



IMCO

INTERNATIONAL CONFERENCE ON
MARINE POLLUTION, 1973
Committee III

INFORMATION MATERIAL RELATED TO THE CONSIDERATION
OF THE DRAFT INTERNATIONAL CONVENTION FOR THE PREVENTION OF POLLUTION
FROM SHIPS, 1973, ANNEX II

Submitted by the Government of the United
States of America

Attached hereto* for information is a "Model Study of the Dilution
of Soluble Liquids Discharged from Tankers" submitted by the Government
of the United States of America.

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Report No. CG-D-12-74

TASK NO. 4241.2/7

MODEL STUDY OF THE DILUTION OF SOLUBLE LIQUIDS
DISCHARGED FROM TANKERS

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SEPTEMBER 1973

FINAL REPORT

Document is available to the public through the
National Technical Information Service,
Springfield, Virginia 22151

Prepared for
DEPARTMENT OF TRANSPORTATION
UNITED STATES COAST GUARD
Office of Research and Development
Washington, D.C. 20390

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1. Report No. CG-D-12-74	2. Government Accession No.	3. Recipient's Catalog No.	
4. Title and Subtitle MODEL STUDY OF THE DILUTION OF SOLUBLE LIQUIDS DISCHARGED FROM TANKERS		5. Report Date September 1973	6. Performing Organization Code
7. Author(s) John A. Mercier, Richard I. Hires, Meige Wu		8. Performing Organization Report No.	
9. Performing Organization Name and Address Stevens Institute of Technology Davidson Laboratory Castle Point Station Hoboken, New Jersey 07030		10. Work Unit No. (TRAIS) 734241.2/7	11. Contract or Grant No. DOT-CG-33,148-A
12. Sponsoring Agency Name and Address Department of Transportation U. S. Coast Guard Office of Research and Development Washington D. C. 20590		13. Type of Report and Period Covered Final Report	
14. Sponsoring Agency Code			
15. Supplementary Notes			
16. Abstract <p>A program of model experimental research was undertaken to study the dispersion of effluent discharged from chemical tankers. The effects of discharge location, volume rate and velocity of discharge were investigated as well as the effects of ship speed and propeller action. The experimental study consisted of tests in a circulating water channel as well as tests in a towing tank. The tests in the water channel included measurements of the dilution of a released tracer for the following conditions: 1) an unobstructed flow in the channel, 2) a propeller operating in the channel, 3) a foreshortened model of a typical chemical tanker fixed in the water channel without a propeller, and 4) the same model but with an operating propeller. The tests in the towing tank included measurements of the dilution of a tracer released from an geometrically scaled, 8 ft. long tanker model operating with and without a propeller. This work was undertaken to provide guidance to the U. S. Coast Guard in regard to minimizing the environmental impact of washwater discharged during tank cleaning operations.</p>			
17. Key Words Hazardous Polluting Substance Discharge, Chemical discharge, tanker discharge, tank cleaning operations, environmental impact.		18. Distribution Statement Document is available to the public through the National Technical Information Service, Springfield, Virginia 22151	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 120	22. Price

SUMMARY

A program of model experimental research was undertaken to study the dispersion of effluent discharged from chemical tankers. The effects of location, volume rate, and velocity of discharge were investigated as well as ship speed and propeller action. This work was undertaken to provide guidance to the U.S. Coast Guard in regard to minimizing the impact on the environment of discharged washwater from tank cleaning operations and may be considered to be an extension of a contribution from Norway¹ to the International Maritime Consultative Organization's (IMCO) subcommittee on Marine Pollution.

Results of the research carried out with scale models in a circulating water channel and in a towing tank include:

- 1) Discharge should be through the ship's hull at low rates of flow with large diameter pipe penetrations or sea chests.
- 2) The discharge should be located so that the effluent flows into the central region of the wake and is not affected by bow or bilge vortices. Locations in the region just forward of the engine room and from just below the turn of the bilge or outboard to about the height of the shaft centerline are suggested.
- 3) For low velocity discharges into the central region of the ship's wake, the concentration of contaminant will be approximately proportional to the discharge rate.
- 4) The permissible rate of discharge of effluent with P percent concentration of contaminant, to achieve a permissible concentration, C_{perm} , of contaminant at a location just aft of the propellers may be estimated from the following equation:

Permissible Discharge Rate (tons/hr)

$$= 330 \times \frac{C_{perm}}{P/100} \times \text{Min Dil Factor} \left(\frac{L_{pp}}{630} \right)^2$$

where L_{pp} is the length between perpendiculars for a particular

vessel and the Minimum Dilution Factor may be taken to be 3000 according to Table V which gives results for discharge from a 630-ft L_{pp} vessel at 330 tons/hr rate.

- 5) The dilution is expected to be relatively insensitive to ship displacement and trim if the effluent flows into the central part of the ship's wake and is not affected by bow or bilge vortices.

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1. INTRODUCTION

In 1970, there were at least 260 different types of liquid bulk cargo other than oil, transported by ships. The Subcommittee on Marine Pollution of the International Marine Consultative Organization (IMCO) has estimated that at a minimum 16.5 million tons of liquid cargo, other than oil, were shipped in 1970. It has been recognized by IMCO that the cleaning of ship tanks after delivery of this liquid cargo and the subsequent discharge of the washwater into the sea, constitutes a potential source of oceanic pollution. One step towards minimizing the impact of the discharged washwater on the ocean environment is to insure an initial high degree of dilution immediately aft of the ship. It is common practice, at present, for the washwater to be pumped over the side of the ship. A recent report by Norway¹ to the IMCO subcommittee on Marine Pollution showed that this method is far less effective in achieving a high initial dilution than if the washwater is released through the hull of the ship.

In the tests reported by Norway, the over-the-side discharge was accomplished by connecting a hose to a manifold on deck which provided a discharge rate of 150 tons/hour. The discharged water containing Rhodamine-B dye was observed to remain concentrated in a narrow band running parallel to the ship's course. Samples of water were taken at various depths within the discolored band and subsequently analyzed to determine the degree of dilution. The minimum observed dilution was 1:275.

Previous analyses of typical concentrations of contaminants in washwater discharges had shown that the maximum concentration expected would be less than 2%. The minimum observed dilution of 1:275 corresponds therefore to a maximum concentration of noxious substance (assuming that the concentration in the washwater was 2%) of 73 ppm. The subsequent dilution in the sea was observed to occur slowly. After two hours the observed dilutions were still as small as 1:625 ($C_{\max} = 32$ ppm).

The advantage of discharging the tank washwater through the hull is that it becomes mixed with the ship's wake which should insure a much greater dilution than can be accomplished by over-the-side discharge. The tests described in the IMCO report were conducted aboard a fully-laden coastal tanker. A radioactive tracer was released just below the water surface at a position which insured that it would be moved through the propeller. The tracer was dissolved in 0.6 liters of water and released at a uniform rate for 10 minutes. Consequently, there was no attempt to simulate the expected discharge rate of washwater (of the order of 30 to 100 tons/hour) in this test. Samples of the water in the ship's wake were taken following the release of the tracer. Unfortunately, the first measurement of the peak tracer concentration in the ship's wake was not made until 26 minutes after the passage of the ship. A plot of peak tracer concentrations against time was used to obtain an estimate of the initial dilution by a linear extrapolation of the measured values back to the time of passage of the ship. The estimated minimum initial dilution of the tracer was 1:11,800 for a washwater discharge of 100 tons/hour. If the discharge concentration is 2%, the expected maximum concentration in the sea would be then 1.7 ppm.

The Norwegian test results clearly show the dramatic decrease in the initial maximum concentration which occurs when the discharge is mixed in the ship's wake rather than discharged over the side. The present research is intended to extend the Norwegian results in order to elucidate the effects of (1) rate of discharge, (2) method of discharge, (3) discharge location, (4) ship speed, and (5) propeller loading. The test program was carried out on a model scale to allow for a systematic variation of discharge and ship parameters. Arguments for the validity of applying these model-scale test results for the prediction of dilutions expected for full-scale ships are presented in Section II of this report along with a general description of the mechanics of mixing.

The experimental study consisted of six test series: four conducted in the Davidson Laboratory circulating water channel and two in the 312-ft long towing tank. The tests in the water channel, described in Section III of this report, included measurements of the dilution of a released tracer for the following conditions: (1) an unobstructed flow in the channel, (2) a propeller operating in the channel, (3) a foreshortened model of a typical chemical tanker fixed in the water channel without a propeller, and (4) the same model but with an operating propeller. The tests in the towing tank described in Section IV of this report included measurements of the dilution of a tracer released from a geometrically scaled, 8-ft long tanker model operating with and without a propeller.

The towing tank tests were clearly the most important for prediction of full-scale dilutions since these tests much more closely simulated the operation of full-scale tankers than did the water channel tests using a distorted model in a confined channel. The water channel tests were, however, crucial to the success of the towing tank tests. The water channel proved ideal for photographs of the released tracer. In addition, a large number of test conditions could be much more efficiently investigated in the water channel than in the towing tank. The results of the water channel tests were used to aid the design of the definitive tests in the towing tank.

This research was supported by the United States Coast Guard under Contract DOT-CG-33148. Mr. Robert Goldbach, Vice President, Marine Transport Lines, generously offered practical advice and provided drawings of the typical chemical tanker, S.S. MARINE CHEMIST.

II. MECHANICS OF MIXING

Elementary Cases

The diffusion of an admixture in an entering flow, such as an over-board discharge from a ship, to an external flow such as the main flow about a ship's hull, is effected by turbulent mass transfer processes for most flows of engineering significance. The general characteristics of several kinds of important "simple" flows, such as boundary layers, wakes and jets spreading in an external stream of fluid, will be briefly described to show certain significant features which may be relevant to studies of more complex flows, viz., about ship's hull.

Diffusion of tracers from a line source at or near the wall into a developing turbulent boundary layer has been studied by Poreh and Cermak² who distinguish four different "stages" of the diffusion as: the initial stage, an intermediate stage, a transition stage and the final stage, which is of greatest interest for this review. In this region the diffusion boundary layer extent, or thickness, becomes a constant fraction (about 0.64) of the velocity boundary layer thickness. Concentration distributions of the admixture of the tracer are similar at successive stations at distance x from the effective origin of the tracer. Consequently, the maximum concentration of admixture compared to the original concentration of the admixture in the discharge varies inversely as the boundary layer thickness, i.e.,

$$C_{\text{measured}}(x) = \frac{\text{constant} \times C_{\text{discharge}}}{\delta} \quad (1)$$

where δ is the boundary layer thickness. For a flat plate with turbulent flow, the boundary layer thickness may be approximated by

$$\delta = \frac{0.37 x^{4/5}}{(U_{\infty}/\nu)^{1/5}} \quad (2)$$

where U_{∞} is the uniform external velocity and ν is the kinematic viscosity. Hence,

$$\frac{C_{\text{meas}}(x)}{C_{\text{discharge}}} = \text{constant} \cdot x^{-4/5} \quad (3)$$

The mixing is turbulent and is evidently promoted by the momentum and vorticity interchanges associated with the wall shearing stresses.

The characteristics of the diffusion boundary layer, viz., thickness and wall concentration, are shown graphically in comparison with other boundary-layer characteristics in Figure 1, which is taken from a paper by Wu.³ The important features are that the tracer does not disperse outside the velocity boundary-layer, i.e., beyond the limits where turbulent interchange occurs, that the maximum concentration falls off rapidly with downstream distance, and that the diffusion layer, where the tracer concentration is fairly uniform, thickens to a large fraction of the velocity boundary layer thickness within a fairly short distance from the position where tracer is introduced.

The problem of diffusion from a line source is effectively two-dimensional: the corresponding three-dimensional problem of diffusion from a point source into a turbulent boundary layer has not, to the authors' knowledge, been studied. Moreover, in this case which is of greater interest for discharge from chemical tankers, the effect of the momentum of the entering (tracer) fluid may be significant and the mixing of "jets" of fluid with turbulent boundary layers has not been studied for either line sources (plane jets) or point sources (circular jets).

The cases of free jets or wakes in a uniform flow have been studied extensively, however, and in this case as well turbulent diffusion accounts for the important dispersion of admixtures for virtually all cases of engineering significance. A comprehensive description of the general properties as well as various theoretical analyses of turbulent jets and wakes is available in a monograph by Abramovich.⁴ The term "jet" is used to describe the flow of fluid (at different velocities) on either side of a tangential separation surface. In an axisymmetric jet, for instance, the velocity in a relatively small core of fluid is usually appreciably greater than that of the external flow, which may be either "co-flowing" (moving in the same direction), "counterflowing" (moving in an opposing direction), or,

perhaps, oblique. In a "wake," on the other hand, the velocity of the core fluid is generally less although not necessarily appreciably less than that of the external fluid.

A special characteristic of turbulent free jets and wakes is the absence of solid boundaries of flow although such boundaries are ordinarily the original source, at some distance removed, of the jet or wake. Consequently, the very thin laminar sublayer adjacent to the wall, which is the part of a turbulent boundary layer in which viscosity is important, is also absent and the influence of viscosity may be neglected for all cases of free turbulence. This explains the observed similarity of jets, independent of Reynolds number over a very broad range.

In the main region of a jet or wake, at a sufficient distance from the origin, velocity and concentration distributions are similar at successive stations. However, the velocity distribution is not the same as the concentration distribution. Figure 2, taken from Abramovich,⁴ shows the distribution of concentration of an admixture as well as the distribution of temperature differences (which is the same as the concentration distribution since turbulent mass transport accounts for both kinds of mixing) and of velocity differences for an axially symmetric jet in a co-flowing stream.

In case the jet is not discharged in-line-with the stream (either coflowing or counterflowing), it is deflected by the stream and the resulting path of the jet is curved.

The rate of diffusion or growth of a jet is affected by such factors as the ratio of jet velocity to stream velocity, the initial direction of the jet relative to the stream, the turbulence level of the external stream and the uniformity (or spatial variation) of the external stream. Jets with only small differences between their initial velocity and that of the stream, as well as wakes, have the characteristic that their growth is relatively insensitive to the velocity ratio. Two-dimensional jets and wakes behave somewhat differently from circular jets and wakes, as is indicated in the following table, taken from Schlichting's⁵ book, which shows the rate of increase of width and decrease of maximum velocity difference

for various cases of turbulent flow.

TABLE 1
POWER LAWS FOR VARIATIONS OF
WIDTH, MAXIMUM VELOCITY DIFFERENCE AND CONCENTRATION OF ADMIXTURE
WITH STREAMWISE DISTANCE x , FOR VARIOUS CASES OF TURBULENT FLOW

Case	Width, b	Max Velly Difference	Concen- tration
	b	u_m	c
Two-Dimensional Submerged Jet	x	$x^{-1/2}$	$x^{-1/2}$
Circular Submerged Jet	x	x^{-1}	x^{-1}
Two-Dimensional Wake	$x^{1/2}$	$x^{-1/2}$	$\sim x^{-1/2}$
Circular Wake	$x^{1/3}$	$x^{-2/3}$	$x^{-2/3}$
Two-Dimensional Boundary Layer	$x^{4/5}$	x^0	$x^{-4/5}$

The manner in which concentrations of admixtures vary is also included in this table and the case of the two-dimensional boundary layer added. The x -distance is measured from an "effective origin," appropriate to the flow in the main region of the jet and the final stage of the diffusion boundary layer, for instance.

The term submerged jet is applied to jets issuing into otherwise quiescent fluid. For the general case of a jet in a stream $db/dt = \text{variable}$, except in cases of co-flowing jets where the jet velocity is close to the stream velocity, when $b = \text{const} \cdot x$ is also valid.

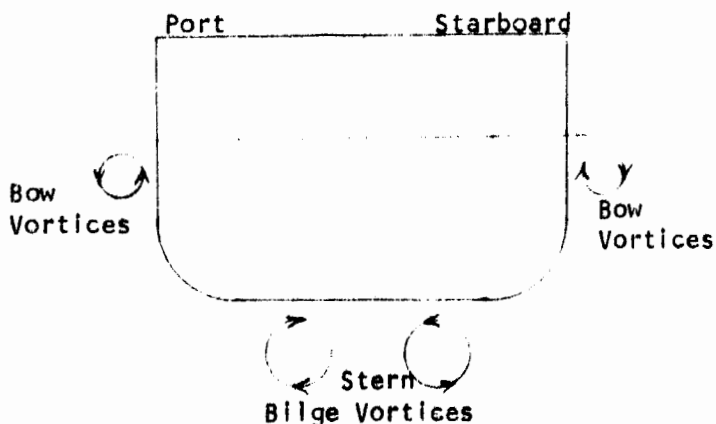
Some photos showing diffusion of admixtures introduced in a variety of ways are given in Figure 3. The irregular "boundaries" of the emitted stream (which, for the velocity ratios shown, amounts to a "wake with base bleed" rather than a jet flow) well illustrate the turbulent fluctuations which occur. It will be noted that some of the streams droop downward, a manifestation of the greater density of the emitted saline solution than of the stream. The drooping depends on the stream speed, which is very low (0.5 ft/sec) for these photos, and at higher test speeds, typical of the ship model tests reported here, is not significant.

Considerations for Overboard Discharges from Ships

In general, it is desirable to effect the greatest possible mixing and dispersion of unavoidable overboard discharges from ships within a short distance abaft the ship in order to minimize potential effects on marine life. Consideration of the results for elementary cases of mixing provides certain insights into methods of discharge which should be adopted to achieve rapid and complete mixing. Results of more detailed investigations by model tests (to be discussed subsequently) will indicate that such considerations, while useful, are incomplete in themselves and that certain interesting and anomalous features of the flow can occur.

Injection into a boundary layer, at least for the case of negligible momentum of the entering material, can produce effective mixing through most of the boundary layer's thickness if the injection location is only a short distance (on the order of ten to twenty boundary layer thicknesses) upstream of the observation position. Thus, it is not necessary to inject effluents through the ship's hull very far forward in order to accomplish good mixing astern of the ship; injection near the stern may be expected to be equally effective.

The flow patterns around full form ships such as chemical tankers and other bulk cargo carriers are complex, as revealed by various investigators, notably Shearer and Steele.⁶ Various means of flow visualization reveal that trailing vortices, having longitudinal axes, are often formed both near the forward end and from the bilges at the aft end of the parallel middle body. The "sense" of the rotational flow in these vortices is ordinarily as depicted in Sketch A but the bow vortices are importantly influenced by the



SKETCH A. APPROXIMATE POSITION AND SENSES OF BOW AND STERN BILGE VORTICES

details of bow shape, especially whether a bulbous bow is adapted (bulbous bows may, in some cases, suppress the bow vortex system). Trim also affects these vortex systems significantly and, consequently, the overall flow patterns and ship resistance (which is, however, incidental to the present discussion). The point of this discussion is that effluent can be convected by the external flow patterns along rather complex paths, depending upon the through-hull injection locations. This is especially so if injection occurs at high velocity (momentum), through a small diameter outlet so that mixing in the wall region of the boundary layer is not possible, and effluent may be convected not in the direction of streamlines in the vicinity of the hull but along streamlines of the external flow which may be appreciably skewed from those next to the hull.

In case of discharge from the ship through a hose over the side, it is important that the effluent be mixed by the boundary layer, which is several feet thick at the stern of a typical chemical tanker. If the discharge occurs at too great a distance abeam of the hull mixing will not benefit from the hull- and propeller-generated turbulence but only from the ambient turbulence of the sea and that of the effluent stream itself; the resulting discharge can be expected to diffuse very much more slowly than a wake-stirred effluent.

The rate of diffusion with time or distance behind the ship can be expected to depend mostly on the ultimate development of the wake of the ship. Previous experimental studies by Schooley and Stewart⁷ and by Kennedy⁸ have shown that the development of wakes of self-propelled bodies in density-stratified flows depend importantly on the density gradients. In general, effluent discharged from chemical tankers will not be neutrally buoyant. While this is considered to have little effect on the near-ship mixing, it may well affect the subsequent dispersion as the wake develops further. Inasmuch as density gradients are typical in the ocean (in fact, a density discontinuity exists at the surface), the separate and/or combined effects of density gradients in the sea and density differences between the sea and the effluent on the diffusion of the effluent in the ship's wake may be expected to be quite complicated.

Some Simplified Analyses

It is interesting to consider some highly simplified analyses of the average concentration of effluent in the wake of a ship based on conjectures concerning the spreading of the effluent in the wake at some (unspecified) longitudinal position. These analyses suggest that results for tests with a particular ship or model give useful guidance for other ships (or models) of generally similar, but not identical, proportions.

In the IMCO report¹ the following equation is used to estimate the average, initial concentration aft of the ship,

$$C_{avg} = \frac{C_D Q_D \rho_D}{BDV_s \rho_{sw}} \quad (4)$$

where

C_D = concentration of noxious substance in the washwater discharge

Q_D = volume discharge rate of washwater

ρ_D = density of washwater

B = beam of ship

D = draft of ship

V_s = ship's speed

ρ_{sw} = density of seawater

C_{avg} = estimate of the mean concentration immediately aft of the ship

Two basic assumptions are made in the derivation of Eq.(4), each of which tends to make it a nonconservative estimate of C_{avg} . The first assumption is that the discharge is uniformly mixed over a plane immediately aft of the ship with an area equal to the beam times the draft. The second is that the volume of water moving through this plane per unit time is simply the area of the plane times the forward speed of the ship.

An alternative formulation to estimate C_{avg} , based on the propeller characteristics, uses the basic assumption that the discharge is moved

through the propeller and that immediately aft of the propeller the concentration is uniform over a plane with an area equal to the area of the propeller disk, i.e., $\frac{\pi D_p^2}{4}$ where D_p is the propeller diameter. In view of the propeller's suction action in pumping fluid aft to produce thrust, these assumptions seem more plausible than the former ones although it is appreciated that the details of the flow are actually of greatest importance. The calculation of the average velocity of the water through this plane can be found for a given ship from

$$V_{avg} = V_s (1 - w) \left[\frac{1 + (C_{Th} + 1)^{\frac{1}{2}}}{2} \right] \quad (5)$$

where:

$$w = \frac{V_s - V_a}{V_s}, \quad \text{the wake fraction,}$$

$$C_{Th} = \frac{8T}{\rho_{sw} \pi D_p^2 V_a^2}, \quad \text{the thrust coefficient,}$$

V_a is the speed of advance of the propeller through the ship's boundary layer flow, and

T is the propeller thrust

The values for w and C_{Th} are known, at least approximately, for any given ship. For example, for a T-2 Tanker, 17,000 dwt, 503' x 68' beam x 30' draft, $w = 0.3$ and $C_{Th} = 1.05$. For many practical applications, a sufficiently good approximation for V_{avg} is to use simply $V_{avg} \approx V_s$. For the

example of the T-2 Tanker $\frac{V_{avg}}{V_s} = 0.85$. The volume flow through the propeller Q_p is

$$Q_p = V_s (1 - w) \left[\frac{1 + (C_{Th} + 1)^{\frac{1}{2}}}{2} \right] \frac{10^2 p}{4}, \quad (6)$$

and the concentration of released substance aft of the propeller under the assumption that it is completely mixed with the volume flux Q_p is

$$C_{avg} = \frac{C_D Q_D \rho_D}{\rho_{sw} Q_p} \quad (7)$$

The difference between using Equation (4) and Equation (7) to find estimates of the average concentration aft of the ship is substantial.

Using the T-2 Tanker as an example and by assuming $V_s = 15.8$ knots, $D_p = 19\frac{1}{2}'$, $C_D = 2\%$, $\rho_D Q_D = 100$ tons/hour, and $\rho_{sw} = 64$ lbs/ft³, then from Equation (4)

$$C_{avg} = 0.35 \text{ ppm}$$

and from Equation (7)

$$C_{avg} = 2.79 \text{ ppm}$$

Equations (4) and (7) can each be used to estimate the initial average concentration aft of the ship used in the tracer experiments described in the IMCO Report. The ship was a 1300 dwt tanker with a beam of 11.6 m and a draft of 3.95 m. The ship speed was 12 knots. No information on the ship's propeller was given in the report but its diameter can be assumed to be approximately two-thirds of the ship's draft. For a discharge of 100 tons/hour and concentration in the discharge of 2% then Equation (4) yields an average initial concentration of

$$C_{\text{avg}} = 2 \text{ ppm}$$

while equation (7) gives

$$C_{\text{avg}} = 17.2 \text{ ppm}$$

assuming that $V_{\text{avg}} = V_s$ and $D_p = 2/3 D$. With either equation the estimated average concentration immediately aft of the ship is greater than the peak concentration, 1.7 ppm, which was determined by extrapolation of the measurements of tracer concentrations. It seems likely that the actual peak value immediately aft of the ship would be considerably greater than the average values calculated from either Equations (4) or (7). Consequently, the extrapolated value of 1.7 ppm used as an estimate of the peak concentration immediately aft of the ship seems to be too small, which casts doubt on the validity of the linear extrapolation used to find this value.

Neither Equation (4) nor Equation (7) is useful for accurate predictions of the peak concentration aft of the ship, since the assumptions on which they are formulated would never be fully satisfied. Furthermore, neither equation accounts for the effect of the location of the discharge along the hull of the ship. Granting the limitations of Equations (4) and (7), they are useful in identifying parameters which would influence the dilution of the washwater. If we define the minimum dilution as simply C_D/C_{peak} , then Equations (4) and (7) suggest that for a given ship the dilution will increase as the ship speed increases, as the propeller loading increases, and as the rate of discharge of the washwater decreases. The chief difference between Equation (4) and Equation (7) is the assumption of the area over which the

contaminant is spread: Equation (4) assumes an area equal to the beam times draft, while in Equation (7) the area is the projected area of the propeller, $\pi D_p^2/4$. For intermediate to large liquid bulk carriers, in the length range from 600 to 900 feet, the ratio of the draft of the ship to the propeller diameter varies within small limits, typically from 1.6 to 2.2. Similarly, the length/beam ratio of these ships varies within small limits, typically from 6.5 to 7.5. The length/draft ratio varies typically from 15.5 to 17.5. The consequence of this similarity in form and propeller size is that the dilution of the discharged wash-water can be expected to vary approximately with the square of the length of the ship, L . To see this, we can simply replace the beam, B , the draft, D , and the propeller diameter, D_p , in Equations (4) and (7) by $B = \alpha L$, $D = \beta L$, $D_p = \gamma L$. Providing that α , β , and γ are nearly constants for most bulk carriers, then both Equations (4) and (7) show dilution varying as the square of the ship length.

The purpose of the model studies described in this report was to determine the dilution of substances discharged through the hull. The experimentation on a model scale allowed for a systematic variation of (1) discharge location, (2) discharge rate, (3) method of discharge, (4) ship speed, and (5) propeller loading. The results obtained from these model studies can be applied to the prediction of the expected dilution in the wake of full scale ships. From the arguments presented above, the dilution, C_D/C_{peak} , may be written

$$C_D/C_{\text{peak}} = K \frac{L^2 V_s}{Q_D} \quad (8)$$

where K is an a priori unspecified proportionality constant which could include effects of propeller loading, discharge location and method of discharge. It must be assumed that K for the model tests and for the prototype, would be the same if the method of discharge, propeller loading, C_{Th} , and discharge location were the same. The volume rate of discharge, Q_D , may be expressed as

$$Q_D = A_D V_{jet} \quad (9)$$

where V_{jet} is the velocity of the wastewater discharging through an orifice of area, A_D . If λ is the scale ratio of the prototype's length dimensions to the model's, then Equation (5) and (6) can be combined to give the following

$$(C_D/C_{peak})_{fs} = K \frac{\lambda^2 L_m^2}{(A_D)_{fs}} \left(\frac{V_s}{V_{jet}} \right)_{fs} \quad (10)$$

where subscript m refers to model parameters and fs to the full-scale ship. If $(A_D)_{fs}$ can be represented by $\lambda^2 (A_D)_m$, then

$$(C_D/C_{peak})_{fs} = K \frac{L_m^2}{(A_D)_m} \left(\frac{V_s}{V_{jet}} \right)_{fs} \quad (11)$$

III. WATER CHANNEL TESTS

Apparatus

The Davidson Laboratory Circulating Water Channel is shown in Figure 4. The flow in the test section is controllable from approximately 1/3 to 15 fps. The output from a tach generator mounted on the drive shaft of the impeller had been previously calibrated against the speed of the flow in the water channel. During the present tests in the water channel, water speed was determined from the tach generator output signal and continuously monitored during the tests. A cover plate to suppress free-surface effects was built of one-inch thick styrene plastic for use during all four series of tests in the water channel. The cover plate was transparent to aid in visual observations of the dyed tracer. For the open-water test series (with and without a propeller), the cover plate's center section, as shown in Figure 5, had 3 parallel slots 20 inches long, 3/16-inch wide, 2 inches apart through which the tube for injecting the tracer could be inserted into the test section. For the open-water propeller test series, a right angle drive was mounted through the cover plate which is also shown in Figure 5. For the tests employing the foreshortened tanker model, the hull was attached to the cover plate and the two styrene strips in the center section between the slots were removed to provide access to the interior of the model.

The tracer solution (5% salt, 5% Tintex fabric dye dissolved in tap water) was injected in the open water tests through an 0.097-inch I.D. tube with a right angle bend. The tracer was pumped by a Sage Instrument Company Model 7122-21 variable speed syringe pump. The flow rate was continuously adjustable from 0.21 ml/hr to 140 ml/hr. A calibration curve of dial setting against flow rate was obtained and used for all tests including those in the towing tank.

For the open-water propeller tests, a right angle drive system was constructed. A D.C. motor with continuously adjustable speed control was mounted above the cover plate and coupled to a drive shaft supported in a streamlined strut. The strut was mounted directly to the cover plate.

The strut terminated in a shaped pod containing an electric-drill-type, right angle gear to which the propeller shaft was attached. The photographs in Figure 5 show this drive system.

A previous project at the Davidson Laboratory had employed a similar system for open-water propeller testing. Consequently, the thrust characteristics of this installation were available in the form of conventional propeller K_T vs. J curves. Figure 6 shows this curve for the propeller used in the present open-water tests as well as a curve of the thrust coefficient, C_{Th} . The propeller characteristics are also listed on the figure.

The model used in the water channel to simulate the flow over the afterbody of a tanker was developed from techniques suggested by similar work at the Swedish State Shipbuilding Experimental Station.⁹

The hull lines shown in Figure 7 are based on plans for a T-6 Tanker, the S.S. MARINE CHEMIST, which were supplied by Mr. R. D. Goldbach of Marine Transport, Inc. The stern profile and rudder shape are geometrically scaled to 1:76.5 and are also shown in Figure 7. The breadth of the model is considerably narrower than a geometrically scaled model in order to reduce blockage effects in the channel. The length of the model corresponds to only the aft 7 stations plus a very abbreviated bow shape. The model was mounted in the water channel to simulate a partial draft condition in which the entire propeller aperture is just submerged.

The foreshortened model was built of fiberglass and was outfitted with rudder, stern tube, and propeller motor mounted on a thrust balance. The propeller was the same one used in the towing tank tests and is described on page 22. The feedback-controlled propeller motor's drive shaft rate of rotation was determined from a magnetic pulse sensor. The model was provided with 32 through-hull discharge ports, as shown in Figure 8.

The apparatus for determining the concentration of the tracer solution was essentially the same as for the towing tank tests and is described in Section IV and in Figures 21 and 23. The only differences between the water channel and towing tank tests were the use of three probes in the water channel (as opposed to five in the towing tank) and the use of $\frac{1}{2}$ -inch spacing between probes (as opposed to either 2 or 4 cm spacing in the towing tank).

Series I: Open-Water Tests

For the tests in the unobstructed water channel test section, the tracer solution was introduced upstream of the three conductivity sensors through the 0.097-inch I.D. tube. For each test condition the sensors position was systematically varied in order to determine the peak tracer concentration over a plane downstream of the injection. Photographs of the dye for each condition were taken through the glass sidewalls of the channel test section. Examples of these photographs are shown in Figure 3.

In the open-water tests the effects of discharge rate, water speed, method of discharge and downstream distance on the dilution of the tracer was determined. The instantaneous conductivity measurements as observed on the oscillograph records were highly variable. For reliable estimates of the time-averaged concentration distribution, it was necessary to average the sensor signals over a period of five seconds. This procedure was followed for all four series of tests in the water channel. Figure 9 shows a typical time-averaged distribution of tracer concentration for the open-water tests. The chief result of the concentration measurements was the determination of the maximum time-averaged concentration which corresponds to the minimum dilution ratio. All results of the water channel and towing tank tests are reported as the ratio of the measured concentration to the initial concentration of the tracer at its point of discharge. The reciprocal of this ratio is the dilution ratio, e.g., a measured value of C_{meas}/C_D of 5×10^{-4} represents a dilution ratio of 2000:1.

The chief results of the open-water test series are summarized in Figure 10. In Figure 10(a), the ratios of the peak, time averaged, concentration, C_{peak} , to the initial concentration, C_D , with the conductivity probes 15 inches from the discharge have been plotted against the ratio of the jet speed, V_{jet} , to the water channel speed, V_{stream} . For a fixed water channel speed and fixed discharge port area, the ratio $V_{\text{jet}}/V_{\text{stream}}$ simply represents variations in the rate of discharge. The fact that Figure 10(a) shows C_{peak}/C_D values for three different water channel

speeds lying approximately on the same C_{peak}/C_D versus $V_{\text{jet}}/V_{\text{stream}}$ straight-line curve indicates that the dilution ratio varies directly with the ratio $V_{\text{jet}}/V_{\text{stream}}$. The effect of method of discharge is also indicated on Figure 10(a). The methods of discharge tested included co-flowing jet discharges with angle, α , between the jet and stream, equal to 0° ; contraflowing jets with $\alpha=180^\circ$; and jet discharges with $\alpha=45^\circ$. The effect of method of discharge was not significant except for one case, that of a contraflowing jet with $V_{\text{stream}} = 0.5 \text{ ft/s}$.

Figure 10(b) shows the effect of downstream distance on peak concentration. In Section II, arguments were presented for a variation in jet concentration proportional to $x^{-2/3}$ where x is downstream position. The results shown in Figure 10(b) seem to confirm this dependence. However, the paucity of data does not allow a definite conclusion to be drawn.

Series II: Open-Water Propeller Tests

With the propeller (described in Figure 6) operating in the water channel, procedures similar to those described above for Series I were used to determine the effect of discharge rate, method of discharge, water speed, and propeller loading on the dilution of the tracer downstream of the propeller. Photographs and conductivity measurements were made for each test condition except for the effect of discharge location for which only photographs were taken. Examples of the photographs for the open-water propeller tests are shown in Figure 11.

The conductivity measurements were all made for a discharge location 10 inches forward of the propeller, and one-inch below the propeller centerline and for the conductivity sensors mounted 5 inches downstream of the propeller. Figure 12(a) shows the results of the conductivity measurements presented as a plot of C_{peak}/C_D versus $V_{\text{jet}}/V_{\text{stream}}$. The thrust coefficient for the results in Figure 12(a) was held constant at 3.0. The values of C_{peak}/C_D for variations in V_{stream} and discharge method ($\alpha=0^\circ$ and $\alpha=45^\circ$) do not collapse as well onto a single straight-line curve for this test series as they did for Series I. The line drawn through the measured values

in Figure 12(a) is an approximate best fit. It is difficult to discern any clear trends in the data with respect to the effects of water speed or discharge method. It should be noted, however, that the values of C_{peak}/C_D in Series II are approximately 4 times smaller than the values obtained in Series I at the same ratio of discharge velocity to water speed. Also shown in Figure 12(a) is the theoretical curve for the dependence of the ratio of the average concentration to the initial concentration on $V_{\text{jet}}/V_{\text{stream}}$ obtained from Equation (7) in Section II. Since no attempt was made to obtain estimates of the spatially averaged dye concentration over a plane downstream of the propeller, a true test of Equation (7) cannot be made. It is apparent, however, that the theory is not inconsistent with the test results.

Further evidence on the validity of Equation (7) is provided in Figure 12(b). In this figure the results for a systematic variation in thrust coefficient, C_{Th} , for $V_{\text{jet}}/V_{\text{stream}} = 0.5$ are depicted as a plot of C_{peak}/C_D versus $2/[(1 + C_{\text{Th}})^{\frac{1}{2}} + 1]$, and from Equation (6), a linear relationship would be expected. The measured results tend to confirm this dependence of C_{peak}/C_D on C_{Th} .

Series III and IV: Simulated Hull With and Without Propeller

With the distorted hull model fixed in the water channel, an extensive series of tests for the hull-with-propeller case was undertaken to determine the effect of discharge location, discharge rate, method of discharge, water speed, and propeller loading on the dilution of the discharge aft of the model. A short series of tests for the hull-without-propeller case was undertaken to provide information on the relative importance of the propeller on the "observed" dilutions. Procedures similar to those used in the previous series of tests were employed. Typical photographs showing the disposition of the dye near the stern of the model are shown in Figure 13.

The conductivity measurements were made 10 inches aft of the propeller. The effect of discharge location on the ratio C_{peak}/C_D is presented in Table II for $V_{\text{jet}}/V_{\text{stream}} = 0.2$, $V_{\text{stream}} = 1.0$ ft/s and $C_{\text{Th}} = 3$. The

chief result to be found in this tabulation is that there is only slight effect of discharge location on dilution aft of the ship. The discharge through the two locations (26 and 32) closest to the propeller did, however, result in somewhat higher dye concentrations.

The effect of method of discharge ($\alpha=45^\circ, 90^\circ$ and 135°) on the dilution was investigated. The result was that there was no measurable effect on the dilution.

The effect of discharge rate and water speed was determined for discharge locations 17, 20 and 32 for $C_{Th}=3.0$. The results are presented as plots of C_{peak}/C_D versus V_{jet}/V_{stream} in Figure 14 (location 17), Figure 15 (location 20), and Figure 17 (location 32). Also presented in Figure 14 are the results for the effect of V_{jet}/V_{stream} on C_{peak}/C_D for the case of the hull with no propeller. The values of C_{peak}/C_D for the hull-without-propeller case were about twice those obtained for the hull-with-propeller case. The results for all three discharge locations reveal an essentially linear dependence of C_{peak}/C_D on V_{jet}/V_{stream} . The results are essentially unaffected by variations in V_{stream} . The linear dependence of C_{peak}/C_D on V_{jet}/V_{stream} was anticipated in both the Norwegian (Eq.(4), Section II) and Propeller (Eq.(7), Section II) theories presented in Section II. The calculated dependence of C_{avg}/C_D on V_{jet}/V_{stream} as deduced from these two theories are presented in Figure 14.

Finally, Figure 17 shows the dependence of C_{peak}/C_D on $2/[(1+C_{Th})^{1/2}+1]$ at discharge locations 17, 20, and 23 for $V_{jet}/V_{stream} = 0.2$. No clear trend in these results could be discerned.

IV. TOWING TANK TESTS

Model and Apparatus

A 1:76.5 scale model of a typical chemical tanker, the T-6 type SS MARINE CHEMIST, was built of wood and outfitted with rudder, stern tube, propeller motor with thrust-measuring balance and bilge keels extending from stations 8 to 13. Lines for this ship were kindly loaned by Mr. Robert Goldbach of Marine Transport Lines. A body plan and bow and stern profile is shown in Figure 18. Since the present tests were to focus on liquid discharges in the ballast condition, the model was built with appreciably less freeboard than the ship and with no sheer.

Turbulence-stimulating sand-strips, 1/4-inch wide at station 0 (the forward perpendicular) and 1/2-inch wide at station 1 (5-inch aft of F.P.) are somewhat larger than ordinarily used for conventional resistance testing purposes to assure early transition of boundary layer flow, which importantly affects early mixing of injected materials, to fully turbulent flow, as on the ship.

