is difficult for cohesive material. If concentrations are not very high one can assume the fall velocity for cohesive particles can be written

$$W = \beta C^{4/3} \qquad (6)$$

where C is the concentration and β is a constant. Thus, the most practical modeling scheme is to use the same material in both the model and the prototype, but model the cohesive particle concentration using

$$C_m = \left(\frac{L_R}{T_R}\right)^{3/4} C_p \qquad (7)$$

However, this requires using a smaller volume of cohesive material in the model than required by length scaling alone which then changes the bulk density and thus changes the time scaling given by Equation 2.

14. Requiring W_j/W_o to be the same in the model and the prototype is probably not required if individual particles are not falling from the cloud. Thus, an adequate description of the bulk behavior during convective descent of a cloud impacting the bottom can be approximately obtained without forcing the invariance of W_j/W_o . However, an accurate scaling of the amount of

sediment left behind in the water column requires that this ratio be the same in the model and prototype.

Dynamic Collapse Phase

15. In all of the disposal tests in this study, the descending sediment cloud impacted the bottom with a resultant lateral surge being formed. As shown by Soldate, Pagenkopf, and Morton (1988), the Buckingham Pi theorem yields six dimensionless parameters. These are

$$\frac{U_o^2}{g_i' h_o} , \frac{U_o D_b}{\nu} , \frac{U_o h_o}{\nu} , \frac{t_i U_o}{r_o} , \frac{t_i U_o h_o}{r_o^2} , \frac{\rho_i}{\rho_a(d)} \qquad (8)$$

where

r_o = initial radius of bottom cloud

h_o = initial height of bottom cloud

U_o = initial speed of bottom cloud

ν = kinematic viscosity

D_b = mean bottom sediment diameter

ρ_i = initial bulk density of bottom cloud

t_i = time required for cloud to impact the bottom

$\rho_a(d)$ = density of receiving water at the bed

$$g_i' = \left(\frac{\rho_i - \rho_a(d)}{\rho_i} \right) g \ ,$$

With a length scale L_R, the first expression results in the same time scale T_R as in the convective descent phase; i.e., Equation 2.

16. The radial speed and extent of the surge in a quiescent water body are primarily dependent on the total energy at impact available to drive the surge which is ultimately dissipated by frictional losses due to interaction of the surge with the seafloor. The effect of friction will be the same in the model and the prototype if the shear velocity U_{*_m} in the model is

$$U_{*_m} = \frac{L_R}{T_R} U_{*_p} \qquad (9)$$

17. For a steady turbulent uniform flow, the velocity profile is logarithmic beginning at some height Z_o above the bed. Similarity between model and prototype requires that the roughness Reynolds number $U_* k_s / \nu$ (k_s = bed roughness) be the same in both model and prototype. Assuming the bed roughness is approximately the bed particle diameter yields

$$D_{b_m} = \left(\frac{T_R}{L_R} \right) D_{b_p} \tag{10}$$

where $\nu_m = \nu_p$. If one assumes that g_i' is approximately the same in the model and prototype, Equation 10 states that if the speed and extent of the surge are to be approximately scaled then the model bed should be substantially rougher than the prototype. This criterion was probably not entirely adhered to in these tests since the model bottom was relatively smooth concrete.

18. The behavior of suspended particles in the bottom surge is dependent on the ratio $W_j/(0.4U_*)$. If the ratio is much less than unity the particles will tend to remain suspended whereas if the ratio is much greater than unity the particles will tend to settle. With the model bottom being too smooth this ratio is probably too large in the model, resulting in more rapid deposition than might occur in the prototype. However, it should be noted that the surge is neither steady nor uniform. Thus, the above discussion is not entirely applicable.

Summary

19. Scaling of the prototype is approximately possible for the bulk behavior of both convective descent and dynamic collapse phases provided that the model Reynolds number for each phase is high enough so that turbulent flow occurs (except toward the end of dynamic collapse). Froude number similitude is always required. Flow Reynolds number similitude is never achieved in the water column and is probably not required unless collapse occurs in the water column. For a steady turbulent uniform surge, similitude is required for the roughness Reynolds number applicable to the bottom sediments if frictional

effects are to be accurately scaled. It is doubtful this has been fully accomplished in this study.

20. The Reynolds number requirements put a limit on the scales that can be used. The flow Reynolds number in the model at the beginning of either the convective descent or dynamic collapse phases should be high enough to cause turbulent flow. To meet this criterion in typical disposal operations, the length scale factor should exceed 1:100. This restriction is met in this study since the length scale factor is 1:50.

PART III: PHYSICAL TEST FACILITY

Description of Facility

21. A preliminary investigation by Soldate, Pagenkopf, and Morgan (1988) suggested several factors to consider in choosing a model facility. The geometric scales of the model were fixed through a combination of numerical model predictions and results from a scaling laws investigation. Under the assumption that the facility would be undistorted, it was estimated that a facility 40 ft by 40 ft would be sufficient for all but about 20 percent of anticipated test needs (i.e., allowing disposals to be simulated without the bottom surge striking the boundaries of the facility). This estimate was based on a model-to-prototype scale of 1:100 or greater.

22. The physical test facility was constructed in a deep basin of dimensions 100 ft by 50 ft by 15 ft. Braced, 1-ft-thick concrete walls fitted with two 10-ft by 13-ft windows were built to enclose an L-shaped viewing area. The windows provided views of the test area that were perpendicular to each other. The floor and the walls opposite viewing windows were painted white with a black, 1-ft spacing grid. The fourth wall, opposite a viewing window, was a movable backdrop, giving the facility size flexibility. However, preliminary tests at 4-ft depth proved that chemically treating 120,000 gal of water for clarity was impractical. The facility was then further modified by constructing a fixed concrete block wall, resulting in a 32-ft by 41-ft test area. A plan view of the facility is given in Figure 3 and an overhead photograph is shown in Figure 4.

23. The water supply system used for the facility was the local city water system. Water clarity was a major factor in the quality of visual data obtained; therefore, the water was chlorinated and two 36-in.-diam sand filters were employed. Tests were arranged to minimize changes in water level, thereby minimizing the facility's impact on the local water system.

Disposal Vessels

24. Two types of disposal vessels were used for testing — a split hull scow and a hinged-door hopper. The split-hull barge was constructed at a 1:50 scale and is based upon an actual design obtained from the McDermott Company

of New Orleans, LA. Its dimensions are 57 in. by 13.5 in. by 7.5 in., with a disposal volume of 0.9 cu ft. The opening and closing of the barge are controlled by an air line attached to two small hydraulic cylinders mounted on the vessel as illustrated in Figure 5. The barge opens essentially instantaneously.

25. The hinge-door multihopper disposal vessel was roughly based on the *Wheeler*, a Corps hopper dredge. The dimensions of the test model are 2.09 ft by 2.96 ft, with six hoppers. Each hopper has a maximum capacity of 0.28 cu ft. This vessel was designed as a free-standing unit, with the flotation provided separately by a modified 12-ft-long john boat. A plan view of the hopper disposal vessel along with a photograph are provided in Figures 6 and 7. The door latches were operated manually by a person sitting in the john boat. The order of door opening was not consistent throughout the testing. However, the doors were always opened two at a time. The usual order of door opening was 1 and 2; 5 and 6; and 3 and 4.

Test Procedure

26. Tests were concerned with tracking the movement of the disposal material from the vessel to its final resting place. All tests were conducted in a static and unstratified pool. Each test was videotaped from each of the viewing windows shown in Figure 3. The cameras were placed to provide maximum viewing of the descent and bottom surge. Still photos from above the water surface were taken for most of the tests. Water samples were taken to determine suspended sediment concentrations. Samplers were placed in three different locations, each taking three to five simultaneous samples from the water column. The size and arrangement of the discrete water sampler bottles are shown in Figure 8.

27. For tests in which the vessel was stationary, the video recorders were mounted on tripods and focused to provide maximum viewing of the convective descent and the bottom surge. Each sampler was opened when the bottom surge had travelled 1 ft past the sampler location. The cameras generally ran until the energy of the surge had dissipated. Overhead photos were taken throughout the tests from various above-surface viewpoints.

28. The procedure changed slightly for moving disposal tests. The vessel was manually pulled in a straight line toward one viewing window with

the direction of movement being parallel to the other viewing window. Both cameras were mounted on tripods as for stationary tests, but the side-view camera followed the barge, keeping the plume centered. Generally the velocity of the vessel was essentially constant.

29. Four materials were used as disposal material: sand, finely crushed coal, silt, and buckshot clay. The coal was of a gradation that would pass through a No. 16 sieve but not through a No. 100 sieve. The silt was local silt, wet-sieved through a No. 200 sieve. The split-hull barge was tested with all four materials. However, the hopper was only tested with the silt. The sand and coal were generally very wet, but usually under no standing water at the time of the disposal. The silt and clay were mixed with water to form a slurry, with a sample of the slurry being taken before each test to determine its bulk density. The slurry was pumped into the test vessel and disposed as soon as possible to minimize settling within the vessel.

30. Both stationary and moving disposal tests were conducted with the split-hull barge. These tests were conducted using primarily sand, coal, and silt as the disposal material. In addition, one test was conducted using buckshot clay. The volume of each dump was 0.9 cu ft. At a scale of 1:50, this represents a disposal of approximately 4,000 cu yd of material. The water depth in the test facility varied from 2.0 to 6.0 ft, representing disposals in prototype depths of 100 to 300 ft.

31. The data collection consisted of videotaping, suspended sediment samples taken at generally three vertical locations at three horizontal positions, and surveys of the bottom deposition for the coal and sand tests. From the videotapes, descent and bottom surge speeds were determined.

Stationary Tests

32. Eight stationary tests were conducted. Four of the tests were conducted with crushed coal as the disposal material, one was with sand, one was with buck-shot clay, and two were with silt. Characteristics of these disposals are given in Table 1.

Table 1

Characteristics of Stationary Split-Hull Barge Disposal Tests

Test No.	Water Depth ft	Material	Volume cu yd	Bulk Density gm/cc	Grain Size mm
10	2.0	Coal	0.9	1.3	0.15-1.19
1	4.0	Coal	0.9	1.3	0.15-1.19
2	4.5	Coal	0.9	1.3	0.15-1.19
5C	6.0	Coal	0.9	1.3	0.15-1.19
3	4.5	Sand	0.9	2.6	0.15-0.8
22	2.6	Silt	0.9	1.06	0.074
24	4.0	Silt	0.9	1.14	0.074
20	6.0	Clay	0.9	1.13	<0.074

Short-term dynamics

33. As previously discussed, placement of dredged material in open water proceeds by a distinct series of processes: descent through the water column, either the spread of a bottom surge generated by the bottom impact or

collapse within the water column at the level of neutral buoyancy, and finally passive transport-diffusion by the ambient currents. All of the disposal tests conducted released material in a dispersed form, and thus the material was normally transported to the bottom as a dense jet. This behavior was true for all tests, although the leading edge of the jet for the clay disposal resembled an ellipsoidal cloud. Typically, the volume of fluid in the jet reaching the bottom was 25 to 50 times the initial volume released based upon the average descent speed of the jet, the duration of jet descent, and jet dimensions at the moment of impact.

34. Figure 9 illustrates the basic behavior during convective descent of a disposal of a load of crushed coal. The time sequence shown was constructed from still photos taken from video of Test 5C for disposal in 6 ft of water. Figure 10 shows a similar sequence of still photos but for the disposal of a clay slurry in 6 ft of water (Test 20). The more cloud-type behavior can clearly be seen. Figure 11 shows the same disposal, but viewed from the side rather than from the end.

35. Using videos to determine timings, Table 2 presents average descent speeds of the disposal jet and the bottom surge speed as a function of lateral spread. As expected, the average descent speed of a disposal increases as the depth decreases since the greater depth allows for entrainment of the ambient fluid and, thus, a decrease of the descent velocity. The initial surge speed seems to be approximately the average descent speed.

Table 2

Short-Term Characteristics of Stationary Barge Tests

		Water Depth	Descent Speed	Surge Speed, ft/sec							
				End View				Side View			
Test	Material	ft	ft/sec	0-1 ft	1-2 ft	2-3 ft	3-4 ft	0-1 ft	1-2 ft	2-3 ft	3-4 ft
1	Coal	4.0	0.44	0.48	0.48	0.48	0.24	0.43	0.29	0.11	-
2	Coal	4.5	0.44	0.27	0.27	0.20	-	0.38	0.19	0.11	-
5C	Coal	6.0	0.43	0.33	0.31	0.20	-	-	-	-	-
22	Silt	2.8	1.47	0.40	0.22	-	-	0.83	0.24	-	-
24	Silt	4.0	0.73	0.40	0.26	-	-	0.31	0.16	0.12	-
20	Clay	6.0	0.67	0.90	0.71	-	-	0.42	0.26	-	-

36. If it is assumed that on impact the cloud is cylindrical and that the cylindrical cloud spreads radially on the bottom, conservation of volume flux requires that the initial speed of the surge U_0 be

$$U_o = \frac{W_i d_i}{4 h_o} \quad (11)$$

where

W_i = impact speed

d_i = diameter of cylindrical cloud

h_o = height of cylindrical cloud at impact

Thus, for the initial surge speed to be equal to the impact speed, the initial height should be about 1/4 of the initial diameter. An inspection of Figure 9e reveals that such a ratio of surge height to diameter very quickly occurs.

37. Normally one would expect the surge speed to decrease with distance from the impact point. However, as illustrated in the data presented for Test 1, this is not always the case. With the density of the disposal material decreasing from the bottom of the vessel to the top, if the material leaves the vessel in a continuous fashion the energy feeding the surge would be greatest at the initial impact and then decrease as the remaining disposal material enters the surge. Under such conditions the surge speed would decrease with lateral spread. However, it was observed that quite often material left the disposal vessel as distinct globs. In such cases the surge temporarily accelerates as relatively dense globs of material impact the bottom and add additional energy to the expanding bottom surge.

38. Modeling this behavior is difficult since it requires a knowledge of how the material will leave the disposal vessel. However, as a result of insight gained from these disposal tests, such disposal operations can be modeled as a sequence of convecting clouds with varying characteristics. This is discussed in more detail later.

39. As previously noted, these results cannot be absolutely scaled to the prototype. However, based upon a representative length of 2.0 ft and a descent velocity of 0.50 cu ft/sec (with a value of 10^{-5} sq ft/sec for the kinematic viscosity of water), the model Reynolds number is 10^5. Thus, since the volume of material disposed results in turbulent flow conditions and, therefore, the drag coefficient is approximately the same in the model and the prototype, data concerning the convective descent can be approximately scaled to the prototype. For example, with a 1:50 scaling, the average prototype

descent speed based upon the tests with coal is computed from Equation 3 to be approximately 7.84 ft/sec. This value falls in the range of average descent speeds recorded by Bokuniewicz et al. (1978). Their recorded values ranged from 1.64 ft/sec to 9.19 ft/sec for a range of disposal material and water depths.

40. As shown in Figure 12, the field data collected by Bokuniewicz et al. (1978) show the travel time for a bottom surge to reach 150-ft ranges from about 75 sec to perhaps 200 sec, depending upon the disposal site and disposal conditions. Using results from the end view of the coal tests and neglecting differences in the bulk density of the model and prototype surges, the scaled times to travel 150 ft in the prototype range from about 47 sec to 85 sec.

Suspended sediment data

41. Since the ratio W_j/W_0 is not scaled (see paragraph 12), suspended sediment data may not be entirely representative of the prototype. However, these data can be used to aid in verifying numerical models if the models are applied to the actual laboratory tests.

42. As previously discussed, discrete water samples were collected at three horizontal positions surrounding the disposal barge. The locations of these positions relative to the disposal vessel for each test listed in Table 1 and corresponding vertical profiles of the concentrations are shown in Figures 13-26. At each position, three or four water depths were sampled simultaneously. These samples were then sieved, dried, and weighed to determine the amount of sediment collected.

43. Suspended sediment concentrations are presented in Table 3. When analyzing these results it should be remembered that these samples were collected over about a 5-sec interval beginning at the elapsed time after bottom impact given in Table 3. The data collection at each location was initiated when the leading edge of the surge had moved 1 ft past the water sampler pole.

44. Generally the concentration would be expected to decrease with vertical distance from the bottom. However, due to the turbulence occurring in the head of the surge this may not be the case when data are collected near the leading edge of the surge. From an inspection of Figures 16, 18, 20, 24, and 26, this behavior is clearly evident when comparing data collected at 3 in. and 6 in. from the bottom.

45. Suspended sediment concentrations as high as 15-20 gm/ℓ were

Table 3

Suspended Sediment Concentrations from Stationary Split-Hull Barge Tests

Test	Material	Water Depth ft	Pole	Elapsed Time sec	Concentration, gm/ℓ				
					3 in.	6 in.	1 ft	2 ft	3 ft
1	Coal	4.0	A	50	0.483	0.368	·	0.068	-
			B	17	10.077	3.003	0.209	0.018	-
			C	2	2.298	1.676	0.080	0.000	-
2	Coal	4.5	A	60	0.206	0.521	0.283	0.007	-
			B	-	2.534	2.426	3.051	0.156	-
			C	17	8.534	5.113	0.009	0.025	-
3	Sand	4.5	A	-	2.494	2.769	1.112	0.030	-
			B	-	13.907	17.074	0.352	0.001	-
			C	-	6.803	5.329	0.455	0.002	-
5C	Coal	6.0	A	30	2.347	4.615	2.703	0.216	0.025
			B	17	14.137	18.319	5.720	-	0.020
			C	54	0.951	0.840	0.317	0.005	0.006
20	Clay	6.0	A	47	1.035	0.841	0.759	0.066	0.068
			B	13	-	-	-	0.118	-
			C	42	-	2.[illegible]79	-	-	-
22	Silt	2.8	A	23	0.388	0.615	0.[illegible]	0.107	-
			B	12	3.306	1.300	0.[illegible]	0.175	-
			C	37	0.609	0.423	0.149	0.024	-
24	Silt	4.0	A	21	1.900	2.353	0.918	0.129	-
			B	12	1.932	1.544	0.562	-	-
			C	35	0.912	1.206	0.868	0.049	-

collected over the lower 6 in. of the sand and coal surges at distances 2-4 ft from the edge of the barge. For the fine grain silt and clay disposals, maximum surge concentrations were generally only 2-3 gm/ℓ over the lower 6 in. of the surge. Detailed field data on vertical profiles of suspended sediment concentrations in disposal surges do not exist, so it is difficult to assess whether the bottom surge concentrations in these tests are representative of the prototype. However, since similar results were obtained for the sand and coal disposals, although the particles are vastly different, it appears that the theoretical scaling requirement associated with the sediment is not important in the surge head. Thus, the concentrations collected over perhaps the lower 1 ft of the surge may be a good representation of concentrations to be expected over the lower 25-50 ft of the water column during the disposal of a 4,000-cu-ft load in water depths of about 200 ft.

Bottom deposition

46. After all disposal material had settled, bottom surveys were conducted for the tests involving sand and crushed coal. This was accomplished by measuring the thickness of the bottom deposit at the intersection of the grid lines painted on the bottom of the test facility. Bottom deposits from the fine grained disposal tests were too thin to measure, but a qualitative description is given in Table 4. The deposition data were used to construct the bottom deposition contour plots presented in Figures 27-30. Maximum depositional thicknesses of about 0.05 ft scales to the prototype as 2.5 ft. Ninety-five percent or more of the material is deposited in approximately a circular pattern with a radius of 4-5 ft, corresponding to a prototype radius of 200-250 ft. These values correspond approximately with those observed by Bokuniewicz et al. (1978). Although more tests at varying depths are required, these data imply that the spread of the bottom surge, and thus the area over which bottom deposition occurs, increases with depth. There appears to be little difference between the spread of the sand and crushed coal disposal material, lending further credence to the belief that scaling the bottom surge dynamics does not require an accurate scaling of the model sediment based upon the scaling laws developed by Soldate, Pagenkopf, and Morton (1988). Bottom deposition data are summarized in Table 4.

Table 4

Summary of Bottom Deposition Patterns from the Stationary Split-Hull Barge Tests

Test	Maximum Thickness ft	Horizontal Dimensions ft x ft	Shape
1	0.035	Diameter ≅ 5 ft	Circular
2	0.040	Diameter ≅ 5.5 ft	Circular
10	0.050	7 x 11	Elliptical
5C	0.030	12 x 13	Rectangular

(Continued)

Table 4 (Concluded)

Test	Maximum Thickness ft	Horizontal Dimensions ft x ft	Shape
3	-	-	-
22	-	20 x 12	Elliptical
24	-	16 x 18	Elliptical
20	-	Covered entire test area	-

Moving Tests

47. Seven tests with the split-hull barge were conducted with the disposal vessel moving. Four tests were with crushed coal and three tests were with a sediment primarily composed of silt. Characteristics of these disposals are given in Table 5.

Table 5

Characteristics of Moving Split-Hull Barge Disposal Tests

Test	Water Depth ft	Material	Barge Velocity ft/sec	Volume cu ft	Bulk Density gm/cc	Grain Size mm
1C	4.0	Coal	0.40	0.9	1.3	0.15-1.19
2C	4.0	Coal	0.28	0.9	1.3	0.15-1.19
3C	4.0	Coal	0.42	0.9	1.3	0.15-1.19
4C	6.0	Coal	-	0.9	1.3	0.15-1.19
21	2.0	Silt	-	0.9	1.27	0.074
23	2.3	Silt	0.44	0.9	1.10	0.074
25	4.0	Silt	0.43	0.9	1.05	0.074

Short-term dynamics

48. Unlike the stationary disposal tests in which virtually all of the material was quickly transported to the bottom, the moving tests also resulted in an upper water column plume consisting of fine material sheared from the

main body of descending material. If the water column had been sufficiently stratified, it is probable that extremely fine material would have been trapped above the pycnocline for an extended period of time.

49. The same basic placement processes previously discussed also take place in moving disposal operations. The vast majority of the material descends through the water column as a result of its excess density and impacts the bottom, with the end result being the generation of a bottom surge. In all of the tests, the descending jet was composed of distinct "globs" of material, with each succeeding glob contributing to the surge initiated by the first glob. The barge speed and the manner in which material leaves the vessel determine the importance of the interaction of these separate globs.

50. The basic behavior discussed above can be seen in Figures 31 and 32. Figure 31 consists of a series of photographs taken at four times during the disposal looking at the end of the barge as it moves toward the observer. From this viewpoint, the disposal very much resembles that from a stationary barge. However, a very different perspective is obtained from Figure 32 which gives side views of the placement processes. The globular nature of the disposal within the overall structure of a descending jet can clearly be seen.

51. As previously discussed in connection with the stationary disposal tests, modeling such disposal operations can probably best be accomplished by treating the disposal as a series of convecting clouds with different characteristics. Each cloud would be created at a different location due to the moving nature of the disposal operation and would possess varying bulk density and sediment characteristics.

52. Table 6 was constructed from data obtained from videos and presents average descent speed of the disposal jet and the bottom surge speed as a function of lateral distance. A comparison of Tables 2 and 6 reveals that descent speeds and bottom surge speeds are similar for both stationary and moving disposals.

Suspended sediment data

53. Discrete water samples for determining water column concentrations were collected as in the stationary disposal tests. However, for the moving disposals, the three water sampler poles were generally placed along the same grid line with the barge moving along a line parallel to the row of poles. The locations of the poles and corresponding vertical profiles of suspended

Table 6

Short-Term Characteristics of Moving Barge Tests

Test	Material	Water Depth ft	Descent Speed ft/sec	Surge Speed, ft/sec End View 0-1 ft	1-2 ft	2-3 ft	3-4 ft	Side View 0-1 ft	1-2 ft	2-3 ft	3-4 ft
1C	Coal	4.0	0.44	0.50	0.50	0.33	0.25	0.25	0.33	0.17	-
2C	Coal	4.0	0.36	0.33	0.25	0.33	0.25	0.25	0.25	0.17	-
3C	Coal	4.0	0.44	0.50	0.33	0.33	0.20	0.33	0.20	0.17	0.12
4C	Coal	6.0	0.43	0.33	0 25	0.25	0.17	0.50	0.33	0.20	0.17
21	Silt	2.0	-	-	-	-	-	-	-	-	-
23	Silt	3.3	0.77	0.50	0.50	0.25	-	0.50	0.33	0.25	0.20
25	Silt	4.0	0.50	0.50	0.25	-	-	0.33	0.17	-	-

sediment concentration for the moving tests are shown in Figures 33-44, with the center line of the movement of the barge also displayed. Movement of the barge was initiated in each test before arriving at pole C, with the barge opened as pole C was encountered. Barge speeds are given in Table 5 and in all cases were less than 0.5 ft/sec.

54. Concentrations at the three horizontal positions shown at up to four vertical locations along with the timing of those concentrations are presented in Table 7. The plots illustrating the vertical profiles of the suspended sediment concentrations were constructed from data presented in Table 7.

Table 7

Water Column Concentrations from Moving Split-Hull Barge Tests

Test	Material	Water Depth ft	Pole	Time sec	Concentration, gm/ℓ 3 in.	6 in.	1 ft	2 ft	3 ft
2C	Coal	4.0	A	66	0.732	0.746	0.080	–	–
			B	27	4.057	4.265	2.997	–	–
			C	18	2.100	2.282	0.114	0.008	–
3C	Coal	4.0	A	62	0.529	0.287	0.040	–	–
			B	36	3.123	2.589	1.123	0.063	–
			C	26	6.750	4.059	1.797	–	–
4C	Coal	6.0	A	52	1.791	1.903	1.286	0.194	–
			B	31	5.243	–	3.386	0.747	0.002
			C	22	3.294	2.899	1.948	0.276	–
21	Silt	2.0	A	–	1.509	1.126	0.918	0.102	–

(Continued)

Table 7 (Concluded)

Test	Material	Water Depth ft	Pole	Time sec	Concentration, gm/ℓ 3 in.	6 in.	1 ft	2 ft	3 ft
			B	-	2.288	1.262	0.844	0.151	-
			C	-	4.768	2.223	0.791	0.140	-
23	Silt	2.3	A	36	1.021	0.676	0.762	0.157	-
			B	15	2.341	0.432	0.194	0.066	-
			C	8	2.244	2.329	0.479	0.062	-
25	Silt	4.0	A	48	1.065	1.106	0.609	0.135	-
			B	14	1.388	0.382	0.841	0.104	-
			C	-	1.991	1.738	0.979	0.112	-

55. An inspection of the videos clearly shows that for moving disposals the fine material leaving the disposal vessel at the end of the disposal tends to create an upper water column plume. Material then settles out of the upper water column due to particle settling as opposed to being transported to the bottom through an energetic convective descent phase. However, due to a combination of the timing of the discrete water samples as well as the small amount of material present in the upper portion of the water column, virtually no suspended material was collected in the uppermost bottles.

56. Similar to the surge created by the stationary disposals, in some cases the concentration is lower near the bottom of the surge than higher up in the water column. The reason is partly due to the turbulence in the surge head but also may be due to globs of material falling through the water column after the initial impact of material with the bottom.

Bottom deposition

57. Similar to the stationary tests, bottom surveys were conducted for the moving tests with crushed coal. Contour plots of bottom deposition are given in Figures 45-47. The elongated more elliptical shape is, of course, due to the moving source of disposal material. Although the bottom deposition was too thin to measure for the silt tests, a general description of the extent of deposition is given in Table 8. The disposal material tended to be deposited in a more rectangular pattern for the fine grained material. This was due to the material leaving the barge in a more uniformly continuous fashion than for the case of the more coarse crushed coal. As to be expected,

the maximum thickness is greater for the case of a stationary disposal of coarse grained material. However, for the case of the fine grained material the area of deposition appears to be about the same.

Table 8

Summary of Bottom Deposition Patterns from the Moving Split-Hull Barge Tests

Test	Maximum Thickness ft	Horizontal Dimensions ft x ft	Shape
2C	0.025	8 x 13	Elliptical
3C	0.025	10 x 13	Elliptical
4C	0.025	10 x 13	Elliptical
21	-	15 x 19	Rectangular
23	-	10 x 18	Rectangular
25	-	18 x 20	Irregular

PART V: HOPPER DISPOSAL TESTS

58. Two stationary and three moving disposals were conducted from the disposal vessel shown in Figure 7. As previously noted this vessel resembles a section of a hopper dredge and has been constructed to a 1:50 scale. The six separate bins were filled with material in all tests and opened in pairs. Each bin contained 0.28 cu ft resulting in the total volume of each disposal being 1.68 cu ft, representing about 8,000 cu yd in the prototype. Initially, disposals with both sand and crushed coal were attempted. However, in each case the disposal material bridged the bottom opening resulting in little of the material being disposed. Therefore, all remaining disposal tests from the hopper disposal vessel were conducted with a slurry of silty material. As with the split-hull barge tests, the data collection consisted of videotaping and taking suspended sediment samples at three vertical locations at three horizontal positions.

Stationary Tests

59. Only two stationary tests were conducted. One was in a water depth of 2.0 ft and the other was in 4.0 ft. Characteristics of the disposals are given in Table 9. In each case the disposal was accomplished by opening the three pairs of doors in such a manner that most of the material had left the bins before opening the next pair of doors. The opening sequence was a pair of end bins, the next pair of end bins, and finally the middle pair of bins.

