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US Army Corps
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Waterways Experiment
Station

Ship Navigation Simulation Study, Houston-Galveston Navigation Channels, Texas

Report 2
Houston Ship Channel, Bayou Segment

by Dennis W. Webb, Larry L. Daggett

WES

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Prepared for U.S. Army Engineer District, Galveston

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Report 2 of a series

Prepared for U.S. Army Engineer District, Galveston
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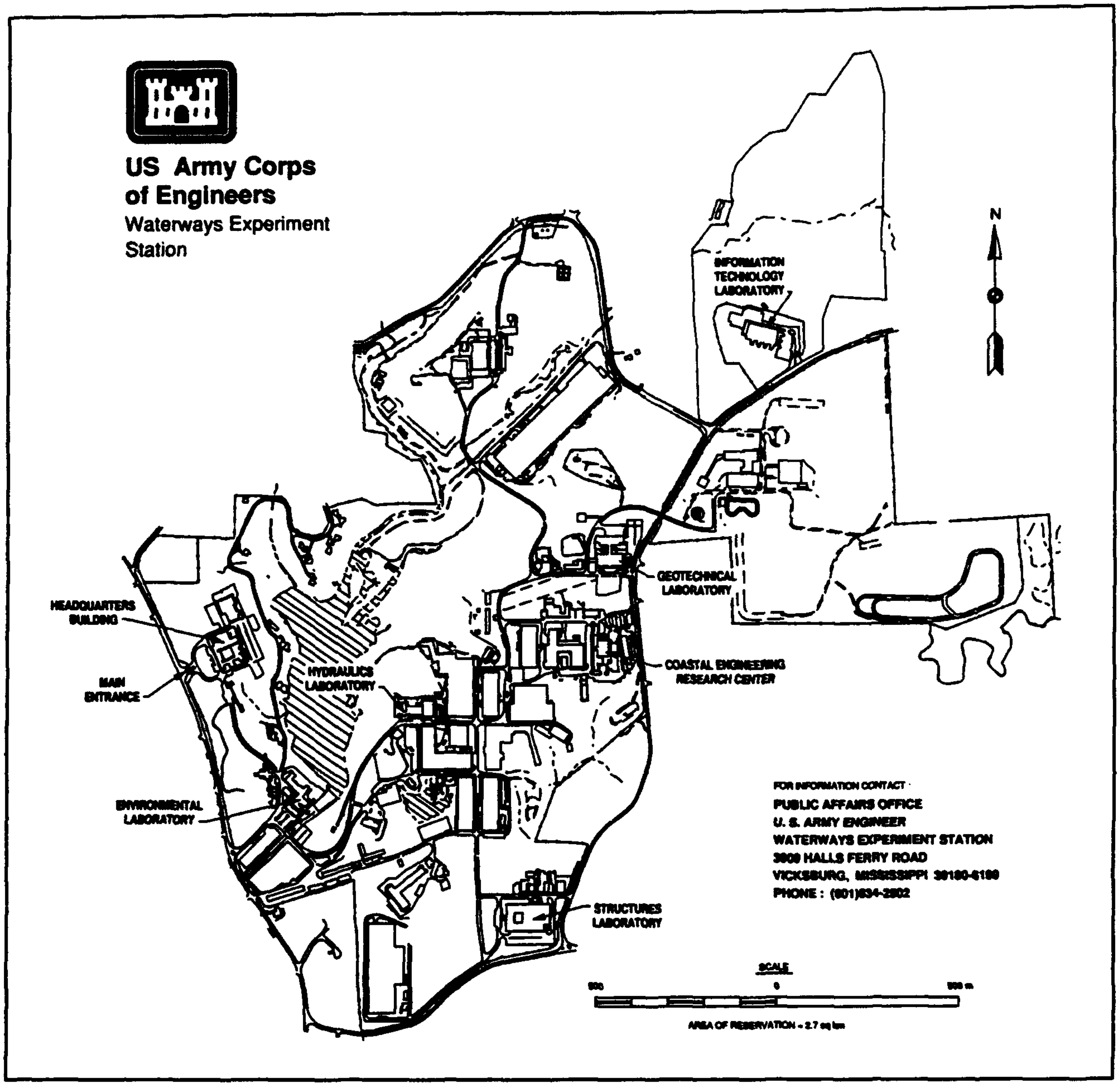

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Preface

This investigation was performed by the Hydraulics Laboratory of the U.S. Army Engineer Waterways Experiment Station (WES) for the U.S. Army Engineer District, Galveston (SWG). The study was conducted with the WES research ship simulator during the period April 1990-June 1991. SWG provided survey data of the prototype area. Current modeling was conducted by the Estuarine Processes Branch, Estuaries Division, Hydraulics Laboratory. This is Report 2 of a series. Report 1 discusses the navigation study for the bay segment of the Houston Ship Channel.

The investigation was conducted by Mr. Dennis W. Webb of the Navigation Branch, Waterways Division, Hydraulics Laboratory, under the general supervision of Messrs. Frank A. Herrmann, Jr., Director of the Hydraulics Laboratory; Richard A. Sager, Assistant Director of the Hydraulics Laboratory; M. B. Boyd, Chief of the Waterways Division; and Dr. Larry L. Daggett, Chief of the Navigation Branch. Ms. Donna Derrick and Mr. Keith Green, Civil Engineering Technicians, Navigation Branch, assisted in the study. This report was prepared by Mr. Webb and Dr. Daggett.

Acknowledgment is made to Dr. Thomas Rennie and Mr. Al Meyer, Engineering Division, SWG, for cooperation and assistance at various times throughout the investigation. Special thanks go to the Houston Pilots Association for participating in the study.

At the time of publication of this report, Director of WES was Dr. Robert W. Whalin. Commander was COL Leonard G. Hassell, EN.

Conversion Factors, Non-SI to SI Units of Measurement

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

Multiply	By	To Obtain
cubic feet	0.02831685	cubic meters
degrees (angle)	0.01745329	radians
feet	0.3048	meters
knots (international)	0.5144444	meters per second
miles (U.S. statute)	1.609347	kilometers

1 Introduction

The Houston-Galveston navigation channels are located along the Gulf of Mexico coast in eastern Texas (Figure 1). These channels include the Entrance Channel, Galveston Channel, Bolivar Roads, Texas City Channel, and the Houston Ship Channel (HSC), which branches off the Bolivar Roads Channel, traverses Galveston Bay, and ends in Houston. This report focuses only on the riverine or bayou segment of the HSC, shown in Figure 2. This section of channel is composed of a series of curves. The HSC, which serves the Port of Houston, is one of the busiest channels in the country. As reported by Houston ship pilots, the number of ship movements recently has been approaching 1,000 per month. The channel is used by a wide variety of traffic including tankers, bulk carriers, car carriers, and containerships. Numerous refineries above Morgan's Point provide destinations for the tankers; bulk loading facilities also line the channel in the same area. Containerships predominantly call at container terminals at Morgan's Point and Bayport, which is accessed via a privately maintained side channel.

Existing Conditions and Navigation Problems

The present deep-draft navigation channel in the bayou segment of the HSC as maintained by the U.S. Army Engineer District (USAED), Galveston, is 40 ft[1] deep below mean low tide (mlt) and 400 ft wide. Ships with beams in the neighborhood of 140 to 145 ft use the channel; however, meeting/passing of two such ships is closely monitored and controlled by pilots and is not allowed except under certain circumstances. On the other hand, smaller ships such as Panamax types (106-ft beams) meet and pass each other on a regular basis. Critical navigation problems in the study area include meeting and passing of two large, loaded vessels, a highly constricted channel between Cargill and Oxy-Chem, and three severe turns. These turns are located at the Baytown Bridge, the Exxon terminal, and the Lynchburg ferry.

Tidal driven currents are not a navigation problem in this area. These

[1] A table of factors for converting non-SI units of measurement to SI units is presented on page vi.

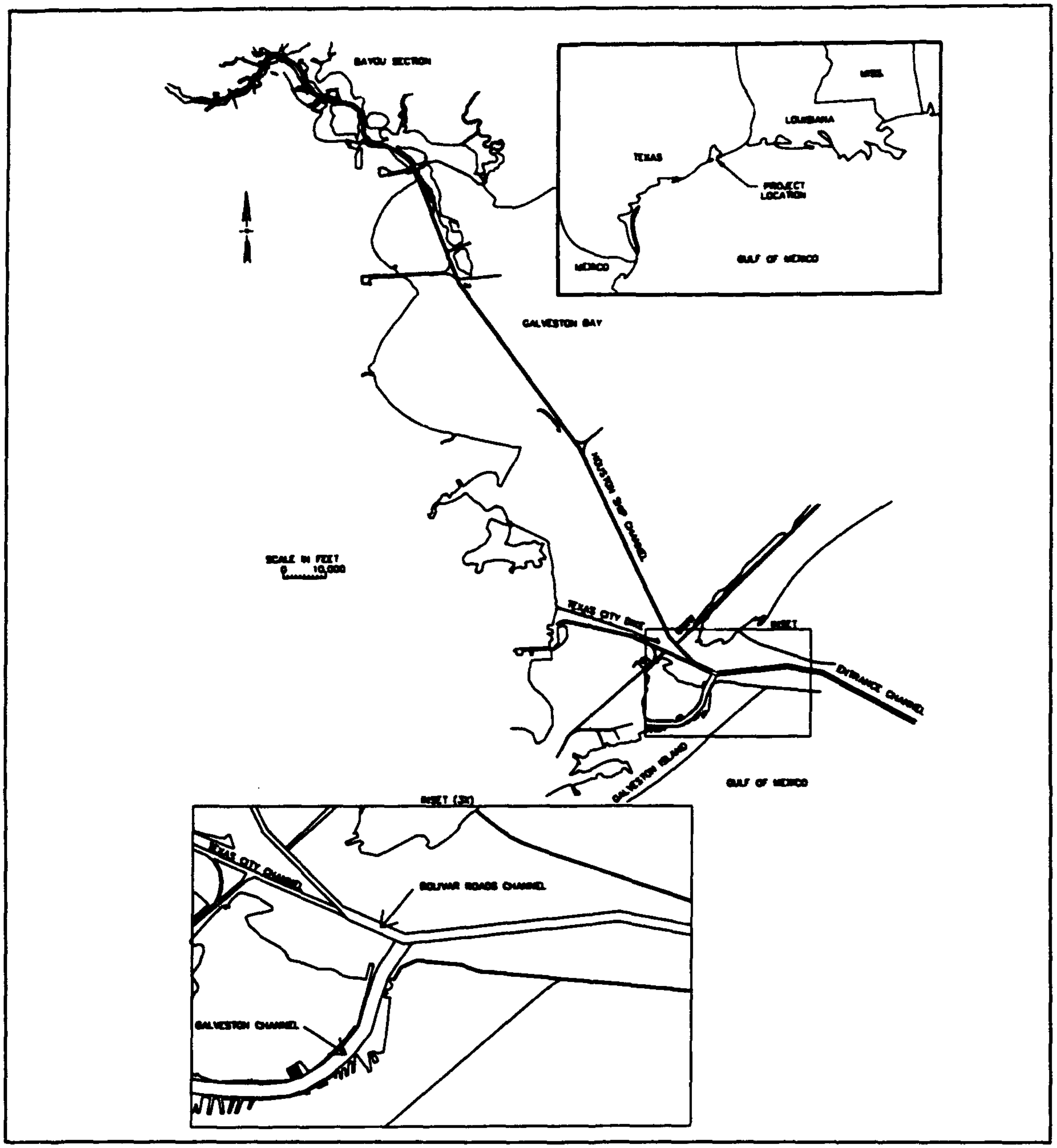


Figure 1. Location and area map

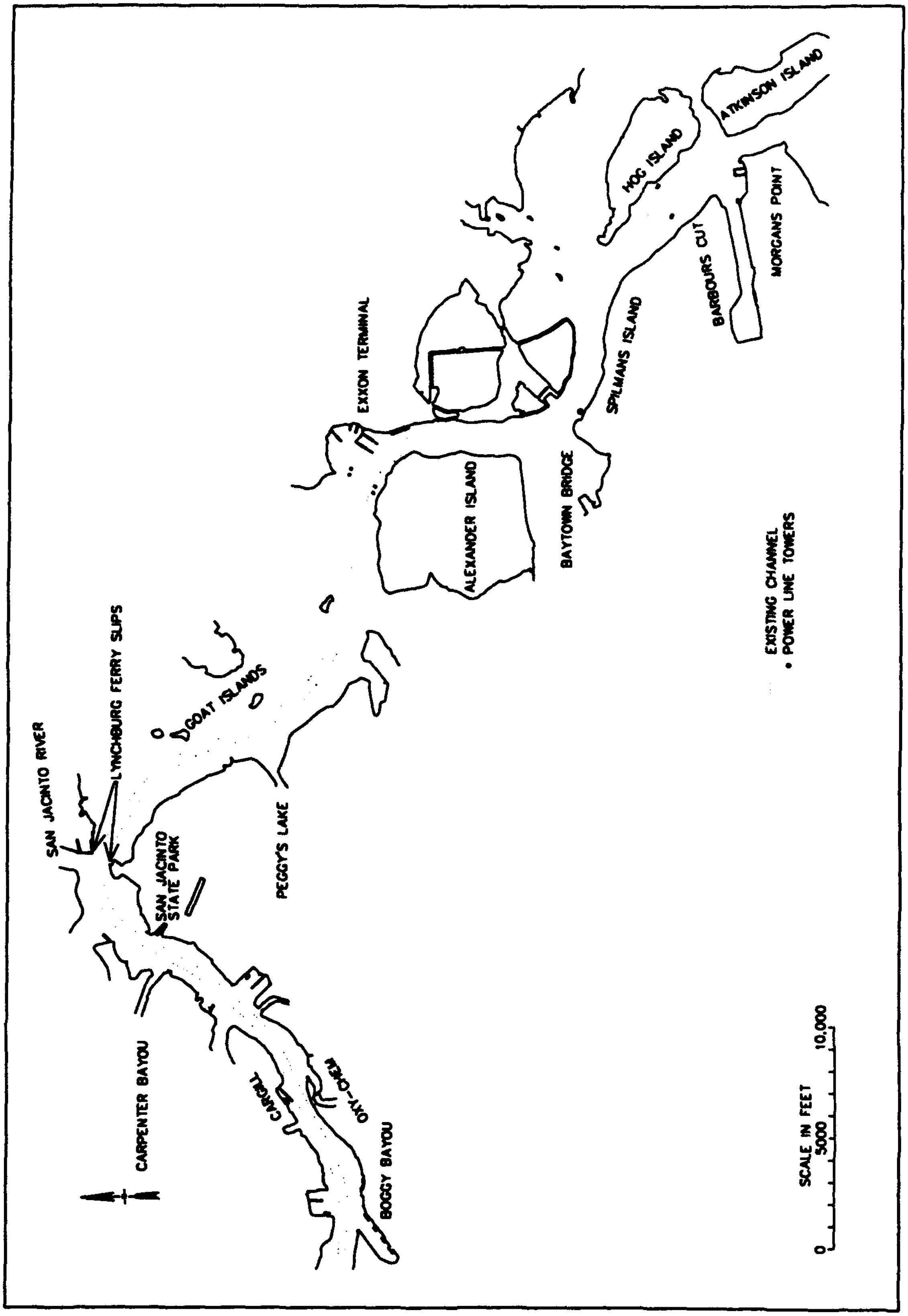


Figure 2. Houston Ship Channel, bayou section project map

currents are small, in the 1-fps range, and are aligned with the channel. Currents are a problem only during heavy rains, when freshwater inflow from the San Jacinto River produces crosscurrents at the Lynchburg turn.

Proposed Channel Improvement

The Galveston District has proposed a phased improvement plan for the HSC. The Phase I channel is proposed to be a minimum of 530 ft wide and 45 ft deep mlt, and the Phase II channel is to be a minimum of 600 ft wide and 50 ft deep mlt (USAED, Galveston, 1987). The two proposed channels along with the existing channel comprised the three channels tested in the navigation study at the U.S. Army Engineer Waterways Experiment Station (WES). The feasibility report (USAED, Galveston, 1987) indicates a realignment of the proposed channels (Figure 3) in the bayou segment. However, WES proposed a redesign of the alignment of the proposed channels (Figure 4) so that the proposed curved channel would be a series of straight reaches, to keep the new channel as close as possible to the existing channel and to avoid encroaching on the San Jacinto State Park and a bird rookery on Alexander Island. Some aspects of the proposed redesign were based on discussions with HSC pilots and the District. The curves were replaced with the straight reaches because straight channels are generally regarded as safer to navigate because it is easier to make a turn and align the vessel on ranges. Additionally, straight reaches provide the ship handler with better knowledge of the ship's location in the channel because the buoys along a straight reach will appear in a line, and ranges show the ship's location in the channel. Straight reaches are easier to mark with aids to navigation and require fewer aids to navigation than curved channels. Also, because a vessel's position in a straight reach is easier to determine, straight reaches are easier to dredge than curved channels. The channel alignment at Baytown Bridge was chosen to allow vessels to begin their turn prior to passing through the bridge for both inbound and outbound transits. The proposed channel north of Alexander Island and west of the Exxon terminal was widened an additional 200 ft on the north side to allow inbound vessels to swing further north while meeting an outbound vessel. This allows the outbound ship to remain in the center of the channel in preparation for the turn south at Exxon. This turn is difficult for an outbound ship forced to remain on the south side of the channel because the radius of the turn is thus increased and bank effects will want to turn the ship to north. The channel east and west of the San Jacinto River was widened to allow the ships to be straight in the channel while passing through the confines of the ferry slips. The proposed channel alignment also included two holding areas, one located west of the San Jacinto State Park, and the other located east of Boggy Bayou. Due to the location of the Cargill and Oxy-Chem docks, the reach between them is limited to a Phase II width of 530 ft (Figure 5), without relocation of either of the docks. All channel widths and alignments tested were furnished to the District for their approval prior to testing. Existing channel bottom and bank conditions (bank slope and overbank depth) were obtained from the most recent postdredging survey conducted by the

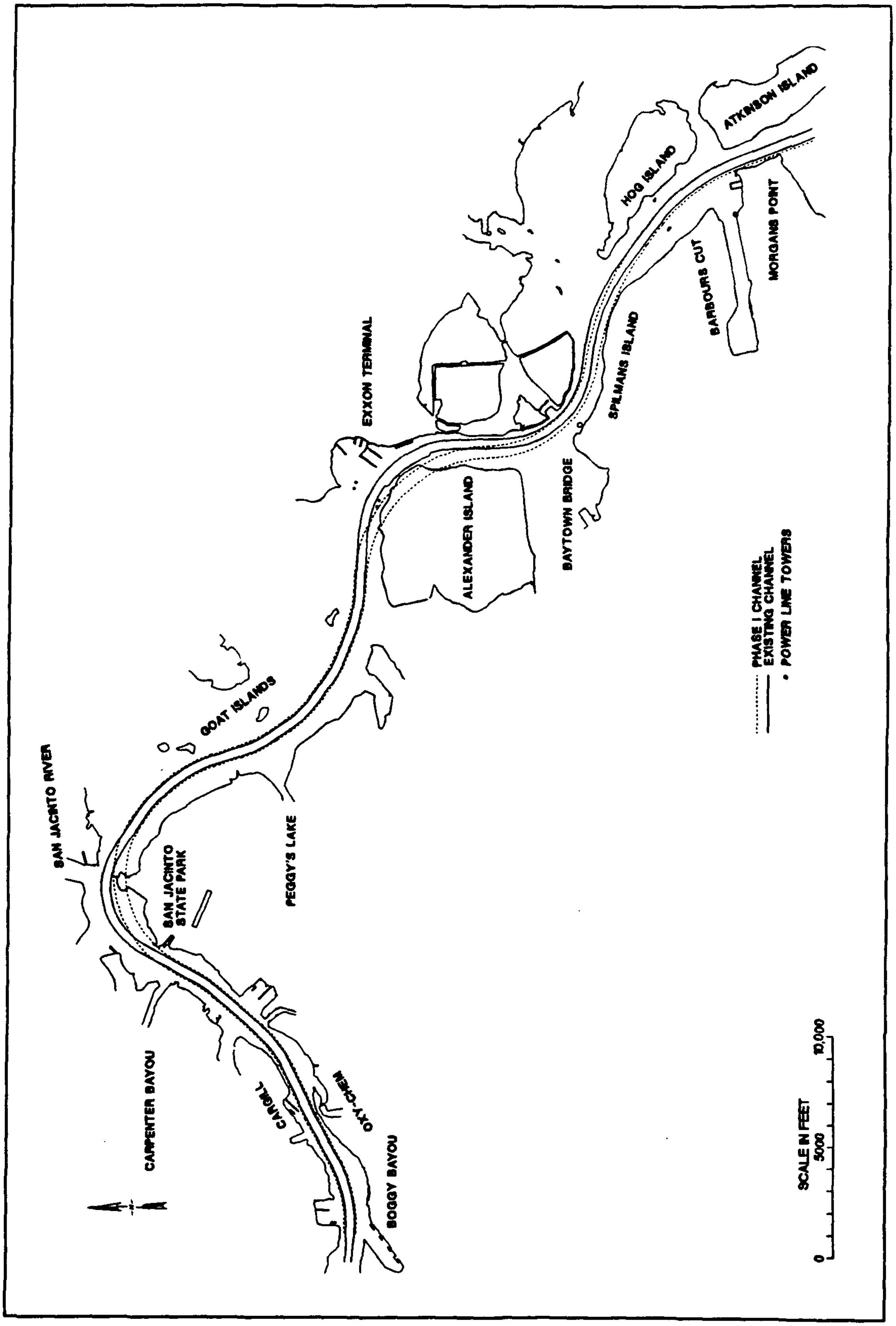


Figure 3. SWG proposed alignment

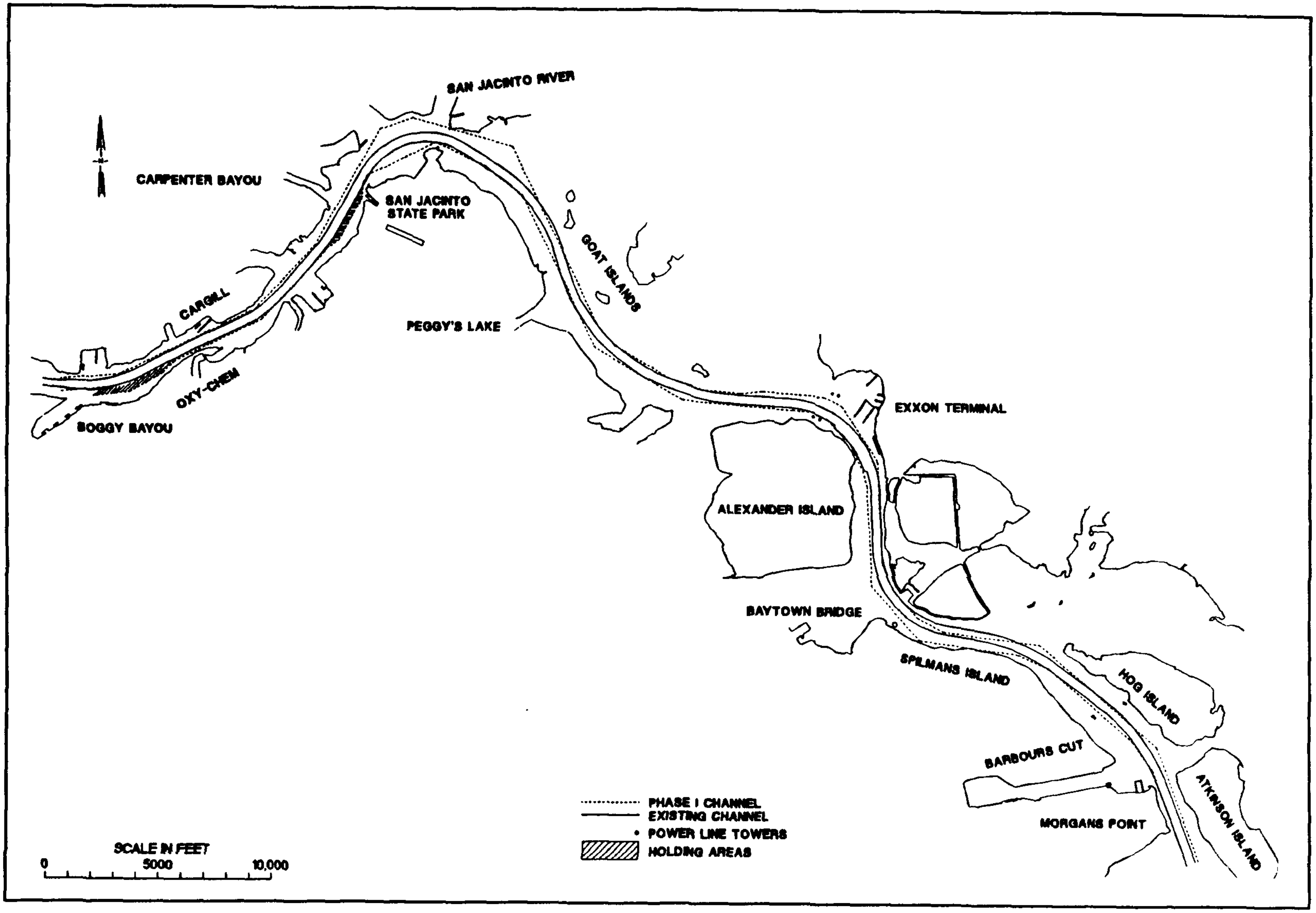


Figure 4. WES proposed alignment

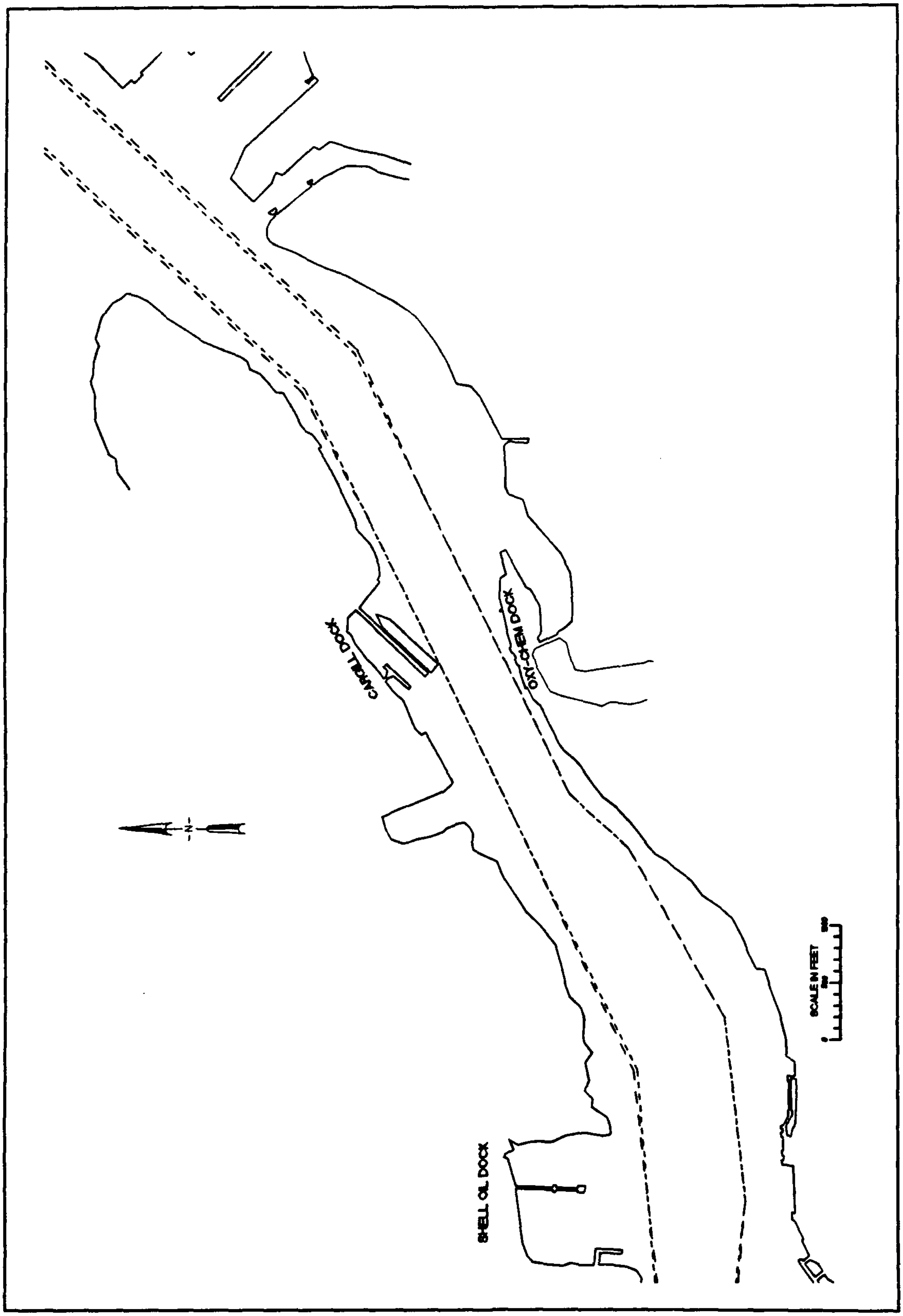


Figure 5. Proposed alignment at Cargill

District. Bank conditions for the proposed channel were the same as for the existing channel.