A propeller model was selected from the Davidson Laboratory library having characteristics which may be compared with those of the propeller fitted to the SS MARINE CHEMIST as follows:

	<u>SS MARINE CHEMIST</u>	<u>DL Hull 4052, Prop 33L (corres. full-scale values)</u>
Diameter	21'-4"	21'-5"
Number of Blades	4	4
Pitch/Diameter(at 0.7R)	0.754	0.795
Blade Area Ratio	0.562	about 0.65
Direction of Rotation	RH	LH

The model propeller's characteristics are sufficiently similar to those of the typical chemical tanker to give similar operating conditions of RPM, thrust loading coefficient, magnitude of propeller slipstream rotation, etc.

Six holes, with brass tubes having 0.097 in. ID were fitted at station 16 (3 tubes) which is slightly forward of the engine room, at station 10 (2 tubes) amidships, and at station 3 (1 tube) near the forward collision bulkhead for injection of the simulated discharge. The locations are indicated in the body plan, Figure 18. All injection tubes are on the port side of the model (in spite of the indication of Figure 1, where all forebody stations are opposite to afterbody stations) so that underwater still photos could be made through a mirror box on the east side of the tank. Other methods of overboard discharge, viz., through a hose trailed over the side of the vessel in various attitudes were investigated using flexible pvc tubing fitted with a brass, 0.097 in. ID nozzle. Lengths of reduced diameter tubing, having 0.066 in. ID and 0.030 in. ID could be inserted in the 0.097 in. ID tubes to provide modified injection characteristics.

Tests were carried out in Davidson Laboratory Tank No. 3, which is 312 ft long, 12 ft wide and 6 ft deep. A towing carriage runs on a mono-rail over the centerline of the tank, driven by electric or electrohydraulic drive motor through a continuous-loop towing cable.

Tracer solution, consisting of 5 percent table salt, 5 percent Tintex fabric dye and 90 percent tap water (by weight) was pumped to the injection holes from a Sage Instrument Co. model 7122-21 variable speed syringe pump. A linear motion transducer was connected to the syringe-driving block to

monitor the rate of injection. This piece of equipment is shown in the photograph, Figure 19. The achievable flow rate, using one or two 50cc syringes, can be adjusted by the potentiometer speed range switch settings between 0.21 ml/hr and 140 ml/min. The pump was started and stopped during tests by a switch controlling the power from a feed rail to the pump.

Using specific gravity (γ), injection velocity (V_{jet}), and outlet diameter (D_o) as characteristic values, we obtain an "internal Froude Number" of $F_i = V_{jet} / \sqrt{g(\gamma-1)D_o}$. Substituting values of V_{jet} and D_o which are typically found in the tests and 1.07 for γ , we obtain $F_i \approx 9.50$. For values of F_i of this order of magnitude, it is generally considered that buoyancy effects are not important compared to inertial effects, which has been confirmed by flow observations in the water channel tests. This conclusion may not hold for the flow at large distances from the ship or model.

The towing force between the model and towing carriage was sensed by a stiff-spring-element force balance (0.020 in deflection = 40lb maximum force) with a linear variable differential transformer (LVDT) to detect deflection. The output signal from the transducer was carried over towed cables from the carriage to integrating digital voltmeters (IDVM's) at the dock end of the tank. Tow force was averaged over 15 sec duration to minimize anomalies due to oscillations of the record (the natural frequency of the model-force balance-towing apparatus system is about 5 cycles per second). The tow-force balance is connected to the model through a free-to-trim pivot box and to the carriage through a free-to-heave mast system which effectively restrains model roll, yaw and sway. A photograph of the model and towing apparatus is given in Figure 20.

The propeller was driven by a feedback controlled motor whose speed was adjustable at the instrumentation area near the dock end of the towing tank. The propeller motor was connected to the model through a thrust force balance, similar to that used to sense tow force whose output was also averaged by an IDVM for 15 sec. Propeller RPM were measured with a frequency meter detecting the output of an electronic pulse generator mounted on the propeller shaft.

The conductivity probes constitute one leg of a Wheatstone bridge circuit, as indicated in the sketch and schematic diagram of Figure 21. A variation of the conductivity of the liquid between the two stainless steel wire tips results in an unbalancing of the bridge. Excitation and signal conditioning were accomplished with Sanborn Model 350-1100B Carrier-amplifiers having adjustable sensitivity. Calibration data for the five probes are given in Figure 22, and best-fit linear curves were derived, as shown. The highly turbulent signals are averaged by IDVM's over a period of 5 sec.

The probes were attached to a positioning device, shown in Figure 23, where the longitudinal (x), transverse (y) and vertical (z) positions can conveniently be adjusted. Centimeter scales are used for the y-z slider apparatus. Five probes are attached to a horizontal transverse bar: 15 alternate locations are possible with 2cm spacings between them.

Underwater photographs of the portside afterbody of the model, showing injected dye-stream diffusion (when the dye is injected at a very fast rate, and is therefore sufficiently intense), were attempted with a camera triggered by a photo-cell circuit, through a mirror box which can be seen in Figure 20.

In order to enhance the mixing of injected saline solution into the towing tank water and, hence, avoid spurious measurements, an array of rods was attached to an independently-driven carriage and towed along the length of the tank toward the dock end (in the direction in which the model backs up) and back to the far end of the tank between runs. A photograph of this stirrer is shown in Figure 24.

Test Program and Procedure

The model was ballasted to an intermediate loading condition typical of ballast operation of chemical tankers, which is considered to be the usual loading condition when tank cleaning wash water would be discharged overboard. Drafts corresponding to 22-ft forward and 28-ft aft or 0.60 and 0.71 times load draft, respectively, were used. The corresponding full size displacement of 30,600 tons is about 65% of the fully laden displacement.

All measurement systems, including tow force and propeller thrust

balances and conductivity probes were calibrated prior to starting the tests. The conductivity probes calibrations were checked frequently during the course of testing by immersing them in beakers of diluted samples of known concentration of the tracer solution injected during the tests. Repeat calibrations agreed with each other within $\pm 5\%$.

A brief program of experiments to measure the distribution of effluent behind the unpropelled model, without propeller, for a few test conditions, was conducted but the majority of experiments were conducted with the self-propelled model which realistically represents ship operation. Tests were conducted to determine the influence of a number of aspects of discharge condition and rate of dispersion with distance behind the model. These conditions may be grouped as indicated in Table III below: more complete descriptions of test conditions are given in Tables IV-IX which also contain some of the important results of tests.

TABLE III
TEST CONDITIONS

Test Conditions	No. of Tests	Details in:
1) Location of Discharge (No Propeller)	5	Table IV
2) Location of Discharge (Self-Propelled)	9	Table V
3) Rate of Discharge	6	Table VI
4) Size of Discharge Port	5	Table VII
5) Propeller Loading	5	Table VIII
6) Measuring Probe Longitudinal Position	9	Table IX

Tables IV through IX are located after the list of references.

A complete test for a given condition of discharge and/or measurement required several variations in the location of the array of probes in the vertical and transverse directions. As the position of the array of probes must be adjusted manually (see Fig. 23), the model and towing carriage must be stopped to make the adjustments; a technician stationed at a distance about 130 feet from the starting dock of the tank effected a change in

probe array position from a movable platform so that two sets of data could be obtained during one passage of the model along the length of the tank (the Davidson Laboratory monorail system does not accommodate a man-carrying test carriage).

During a test run, the signals from the probes as well as other transducer outputs, including the syringe-driving block position transducer on the pump, were recorded as oscillographs. The syringe pump occasionally would not function, the block being mechanically bound-up, and this would be immediately revealed by the oscillograph record so that the evidence of the transducer outputs (no signal) could be unambiguously interpreted as due to pump inaction rather than probe positions being outside the path of the effluent.

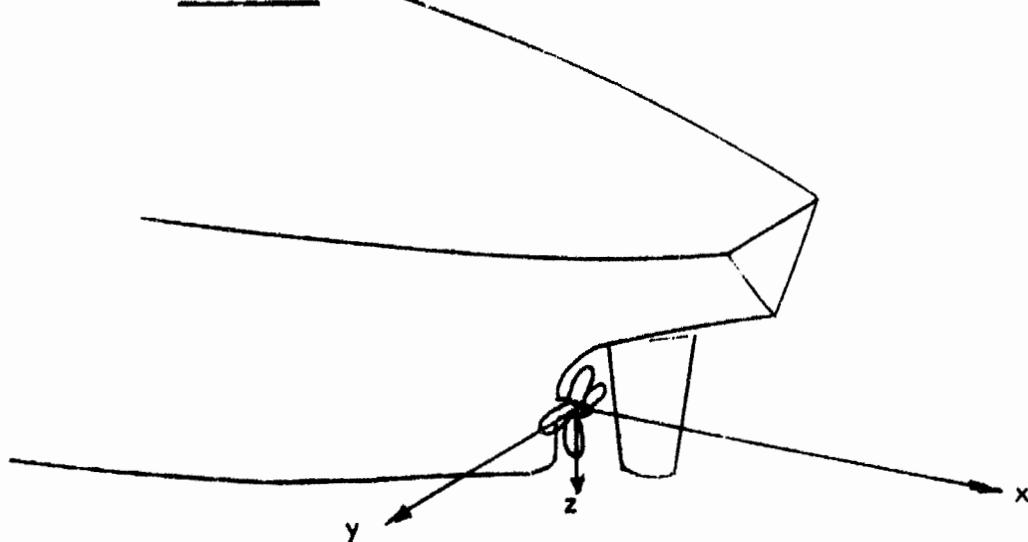
Time averages of the conductivity probe outputs were evaluated by first recording IDVM-integrated signals at the dock end of the tank prior to running the test. Then, with the model running at steady speed the syringe pump was turned on remotely and after a few seconds time for the flow to become steady, the IDVM's were automatically turned on. The difference between the running reading and the initial reading at the dock represents the time-average of the effluent concentration at the measurement location during steady discharge.

After completing a run along the length of the tank, the model was towed back to the dock and, at the same time, the array of stirring rods (see Figure 24) was towed first towards the dock, then to the far end, to effect improved mixing of the injected saline solution. While the model was in the dock, waiting for the tank water to become sufficiently calm to proceed with the next test, adjustments and changes were made to measuring probe arrays, the syringe pumps refilled, if necessary, and other model changes effected. The time between successive starts of runs was about six to eight minutes during the testing work.

Results

Complete test results are presented in Figures 25 to 53 in the form of plots of the ratio of measured concentration to the concentration of the tracer discharged from the model, C_{meas}/C_D , as a function of position in a plane at a given distance aft of the propeller plane. The coordinate system, indicated in Sketch B, has its origin at the center of the propeller (when the model is floating at zero speed) with x positive aft, y positive to port and z positive downward. This coordinate system advances with the ship but does not move vertically to adjust to the vertical displacement of the propeller center due to squat and trim.

SKETCH B. COORDINATE SYSTEM WITH ORIGIN AT CENTER OF PROPELLER



The maximum values of measured concentrations for each test are listed in Tables IV through IX in the form of dilution factors, C_D/C_{peak} . The position at which the maximum concentration was found is also listed in the tables.

The information concerning operating conditions, speeds etc., are given in the Figure captions and Tables in terms of ship-scale units. Froude scaling is used, i.e., velocities are proportional to the square roots of the linear dimensions. An exception is made in the case of the plots of C_{meas}/C_D : here, the transverse (y) scale is the same as the physical dimensions of the test set-up and the z -position parameter is

expressed in terms of model scale dimensions. In regard to this presentation, it should be noted that the half-beam of the model is less than 18cm, so the results presented indicate that the dispersion of effluent, at least at the downstream measurement locations studied, can be seen to be relatively small compared with the dimensions of the ship's cross-section.

More complete discussions of these results are given in the following Section V.

For one test condition a number of repeat runs were carried out to obtain an estimate of the precision of the test results. All of these test results are exhibited in Table X, below. The results of statistical interpretation¹⁰ of this very small sample of data may be expressed as: there is a probability of 0.8 that at least 86% of the measurements of C_{meas}/C_D for this test condition will be within $\pm 0.7 \times 10^{-4}$. While this statement is not as strong as may be desired, certain other features of the measurements may be pointed out, viz., the greatest discrepancy between an individual measurement and the average of the sample (for channel 3) amounts to 15% of the mean value. Furthermore, for measurements which indicate small or no saline admixture, the evidence of the oscillographic records confirms the IDVM results. Negative concentrations of saline admixture are, of course, not possible.

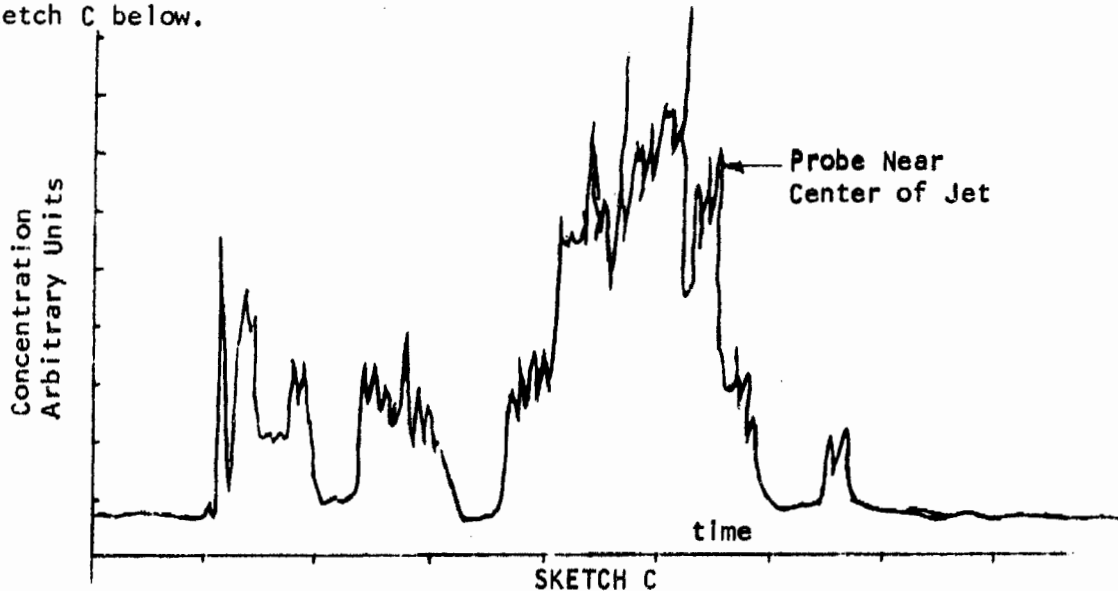
TABLE X

RESULTS OF REPEAT RUNS

RUN	CH 1	CH 2	CH 3	CH 4	CH 5
148-A	1.9	4.9	4.5	3.0	0.2
153-B	2.2	5.2	4.1	2.9	0.0
154-A	2.0	5.1	3.6	2.7	0.2
154-B	2.0	4.8	3.4	2.9	0.2

The concentration measurements exhibit highly turbulent fluctuations with oscillations comparable in magnitude to the mean values. An example of an oscillographic record of flow obtained from a probe in the wake behind an

ejector tube, such as shown in Figure 3, in the water channel is shown in Sketch C below.



EXAMPLES OF OSCILLOGRAPHIC RECORD OF CONDUCTIVITY PROBE

Records obtained during towing tank tests are quite similar. Two significant observations based on this oscillographic trace are: 1) when there is no effluent discharged through the tube there is no response from the probe, hence, the probes do not respond to fluctuations in the velocity of flow but only to the saline tracer, and 2) for steady discharge of effluent from the tube, a fixed probe may not experience steady-state signal but may have null response for certain periods. This can be related to visual observations of long-period meandering of the effluent path in the stream, which may well occur for discharges into the boundary layer and, subsequently, the wake of a ship or model.

Attempts to photograph discharge of the dyed tracer solution proved unsuccessful because of the rapid diffusion in the boundary layer. Even with the maximum discharge rate achievable with the syringe pump, corresponding to an unrealistic 495 tons/hr full size, the tracer was so diffused as to be practically imperceptible in photographs of the afterbody and propeller aperture. Consequently, no photographs are presented.

V. DISCUSSION

The towing tank test results will be considered in more detail in this section of the report and certain significant aspects discussed. Water channel test results, which were presented and discussed in Section III, will be referred to where appropriate.

Effect of Discharge Location

Tables IV and V contain results showing the effect of discharge of effluent from relatively large ports in the hull at locations indicated in Figure 18 as well as three locations of discharge through a tube over the side of the model. Table IV contains results for the model without propeller while Figures exhibiting test data for these conditions are given in Figures 25,26,27,29 and 30. Results for the self-propelled model are given in Table V and Figures 31 to 38. It is interesting that, while the minimum dilution factors do not vary greatly for a given discharge rate (at least for discharge through hull ports), the locations of the peak concentrations do vary.

Contour plots of constant (average) concentration distributions for discharge from various locations are given in Figures 54 to 61, for self-propelled model tests. Some inferences may be drawn from these contours in regard to the flow patterns around the hull and to preferred discharge locations to assure the best possible mixing in the far wake behind the ship as well as near the propeller:

(1) Discharges from locations 4, 5 and 6 (Figures 57-59) at Stations 10 and 3 are swept upward and outward, especially from the two locations under the turn of the bilge (numbers 4 and 6). This must be due to flow induced by the trailing bilge vortices generated at the aft end of the parallel middle body.

(2) Discharges from locations 1,2 and 3 (Figures 54-56) at Station 16 flow through the propeller. The effluent from the discharge port under the centerline of the ship (location 1) is not well-mixed at a distance $0.1 L_{pp}$

aft of the propeller plane, however, perhaps because mixing in the relatively thin boundary layer on the hull bottom is not as great as in the boundary layer and separated flow zone behind discharge locations 2 and 3. Subsequent mixing in the wake will probably be equally complete for all three locations but initial dilution is more effective from locations away from the ship's centerline and these are consequently more favorable.

(3) Discharges from hoses laid over the side of the deck may be directed either close by the ship's hull or well abeam. Three cases were simulated in these tests with contours of distributions for two cases shown in Figure 60 and Figure 61. For Case A (Figure 60), the discharge is from a location directly at the side of the ship at Station 16 from a height about 4-ft above the stillwater line. In Case B (Figure 61), the discharge is similar except at Station 10. In both of these cases the tracer enters the hull boundary layer which is several feet thick amidships on the full-scale ship. For Case C (Table V), for which the peak concentration is much higher than measured in any other test, the effluent was discharged from a location corresponding to 4-ft above water level at a distance 20-ft abeam of Station 16, simulating a hose discharge far from the hull's surface and well outside the boundary layer. The mixing of the tracer is very slight in this case: it proved to be quite tedious to find a position for the probe array where any tracer could be found. Only one of the sensors, which were spaced 2cm apart a distance 127cm downstream of the discharge location, detected any concentration at all and this was sensitive to the transverse position of the probe. The effluent appears to simply lie on the surface along a coherent path behind the discharge location and mixing is effected very slowly only by ambient turbulence and/or molecular diffusion. This observation, which seems to be much like what was reported in the Norwegian IMCO contribution,¹ for over-the-side discharge, indicates that this method of discharge is, in general, unsatisfactory.

(4) The influence of variations in ship speed on the measured concentrations was evaluated only for one condition without the propeller working, as indicated in Table IV and Figures 27, 29 and 30. For reduced speed (about 14.5 kts) the peak measured concentration, with fixed discharge rate corresponding to 330 tons/hr, is somewhat increased while for increased speed the peak measured concentration is reduced, as would be expected on physical grounds and the

reasoning that lead to Eqs.(8),(10) and (11)--(Section 11); the accuracy of the present measurements does not permit a statement that the peak concentration is, in fact, inversely proportional to ship speed as is implied by those equations.

Effect of Rate of Discharge

Contour charts showing the distribution of tracer for discharge from location 2 at both a lesser and a greater rate than shown in Figure 55 are presented in Figures 62 and 63, respectively. The distributions are quite similar. The peak concentration factors are plotted in Figure 64 as a function of the ratio of discharge velocity to ship speed, for the two discharge locations for which several rates of discharge were used. The peak concentration factors are seen to be proportional to the discharge velocities, as assumed in developing the simplified Eqs.(8),(10) and (11).

The ratios of discharge velocity to ship speed differ from the nominal values of 0.2, 0.4 and 0.6 because, for these cases, the actual model speed, which varied somewhat from run to run, corresponding to the maximum measured concentration of effluent, was used.

Two aspects of this finding should be emphasized: (1) it applies to the two discharge locations covered in these tests and may not be equally applicable to all possible discharge locations, and (2) for these cases corresponding to 7.33-in I.D. discharge ports, the discharge velocities are all low enough that the momentum of the discharged tracer is probably not important.

Effect of Discharge Pipe Size

Results for two cases, discharge from location 2 at Station 16 and location 6 at Station 3, where the discharge pipe diameter has been varied while the volume rate of discharge was held fixed, are listed in Table VII.

In case of discharge from location 6, where the effluent is swept upward and outward, the influence of the pipe diameter (or, alternatively, the discharge velocity) is relatively small on both the peak measured concentration and its location.

However, for discharge from location 2, both the peak measured concentration and its location are importantly affected by the pipe size. Higher discharge velocities, with fixed volume rate of discharge, result in less dilution, which must be associated with discharge jet momentum transporting effluent through the boundary layer to a region where the external flow sweeps it upward and outward. Contour charts are given in Figures 65 and 66, which may be compared with Figure 55 (results of tests corresponding to the 5.00-in I.D. pipe are not very complete and the derived dilution factor is subject to more uncertainty than other results).

Overboard discharge of effluent should be through large-diameter pipes or sea-chest, at low volume rates, so that mixing can readily take place in the boundary-layer adjacent to the hull.

Effect of Propeller Loading

Ratios of peak concentration to discharged concentration, obtained from Table VIII, are plotted in Figure 67 as a function of $2/[(1+C_{Th})^{\frac{1}{2}}+1]$. The results of the test without the propeller at a discharge rate of 165 tons/hr were adjusted to 330 tons/hr by assuming the peak concentration to be proportional to the volume discharge rate. The present towing tank results, in contrast to the water channel test results with an open-water propeller exhibited in Figure 12(b), do not indicate an important influence of propeller loading. Boundary layer and separated wake mixing evidently account for the predominant part of the mixing; nevertheless, it is considered sensible to discharge the effluent so that it passes through the propeller and subsequent mixing augmented by the added turbulence and vorticity associated with the propeller action.

It must be pointed out that the present investigation of the effect of propeller loading, by varying RPM of a given propeller and either towing or retarding the model while maintaining fixed speed, rather than self-propulsion, does not correspond to operational conditions. In that case, propeller loading is affected principally by the ratio of propeller size to ship size (e.g., midship section size). Large ships with moderate propeller RPM have high values of C_{Th} while small ships with low RPM have low values of C_{Th} . However, since the present investigation indicates that propeller

loading is not very important, it should not be required to carry out further studies on this aspect unless better resolution of dilution factors is required.

Effect of Longitudinal Position

The progressive dilution of effluent as it is left further behind the ship is an important feature concerning the effect of discharges. Values of peak measured concentration, C_{peak}/C_D , for discharges from two locations (Table IX) are presented in Figure 68a as a function of longitudinal position for distances up to 0.7 of the ship's length. Minimum dilution factors, C_D/C_{peak} , are shown in Figure 68b. Some of the results for discharge from location 2, without propeller, have been adjusted for discharge rate, assuming C_{peak} is proportional to discharge rate so that all results correspond to 330 tons/hr discharge rate.

There is not sufficient data to deduce a functional dependence of C_{peak}/C_D on x , such as the $x^{-2/3}$ relation for the circular wake quoted in Section II, for the case of either the self-propelled or non-propelled ship wake.

The dependence on longitudinal position is clearly very strong and very important: dilution can be doubled (concentration halved) within about $0.3 L_{\text{pp}}$, which corresponds to a duration of 7 sec for a ship speed of 16.5 knots.

Discharge from location 2, where the effluent flows through the propeller stream tube and into the middle of the ship's wake produces more rapid mixing with downstream position than discharge from location 4 where effluent is swept upward and away from the center of the wake.

To Achieve A Desired Minimum Dilution

The results presented on effect of location of discharge, rate of discharge, discharge pipe size and distance of measurement station aft of the ship indicate that discharge at low rates through the hull surface by large pipes or sea chests such that the effluent is readily mixed by the boundary layer and flows into the propeller slip stream assures the most

effective mixing and rate of mixing possible. Overboard discharges from locations 3 or 2, or in between, at about Station 16, i.e., just forward of the engine room bulkhead are recommended.

Based on results for these discharge locations, and assuming proportionality of peak concentration to discharge rate, the maximum rate of discharge of washwater containing P percent concentration of contaminant can be estimated, for a prescribed maximum measured concentration, C_{perm} , at a location $0.1 L_{pp}$ aft of the propeller, may be estimated from the following equation:

$$\frac{\text{Permissible Discharge Rate (tons/hr)}}{330} = \frac{100 C_{perm}}{P} \times \text{Min Dil Factor} \quad (12)$$

The minimum dilution factor may be obtained from Table V where results corresponding to 330 tons/hr discharge rate are given. For locations 2 and 3, this factor is about 3000. Thus, to achieve dilution of washwater containing 2% contaminant to a maximum concentration of 1 part per million, the maximum discharge rate would be $330 \times 100 \times 10^{-6} \times 3000 / 2 \approx 50$ tons/hr. If a ship must discharge 500 tons of washwater after tank cleaning, this rate indicates that pumping could be completed within 10 hours at sea, a reasonable time.

Applications To Other Ships

The present series of tests are admittedly ad hoc, yet it is considered reasonable to apply results for this ship's model and its loading condition to other chemical tankers operating at other conditions of loading and trim. Provided the effluent flow does not come under the strong influence of bow or bilge vortices, i.e., for discharge into the central zone of the ship's wake, effects of displacement and or trim may reasonably be neglected.

For other chemical tankers, all of which have fairly similar proportions, the scaling rule suggested by Eq.(8) may be applied. In this case the permissible discharge rate for a ship with length between perpendiculars, L_{pp} , should be assessed according to

$$\frac{\text{Perm. Discharge Rate (tons/hr)}}{330} = \frac{100 C_{perm}}{P} \times \text{Min Dil Factor} \times \left(\frac{L_{pp}}{630}\right)^2 \quad (13)$$

Dilution of discharges from significantly different ship types, such as barges, should be expected to be somewhat different from that from tankers and may require further experimental study. Dilution factors obtained here for flow of effluent in the central region of the wake may be used as tentative values.

VI. CONCLUSIONS AND RECOMMENDATIONS

The following conclusions and recommendations concerning methods, rates and locations of discharge of washwater and residual liquid cargo (other than oil or petroleum products) from cleaning of the tanks of soluble chemical cargo carriers, are based on the results of model tests reported herein together with analyses of these results and deductions based on published descriptions and experience of wake flows in general and ship flows in particular.

1. Discharges should be through the ship's hull at low rates of flow with large diameter pipe penetrations or sea chests.
2. Discharges should preferably be located so that the effluent flow is not affected by bow or bilge trailing vortices. Locations just forward of the engine room (about $0.2 L_{pp}$ forward of the after perpendicular) in the region from just below the turn of the bilge outboard to about the height of the shaft centerline are suggested.
3. For low velocity discharges into this central region of the ship's wake, the concentration of contaminant will be approximately proportional to the discharge rate.
4. Equation (12) or (13) may be used to estimate the permissible rate of discharge of effluent with a known concentration of contaminant to achieve a desired maximum concentration of contaminant at a location in the rear wake of the ship.

Further studies of this subject should include:

- A) Full-scale verification of the concentration profiles in the near wake of the ship with the recommended through-hull discharge locations.
- B) Further studies on either model scale (which is generally less expensive) or full scale of the rate of dispersion of effluent with downstream location, extending to at least

several ship lengths aft, for discharge from the recommended through-hull locations.

- C) Special ship types, such as barges, should be the subject of separate experimental investigations on either model scale (again, generally less expensive) or full scale.

VII. REFERENCES

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TABLE IIEFFECT OF LOCATION FOR NORMAL DISCHARGES
HULL WITH PROPELLER TEST SERIES

$$V_{\text{jet}}/V_{\text{stream}} = 0.2$$

$$V_{\text{stream}} = 1.0 \text{ ft/s}$$

$$C_{\text{Th}} = 3$$

Jet Location Number	$C_{\text{peak}}/C_{\text{D}}$	Minimum Dilution Factor $C_{\text{D}}/C_{\text{peak}}$
2	2.0×10^{-4}	5,000:1
5	3.0	3,333:1
8	3.4	2,940:1
11	2.8	3,570:1
14	2.6	3,850:1
17	2.8	3,570:1
20	4.0	2,500:1
23	3.2	3,120:1
26	5.2	1,920:1
32	4.6	2,170:1

TABLE IV

TEST CONDITIONS FOR VARIATIONS OF DISCHARGE LOCATION
WITHOUT PROPELLER

Ship Speed \approx 1.65 knots

Discharge Pipe Diam \approx 7.33" I.D.

Discharge Rate = 165 tons/hr

Discharge Velocity/Ship Speed = 0.2

Meas. Probes 0.1 L_{pp} Aft of Propeller Plane

Discharge Location	Data in Figure	Minimum Dilution Factor C_D/C_{peak}	Location of Peak Concentration y/beam z/beam	
1	25	5700	0	-0.2
2	27	5300	0.1	0.3
3	26	5300	0.0	0.2
2	29 ¹	4000	0.1	0.3
2	30 ²	5400	0.1	0.2

¹ Ship Speed \approx 14.5 knots

² Ship Speed \approx 18.5 knots

TABLE VTEST CONDITIONS FOR VARIATIONS OF DISCHARGE LOCATION
WITH PROPELLERShip Speed \approx 16.5 knotsPropeller RPM \approx 120 $C_{Th} \approx 2.75$ (Model Self-Propulsion Point)

Discharge Pipe Diam = 7.33" I.D.

Discharge Rate = 330 tons/hr

Discharge Velocity/Ship Speed = 0.4

Meas. Probes $0.1 L_{pp}$ Aft of Propeller Plane

Discharge Location	Data in Figure	Minimum Dilution Factor C_D/C_{peak}	Location of Peak Concentration	
			y/beam	z/beam
1	31	2000	-0.1	0.2
2	32	3100	-0.1	0.2
3	33	3000	0	0
4	34	3200	0.4	-0.2
5	35	2700	0.3	-0.2
6	36	2400	0.5	-0.1
A	37	3400	0.3	-0.2
B	38	3200	0.2	-0.2
C ¹	no figure	less than 1100	0.6	-0.35

¹ probes $0.3 L_{pp}$ aft of propeller plane for this measurement

TABLE VI

TEST CONDITIONS FOR VARIATIONS OF DISCHARGE RATE

Ship Speed \approx 16.5 knotsPropeller RPM \approx 120 $C_{Th} \approx 2.75$ (Model Self-Propulsion Point)

Discharge Pipe Diam = 7.33" I.D.

Meas. Probes $0.1 L_{pp}$ Aft of Propeller Plane

Disch Location	Disch Rate tons/hr	$\frac{\text{Disch Vel}}{\text{Sh Speed}}$	Data in Figure	Minimum Dilution Factor C_D/C_{peak}	Location of Peak Concentration	
					y/beam	z/beam
2	165	0.2	39	6100	-0.1	0.2
2	330	0.39	32	3100	-0.1	0.2
2	495	0.55	40	1900	-0.05	0.15
4	165	0.21	41	6200	0.4	-0.2
4	330	0.42	34	3200	0.4	-0.2
4	495	0.60	42	2000	0.6	-0.1

TABLE VII

TEST CONDITIONS FOR VARIATIONS OF SIZE OF DISCHARGE PORT

Ship Speed \approx 16.5 knotsPropeller RPM \approx 120

Discharge Rate = 330 tons/hr

Meas. Probes 0.1 L_{pp} Aft of Propeller Plane

Discharge Location	Discharge Pipe Diam	<u>Disch Vel</u> Sh Speed	Data in Figure	Minimum Dilution Factor	Location of Peak Concentration	
				C_D/C_{peak}	y/beam	z/beam
2	7.33" I.D.	0.39	32	3100	-0.1	0.2
2	5.00" I.D.	2.75	43	2100	0.2	-0.3
2	2.27" I.D.	13.40	44	2600	0.2	-0.2
6	7.33" I.D.	0.40	36	2400	0.5	-0.1
6	2.27" I.D.	13.40	45	2100	0.3	-0.1

TABLE VIII

TEST CONDITIONS FOR VARIATIONS OF PROPELLER LOADING

Ship Speed \approx 16.5 knots

Discharge Pipe Diam = 7.33" I.D.

Discharge Rate = 330 tons/hr

Discharge Velocity/Ship Speed = 0.4

Meas. Probes 0.1 L_{pp} Aft of Propeller Plane

Discharge Location	Propeller RPM	Approx ¹ C_{Th}	Data in Figure	Minimum Dilution Factor	Location of Peak Concentration	
				C_D/C_{peak}	y/beam	z/beam
2	No propeller	0	27 ^a	5300	0.1	0.3
2	73	0	28	2600	0.1	-0.2
2	100	2.23	46	2500	-0.2	0.2
2	120	2.75 ^a	32	3100	-0.1	0.2
2	140	4.83	47	2700	-0.1	0.1

$${}^1 C_{Th} = \frac{8 \text{ thrust}}{\rho \frac{\pi D^2}{4} V_s^2 (1-w)^2}, \quad (1-w) \text{ assumed} = 0.65$$

^a Discharge Rate = 165 tons/hr for this test without propeller^a Corresponds to model self-propulsion point at 16.5 knots full scale (3.2 ft/sec model size)

TABLE IX

TEST CONDITIONS FOR VARIATIONS
OF MEASURING PROBE LONGITUDINAL POSITION

Ship Speed \approx 16.5 knots

Propeller RPM \approx 120

$C_{Th} \approx$ 2.75 (Model Self-Propulsion Point)

Discharge Pipe Diam = 7.33" I.D.

Discharge Rate = 330 tons/hr

Discharge Velocity/Ship Speed = 0.4

Discharge Location	Measurement Probe Aft of Prop Plane	Data in Figure	Minimum Dilution Factor C_D/C_{peak}	Location of Peak Concentration	
				y/beam	z/beam
2	0.1 L_{pp}	32	3100	-0.1	0.2
2	0.3 L_{pp}	48	5100	-0.1	0.1
2	0.7 L_{pp}	49	10900	-0.2	0.2
4	0.1	34	3200	0.4	-0.2
4	0.3	50	4300	0.7	-0.1
4	0.7	51	6000	0.2	-0.1
2 ¹ , ^a	0.1	27	5300	0.1	0.3
2 ¹ , ^a	0.3	52	6300	0	0.5
2 ¹	0.7	53	20800	0	-0.2

¹ No propeller for these tests

^a Discharge Rate = 165 tons/hr

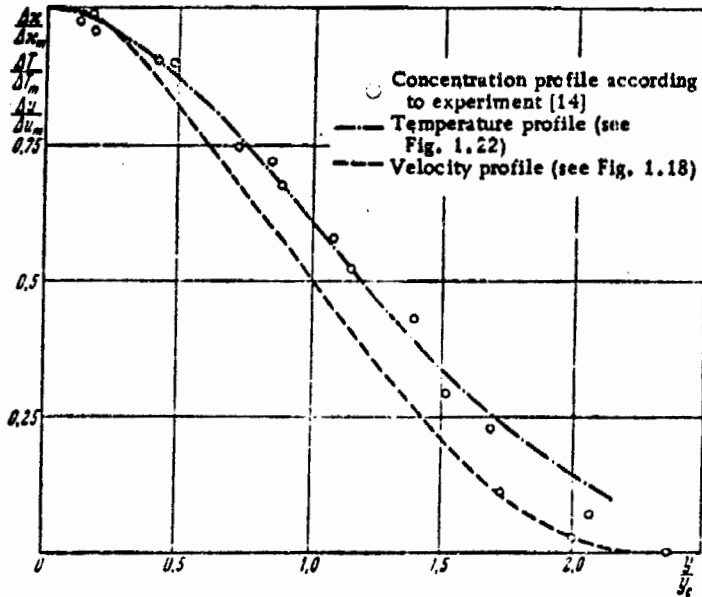


Fig. 1.24. Dimensionless profiles for concentration of admixture by weight (helium) in main region of axially symmetric air jet in coflowing stream of air according to Forstall and Shapiro

- Δx difference between admixture concentration at y and in external stream
- Δx_m maximum difference between admixture concentration at core of jet and in external stream
- ΔT difference between temperature at y and in external stream
- ΔT_m maximum difference between temperature at core of jet and in external stream
- Δu difference between velocity at y and in external stream
- Δu_m maximum difference between velocity at core of jet and in external stream

FIGURE 2. DISTRIBUTIONS OF ADMIXTURE, TEMPERATURE AND VELOCITY IN MAIN REGION OF AXIALLY SYMMETRIC JET IN CO-FLOWING STREAM FROM ABRAMOVICH⁴