Table 9

Characteristics of Stationary Hopper Disposal Tests

Test	Water Depth ft	Material	Volume cu ft	Bulk Density gm/cc	Grain Size mm
1H	2.0	Silt	1.68	1.155	0.074
5H	4.0	Silt	1.68	1.180	0.074

Short-term dynamics

60. The same basic behavior or placement processes observed in the split-hull barge tests also were observed in the hopper disposals; the material descended through the water column as a jet entraining ambient fluid.

Impact with the bottom again resulted in the formation of a bottom surge. However, this surge tended to have more of an elliptical shape rather than the radial surge observed in the stationary split-hull barge disposals. Figures 48 and 49 contain a series of still photographs illustrating the descent and bottom surge phases.

61. The two jets from each pair of doors quickly interacted and then resembled a single jet descending through the water column. The interaction occurred within about 1 ft from the bottom of the disposal vessel. However, as illustrated in Figure 49, the jets created by the individual pairs of doors do not interact with each other before bottom encounter. Average descent and bottom surge speeds are given in Table 10. The number of pairs of bins that have impacted the bottom and are contributing to the speed of the surge head at a particular location is noted.

Table 10

Short-Term Characteristics of Stationary Hopper Tests

			Descent Speed of Pairs of Jets, ft/sec			Surge Speed, ft/sec							
						End View				Side View			
Test	Material	Water Depth ft	End	Mid	End	0-1 ft	1-2 ft	2-3 ft	3-4 ft	0-1 ft	1-2 ft	2-3 ft	3-4 ft
1H	Silt	2.0	-	-	-	0.67(1)*	0.34(2)	0.26(2)	0.16(3)	0.45(1)	0.26(2)	0.31(2)	-
5H	Silt	4.0	1.48	1.60	1.48	0.50(1)	0.36(2)	0.23(3)	-	0.52(1)	0.59(2)	0.50(3)	-

* Number of pairs of bins contributing to the surge.

Suspended sediment data

62. These data were collected in the same manner as those collected during the split-hull barge disposal tests. The locations of the poles with the bottles for collecting discrete water samples for the two stationary tests are shown in Figures 50 and 52. Suspended sediment concentrations determined from these samples are presented in Table 11. Figures 51 and 53 are plots of these data illustrating the vertical profiles. Results from these tests seem to imply that concentrations in the upper water column are greater for the case of a hopper-dredge-type disposal than from a split-hull barge for a similar type of disposal material.

Bottom deposition

63. Deposition of the silty material on the bottom was not of sufficient thickness to conduct a bottom survey. Results of visual observations after the material had settled from the water column are given in Table 12.

Table 11

Suspended Sediment Concentrations from Stationary Hopper Tests

Test	Material	Water Depth ft	Pole	Time	Concentration, gm/ℓ 3 in.	6 in.	1 ft	2 ft	3 ft
1H	Silt	2.0	A	27	0.974	0.971	1.271	0.109	—
			B	15	1.806	0.421	0.529	—	—
			C	27	1.038	1.103	0.553	0.043	—
5H	Silt	4.0	A	16	1.697	—	0.015	0.021	0.140
			B	20	2.015	—	0.015	0.018	0.089
			C	11	4.091	—	0.738	0.203	0.737

Table 12

Summary of Bottom Deposition Patterns from the Stationary Hopper Tests

Test	Horizontal Dimensions ft x ft	Shape
1H	—	—
5H	Covered virtually the entire 40-ft x 50-ft test area, but not uniformly	

Moving Tests

64. Three disposals from the hopper vessel were conducted with the vessel moving. Characteristics of these disposals are given in Table 13.

Table 13

Characteristics of Moving Hopper Disposal Tests

Test	Water Depth ft	Material	Barge Speed ft/sec	Volume cu ft	Bulk Density gm/cc	Grain size mm
2H	2.0	Silt	0.357	1.68	1.056	0.074
3H	4.0	Silt	0.368	1.68	1.111	0.074
4H	4.0	Silt	0.285	1.68	1.125	0.074

Short-term dynamics

65. The main body of the jet formed by the interaction of the individual jets continued its descent through the water column. However, as with the split-hull barge tests, some material was sheared off and formed an upper water column plume that was not generated in the stationary disposal tests in a quiescent body of water. The merging of the individual jets, descent through the water column of the merged jet, and the resulting bottom surge created as a result of the bottom impact are illustrated in Figures 54 and 55. A summary of the average descent and bottom surge speeds determined from videotapes is given in Table 14. The reason for the large increase in surge speed in Test 4H at 3 to 4 ft, as viewed from the side, is because the jet from the last pair of doors has just impacted the bottom.

Table 14

Short-Term Characteristics of Moving Hopper Tests

		Water Depth	Descent Speed of Pairs of Jets, ft/sec			Surge Speed, ft/sec							
						End View				Side View			
Test	Material	ft	End	Mid	End	0-1 ft	1-2 ft	2-3 ft	3-4 ft	0-1 ft	1-2 ft	2-3 ft	3-4 ft
3H	Silt	4.0	1.74	1.82	1.54	0.50(1)*	0.22(1)	0.17(2)	-	-	-	-	-
4H	Silt	4.0	2.10	1.33	1.33	0.71(1)	0.30(1)	0.22(2)	0.18(3)	0.43(1)	0.26([illegible])	0.18(2)	0.62(3)

* Number of pairs of bins contributing to the surge.

Suspended sediment data

66. Locations of the poles containing the bottles for collecting discrete water samples for each of the three moving hopper tests are shown in Figures 56, 58, and 60. A summary of the water column concentrations is presented in Table 15. Vertical profiles at the pole locations for each test are presented in Figures 57, 59, and 61.

Table 15

Water Column Concentrations from Moving Hopper Tests

		Water Depth		Time	Concentration, gm/ℓ					
Test	Material	ft	Pole	sec	3 in.	6 in.	1 ft	1.5 ft	2 ft	3.5 ft
2H	Silt	2.0	A	30	13.818	1.176	0.403	0.092	—	—
			B	31	0.503	0.500	0.577	0.184	—	—
			C	—	0.729	0.314	0.091	0.039	—	—

(Continued)

Table 15 (Concluded)

Test	Material	Water Depth ft	Pole	Time sec	Concentration, gm/ℓ 3 in.	6 in.	1 ft	1.5 ft	2 ft	3.5 ft
3H	Silt	4.0	A	52	2.217	—	1.103	—	0.494	0.098
			B	26	0.297	—	0.874	—	0.511	0.072
4H	Silt	4.0	A	16	1.351	—	—	—	0.411	0.029
			B	26	2.760	—	0.554	—	0.289	0.052
			C	43	2.051	—	0.840	—	0.780	0.096

Bottom deposition

67. Although the deposition of the silty material was too thin to measure, an indication of the depositional pattern was obtained through visual observations after sufficient time had elapsed to allow for complete settling. These observations are summarized in Table 16.

Table 16

Summary of Bottom Deposition Patterns from the Moving Hopper Tests

Test	Horizontal Dimensions ft x ft	Shape
2H	14 x 19	Elliptical
3H	15 x 19	Elliptical
4H	Covered virtually the entire test area, but not uniformly	

PART VI: SUMMARY AND CONCLUSIONS

Summary

68. An integral part of the process of managing disposal sites and assessing the environmental impact of dredged material disposal operations is the ability to accurately predict the fate of the disposed material immediately after disposal. Numerical models for such predictions have been developed. These models compute the movement of the disposal material during its descent through the water column, its collapse at a neutrally buoyant level or on the seafloor, and finally the passive transport-diffusion of material remaining in the water column.

69. Although numerical models have been developed for predicting the short-term fate of dredged material disposal in open water, a common deficiency of those models is the lack of adequate field and/or laboratory data sets for model verification. Under the Dredging Research Program Technical Area 1 "Analysis of Dredged Material Placed in Open Water," both field and laboratory data on placement processes have been collected. This study has focused upon conducting scaled laboratory disposal tests for the purpose of providing guidance on model modifications and for providing data sets for model verification. As part of the study an investigation of scaling laws was conducted by Soldate, Pagenkopf, and Morton (1988).

70. The laboratory disposal tests were made in a deep basin containing a test section of dimensions 41 ft by 32 ft and a maximum testing depth of 8 ft. Tests with both a 1:50-scale split-hull barge and a 1:50-scale multi-hopper disposal vessel for a range of material types was conducted. Both stationary and moving disposals were made. Data collection primarily depended upon videotaping, bottom profiling, and collecting discrete water samples. The videos provided useful qualitative information for guiding model modifications as well as quantitative information on descent and surge speeds. The discrete water samples provided a spatial distribution of suspended sediment concentrations.

Conclusions

71. The investigation of scaling considerations concluded that as long

as the model disposal operation created turbulent flow conditions the bulk behavior of the descent and bottom surge phases could be approximately scaled to the prototype. This is because the convective descent drag coefficient is relatively independent of the Reynolds number for turbulent flow conditions and because the processes being modeled are largely gravity driven. Comparing results on descent and surge speeds scaled to the prototype with field data collected by Bokuniewicz et al. (1978) tends to substantiate this conclusion. While suspended sediment concentrations should not be entirely representative of those in the prototype since complete similitude of the particle settling velocity is not achieved, it appears that concentrations collected in the model bottom surge head may be representative of those in the prototype since the turbulence in the surge head tends to keep the material in suspension.

72. Several data sets consisting of descent and bottom surge speeds, bottom depositional patterns, and spatial representation of the suspended sediment in or near the bottom surge have been collected. These data will be used at both the physical model scale and prototype scale for numerical model verification.

73. One of the most valuable uses of the physical model disposal facility has been in allowing the dynamic placement processes of descent and bottom surge to be visually observed. As a result of these observations it has been concluded that the existing numerical disposal models do not adequately represent actual disposal operations. There are no instantaneous disposals of material that are uniformly distributed within the disposal vessel. In addition, moving disposal vessels tend to create upper water column plumes as a result of a shearing effect which can leave extremely fine material in the upper water column.

74. Within the framework of the existing numerical disposal model, modifications to allow for the observed behavior of real disposal operations are being planned. These modifications are concerned with representing the disposal operation as a sequence of small clouds convecting downward as a result of their negative buoyancy. A stripping of fines from each of these clouds will result in the creation of small Gaussian clouds that are passively transported and diffused by the ambient environment. It is concluded that with such modifications not only upper water column suspended sediment concentrations but also bottom deposition can be more accurately modeled in real disposals of dredged material. Details concerning the modified model and

results from application to the data presented in this report, as well as field data, will be published in a separate report.

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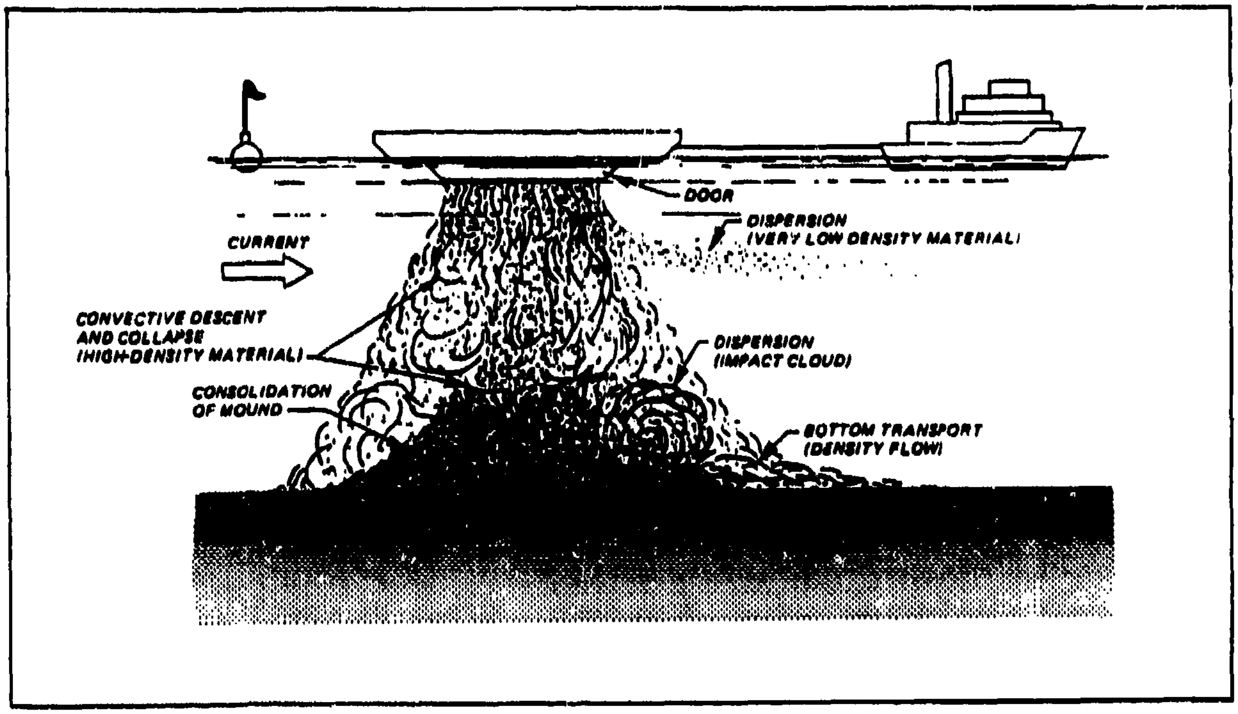


Figure 1. Dredged material placement processes (from Moritz and Randall (1992))