Purpose and Scope of Investigation

The navigation study was conducted using the WES Hydraulic Laboratory's ship simulator facility. The objectives of the study were to

a. Test the adequacy of the Phase I and Phase II channels for two-way traffic.

b. Design safe turns at the Baytown Bridge, Exxon terminal, and at the Lynchburg ferries.

c. Determine if the reach between Cargill and Oxy-Chem docks is safe for two-way traffic.

Because of the size of the databases required for simulation, the bayou segment of the HSC was divided into two study areas (Test Reaches A and B) for simulation. The two reaches as implemented on the WES ship simulator are shown in Figure 6.

The test scenarios consisted of transits over the entire length of Test Reaches A and B, as well as some shorter runs. Ship meeting and passing occurred during all real-time piloted simulator tests. Four different locations were tested for meeting and passing (Figure 7). In Test Reach A, the meeting and passing occurred south of the Exxon terminal (Passing Zone 1). In Test Reach B, the meeting and passing occurred in the straight reach near Goat Islands (Passing Zone 2). This straight reach was tested to determine the necessary channel width for two-way traffic for the straight portions of the bayou segment. Shorter simulation runs in Test Reach B with meeting and passing were conducted at the Lynchburg turn (Passing Zone 3), and at the Cargill reach (Passing Zone 4).

The simulation model replicated the actual meeting/passing maneuver as closely as possible with interactive hydrodynamics affecting two ships moving in opposing directions. One of the ships had human pilot control while the other, the traffic ship, was controlled by a numerical line-following autopilot. Data input for the autopilot controlled when and by how much the traffic ship moved toward the side of the channel prior to meeting the piloted ship. The tests were conducted with 1-ft underkeel clearance.

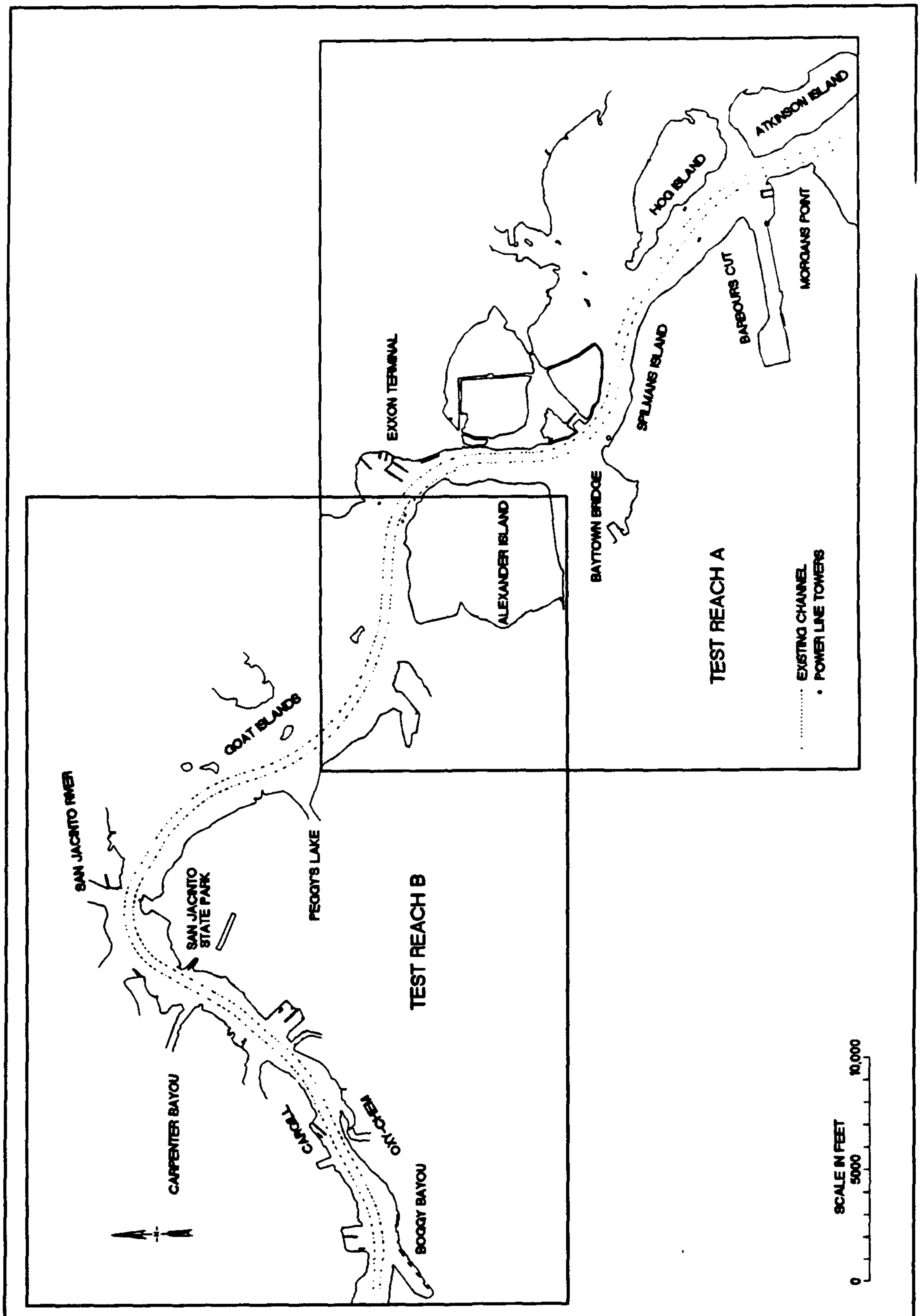


Figure 6. Test Reaches A and B

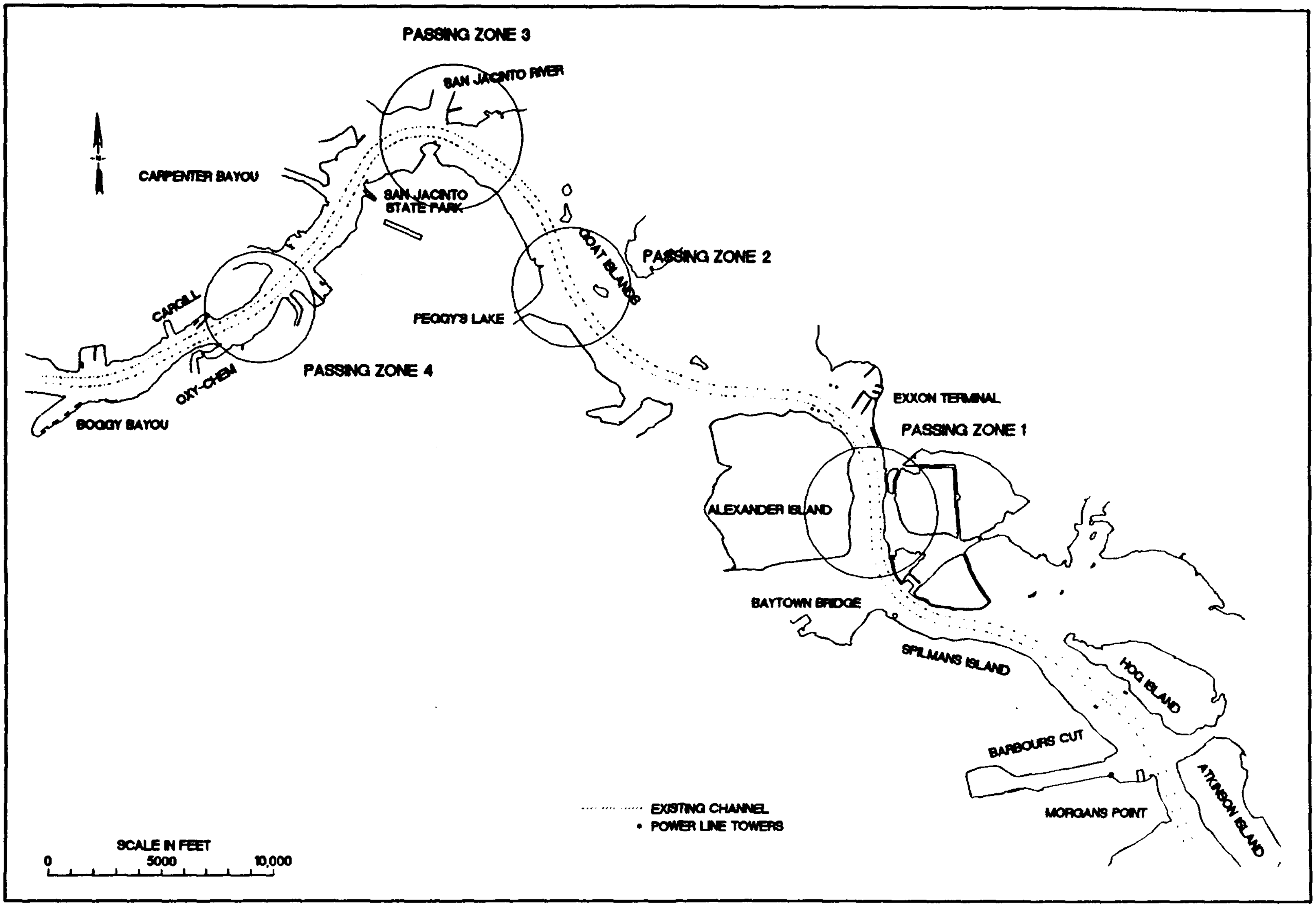


Figure 7. Simulation passing zones

2 Data Development

In order to simulate the study area, it was necessary to develop information relative to five types of input data:

a. The channel database contains dimensions for the existing channel and the proposed channel modifications. It includes the channel cross sections, bank slope angle, overbank depth, initial conditions, and autopilot track-line and speed definition.

b. The visual scene database is composed of three-dimensional images of principal features of the simulated area, including the aids to navigation, docks, and buildings.

c. The radar database contains the features for the plan view of the study area.

d. The ship data file contains characteristics and hydrodynamic coefficients for the test vessels.

e. The current pattern data in the channel include the magnitude and direction of the current and the water depth for each cross section defined in the channel database.

Channel

Channel cross sections are used to define the ship simulator channel database. The information used to develop the channel database came from the District-furnished hydrographic survey charts of May 1986. This was the latest information available concerning depths, dimensions, and bank lines of the channel. State planar coordinates as shown on the annual survey were used for the definition of the data. Prototype survey ranges were used to locate the simulator cross sections. If the prototype survey ranges were not spaced close enough for simulator purposes, a new range was interpolated. In areas where the prototype survey ranges did not exist, data were obtained from navigation charts.

The ship simulator model uses eight equally spaced points to define each cross section. At each of these points, a depth, current magnitude, and direction are required. For each cross section, the width, right and left bank slopes, and overbank depths are required. The channel depths at each of the eight points were provided by a TABS-2 model study (Lin 1992) conducted simultaneously with the development of the simulation databases that computed the current magnitudes and directions.

The channel side slope and overbank depth are used to calculate bank force. The shallower the overbank and the steeper the side slope, the greater the computed bank effects. A small difference (1 to 2 ft) in channel bottom and overbank depth produces negligible bank forces and moments.

A comparison between a typical simulator database cross section and the corresponding prototype cross section is shown in Figure 8. The prototype cross sections were taken during May of 1986. These cross sections were taken near the Lynchburg turn, with the dotted line representing the prototype cross section and the dashed line representing the simulated cross section.

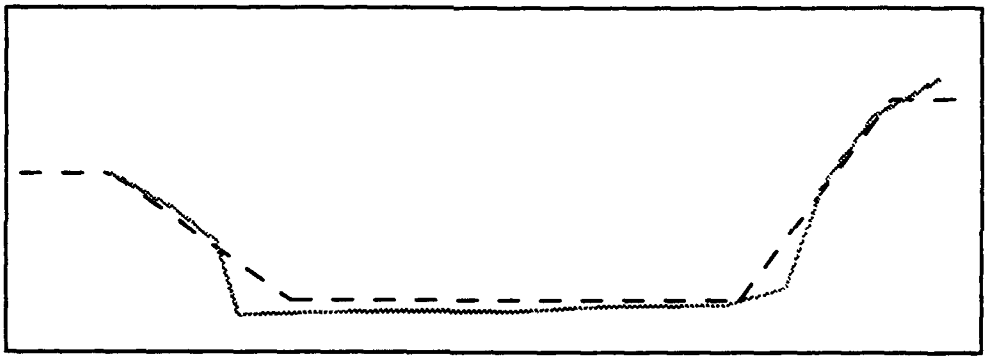


Figure 8. Cross-section comparison

Visual Scene

The visual scene database was created from the same maps and charts noted in the discussion of the channel. As in the development of the channel data base, the state planar coordinate system was used. Aerial and still photographs and pilot's comments obtained aboard a transiting ship during a reconnaissance trip to Houston constituted other sources of information for the scene. These allowed inclusion of the significant physical features and also helped determine which, if any, features the pilots use for informal ranges and location sightings. All aids to navigation such as buoys, channel markers, buildings, docks, docked vessels, towers, ferry slips, dolphins, and tanks were included in the visual scene.

The visual scene is generated in three dimensions: north-south, east-west, and vertical elevation. As the ship progresses through the channel, the three-dimensional picture is constantly transformed into a two-dimensional perspective graphic image representing the relative size of the objects in the scene as a function of the vessel's position and orientation and the relative direction and position on the ship's bridge for viewing. The graphics hardware used for the Houston Ship Channel-Bayou Segment project was a stand-alone computer connected with the main computer to obtain information for updating the viewing position and orientation. This information includes parameters such as vessel heading, rate of turn, forward and lateral velocity, and position. Also, the viewing angle as set by the pilot is passed to the graphics computer for the look-around feature on the simulator console, which encompasses a 40-degree field of view. This feature simulates the pilot's ability to see any object with a turn of his head. The pilot's position on the bridge can also be changed from the center of the bridge to any position wing to wing to simulate the pilot walking across the bridge to obtain a better view, e.g., along the edge of the ship from the bridge wing.

Included in the visual scene was a large vessel docked at the Cargill terminal. This ship was located on the channel side of the dock with its bow nearly reaching the channel. The size and location of this vessel was obtained from an aerial photo. The vessel was included to present a "worst case scenario" for testing the reach between Cargill and Oxy-Chem.

Radar

The radar data base is used by the radar software to create a simulated radar for use by the test pilots. The radar data base contains x- and y-coordinates that define the border between land and water. The file also contains coordinates for the bank line and any structure on the bank or extending into the water such as bridges and aids to navigation. In short, these data basically define what a pilot would see on a shipboard radar. The radar image is a continuously updated plan view of the vessel's position relative to the surrounding area. Three different ranges of 0.5 mile, 0.75 mile, and 1.5 miles were programmed to enable the pilot to choose the scale needed. A second radar screen with a 0.25-mile range was also provided.

Current

A current data base contains current magnitude and direction at eight points across the channel at each of the cross sections defined in the channel. Channel bottom depths are also given at each of these eight points and are included in the channel definition. Interpolation of the data between cross sections provides continuous and smooth current patterns.

The tidal current was derived from the TABS-2 model study (Lin 1992). Results from this hydrodynamic model were used to develop the current data bases. Because the alignments of the existing channel and the proposed channel are somewhat similar, and in order to keep within time and cost restraints, the hydrodynamic model grid was not modified to reflect the change in alignment. However, the proposed channel improvements significantly increa..d the volume of water in the bayou area, thus reducing the magnitude of the currents. In order to estimate the currents in the improved channels, currents were calculated with the existing channel widened to 530 ft and deepened to 45 ft and also with the existing channel widened to 600 ft and deepened to 50 ft. The results of these runs were then assumed to reflect the currents in the realigned channels. In the bayou segment, where currents are typically aligned with the channel and the magnitude of the currents is small, this is a reasonable assumption.

The currents used in the simulation of the bayou segment of the HSC were calculated at slack tide with a freshwater inflow of 15,000 cfs from the San Jacinto River. Slack tide was chosen because both the ebb and flood tides tend to dampen out the crosscurrents caused by freshwater inflow.

Test Ship

The ship files contain characteristics and hydrodynamic coefficients for the test vessels. These data are the computer's definition of the ship, i.e., the ship model. The coefficients govern the reaction of the ship to external forces, such as wind, current, waves, banks, underkeel clearance, and ship/ship interaction; and internal controls, such as rudder and engine revolutions per minute (rpm) commands. In addition, the bow of the ship would also be seen in the visual scene by the pilot from the ship bridge. Visual images of the ship bows for all design ships had been created for previous studies at WES. The test ships were chosen based on the District's economic analysis of future shipping business and operations. The numerical ship models for the HSC simulations were developed by Tracor Hydronautics, Inc. of Laurel, MD (Ankudinov 1991a). Table 1 lists the particulars of the ships used in the simulations.

Table 1
Test Ship Characteristics

Ship Type	Length Overall ft	Beam ft	Draft ft	Test Channel
Bulk carrier	775	106	39	Existing
Tanker	920	144	39	Existing
Bulk carrier	971	140	44	530-ft
Tanker	990	156	44	530-ft
Bulk carrier	971	140	49	600-ft
Tanker	1013	173	49	600-ft

For all tests conducted in the bayou segment, the inbound vessel was the loaded tanker and the outbound vessel was the loaded bulk carrier. This reflects actual traffic entering and leaving the HSC, with oil being imported on the tanker and grain being exported on the bulk carrier. It is noted that the "design ship" combination used for the existing channel simulation tests exceeds the Navigation Safety Guidelines for the bayou section of the HSC published by the Houston Ship Pilots (HSP) dated 19 July 1989. The largest loaded ship allowed to pass under normal circumstances is 860 ft long and 120 ft in beam (HSP 1989).

3 Navigation Study

Formal pilot testing was conducted with three professional pilots licensed for the HSC and two WES employees. Pilots 1-3 were Houston pilots and pilots 4 and 5 were WES employees. Involving local professional pilots incorporated their experience and familiarity with handling ships in the study area in the project navigation evaluation. Because three pilots is a small sample size, WES employees were used as pilots for some additional tests. The tests were conducted in Vicksburg, MS on the WES ship simulator.

Validation

The simulation was validated with the assistance of a pilot licensed for the HSC. The following information was verified and fine-tuned during validation:

a. The channel definition.

(1) Bank conditions.

(2) Currents.

b. The visual scene and radar image of the study area.

(1) Location of all aids to navigation.

(2) Location and orientation of the bridges.

(3) Location and orientation of the docks.

(4) Location of buildings visible from the vessel.

The design vessel models had been validated and used in simulation tests of the HSC bay segment, which occurred just prior to the bayou segment testing (Hewlett 1994).

To validate the reaction of the vessel to bank forces, several simulation runs were made with the vessel transiting the entire study area. Special attention was given by the pilot to the response of the ship to the bank forces. Problem areas were isolated, and the prototype data for these areas were examined. The values for the overbank depth, the side slope, or the bank force coefficient were then adjusted. Simulation runs were then undertaken through the problem areas, and if necessary, further adjustment was made. This process was repeated until the pilot was satisfied that the simulated vessel response to the bank force was similar to that of an actual vessel passing through the same reach in the prototype.

The reaction of the vessel to current forces was verified by conducting several simulation runs over the entire study area. The pilot was instructed to pay attention to the current effects. The pilot was satisfied that the vessel response to the currents was similar to responses he had experienced in real life.

The visual scene and radar image of the study area were checked during validation of the other parameters. If the pilot noticed something missing or misplaced, this was checked against prototype information and adjusted accordingly.

Test Conditions

Tests were conducted in a random order. This was done to prevent prejudicing the results as would happen if, for example, all existing conditions were run prior to running the plans. The skill gained at operating the simulator could show the plans to be easier than they might really be.

During each run, the characteristic parameters of the ship were automatically recorded every 5 seconds. These parameters included the position of the ship's center of gravity, speed, rpm of the engine, heading, drift angle, rate of turn, rudder angle, and port and starboard clearances.

The simulator tests were evaluated based on pilot ratings, ship tracks, and statistical analysis of various ship control parameters recorded during testing. The following chapter will present these three methods of analysis.

As previously stated, the traffic vessel was controlled by a numerical, line-following autopilot. For many of the tests conducted, the autopilot lost control of the traffic vessel after meeting the piloted ship. In response to this problem, WES developed the capability to test two piloted simulations simultaneously. The pilots could coordinate the meeting and passing maneuver because the two simulations were in visual, radar, and radio contact with each other. This improvement was added prior to the Galveston Ship Channel and Houston/Galveston Entrance Channels test program. Adding the capability to conduct meeting and passing tests with two piloted vessels not only improved the modeling of a complicated maneuver, but also cut testing time in half because inbound and outbound tests were done at the same time.

Although runs conducted during the test program for the HSC Bayou Section used a computer-controlled autopilot, they still provide valid design guidelines for the channel width required to meet and pass the design vessels. Problems occurred with the autopilot after the vessels were abeam of each other and the required channel width had been established.

4 Study Results

Final Questionnaire

After finishing all test runs, the pilots completed a final questionnaire to give their opinions on the project as well as on the simulation. Some of the comments made by the pilots on the project follow:

1. How will deepening the channel affect ship maneuverability and safety?

"A deeper channel should certainly improve the maneuverability of ships provided they are the same size ships that are presently navigated on the channel."

"Deepening only will facilitate deeper loaded ships which will not maneuver as well as their lighter counterparts and thus safety will be adversely affected."

"For ships and tows using the current channel conditions, maneuverability and safety will be substantially improved. Larger ships will be able to operate with current safety margins."

2. In general, how do you feel about the channel realignment replacing the existing curved channel with a series of straight reaches?

"Am in favor if done properly."

"The straight reaches are better than the existing curved channel."

"I prefer a continuous curve to a series of *short* straight reaches."

3. What is your opinion of the alignment at Baytown Bridge?

"I like the gradual bend that now exists."

"The alignment at the Baytown Bridge is O.K."

"It is an improvement."

4. How do you feel about the widening of the turn at San Jacinto? Can two loaded vessels safely pass in the widened turn?

"Am in favor of widening the channel - yes."

"Two loaded ships can meet provided they are small enough."