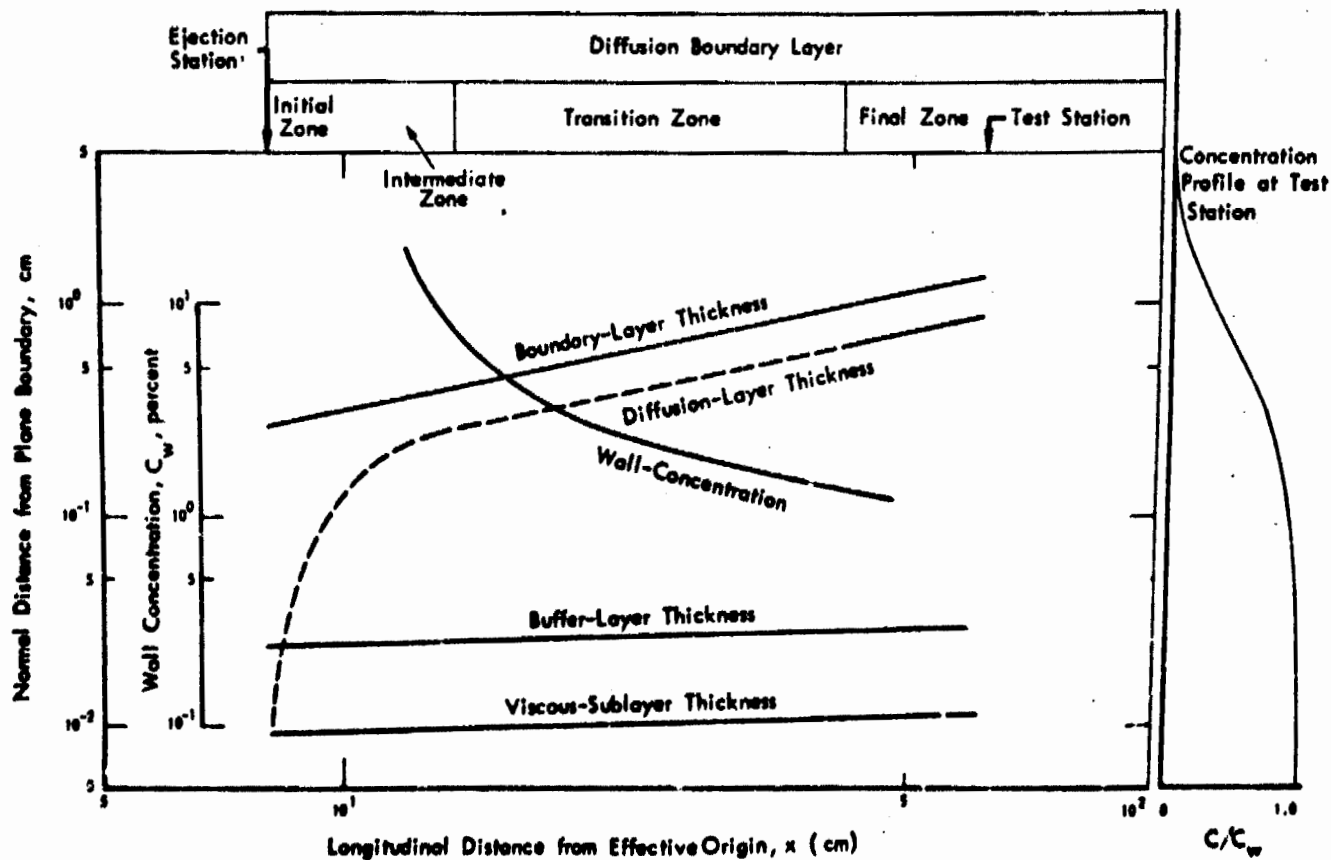
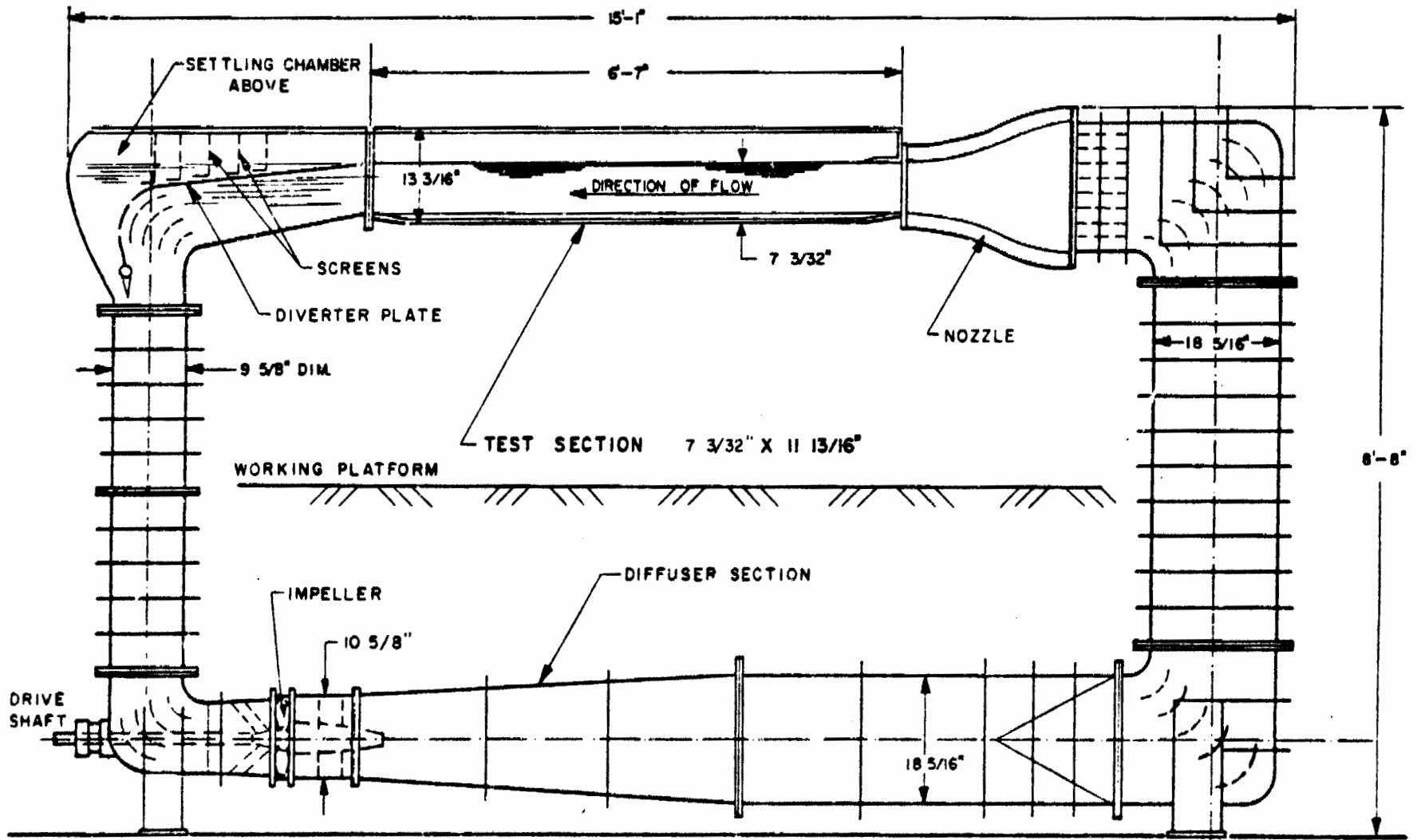


FIGURE 1. CHARACTERISTICS OF DIFFUSION BOUNDARY LAYER ACCORDING TO POREH AND CERMAK,⁸ AS PRESENTED BY WU⁹



R-1697

FIGURE 4. THE DAVIDSON LABORATORY CIRCULATING WATER CHANNEL



a) COFLOWING JET
 $V_{jet}/V_{stream} = 0.20$



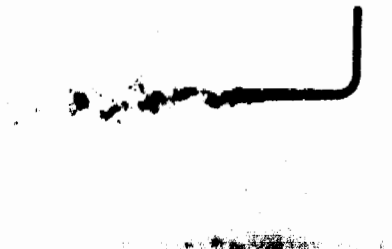
b) COFLOWING JET
 $V_{jet}/V_{stream} = 0.41$



c) COFLOWING JET
 $V_{jet}/V_{stream} = 0.83$



d) COUNTERFLOWING JET
 $V_{jet}/V_{stream} = 0.41$



e) JET AT 45° ANGLE TO MAIN
 STREAM, $V_{jet}/V_{stream} = 0.41$



f) JET AT 90° ANGLE TO MAIN
 STREAM, $V_{jet}/V_{stream} = 0.41$

FIGURE 3. MIXING OF FREE JETS (WAKES) WITH A UNIFORM MAIN STREAM
 (Stream Speed = 0.5 ft/sec)

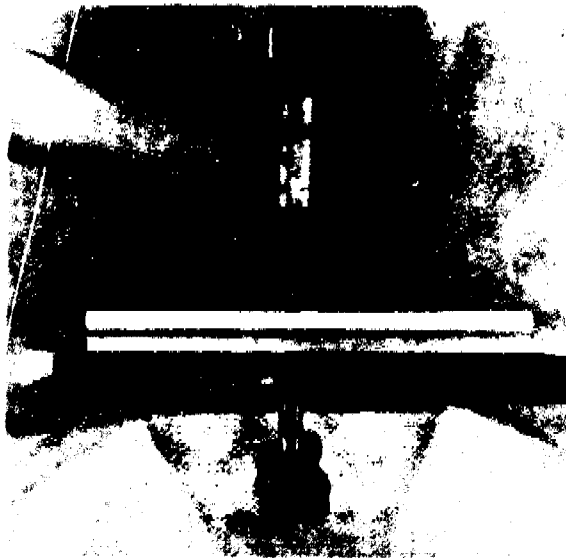


PHOTO 1. END VIEW OF RIGHT-ANGLE DRIVE TO BE USED FOR OPEN-WATER-PROPELLER MIXING TESTS. NOTE TOOTHED WHEEL AND MAGNETIC PULSE-SENSOR ON UPPER END OF MOTOR FOR RPM INDICATOR.

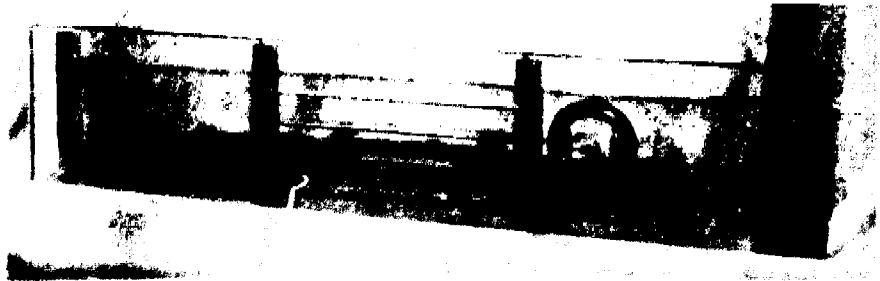


PHOTO 2. SURFACE COVER OF CIRCULATING WATER CHANNEL SHOWING RIGHT ANGLE PROPELLER DRIVE. NOTE SLOTS IN COVER (UPSTREAM OF PROPELLER) FOR LOCATING DYE-INJECTION TUBES.

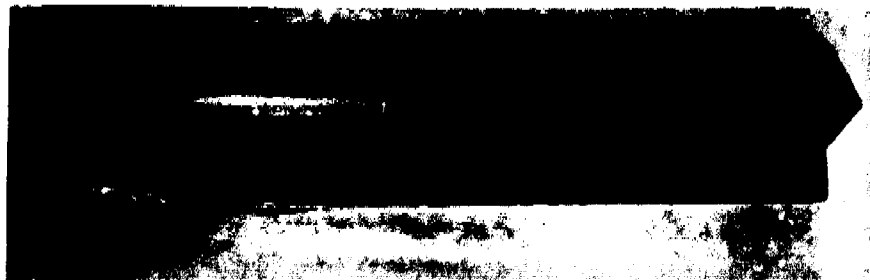


PHOTO 3. PARTIALLY COMPLETED MALE MOLD FOR SIMULATED HULL MODEL FOR WATER CHANNEL TESTS. MODEL APPROXIMATELY SIMULATES TANKER AFTERBODY IN BALLAST CONDITION. BREADTH IS REDUCED TO MINIMIZE CHANNEL BLOCKAGE EFFECTS.

PROPELLER 72-R1

Diam, $D= 2.5''$
 Pitch, $P= 2.5''$
 EAR = 0.83

ρ = Fluid Density, lb-sec²/ft⁴
 T = Thrust, lbs
 V = Water Speed, ft/sec
 n = Rate of Rotation, rev/sec

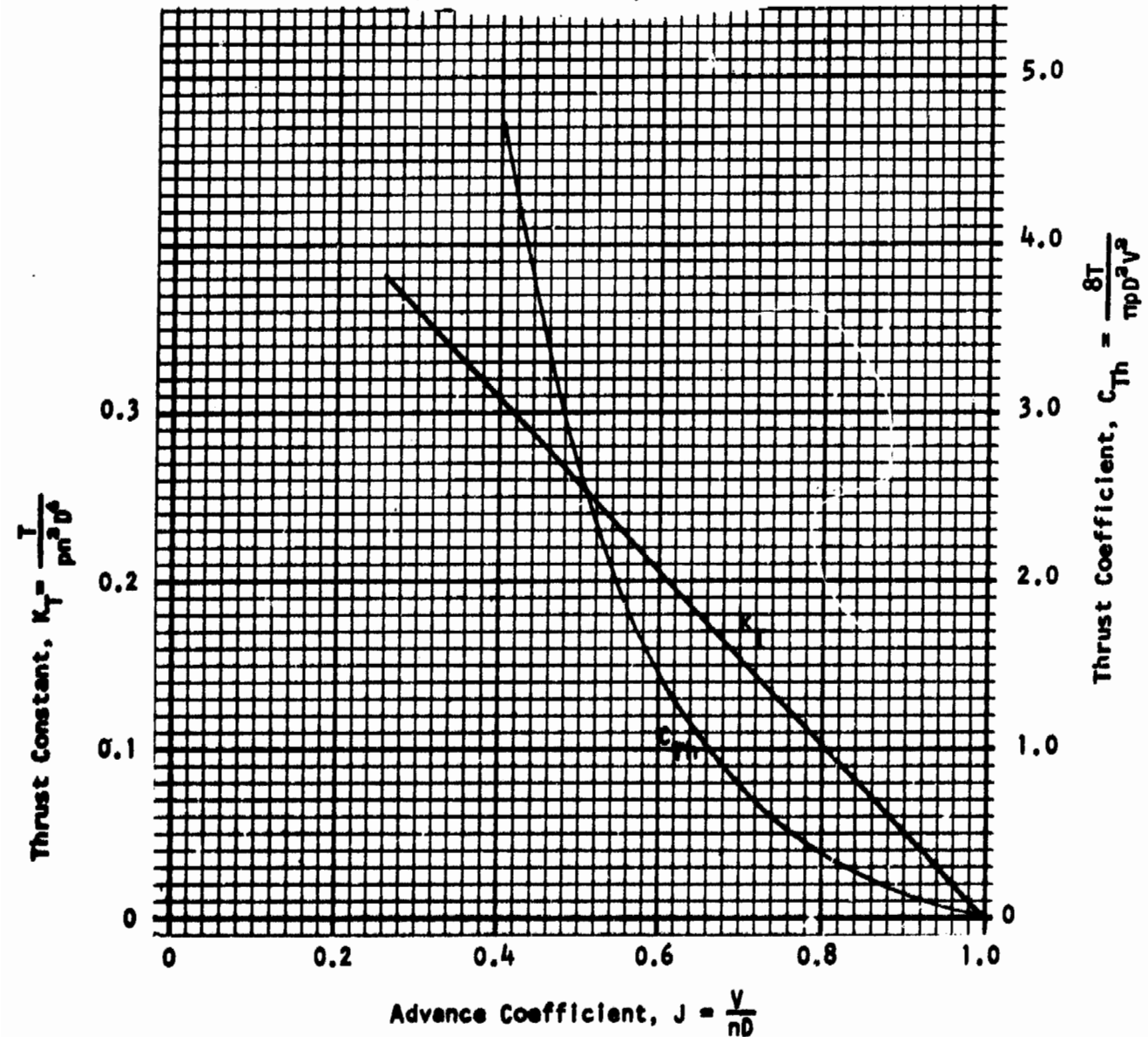


FIGURE 6. THRUST CHARACTERISTICS OF RIGHT-ANGLE DRIVE PROPELLER UNIT

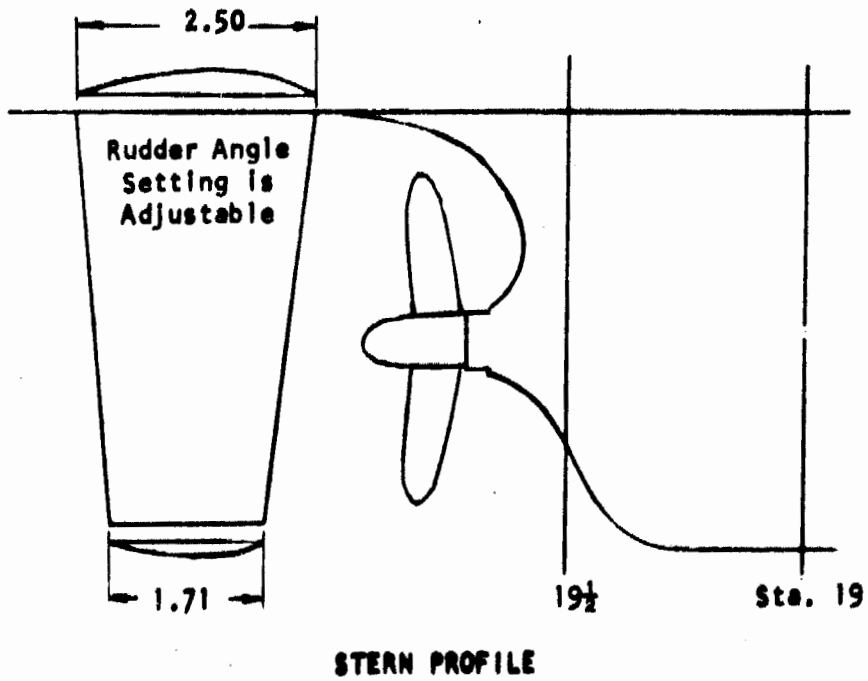
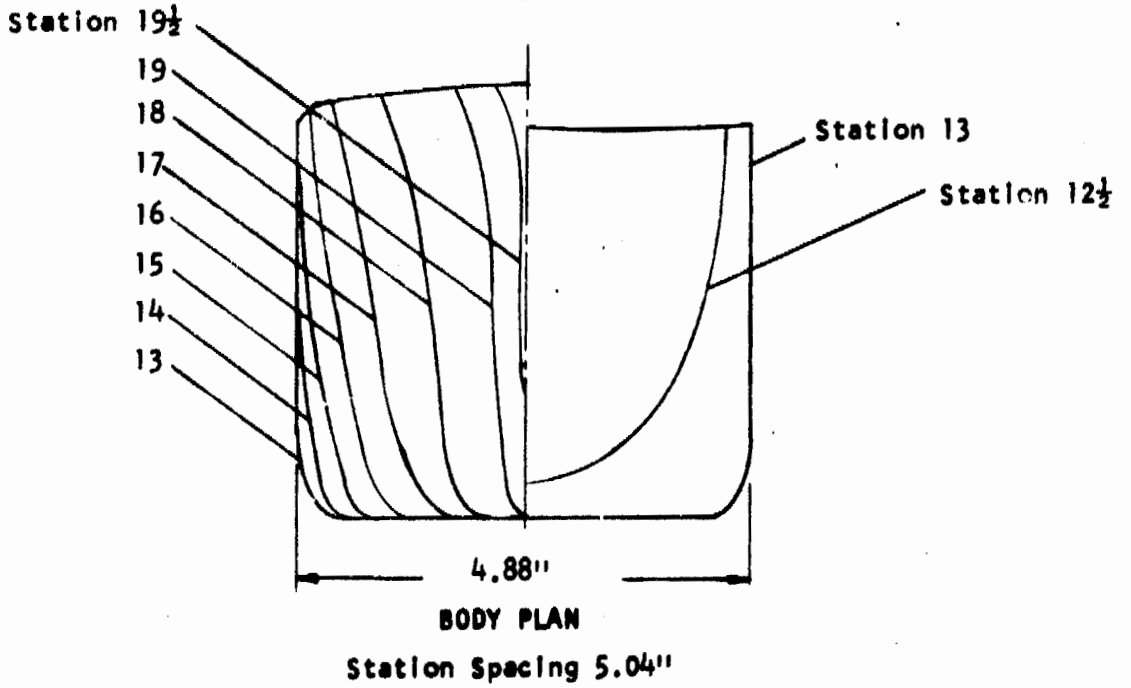
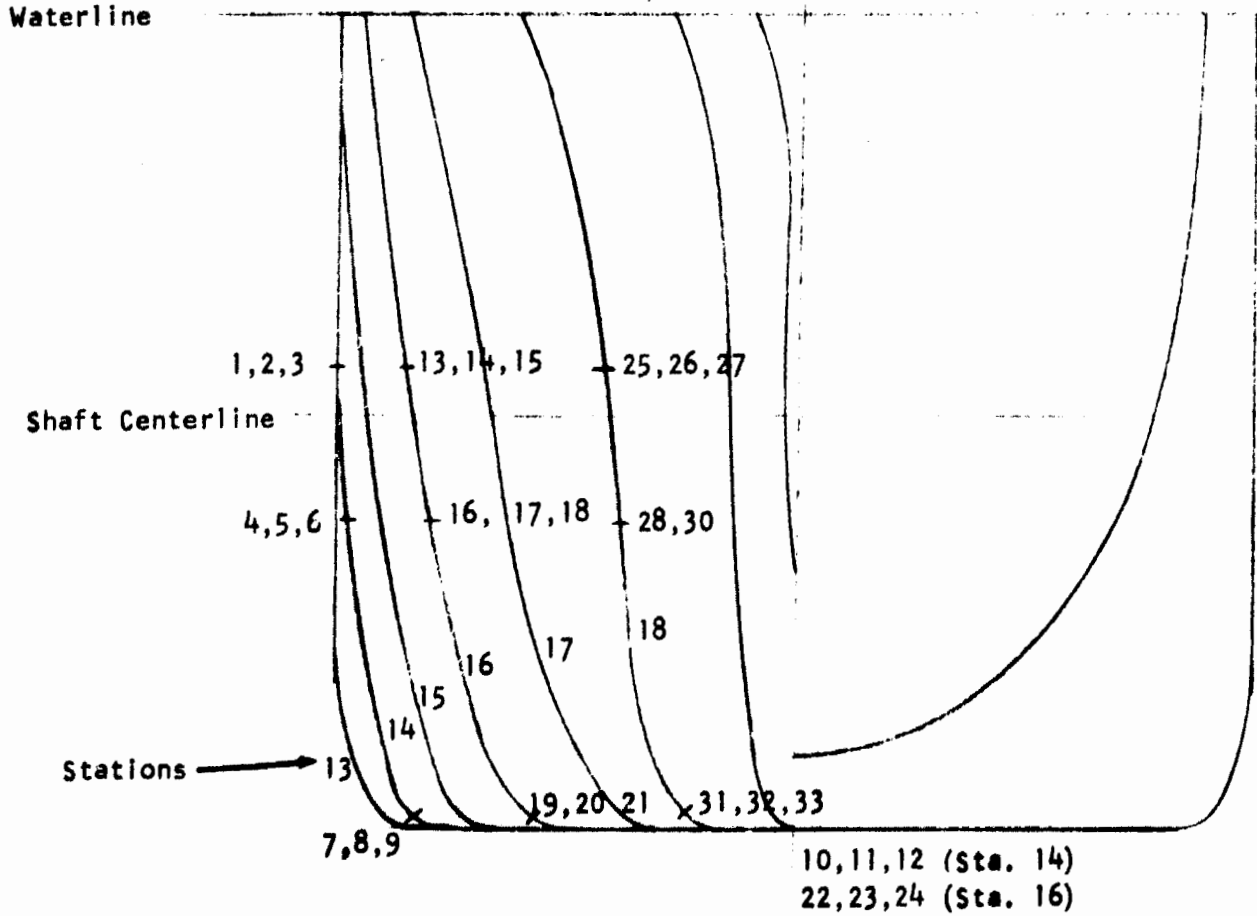


FIGURE 7. BODY PLAN AND STERN PROFILE OF SIMULATED HULL MODEL FOR WATER CHANNEL. CHANNEL COVER PLATE SIMULATES WATERLINE OF SHIP IN BALLAST CONDITION. (ONE-HALF MODEL SIZE)



Locations with discharge normal to hull: 2,5,8,11,14,17,20,23,26,30,32

Locations with discharge 45° upstream: 3,6,9,12,15,18,21,24,27,33

Locations with discharge 45° downstream: 1,4,7,10,13,16,19,22,25,28,31

FIGURE 8. DISCHARGE LOCATIONS ON HULL USED IN WATER CHANNEL

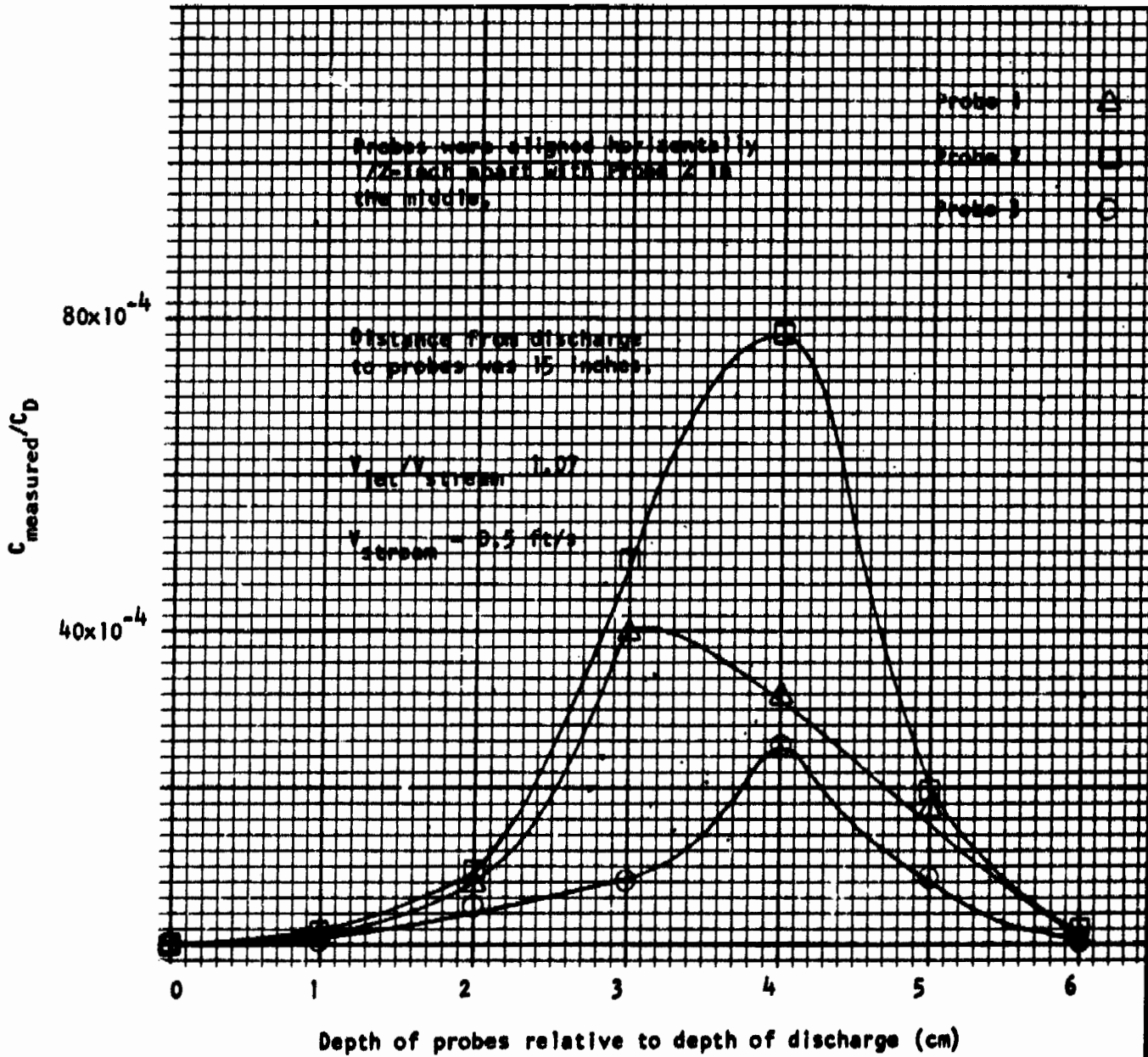


FIGURE 9. TYPICAL CONCENTRATION DISTRIBUTION FOR OPEN WATER TESTS IN THE WATER CHANNEL

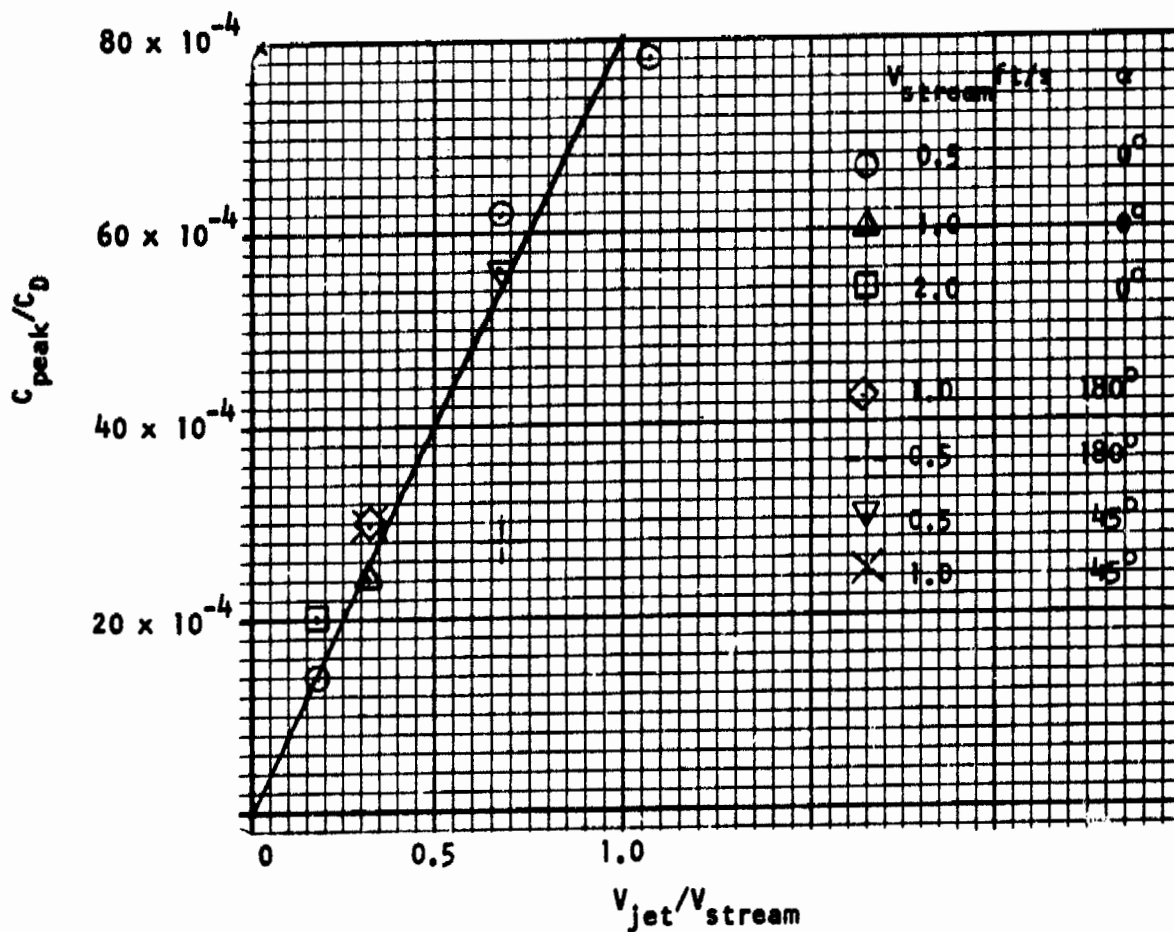


Fig. 10(a)

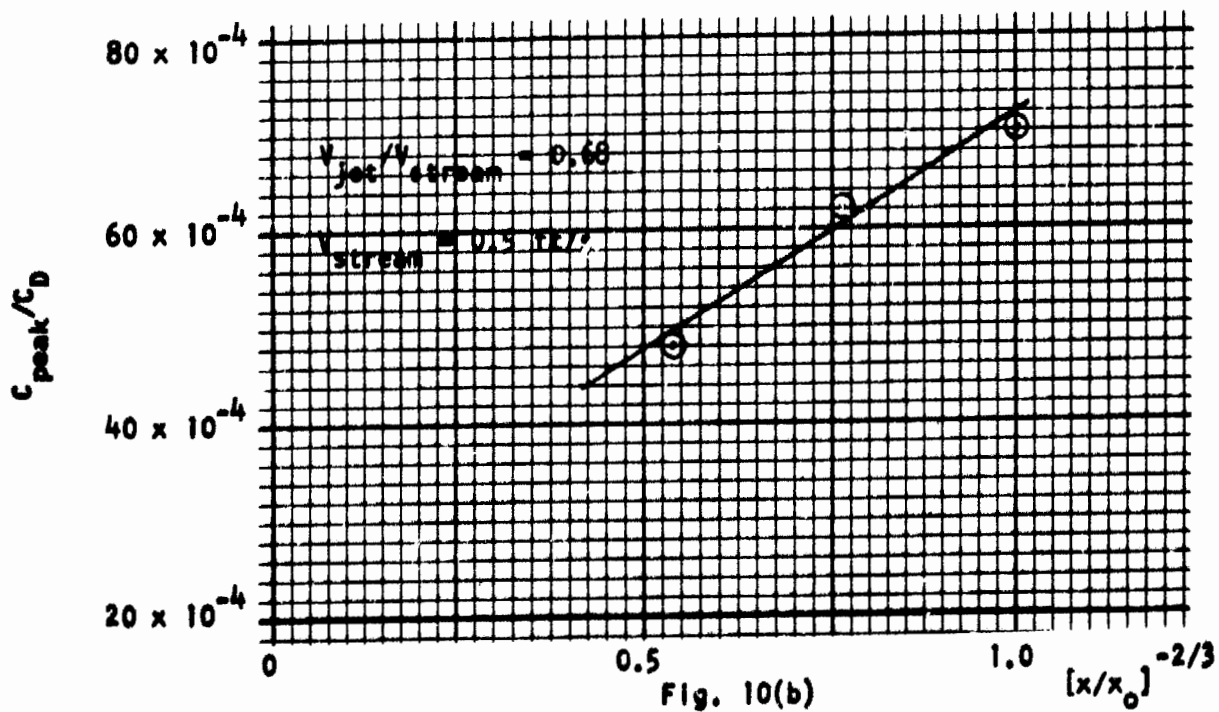


Fig. 10(b)

FIGURE 10. SUMMARY OF OPEN WATER TEST RESULTS



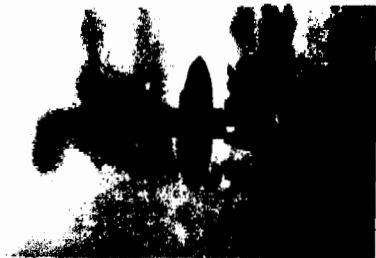
Discharge location: 5 inches forward and 1 inch below propeller centerline. Stream speed was 1 ft/sec., $V_{jet}/V_{stream} = 0.88$ and $C_{Th} = 3$



Discharge location: 10 inches forward and 1 inch below propeller centerline. Stream speed was 1 ft/sec., $V_{jet}/V_{stream} = 0.88$ and $C_{th} = 3$



Discharge location: 15 inches forward and 1 inch below propeller centerline. Stream speed was 1 ft/sec., $V_{jet}/V_{stream} = 0.88$ and $C_{Th} = 3$



Discharge location: 15 inches forward and 1 inch below propeller centerline. Stream speed was 1 ft/sec., $V_{jet}/V_{stream} = 0.42$ and $C_{Th} = 2$

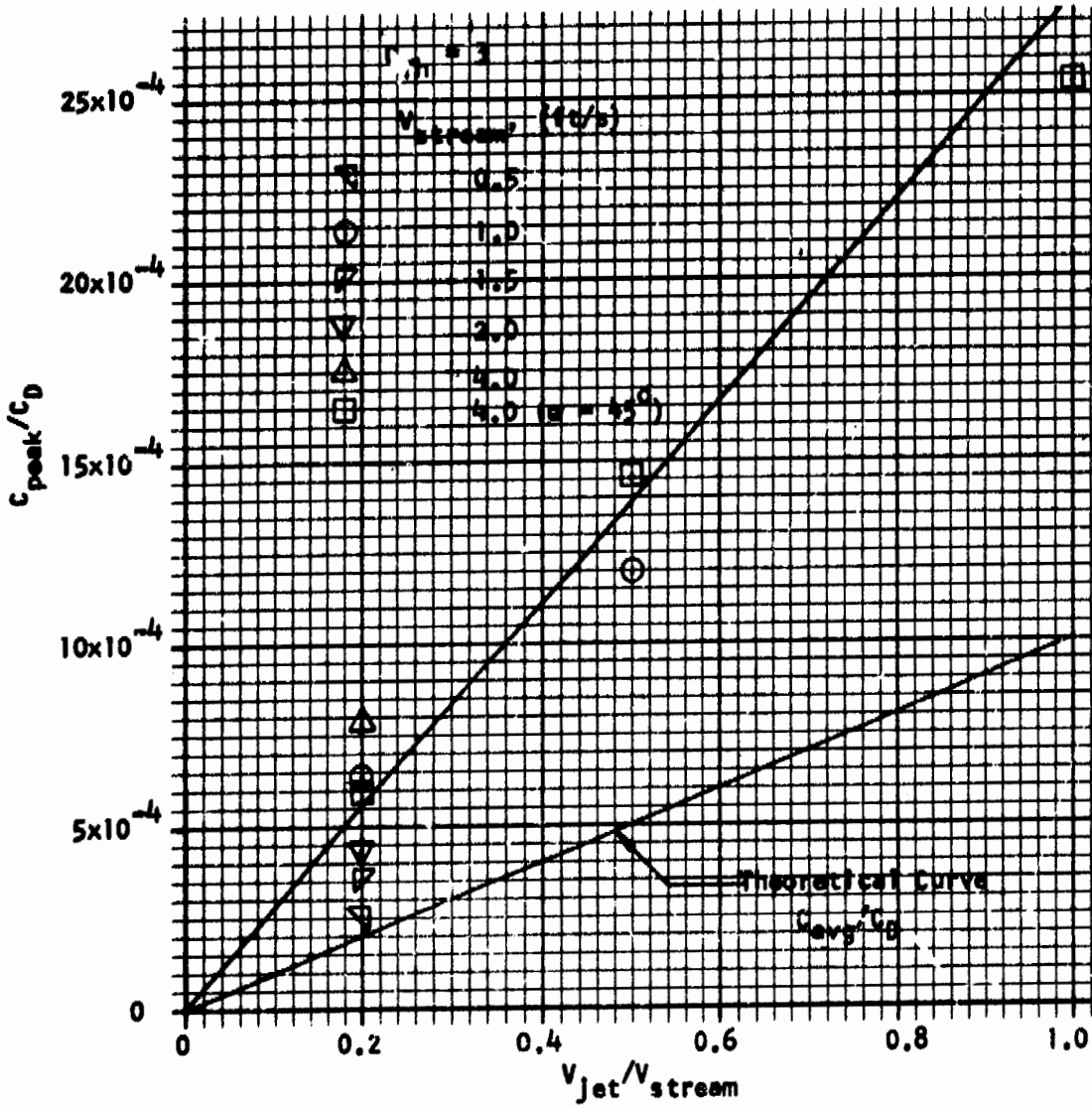


Discharge location: 5 inches forward and 1 inch below propeller centerline. Stream speed was 1 ft/sec., $V_{jet}/V_{stream} = 0.42$ and $C_{Th} = 4$



Discharge location: 5 inches forward and 1 inch below propeller centerline. Stream speed was 1 ft/sec., $V_{jet}/V_{stream} = 0.42$ and $C_{Th} = 5$

FIGURE 11. EXAMPLES OF PHOTOGRAPHS FOR THE OPEN-WATER PROPELLER TESTS



12(b)

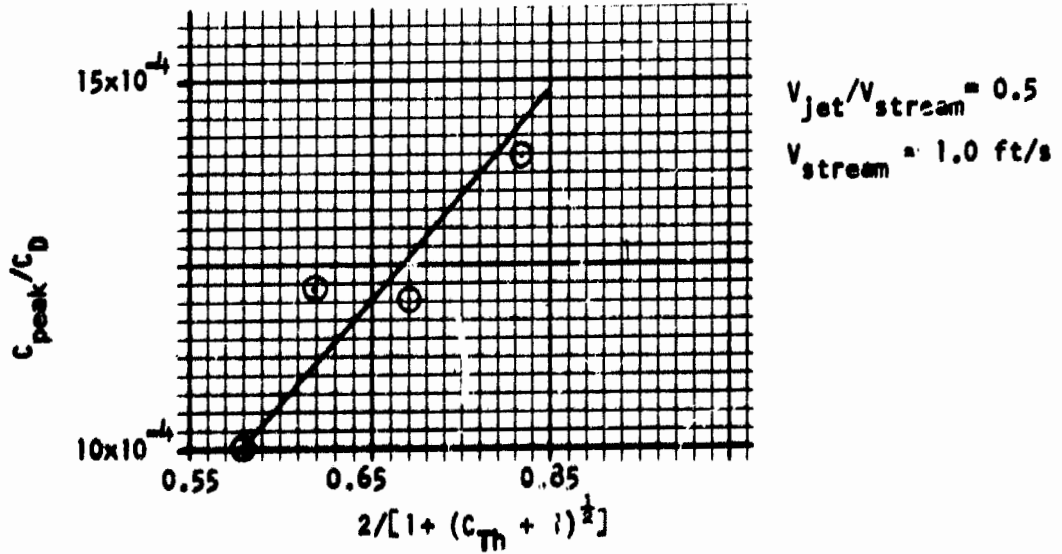
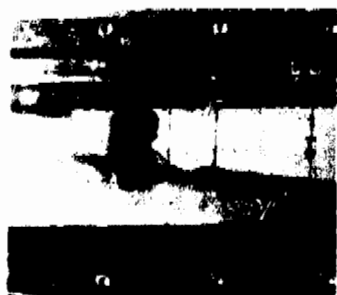
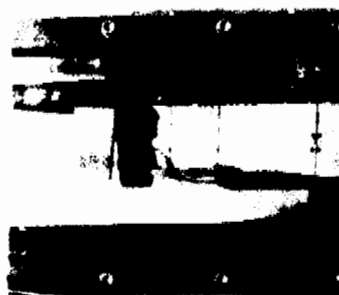