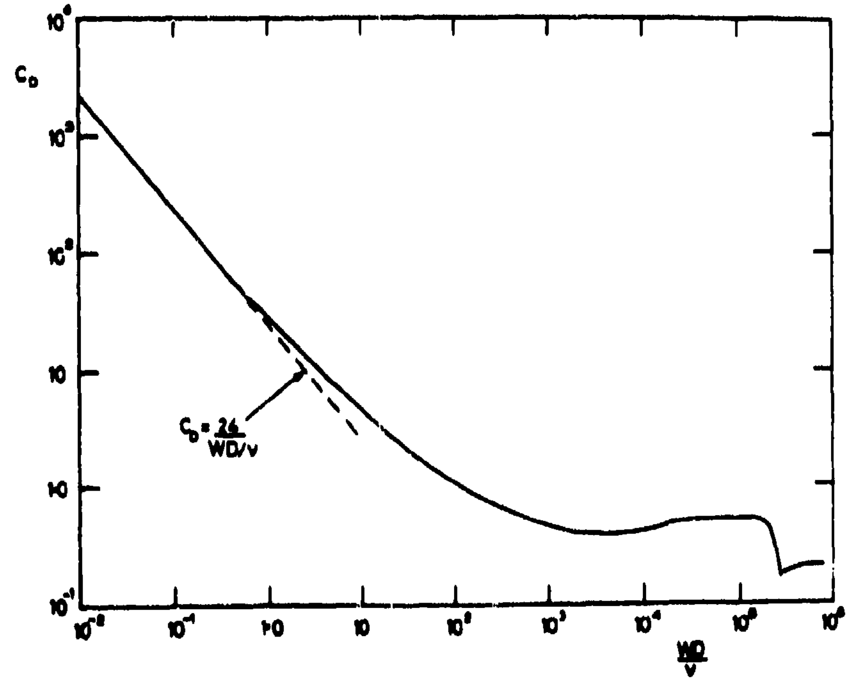


Figure 2. Dependence of drag coefficient, C_D, on Reynolds number

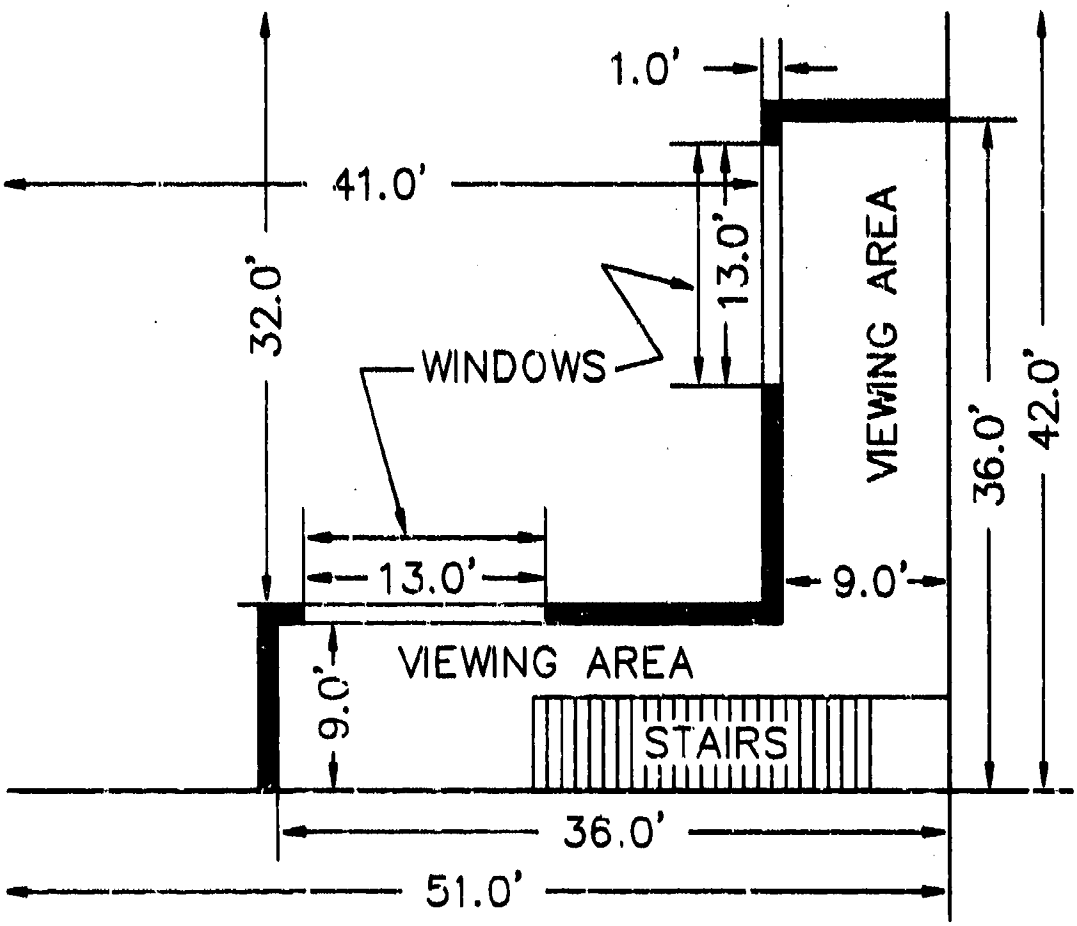


Figure 3. Plan view of physical test facility

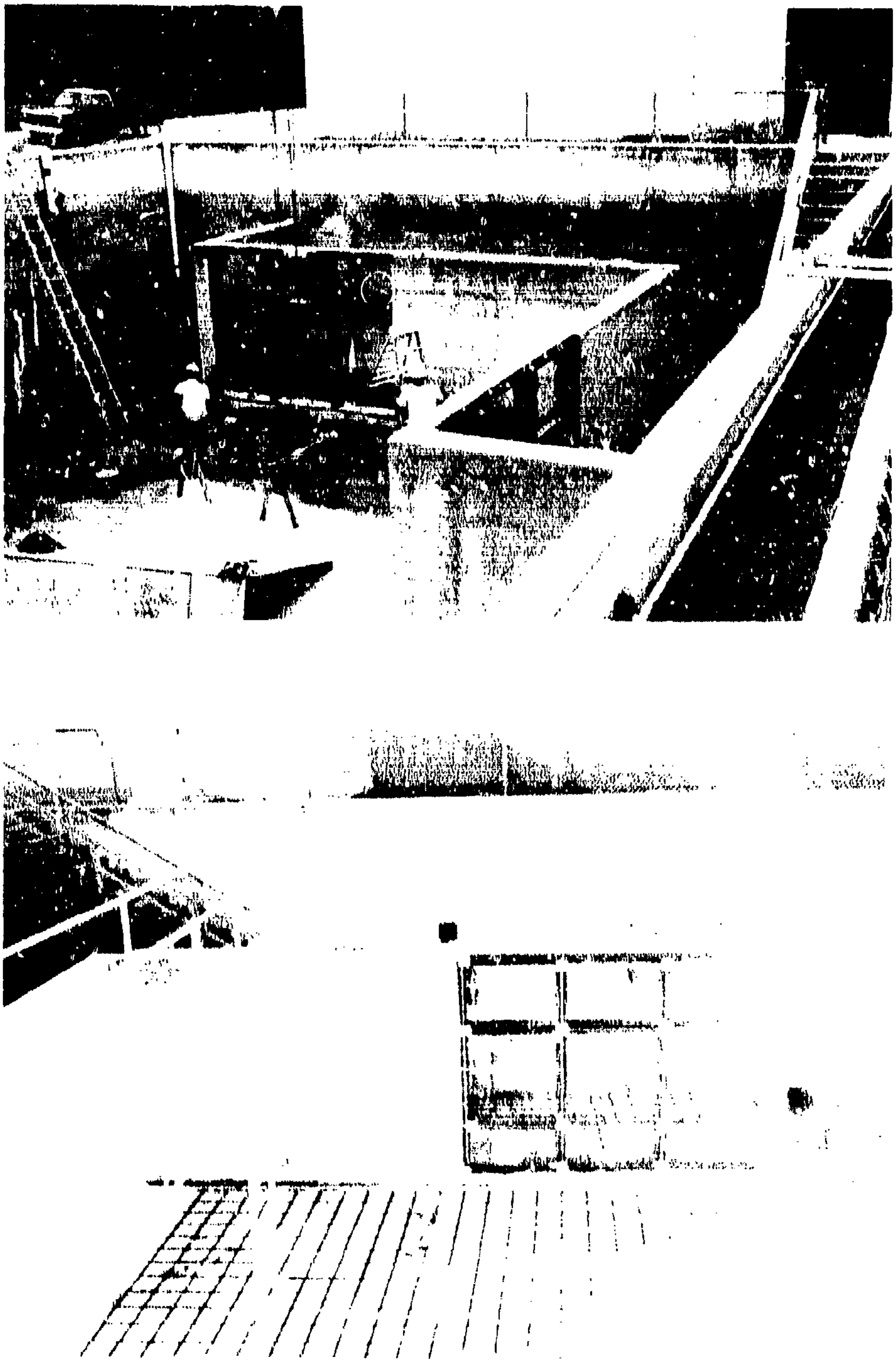


Figure 4. Physical test facility for dredged material placement tests

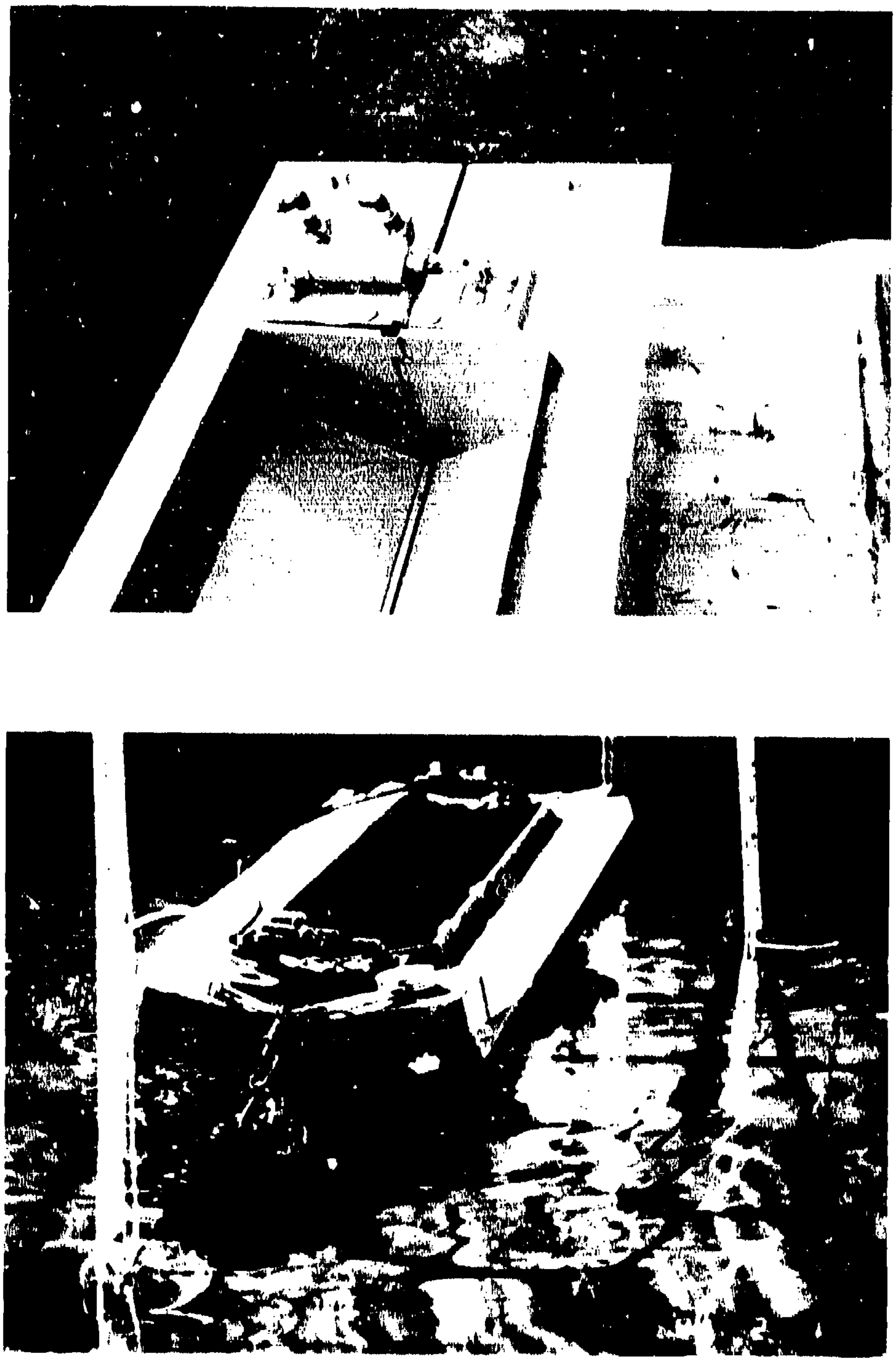


Figure 5. Model split-hull barge

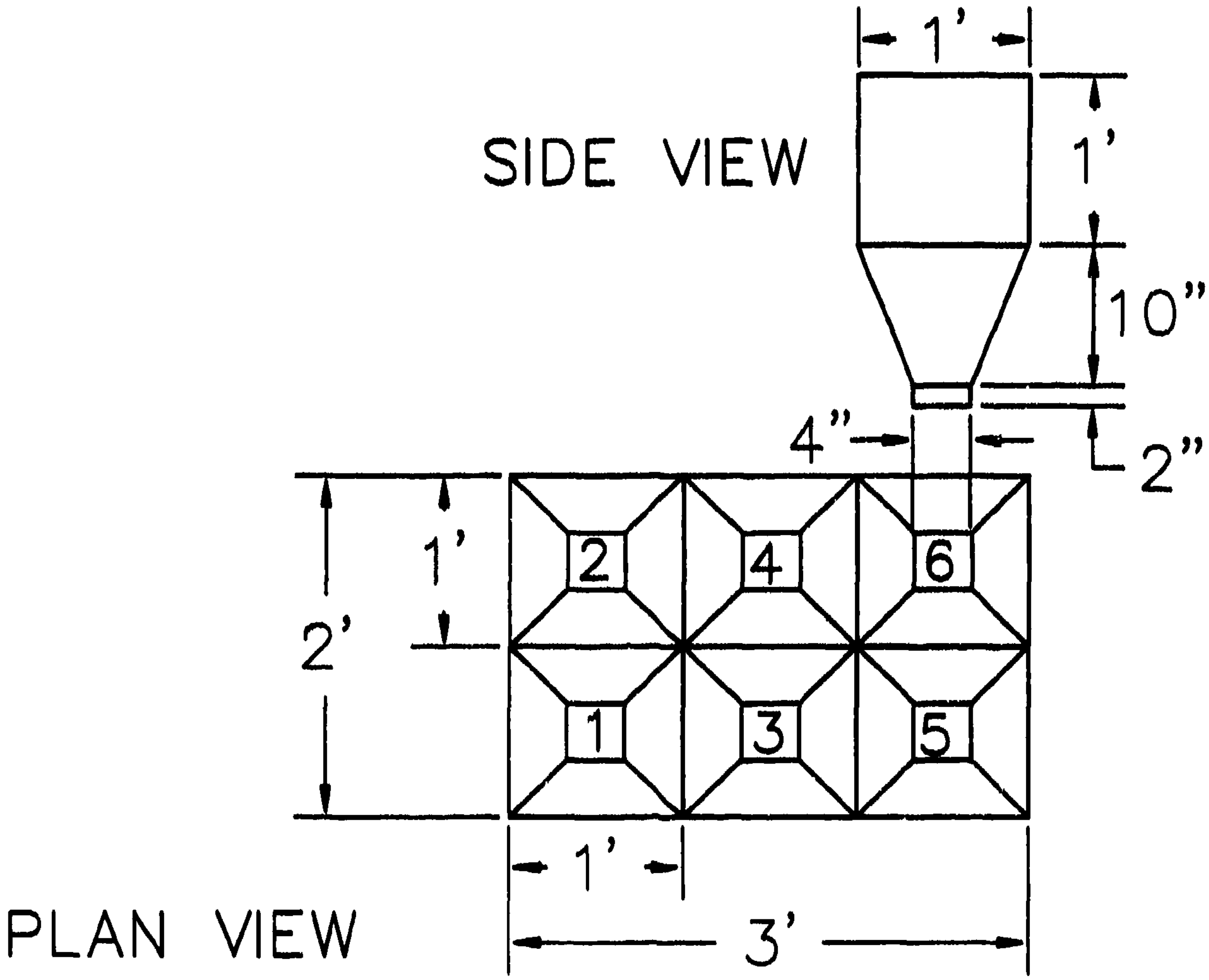


Figure 6. Plan view of the model multihopper disposal vessel

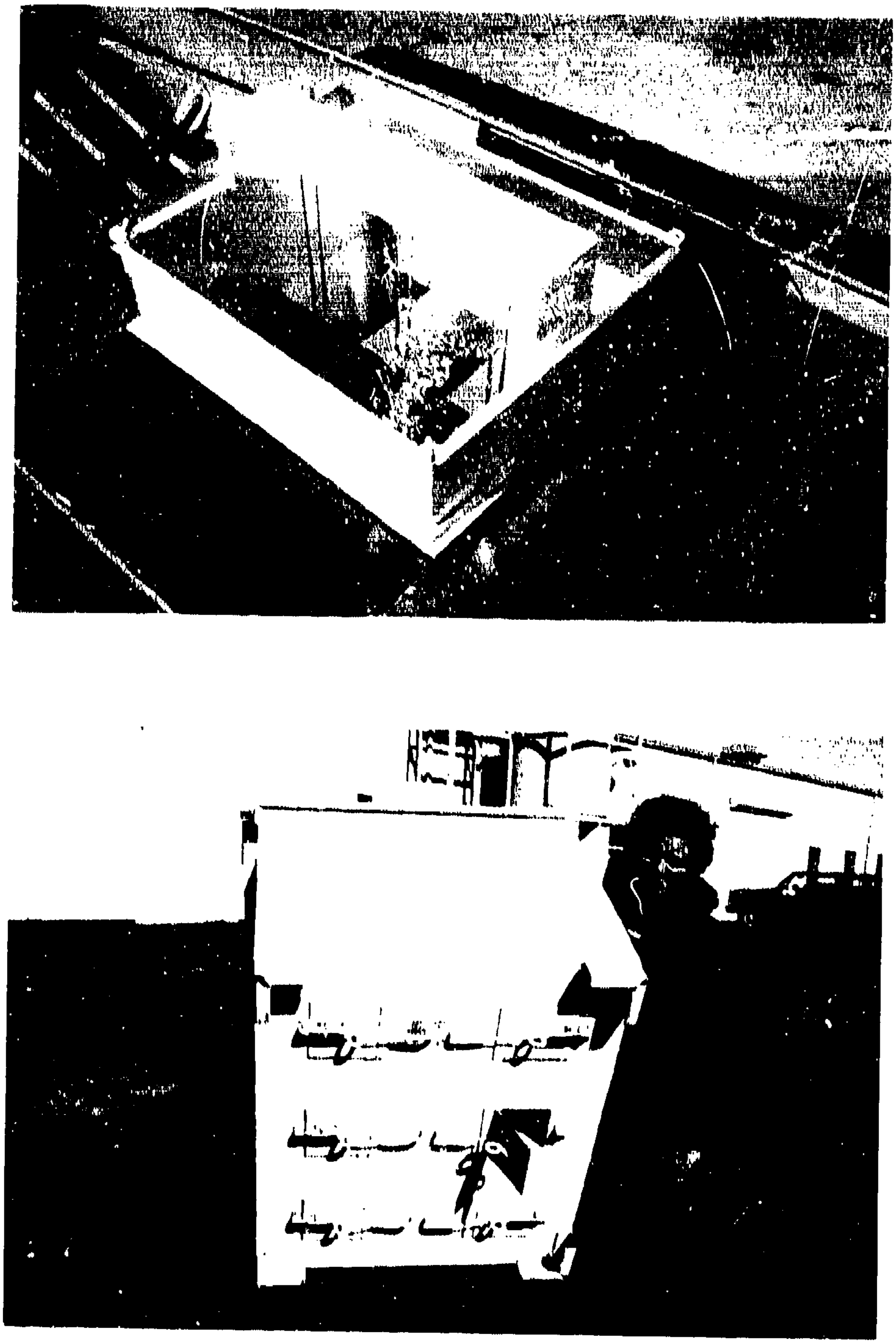
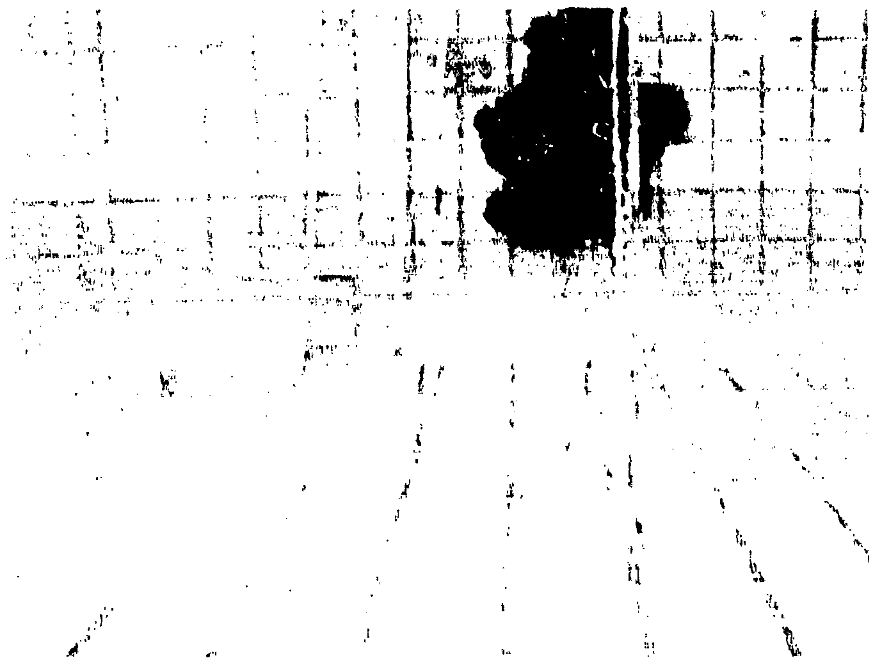


Figure 7. Model hopper disposal vessel

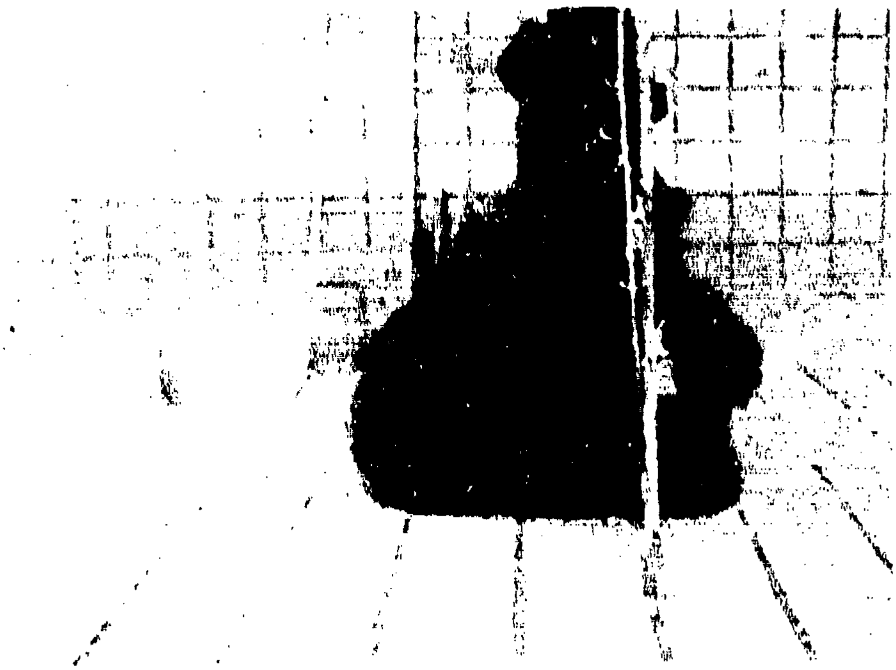
Figure 8. Water sampler pole with bottles



a. Time - 6 sec

b. Time - 11 sec

Figure 9. Still photos from Test 5C viewed from the end (Sheet 1 of 3)

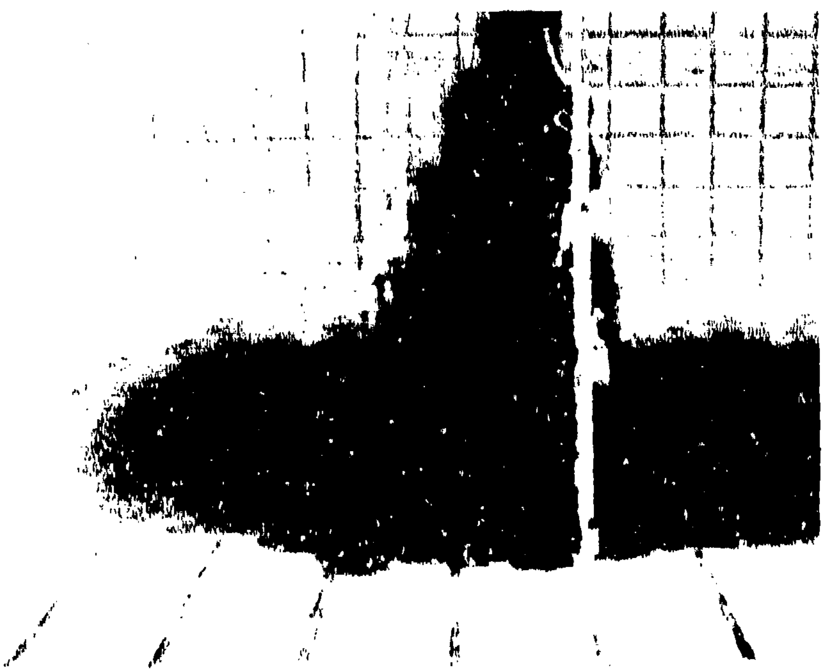


c. Time - 13 sec

d. Time - 15 sec

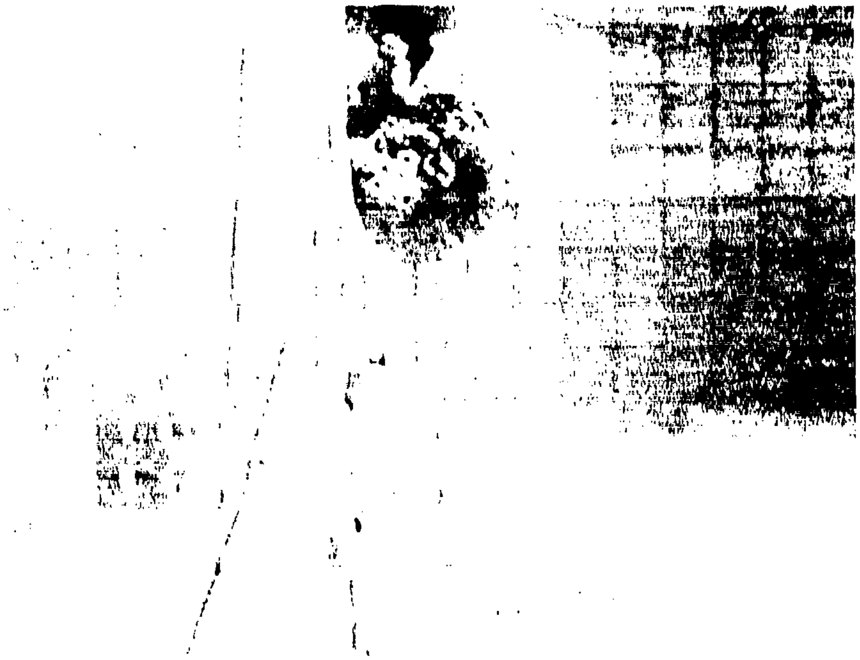
Figure 9. (Sheet 2 of 3)

e. Time - 17 sec



f. Time - 18 sec

Figure 9. (Sheet 3 of 3)



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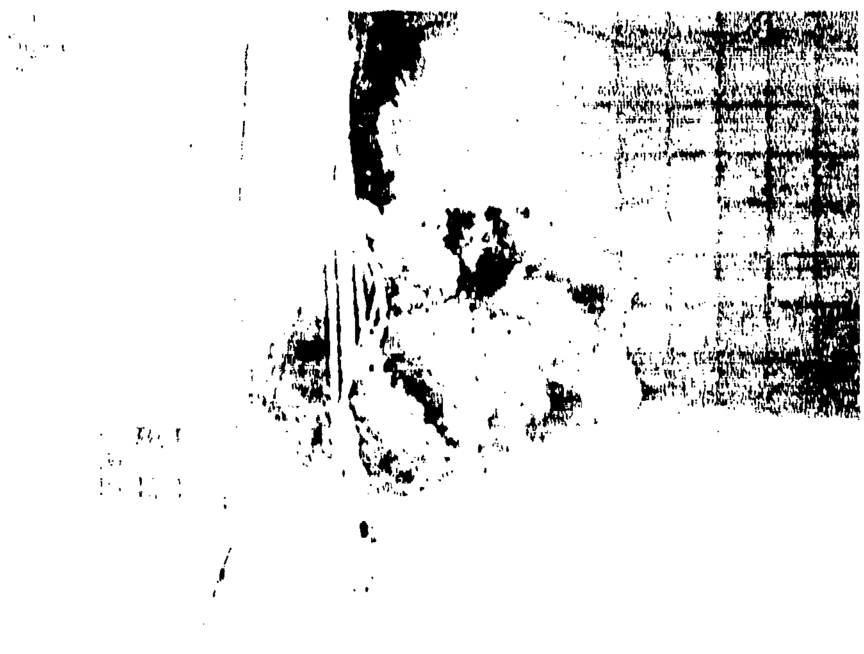
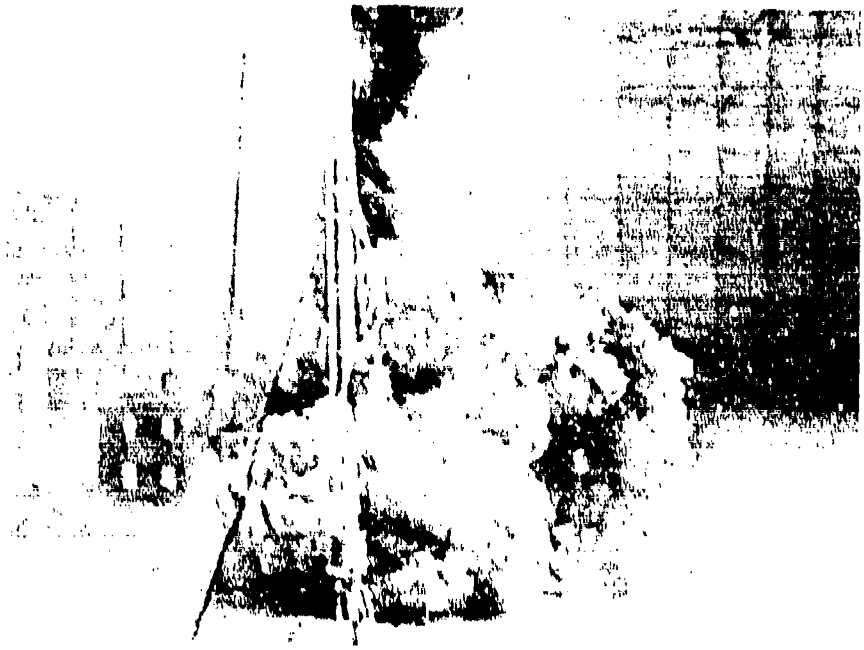


b. Time = 7 sec

Figure 10. Still photos from Test 20 viewed from the end (Sheet 1 of 4)



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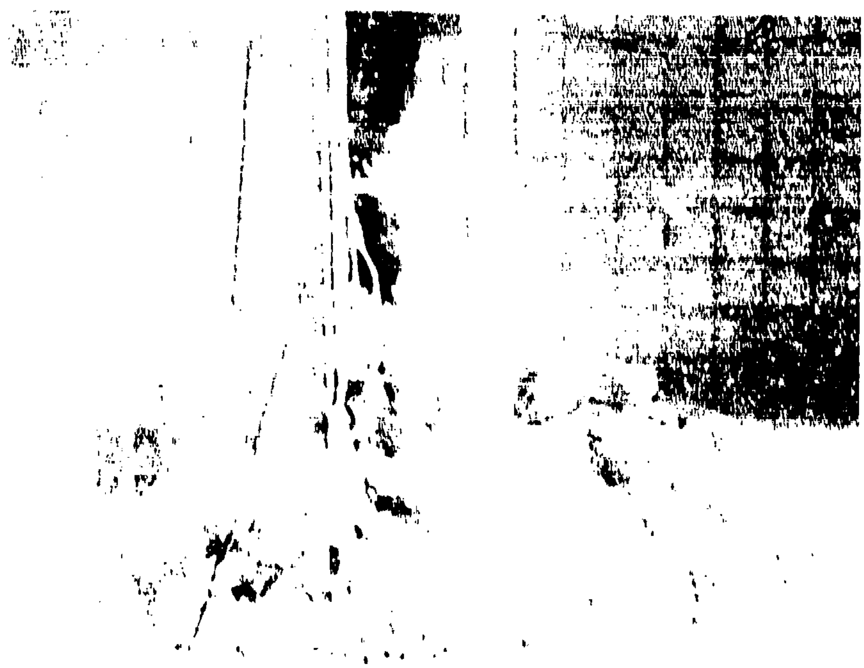
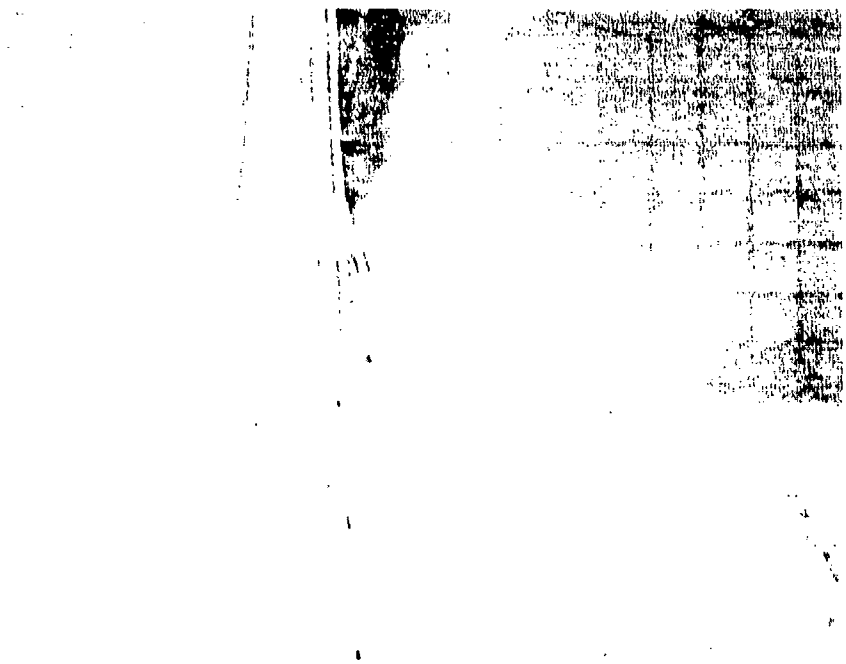


d. Time = 12 sec

Figure 10. (Sheet 2 of 4)

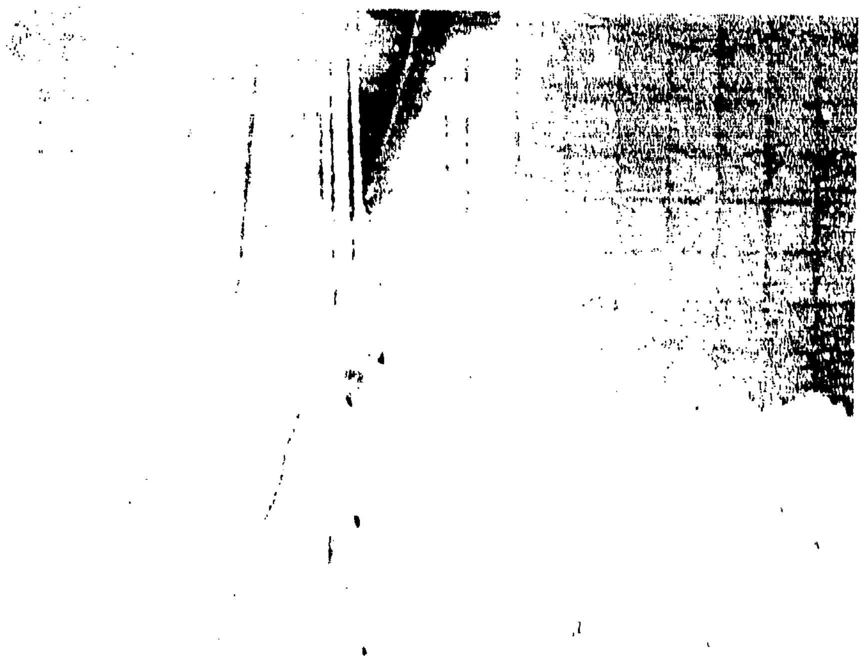
e. Time ~ 14 sec



f. Time ~ 15 sec

Figure 10. (Sheet 3 of 4)

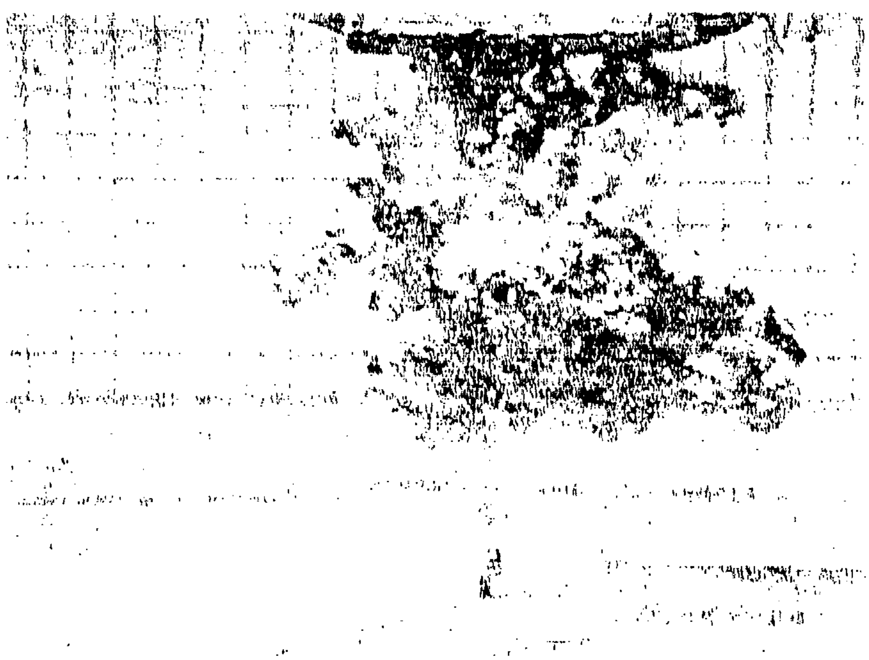
g. Time - 23 sec



h. Time - 25 sec

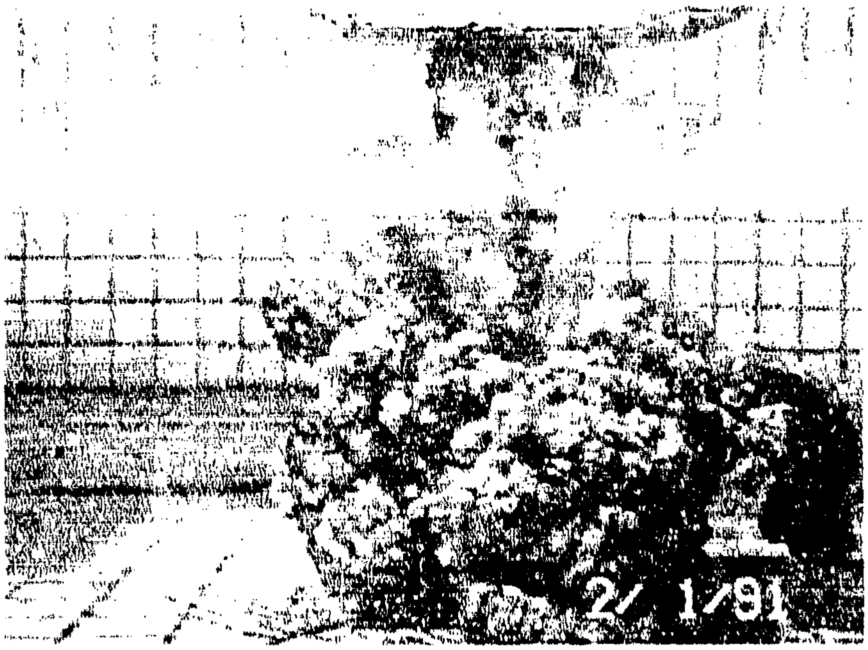
Figure 10. (Sheet 4 of 4)

a. Time - 1 sec

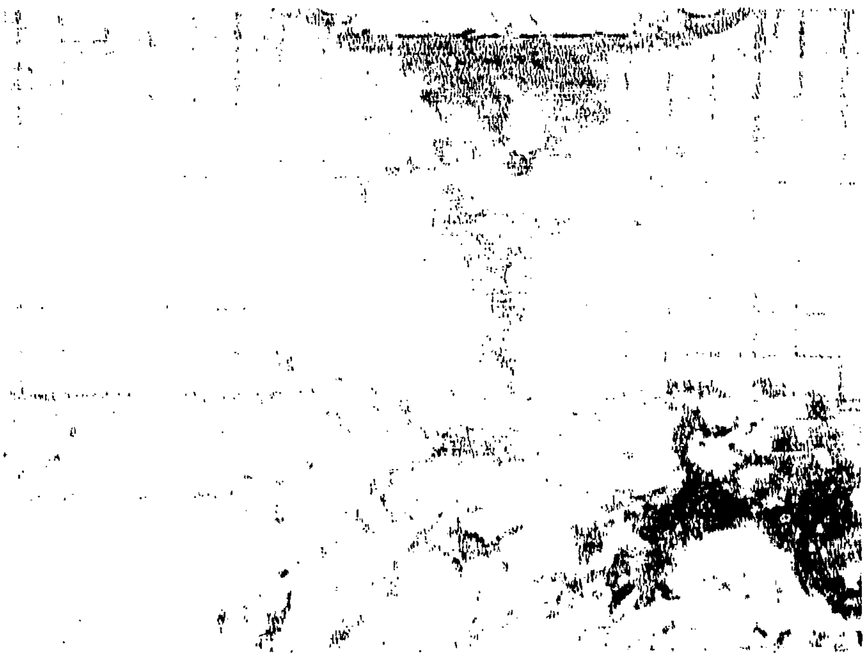


b. Time - 7 sec

Figure 11. Still photos from Test 20 viewed from the side (Sheet 1 of 3)

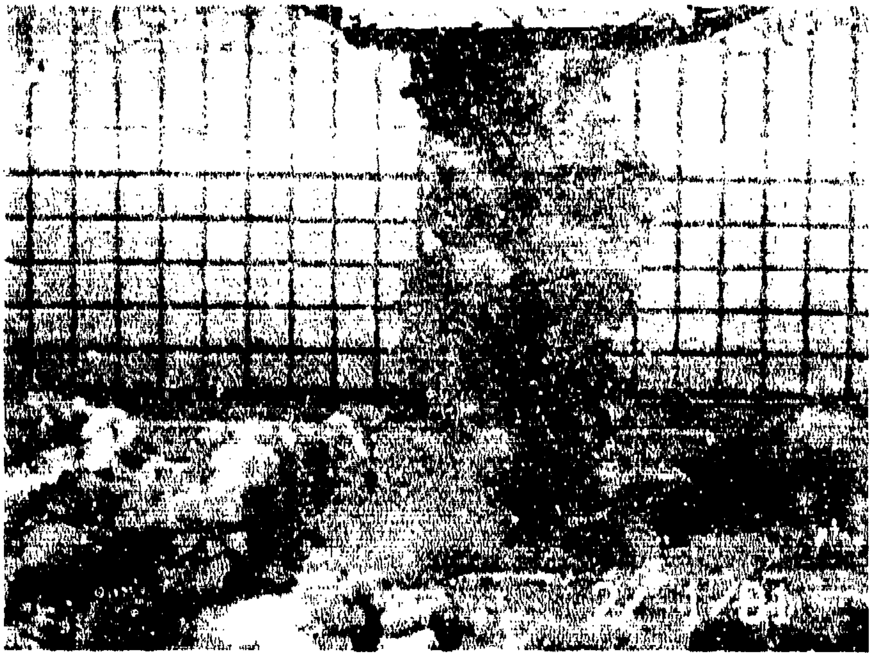


c. Time = 9 sec



d. Time = 12 sec

Figure 11. (Sheet 2 of 3)



e. Time = 15 sec

f. Time = 17 sec

Figure 11. (Sheet 3 of 3)