"I would prefer more of a curve on the north side - east of the ferries. I like the extra room up there and above the ferries on the park side. This is one of the most difficult bends."

5. How do you feel about the channel alignment at Exxon?

"I have no problem with the way it is now, but am certainly open to improvements. I do feel that gradual curves are better than several straights."

"The new alignment at Exxon is good."

"The extra width on the north side above the dock will be an important safety item."

6. Can two vessels safely pass at the Cargill Dock?

"Two small vessels. Yes — two large vessels, no."

"No."

"Not if they're both over 100' wide and loaded and a large ship is at the lower berth."

Composite Ship Track Plots

A complete set of the composite and individual ship track plots for the channel test conditions is presented in Plates 1-100.

Ship Track Plots, Test Reach A

Composite track plots of all runs conducted under identical conditions in Test Reach A are shown in Plates 1-6. Individual track plots of these runs are shown in Plates 7-31. In order to show the track plots at a readable scale, enlarged views (expanded two times) of the turns at Baytown Bridge and Exxon terminal are provided for all runs. Enlarged views (expanded five times) of the vessels at meeting/passing are included for the individual track plots.

Inbound track plots

The composite track plot for inbound runs in the existing channel (Plate 1) shows that the pilots used the bank effects to make the turns. They came close to the channel edge at the turns near Hog Island and Spilmans Island, but had adequate clearance to the 40-ft contour at the Baytown Bridge. This is the same tactic that they use in the prototype. Both piloted inbound runs came close to the Exxon terminal in preparation to meet the vessel between the power line towers. This illustrates why this particular meeting situation is avoided in normal operations if at all possible.

The composite track plots of inbound runs in the Phase I channel (Plate 2) reveals that the pilots used the banks to make their turns, as they did in the existing channel. However, because the turn is not a smooth continuous curve, but two distinct turns, several runs left the channel while going through the bridge. The pilots were able to stay further away from the Exxon terminal than they did in the existing channel and stayed more to the center of the channel through the reaches past Spilmans and Hog Island. Results from the Phase II channel runs (Plate 3) are similar to those in the Phase I channel. None of the test runs approached the Alexander Island edge of the channel in the bend at the Exxon terminal.

Outbound track plots

The composite track plot for outbound runs in the existing channel (Plate 4) shows the pilots coming close to the Exxon terminal, as they did for the inbound runs. The remainder of the run reveals that, as in the inbound tests, the pilots used the bank effects to make the turns. One pilot left the 40-ft contour at the bridge. It should be noted that the pilot who went out of the 40-ft contour was a WES employee, not a Houston pilot. All runs came close to the channel edge at the turns near Hog Island and Spilmans Island.

The composite track plots of outbound runs in the Phase I channel (Plate 5) reveals that the pilots came close to the dock south of Exxon. As in the existing channel, making this turn while meeting another large, loaded vessel is difficult. As in the Phase I and II inbound runs, several runs left the channel while going through, or preparing to go though, the bridge. Results from the Phase II channel runs (Plate 6) are similar to those in the Phase I channel. In the Phase II channel the pilots were able to stay near the channel center line and make the turns in these channels better than in the existing conditions through the reaches from the bridge to Morgans Point.

Ship Track Plots, Test Reach B

Composite track plots of all runs conducted under identical conditions in Test Reach B, are shown in Plates 32-37. Individual track plots of these runs are shown in Plates 38-58. Enlarged views (expanded four times) of the vessels at meeting/passing are included for the individual track plots.

These runs include the meeting and passing situation in the straight reach near Goat Islands. Some difficulties were encountered with the behavior of the traffic ship in this scenario. The traffic ship initiated the meeting and passing maneuver properly by turning starboard at the proper distance from the piloted vessel. However, when the vessels were nearly abeam of each other, the traffic ship broke sharply to the left. Usually, the vessels were completely side by side before this happened, and this behavior did not affect the meeting and passing. However, on several runs, the traffic ship broke left before the two vessels were abeam and struck the piloted vessel in the stern. Because of this, track plots of the traffic vessel have been stopped at the point the ships are abeam. The values for ship to bank clearance (both for the piloted and for the traffic vessel) and ship to ship clearance are presented in Table 2.

Inbound Track Plots

The composite track plot for inbound runs in the existing channel (Plate 32) shows that the pilots used the bank effects to make all turns, including the sharp turn at San Jacinto. One pilot lost control of his ship after the meeting and passing, because the traffic ship did not move over far enough in the channel. He recovered prior to the San Jacinto turn and completed the run. All of the meeting and passing situations took place near the bend below Goat Islands with the piloted ship just recovering from the turn. None were considered safe passings; the average minimum total clearance for the passing situation in the existing channel was only 95 ft. It should be noted that the use of the "design ship" for the existing channel in this section violates the Navigation Safety Guidelines for this reach (HSP 1989). The largest loaded vessel tested was 920 ft long with a 144-ft beam; the maximum allowed by the guidelines is 860 ft long and a 120-ft beam. It should be noted that the pilots tend to move back to the south side of the San Jacinto State Park immediately after completing the turn and move across the channel from south to north while passing the Cargill and Oxy-Chem terminals.

The composite track plot of inbound runs in the Phase I channel (Plate 33) reveals that the pilots had no problems maneuvering the series of straight reaches between Alexander Island and the San Jacinto turn. The pilots kept their ships in the center portion of the channel at the turn, not using the bend wideners. After completing the turn at San Jacinto, the pilots used the bank effects to determine their position in the channel for the remainder of the transit. This area of the channel is poorly marked. The bank effects and land boundaries are the pilot's primary means of determining channel location. Because of this, the pilots allowed their ships to go into the holding area southwest of the San Jacinto State Park. This is not a difficult area to navigate and requires only a small amount of rudder to make these turns. It is very likely that the pilots could have easily kept their ships out of the holding areas if the holding areas were occupied by other vessels. During one run of this

Table 2
Clearances at Passing, Test Reach B

Piloted Ship	Traffic Ship	Minimum Clearance, ft: Ship to Bank: Piloted Ship	Minimum Clearance, ft: Ship to Bank: Traffic Ship	Minimum Clearance, ft: Between Ships	Minimum Clearance, ft: Total Clearance
Piloted Ship Inbound					
Existing Conditions (400 ft)					
920x144x39	775x106x39	0	18	0	18
		0	34	74	108
		0	8	87	93
		0	162	0	162
				Average	95
Phase I Conditions (530 ft)					
990x156x44	971x140x44	37	40	54	131
		24	50	60	134
		68	72	47	187
		32	96	68	196
				Average	162
Phase II Conditions (600 ft)					
1013x173x49	971x140x49	78	41	98	217
		29	95	89	213
		21	30	129	180
				Average	203
Piloted Ship Outbound					
Existing Conditions (400 ft)					
775x106x39	920x144x39	52	41	21	114
		56	59	16	131
				Average	123

Note: All negative clearances are assigned a value of 0.0 for averaging to ship clearance and total clearance for runs conducted in Test Reach B.

Table 2 (Continued)					
		Minimum Clearance, ft			
		Ship to Bank			
Piloted Ship	Traffic Ship	Piloted Ship	Traffic Ship	Between Ships	Total Clearance
Phase I Conditions (530 ft)					
971x140x44	990x156x44	42	48	60	150
		48	20	42	110
		45	72	52	169
				Average	143
Phase II Conditions (600 ft)					
971x140x49	1013x173x49	36	72	103	211
		56	75	110	241
				Average	226

scenario, the traffic vessel struck the piloted vessel (Plate 42). Another run (Plate 43) was aborted due to equipment failure and should be considered as good data only until the Goat Island passing area. Neither of these runs were included in the clearance averages calculated in Table 2. The average minimum total clearance at passing for the remainder of the inbound runs in the Phase I channel is 162 ft.

Results from the Phase II channel runs (Plate 34) are similar to those in the Phase I channel. The average minimum total clearance at passing for the three inbound runs in the Phase II channel is 203 ft.

Outbound track plots

The composite track plot for outbound runs in the existing channel (Plate 35) shows the pilots using the banks to make the turns throughout the test reach. The individual track plots (Plate 51 and 52) show the meeting and passing occurred slightly south of the Goat Islands area. These were among the first tests conducted, and the traffic ship database was adjusted to move the passing area. The average minimum total clearance for the outbound runs at passing in the existing channel is 123 ft.

The composite track plots of outbound runs in the Phase I channel (Plate 36) show some of the pilots taking the ships into the holding areas as in the inbound runs. At least one run avoided going into the holding area, and another entered only a portion of the area and still successfully made the turn at San Jacinto. The pilots had a fairly narrow swept path through the San Jacinto turn. The average minimum total clearance at passing for the outbound runs in the Phase I channel is 143 ft.

With the exception of one pilot who left the channel near the San Jacinto River, results from the Phase II channel runs (Plate 37) are similar to those in the Phase I channel. For one run (Plate 56) the passing occurred in a bend and not in the straight reach across from Goat Islands. This run was not included in the clearance averages calculated in Table 2. The average minimum total clearance at passing for the outbound runs in the Phase II channel is 226 ft.

San Jacinto Track Plots

Composite track plots of all runs conducted without meeting and passing at the San Jacinto turn are shown in Plates 59-64. These transits ran the length of Test Reach B, and were previously discussed in the Track B plots. Individual track plots of the runs with meeting and passing at the San Jacinto turn are shown in Plates 65-76.

The composite track plot for inbound runs in the existing channel is shown in Plate 59. The plots of the inbound runs in the Phase I and Phase II channels (Plates 60 and 61, respectively) show that only a small portion of the channel was used for inbound one-way traffic.

The composite track plot for outbound runs in the existing channel is shown in Plate 62. The plots of the outbound runs in the Phase I and Phase II channels (Plates 63 and 64, respectively) show that only a small portion of the channel was used for outbound one-way traffic. The plot of the Phase II runs (Plate 64) does show one pilot going out of the channel at the San Jacinto River.

Plates 65-76 show that not all the widener was used in making the turn, even with meeting and passing. Although most of these runs were successful, the pilots felt that this was an extremely difficult situation and they would avoid passing two large, loaded vessels at this point.

Cargill Reach

Individual track plots of all tests conducted with two vessels meeting and passing between the Cargill Dock and the Oxy-Chem Dock are shown in Plates 77-92. Although some of the runs were successful, others resulted in collisions between the moving ships or the piloted ship and the ship docked at Cargill. Also, several vessels left the authorized channel. The pilots felt that this was the most dangerous passing condition tested and that even if the vessels successfully passed, any vessel docked at either Cargill or Oxy-Chem would have suffered damage to their mooring lines.

Additional Runs Through Bridge

After completion of pilot testing, additional runs through the Baytown Bridge were made using WES personnel as pilots. The purpose of these runs was to determine if suspending channel markers underneath the bridge would help pilots stay near the center of the Phase I and Phase II channels. The track plots of these tests are shown in Plates 93-100. Examination of these plates reveals that none of the runs left the channel.

Statistical Analysis

During each run, the control, positioning, and orientation parameters of the ship were recorded every 5 seconds. These parameters included position, speed, rpm of the propeller, rudder angle, and rate of turn. These statistical parameters are plotted against distance along track. The distance along track is calculated by projecting the position of the ship's center of gravity perpendicular to the center line of the channel and is measured from the beginning of the center line (Figure 9). For reference purposes, the locations of important landmarks are identified.

For all parameters the statistical analysis is presented as a mean of means within a sample channel section. A 500-ft channel section length was used. This means that for each individual run, each parameter was averaged over 500 ft, and these means were averaged over all runs under a given condition, thus a mean of the means.

Statistical Analysis, Test Reach A

A plot of the center line for Test Reach A and the distance from the beginning of the center line are shown in Figure 9.

Mean engine rpm

The plots of mean engine rpm versus distance along track for existing, Phase I, and Phase II channels tested in Test Reach A are shown in Plate 101. For the inbound runs, the average rpm of the ships transiting the Phase I channel was less than the average runs in the existing channel and, except for just prior to the Exxon terminal, less than the runs conducted in the Phase II channel. The average rpm's for outbound runs are similar for all three channels, except that the rpm for the Phase I vessel is slightly lower than the other two for most of the run.

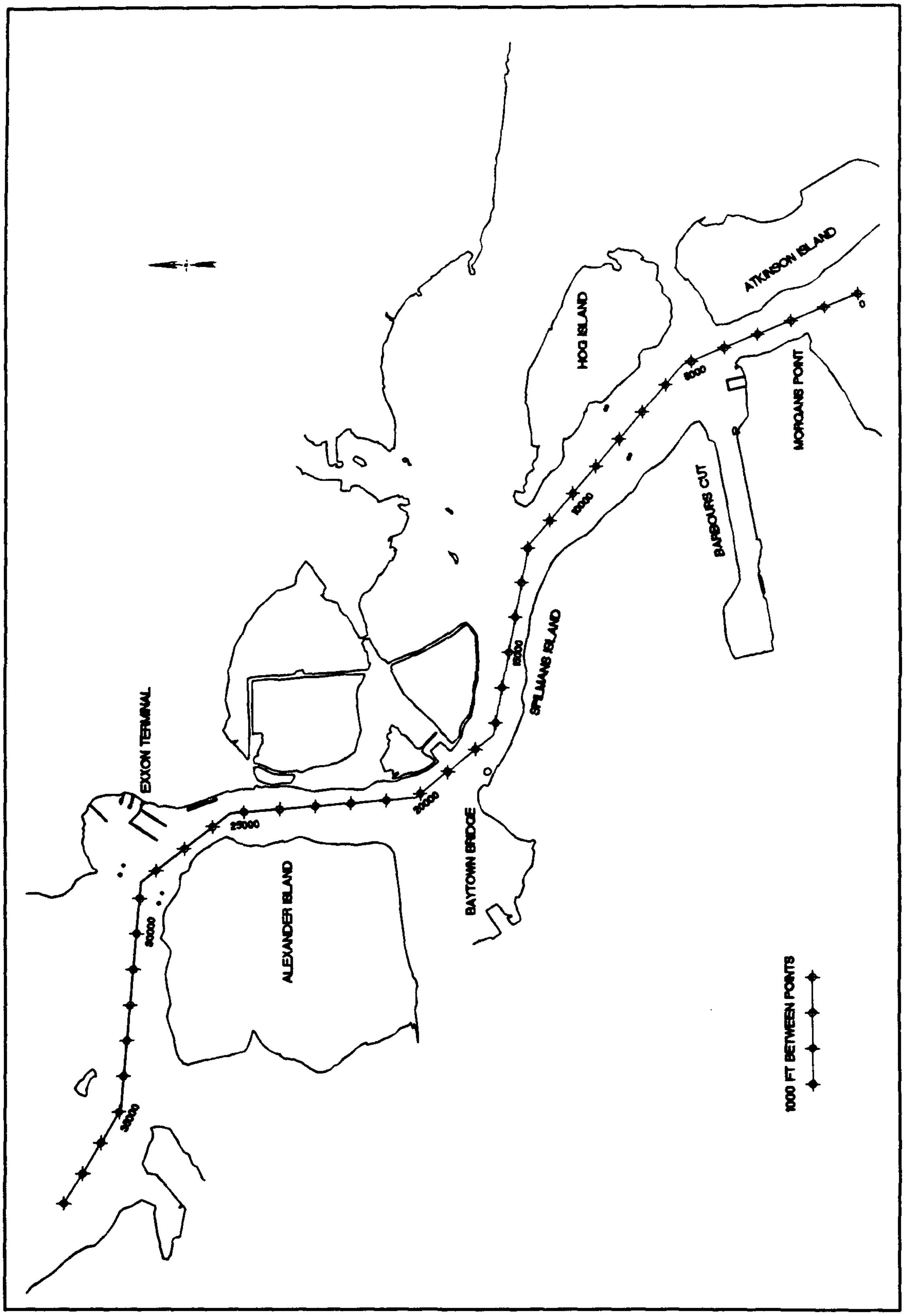


Figure 9. Distance along track, Test Reach A

Average ship speed

The plots of average ship speed versus distance along track for all three channels tested in Test Reach A (Plate 102) show that the vessels traveled at similar speed for all three channels, inbound and outbound. Phase I inbound runs are slightly slower than the existing and Phase II, and both Phase I and Phase II outbound runs are slightly slower than the existing condition over most of the run.

Average rudder angle

The plot of the average rudder angle versus distance along track for Test Reach A is shown in Plate 103. Examination of the inbound runs shows that the existing condition required very different rudder commands from the proposed alignment. The differences at Barbours Cut and at 10,000 ft are due to alignment changes. The differences at the Baytown Bridge turn are due to the change in alignment and more importantly, a change in operation. In order to make the turn in the existing channel, the pilot used rudder in the opposite direction of the turn and allowed the bank forces to carry the vessel through the turn. In the proposed alignment, the vessels turned just before the bridge, went straight through the bridge, and turned again after the bridge. For outbound runs, the differences between the existing and the proposed alignments occurred at Barbours Cut, 12,000 ft, and the Baytown bridge. These differences are due to the alignment changes.

Rate of turn

The plots of the rate of turn versus distance along track for the existing, Phase I, and Phase II channels in Test Reach A are shown in Plate 104. These plots show that through the Baytown Bridge, the vessel transiting the existing channel turned faster than those in the realigned channels for both inbound and outbound runs. Vessels traveling in the Phase I and Phase II channels turned faster before and after the bridge. This again reflects the two turns used to make this bend. Also, vessels in the existing channel turned faster at the Exxon terminal than vessels transiting the aligned channel.

Statistical Analysis, Test Reach B

A plot of the center line for Test Reach B and the distance from the beginning of the center line are shown in Figure 10.

Average engine rpm

The plots of average engine rpm versus distance along track for existing, Phase I, and Phase II channels tested in Test Reach B are shown in Plate 105.

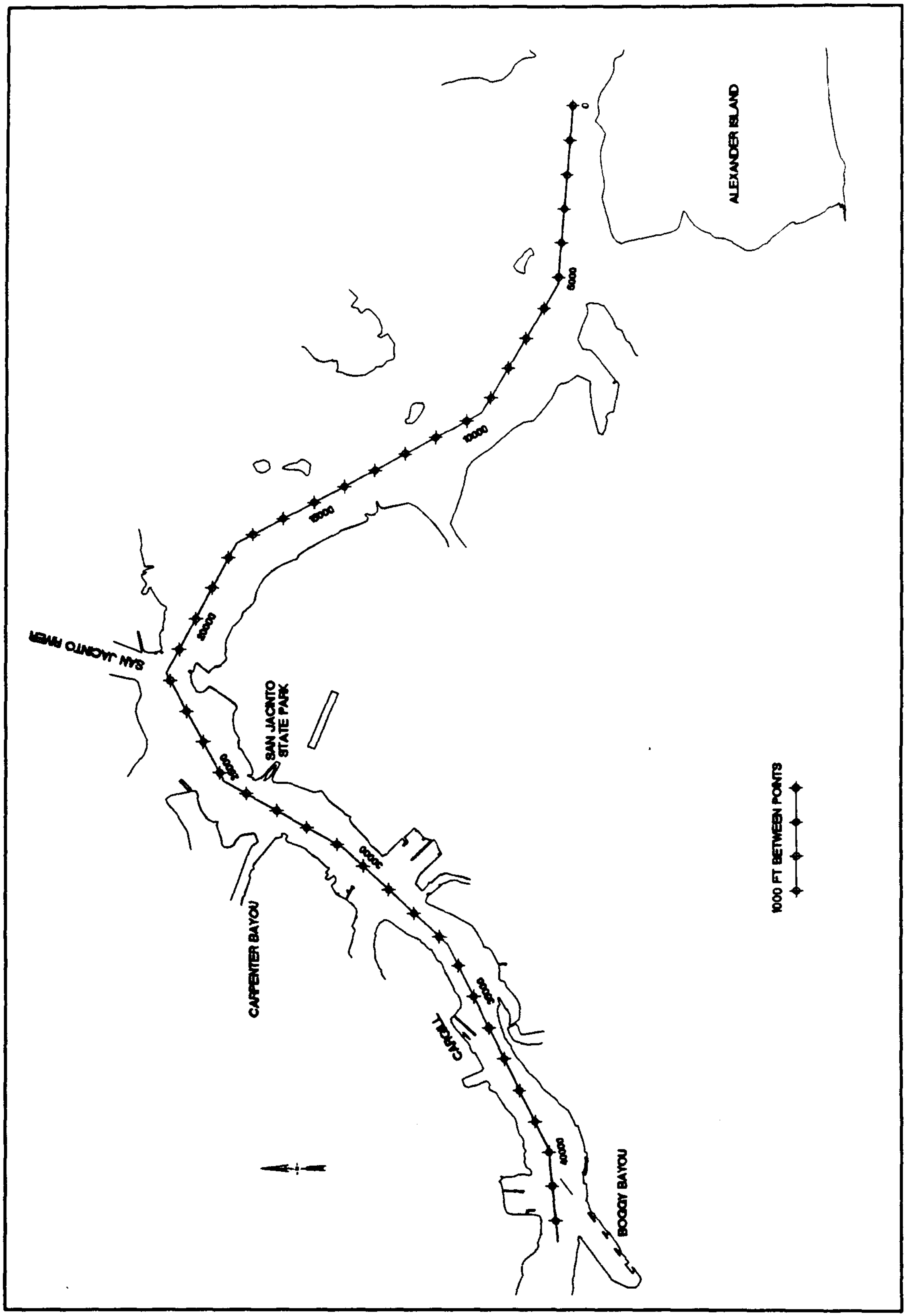


Figure 10. Distance along track, Test Reach B

For the inbound runs, the average rpm of the ships is similar for all channel conditions. The average rpm for outbound runs in the existing channel is significantly less than the rpm for outbound runs in the other two channels, before completing the turn at San Jacinto.

Average ship speed

The plots of average ship speed versus distance along track for all three channels tested in Test Reach B (Plate 106) show that the vessels traveled at similar speed for all three channels for inbound runs. Outbound vessels in the existing channel show a decrease in speed corresponding to the decrease in rpm previously discussed. There is also a higher speed in the existing channel below the San Jacinto bend than was attained in the proposed channels. This is because Houston pilots constituted a higher percentage of the database for existing conditions. Being more familiar with this area, they tended to go faster.

Average rudder angle

The plots of the average rudder angle versus distance along track for Test Reach A are shown in Plate 107. Examination of both the inbound and outbound runs shows that the existing condition required different rudder commands from the proposed channel due to alignment changes. For short periods during the outbound runs in the proposed channels between the Cargill Dock and the San Jacinto bend and in the San Jacinto bend, maximum rudder was used. While maximum rudder does not necessarily imply a potential safety hazard, especially when applied for short periods of time, it can be a guide as to the amount of effort required to navigate a reach. In the turn below the passing area in the existing channel, maximum rudder was used while the runs in the proposed channel used less rudder.

Rate of turn

The plots of the rate of turn versus distance along track for the existing, Phase I, and Phase II channels in Test Reach A are shown in Plate 108. The differences between the existing and the realigned channels are due to the alignment changes.