FIGURE 12. SUMMARY OF OPEN-WATER PROPELLER TEST RESULTS



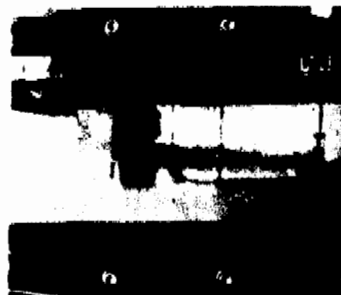
Discharge location: 32
 Stream speed: 1.0 ft/sec.
 $V_{jet}/V_{stream} = 0.5$; $C_{Th} = 5$



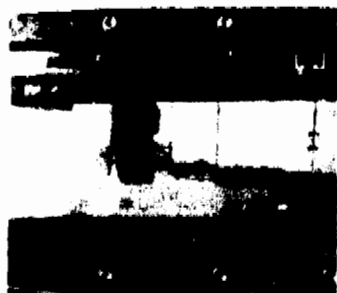
Discharge location: 32
 Stream speed: 1.0 ft/sec.
 $V_{jet}/V_{stream} = 0.5$; $C_{Th} = 2$



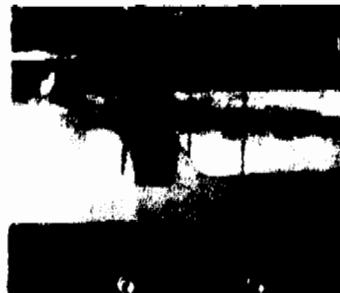
Discharge location: 17
 Stream speed: 1.5 ft/sec.
 $V_{jet}/V_{stream} = 0.5$; $C_{Th} = 3$



Discharge location: 20
 Stream speed: 1.5 ft/sec.
 $V_{jet}/V_{stream} = 0.5$; $C_{Th} = 3$



Discharge location: 32
 Stream speed: 1.5 ft/sec.
 $V_{jet}/V_{stream} = 0.5$; $C_{Th} = 3$



Discharge location: 17
 Stream speed: 1.5 ft/sec.
 $V_{jet}/V_{stream} = 0.5$; no propeller

FIGURE 13. EXAMPLES OF PHOTOGRAPHS FOR THE FORESHORTENED HULL MODEL FIXED IN THE WATER CHANNEL

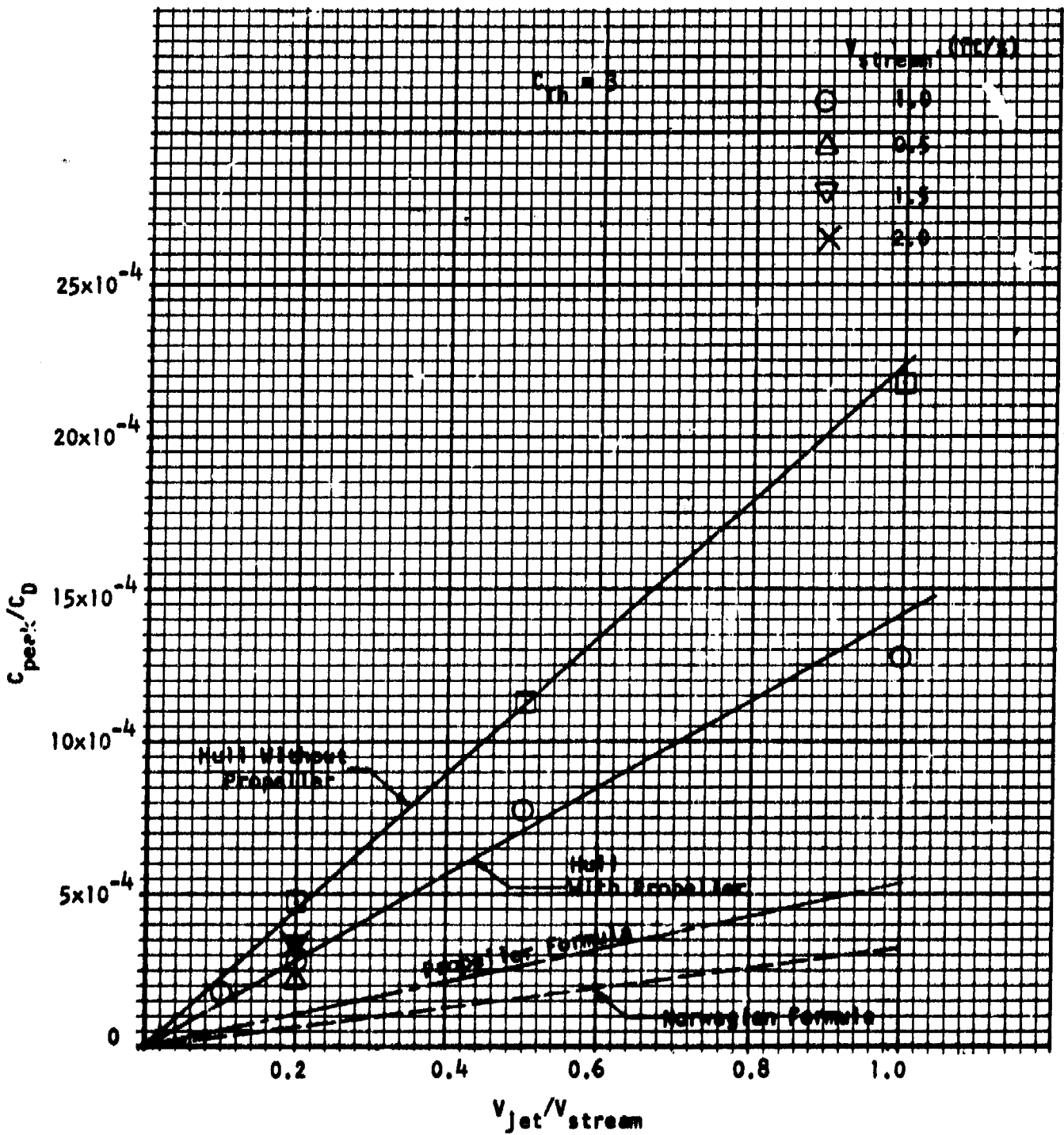


FIGURE 14. C_{peak}/C_D vs. V_{jet}/V_{stream} FOR DISCHARGE LOCATION 17 ON THE HULL FIXED IN WATER CHANNEL WITH AND WITHOUT ITS PROPELLER

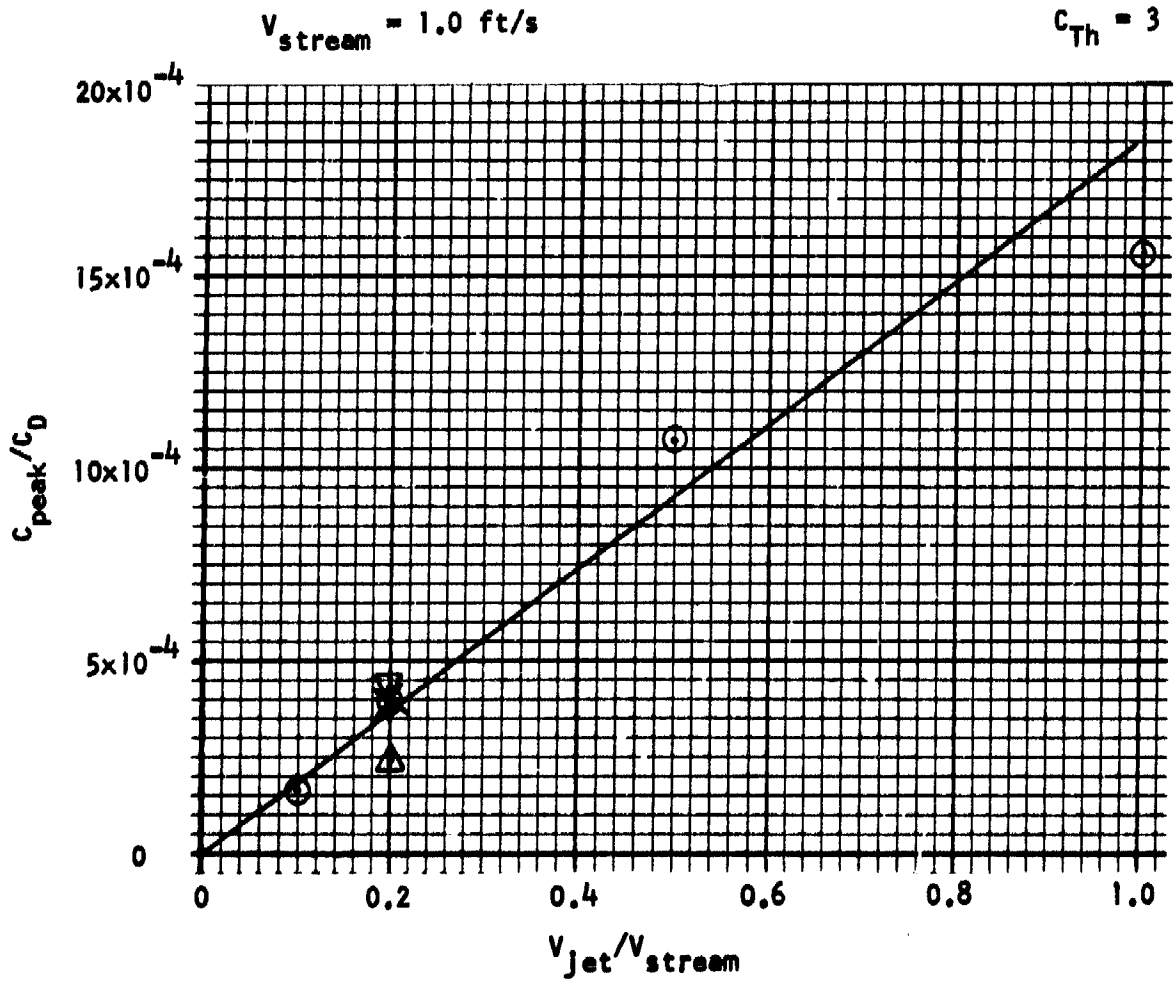


FIGURE 15. C_{peak}/C_D vs. $V_{\text{jet}}/V_{\text{stream}}$ FOR DISCHARGE LOCATION 20 ON HULL FIXED IN WATER CHANNEL

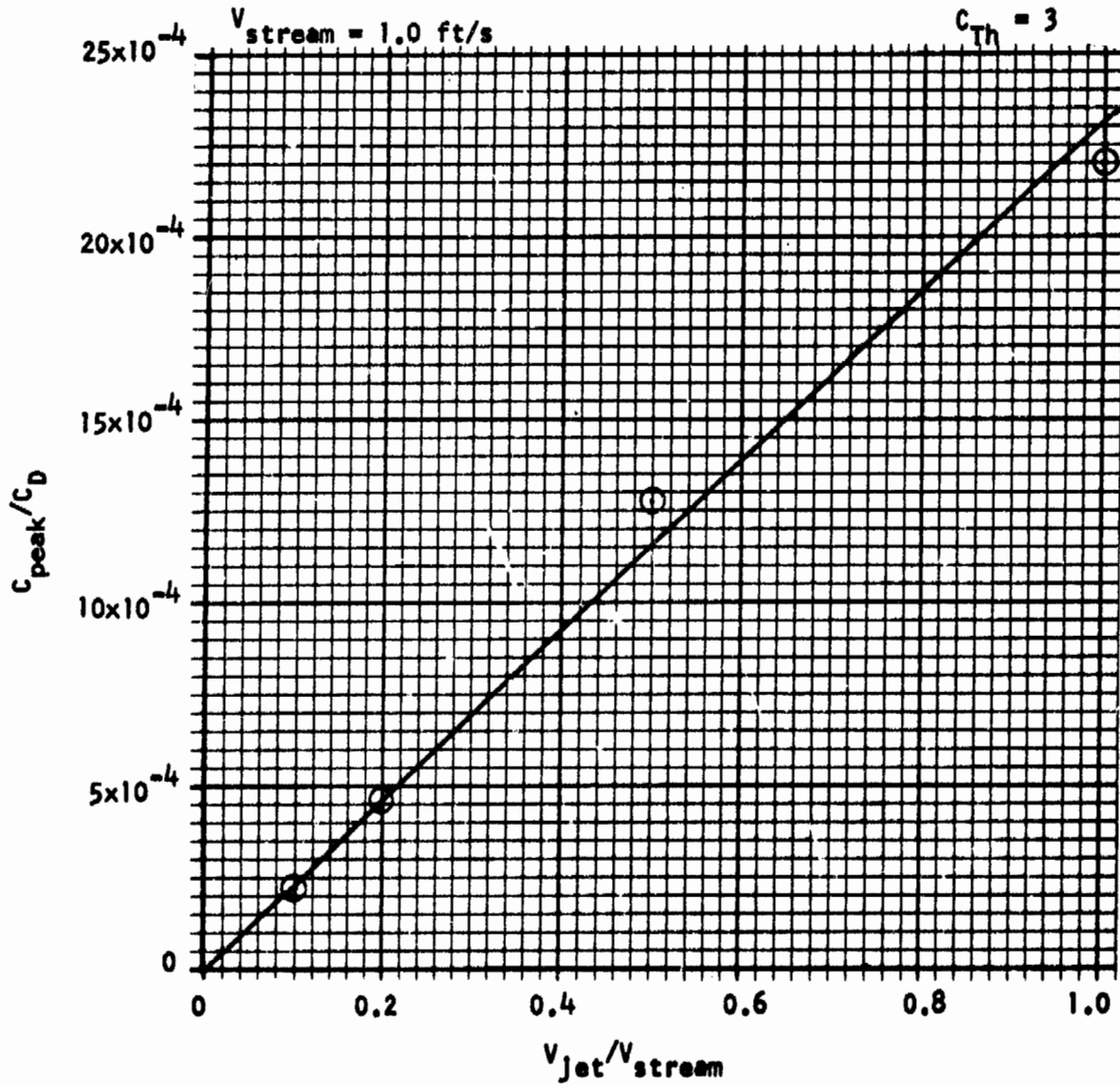


FIGURE 16. C_{peak}/C_D vs. $V_{\text{jet}}/V_{\text{stream}}$ FOR DISCHARGE LOCATION 32 ON HULL
FIXED IN WATER CHANNEL

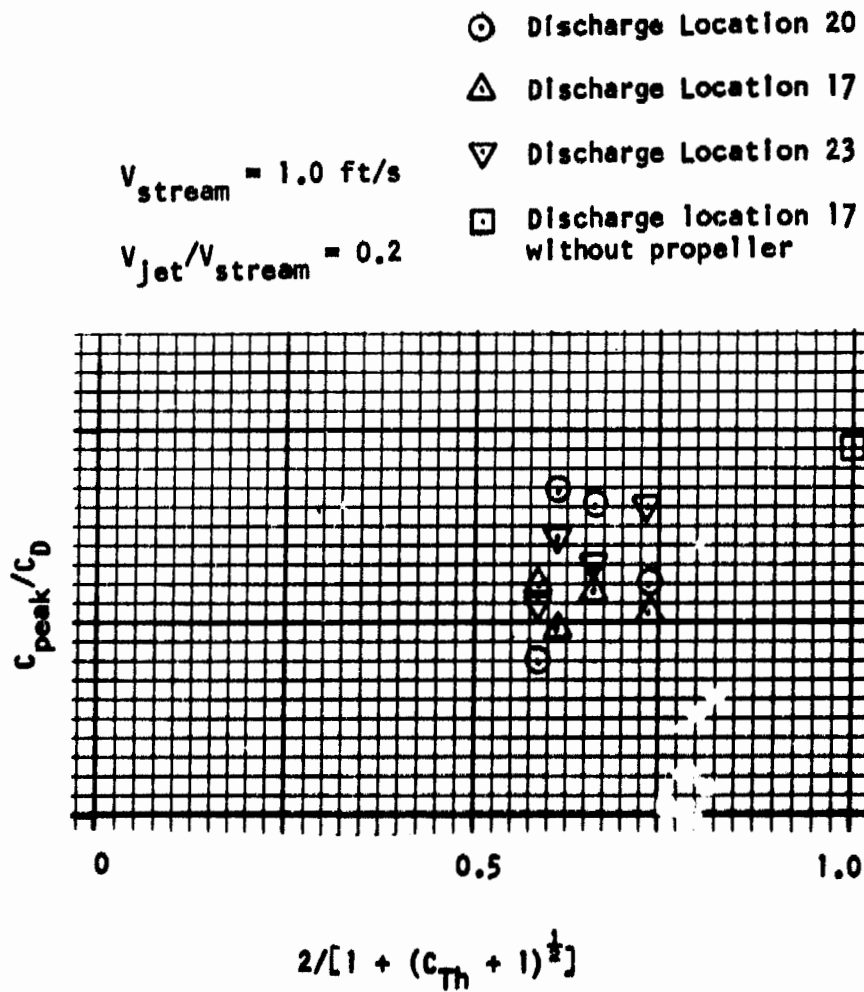


FIGURE 17. C_{peak}/C_D vs. $2/[1 + (C_{Th} + 1)^{1/2}]$ FOR HULL
FIXED IN WATER CHANNEL

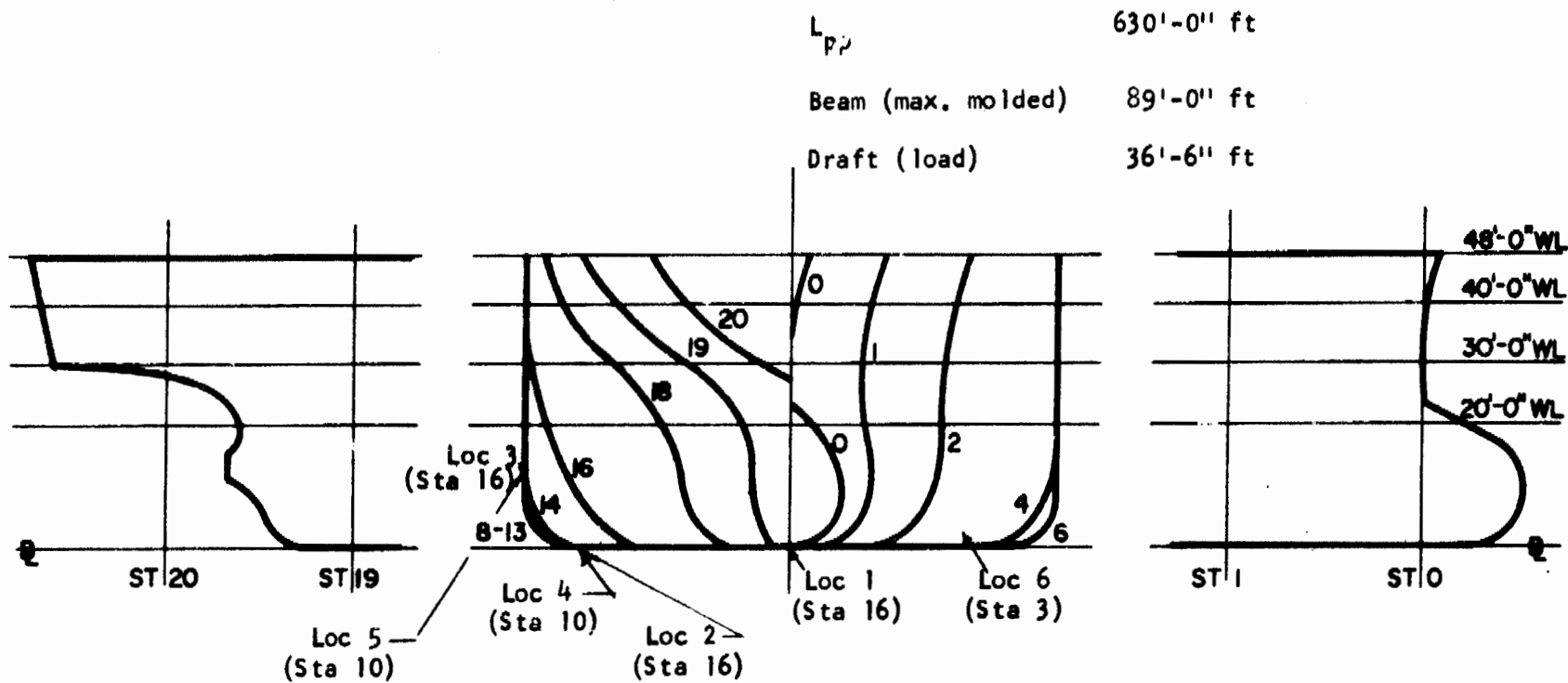


FIGURE 18. BODY PLAN AND PROFILE ENDINGS OF MODEL OF S.S. MARINE CHEMIST SHOWING DYE-INJECTION LOCATIONS

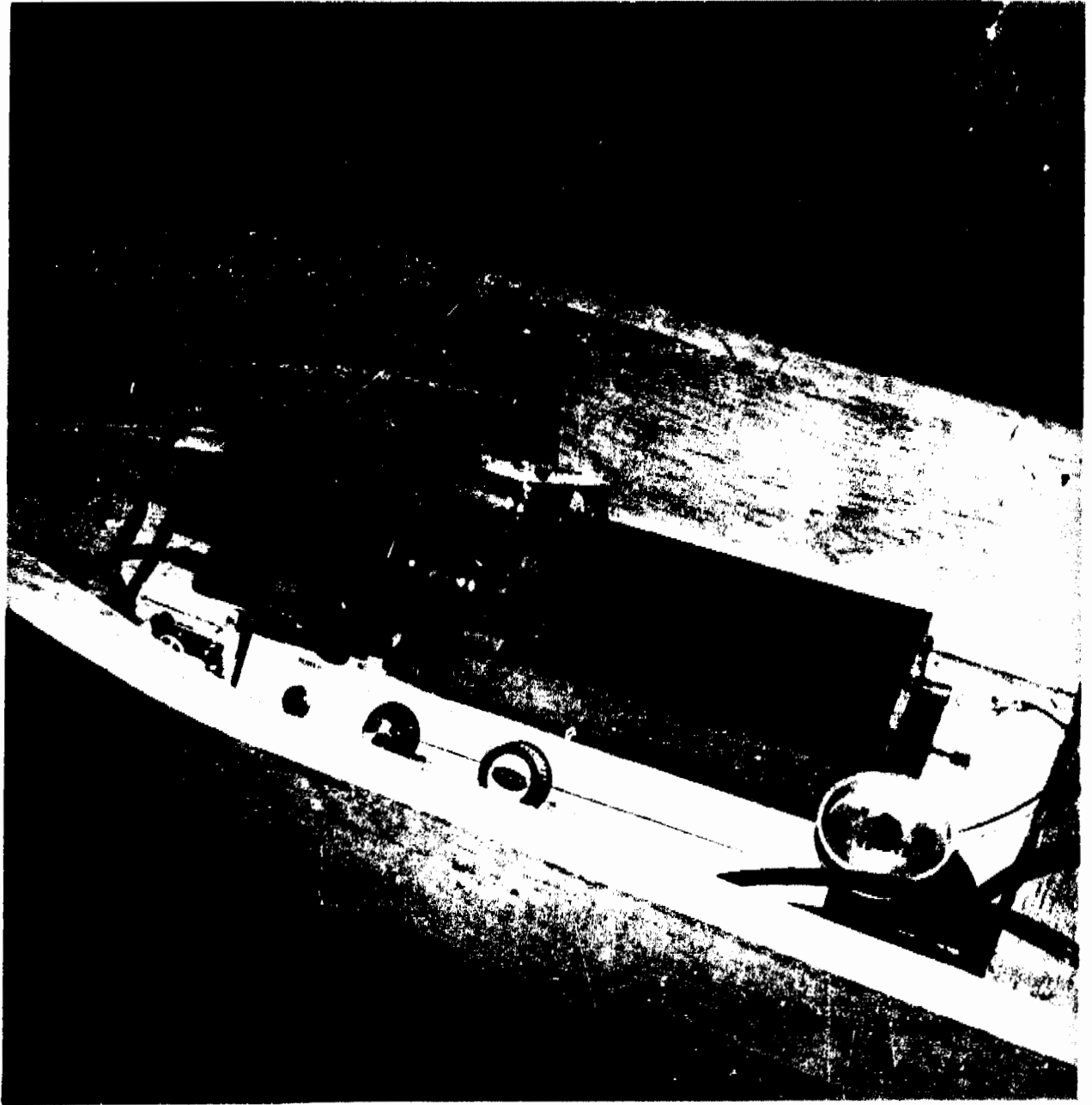
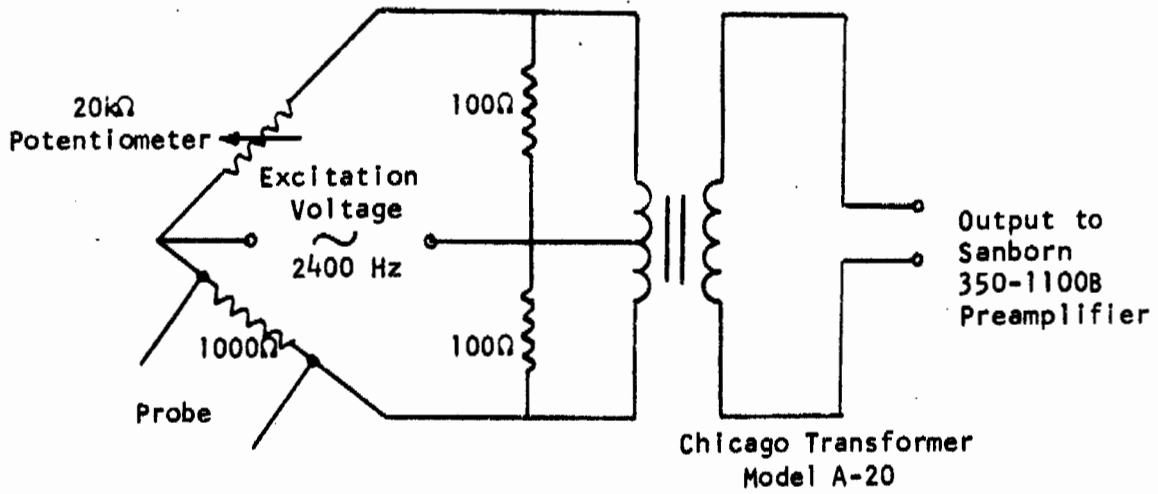


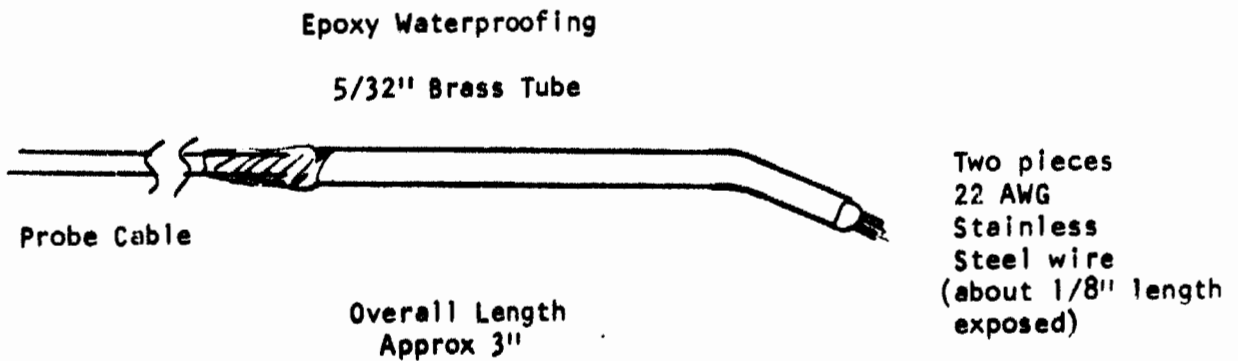
FIGURE 19. SYRINGE PUMP SITUATED IN FORWARD COMPARTMENT OF MODEL



FIGURE 20. SELF-PROPELLED MODEL WITH SALINITY-MEASURING PROBE ARRAY BEHIND. MIRROR BOX FOR UNDERWATER PHOTOS APPEARS IN THE BACKGROUND.



CIRCUIT DIAGRAM



PROBE CONSTRUCTION

FIGURE 21. CONDUCTIVITY PROBE

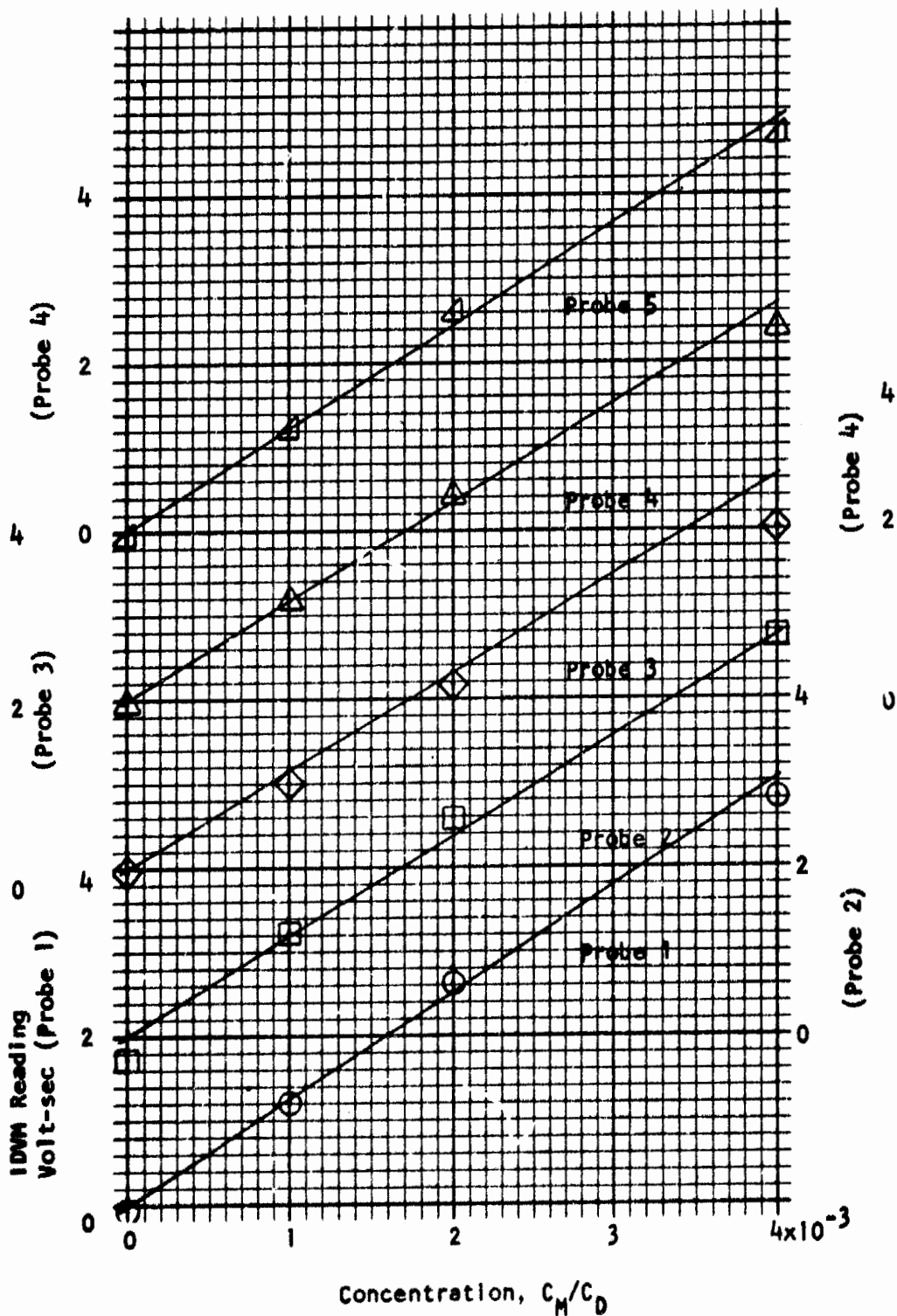
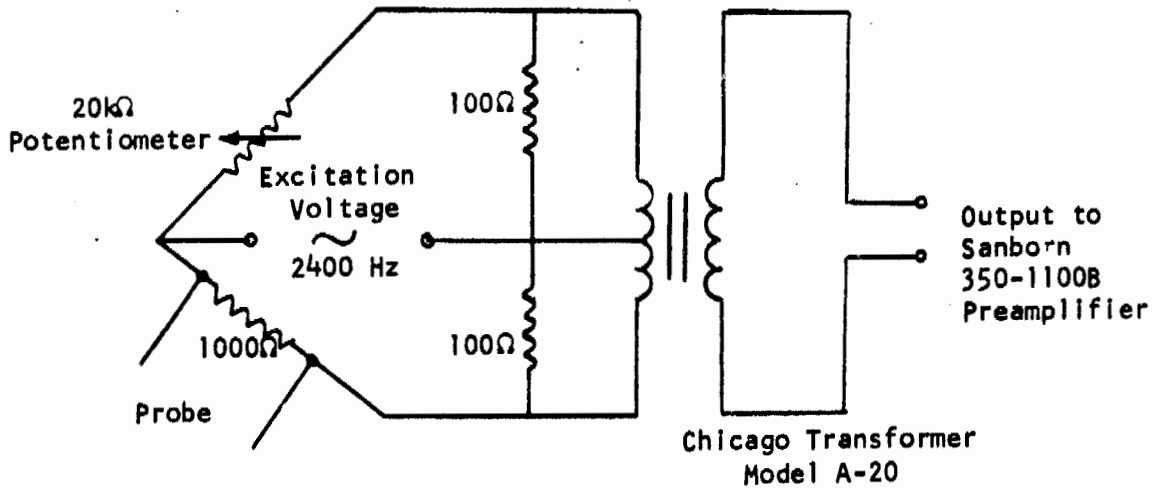
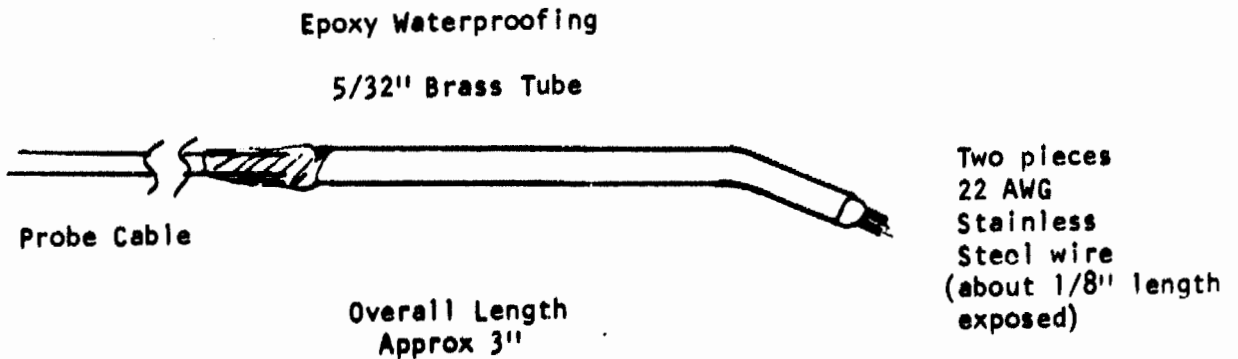