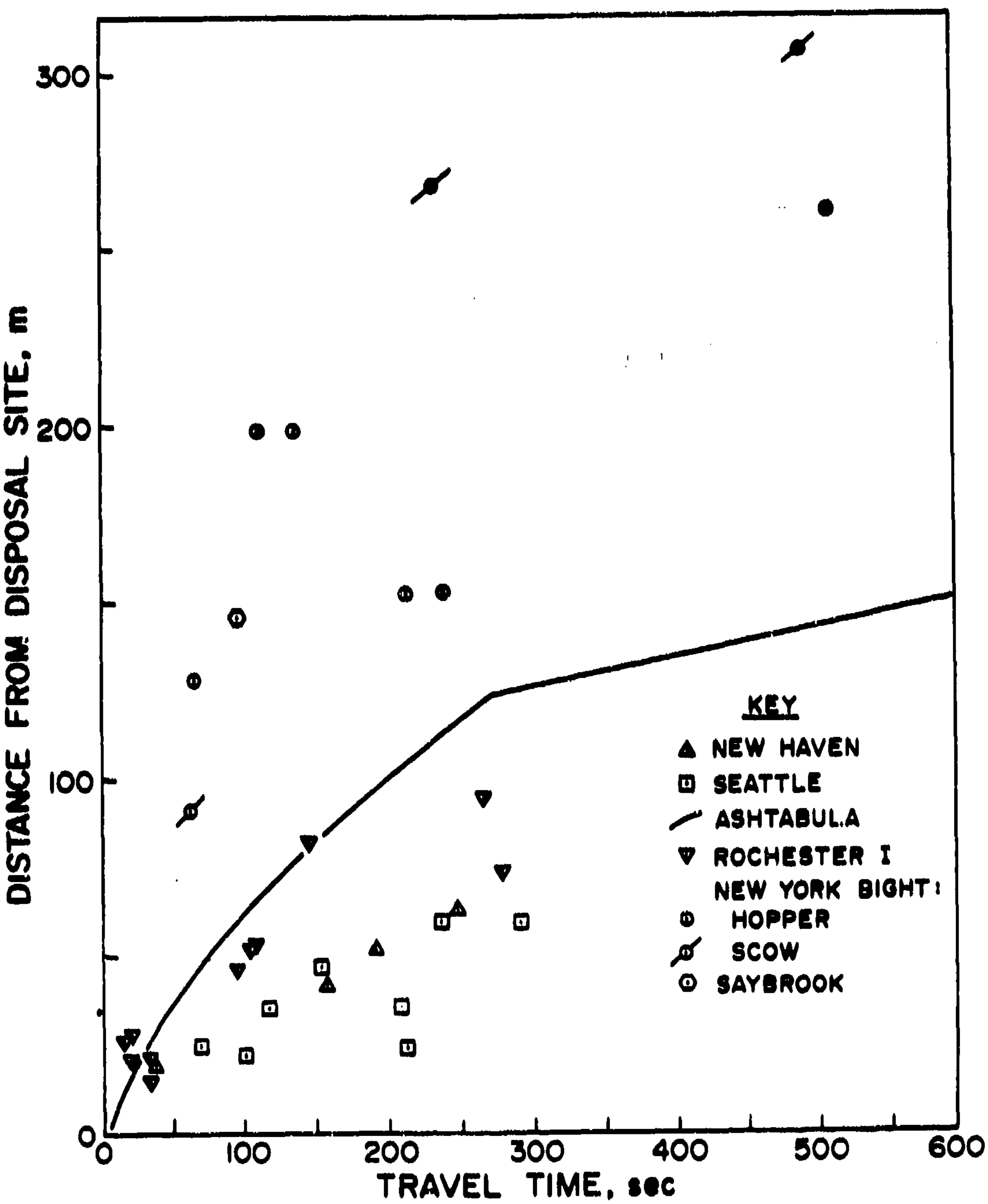


Figure 12. Travel-time diagram from field data from Bokuniewicz et al. (1978)