5 Recommendations

Based on the real-time pilot results, WES proposes the following channel layouts:

a. The proposed channel width of a minimum of 600 ft for the fully deepened (50-ft) project, Phase II, is recommended.

b. The design guidance for two-way navigation channels in EM 1110-2-1613 (Headquarters, U.S. Army Corps of Engineers, 1983) calls for a 60-ft bank/ship clearance for both ships involved in a passing maneuver and 80 ft between ships for a total clearance of 200 ft. In order to meet these criteria (based on average total clearances of 162 and 143 ft for inbound and outbound runs, respectively), either the Phase I 530-ft channel would have to be widened to nearly 590 ft (only 10 ft narrower than Phase II) or the combined beams of meeting and passing ships should be limited to less than 260 ft. Realizing the increased difficulty of setting up for a passing situation in the bayou segment of the HSC and of controlling meeting situations, it is recommended that the 45-ft Phase I channel be widened to the Phase II width. Since the Phase I turns in the bayou segment were the same as the Phase II turns, and the reach at Cargill is limited to 530-ft width (without relocation), the additional widening covers 8.5 miles of the 13.9-mile-long bayou segment, or 61 percent.

c. It is recommended that the turn at San Jacinto be modified to reduce the width in the bend wideners on both sides of the San Jacinto River. If additional piloted tests are conducted, this modification (Figure 11) might be further reduced. Track plots of all runs plotted with both the tested channel and the modified channel are included as Plates 109-120.

d. It is recommended that the turn at Exxon be built as tested in the simulation program.

e. It is recommended that the segment of channel between Cargill and Oxy-Chem docks be restricted to one-way traffic for large vessels. However, the channel width here should not be further reduced because

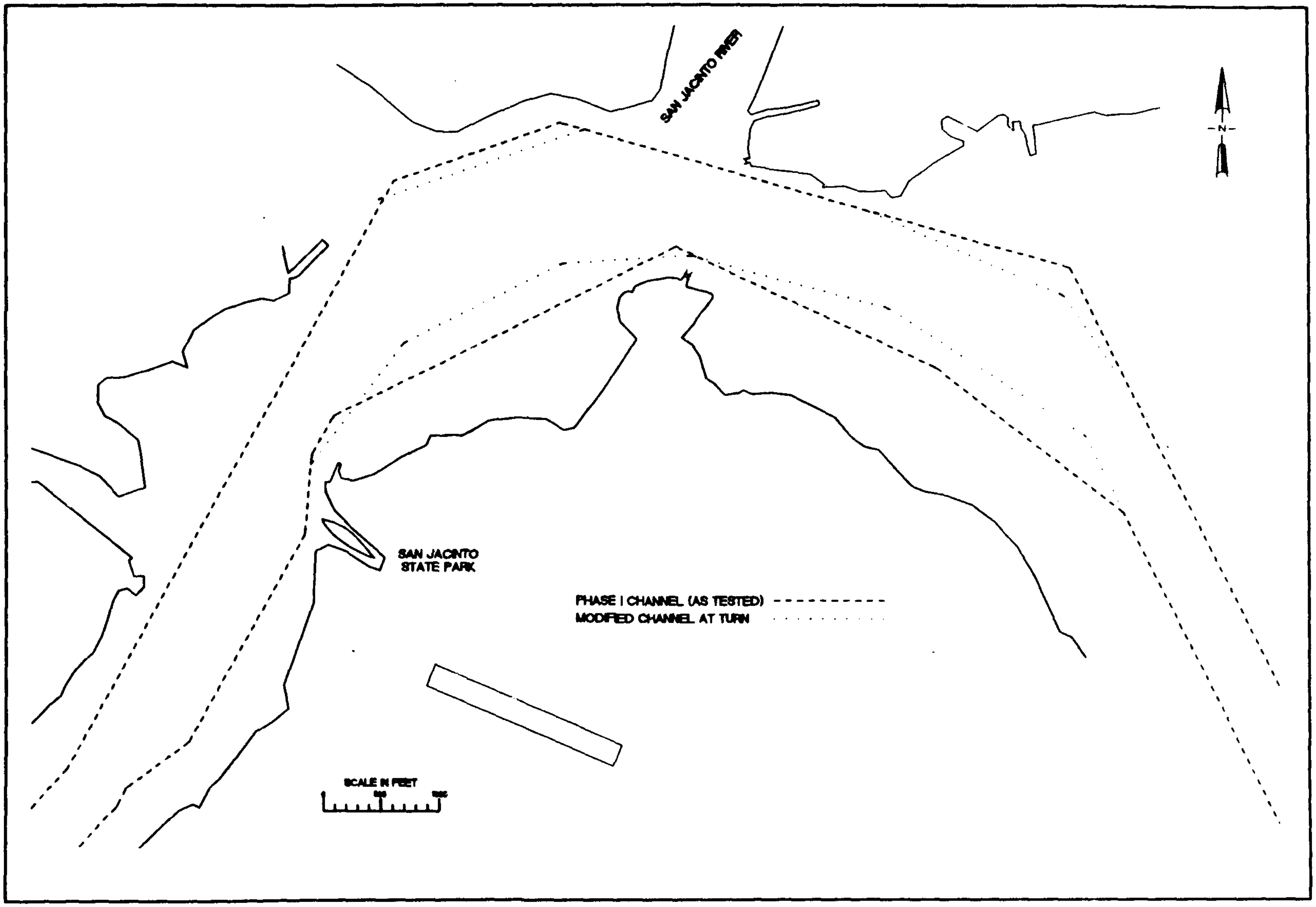


Figure 11. Proposed alignment at San Jacinto turn

smaller vessels may need to meet there, and ships docked at Cargill tend to encroach on the channel.

f. It is recommended that the segment of channel through the Baytown Bridge be built as tested in the simulation program with channel markers suspended from the bridge. An alternative would be to change the design of this bend to conform as near as possible with the existing 40-ft contour line (Plate 1). Additional tests with the local pilots are recommended if this alternative alignment is selected to assure that the larger ships will turn in a similar way as the ships in the existing channel alignment, i.e. a bank-assisted turn.

References

Ankudinov, V. (1991). "Development of maneuvering simulation models for five full form vessels for use in the WES Houston Ship Channel (HSC) navigation study," Technical Report 90062.0122, prepared for U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS, by Tracor Hydronautics, Inc., Laurel, MD.

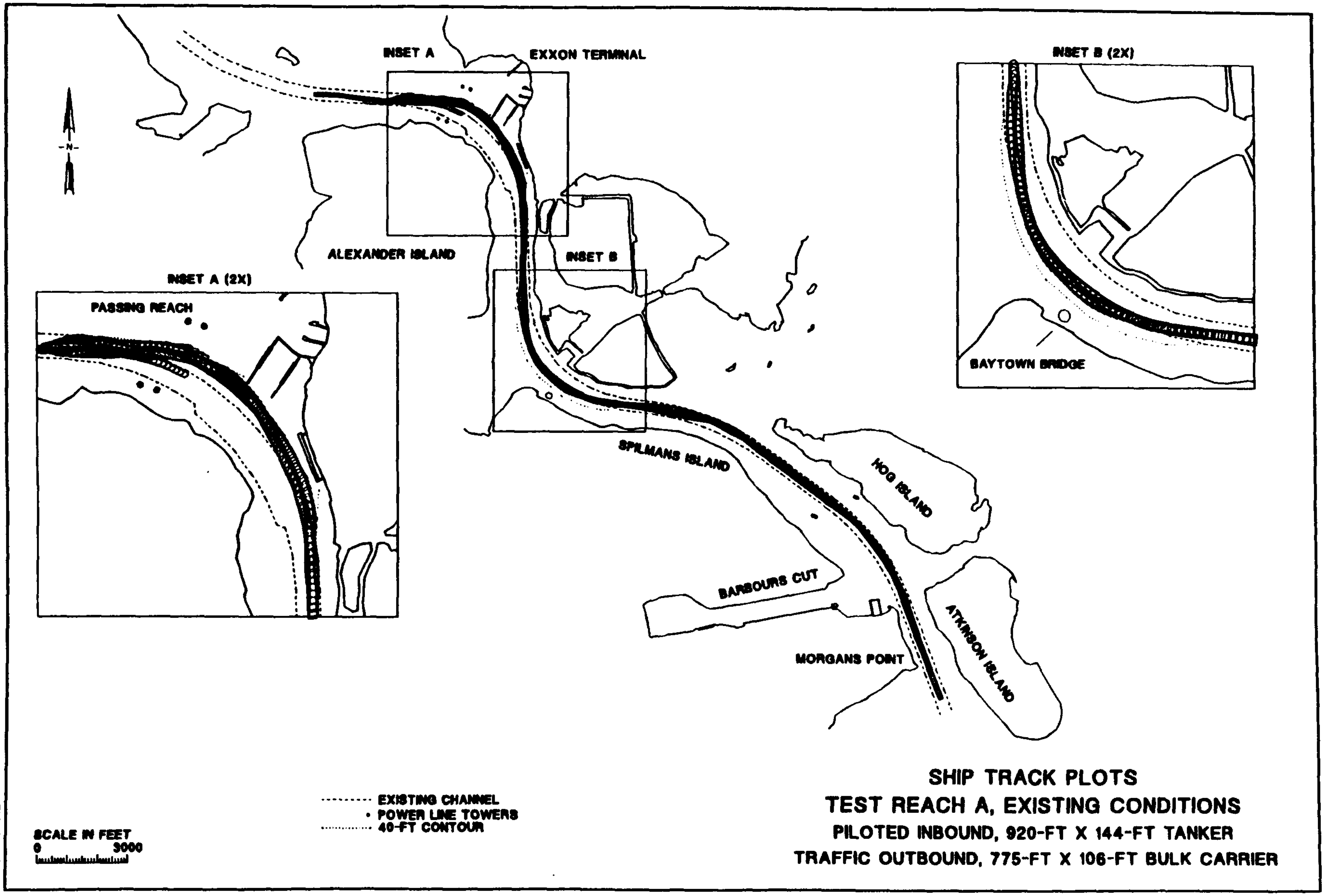
Headquarters, U.S. Army Corps of Engineers. (1983). "Hydraulic design of deep-draft navigation projects," EM 1110-2-1613, U.S. Government Printing Office, Washington, DC.

Hewlett, J. Christopher. (1994). "Ship Navigation Simulation Study, Houston-Galveston Navigation Channels, Texas; Report 1, Houston Ship Channel, Bay Segment" (in preparation), U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

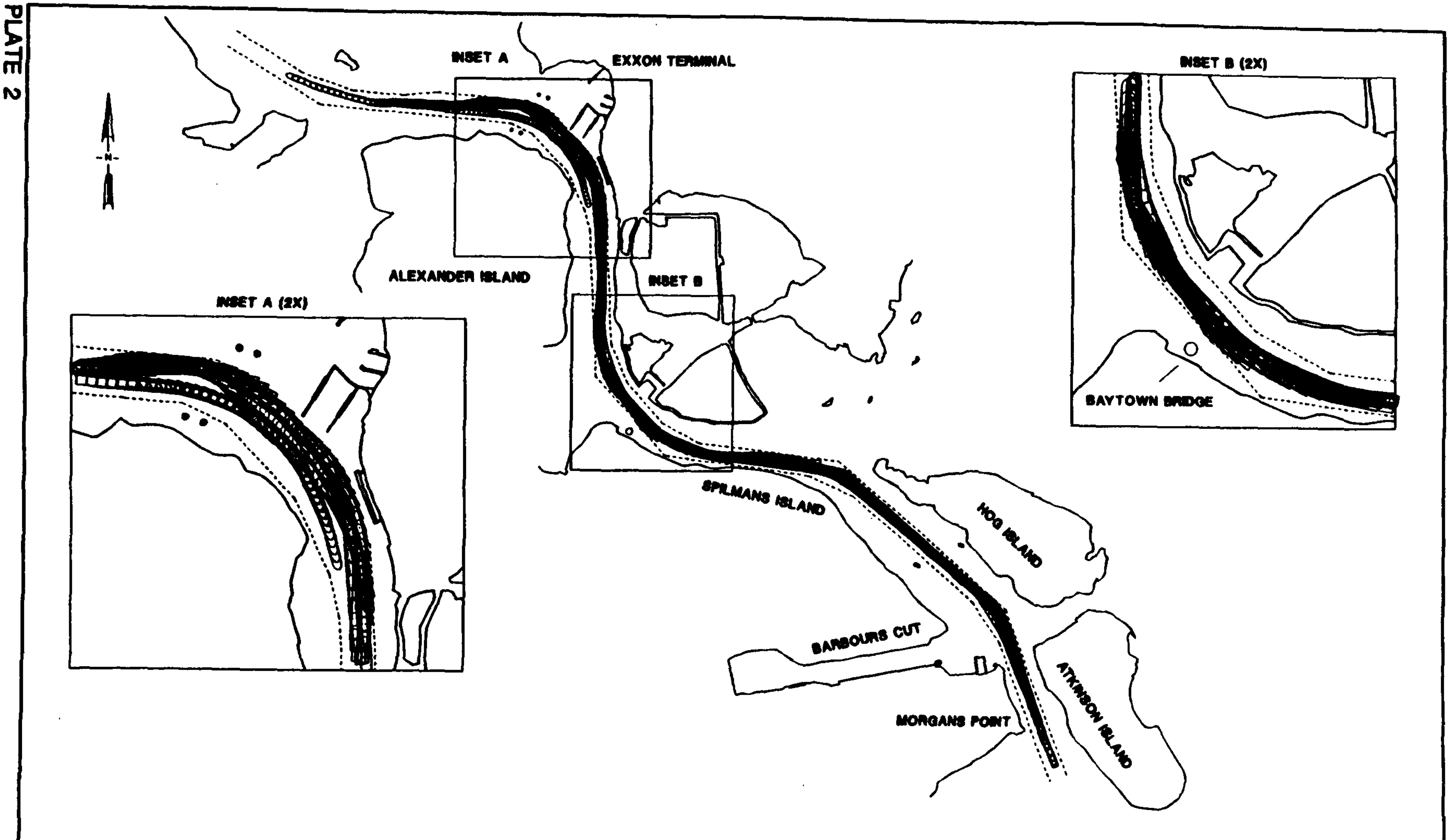
Houston Ship Pilots. (1989). "Navigation safety guidelines on the Houston Ship Channel between Galveston Bar and the Turning Basin," Houston, Texas.

Lin, Hsin-Chi J. (1992). "Houston-Galveston Navigation Channels, Texas Project; Report 2, Two-dimensional numerical modeling of hydrodynamics," Technical Report HL-92-7, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

U.S. Army Engineer District, Galveston. (1987). "Final feasibility report and environmental impact statement, Galveston Bay area navigation study," Galveston, TX.

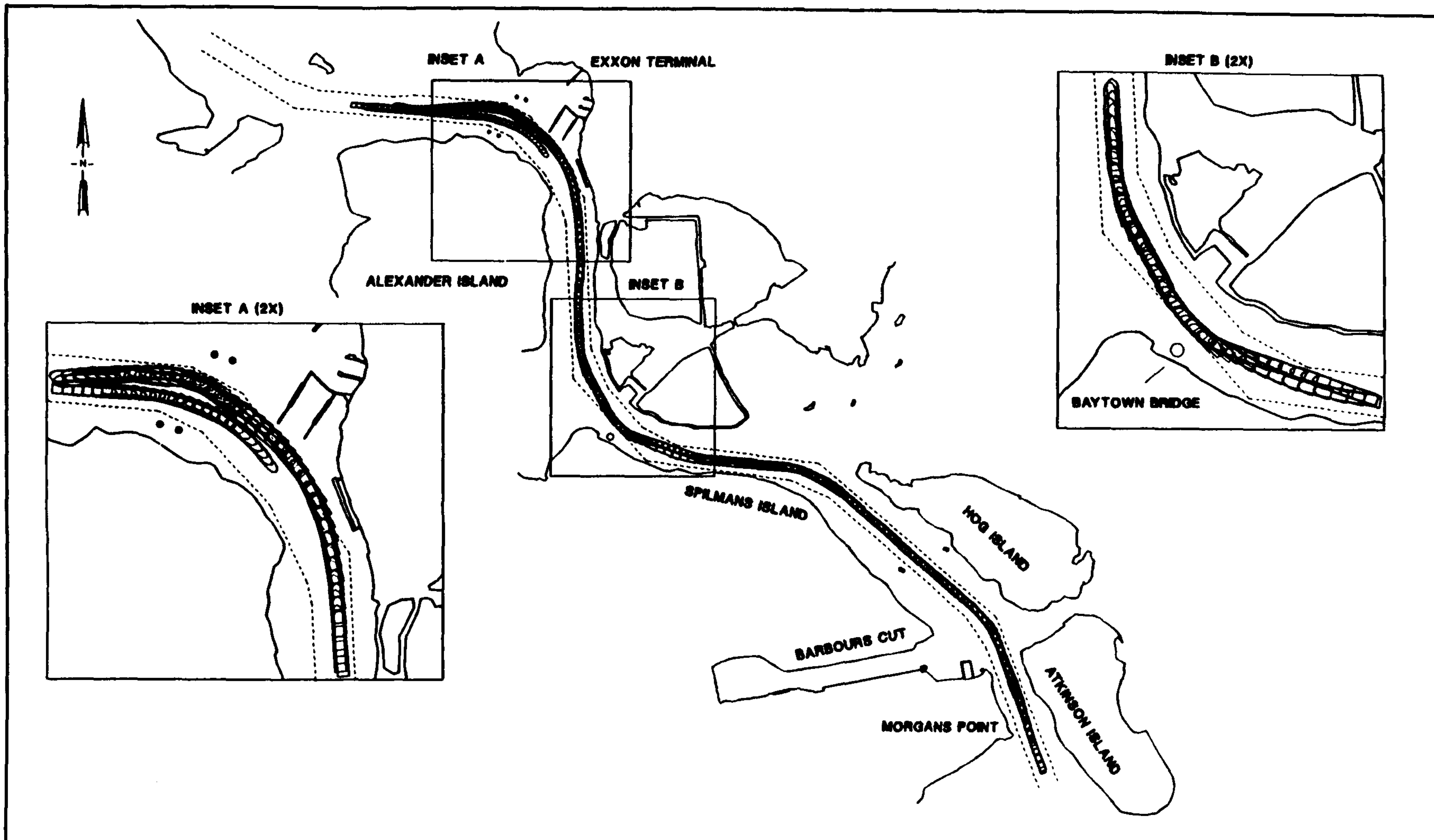


SHIP TRACK PLOTS
TEST REACH A, EXISTING CONDITIONS
PILOTED INBOUND, 920-FT X 144-FT TANKER
TRAFFIC OUTBOUND, 775-FT X 106-FT BULK CARRIER



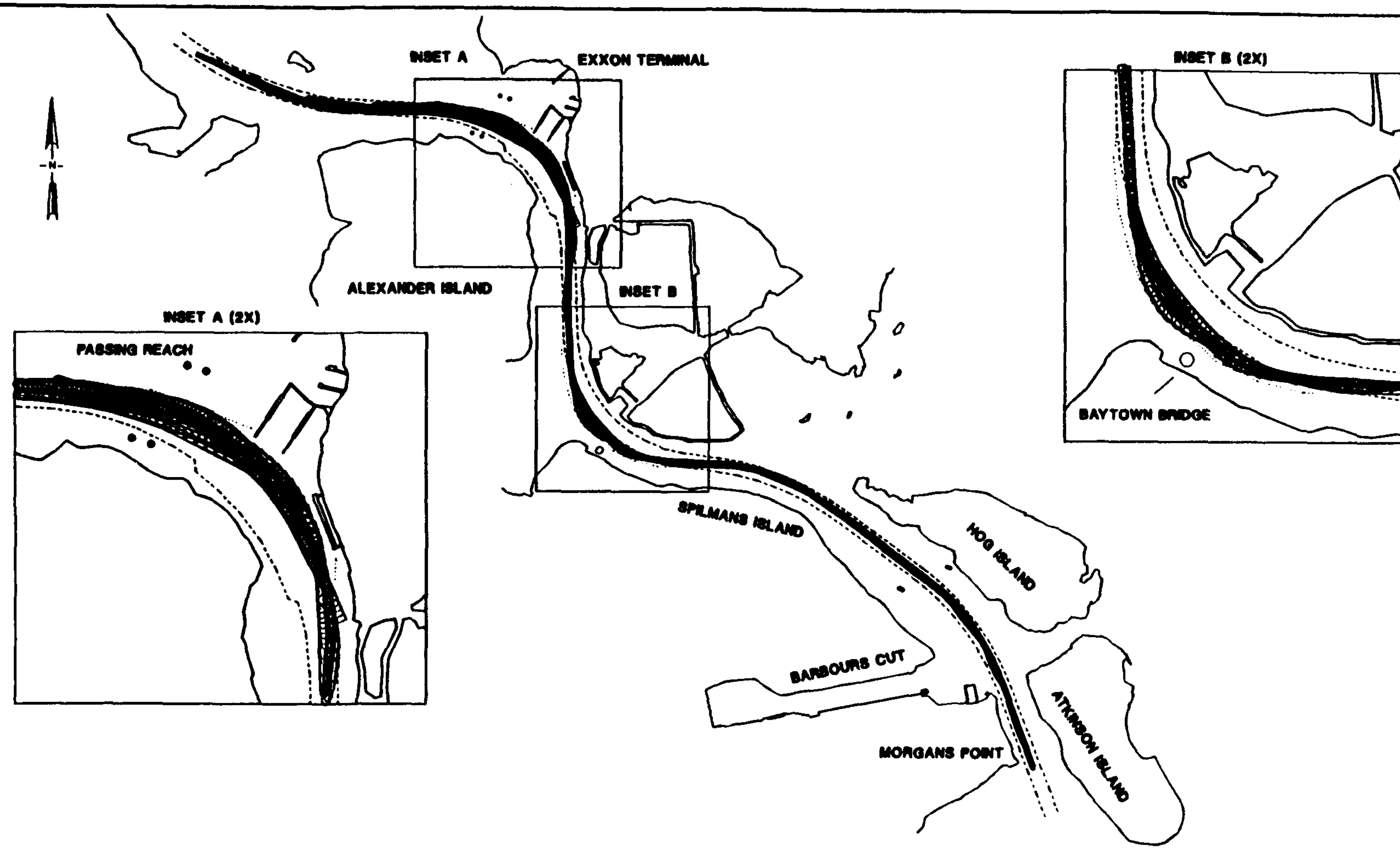
SHIP TRACK PLOTS
TEST REACH A, PHASE I CONDITIONS
PILOTED INBOUND, 990-FT X 156-FT TANKER
TRAFFIC OUTBOUND, 971-FT X 140-FT BULK CARRIER

PLATE 2



SHIP TRACK PLOTS
TEST REACH A, PHASE II CONDITIONS
PILOTED INBOUND, 1013-FT X 173-FT TANKER
TRAFFIC OUTBOUND, 971-FT X 140-FT BULK CARRIER

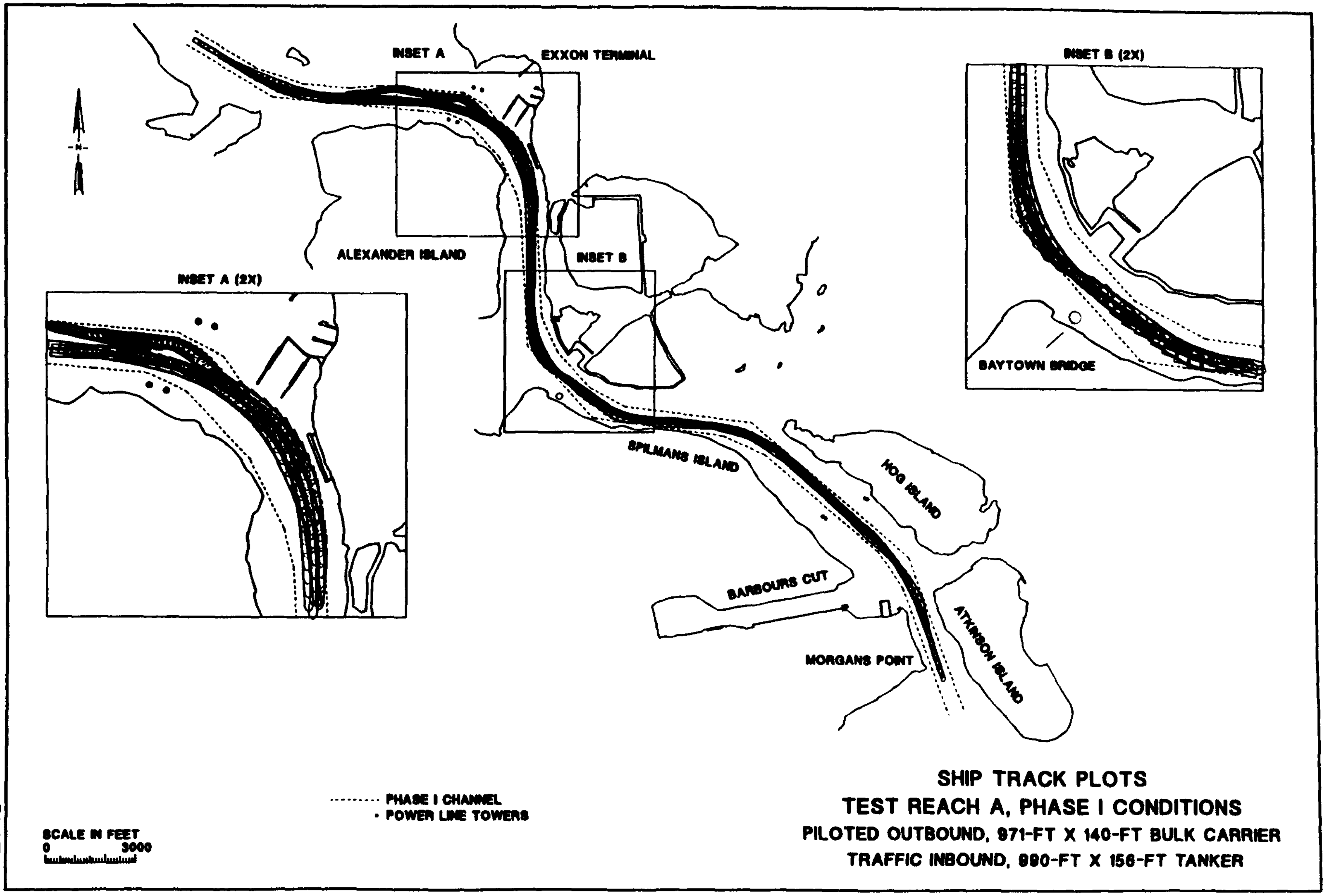
PLATE 4



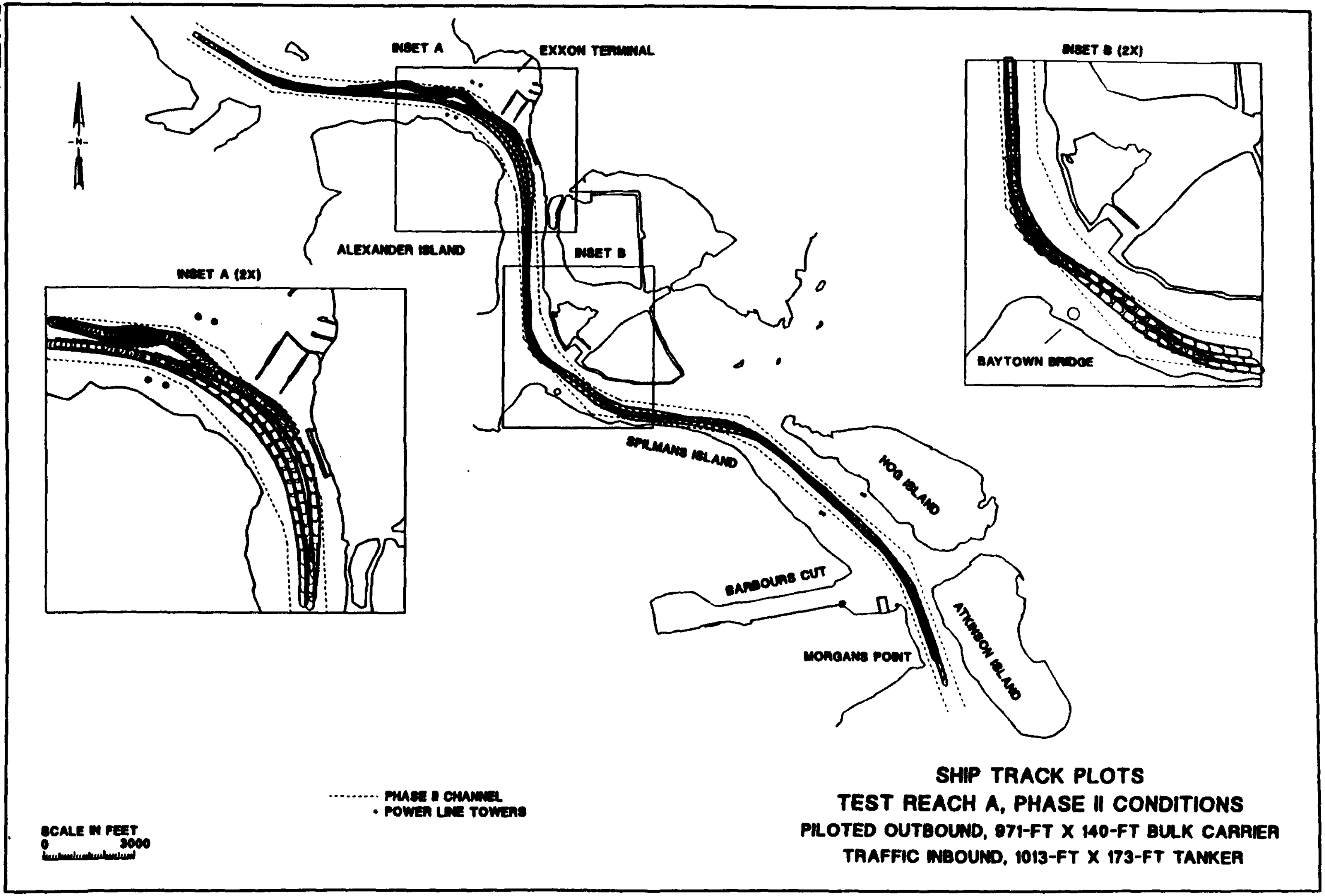
EXISTING CHANNEL
POWER LINE TOWERS
40-FT CONTOUR