FIGURE 22. CALIBRATION CURVES FOR CONDUCTIVITY PROBES



CIRCUIT DIAGRAM



PROBE CONSTRUCTION

FIGURE 21. CONDUCTIVITY PROBE

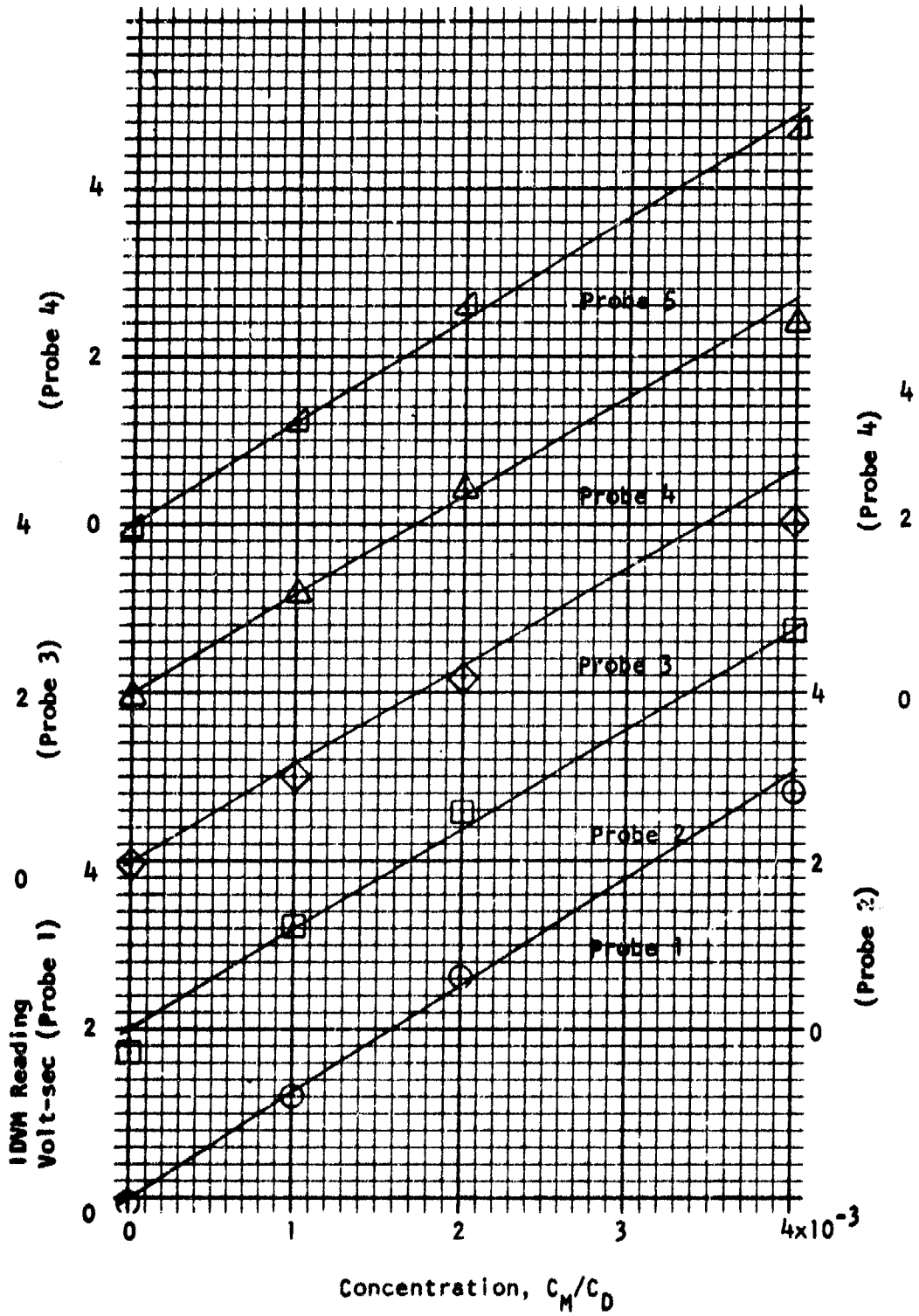


FIGURE 22. CALIBRATION CURVES FOR CONDUCTIVITY PROBES

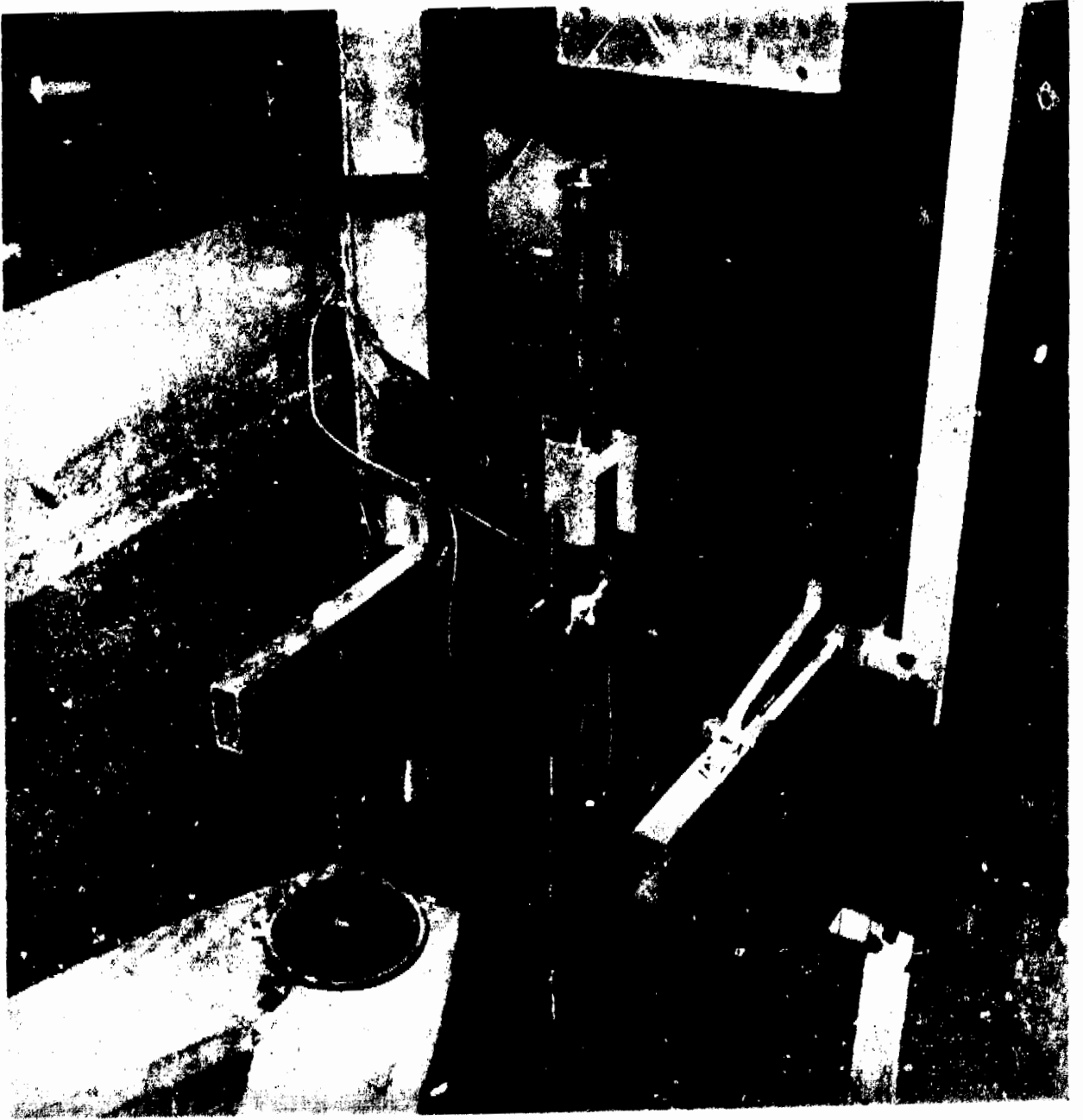


FIGURE 23. CONDUCTIVITY PROBE POSITIONING DEVICE

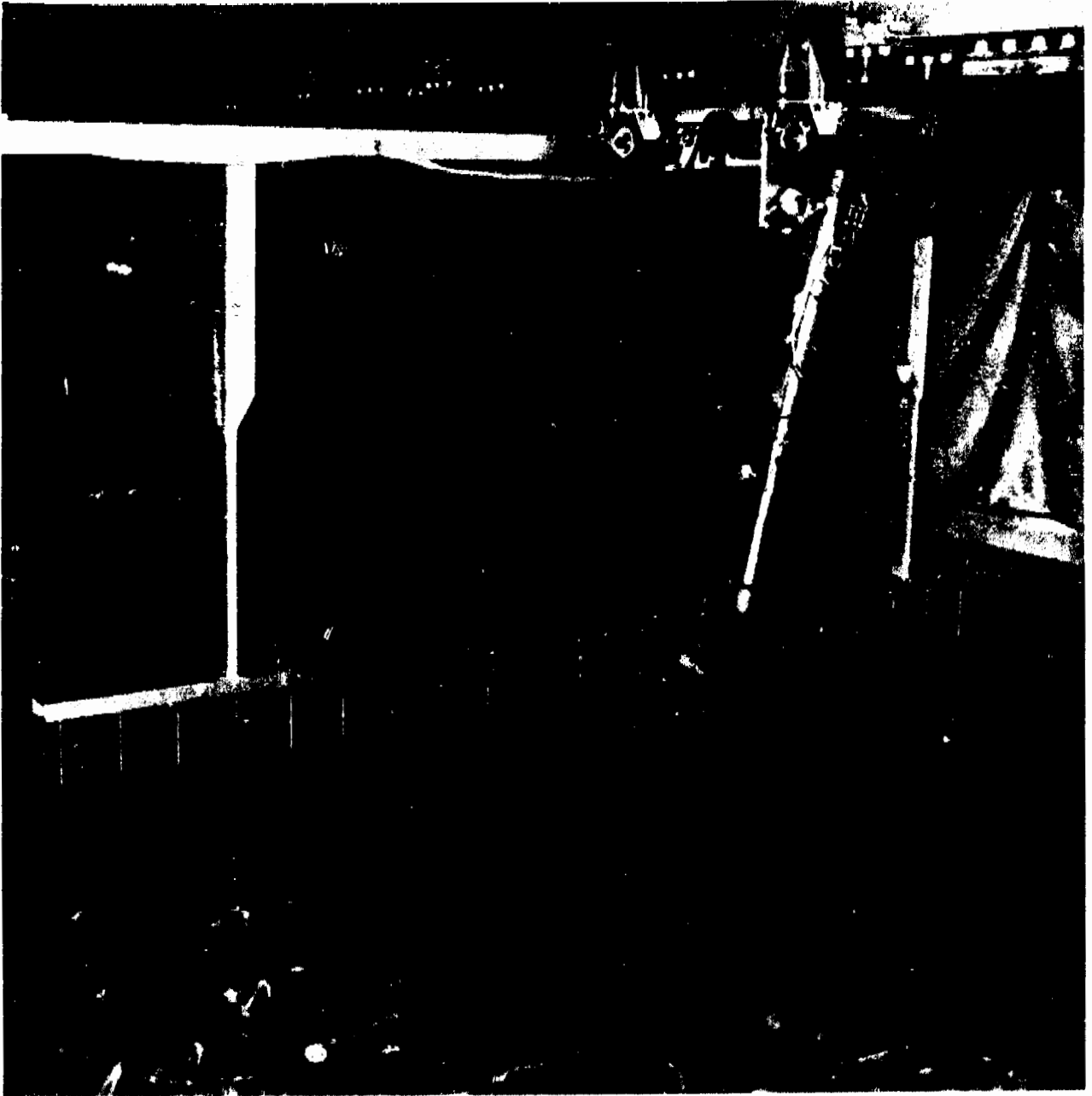


FIGURE 24. MIXING DEVICE (ARRAY OF RODS) IN ACTION BETWEEN TEST RUNS

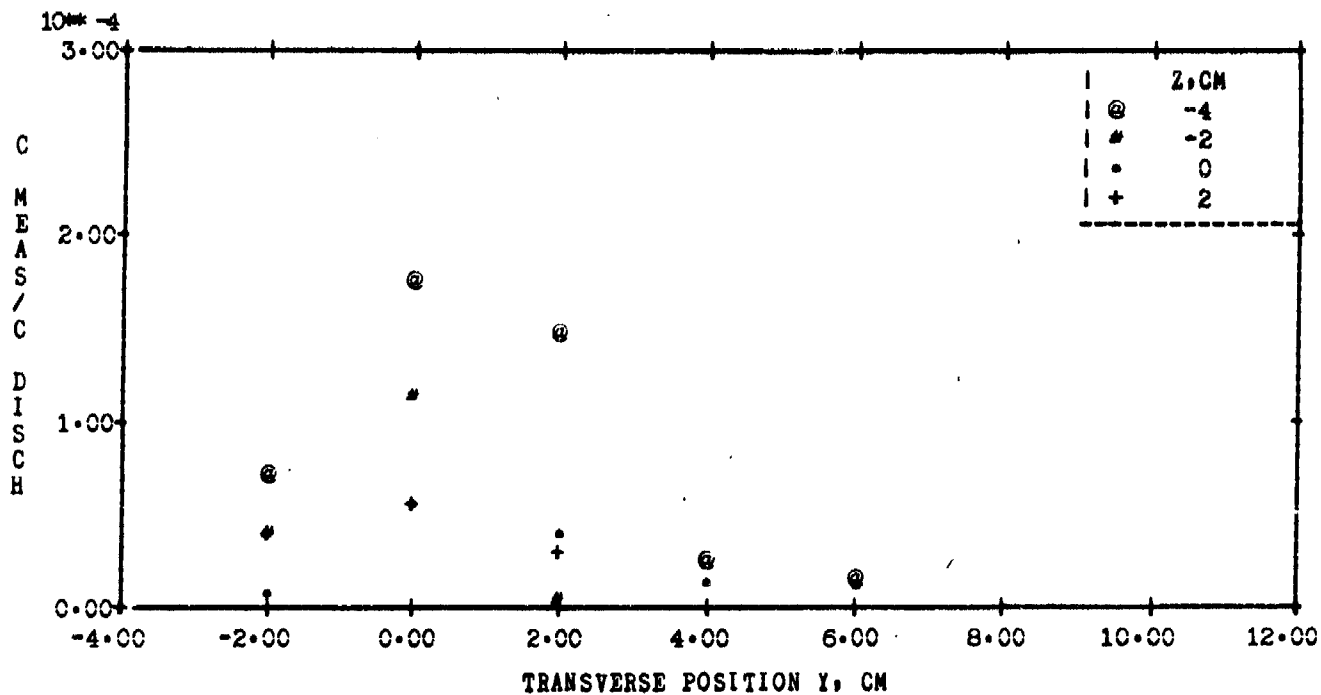


FIGURE 25. TEST 1 CONCENTRATION DISTRIBUTIONS IN SHIP'S WAKE

SPEED = 16.5 KTS NO PROPELLER
 INJECTION LOCATION 3 X PROBE = 0.1 LPP (25.4 CM)
 DISCH RATE = 165 TONS/HR 7.33 IN DISCH PORT DIAM

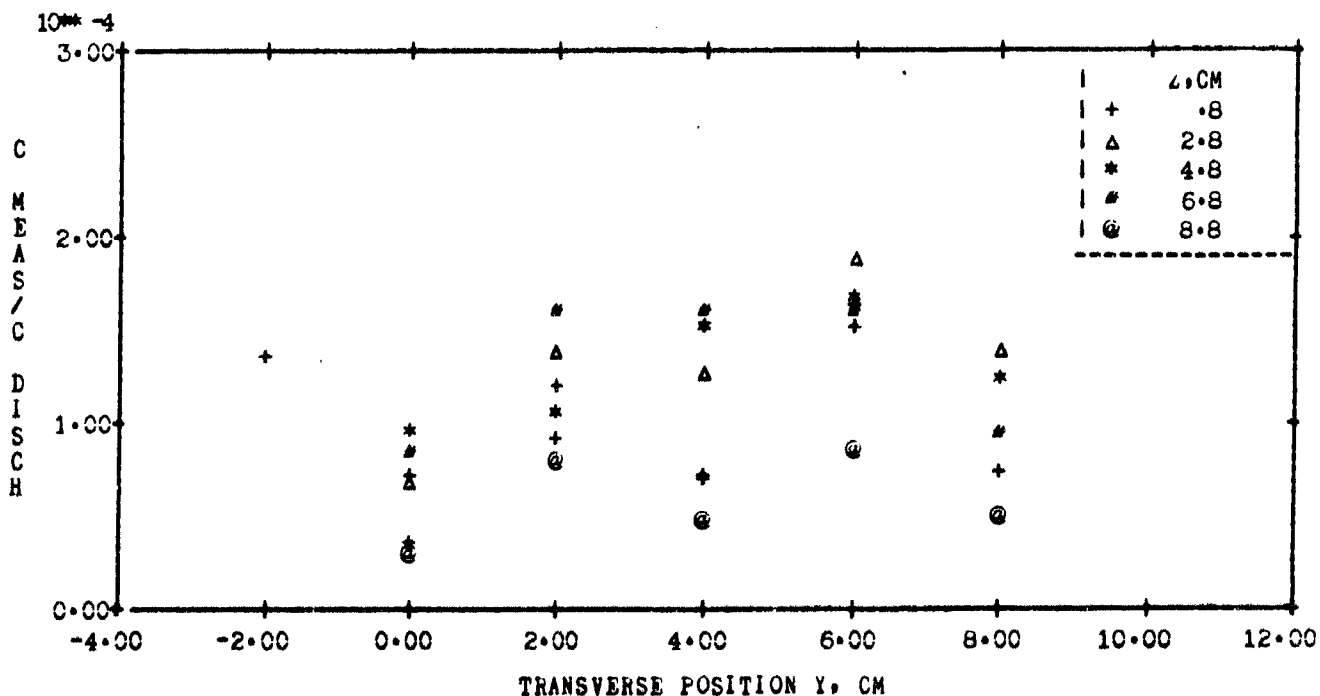


FIGURE 26. TEST 3 CONCENTRATION DISTRIBUTIONS IN SHIP'S WAKE

SPEED = 16.5 KTS
 INJECTION LOCATION 1 X PROBE = 0.1 LPP (25.4 CM)
 DISCH RATE = 165 TONS/HR 7.33 IN DISCH PORT DIAM

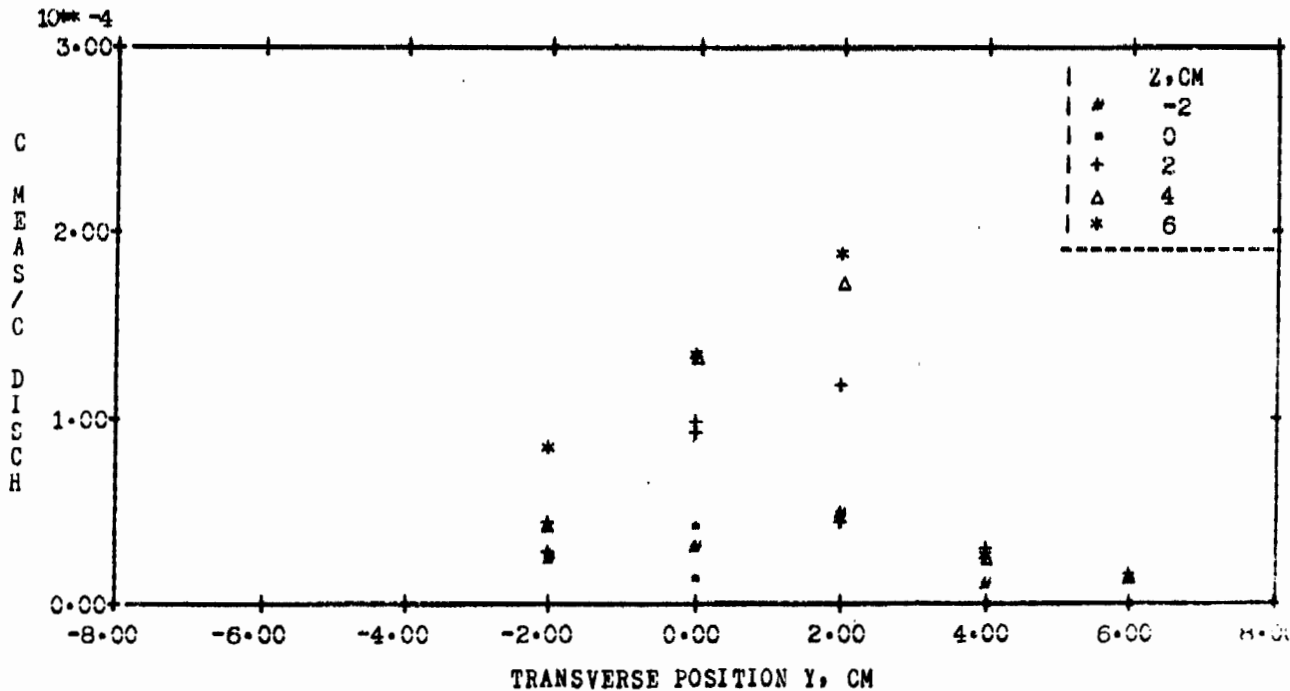


FIGURE 27. TEST 2 CONCENTRATION DISTRIBUTIONS IN SHIP'S WAKE

SPEED = 16.5 KTS NO PROPELLER
 INJECTION LOCATION 2 X PROBE = 0.1 LPP (25.4 CM)
 DISCH RATE = 165 TONS/HR 7.33 IN DISCH PORT DIAM

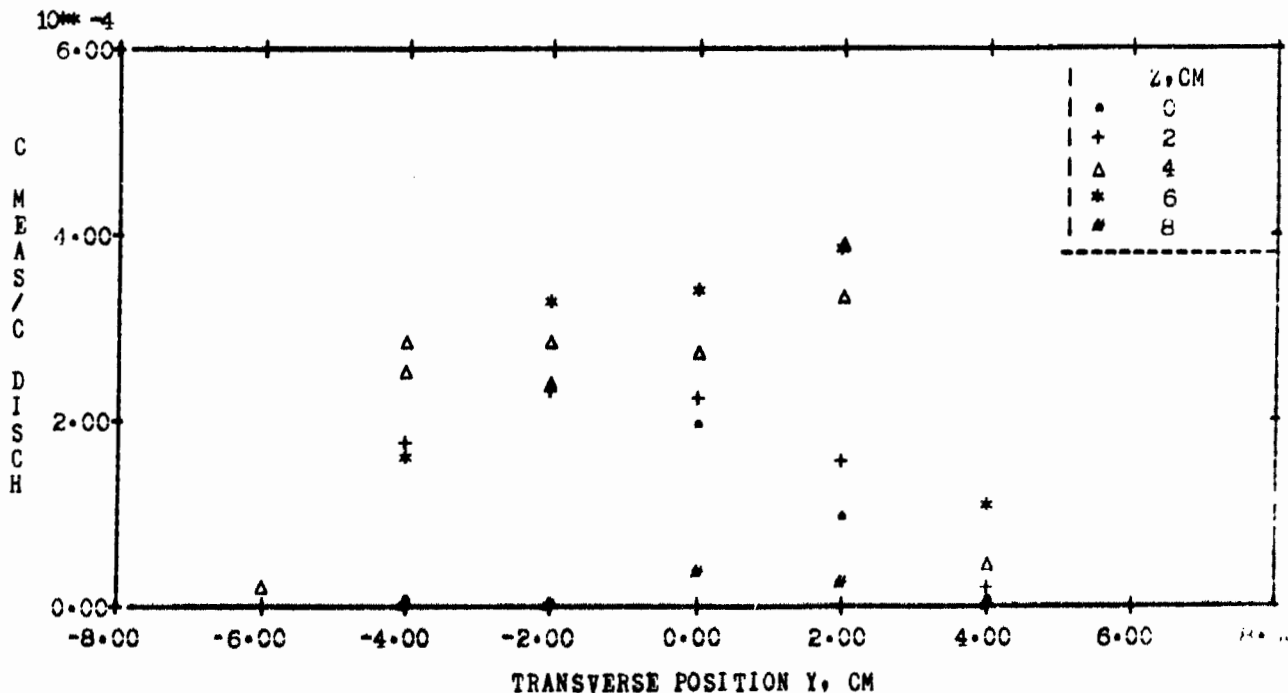


FIGURE 28. TEST 20 CONCENTRATION DISTRIBUTIONS IN SHIP'S WAKE

SPEED = 16.5 KTS PROP RPM = 73, CTH = 0
 INJECTION LOCATION 2 X PROBE = 0.1 LPP (25.4 CM)
 DISCH RATE = 330 TONS/HR 7.33 IN DISCH PORT DIAM

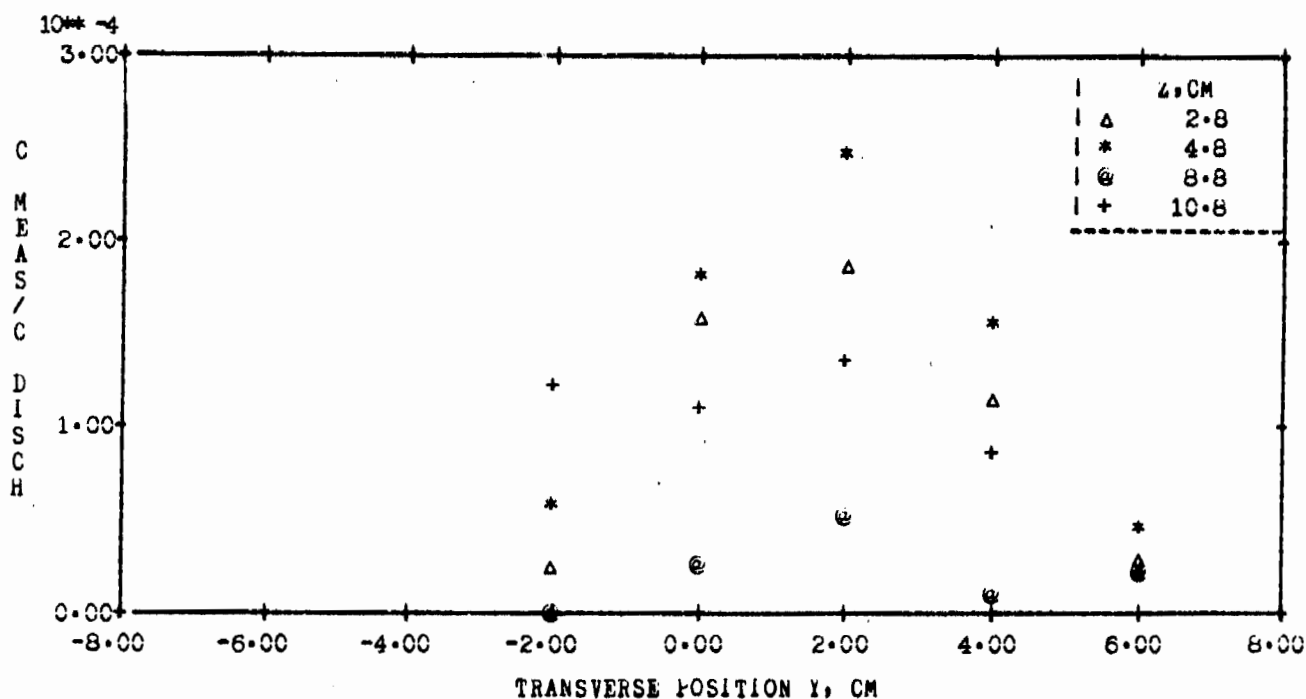


FIGURE 29. TEST 5 CONCENTRATION DISTRIBUTIONS IN SHIP'S WAKE

SPEED = 14.5 KTS NO PROPELLER
 INJECTION LOCATION 2 X PROBE = 0.1 LPP (25.4 CM)
 DISCH RATE = 165 TONS/HR 7.33 IN DISCH PORT DIAM

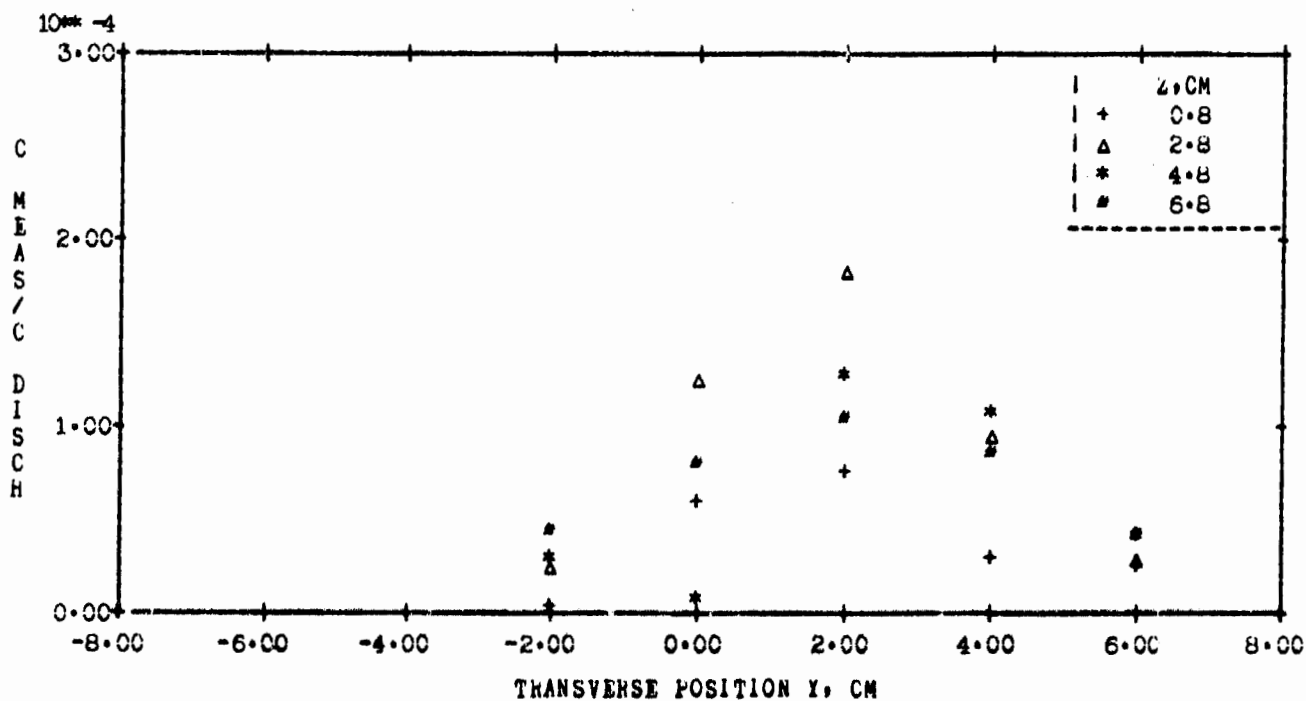


FIGURE 30. TEST 6 CONCENTRATION DISTRIBUTIONS IN SHIP'S WAKE

SPEED = 18.5 KTS NO PROPELLER
 INJECTION LOCATION 2 X PROBE = 0.1 LPP (25.4 CM)
 DISCH RATE = 165 TONS/HR 7.33 IN DISCH PORT DIAM

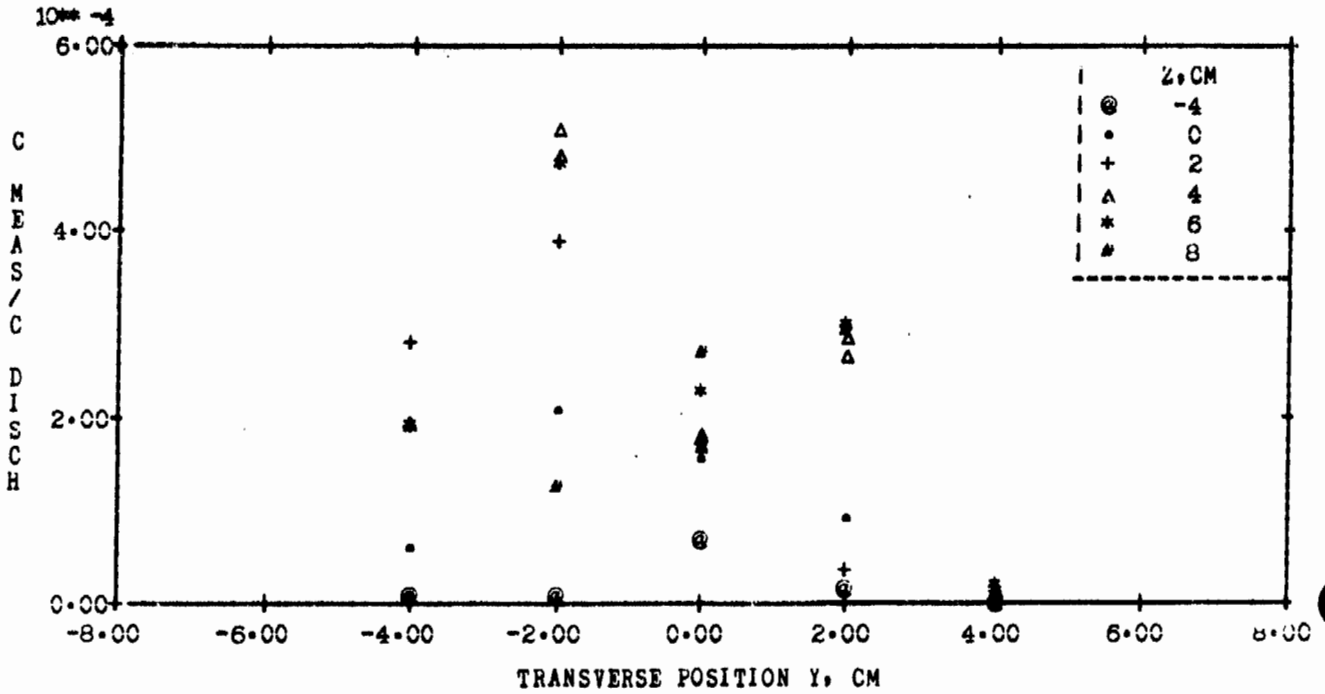


FIGURE 31. TEST 39 CONCENTRATION DISTRIBUTIONS IN SHIP'S WAKE

SPEED = 16.5 KTS PROP RPM = 120, CTH = 2.75
 INJECTION LOCATION 1 X PROBE = 0.1 LPP (25.4 CM)
 DISCH RATE = 330 TONS/HR 7.33 IN DISCH PORT DIAM

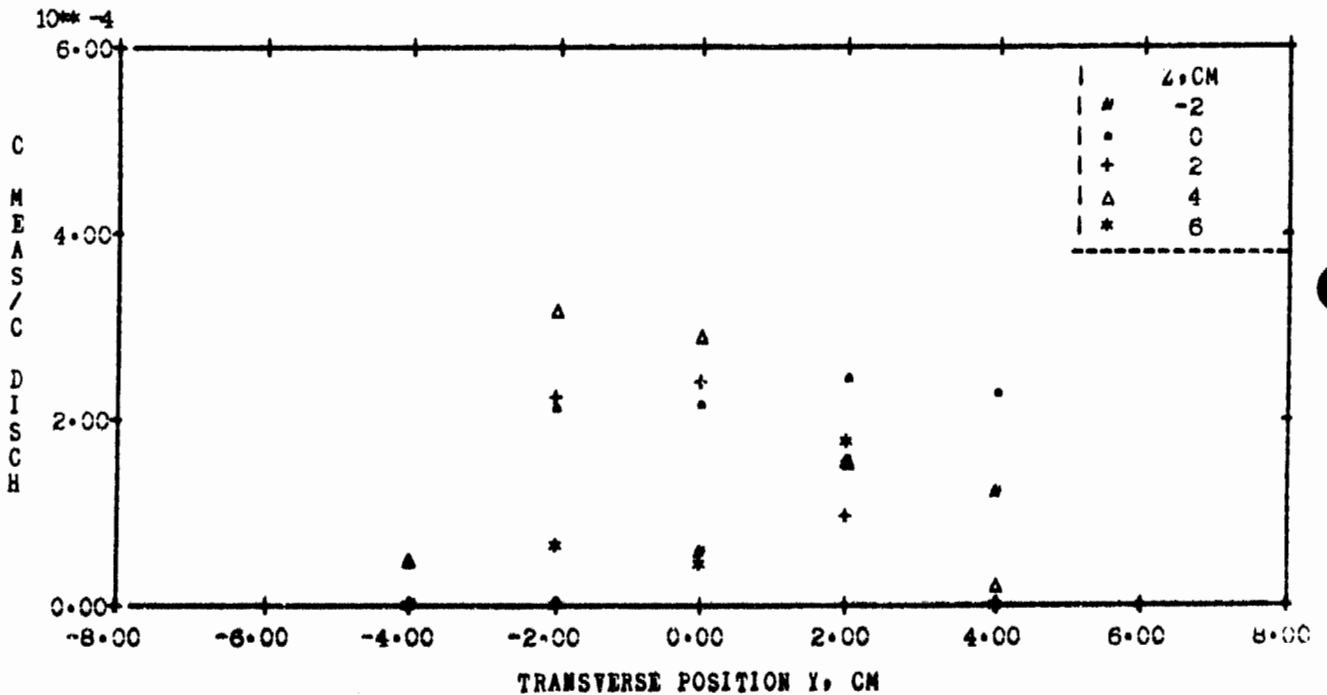


FIGURE 32. TEST 34 CONCENTRATION DISTRIBUTIONS IN SHIP'S WAKE

SPEED = 16.5 KTS PROP RPM = 120, CTH = 2.75
 INJECTION LOCATION 2 X PROBE = 0.1 LPP (25.4 CM)
 DISCH RATE = 330 TONS/HR 7.33 IN DISCH PORT DIAM

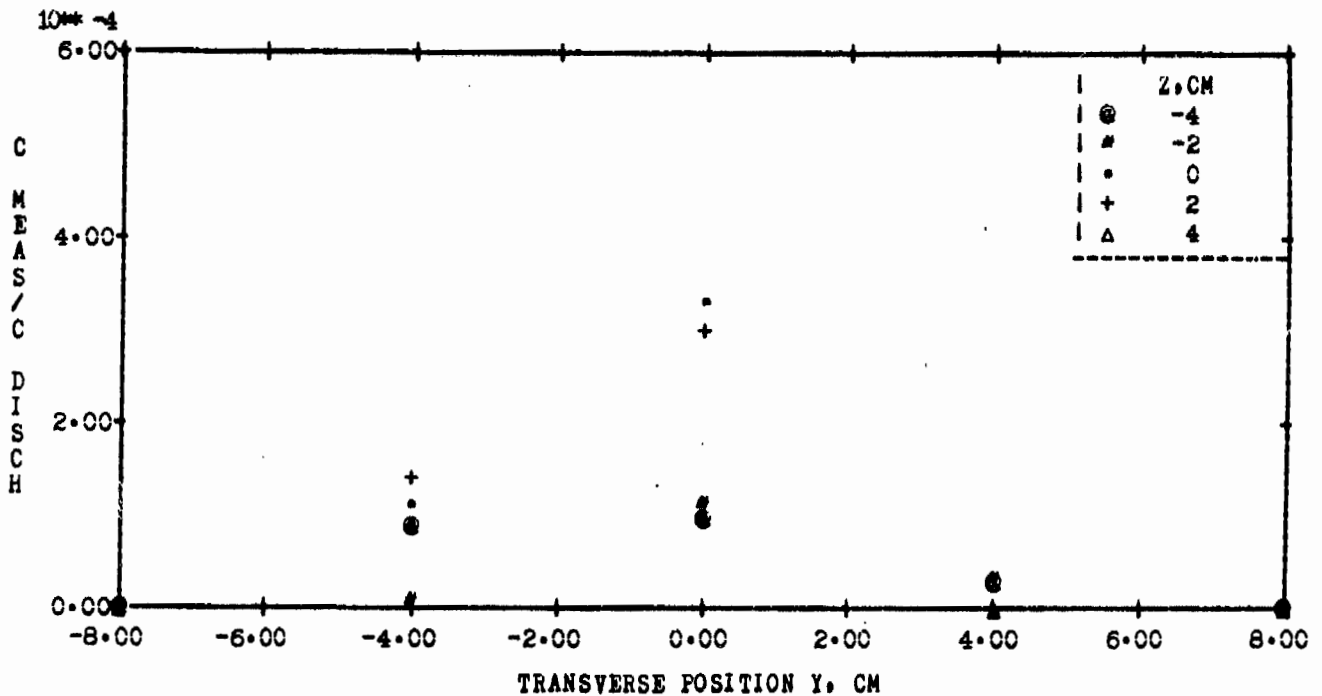


FIGURE 33. TEST 12 CONCENTRATION DISTRIBUTIONS IN SHIP'S WAKE

SPEED = 16.5 KTS PROP RPM = 120, CTR = 2.75
 INJECTION LOCATION 3 X PROBE = 0.1 LPP (25.4 CM)
 DISCH RATE = 330 TONS/HR 7.33 IN DISCH PORT DIAM

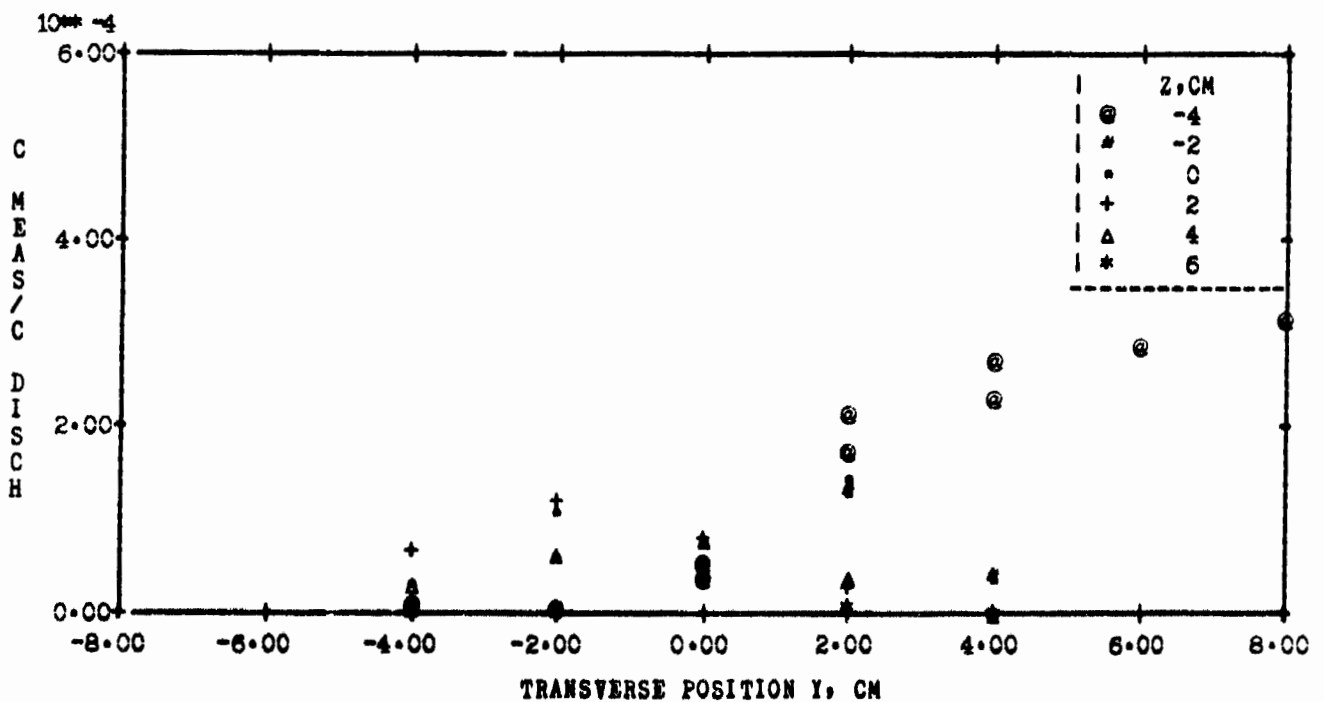


FIGURE 34. TEST 13 CONCENTRATION DISTRIBUTIONS IN SHIP'S WAKE

SPEED = 16.5 KTS
 INJECTION LOCATION 4 X PROBE = 0.1 LPP (25.4 CM)
 DISCH RATE = 330 TONS/HR 7.33 IN DISCH PORT DIAM

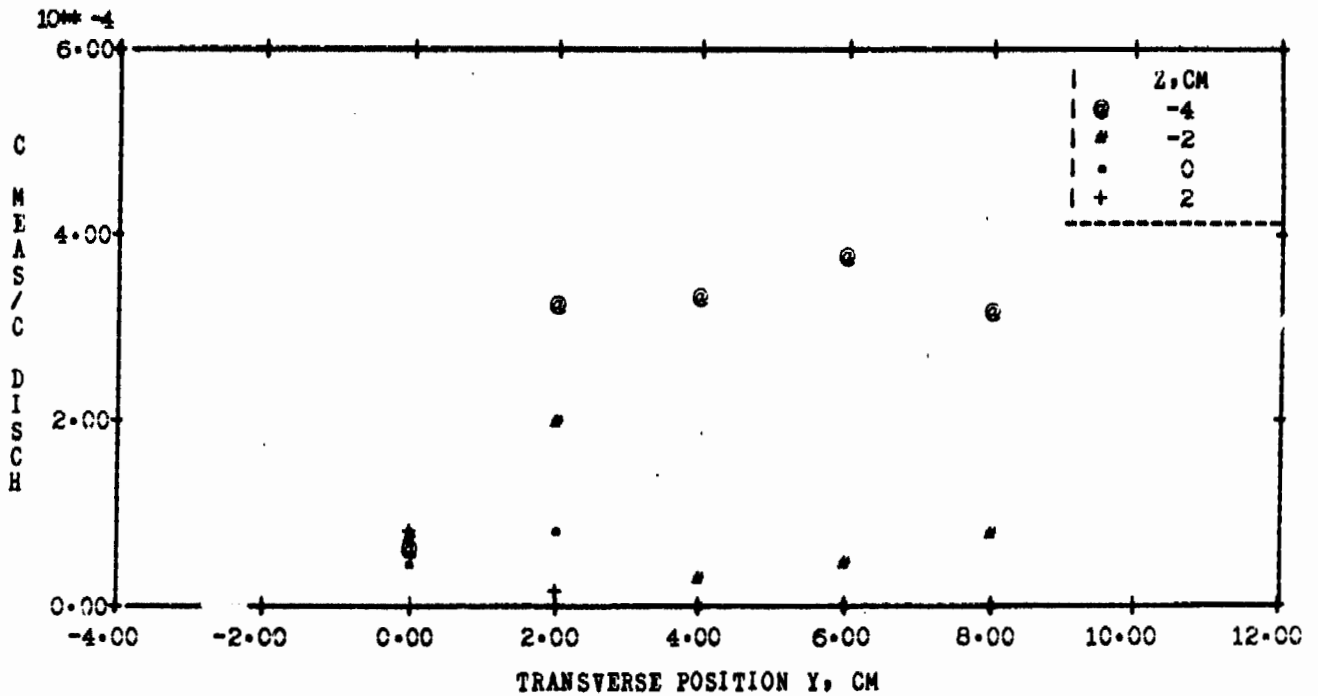


FIGURE 35. TEST 14 CONCENTRATION DISTRIBUTIONS IN SHIP'S WAKE

SPEED = 16.5 KTS PROP RPM = 120, CTH = 2.75
 INJECTION LOCATION 5 X PROBE = 0.1 LPP (25.4 CM)
 DISCH RATE = 330 TONS/HR 7.33 IN DISCH PORT DIAM