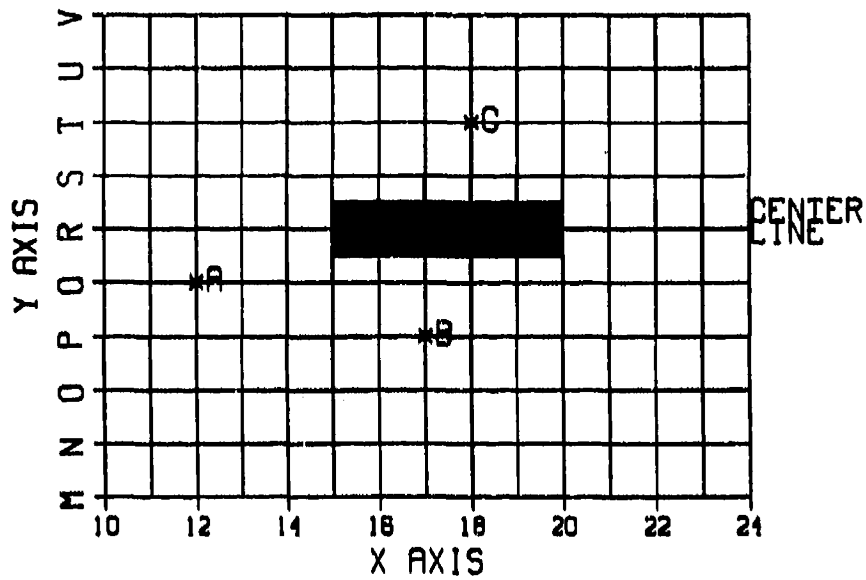


Figure 13. Location of water sampler poles for Test 1

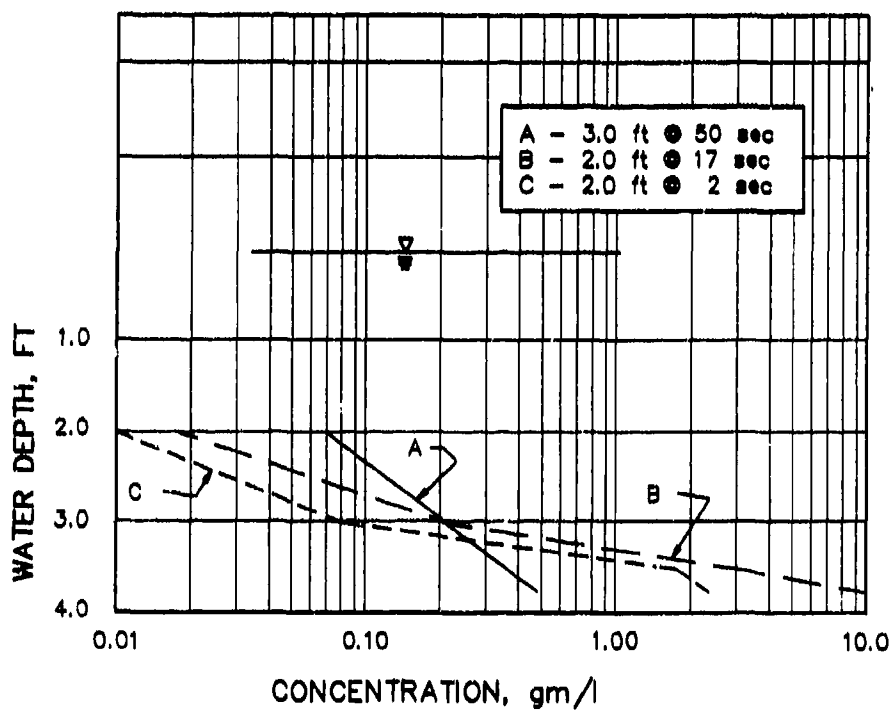


Figure 14. Suspended coal concentrations from Test 1

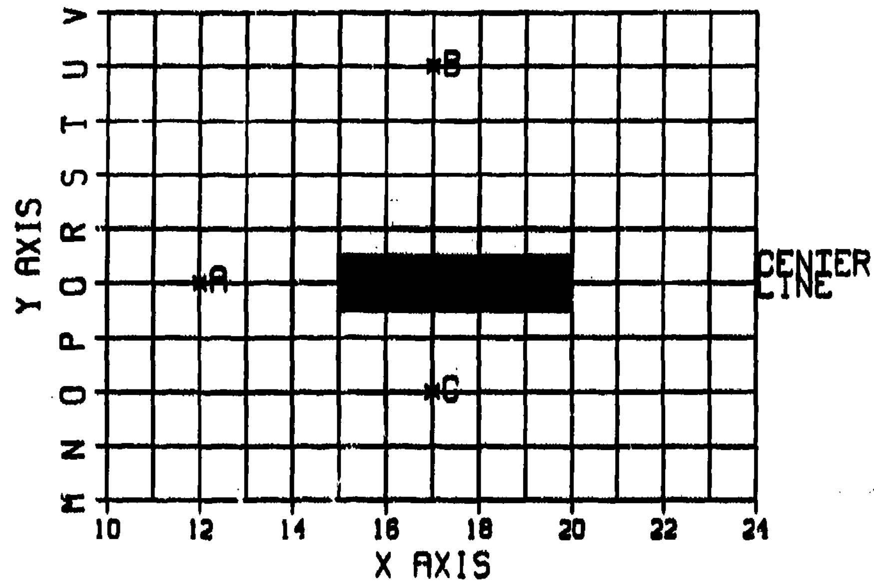


Figure 15. Location of water sampler poles for Test 2

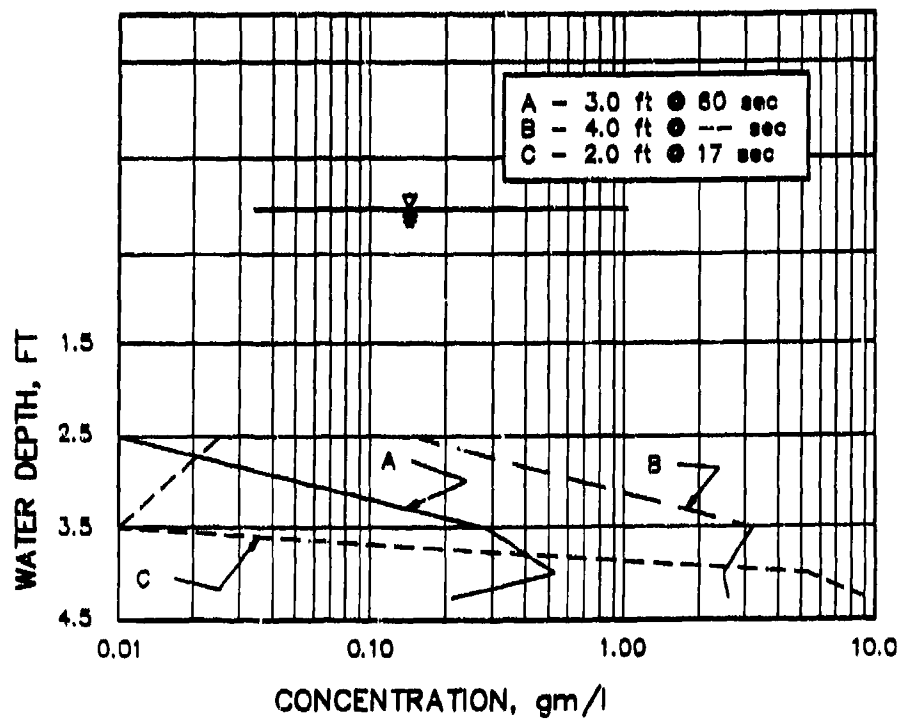


Figure 16. Suspended coal concentrations from Test 2

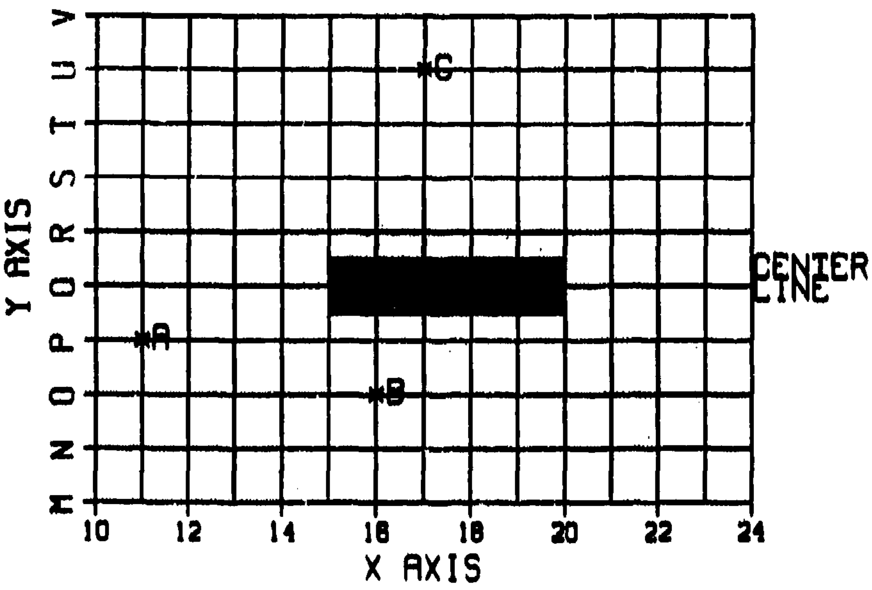


Figure 17. Location of water sampler poles for Test 3

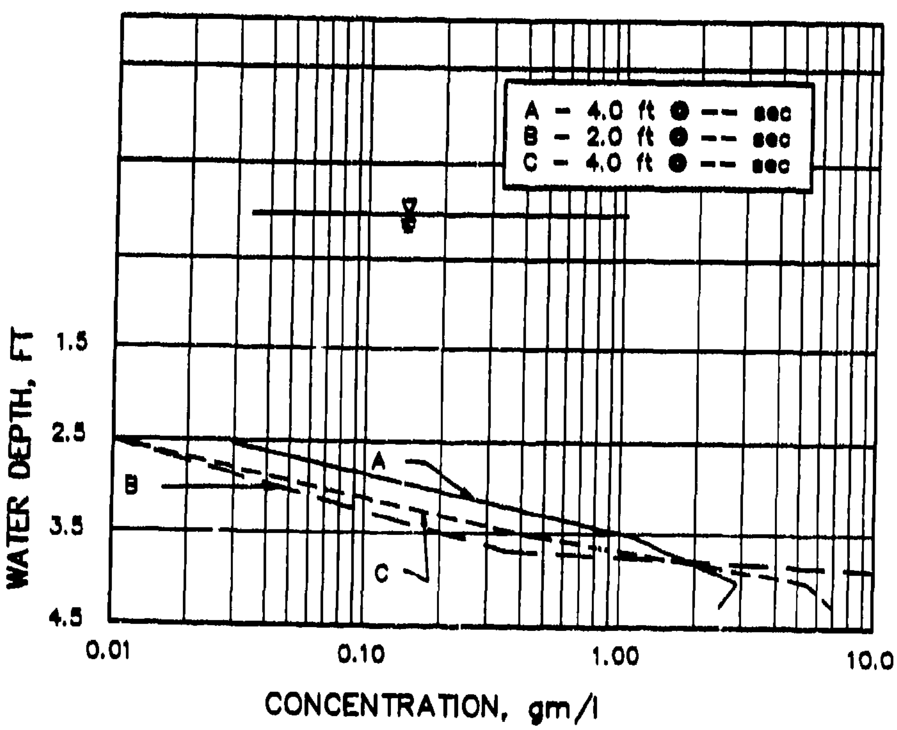


Figure 18. Suspended sand concentrations from Test 3

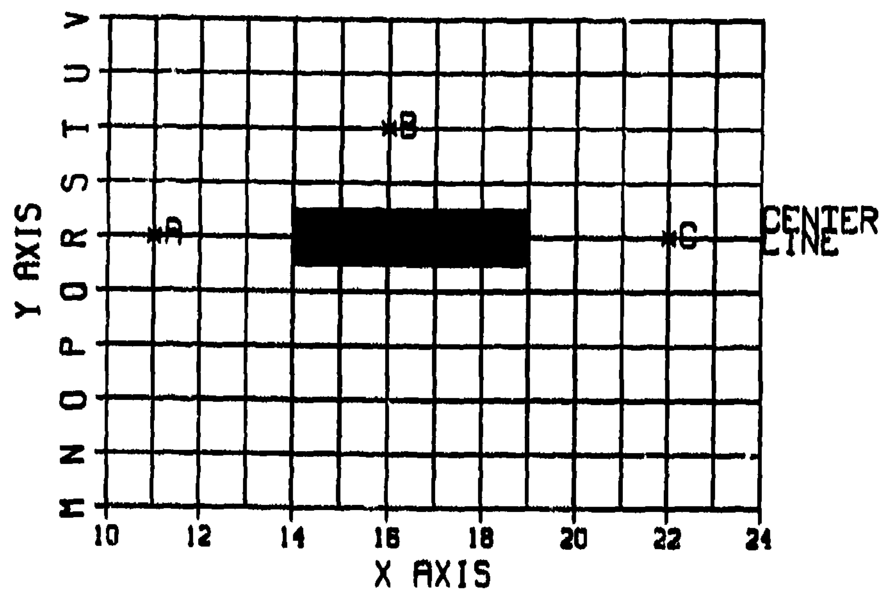


Figure 19. Location of water sampler poles for Test 5C

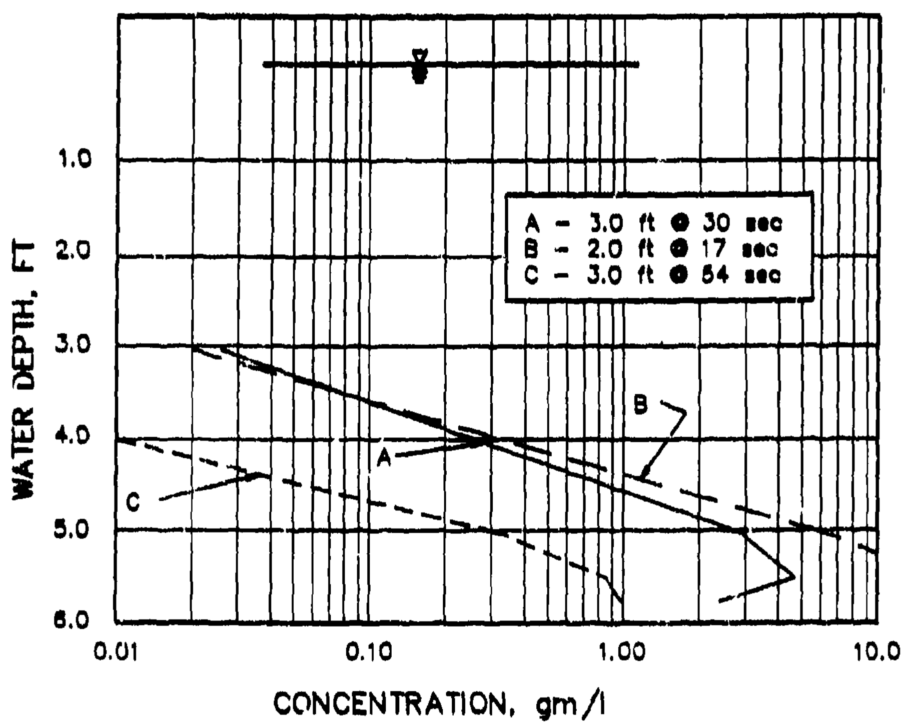


Figure 20. Suspended coal concentrations from Test 5C

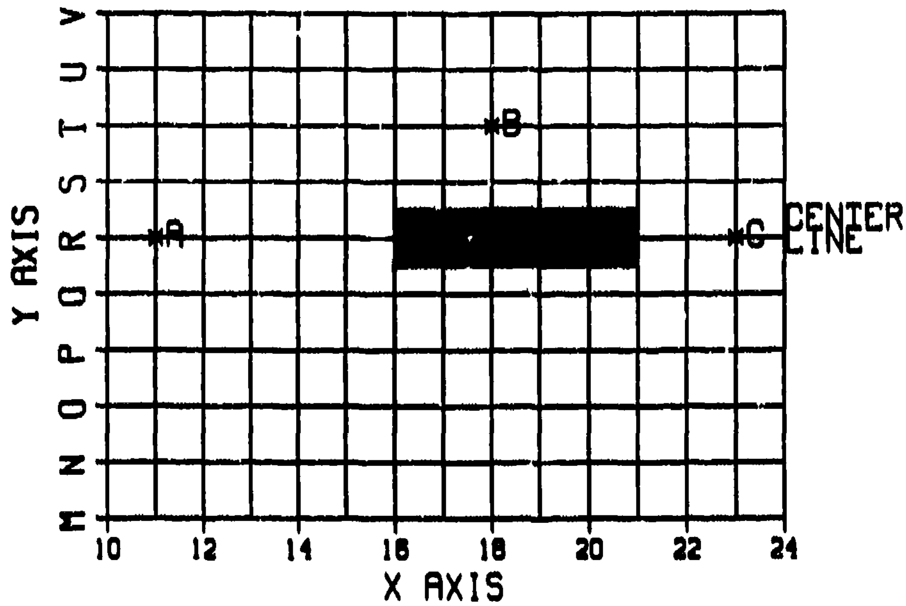


Figure 21. Location of water sampler poles for Test 20

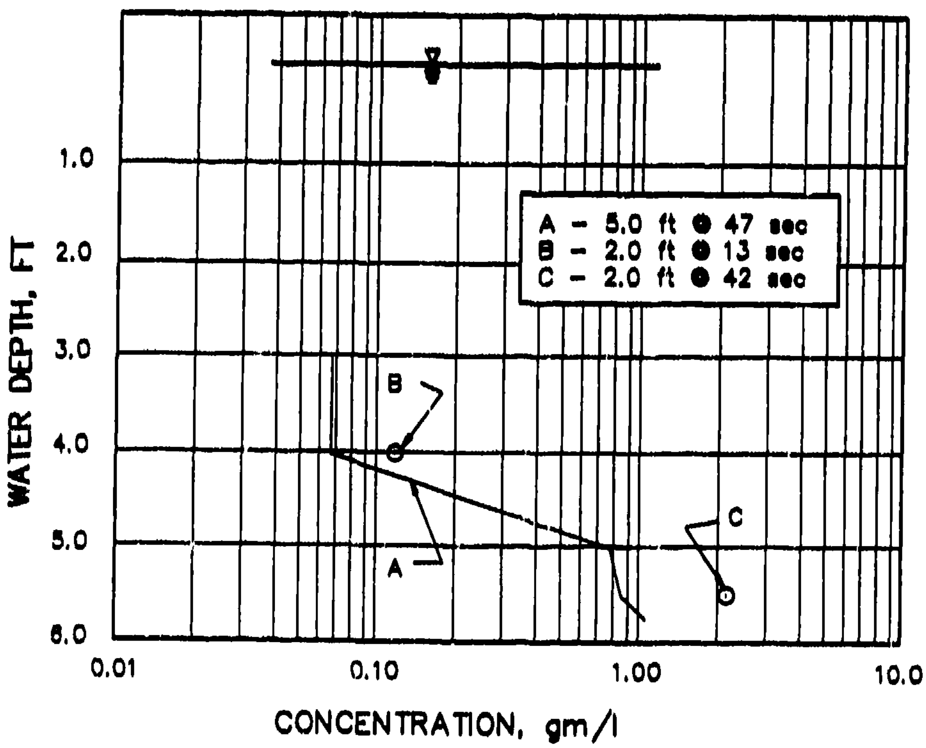


Figure 22. Suspended clay concentrations from Test 20

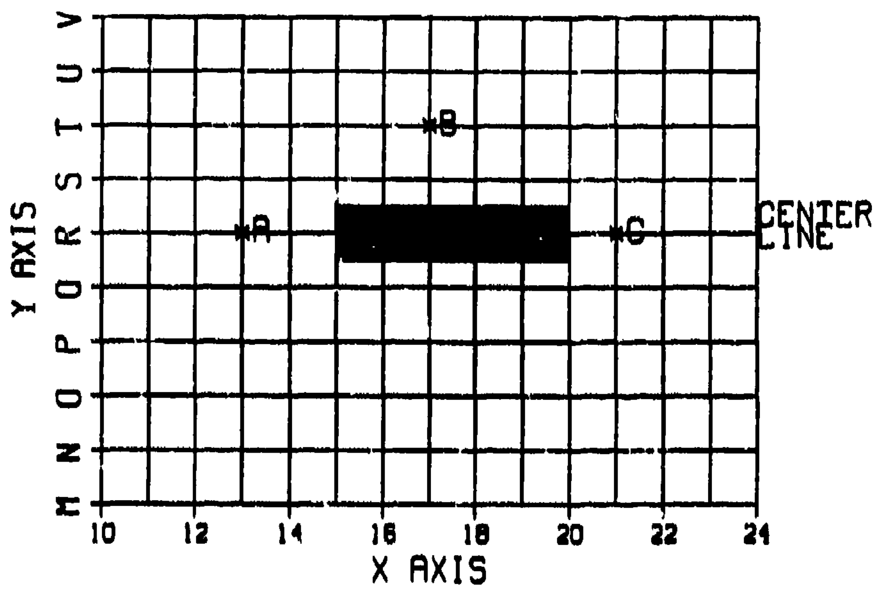


Figure 23. Location of water sampler poles for Test 22

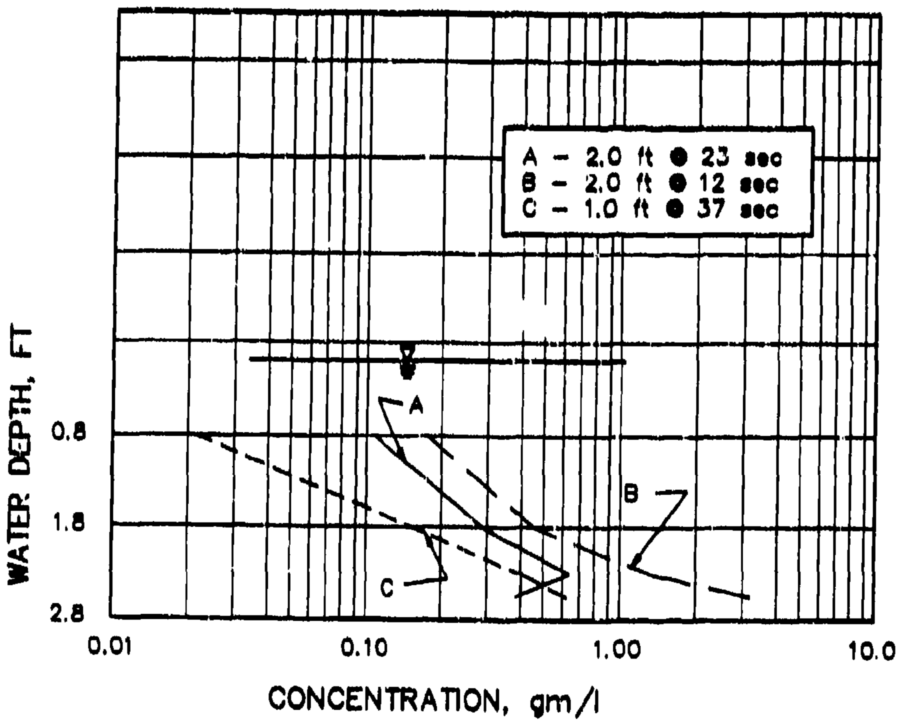


Figure 24. Suspended silt concentrations from Test 22

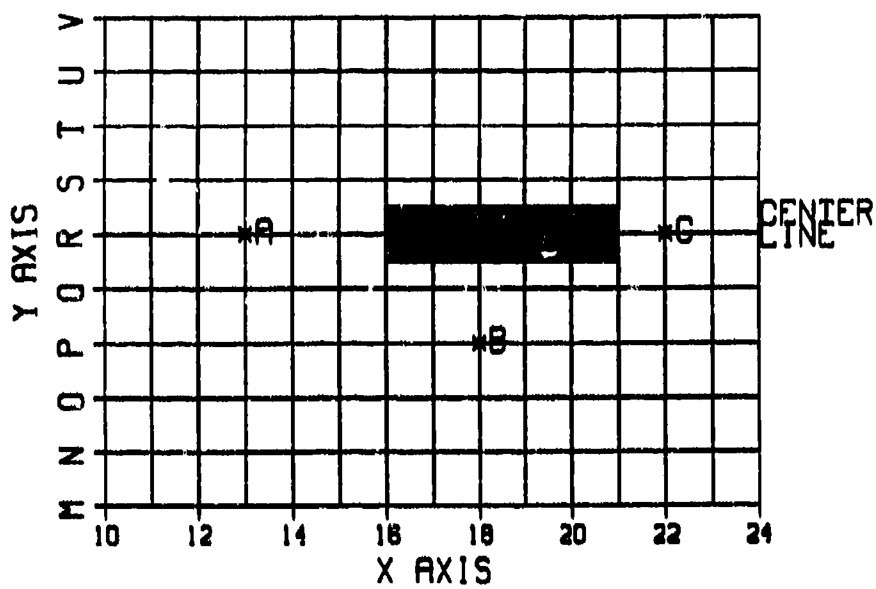


Figure 25. Location of water sampler poles for Test 24

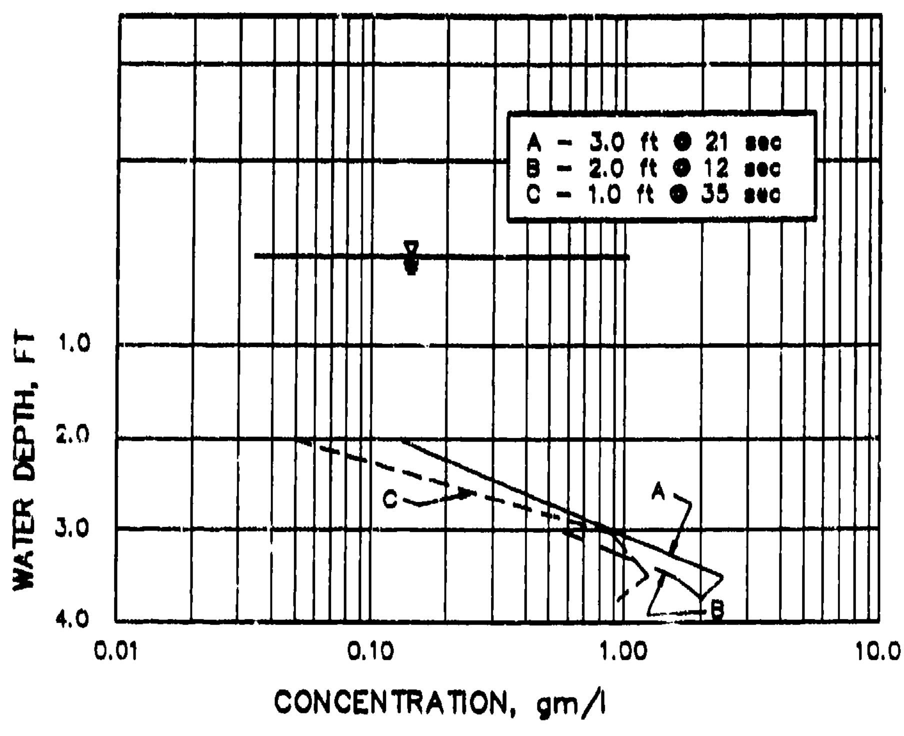


Figure 26. Suspended silt concentrations from Test 24

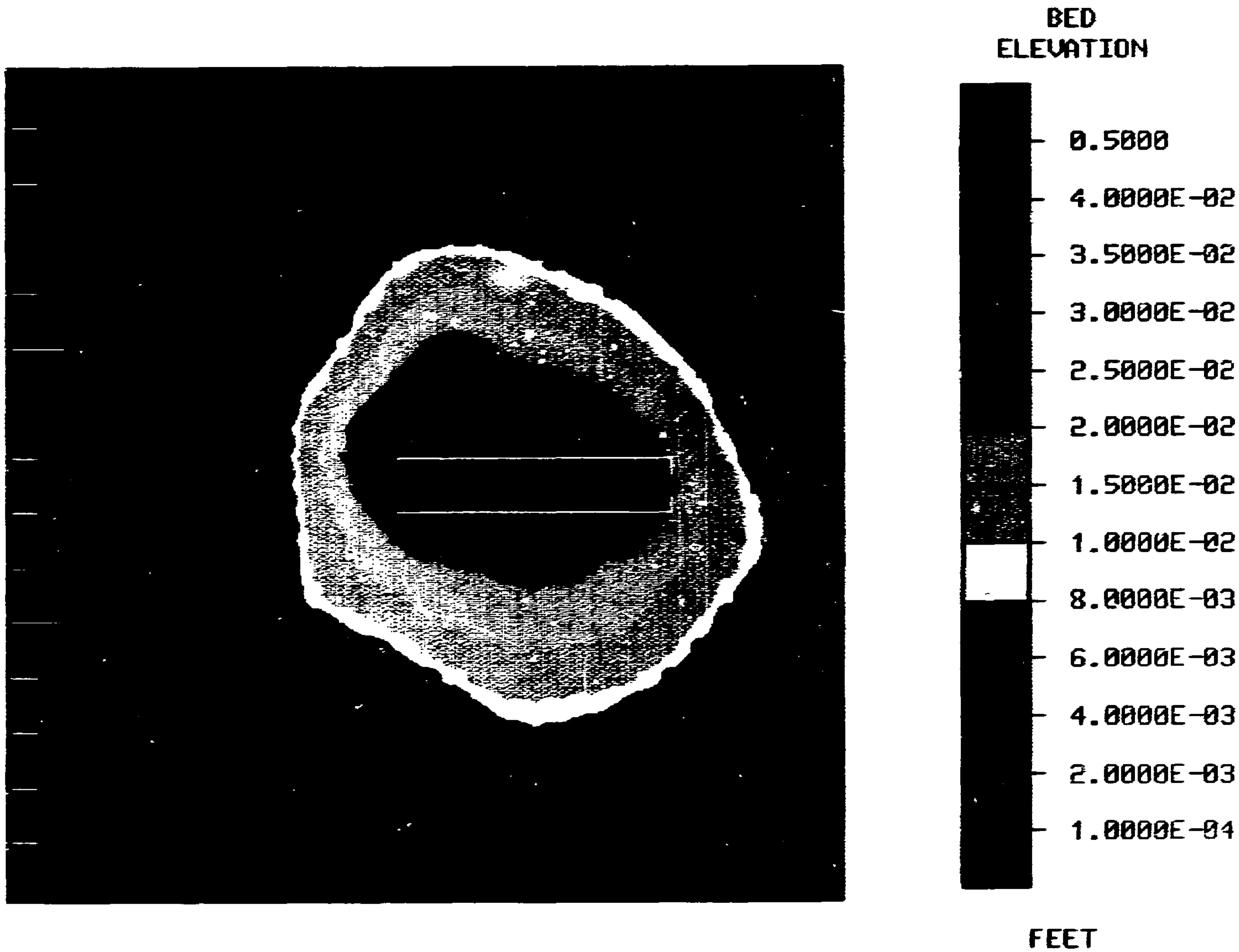


Figure 27. Bottom deposition from Test 1

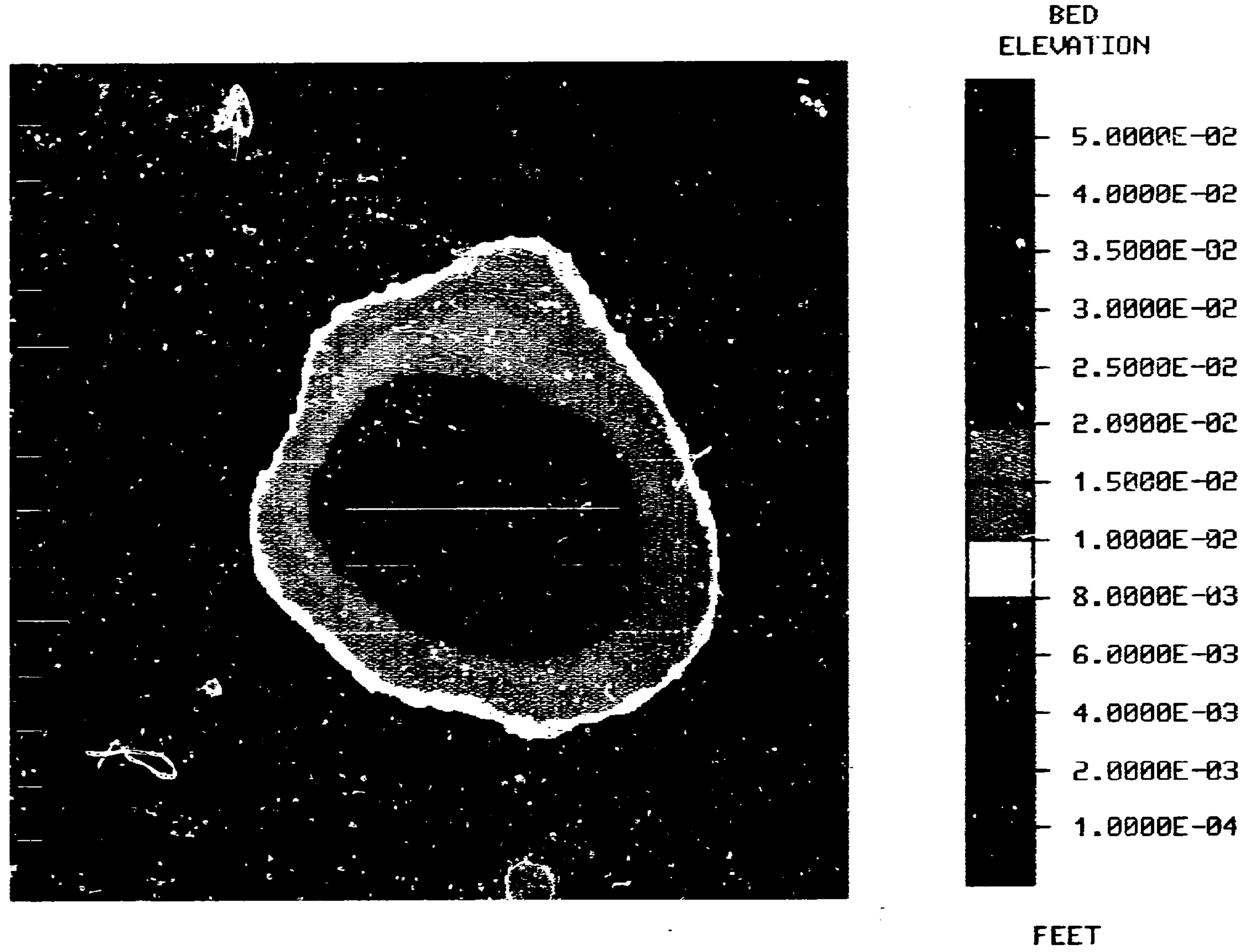


Figure 28. Bottom deposition from Test 2

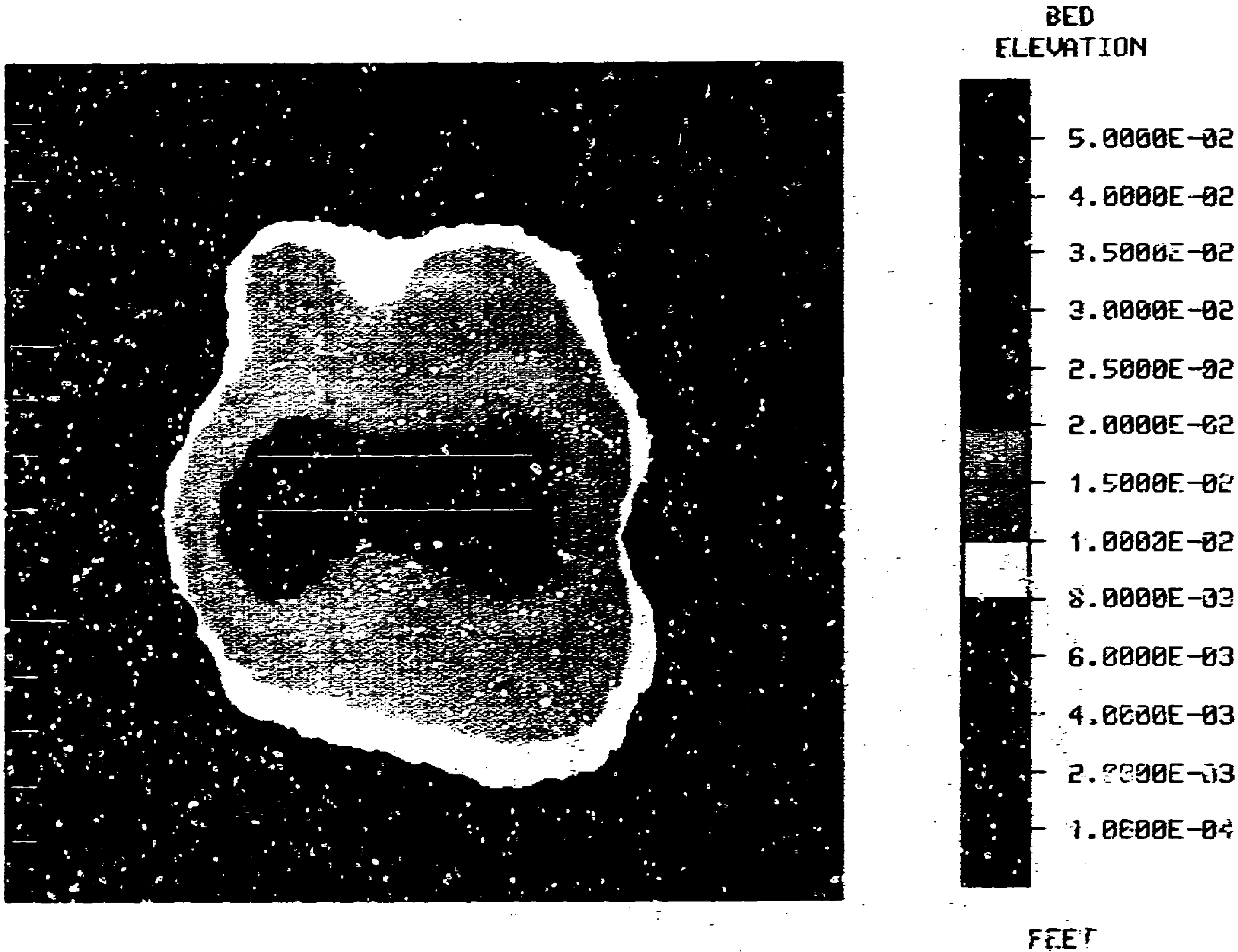


Figure 29. Bottom deposition from Test 5C

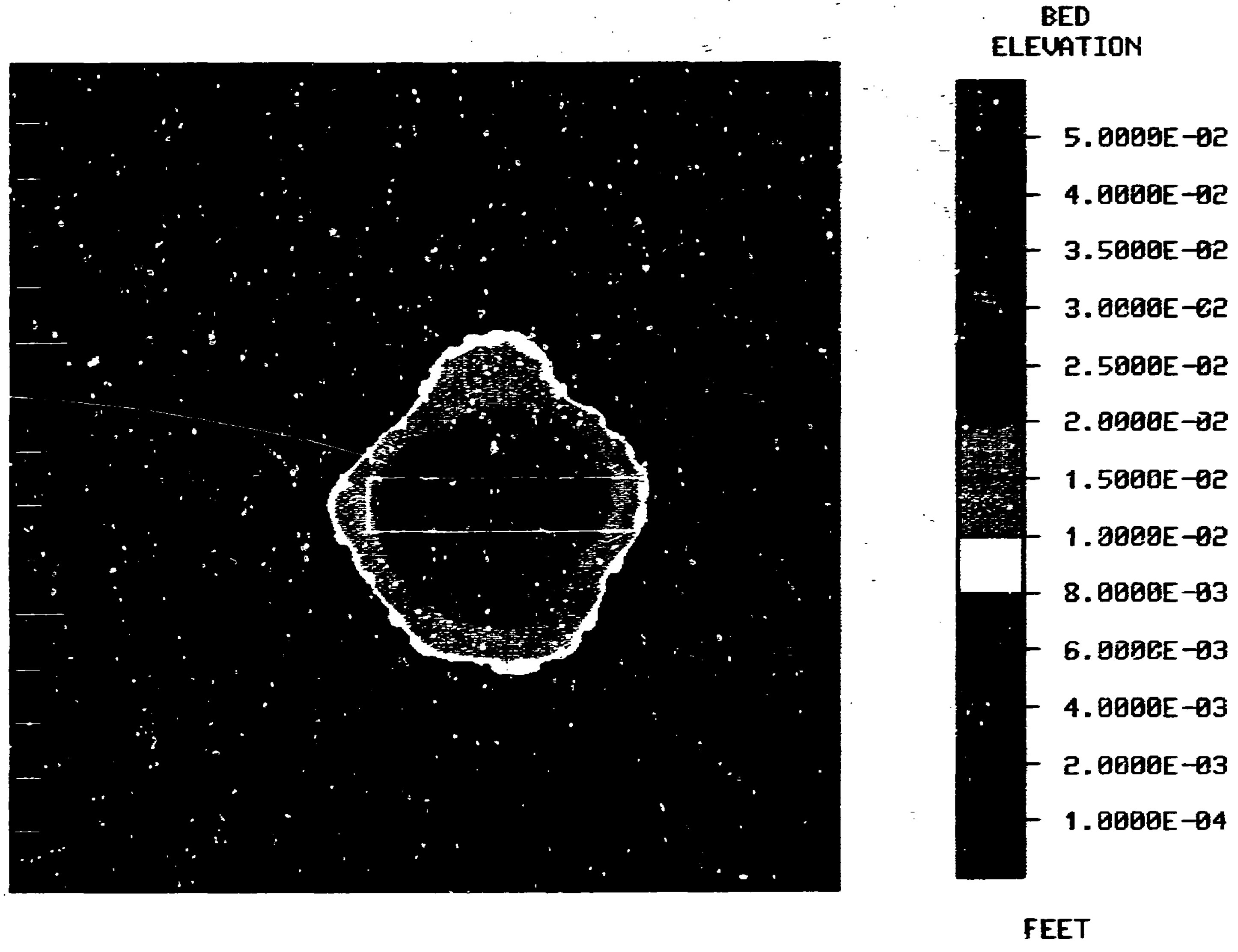
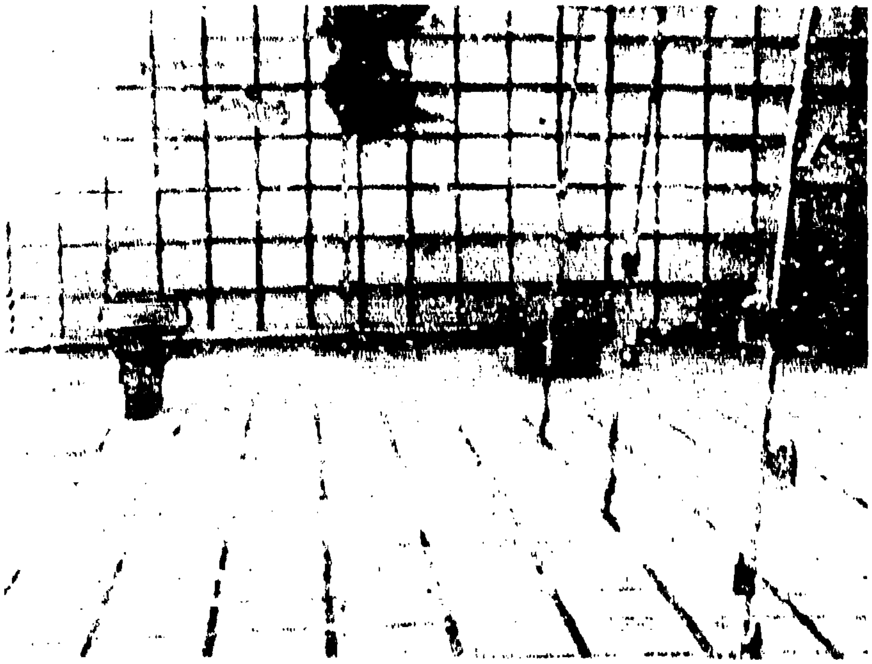


Figure 30. Bottom deposition from Test 10

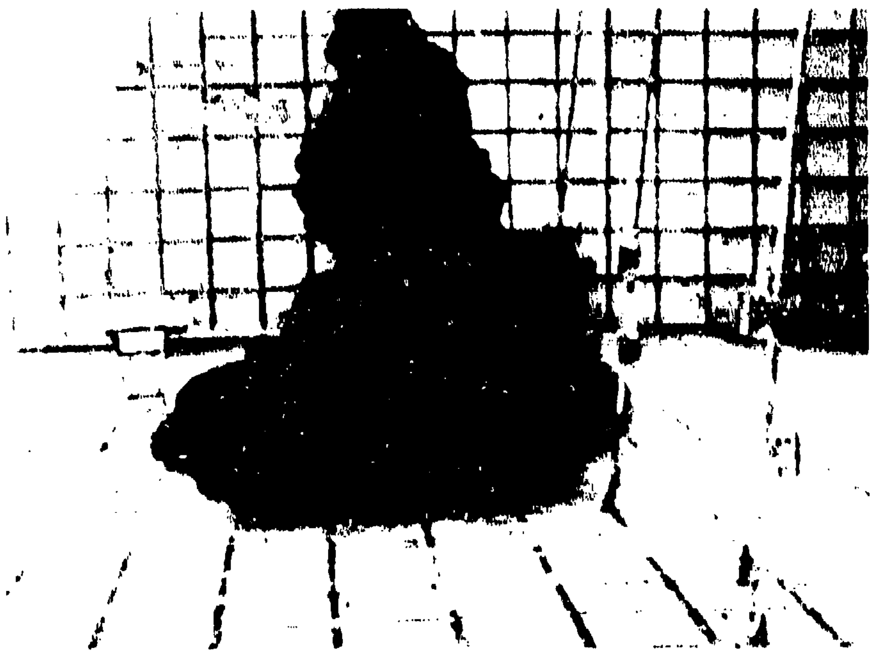


a. Time = 3 sec

b. Time = 12 sec

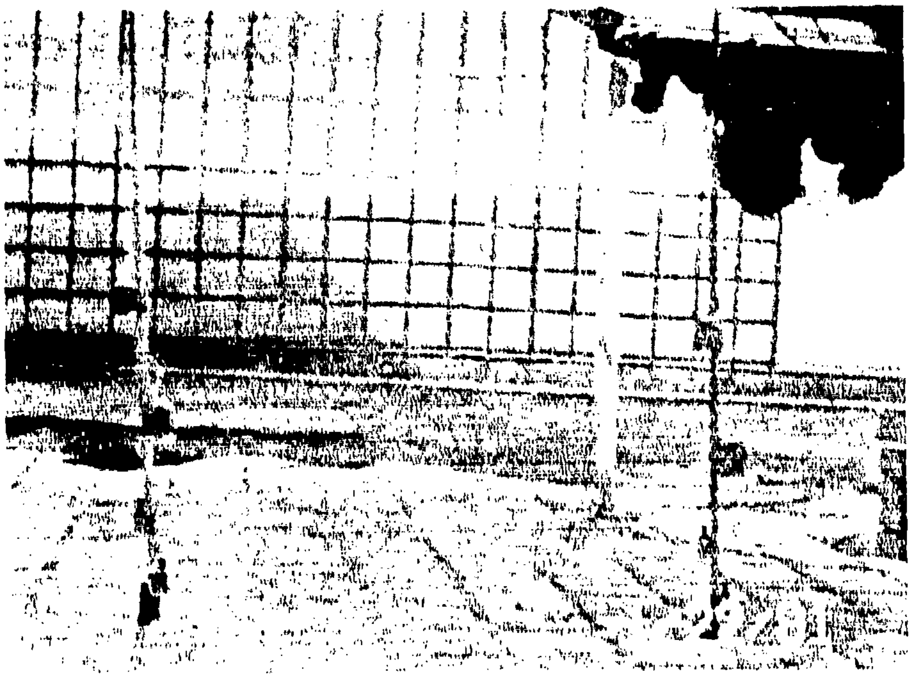
Figure 31. Still photos from Test 4C viewed from the end (Continued)

c. Time = 18 sec



d. Time = 20 sec

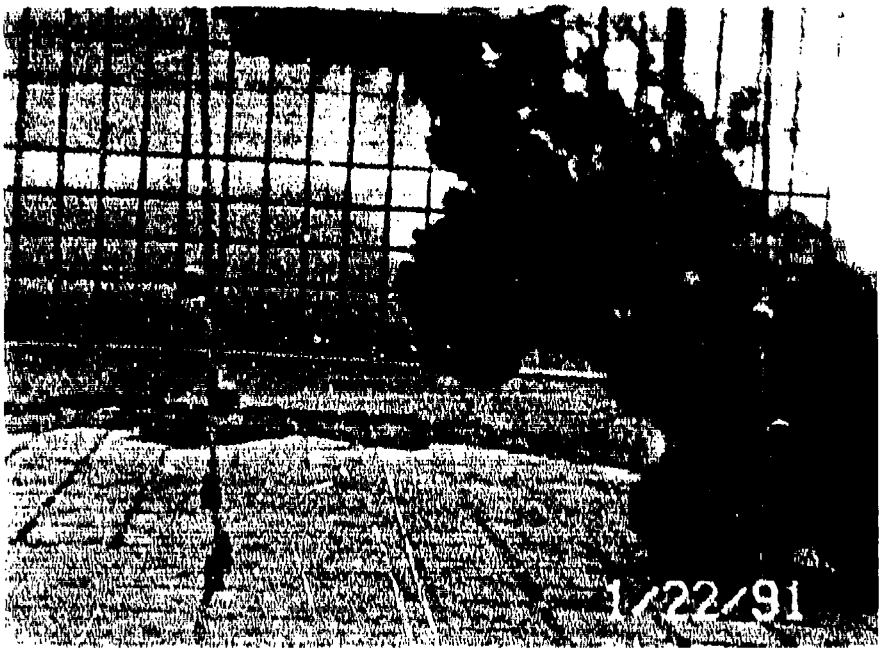
Figure 31. (Concluded)



a. Time = 3 sec

b. Time = 9 sec

Figure 32. Still photos from Test 4C viewed from the side (Continued)



c. Time = 13 sec

d. Time = 15 sec

Figure 32. (Concluded)