SCALE IN FEET
0 3000

SHIP TRACK PLOTS
TEST REACH A, EXISTING CONDITIONS
PILOTED OUTBOUND, 775-FT X 106-FT BULK CARRIER
TRAFFIC INBOUND, 920-FT X 144-FT TANKER

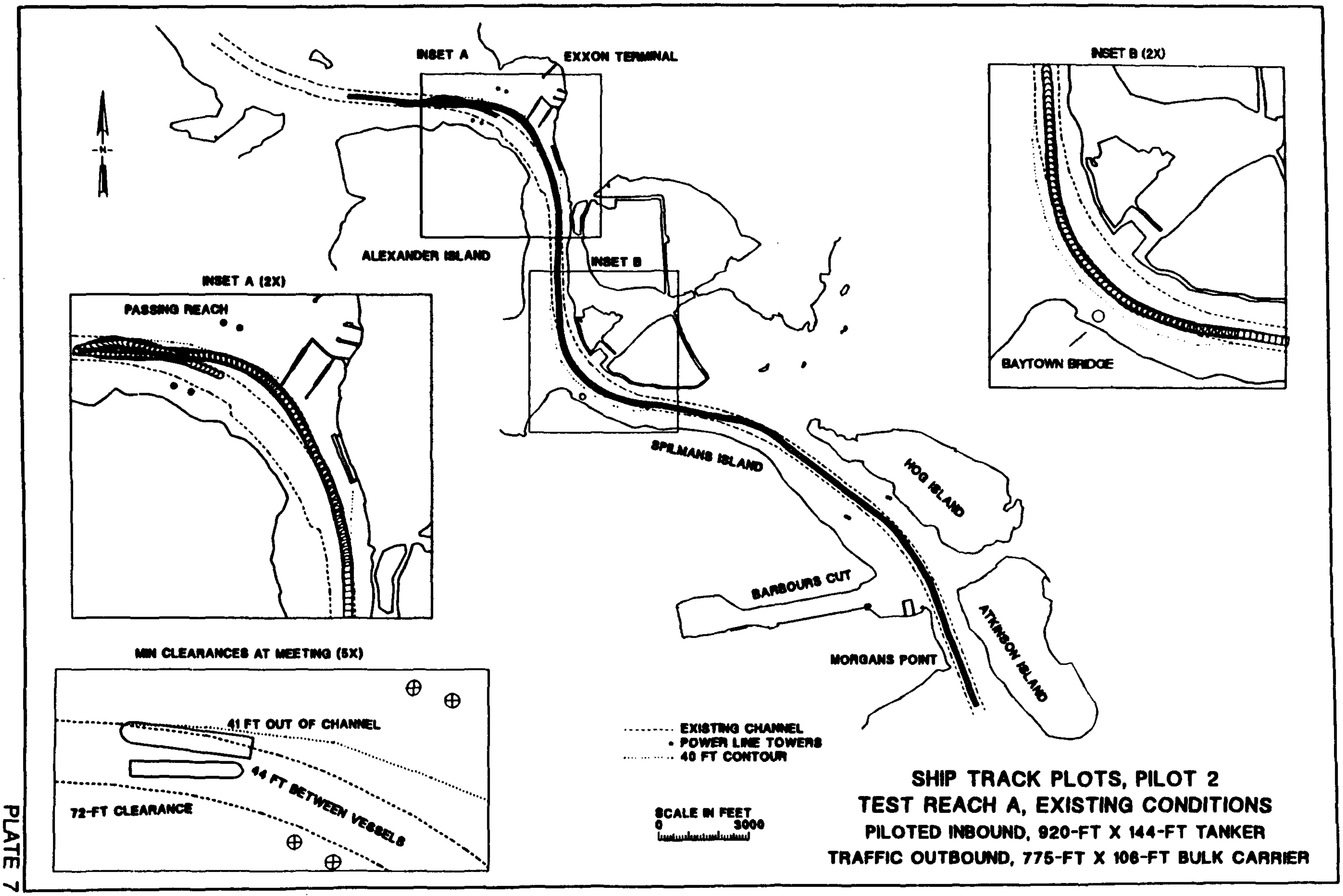


SHIP TRACK PLOTS
TEST REACH A, PHASE I CONDITIONS
PILOTED OUTBOUND, 971-FT X 140-FT BULK CARRIER
TRAFFIC INBOUND, 990-FT X 156-FT TANKER

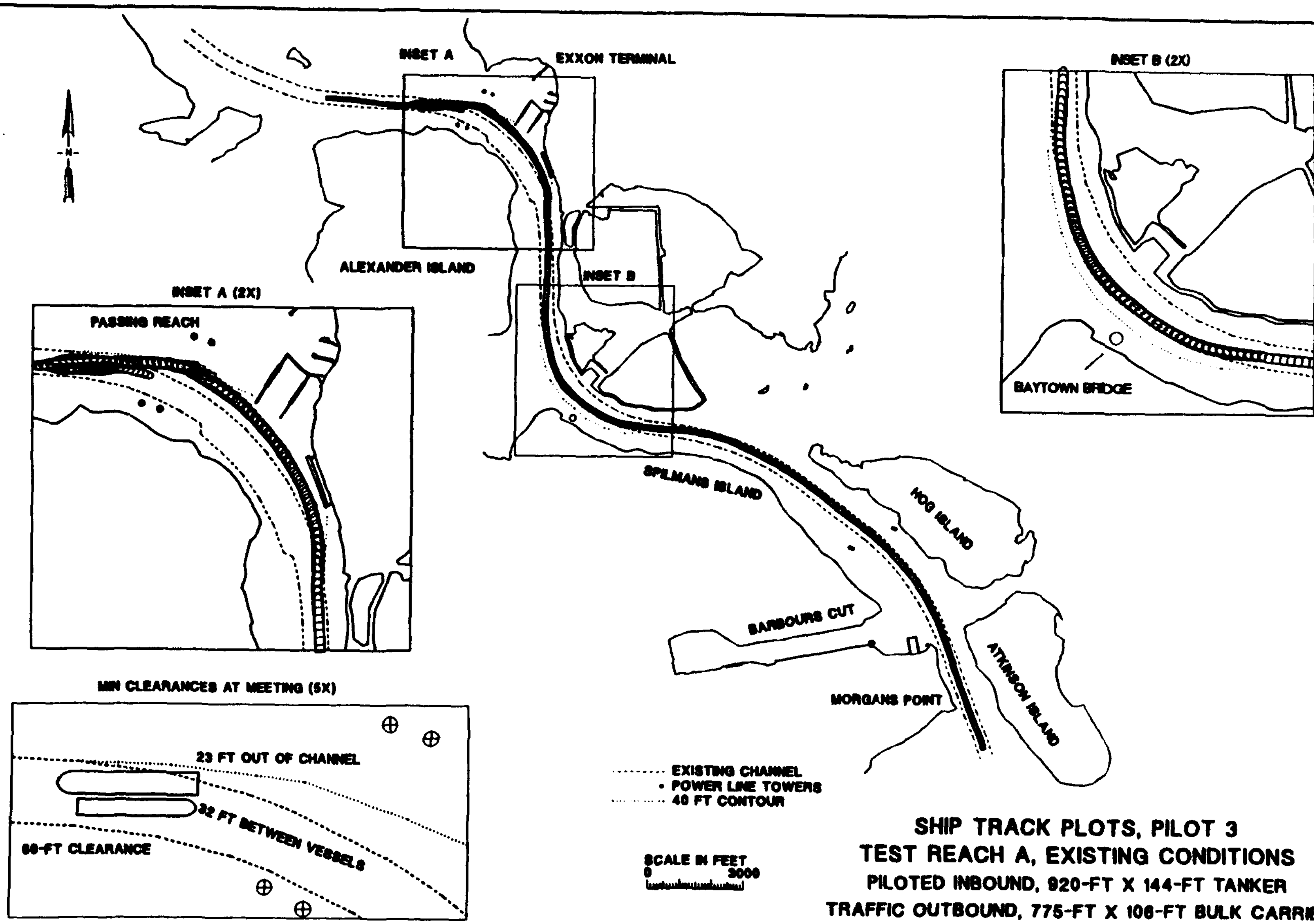


SHIP TRACK PLOTS
TEST REACH A, PHASE II CONDITIONS
PILOTED OUTBOUND, 971-FT X 140-FT BULK CARRIER
TRAFFIC INBOUND, 1013-FT X 173-FT TANKER

PLATE 6

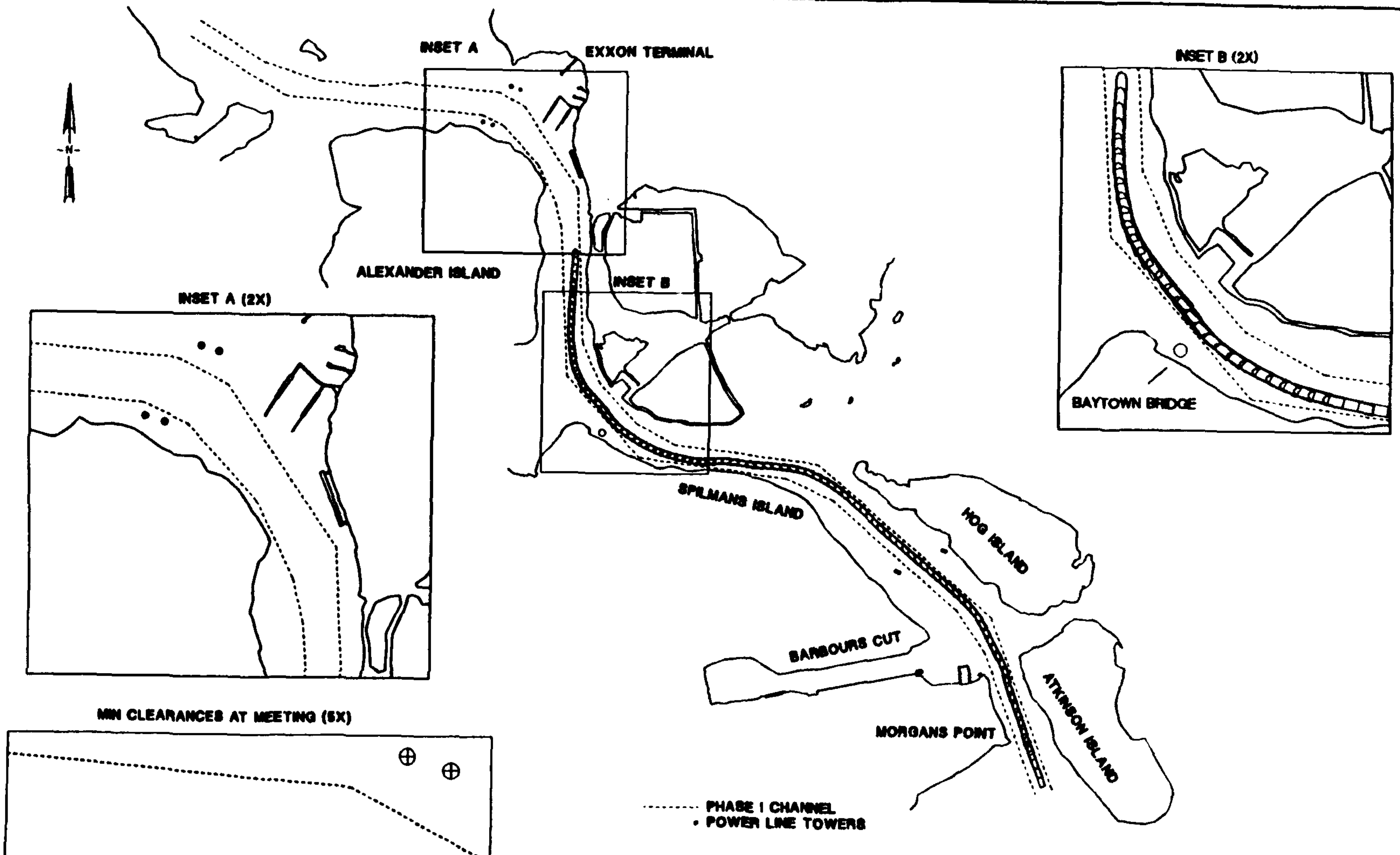


SHIP TRACK PLOTS, PILOT 2
TEST REACH A, EXISTING CONDITIONS
PILOTED INBOUND, 920-FT X 144-FT TANKER
TRAFFIC OUTBOUND, 775-FT X 106-FT BULK CARRIER



SHIP TRACK PLOTS, PILOT 3
TEST REACH A, EXISTING CONDITIONS
PILOTED INBOUND, 920-FT X 144-FT TANKER
TRAFFIC OUTBOUND, 775-FT X 106-FT BULK CARRIER

PLATE 8



SHIP TRACK PLOTS, PILOT 1
TEST REACH A, PHASE I CONDITIONS
PILOTED INBOUND, 990-FT X 156-FT TANKER
TRAFFIC OUTBOUND, 971-FT X 140-FT BULK CARRIER

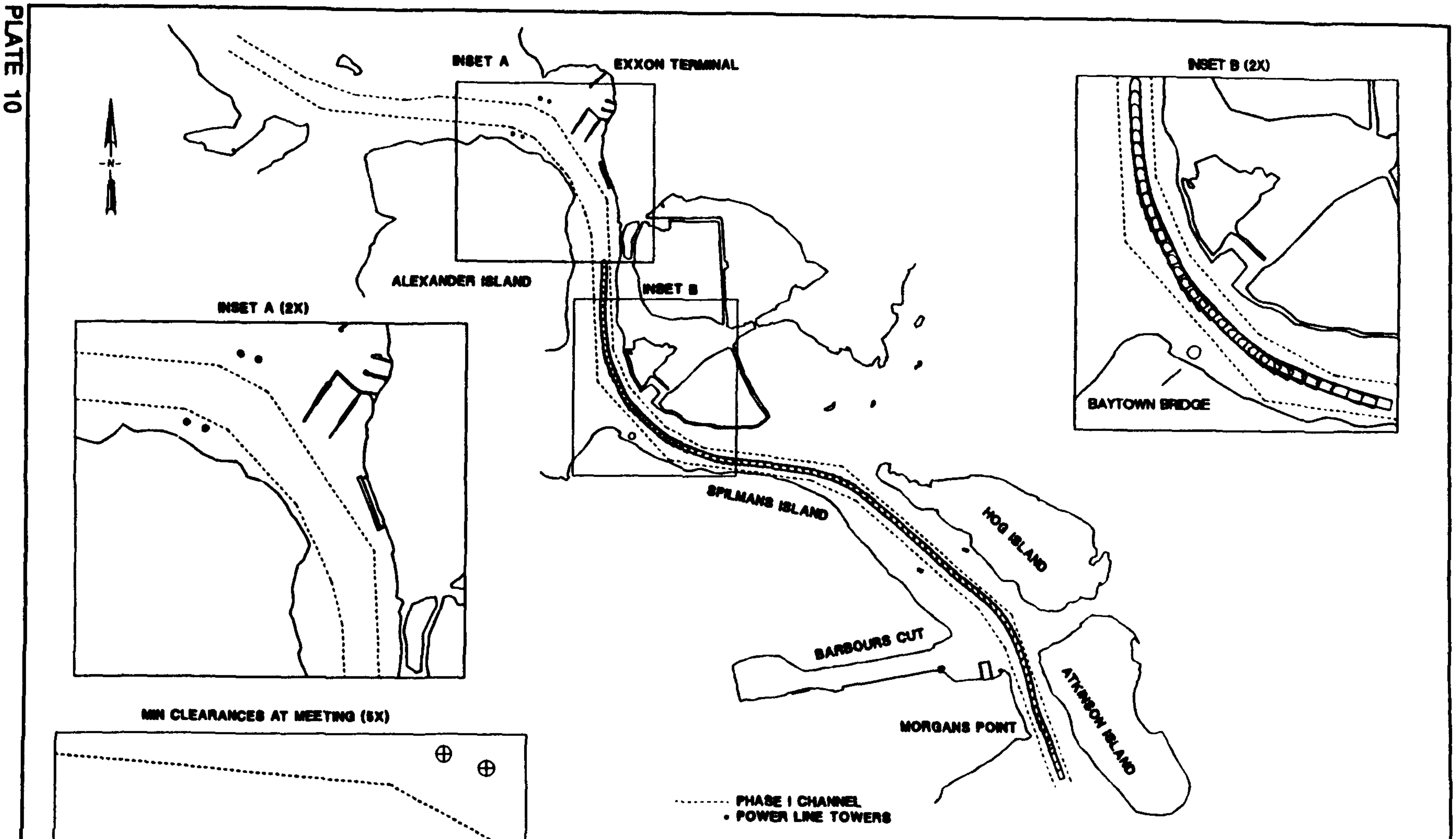
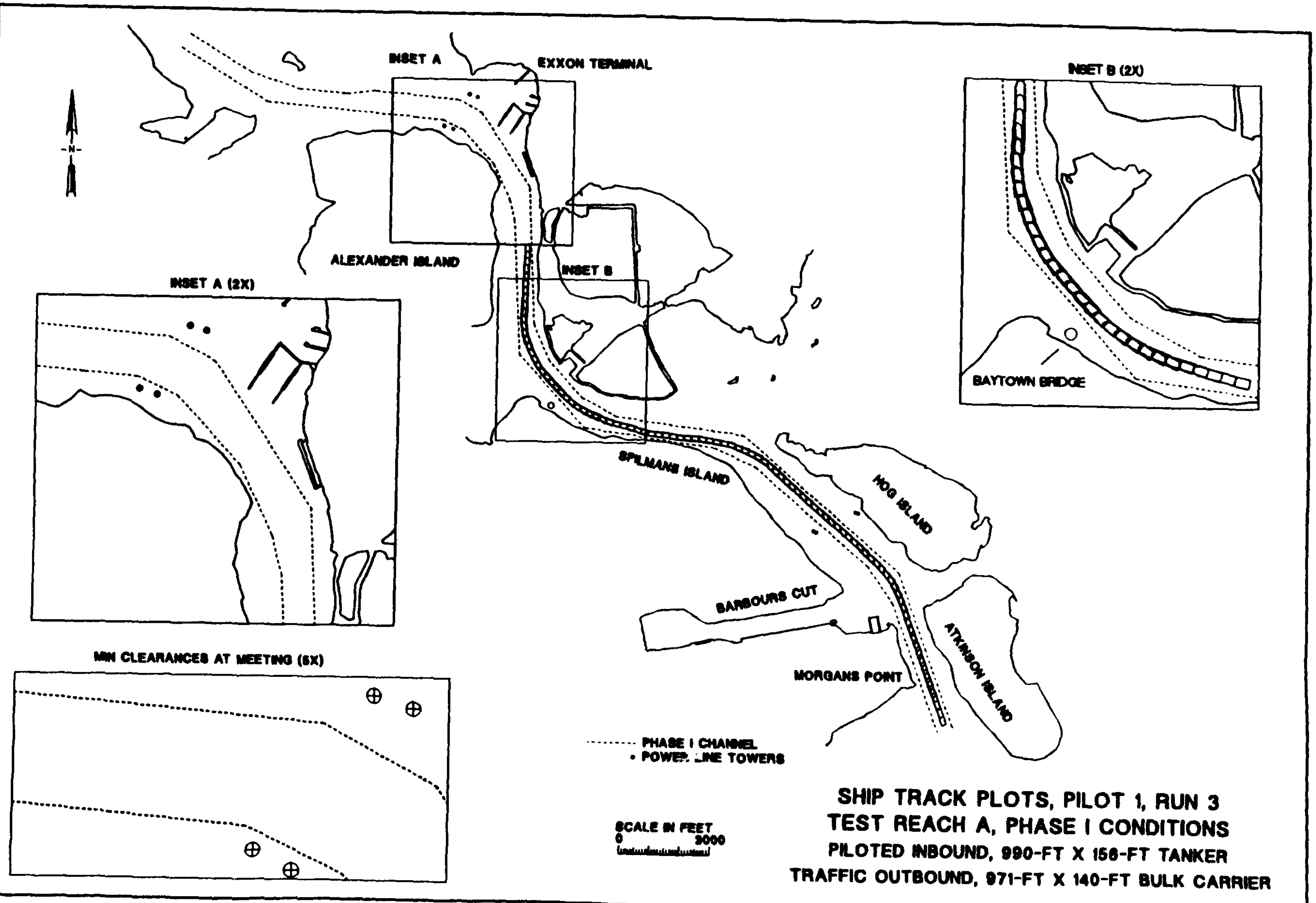


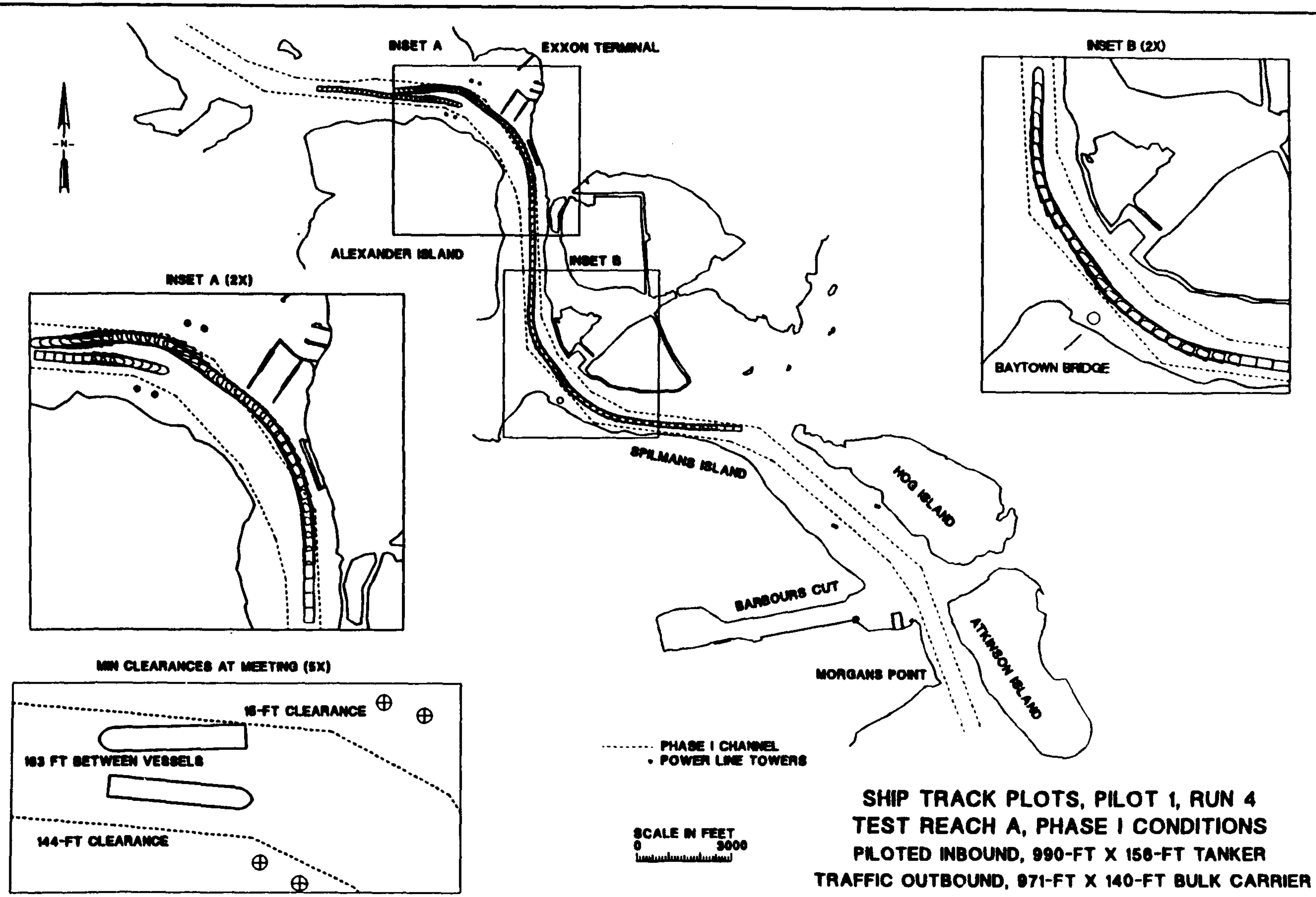
PLATE 10

SHIP TRACK PLOTS, PILOT 1, RUN 2
TEST REACH A, PHASE I CONDITIONS
PILOTED INBOUND, 990-FT X 158-FT TANKER
TRAFFIC OUTBOUND, 971-FT X 140-FT BULK CARRIER