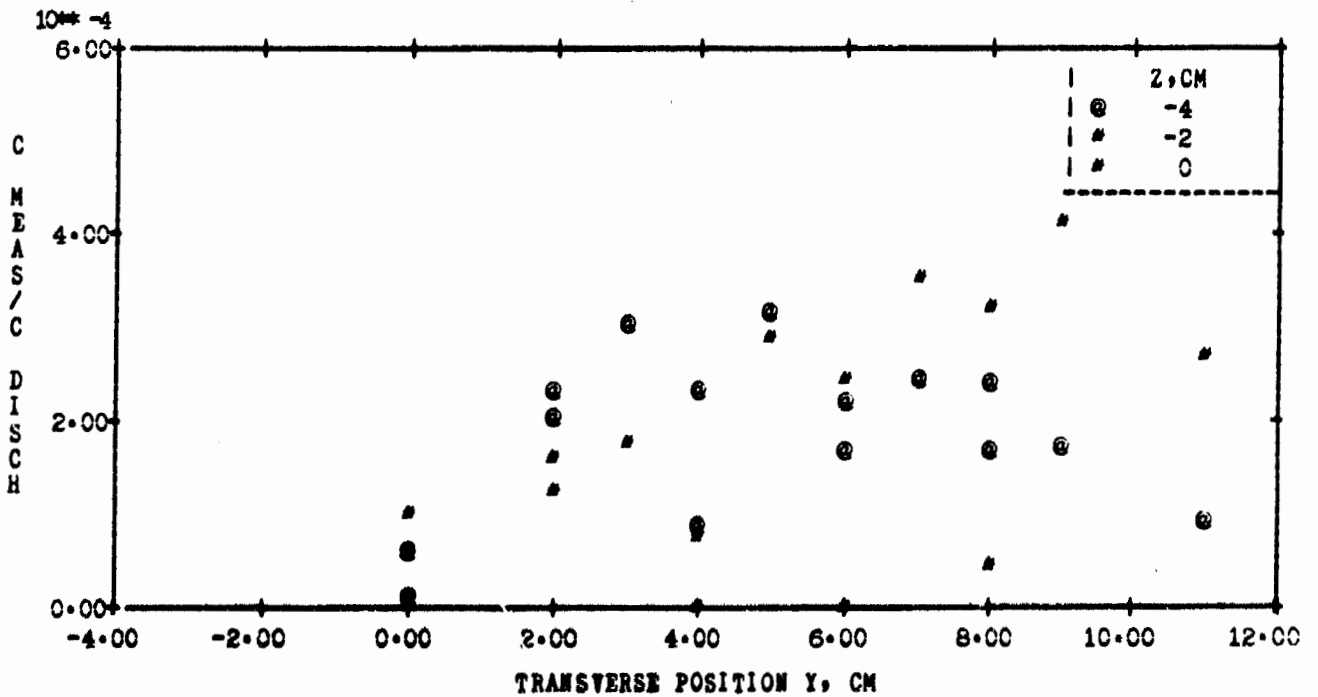


FIGURE 36. TEST 15 CONCENTRATION DISTRIBUTIONS IN SHIP'S WAKE

SPEED = 16.5 KTS PROP RPM = 120, CTH = 2.75
 INJECTION LOCATION 6 X PROBE = 0.1 LPP (25.4 CM)
 DISCH RATE = 330 TONS/HR 7.33 IN DISCH PORT DIAM

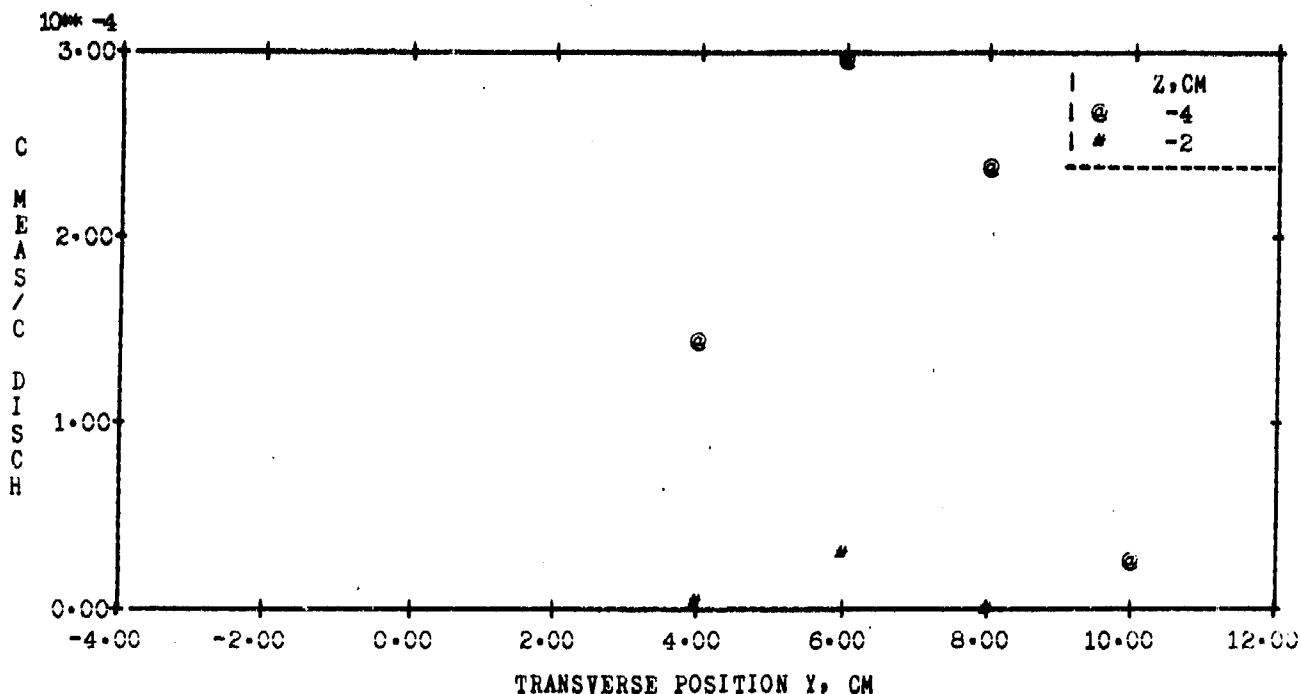


FIGURE 37. TEST 16 CONCENTRATION DISTRIBUTIONS IN SHIP'S WAKE

SPEED = 16.5 KTS PROP RPM = 120, CTH = 2.75
 INJECTION LOCATION A X PROBE = 0.1 LPP (25.4 CM)
 DISCH RATE = 165 TONS/HR 7.33 IN DISCH PORT DIAM

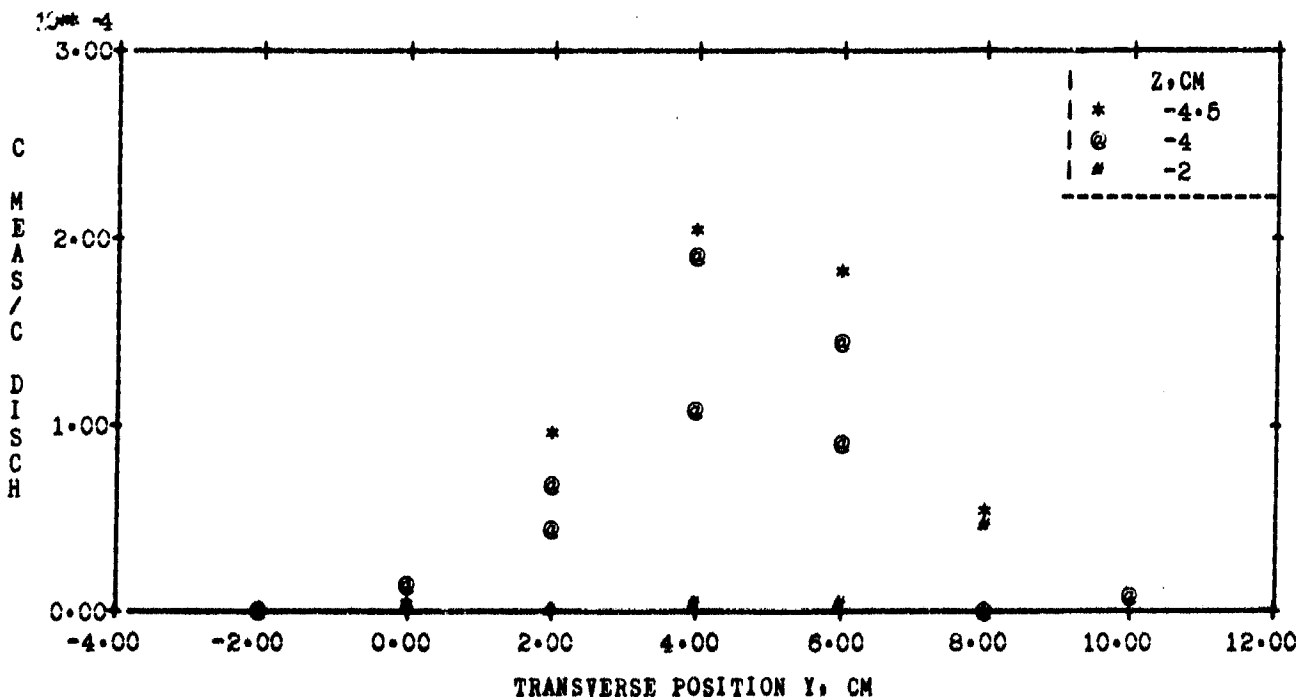


FIGURE 38. TEST 17 CONCENTRATION DISTRIBUTIONS IN SHIP'S WAKE

SPEED = 16.5 KTS PROP RPM = 120, CTH = 2.75
 INJECTION LOCATION B X PROBE = 0.1 LPP (25.4 CM)
 DISCH RATE = 165 TONS/HR 7.33 IN DISCH PORT DIAM

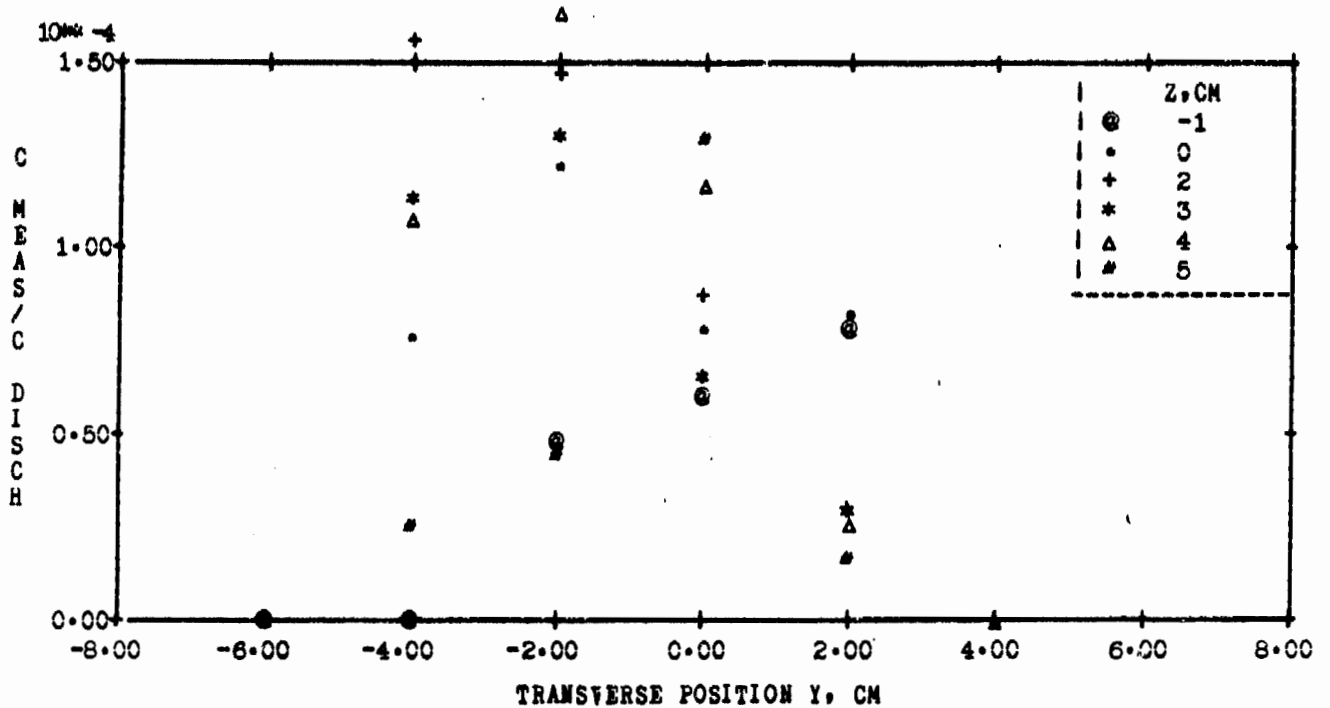


FIGURE 39. TEST 22 CONCENTRATION DISTRIBUTIONS IN SHIP'S WAKE

SPEED = 16.5 KTS PROP RPM = 120, CTH = 2.75
 INJECTION LOCATION 2 X PROBE = 0.1 LPP (25.4 CM)
 DISCH RATE = 165 TONS/HR 7.33 IN DISCH PORT DIAM

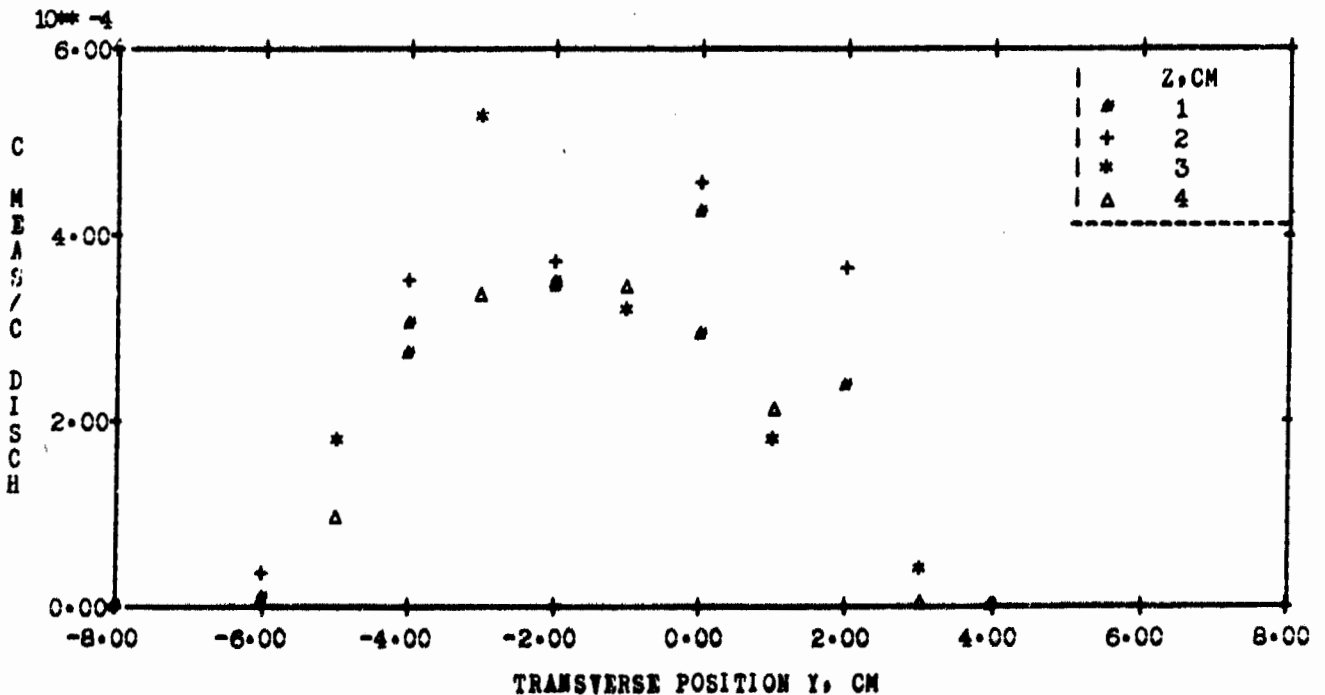


FIGURE 40. TEST 23 CONCENTRATION DISTRIBUTIONS IN SHIP'S WAKE

SPEED = 16.5 KTS PROP RPM = 120, CTH = 2.75
 INJECTION LOCATION 2 X PROBE = 0.1 LPP (25.4 CM)
 DISCH RATE = 498 TONS/HR 7.33 IN DISCH PORT DIAM

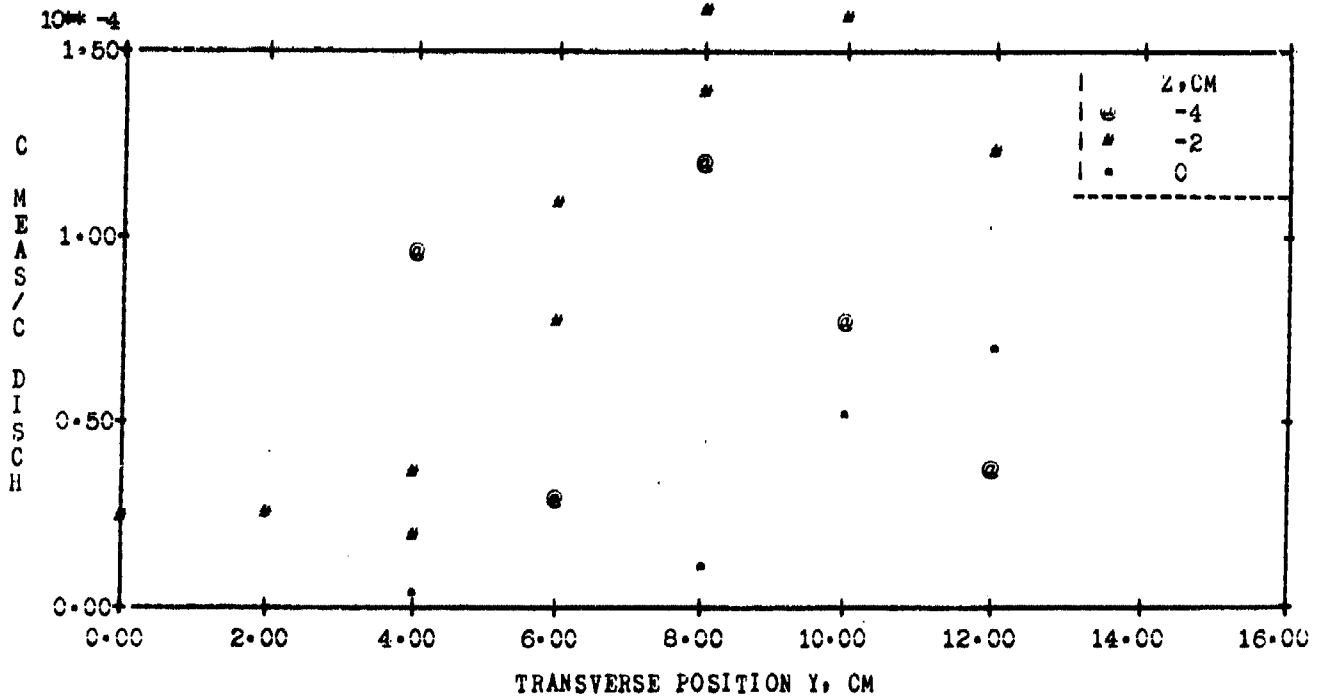


FIGURE 41. TEST 32 CONCENTRATION DISTRIBUTIONS IN SHIP'S WAKE

SPEED = 16.5 KTS PROP RPM = 120, CTH = 2.75
 INJECTION LOCATION 4 X PROBE = 0.1 LPP (25.4 CM)
 DISCH RATE = 165 TONS/HR 7.33 IN DISCH PORT DIAM

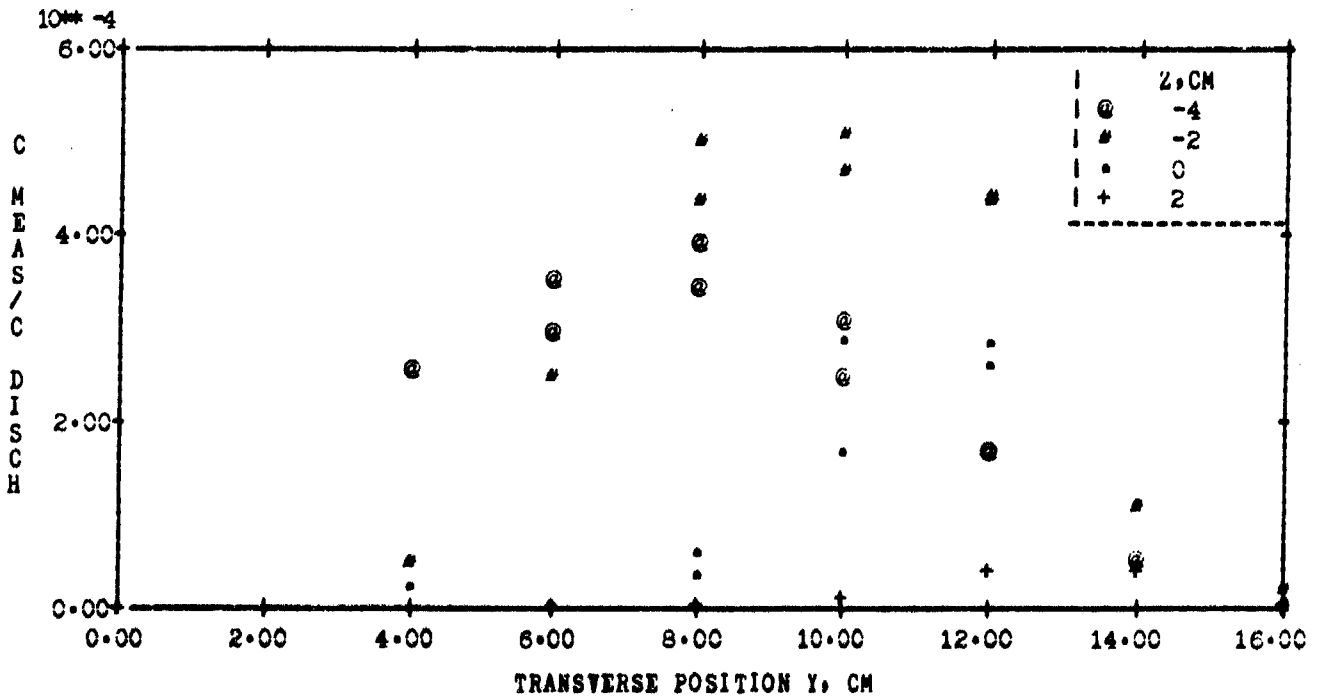


FIGURE 42. TEST 33 CONCENTRATION DISTRIBUTIONS IN SHIP'S WAKE

SPEED = 16.5 KTS PROP RPM = 120, CTH = 2.75
 INJECTION LOCATION 4 X PROBE = 0.1 LPP (25.4 CM)
 DISCH RATE = 495 TONS/HR 7.33 IN DISCH PORT DIAM

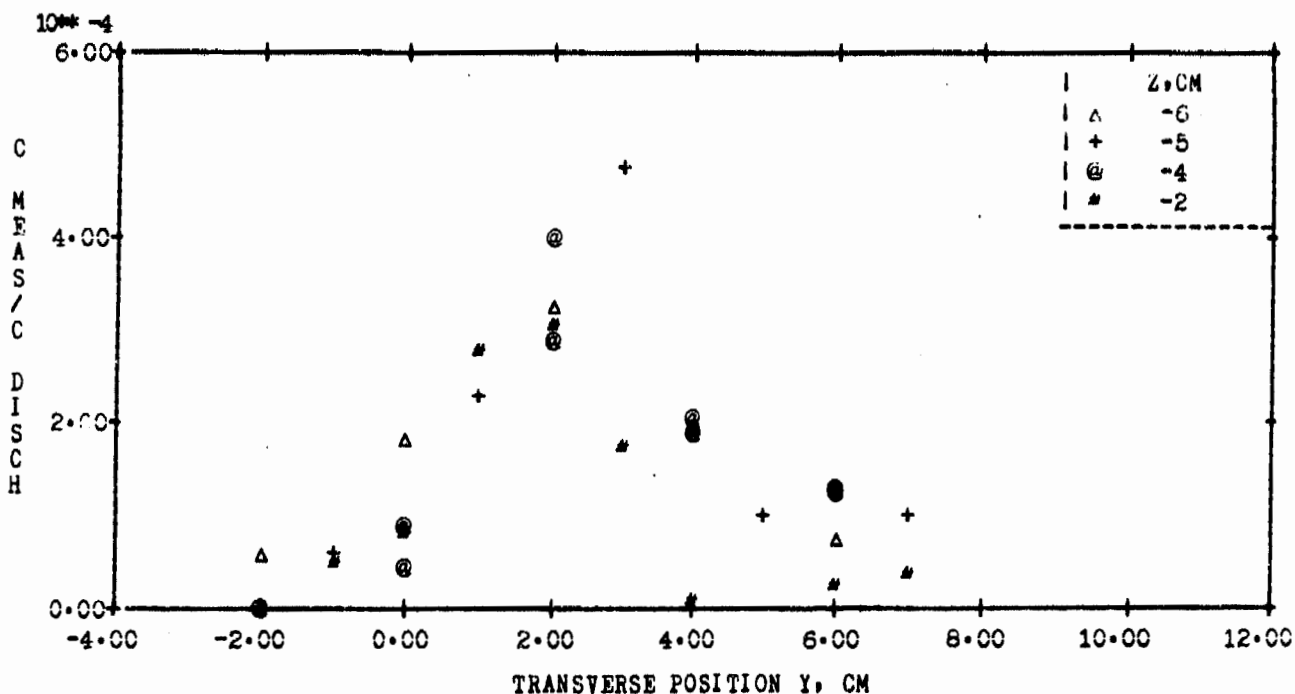


FIGURE 43. TEST 29 CONCENTRATION DISTRIBUTIONS IN SHIP'S WAKE

SPEED = 16.5 KTS PROP RPM = 120, CTH = 2.75
 INJECTION LOCATION 2 X PROBE = 0.1 LPP (25.4 CM)
 DISCH RATE = 330 TONS/HR 5.00 IN DISCH PORT DIAM

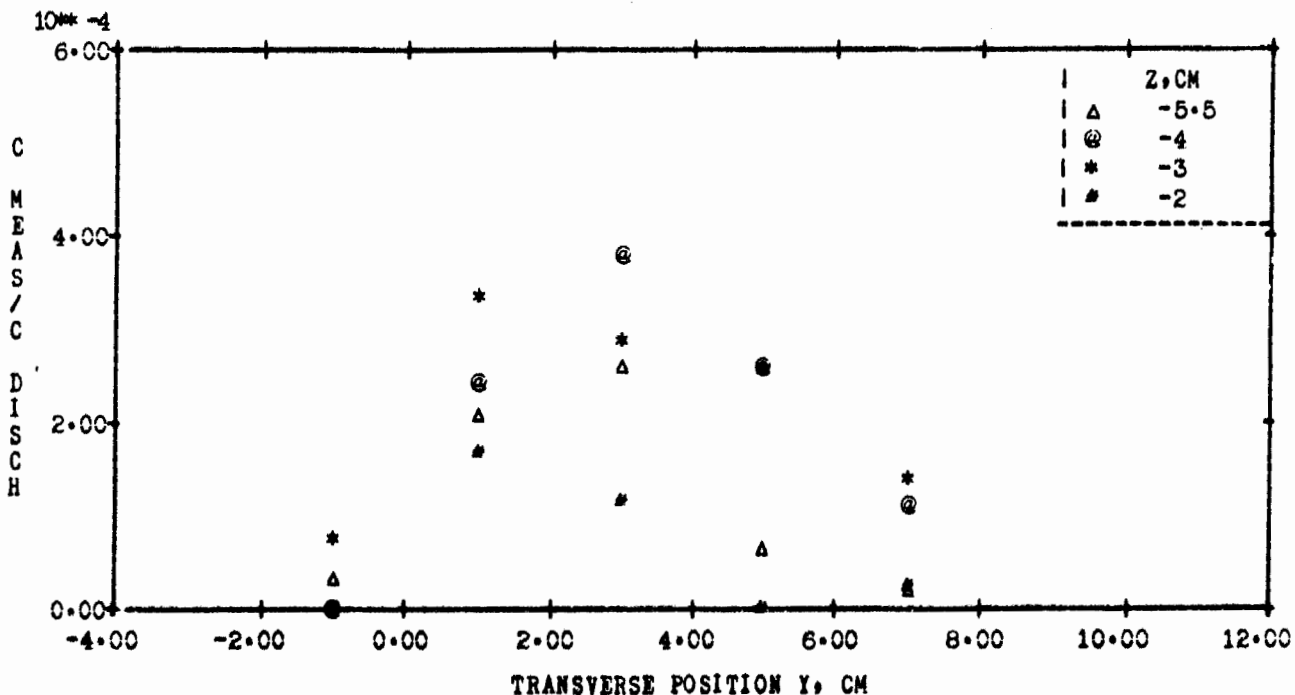


FIGURE 44. TEST 30 CONCENTRATION DISTRIBUTIONS IN SHIP'S WAKE

SPEED = 16.5 KTS PROP RPM = 120, CTH = 2.75
 INJECTION LOCATION 2 X PROBE = 0.1 LPP (25.4 CM)
 DISCH RATE = 330 TONS/HR 2.27 IN DISCH PORT DIAM

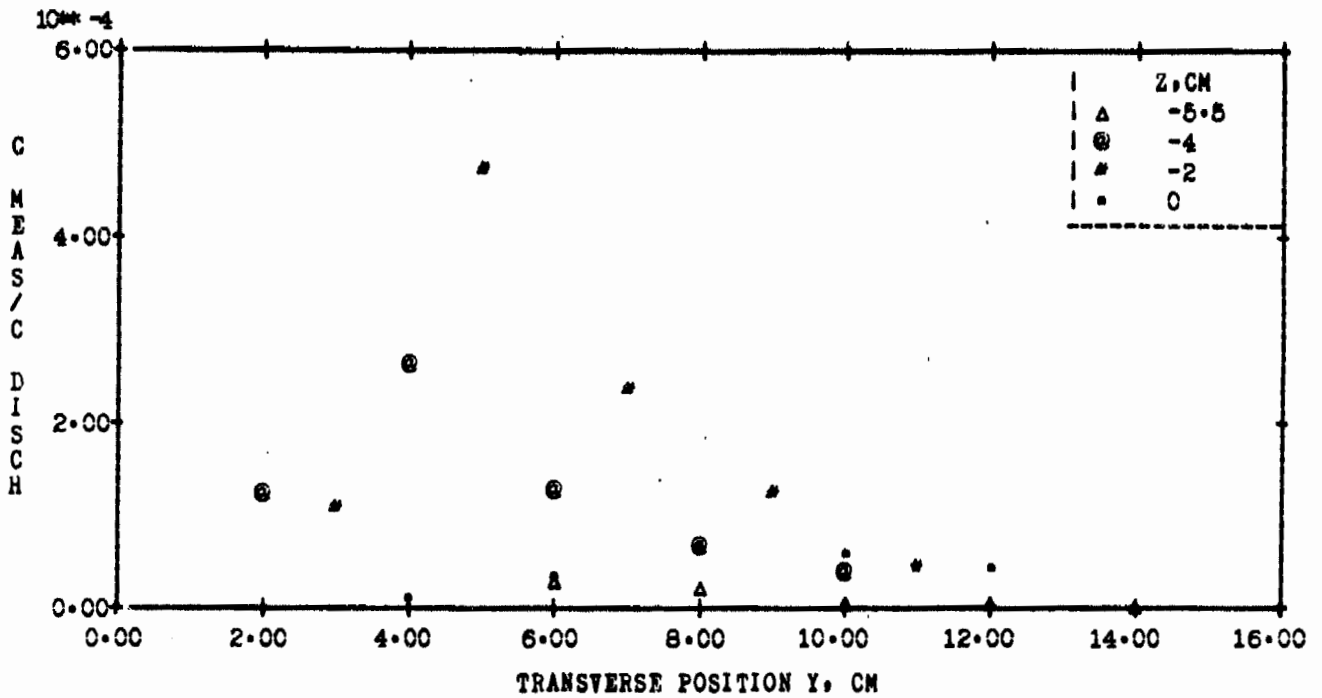


FIGURE 45. TEST 31 CONCENTRATION DISTRIBUTIONS IN SHIP'S WAKE

SPEED = 16.5 KTS PROP RPM = 120, CTH = 2.75
 INJECTION LOCATION 6 X PROBE = 0.1 LPP (25.4 CM)
 DISCH RATE = 330 TONS/HR 2.27 IN DISCH PORT DIAM

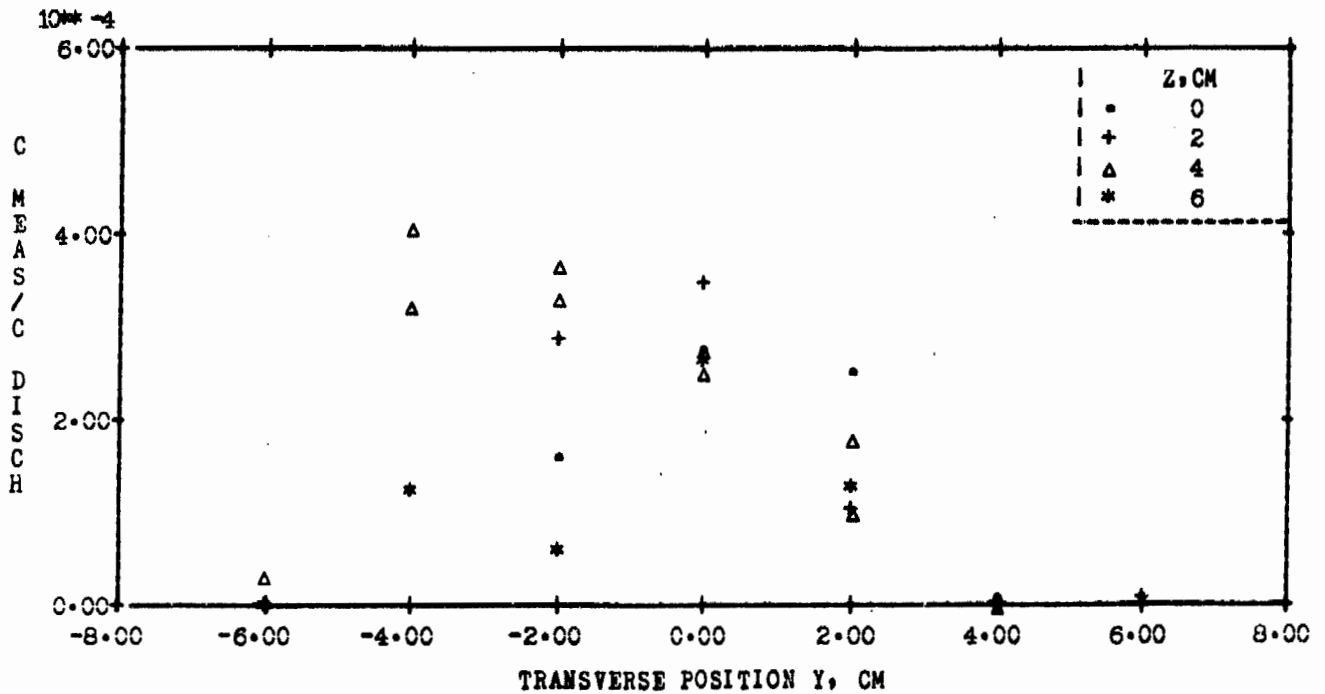
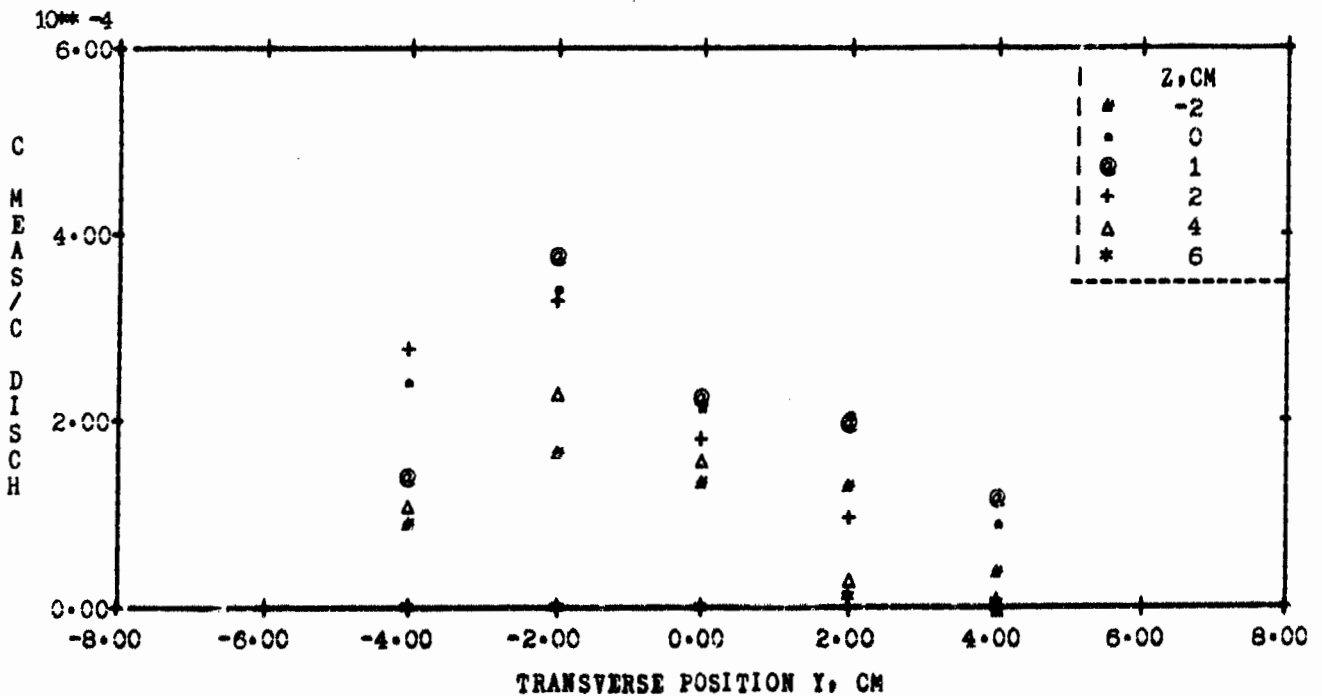