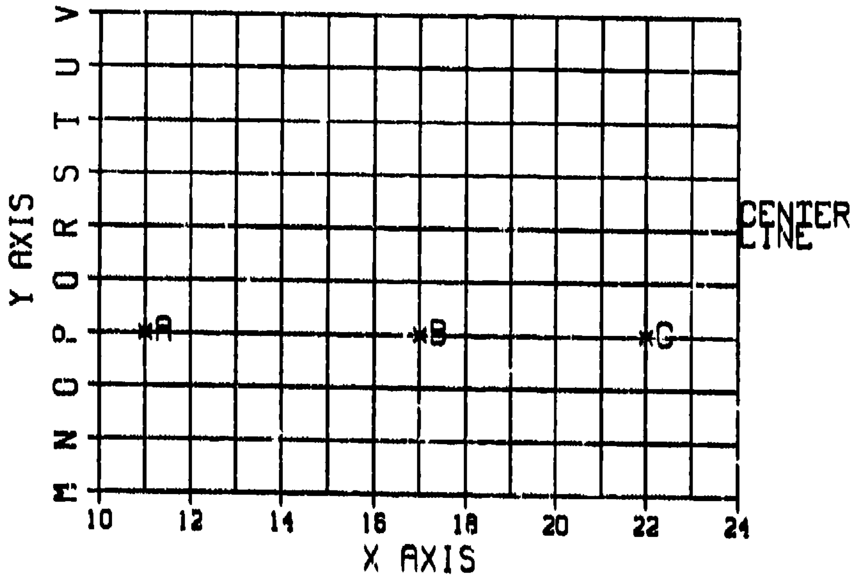


Figure 33. Location of water sampler poles for Test 2C

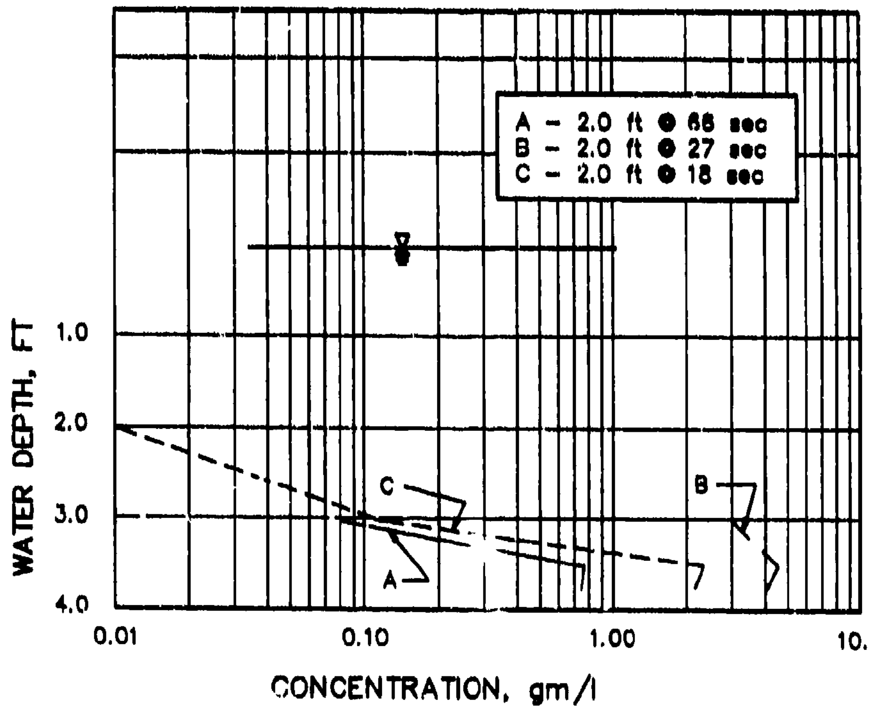


Figure 34. Suspended coal concentrations from Test 2C

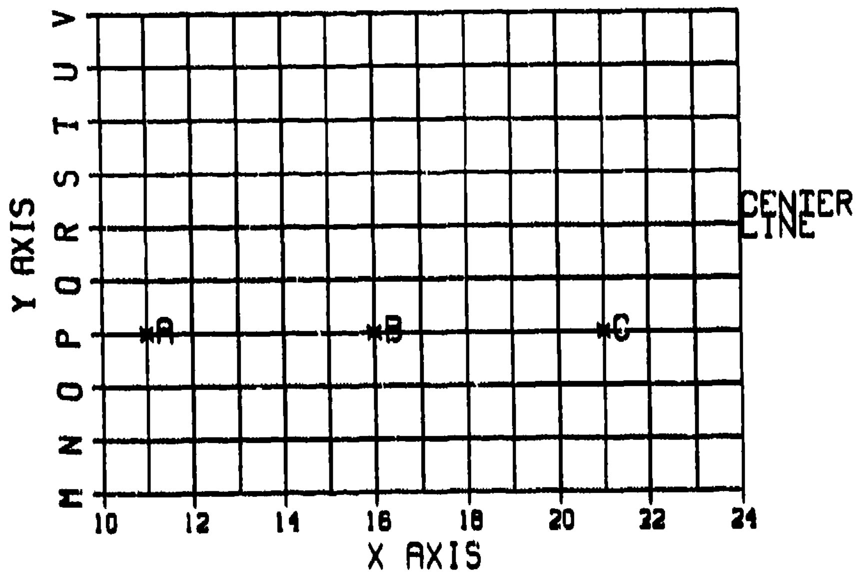


Figure 35. Location of water sampler poles for Test 3C

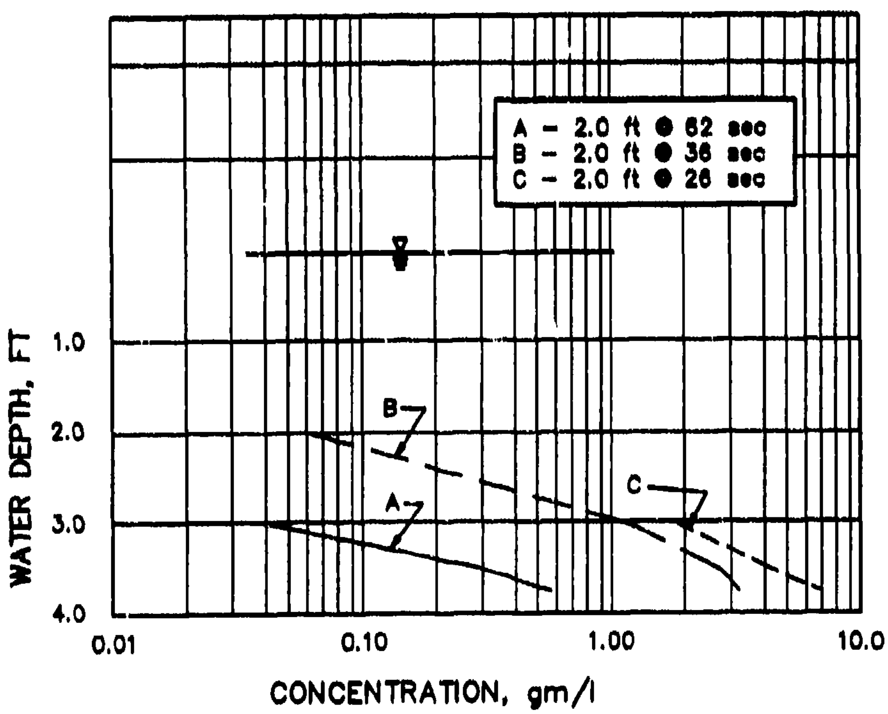


Figure 36. Suspended coal concentrations from Test 3C

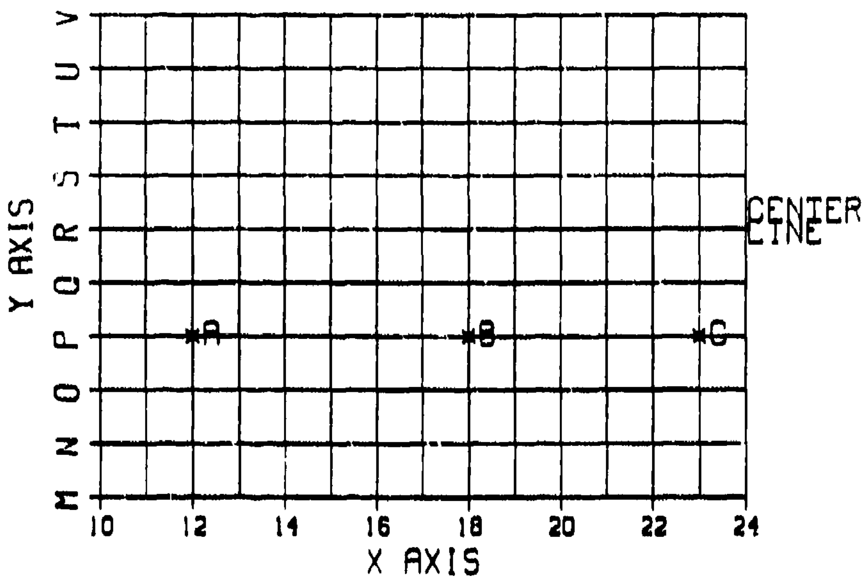


Figure 37. Location of water sampler poles for Test 4C

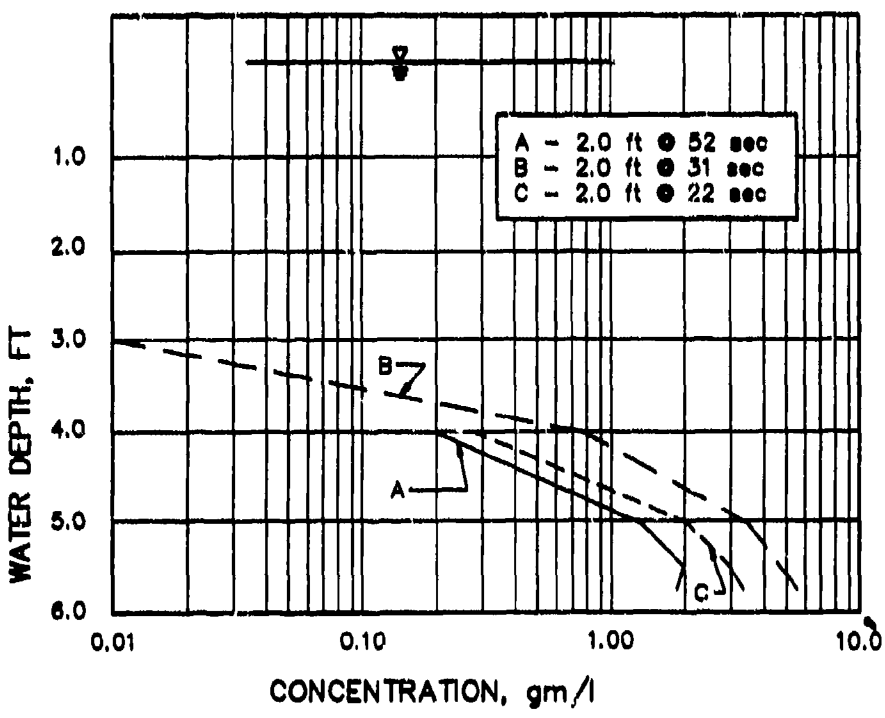


Figure 38. Suspended coal concentrations from Test 4C

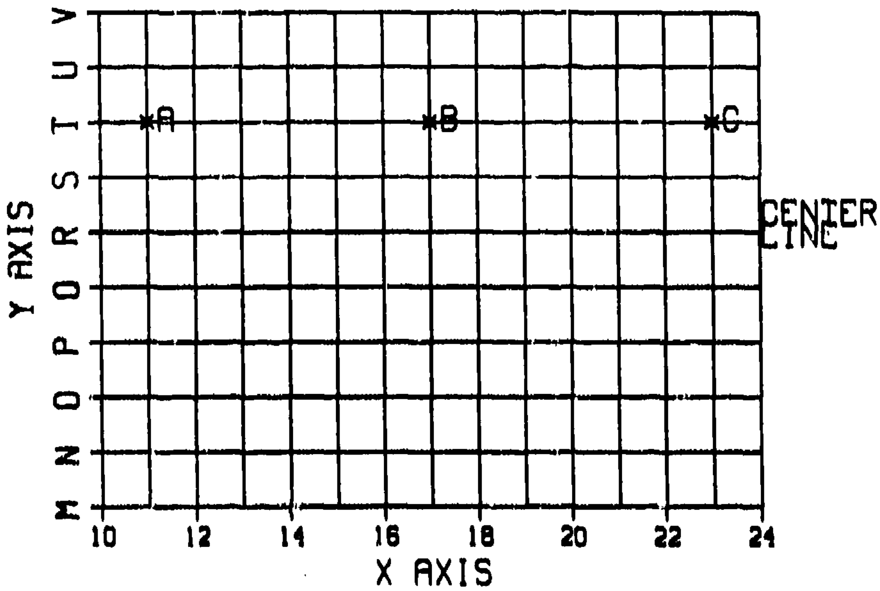


Figure 39. Location of water sampler poles for Test 21

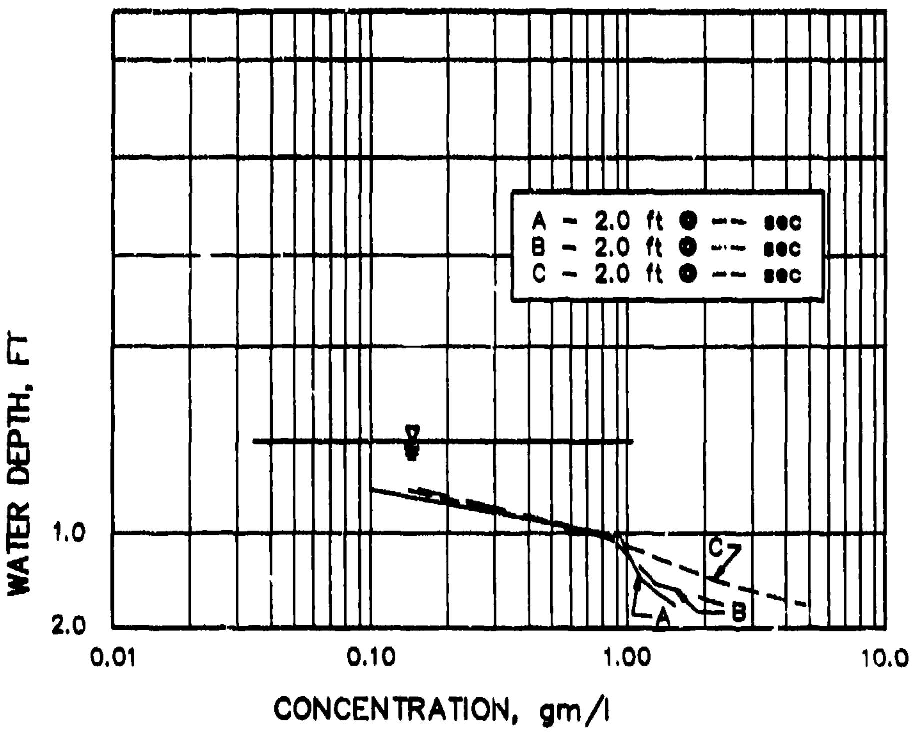


Figure 40. Suspended silt concentrations from Test 21

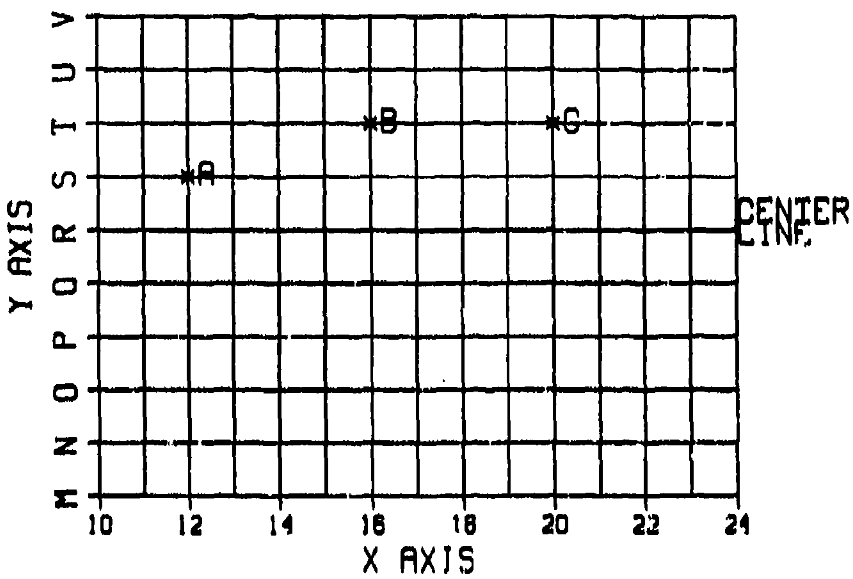


Figure 41. Location of water sampler poles for Test 23

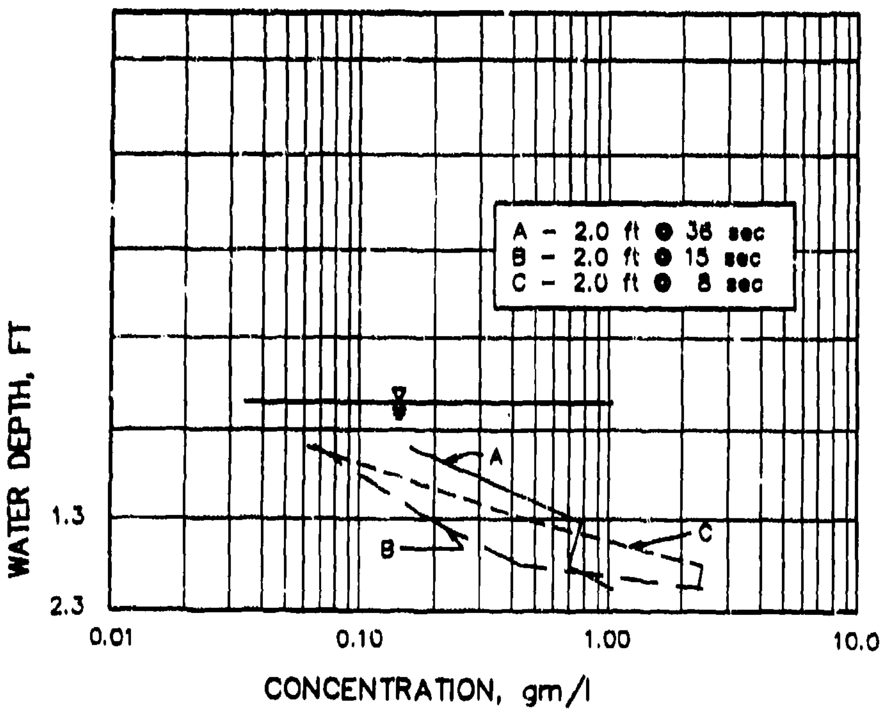


Figure 42. Suspended silt concentrations from Test 23

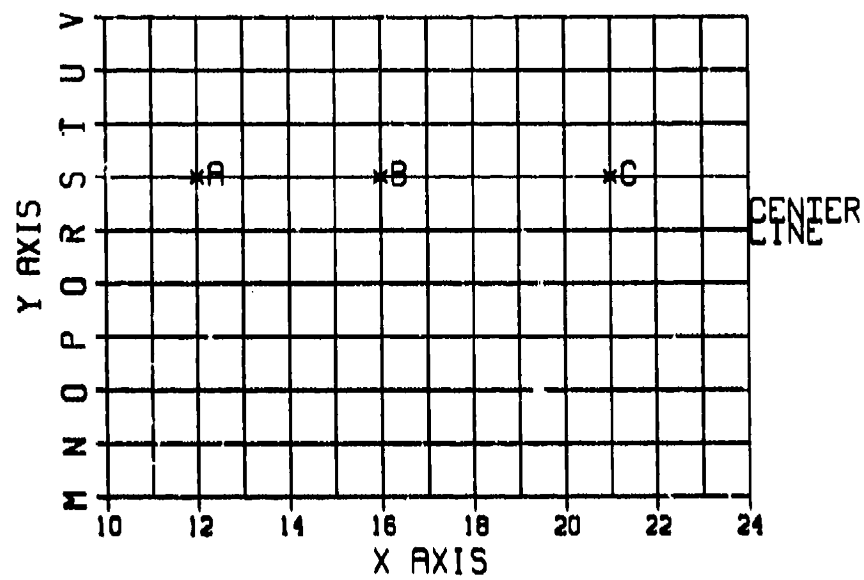


Figure 43. Location of water sampler poles for Test 25

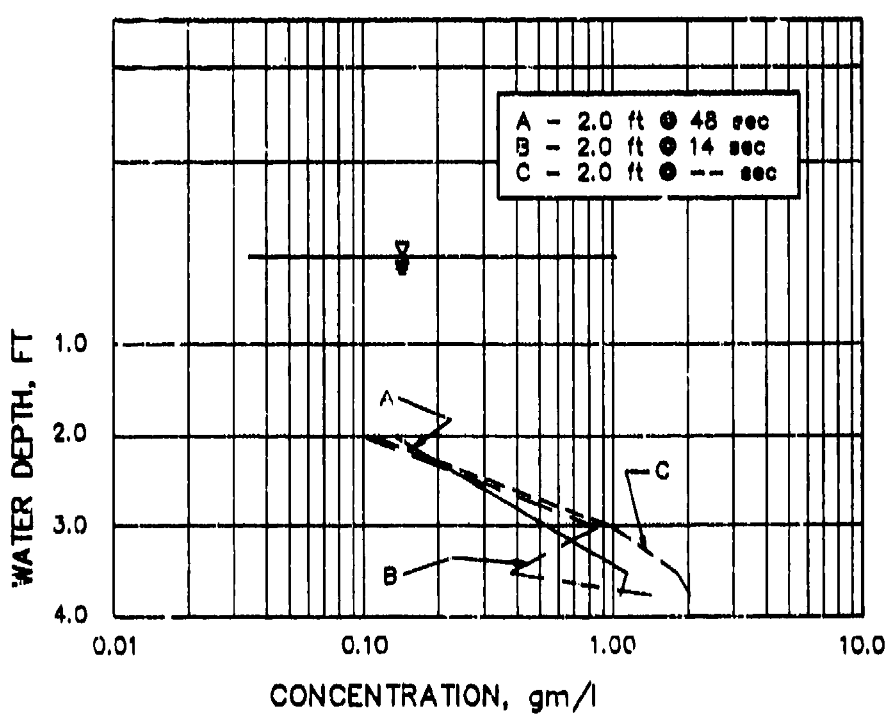


Figure 44. Suspended silt concentrations from Test 25

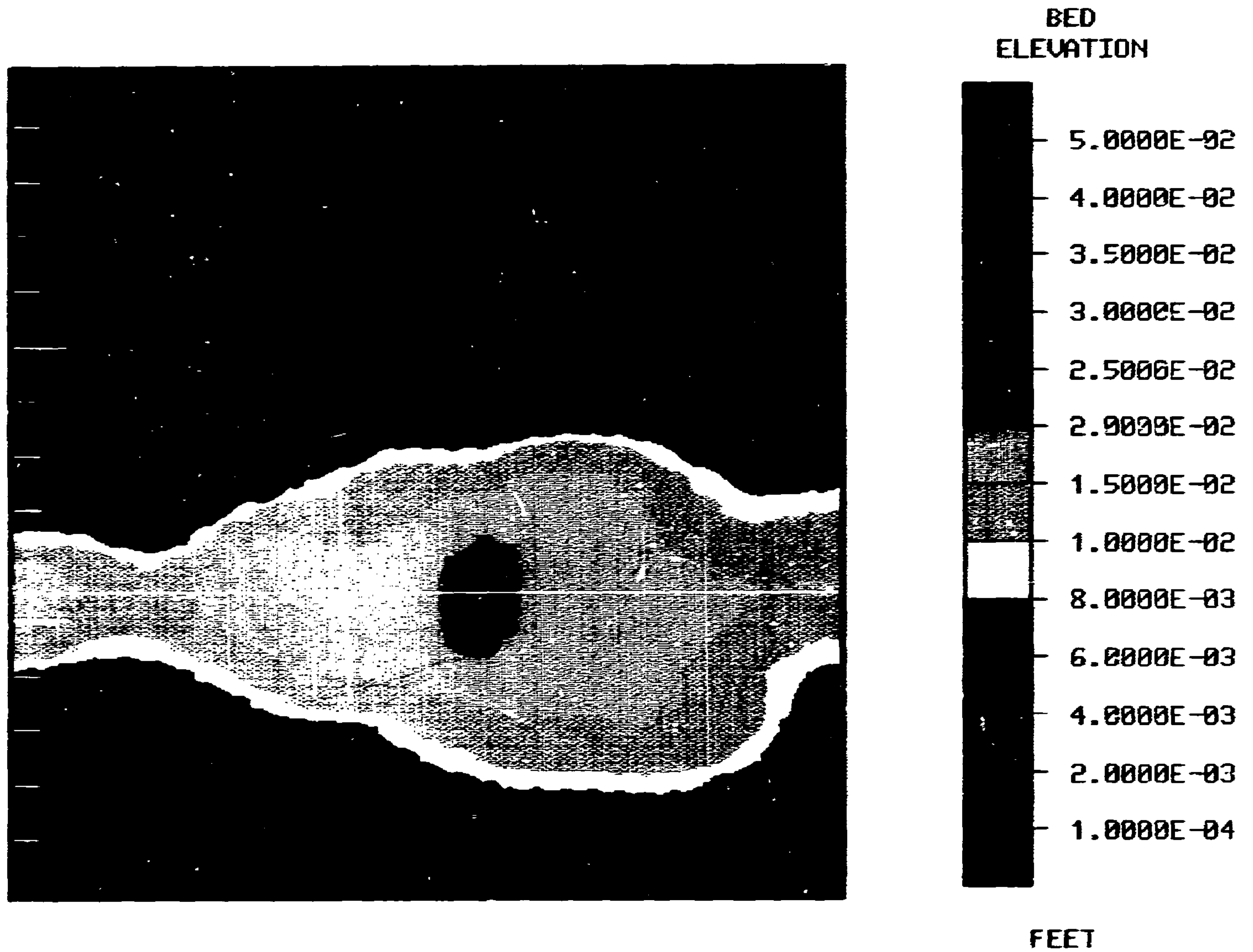


Figure 45. Bottom deposition from Test 2C

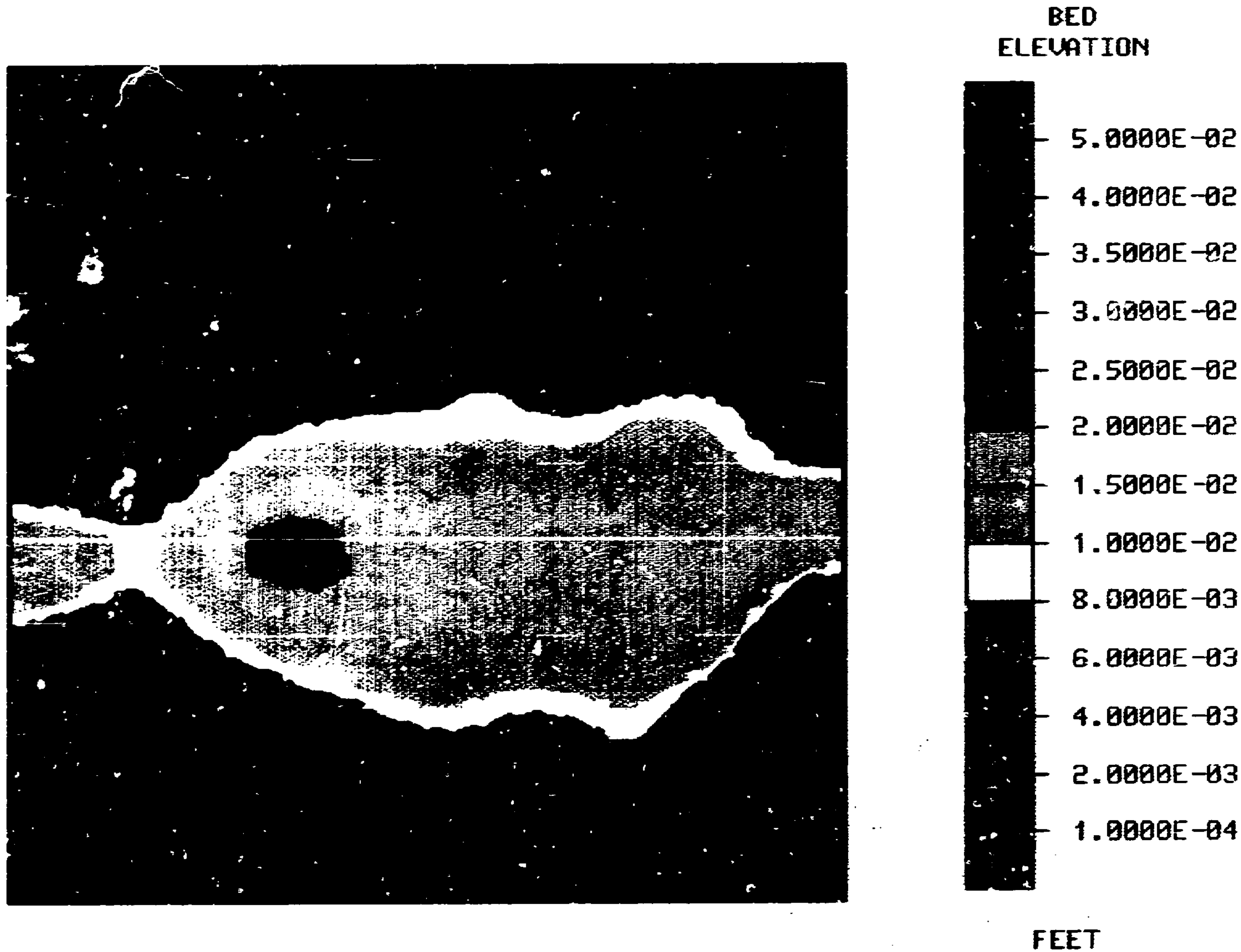


Figure 46. Bottom deposition from Test 3C

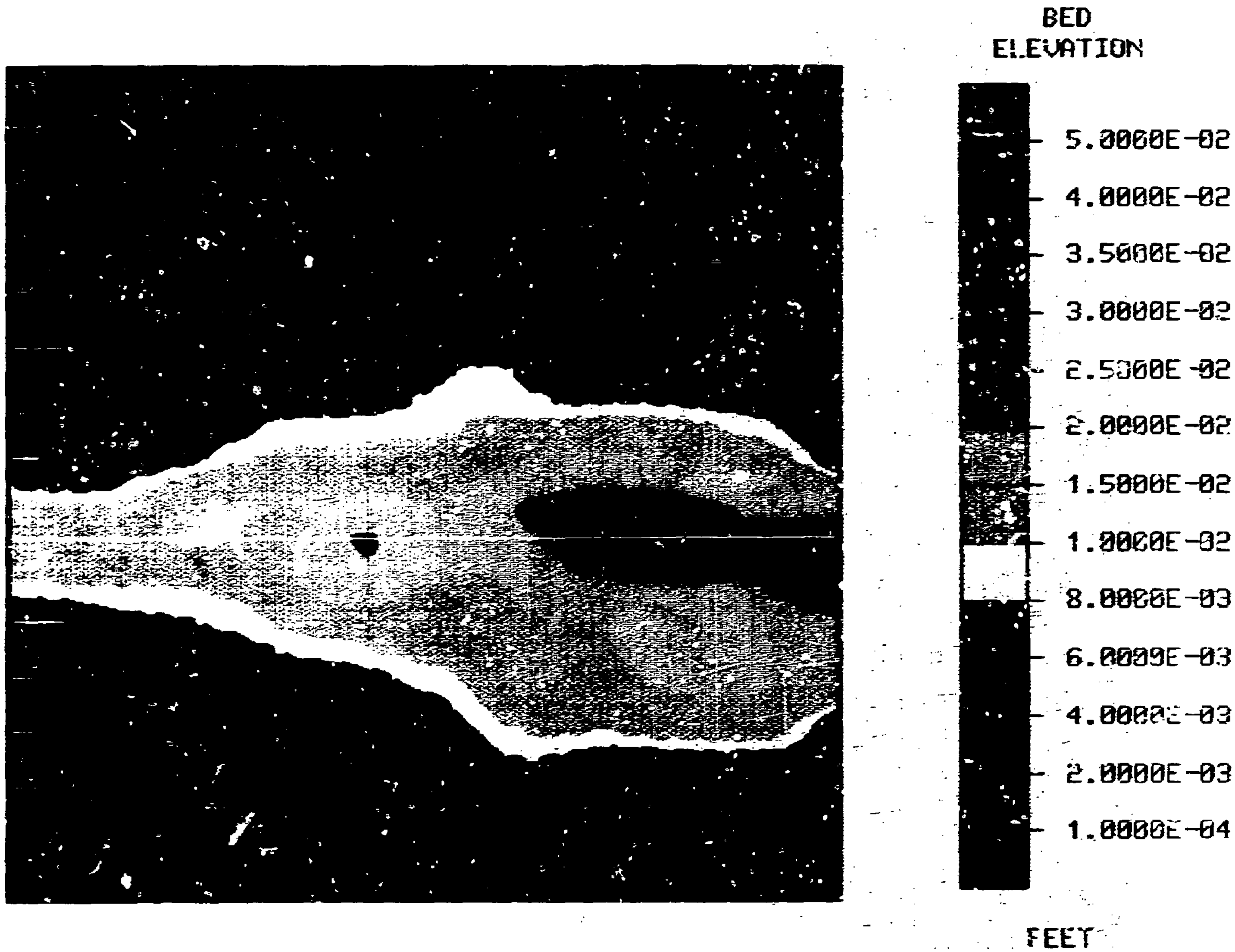