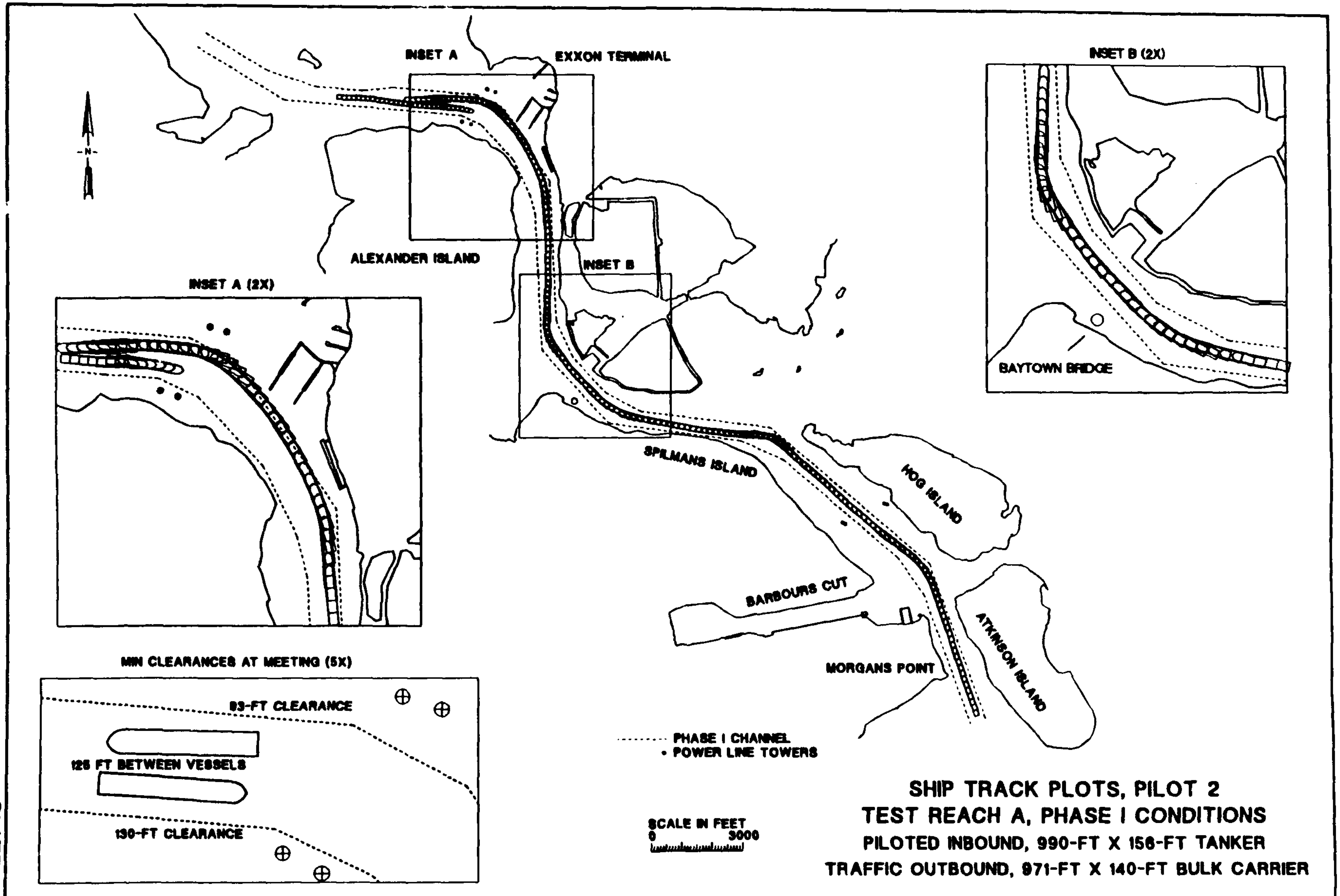


SHIP TRACK PLOTS, PILOT 1, RUN 3
TEST REACH A, PHASE I CONDITIONS
PILOTED INBOUND, 990-FT X 158-FT TANKER
TRAFFIC OUTBOUND, 971-FT X 140-FT BULK CARRIER

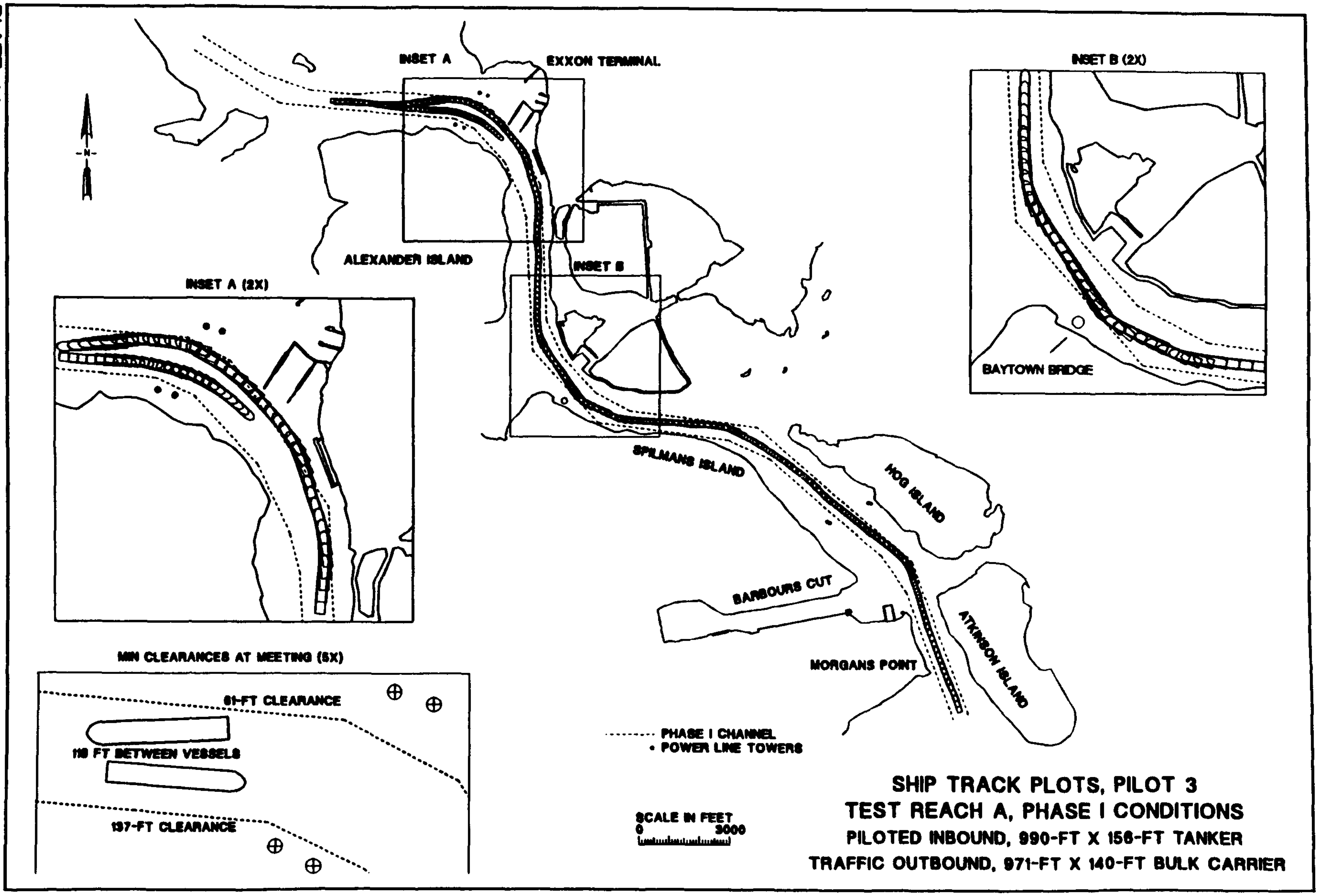
PLATE 12



SHIP TRACK PLOTS, PILOT 1, RUN 4
TEST REACH A, PHASE I CONDITIONS
PILOTED INBOUND, 990-FT X 156-FT TANKER
TRAFFIC OUTBOUND, 971-FT X 140-FT BULK CARRIER

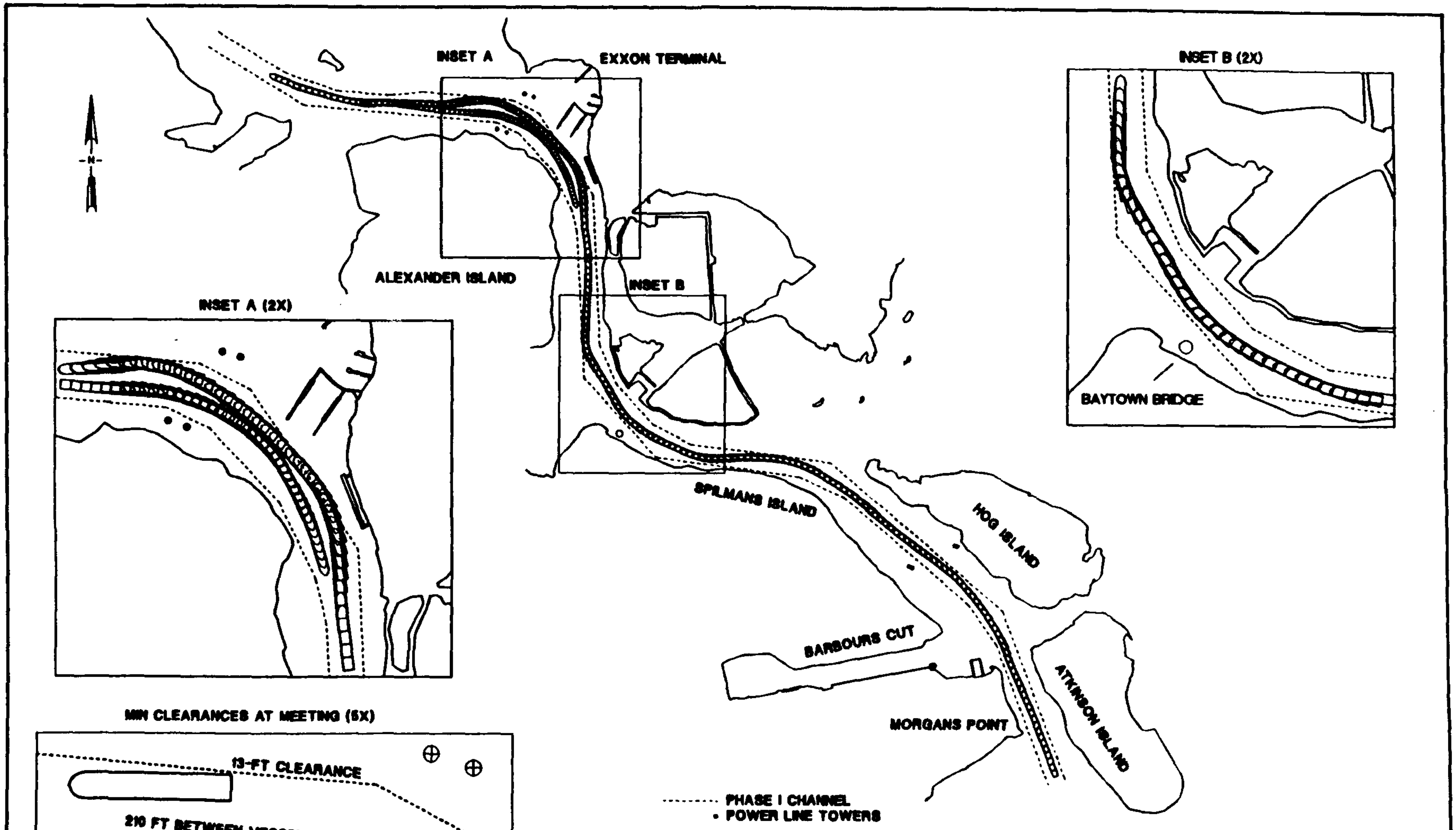


SHIP TRACK PLOTS, PILOT 2
TEST REACH A, PHASE I CONDITIONS
PILOTED INBOUND, 990-FT X 156-FT TANKER
TRAFFIC OUTBOUND, 971-FT X 140-FT BULK CARRIER



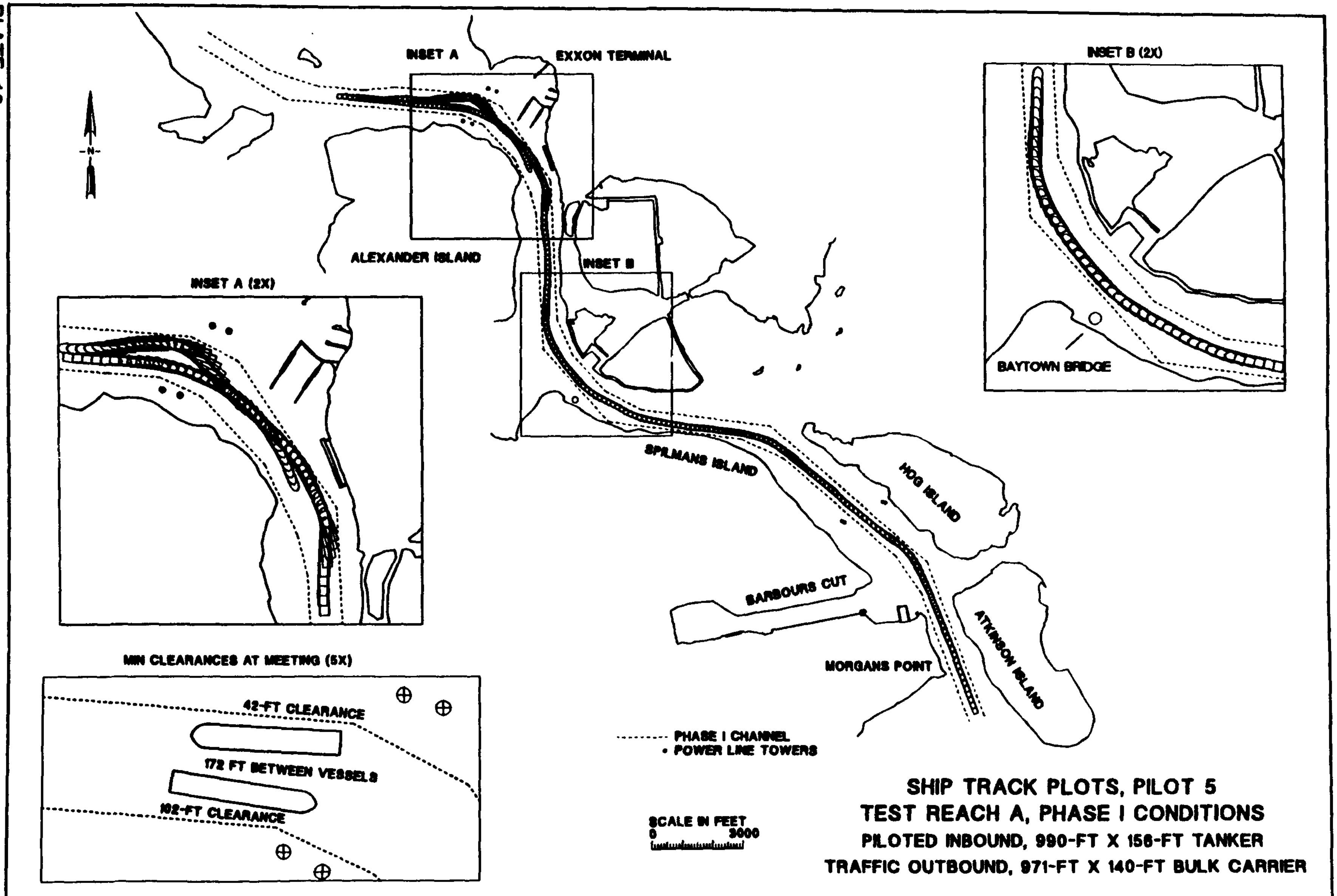
SHIP TRACK PLOTS, PILOT 3
TEST REACH A, PHASE I CONDITIONS
PILOTED INBOUND, 990-FT X 156-FT TANKER
TRAFFIC OUTBOUND, 971-FT X 140-FT BULK CARRIER

PLATE 14

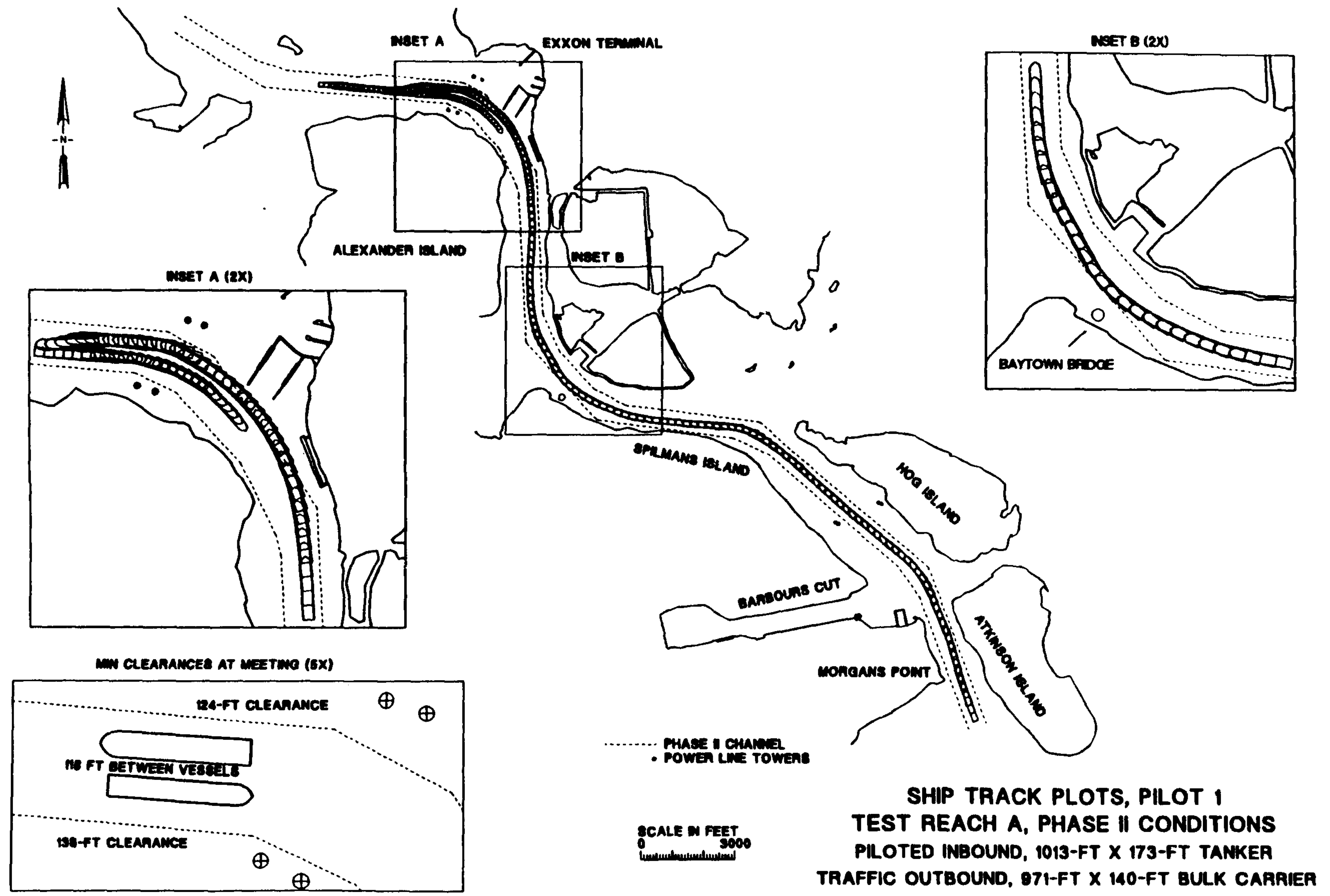


SHIP TRACK PLOTS, PILOT 4
TEST REACH A, PHASE I CONDITIONS
PILOTED INBOUND, 990-FT X 158-FT TANKER
TRAFFIC OUTBOUND, 971-FT X 140-FT BULK CARRIER

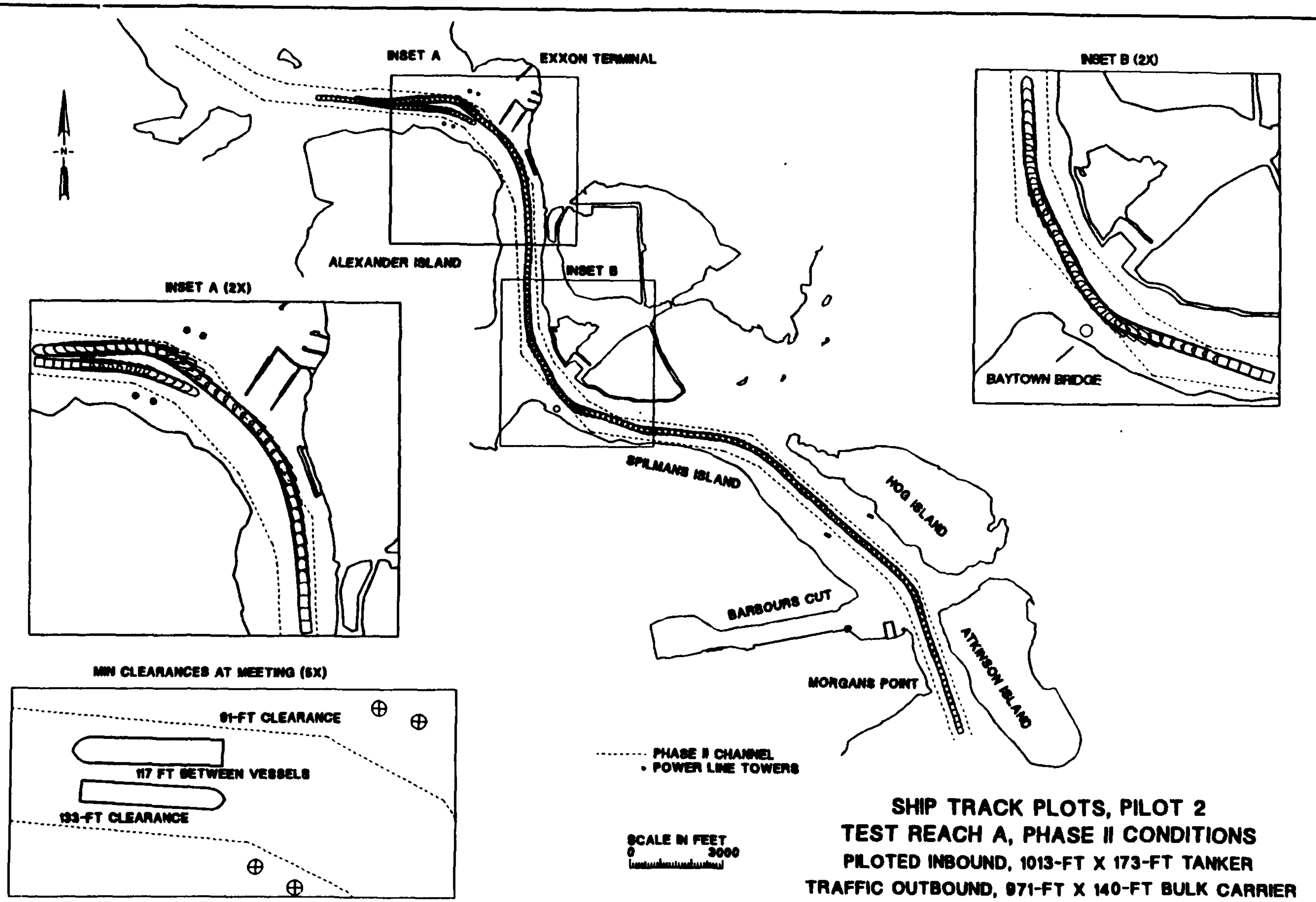
PLATE 16



SHIP TRACK PLOTS, PILOT 5
TEST REACH A, PHASE I CONDITIONS
PILOTED INBOUND, 990-FT X 158-FT TANKER
TRAFFIC OUTBOUND, 971-FT X 140-FT BULK CARRIER