FIGURE 46. TEST 19 CONCENTRATION DISTRIBUTIONS IN SHIP'S WAKE

SPEED = 16.5 KTS PROP RPM = 100, CTH = 2.20
 INJECTION LOCATION 2 X PROBE = 0.1 LPP (25.4 CM)
 DISCH RATE = 330 TONS/HR 7.33 IN DISCH PORT DIAM



FIGUR. 47. TEST 21 CONCENTRATION DISTRIBUTIONS IN SHIP'S WAKE

SPEED = 16.5 KTS PROP RPM = 140, CTH = 4.85
 INJECTION LOCATION 2 X PROBE = 0.1 LPP (25.4 CM)
 DISCH RATE = 330 TONS/HR 7.33 IN DISCH PORT DIAM

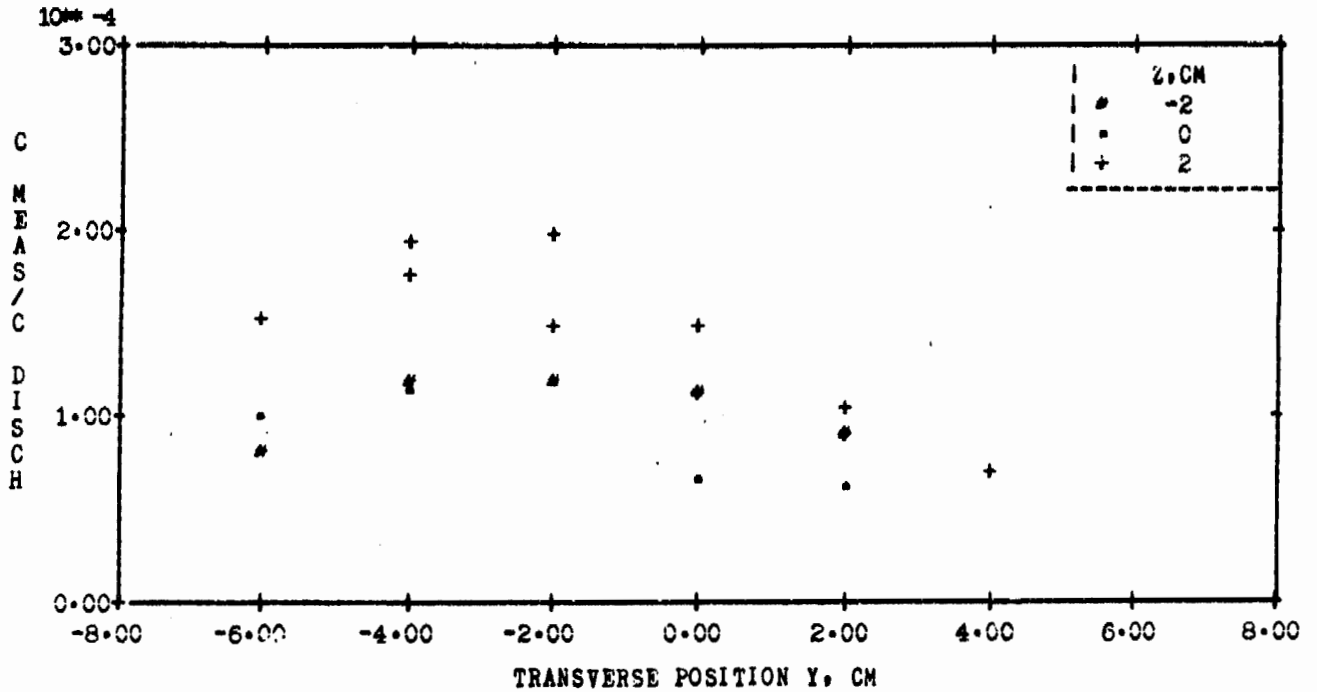


FIGURE 48. TEST 24 CONCENTRATION DISTRIBUTIONS IN SHIP'S WAKE

SPEED = 16.5 KTS PROP RPM = 120, CTH = 2.75
 INJECTION LOCATION 2 X PROBE = 0.3 LPP (76.2 CM)
 DISCH RATE = 330 TONS/HR 7.33 IN DISCH PORT DIAM

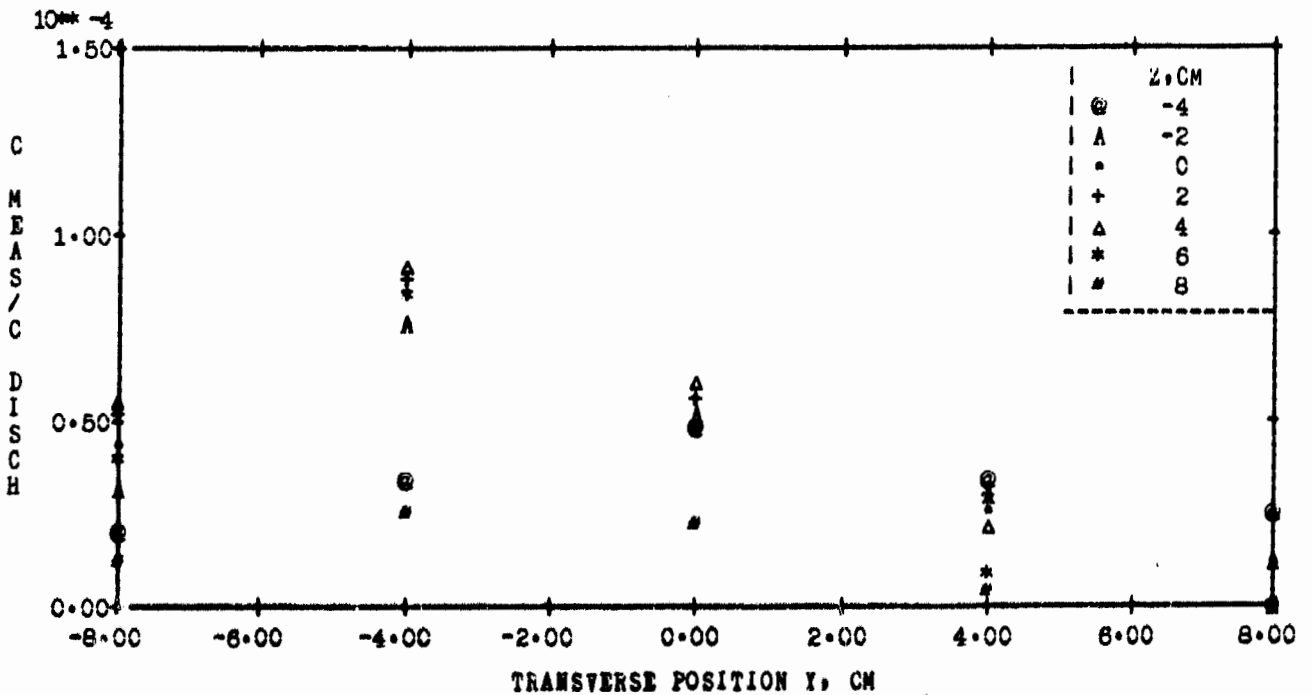


FIGURE 49. TEST 28 CONCENTRATION DISTRIBUTIONS IN SHIP'S WAKE

SPEED = 16.5 KTS PROP RPM = 120, CTH = 2.75
 INJECTION LOCATION 2 X PROBE = 0.7 LPP (177.8 CM)
 DISCH RATE = 330 TONS/HR 7.33 IN DISCH PORT DIAM

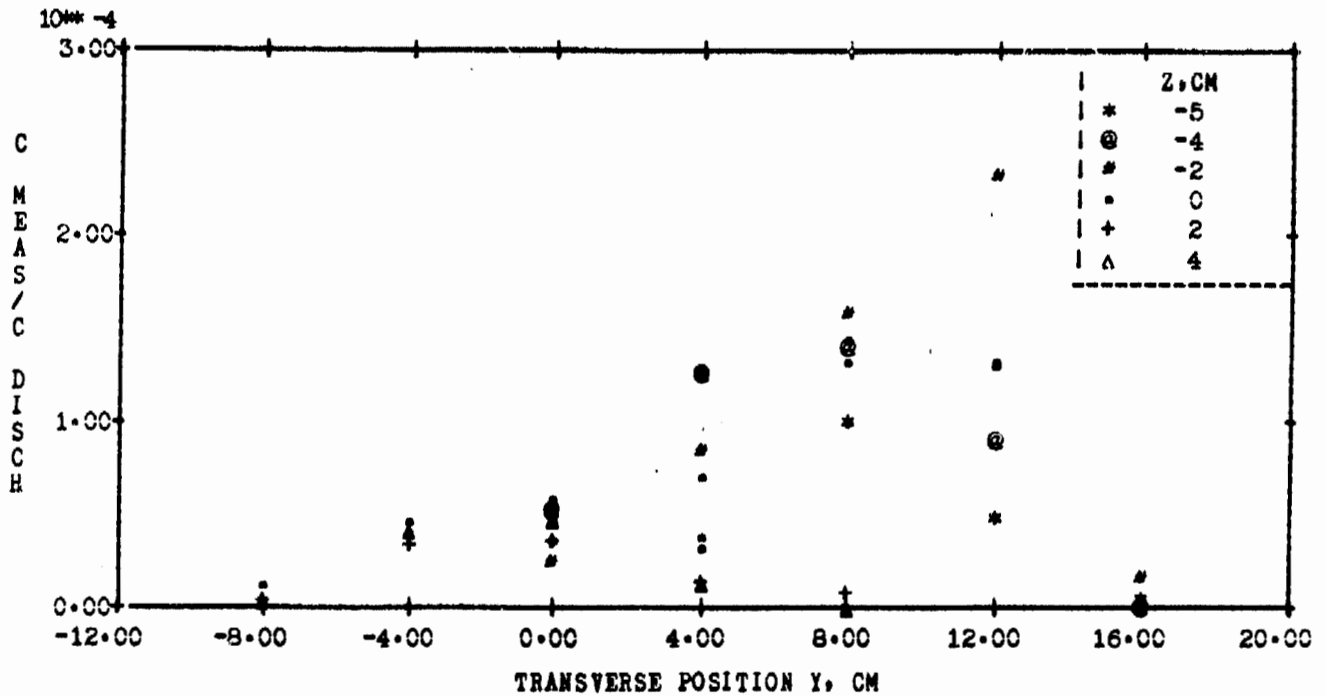


FIGURE 50. TEST 26 CONCENTRATION DISTRIBUTIONS IN SHIP'S WAKE

SPEED = 16.5 KTS PROP RPM = 120, CTH = 2.75
 INJECTION LOCATION 4 X PROBE = 0.3 LPP (76.2 CM)
 DISCH RATE = 330 TONS/HR 7.33 IN DISCH PORT DIAM

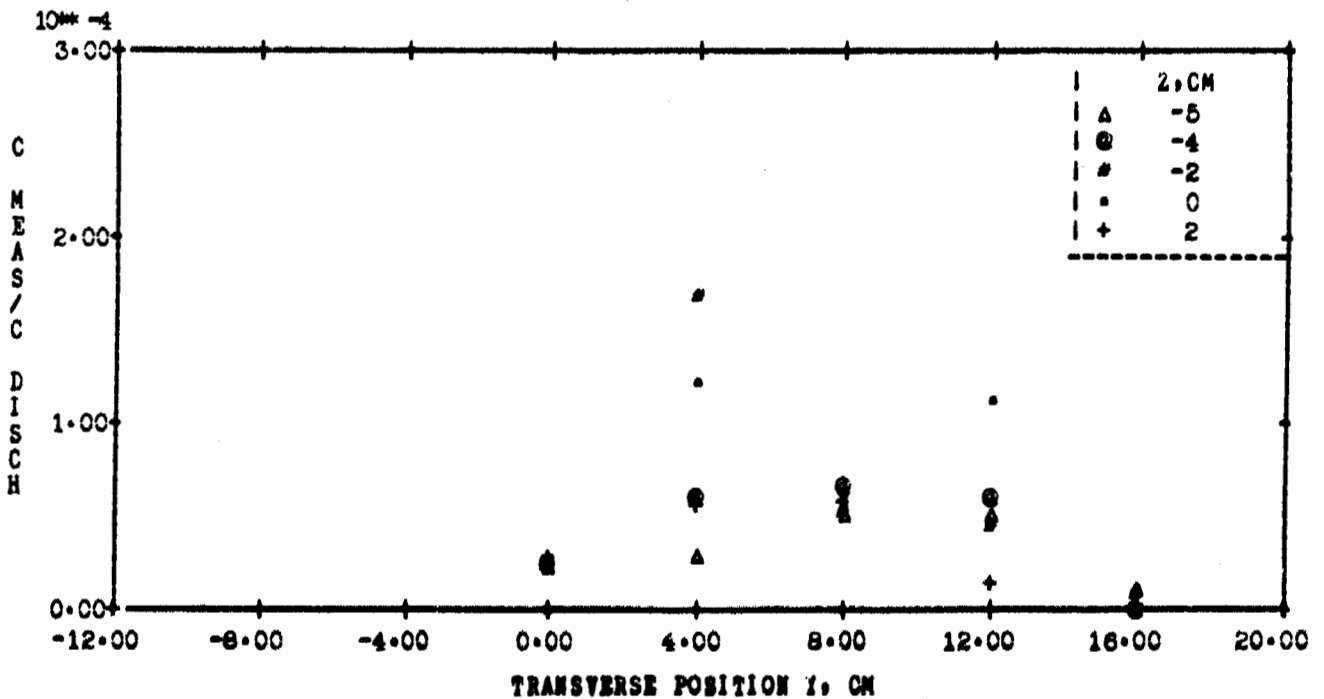


FIGURE 51. TEST 27 CONCENTRATION DISTRIBUTIONS IN SHIP'S WAKE

SPEED = 16.5 KTS PROP RPM = 120, CTH = 2.75
 INJECTION LOCATION 4 X PROBE = 0.7 LPP (177.8 CM)
 DISCH RATE = 330 TONS/HR 7.33 IN DISCH PORT DIAM

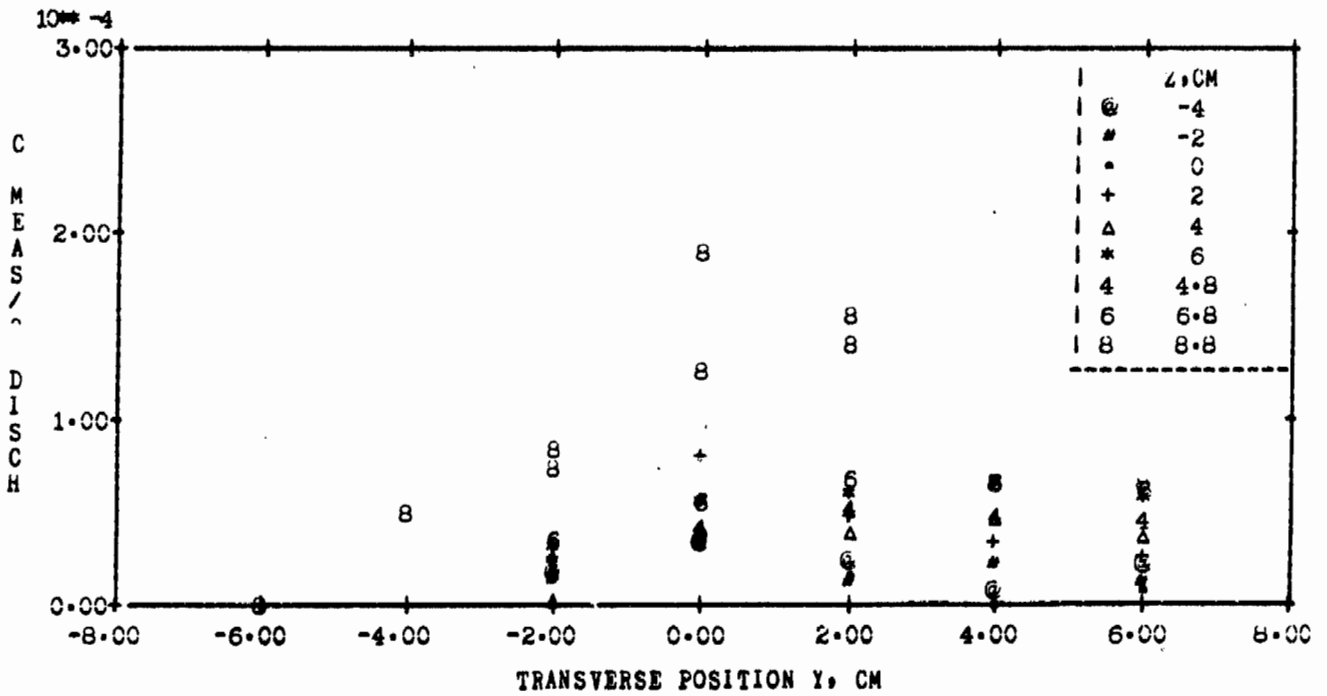


FIGURE 52. TEST 4 CONCENTRATION DISTRIBUTIONS IN SHIP'S WAKE

SPEED = 16.5 KTS NO PROPELLER
 INJECTION LOCATION 2 X PROBE = 0.3 LPP (76.2 CM)
 DISCH RATE = 168 TONS/HR 7.33 IN DISCH PORT DIAM

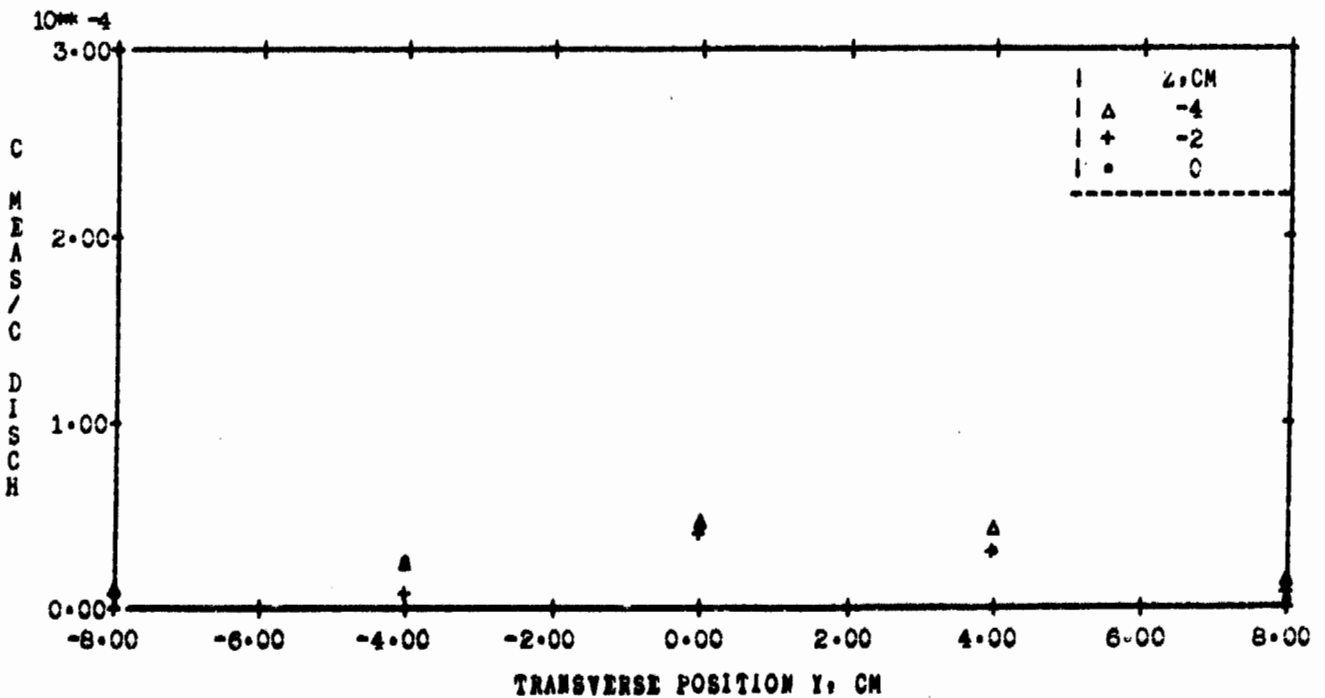


FIGURE 53. TEST 11 CONCENTRATION DISTRIBUTIONS IN SHIP'S WAKE

SPEED = 16.5 KTS NO PROPELLER
 INJECTION LOCATION 2 X PROBE = 0.7 LPP (177.8 CM)
 DISCH RATE = 330 TONS/HR 7.33 IN DISCH PORT DIAM

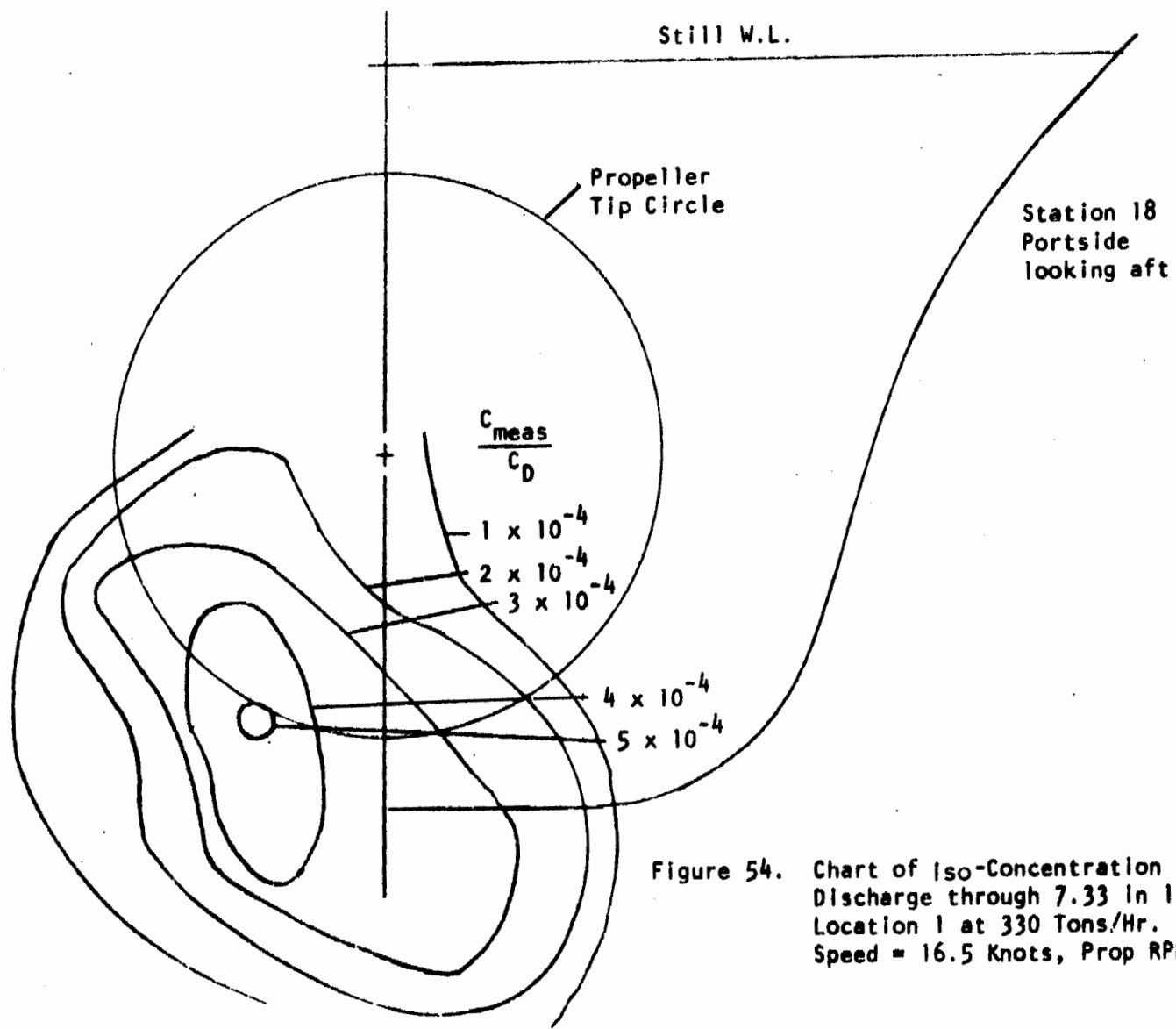


Figure 54. Chart of Iso-Concentration Contours for Discharge through 7.33 in I.D. Pipe from Location 1 at 330 Tons/Hr. Test 39, Ship Speed = 16.5 Knots, Prop RPM = 120

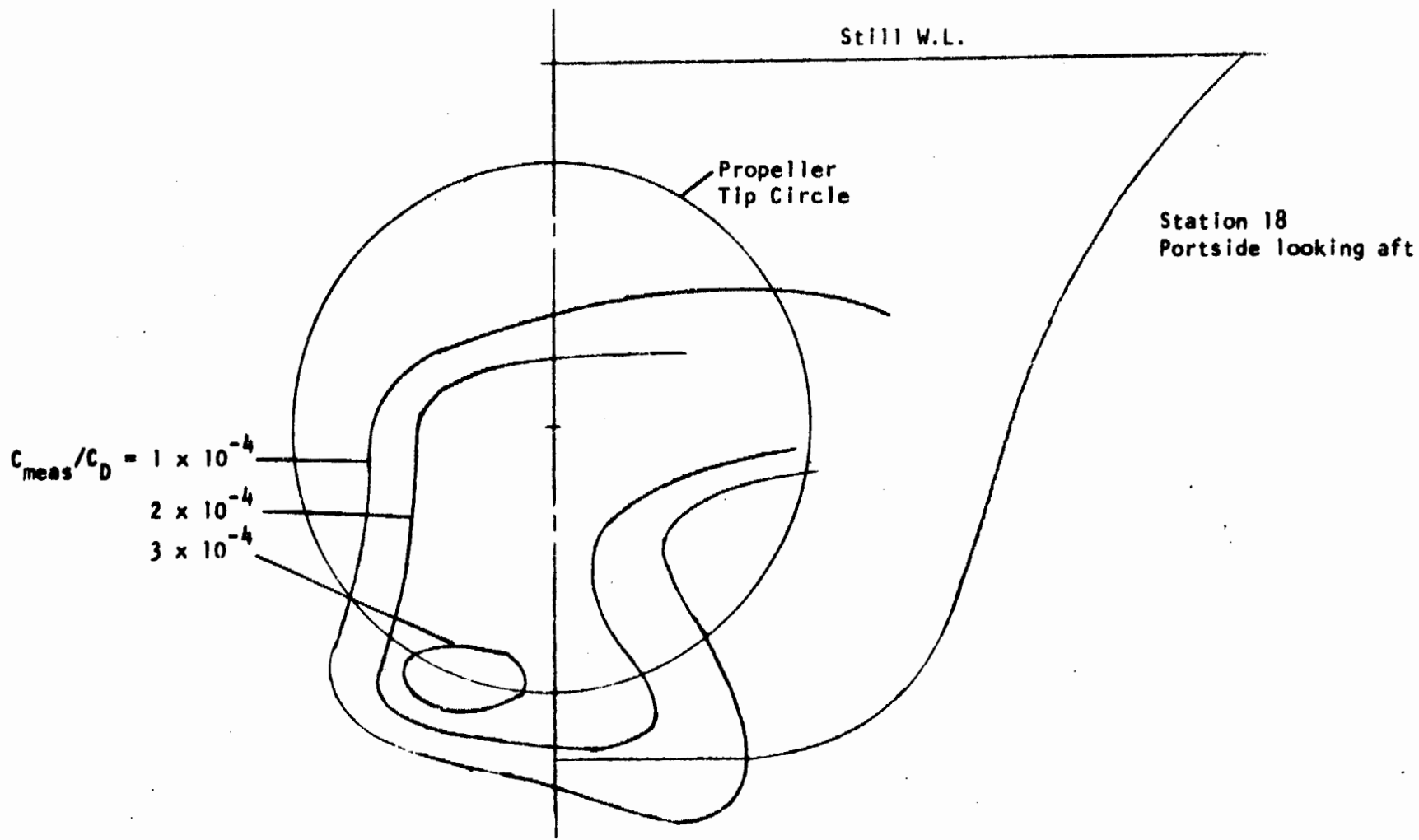


Figure 55. Chart of iso-Concentration Contours for Discharge through 7.33 in. I.D. Pipe from Location 2 at 330 Tons/Hr. Test 34, Ship Speed = 16.5 Knots, Prop RPM = 120

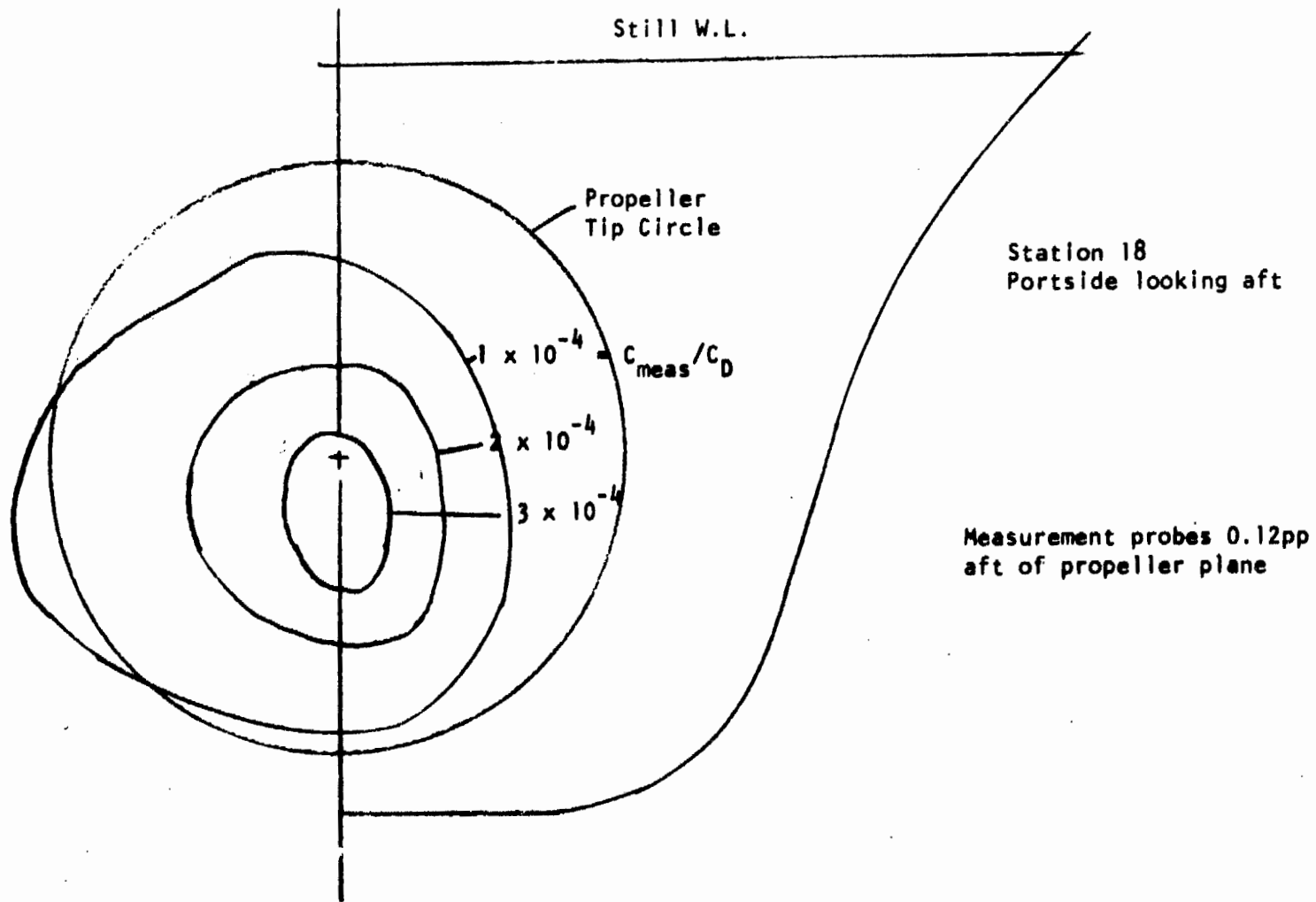


Figure 56. Chart of Iso-Concentration Contours for Discharge through 7.33 in. I.D. Pipe from Location 3 at 330 Tons/Hr. Test 12, Ship Speed = 16.5 Knots, Prop RPM = 120

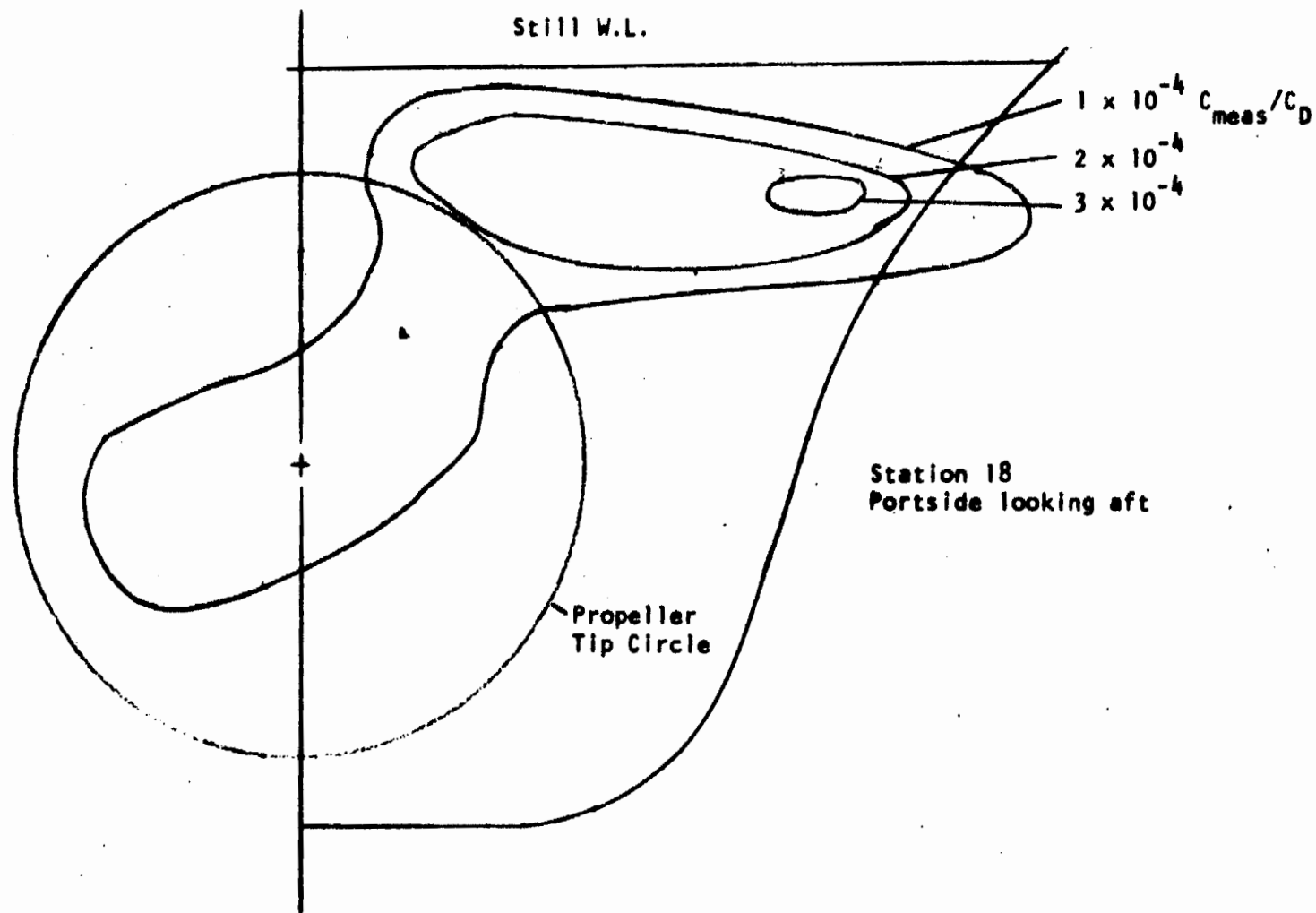


Figure 57. Chart of Iso-Concentration Contours for Discharge through 7.33 in. I.D. Pipe from Location 4 at 330 Tons/Hr. Test 13, Ship Speed = 16.5 Knots, Prop RPM = 120