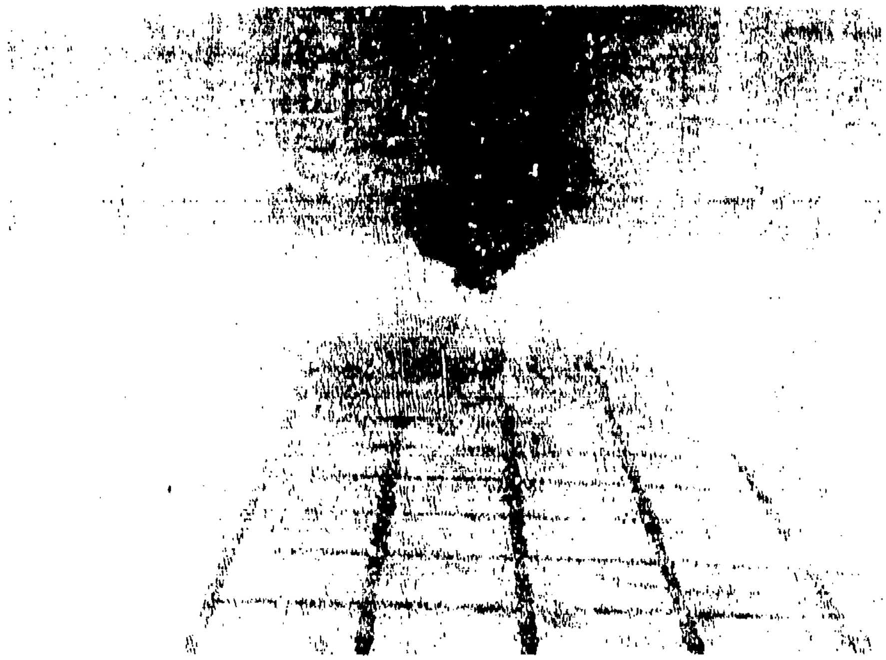
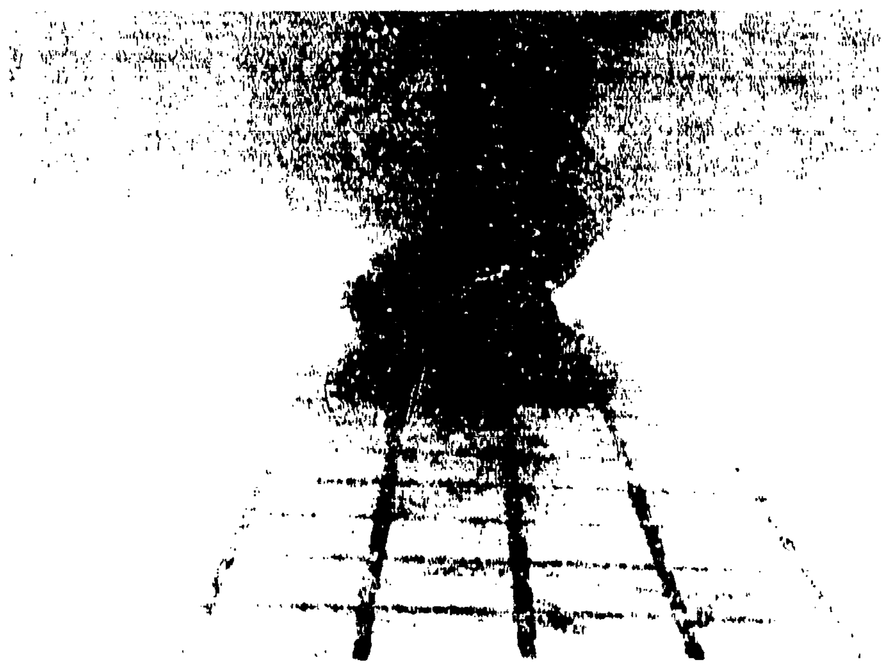


Figure 47. Bottom deposition from Test 4C

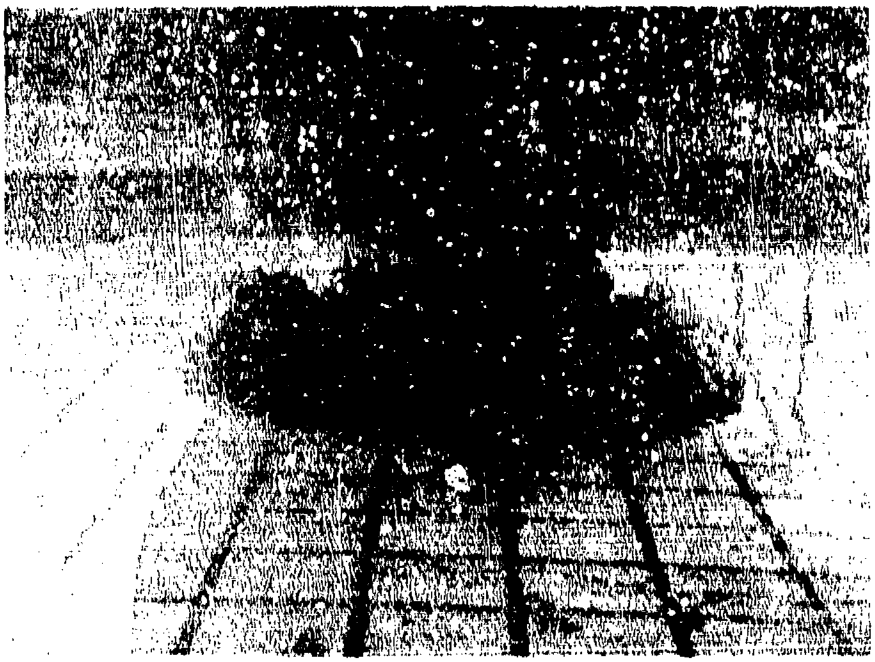


a. Time = 1.5 sec

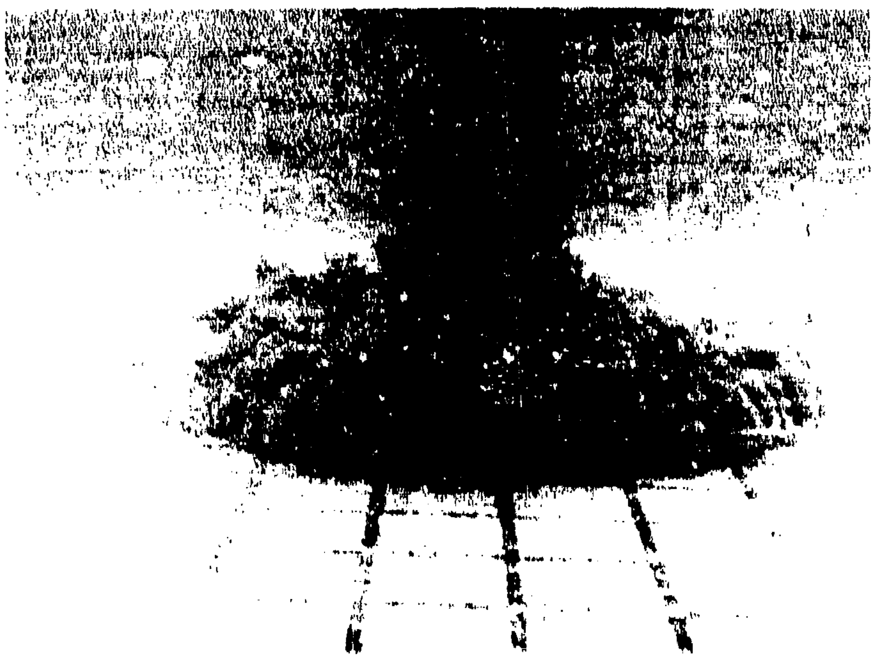


b. Time 3.1 sec

Figure 48. Still photos from Test 5H viewed from the end (Sheet 1 of 3)

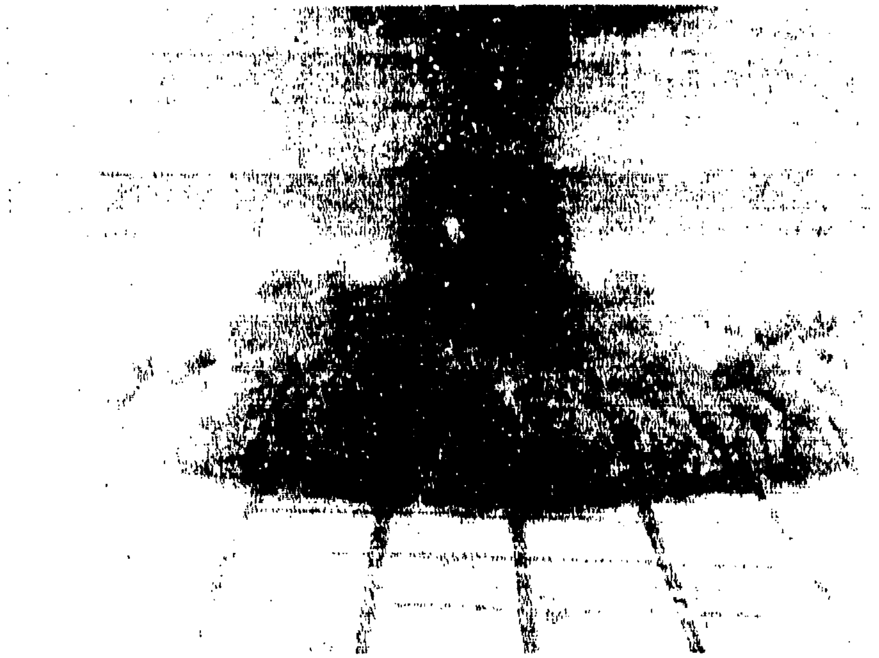


c. Time = 5.3 sec

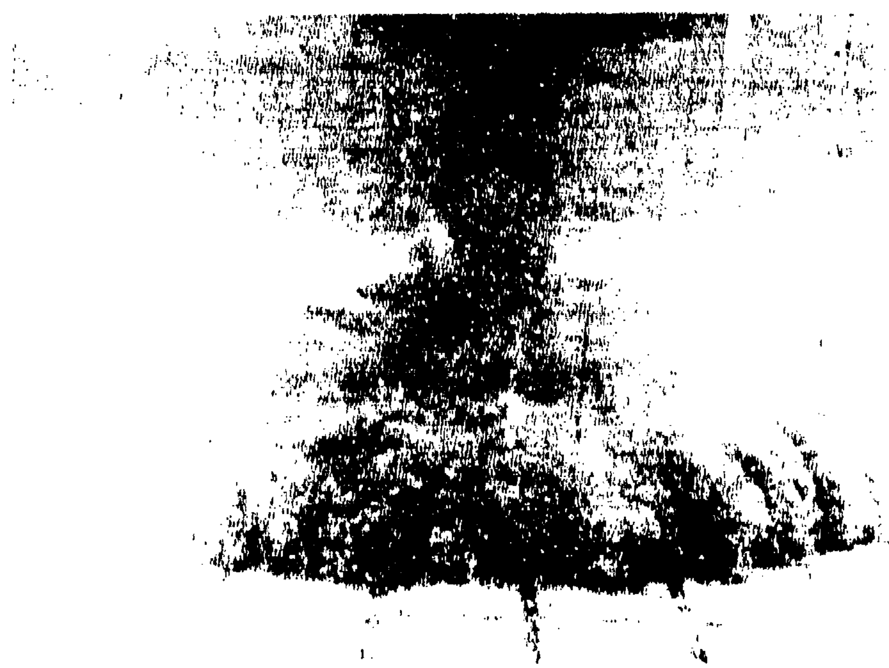


d. Time = 6.8 sec

Figure 48. (Sheet 2 of 3)

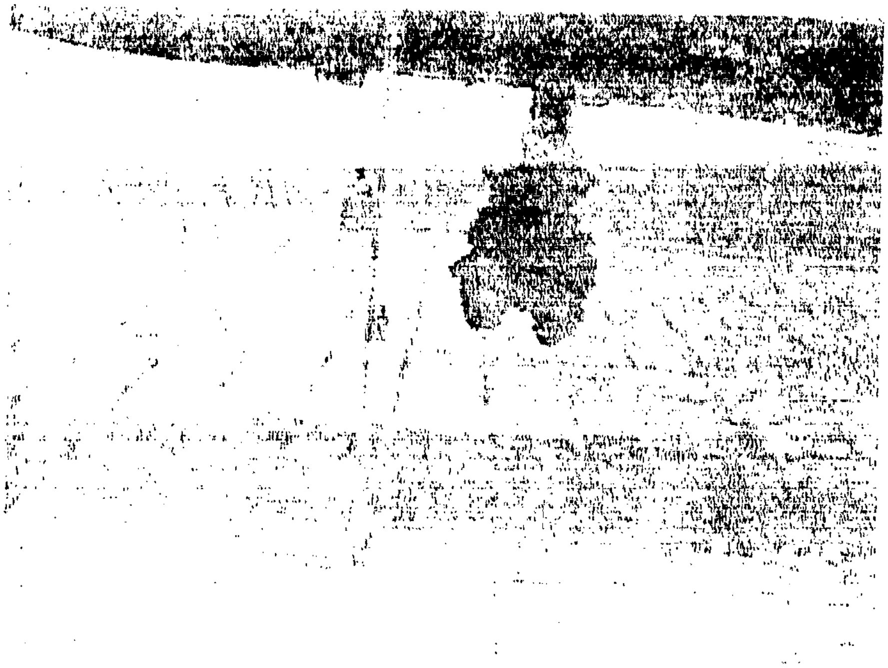


e. Time = 10.0 sec

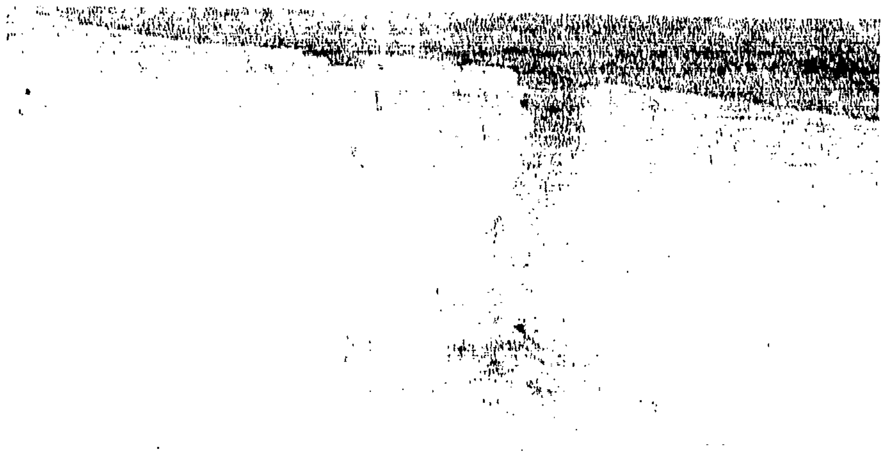


f. Time = 16.5 sec

Figure 48. (Sheet 3 of 3)

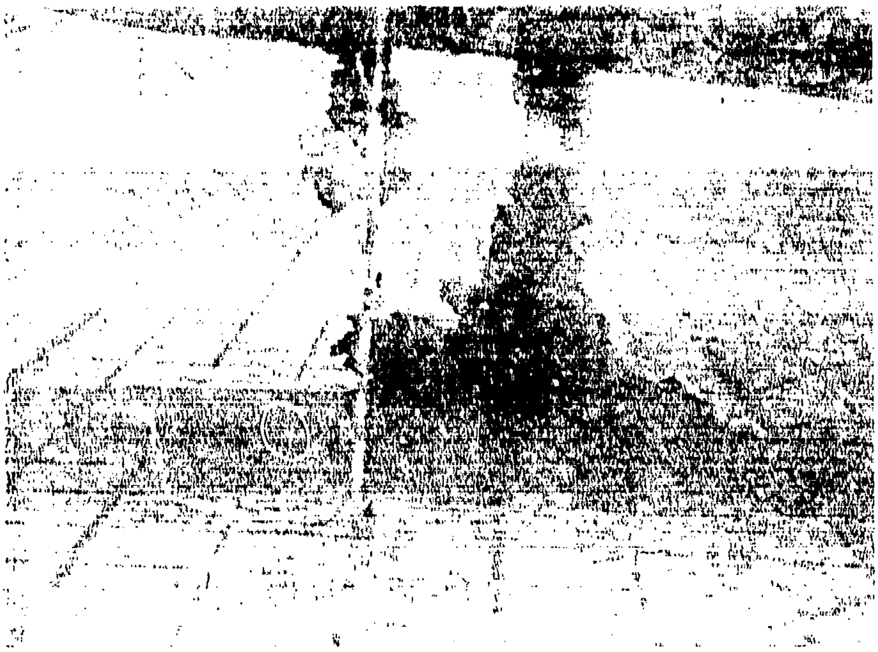


a. Time = 0.8 sec



b. Time = 2.2 sec

Figure 49. Still photos from Test 5H viewed from the side (Sheet 1 of 4)



c. Time - 3.2 sec

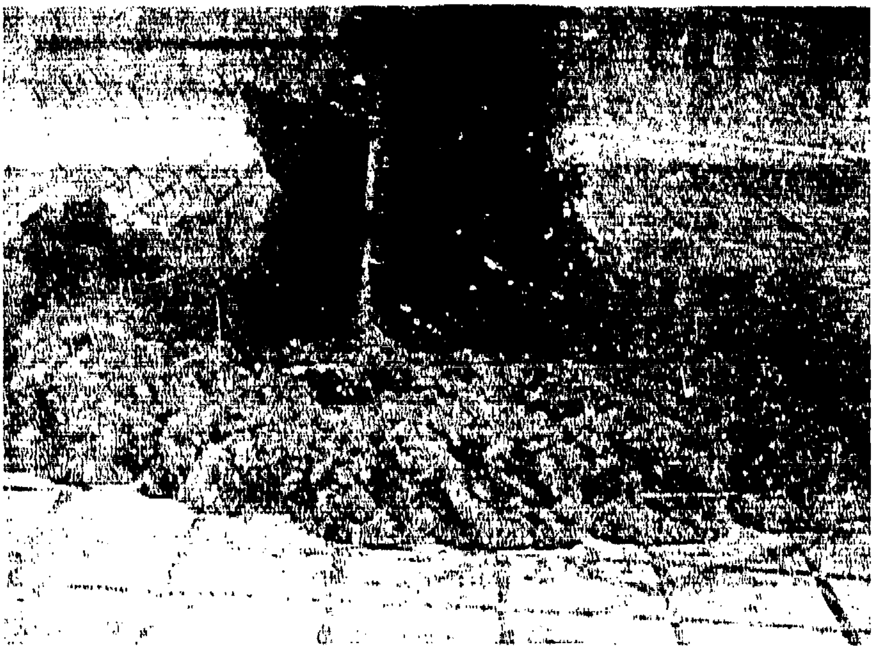
d. Time - 4.4 sec

Figure 49. (Sheet 2 of 4)

e. Time - 6.6 sec

f. Time - 7.8 sec

Figure 49. (Sheet 3 of 4)



g. Time - 11.2

h. Time - 15.3

Figure 49. (Sheet 4 of 4)

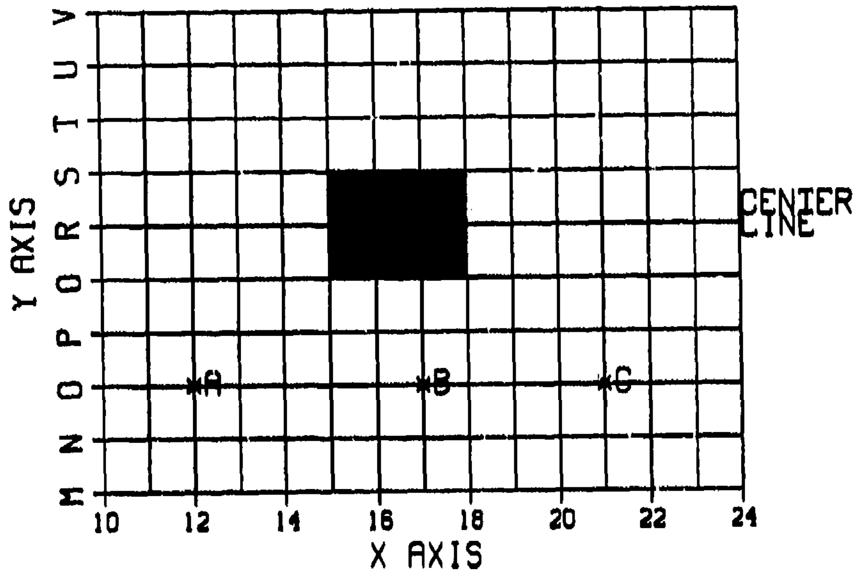


Figure 50. Location of water sampler poles for Test 1H

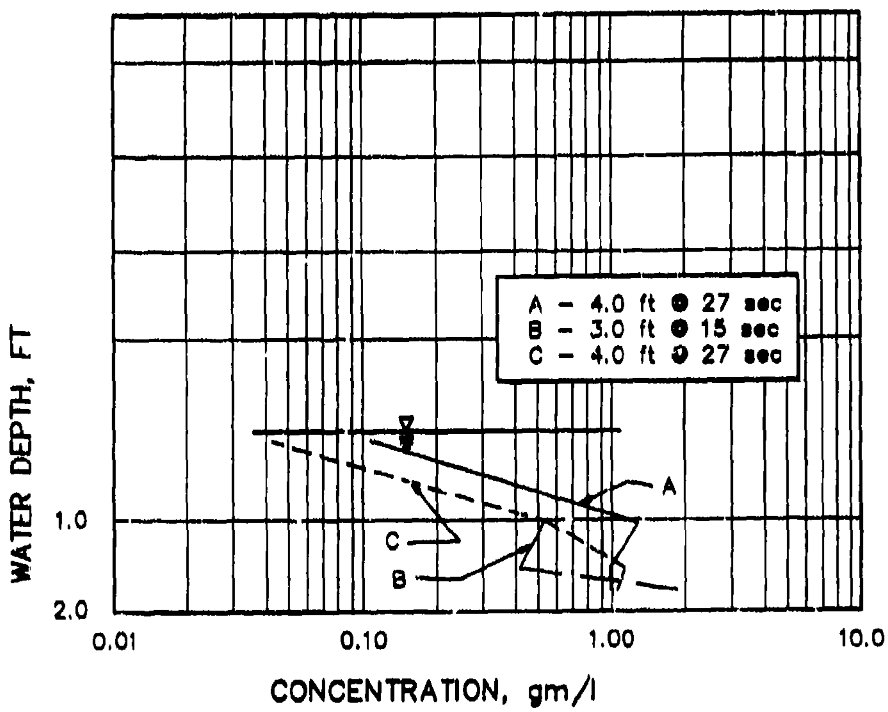


Figure 51. Suspended silt concentration from Test 1H

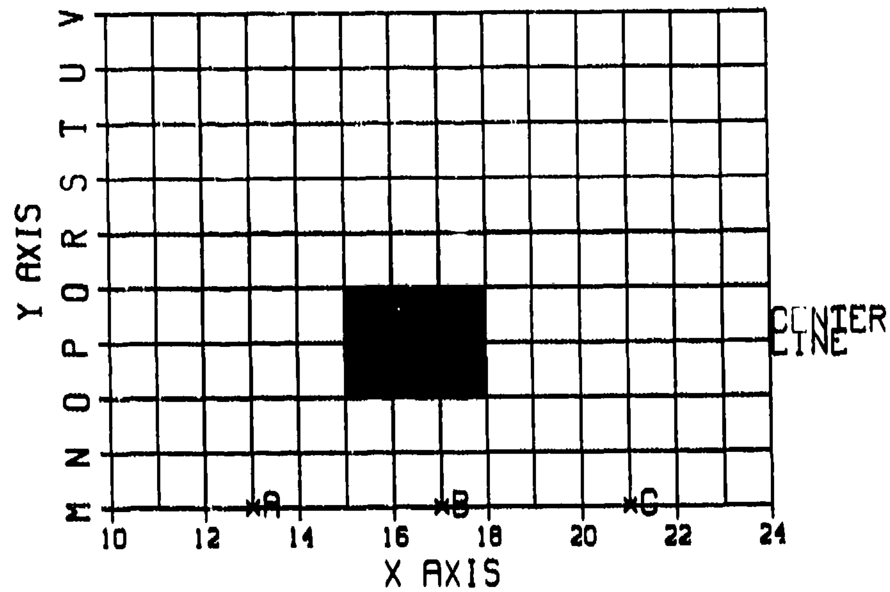


Figure 52. Location of water sampler poles for Test 5H

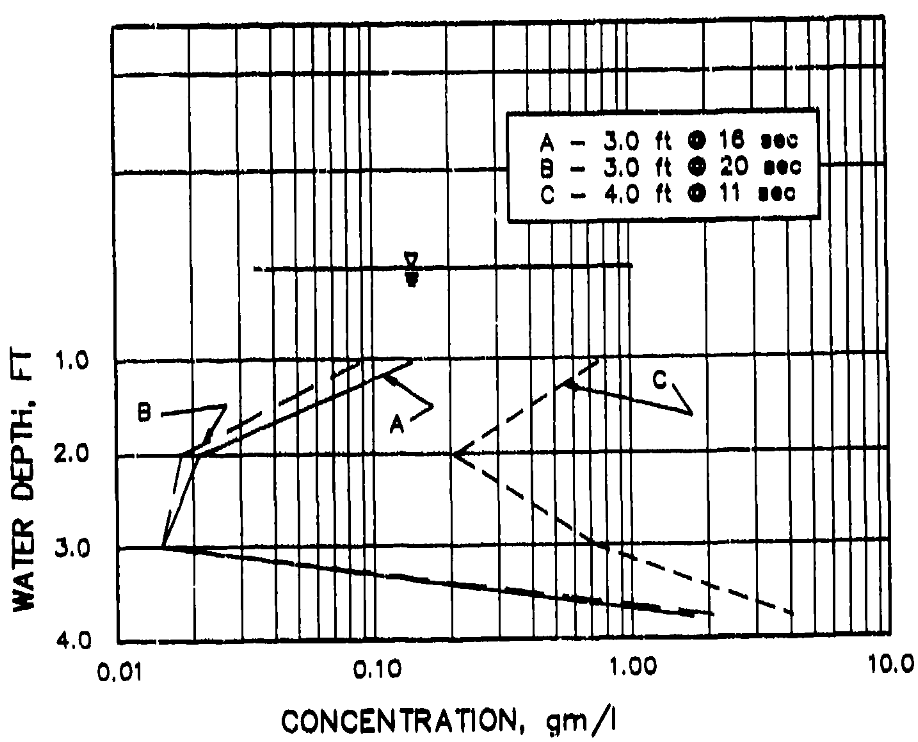
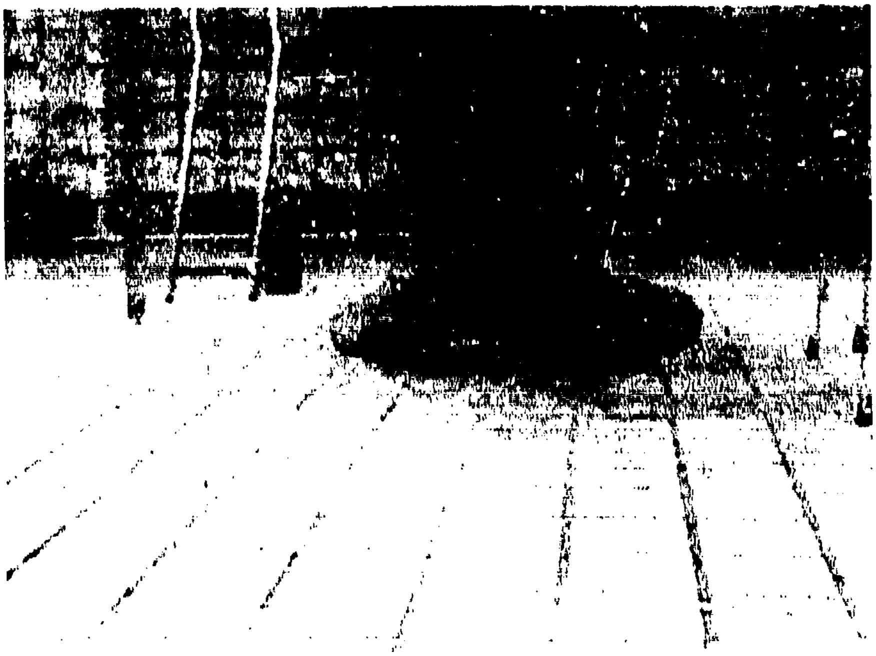