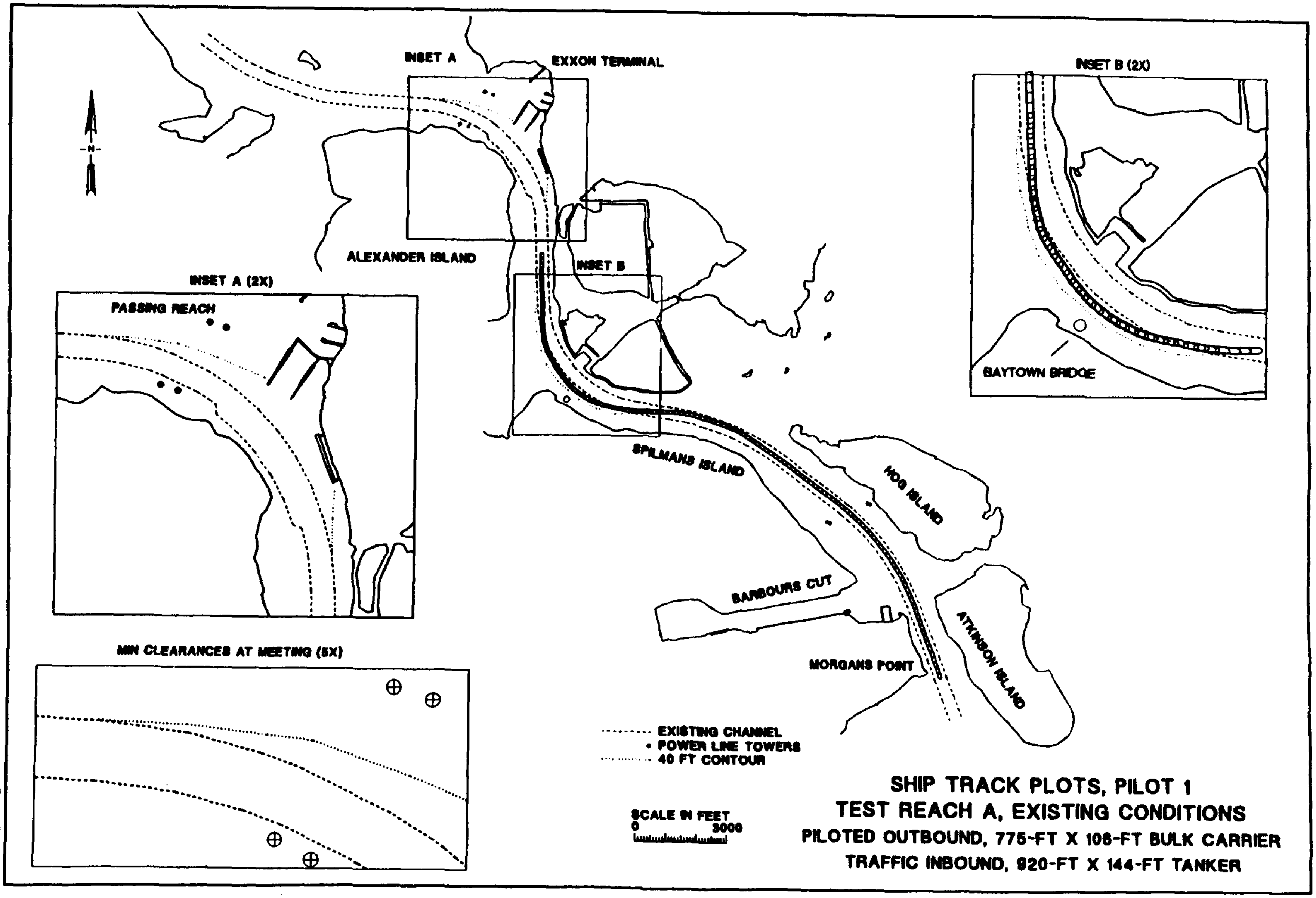


SHIP TRACK PLOTS, PILOT 1
TEST REACH A, PHASE II CONDITIONS
PILOTED INBOUND, 1013-FT X 173-FT TANKER
TRAFFIC OUTBOUND, 971-FT X 140-FT BULK CARRIER

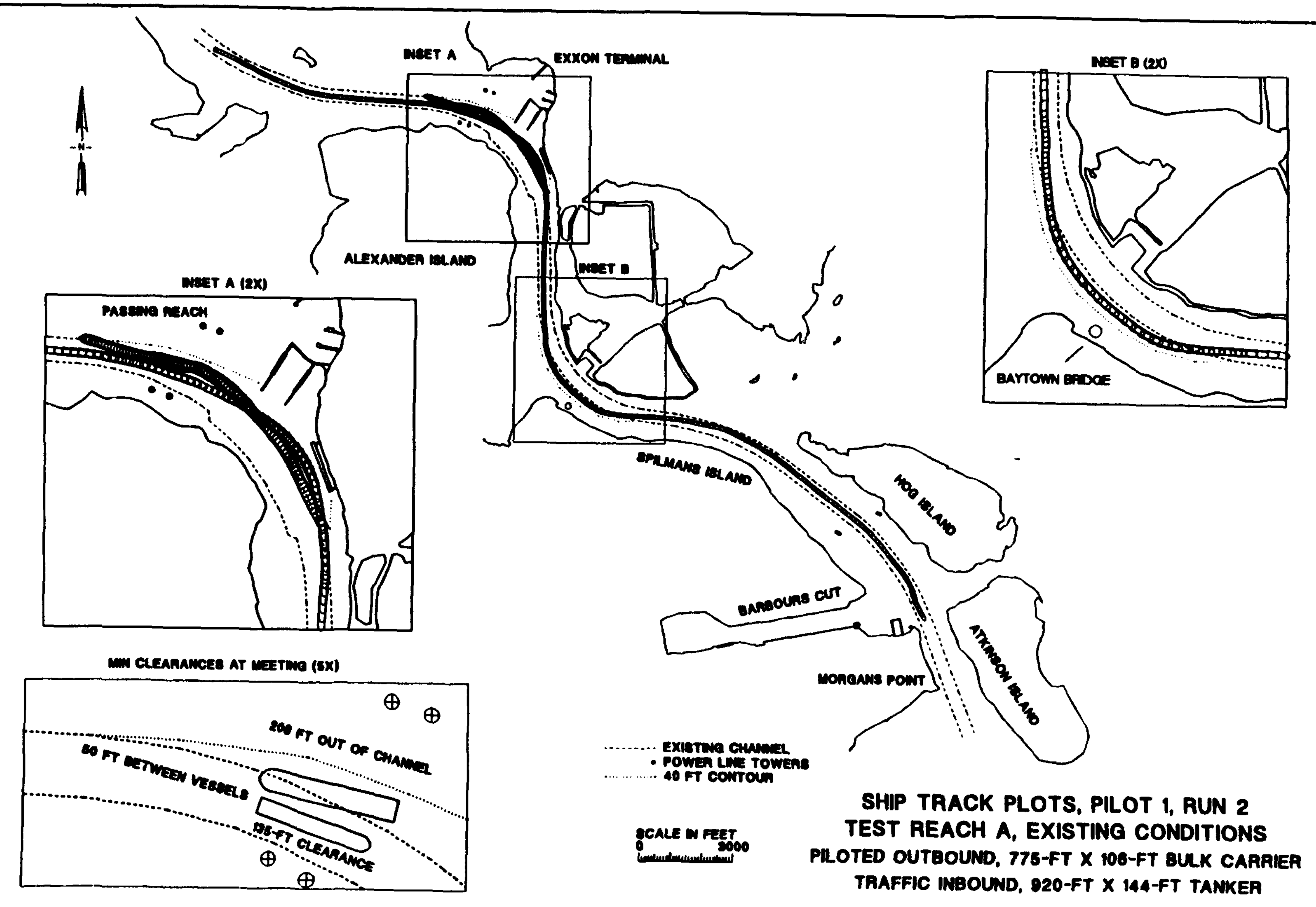


SHIP TRACK PLOTS, PILOT 2
TEST REACH A, PHASE II CONDITIONS
PILOTED INBOUND, 1013-FT X 173-FT TANKER
TRAFFIC OUTBOUND, 971-FT X 140-FT BULK CARRIER

PLATE 18

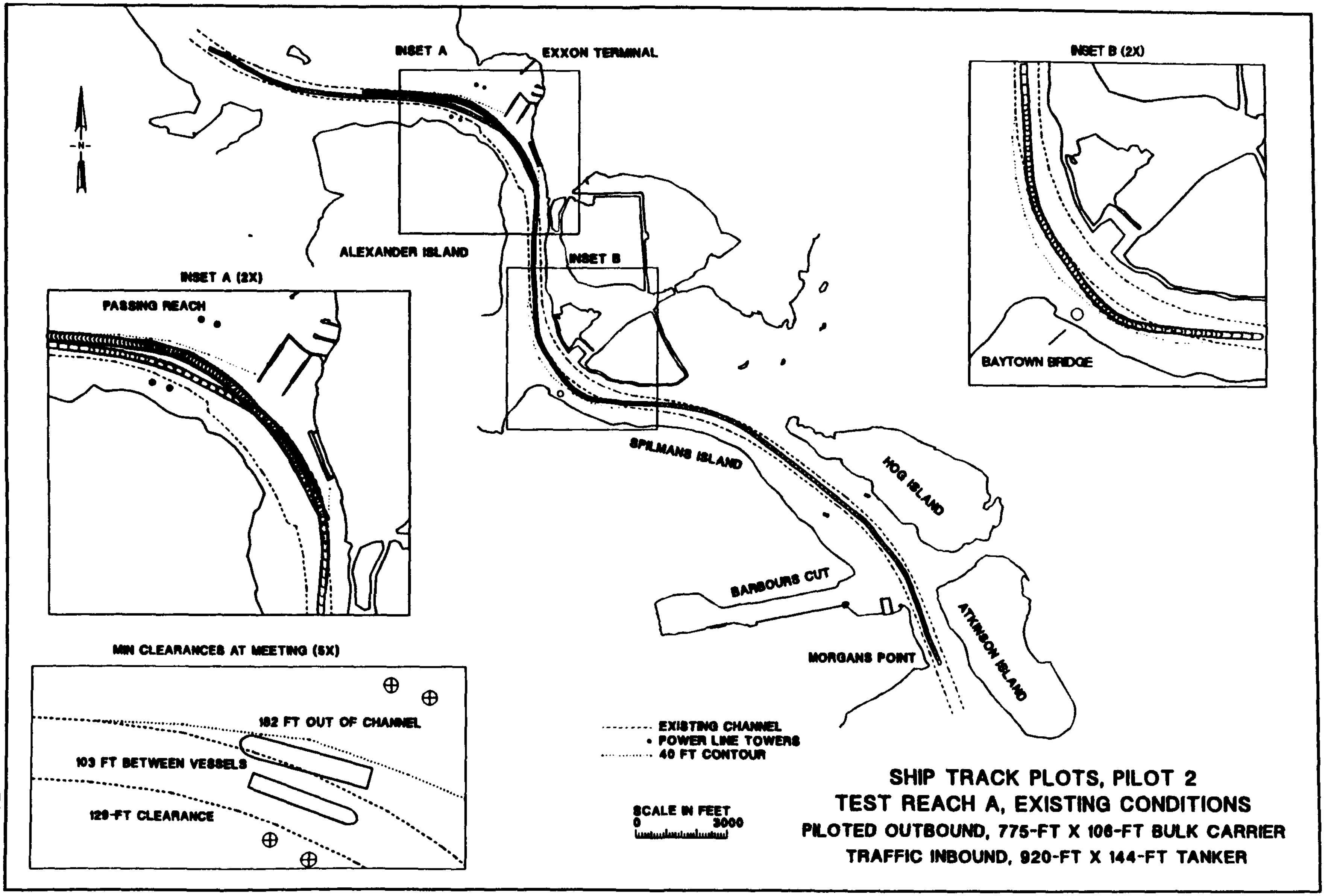


SHIP TRACK PLOTS, PILOT 1
TEST REACH A, EXISTING CONDITIONS
PILOTED OUTBOUND, 775-FT X 106-FT BULK CARRIER
TRAFFIC INBOUND, 920-FT X 144-FT TANKER

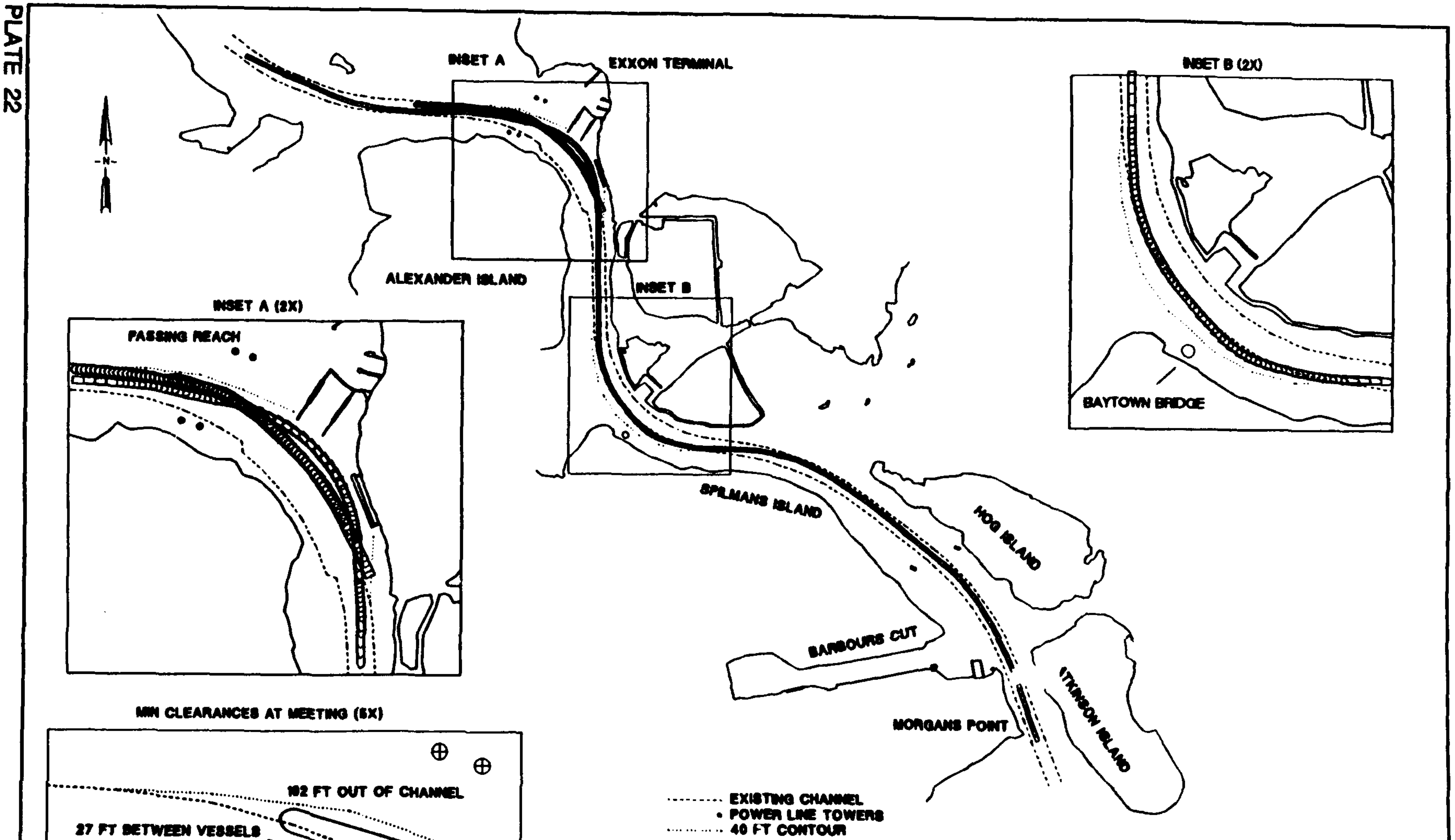


SHIP TRACK PLOTS, PILOT 1, RUN 2
TEST REACH A, EXISTING CONDITIONS
PILOTED OUTBOUND, 775-FT X 106-FT BULK CARRIER
TRAFFIC INBOUND, 920-FT X 144-FT TANKER

PLATE 20

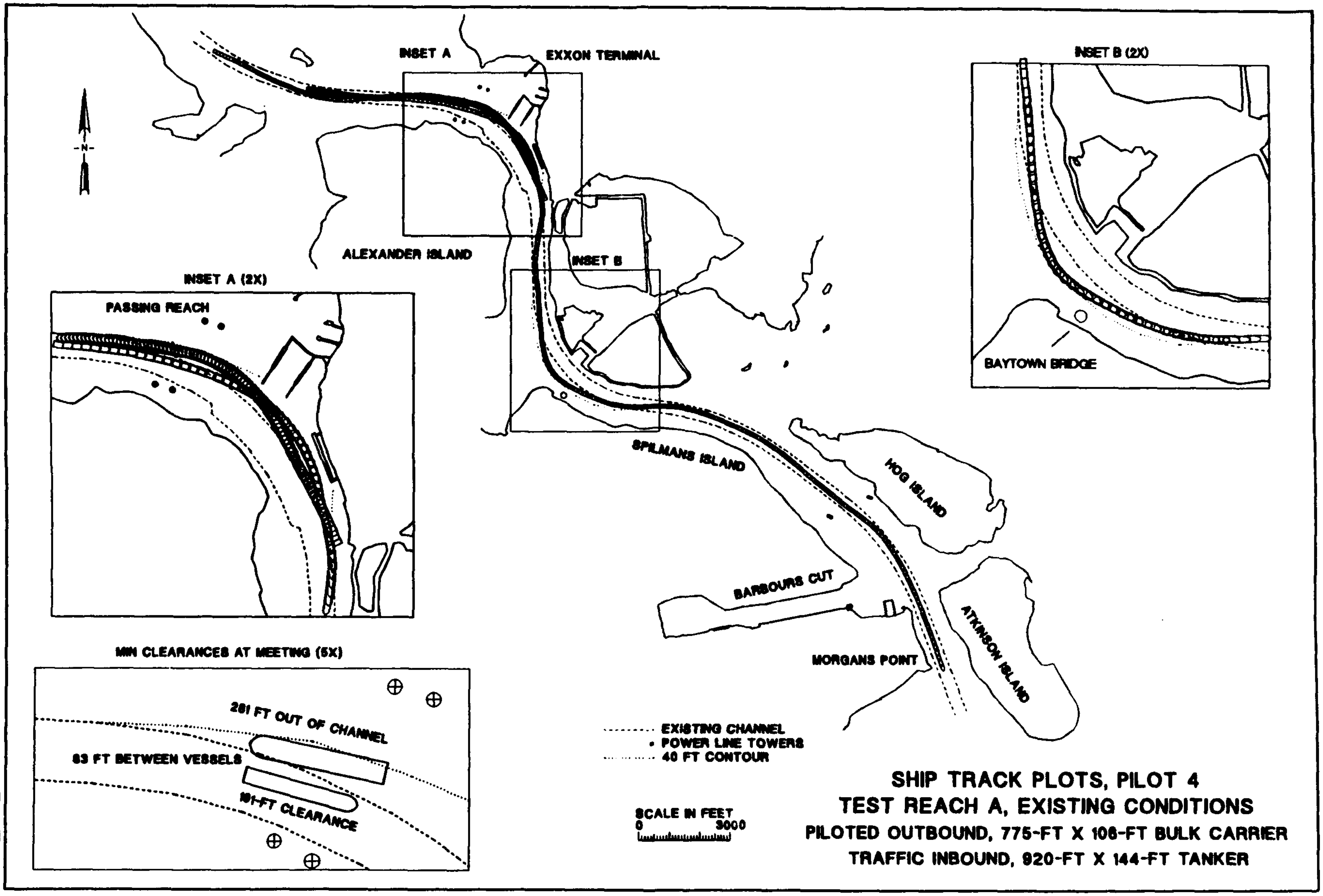


SHIP TRACK PLOTS, PILOT 2
TEST REACH A, EXISTING CONDITIONS
PILOTED OUTBOUND, 775-FT X 106-FT BULK CARRIER
TRAFFIC INBOUND, 920-FT X 144-FT TANKER

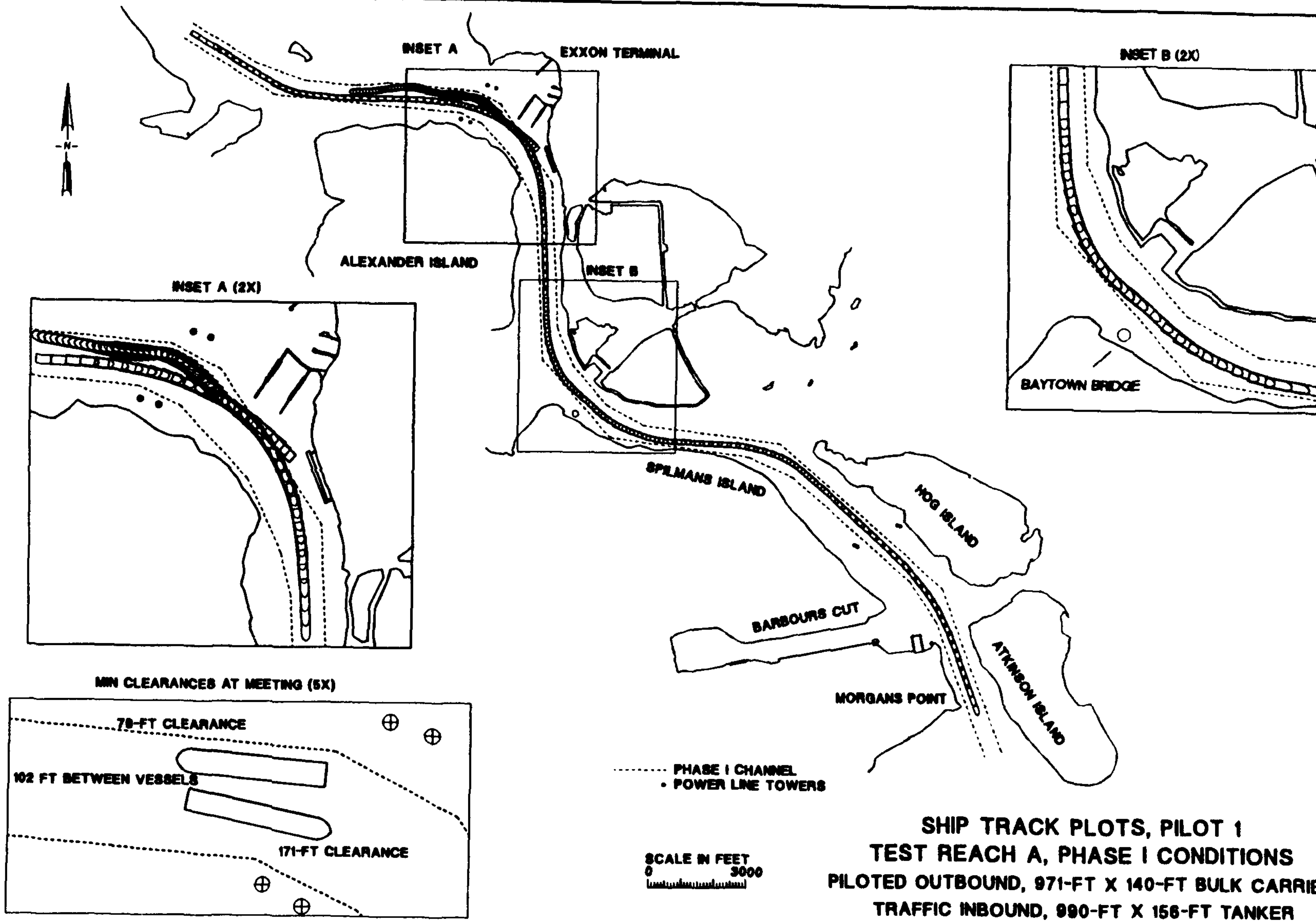


SHIP TRACK PLOTS, PILOT 3
TEST REACH A, EXISTING CONDITIONS
PILOTED OUTBOUND, 775-FT X 106-FT BULK CARRIER
TRAFFIC INBOUND, 920-FT X 144-FT TANKER

PLATE 22

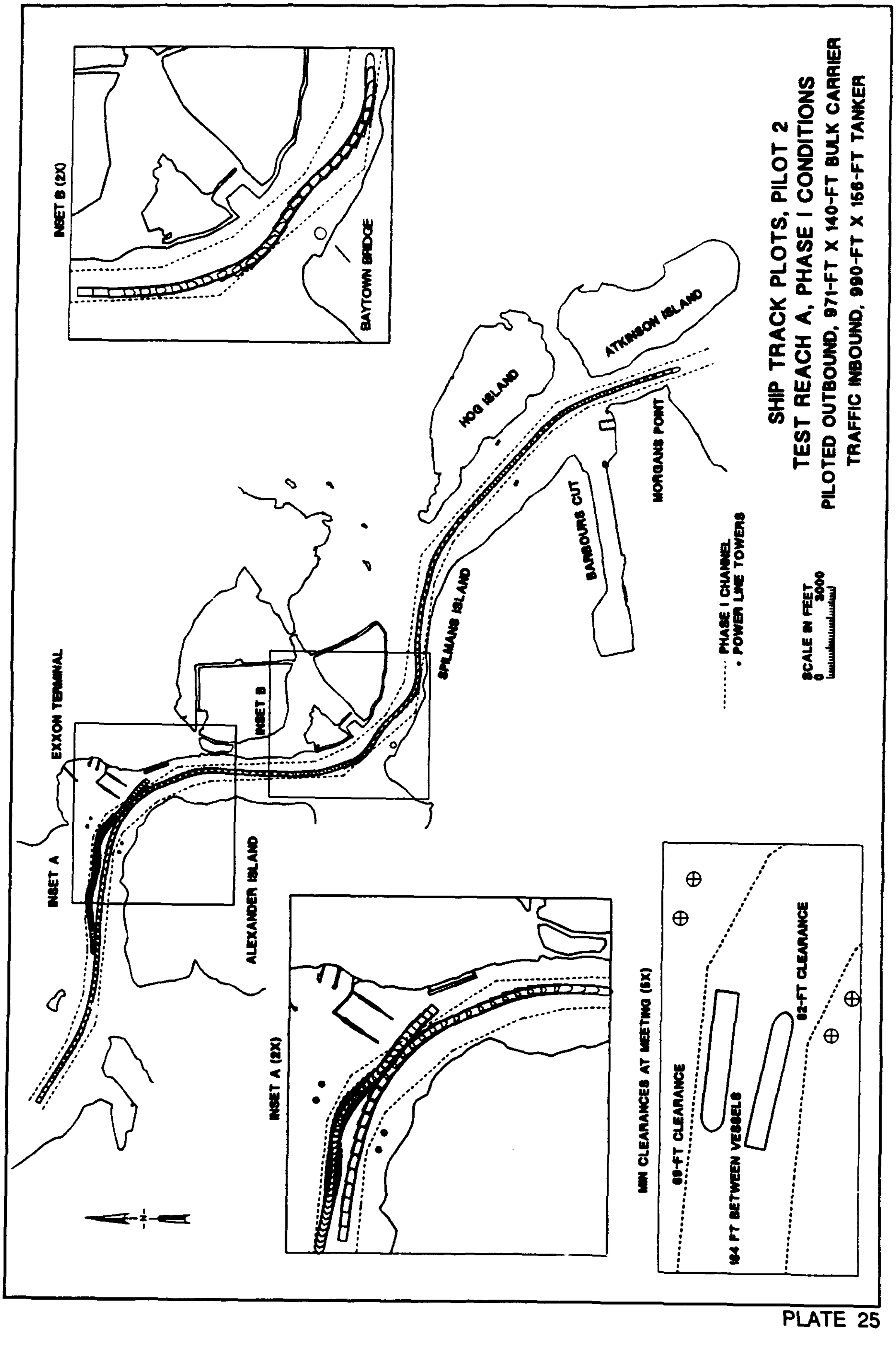


SHIP TRACK PLOTS, PILOT 4
TEST REACH A, EXISTING CONDITIONS
PILOTED OUTBOUND, 775-FT X 106-FT BULK CARRIER
TRAFFIC INBOUND, 920-FT X 144-FT TANKER