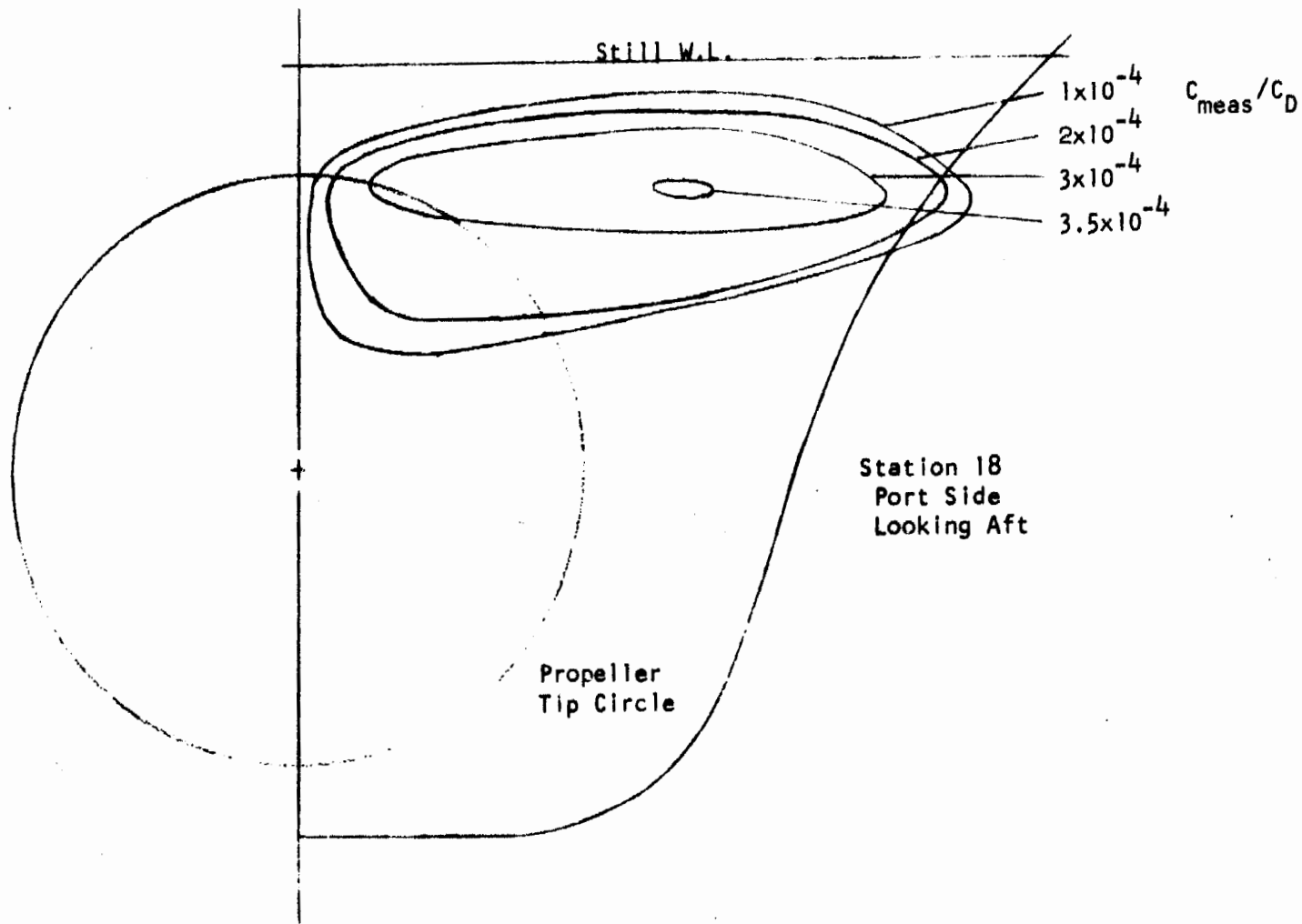


FIGURE 58 CHART OF ISO-CONCENTRATION CONTOURS FOR DISCHARGES THROUGH 7.33 IN. I.D. PIPE
FROM LOCATION 5 AT 330 TONS/HR
TEST 14, SHIP SPEED = 16.5 KNOTS, PROP RPM = 120

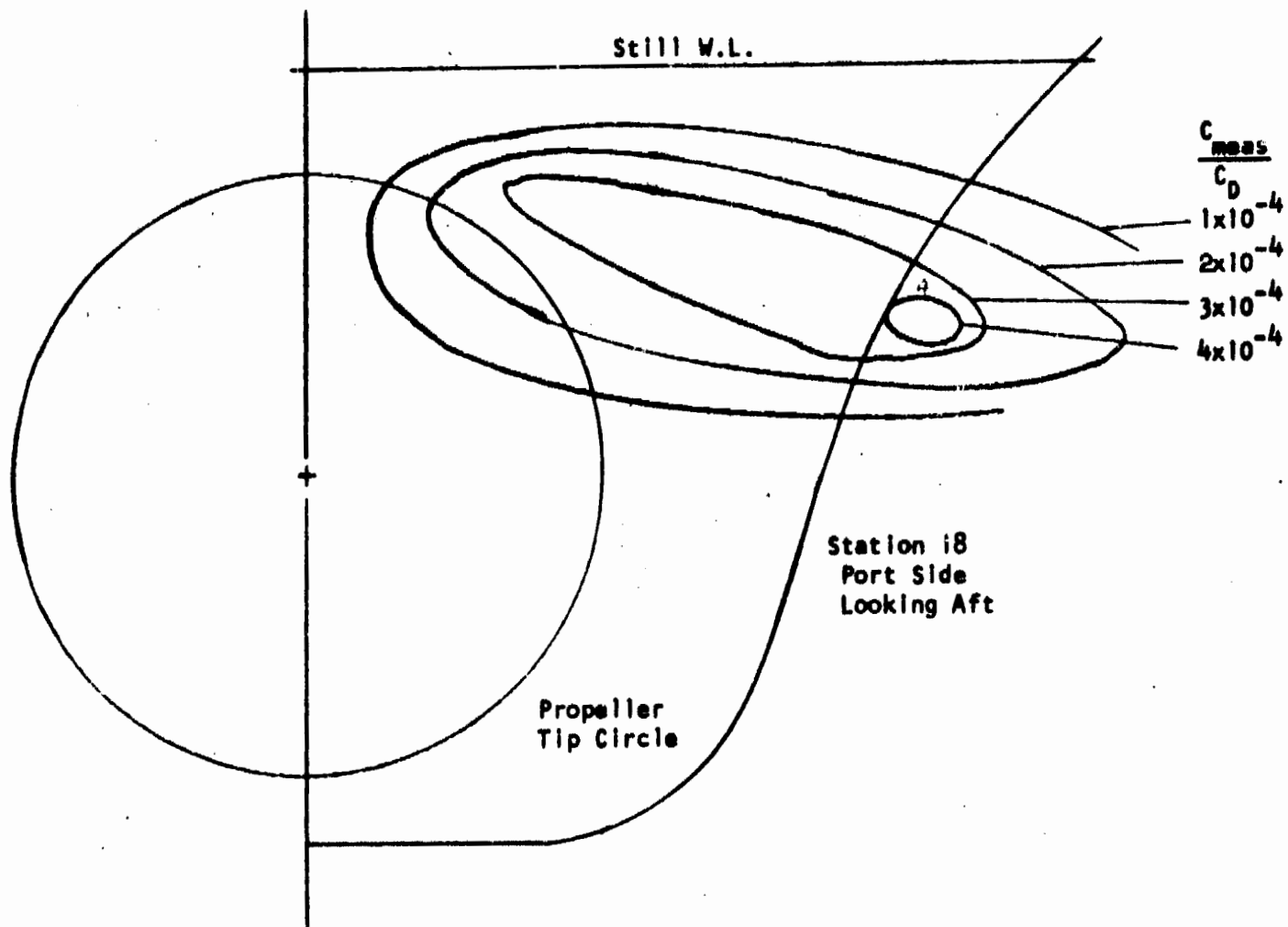


FIGURE 59 CHART OF ISO-CONCENTRATION CONTOURS FOR DISCHARGE THROUGH 7.33 IN. I.D. PIPE FROM LOCATION 6 at 330 TONS/HR TEST15, SHIP SPEED =12.5 KNOTS, PROP RPM = 120

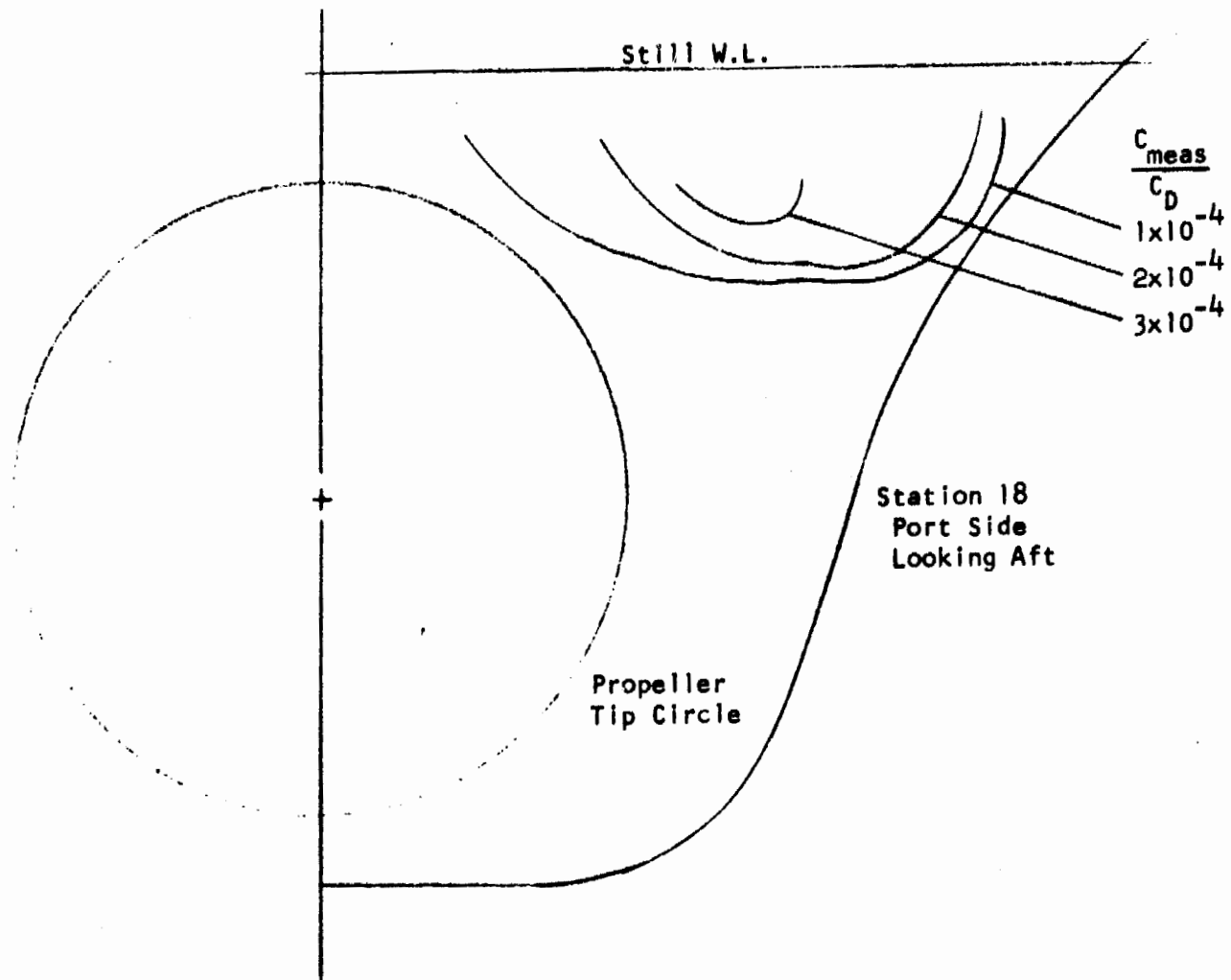


FIGURE 60 CHART OF 150-CONCENTRATION CONTOURS FOR DISCHARGE THROUGH HOSE OVER-THE-SIDE AT LOCATION A AT 330 TONS/HR TEST 16. SHIP SPEED = 16.5 KNOTS, PROP RPM = 120

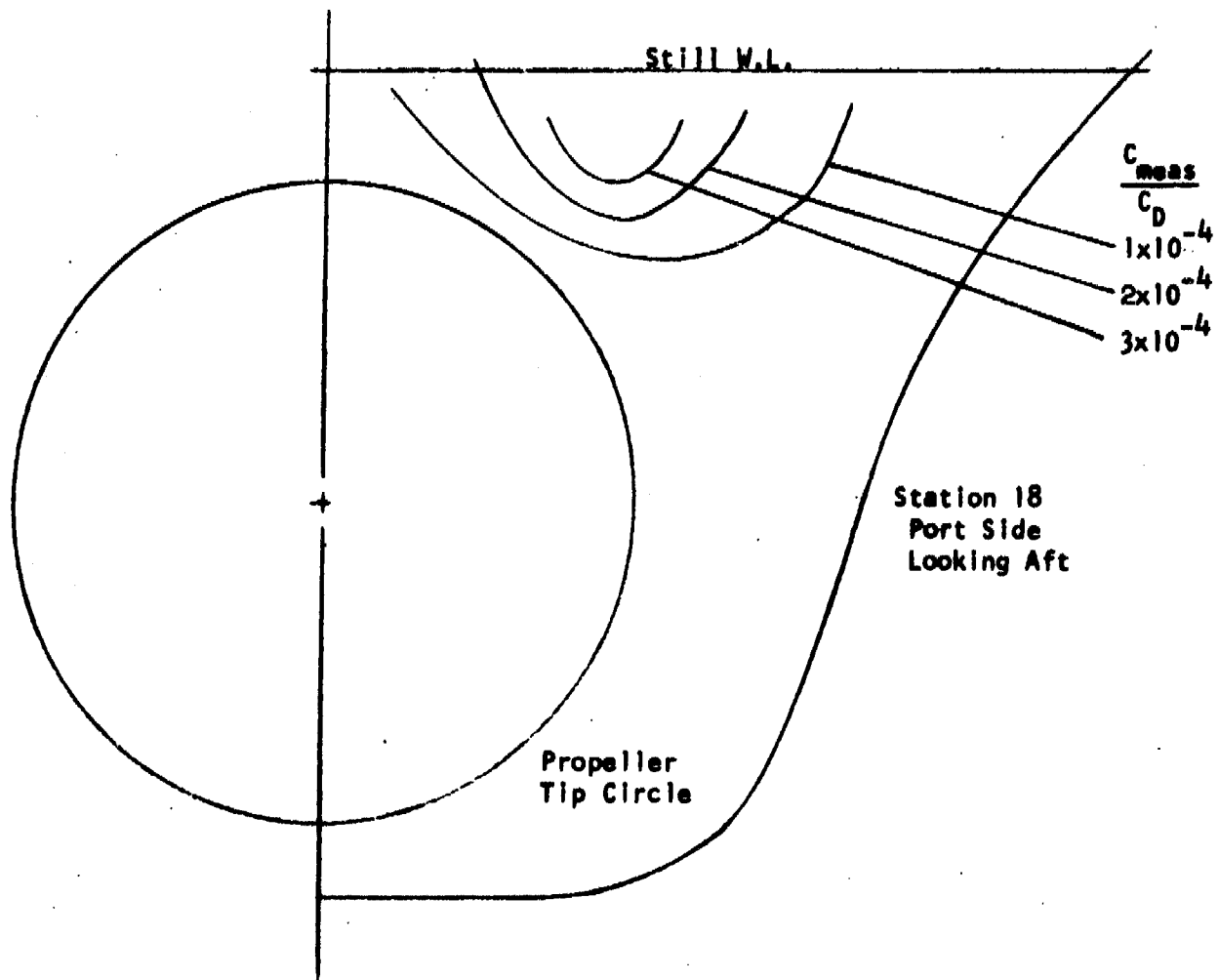


FIGURE 61 CHART OF ISO-CONCENTRATION CONTOURS FOR DISCHARGES THROUGH HOSE OVER-THE-SIDE AT LOCATION B AT 330 TONS/HR Test 17, SHIP SPEED = 16.5 KNOTS, PROP RPM = 120

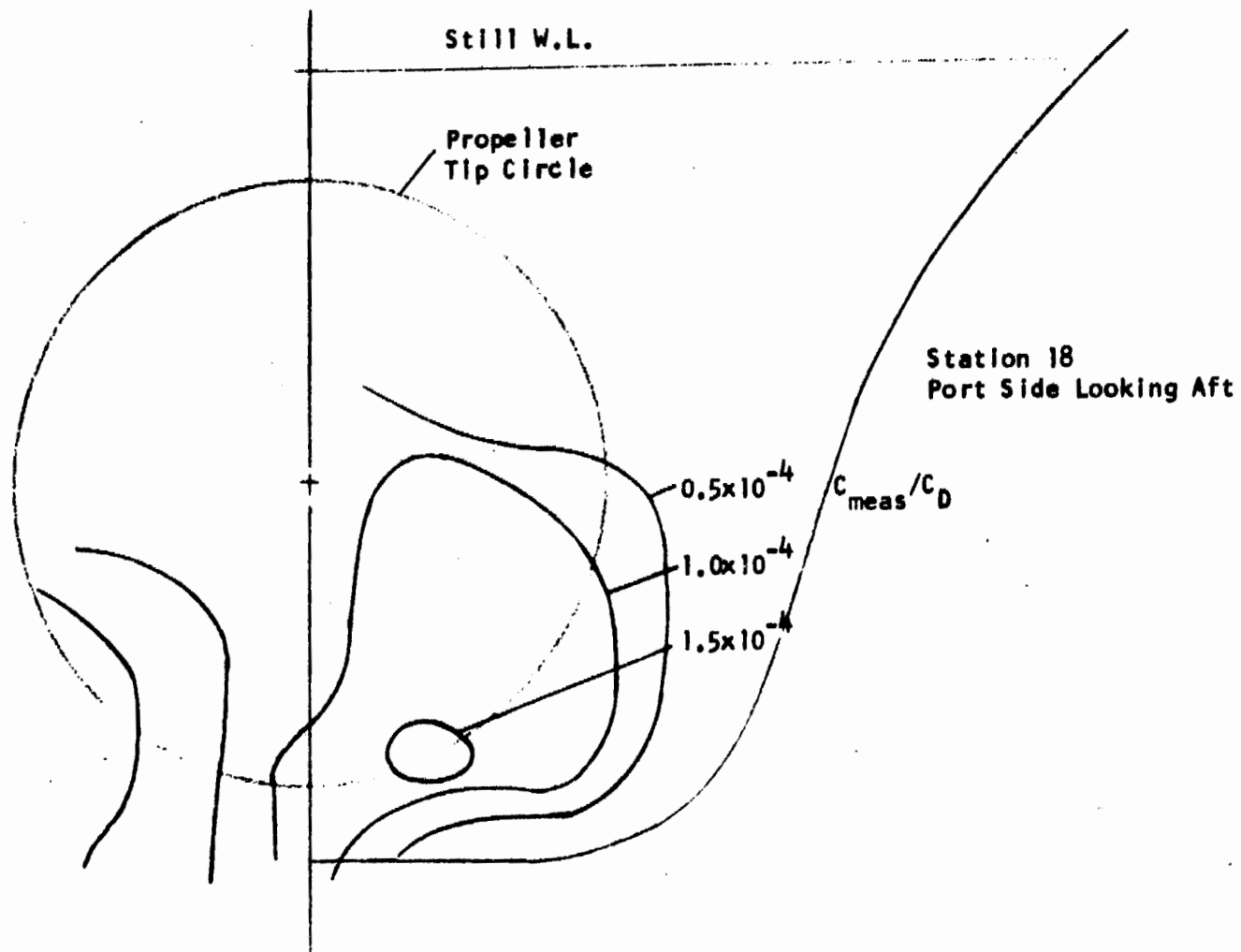


FIGURE 62. CHART OF 150-CONCENTRATION CONTOURS FOR DISCHARGE THROUGH 7.33 IN. I.D. PIPE FROM LOCATION 2 AT 165 TONS/HR TEST 22, SHIP SPEED = 16.5 KNOTS, PROP RPM = 120

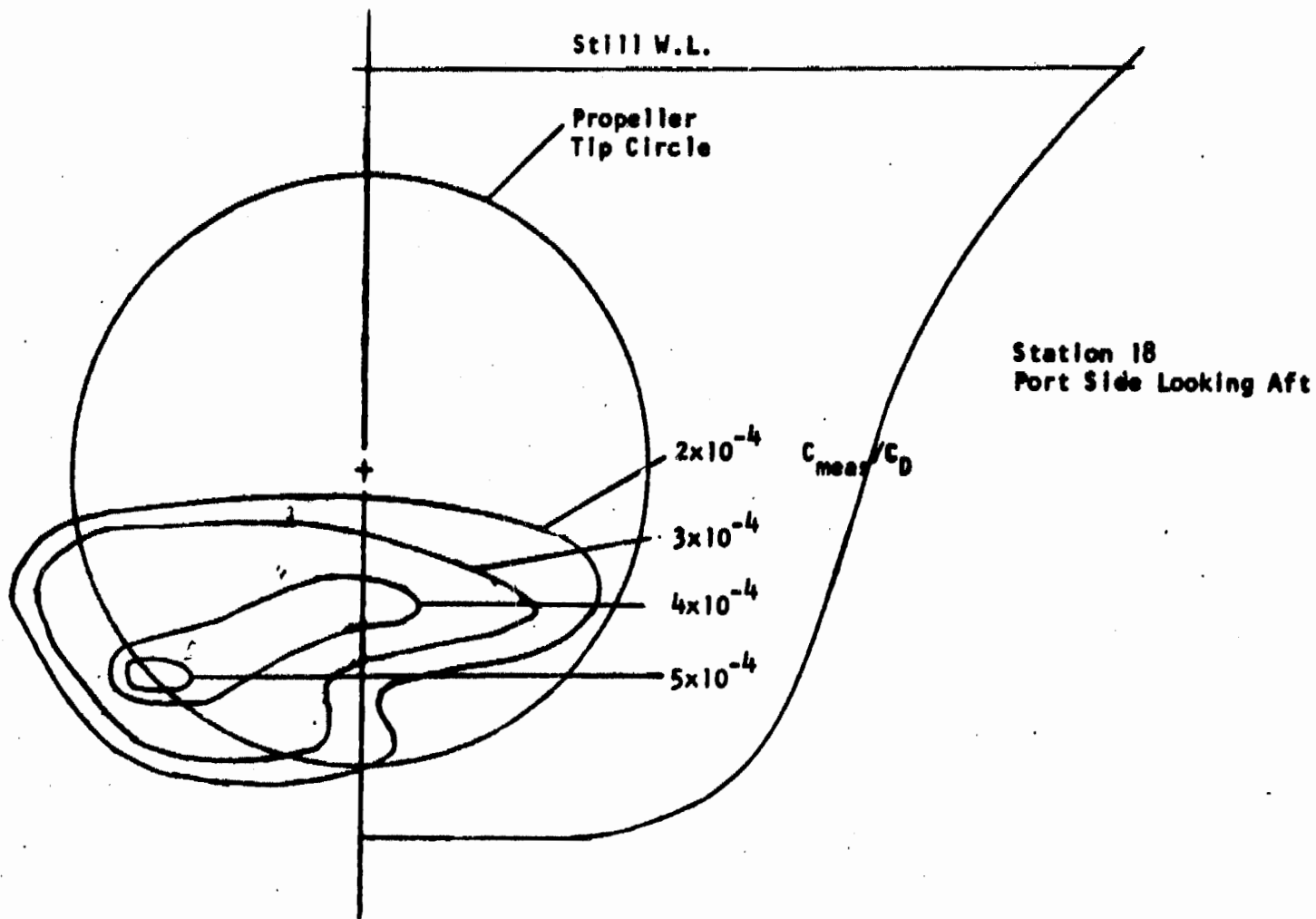


FIGURE 63. CHART OF 150-CONCENTRATION CONTOURS FOR DISCHARGE THROUGH 7.33 in. I.D. PIPE FROM LOCATION 2 AT 495 TONS/HR TEST 23, SHIP SPEED = 16.5 KNOTS, PROP RPM = 120

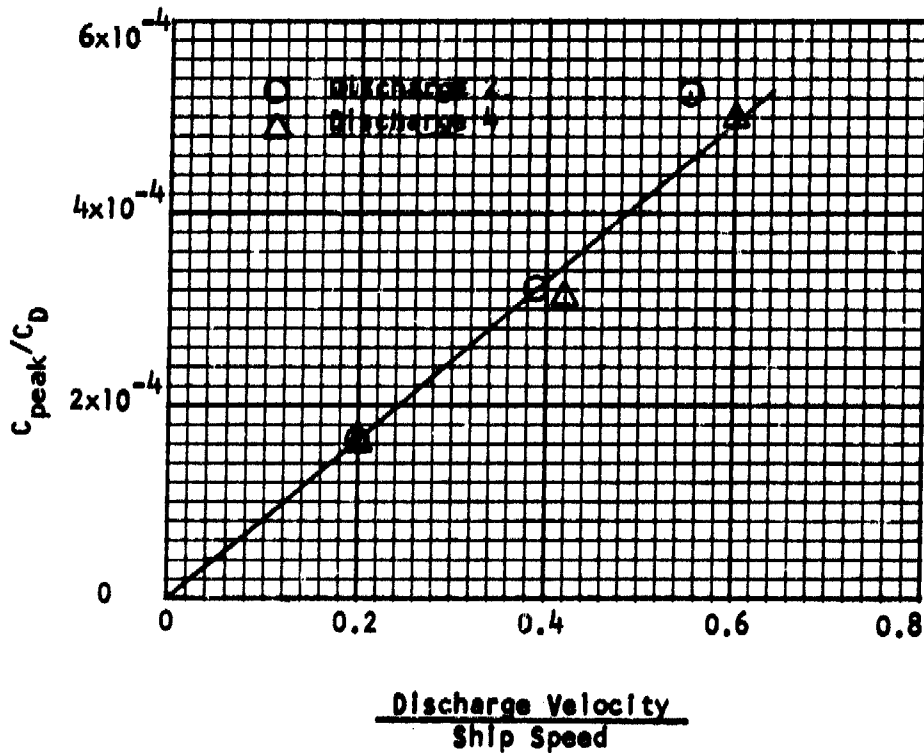


FIGURE 64. PEAK CONCENTRATION PROPORTIONAL TO DISCHARGE RATE FOR 7.33-IN DIAMETER DISCHARGE PORT

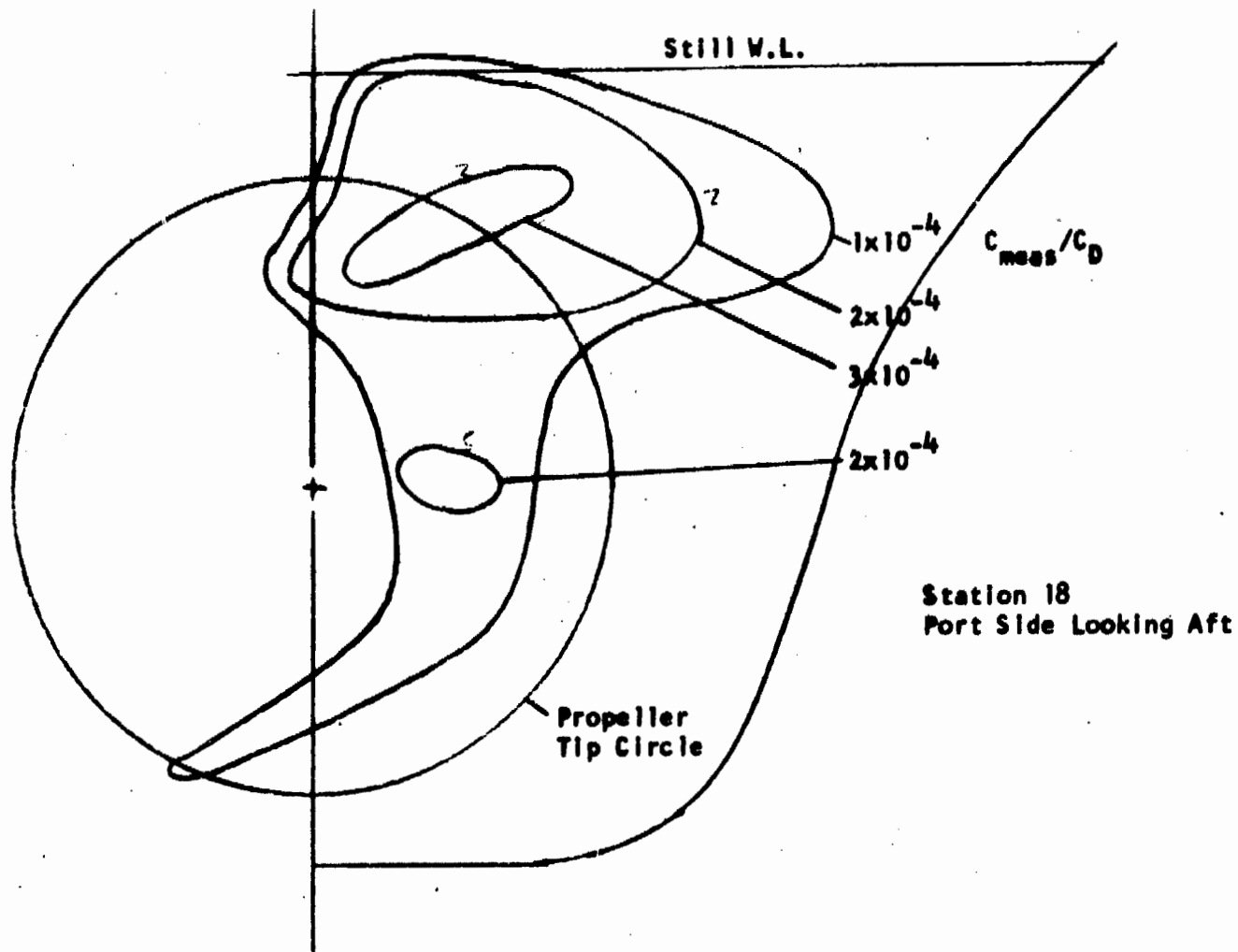


FIGURE 65. CONTF. OF 150-CONCENTRATION CONTOURS FOR DISCHARGE THROUGH 5.00 IN. I.D. PIPE FROM LOCATION 2 AT 330 TONS/HR TEST 29, SHIP SPEED = 16.5 KNOTS, PROP RPM = 120

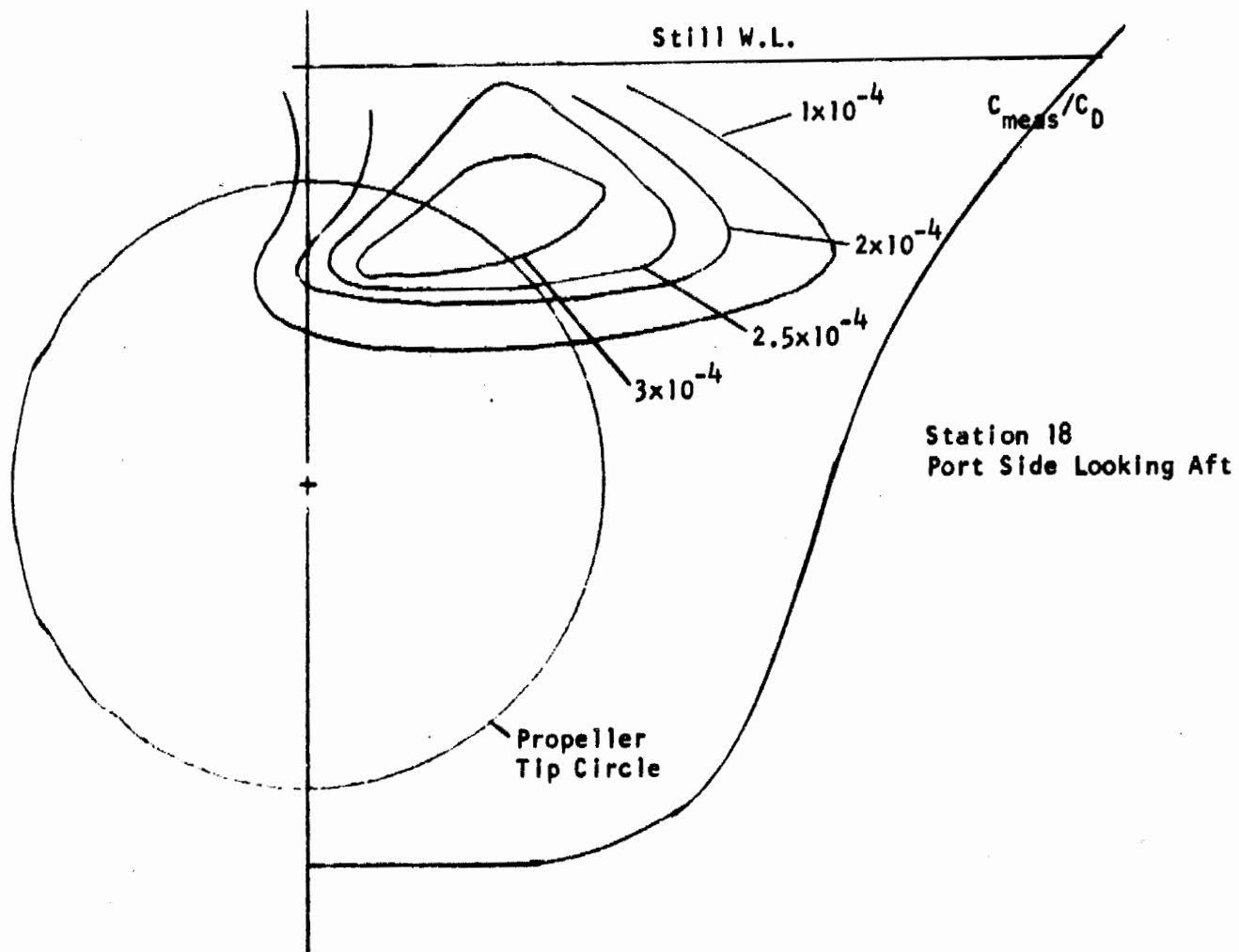


FIGURE 66. CHART OF ISO-CONCENTRATION CONTOURS FOR DISCHARGE THROUGH 2.27 IN. I.D. PIPE FROM LOCATION 2 AT 330 TONS/HR TEST 30, SHIP SPEED = 16.5 KNOTS, PROP RPM = 120

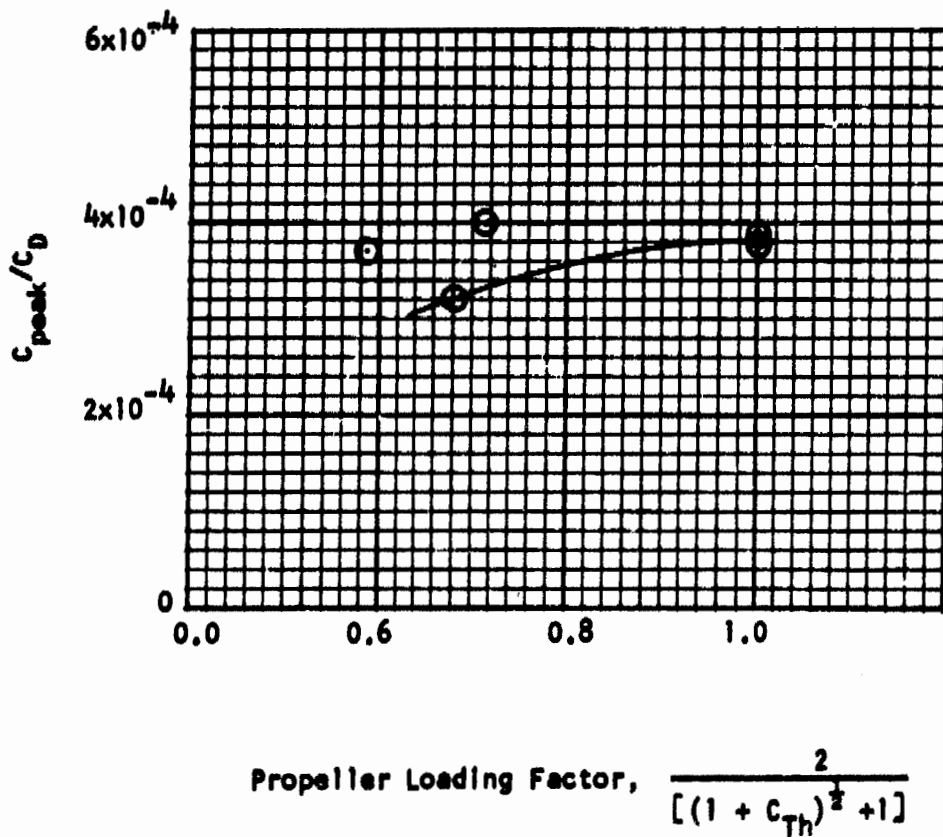
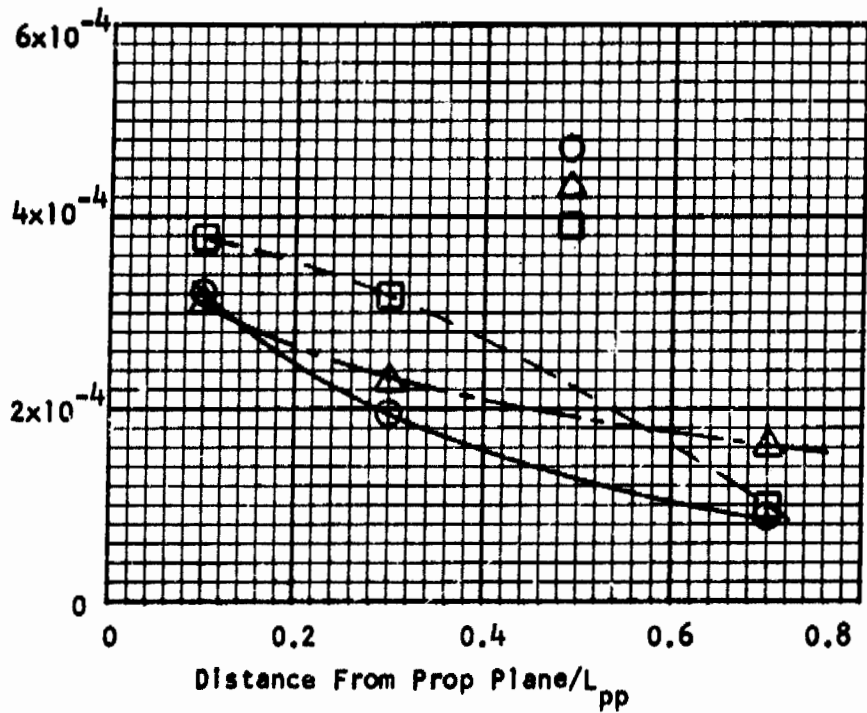
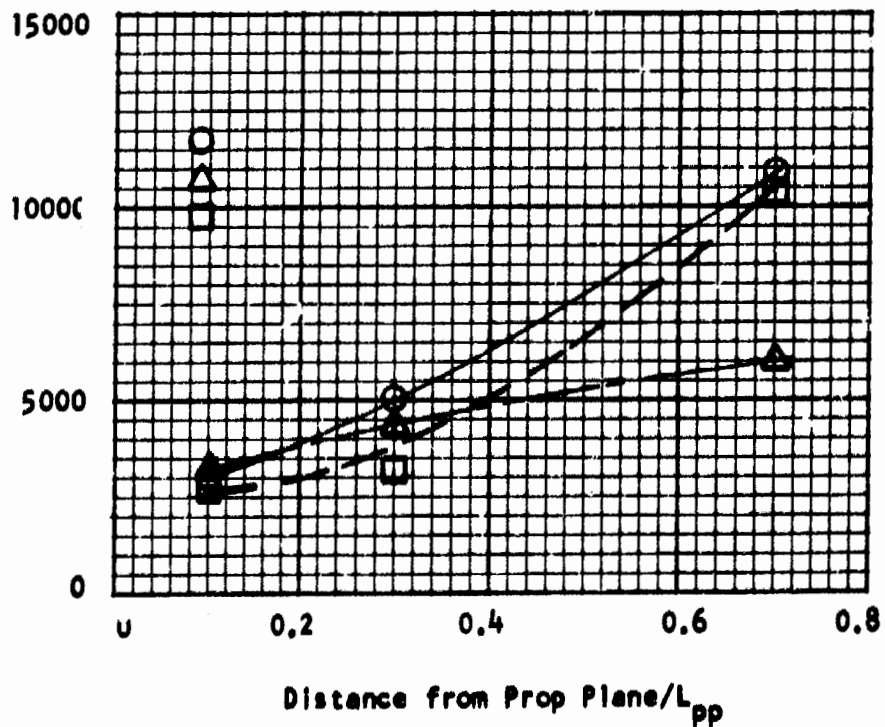


FIGURE 67. EFFECT OF PROPELLER LOADING ON PEAK CONCENTRATION FOR DISCHARGE THROUGH 7.33-IN I.D. PIPE FROM LOCATION 2 AT 330 tons/hr SHIP SPEED = 16.5 KNOTS.



a) Peak Measured Concentration



b) Minimum Dilution Factor

FIGURE 68. EFFECT OF LONGITUDINAL MEASUREMENT POSITION ON PEAK MEASURED CONCENTRATION AND MINIMUM DILUTION FACTOR FOR DISCHARGE THROUGH 7.33 IN. I.D. PIPE AT 330 TONS/HR SHIP SPEED = 16.5 KNOTS