Figure 53. Suspended silt concentration from Test 5H

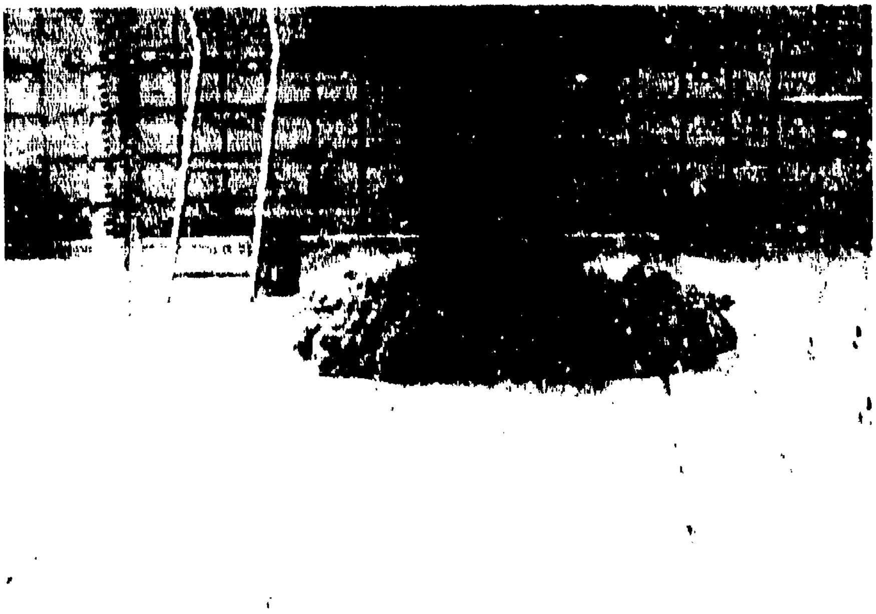
a. Time - 0.9 sec

b. Time - 3.3 sec

Figure 54. Still photos from Test 4H viewed from the end (Sheet 1 of 4)

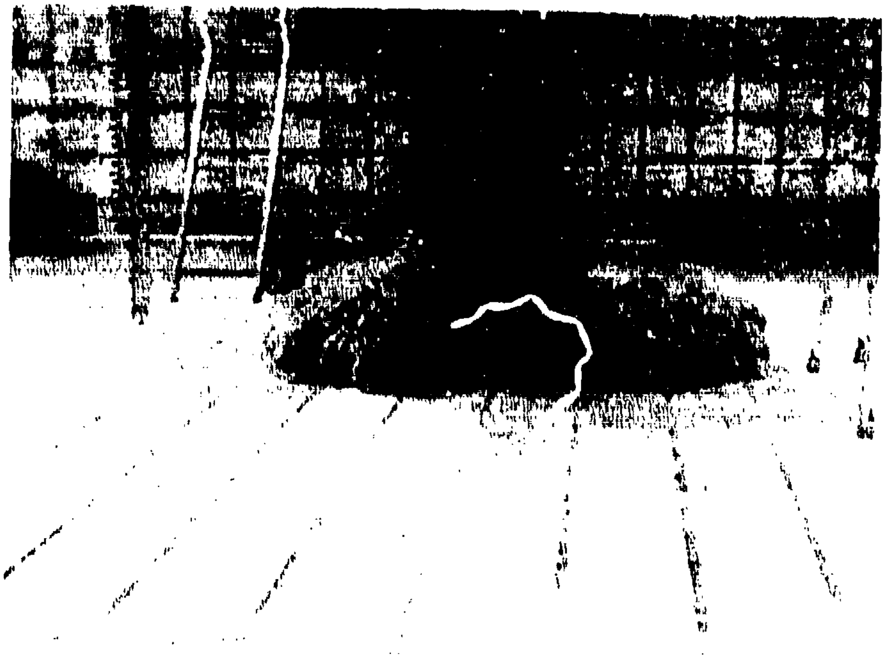


c. Time = 4.2 sec



d. Time = 5.8 sec

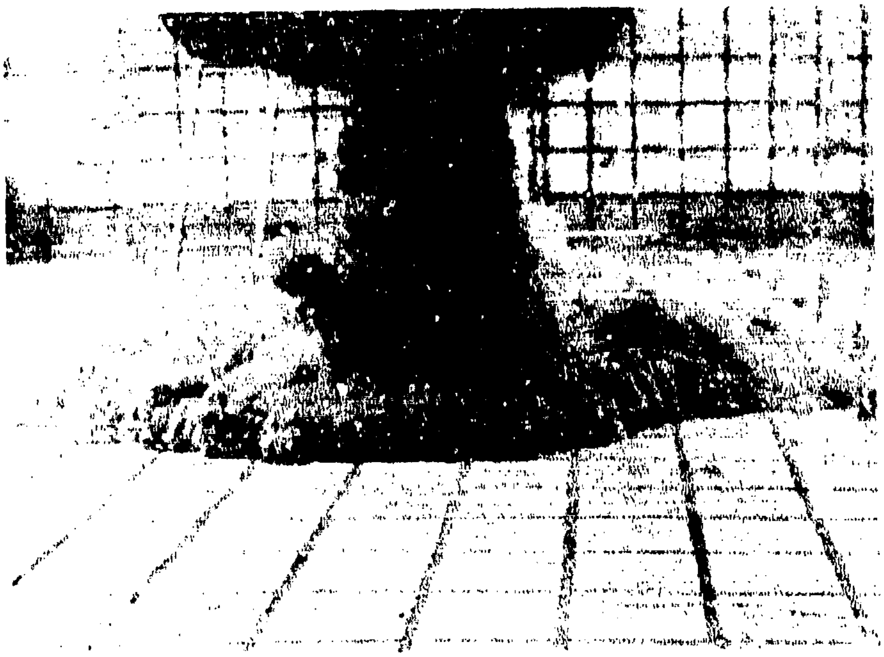
Figure 54. (Sheet 2 of 4)



e. Time = 7.6 sec

f. Time = 10.3 sec

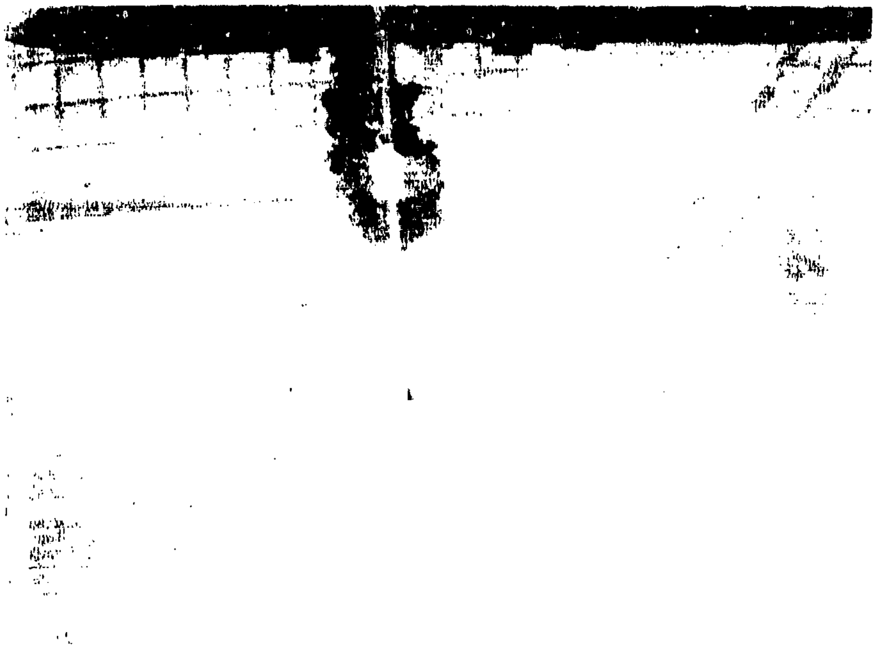
Figure 54. (Sheet 3 of 4)



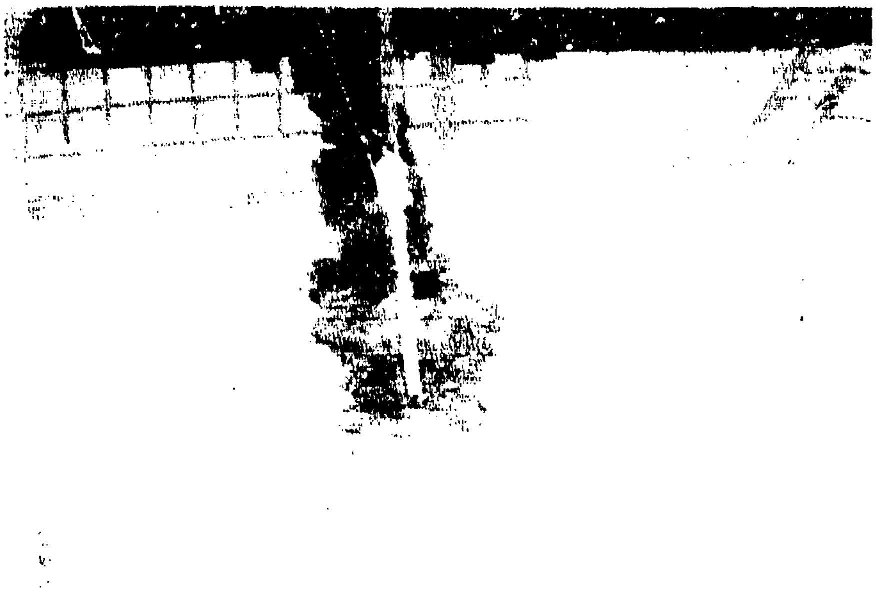
g. Time = 20.5 sec

h. Time = 30.0 sec

Figure 54. (Sheet 4 of 4)



a. Time - 0.6 sec



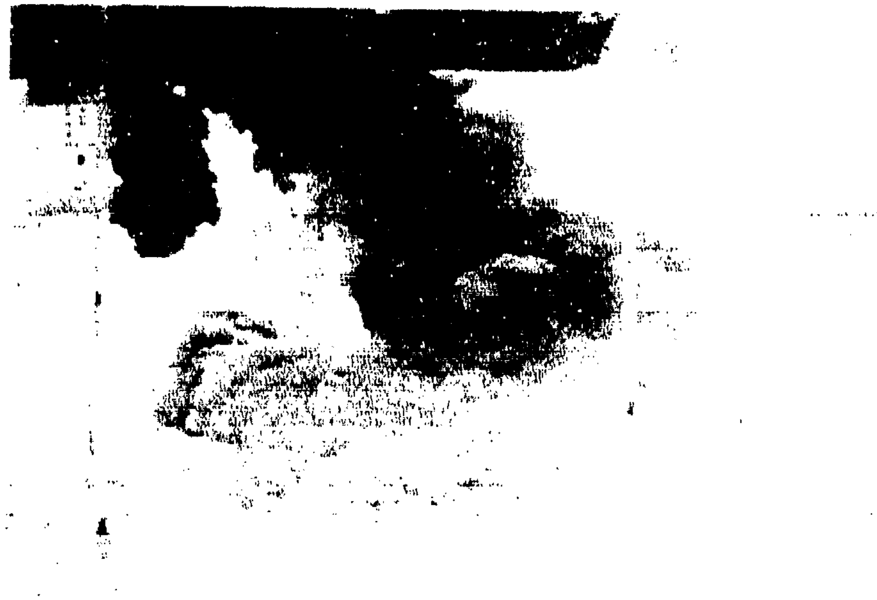
b. Time - 1.9 sec

Figure 55. Still photos from Test 4H viewed from the side (Sheet 1 of 4)

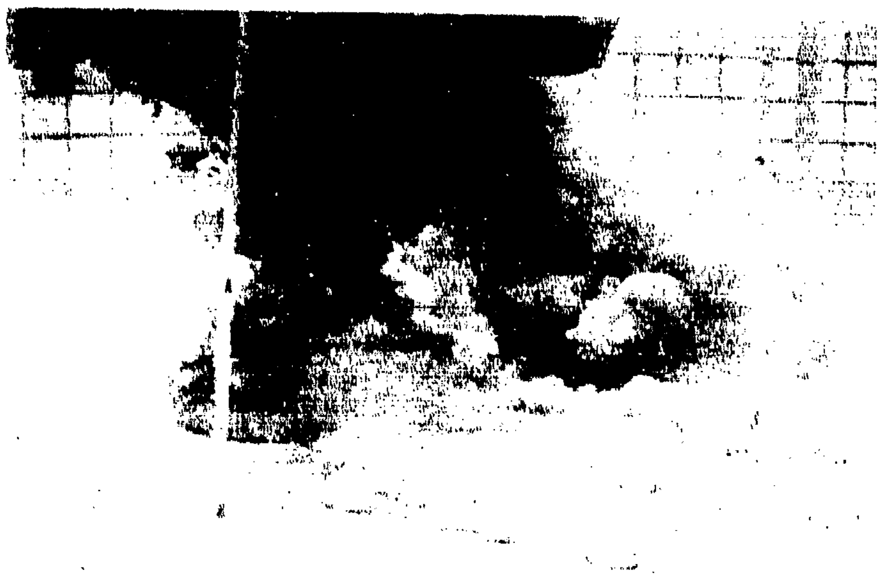
c. Time = 4.9 sec

d. Time = 8.5 sec

Figure 55. (Sheet 2 of 4)

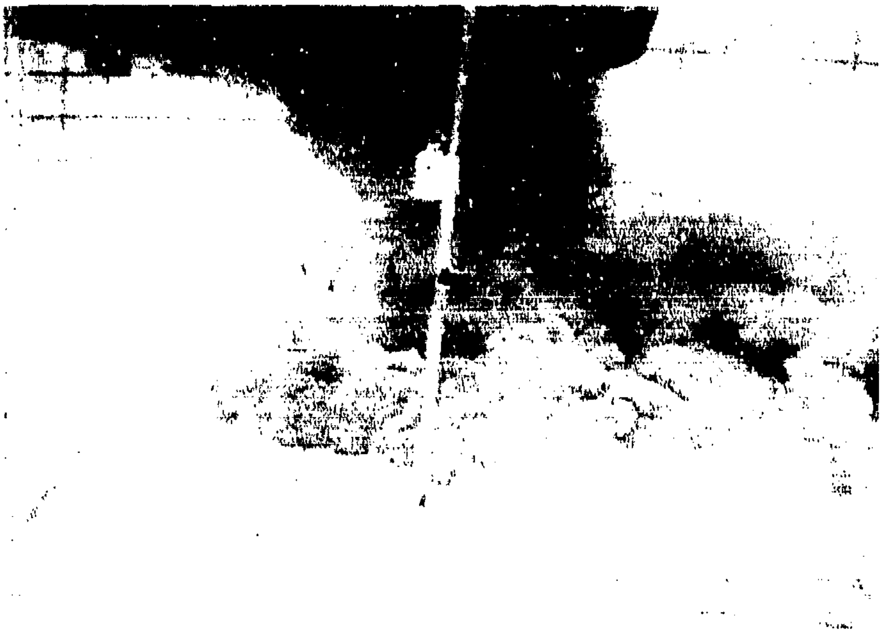


e. Time - 12.7 sec

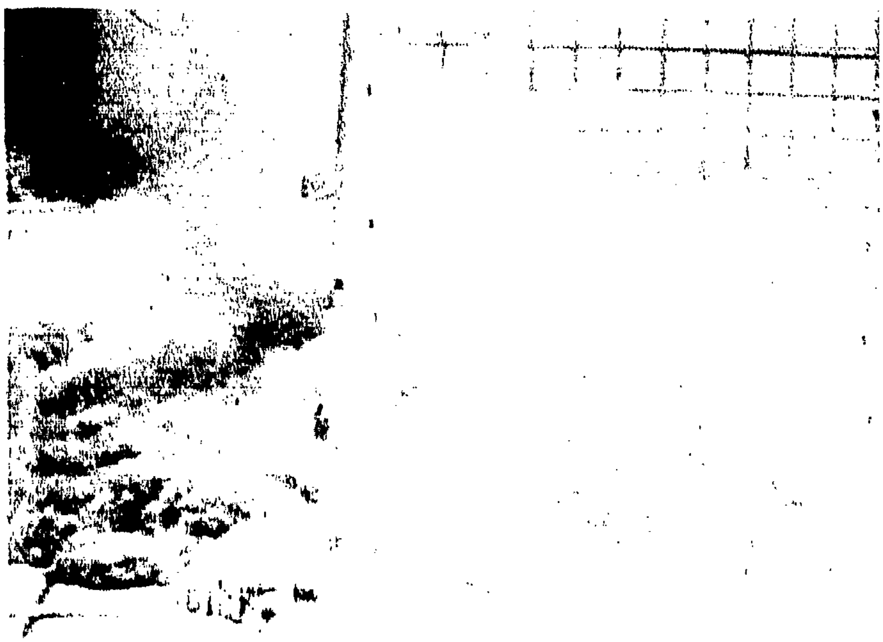


f. Time - 15.4 sec

Figure 55. (Sheet 3 of 4)



g. Time - 20.5



h. Time - 31.5

Figure 55. (Sheet 4 of 4)

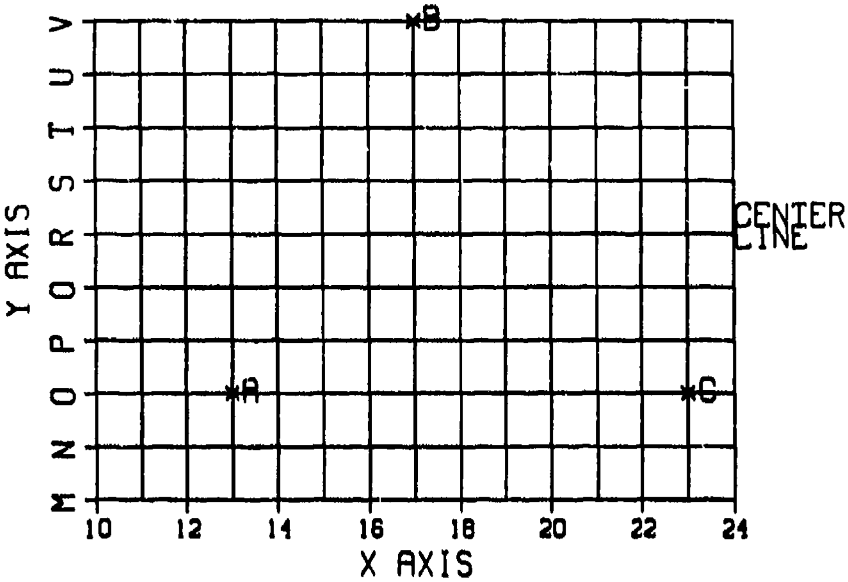


Figure 56. Location of water sampler poles for Test 2H

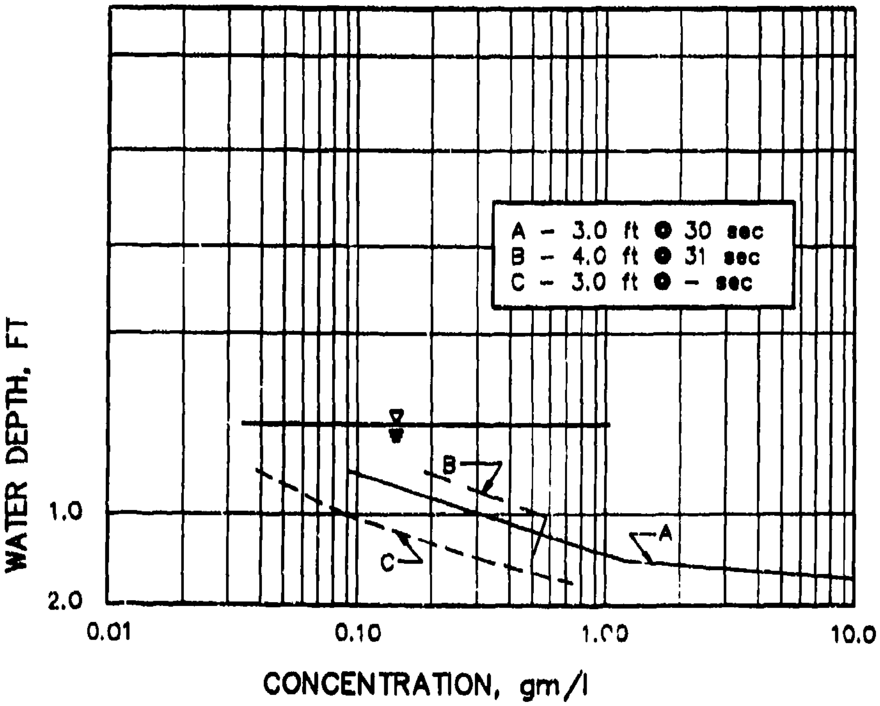


Figure 57. Suspended silt concentration from Test 2H

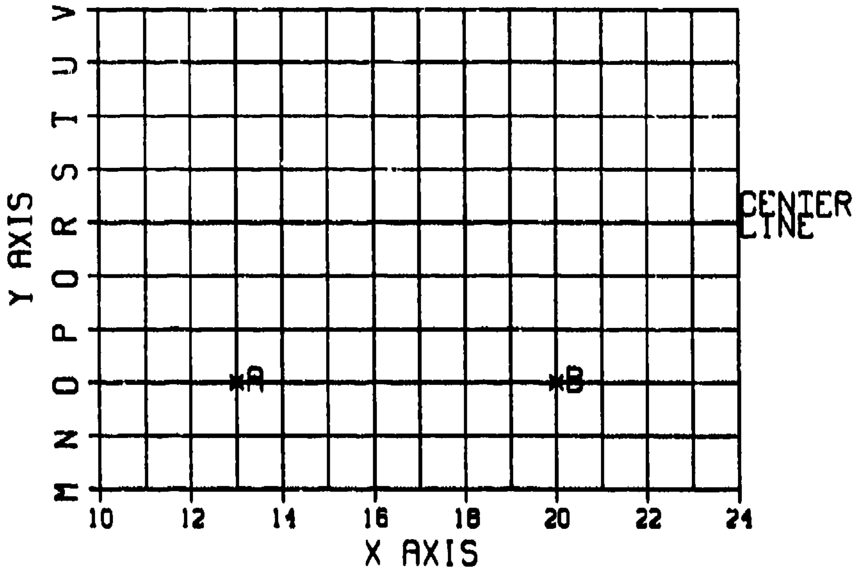


Figure 58. Location of water sampler poles for Test 3H

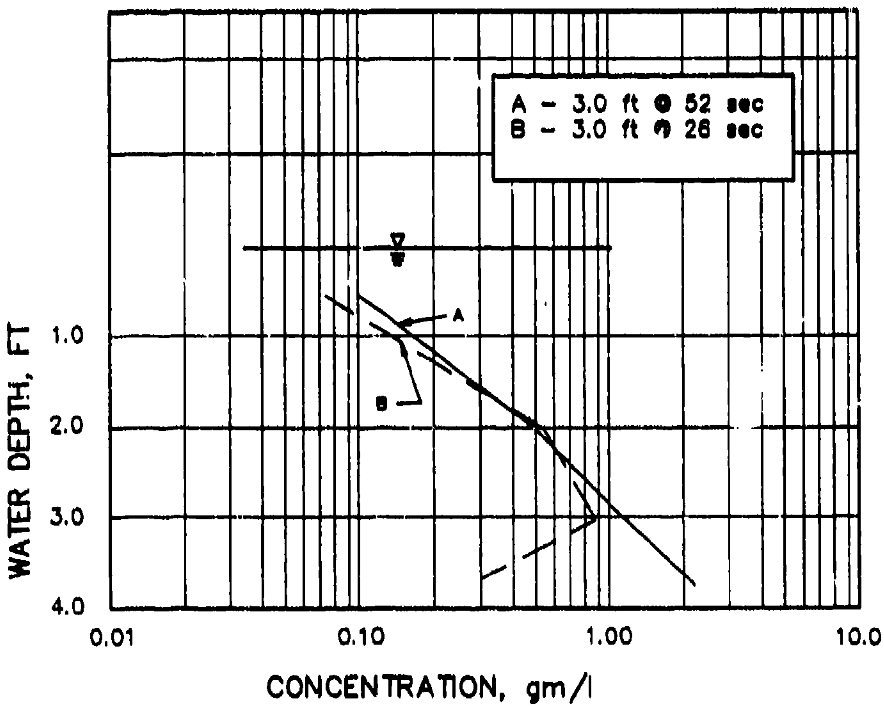


Figure 59. Suspended silt concentration from Test 3H

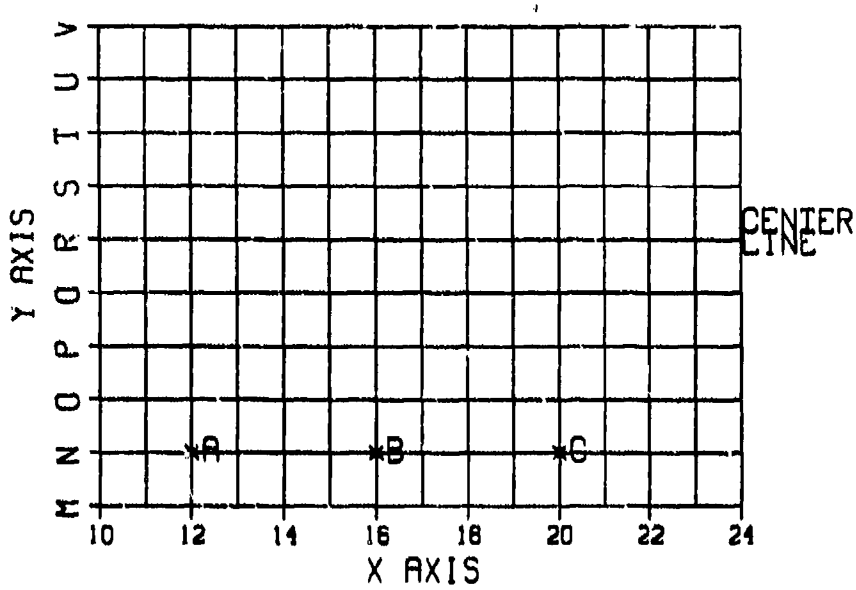


Figure 60. Location of water sampler poles for Test 4H

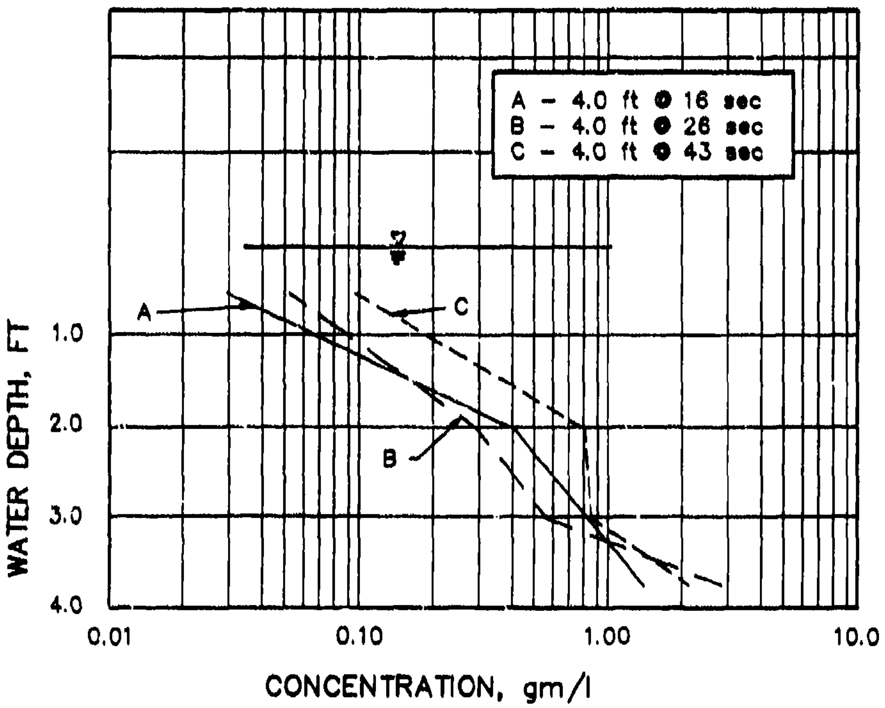


Figure 61. Suspended silt concentration from Test 4H

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13. ABSTRACT *(Maximum 200 words)*

Physical model disposal tests of various types of disposal material have been conducted to provide insight and data sets for modifying and verifying existing numerical disposal models. The tests were conducted in a static and unstratified basin in water depths up to 6 ft. Both stationary and moving disposals from a 1:50-scale split-hull barge and a 1:50-scale multibin hopper vessel were modeled. An analysis of scaling laws concluded that although exact similitude of the Reynolds number and the particle-settling velocity were not achieved, the bulk behavior of the descending cloud or jet and the bottom surge created after bottom encounter can be approximately scaled to the prototype.

The movement of the disposal material from the vessel to its final resting place was tracked during each test through videotaping. Discrete water samples at several locations were obtained to determine suspended sediment concentrations. Bottom surveys at the conclusion of each test provided details on depositional patterns.

14. SUBJECT TERMS

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Disposal tests	Hopper
Dredged material	Scaled models

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