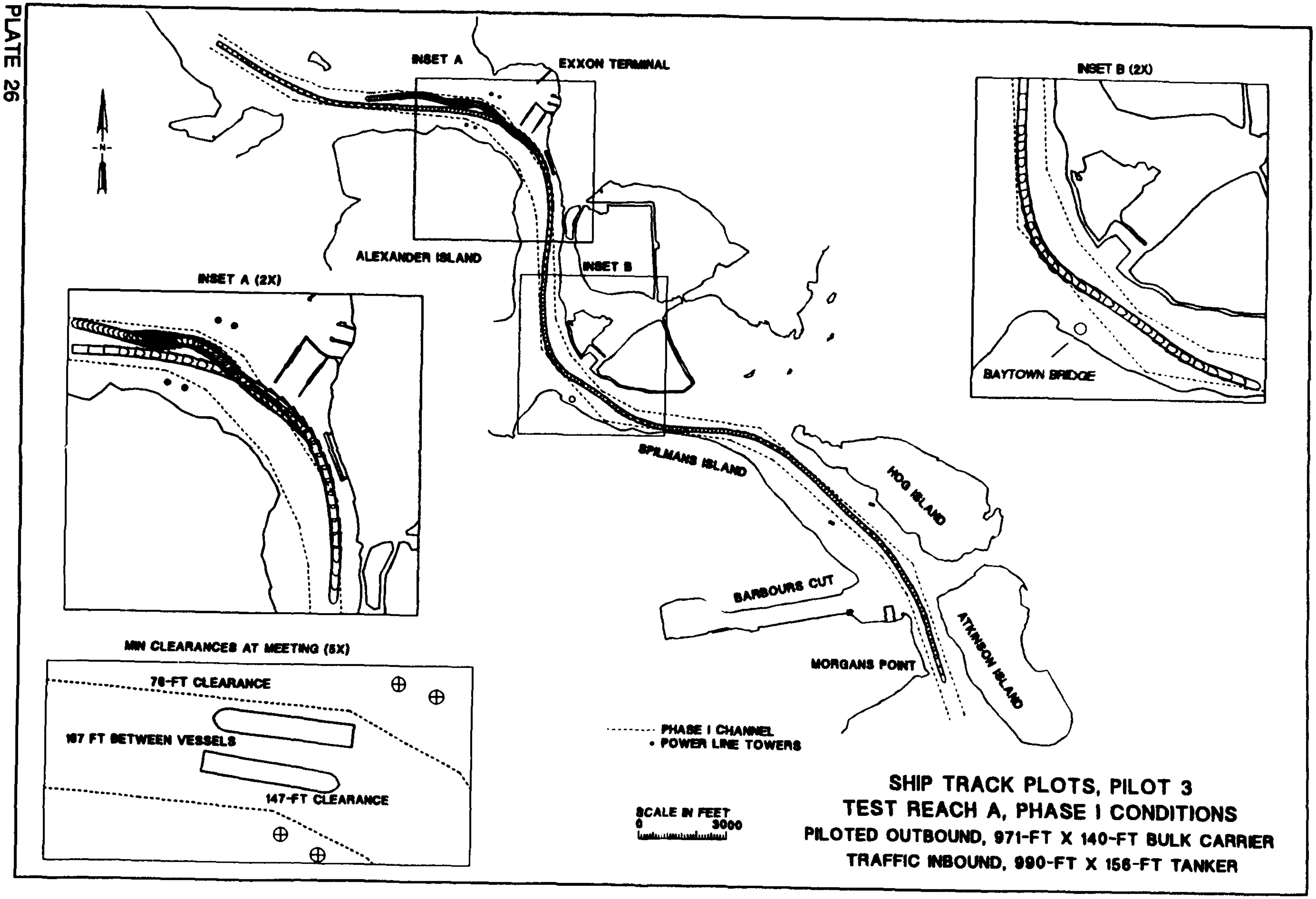
SHIP TRACK PLOTS, PILOT 1
TEST REACH A, PHASE I CONDITIONS
PILOTED OUTBOUND, 971-FT X 140-FT BULK CARRIER
TRAFFIC INBOUND, 990-FT X 156-FT TANKER

PLATE 24

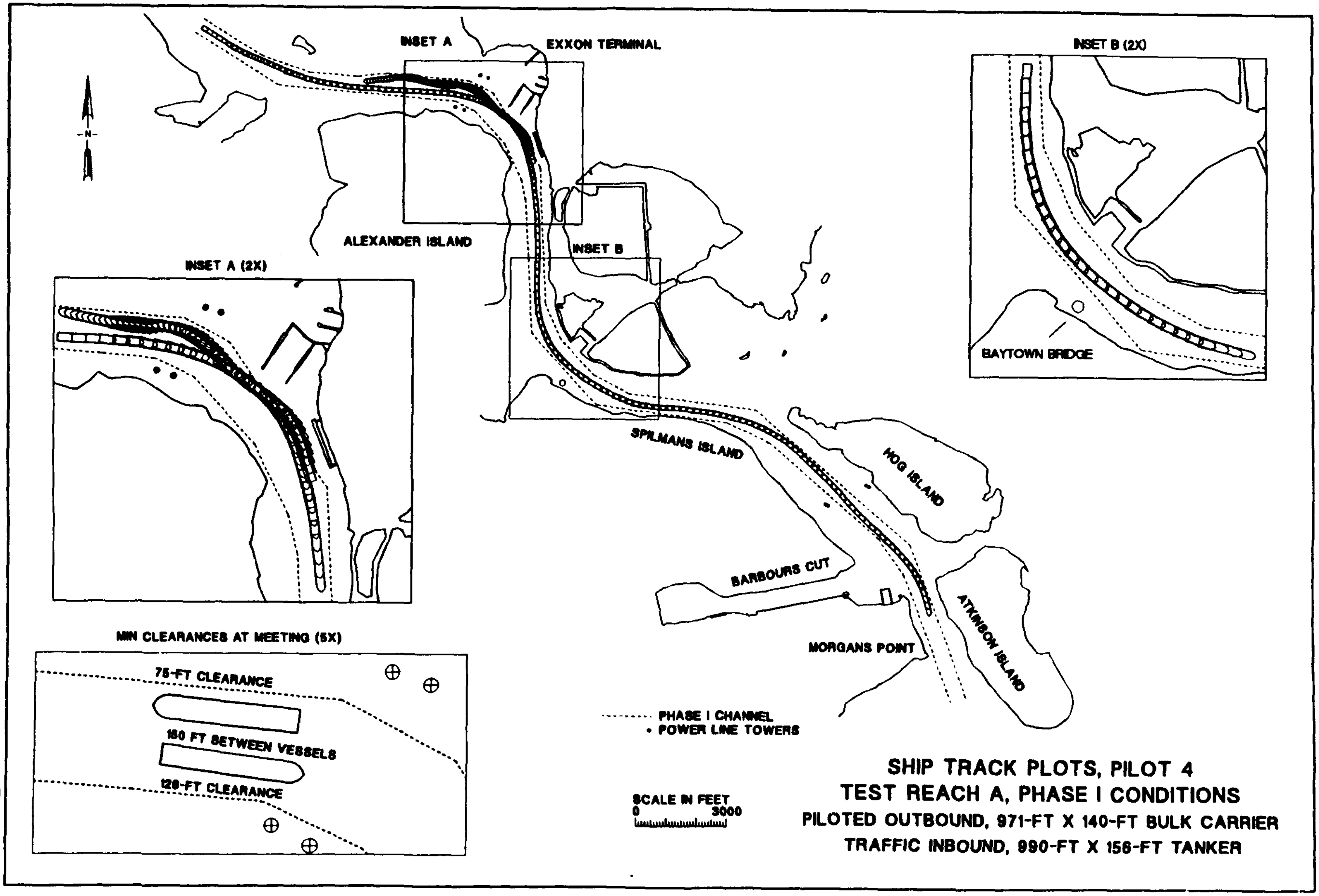


SHIP TRACK PLOTS, PILOT 2
TEST REACH A, PHASE I CONDITIONS
PILOTED OUTBOUND, 971-FT X 140-FT BULK CARRIER
TRAFFIC INBOUND, 990-FT X 156-FT TANKER

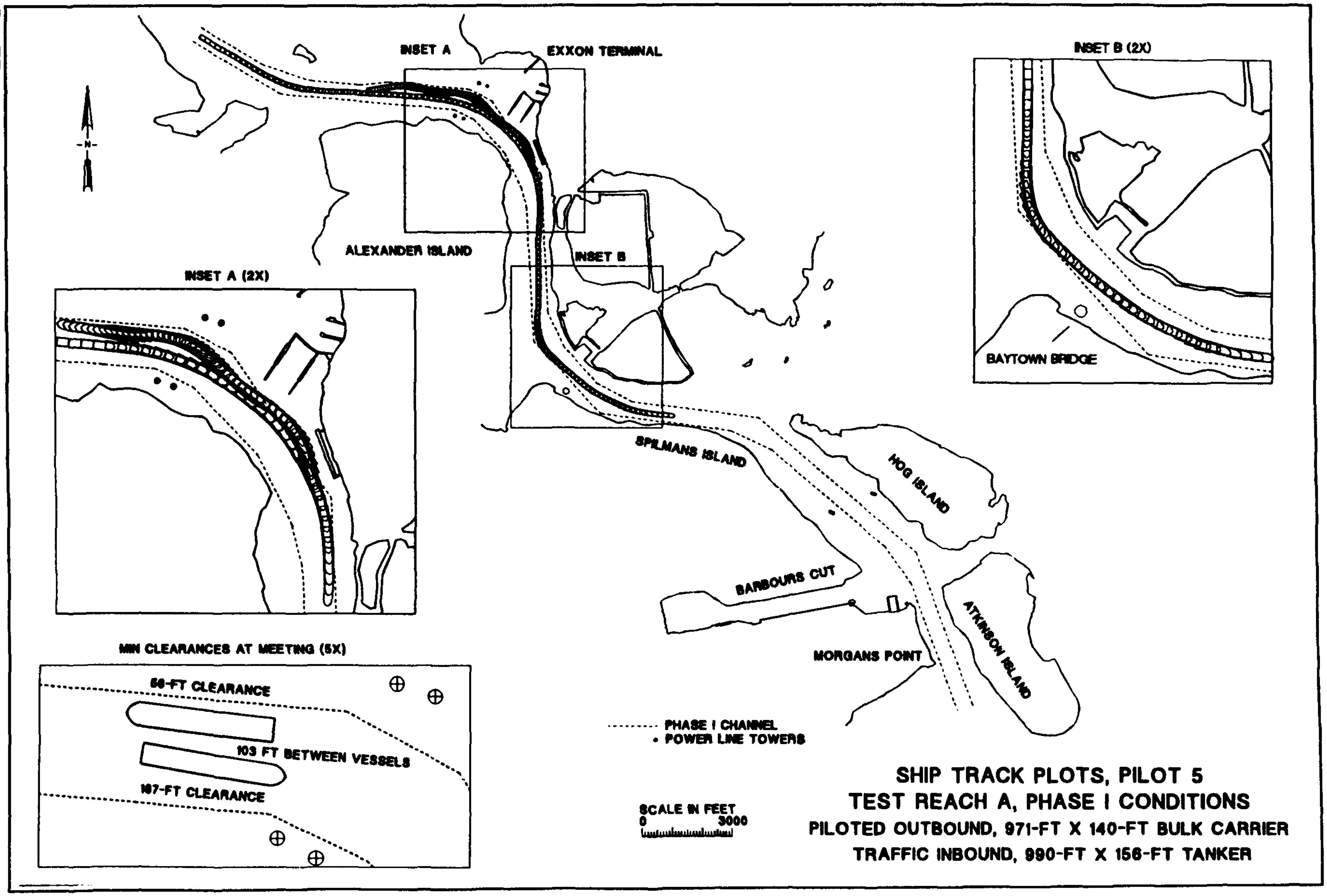
PLATE 25



SHIP TRACK PLOTS, PILOT 3
TEST REACH A, PHASE I CONDITIONS
PILOTED OUTBOUND, 971-FT X 140-FT BULK CARRIER
TRAFFIC INBOUND, 990-FT X 156-FT TANKER

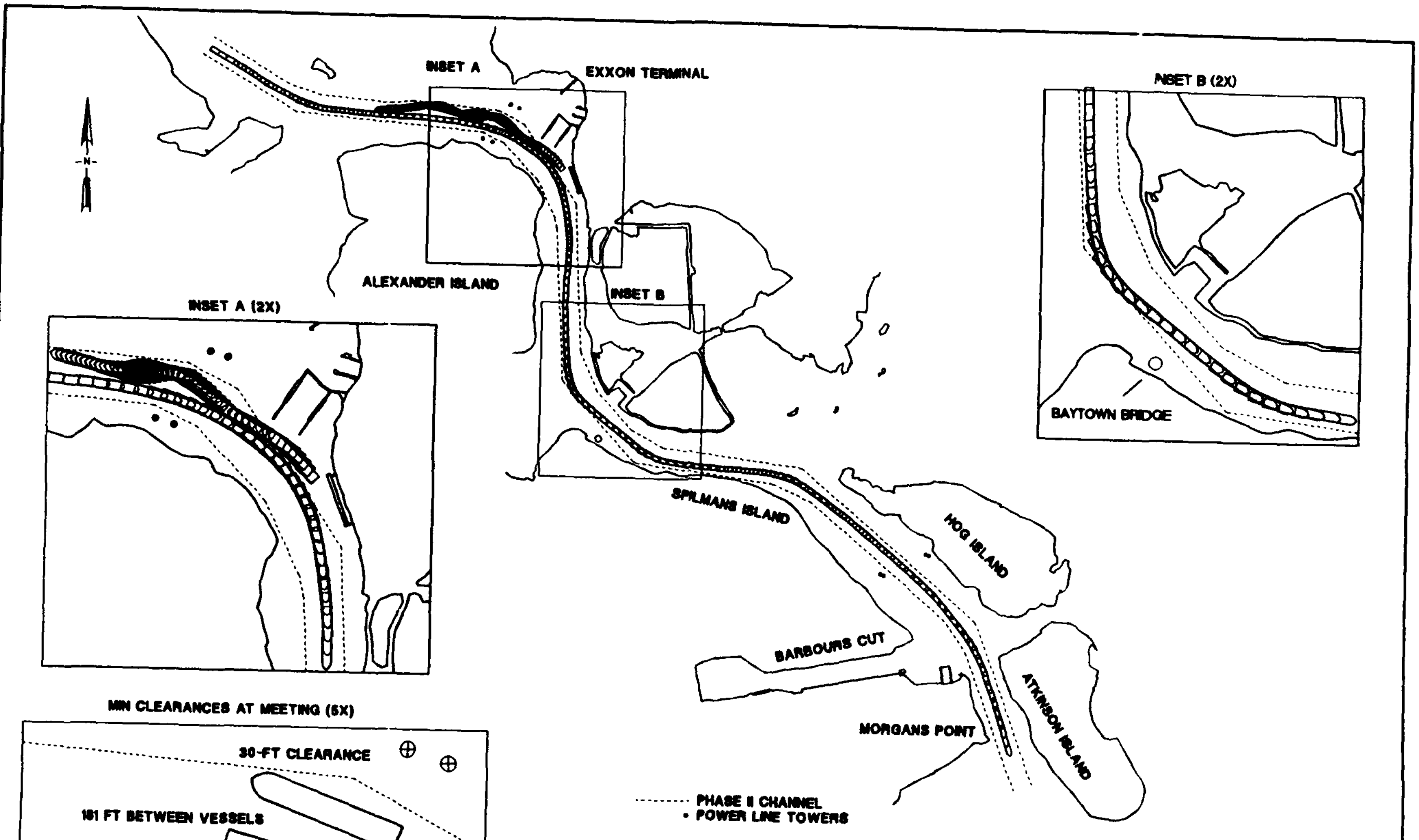


SHIP TRACK PLOTS, PILOT 4
TEST REACH A, PHASE I CONDITIONS
PILOTED OUTBOUND, 971-FT X 140-FT BULK CARRIER
TRAFFIC INBOUND, 990-FT X 156-FT TANKER

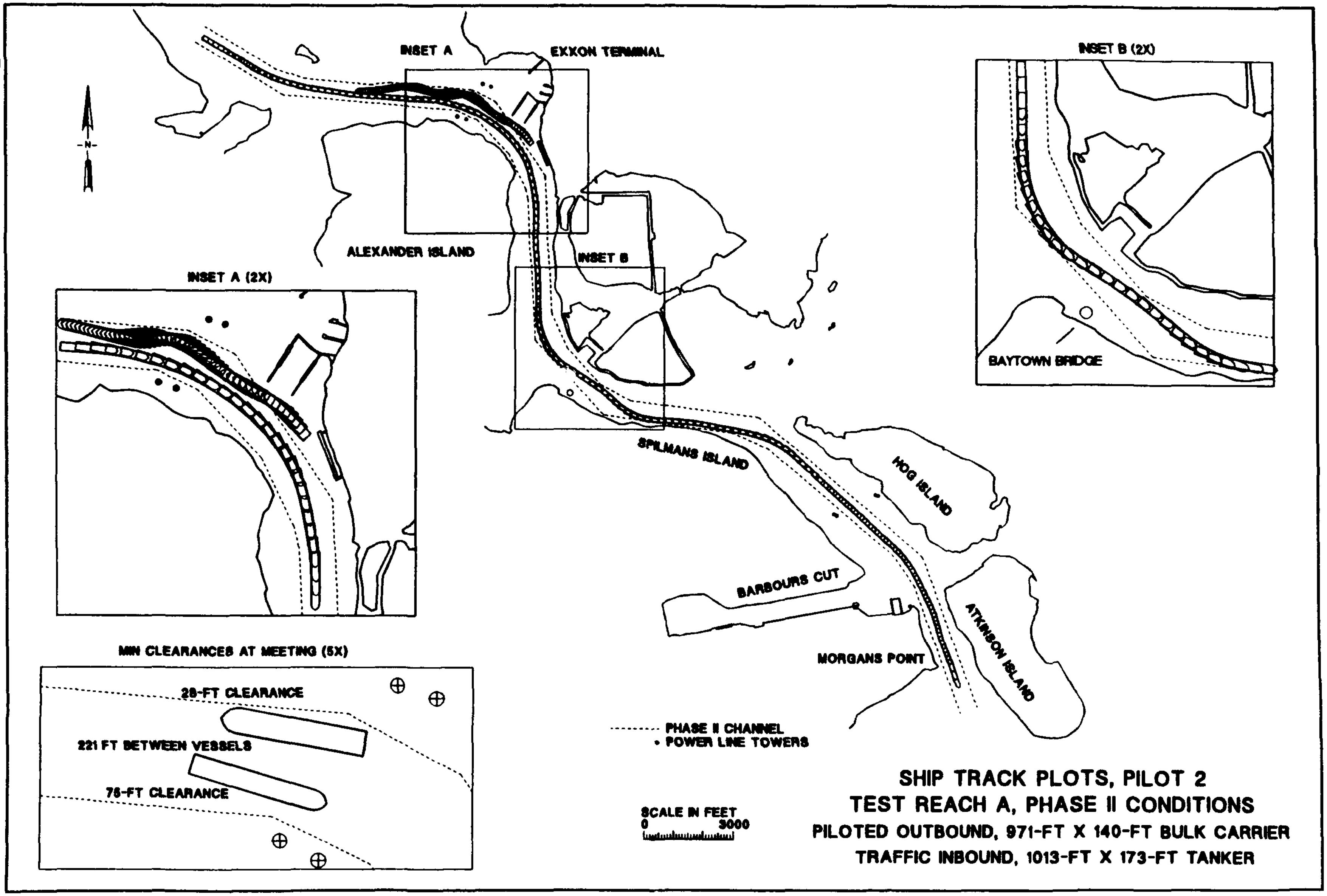


SHIP TRACK PLOTS, PILOT 5
TEST REACH A, PHASE I CONDITIONS
PILOTED OUTBOUND, 971-FT X 140-FT BULK CARRIER
TRAFFIC INBOUND, 990-FT X 156-FT TANKER

PLATE 28

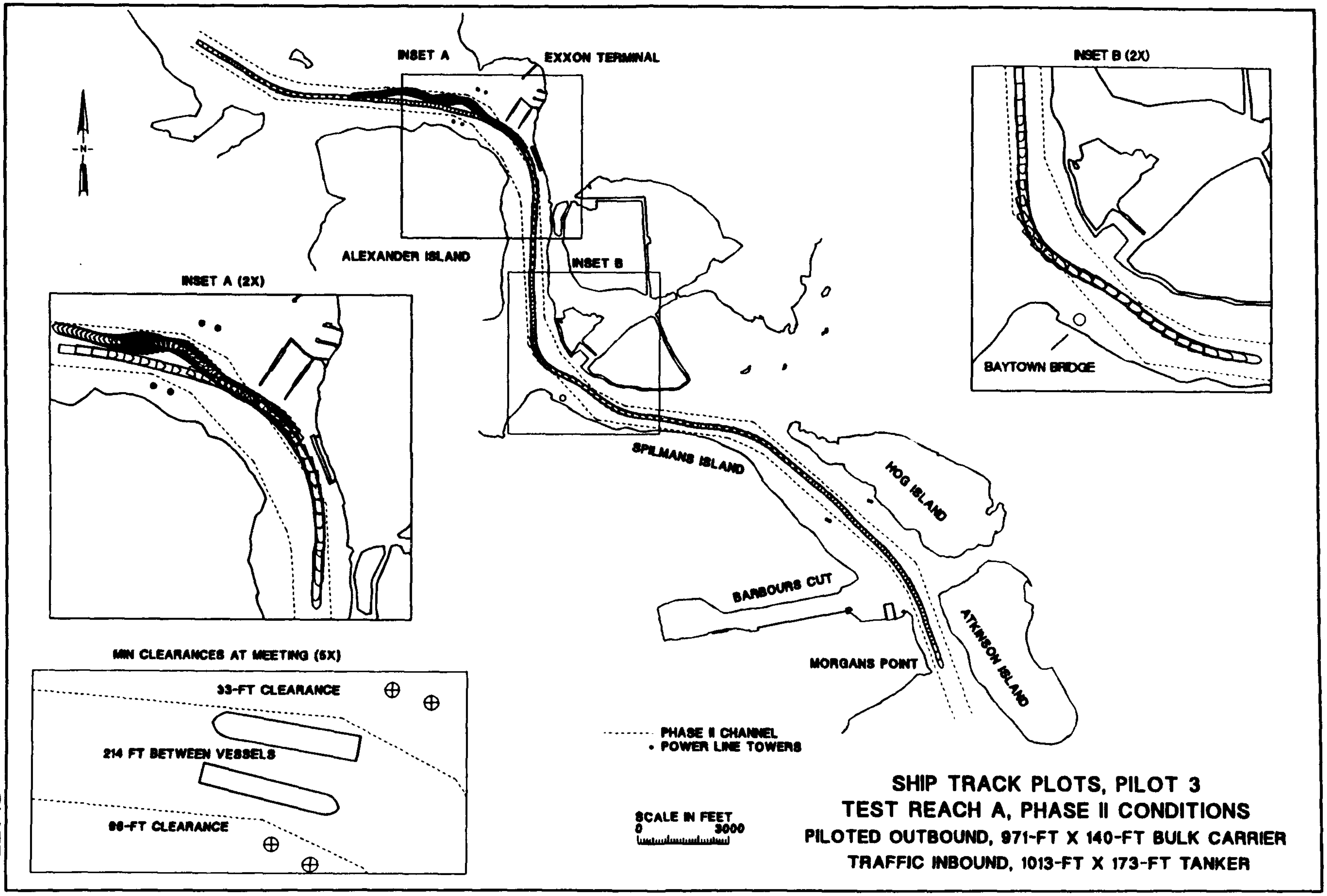


SHIP TRACK PLOTS, PILOT 1
TEST REACH A, PHASE II CONDITIONS
PILOTED OUTBOUND, 971-FT X 140-FT BULK CARRIER
TRAFFIC INBOUND, 1013-FT X 173-FT TANKER



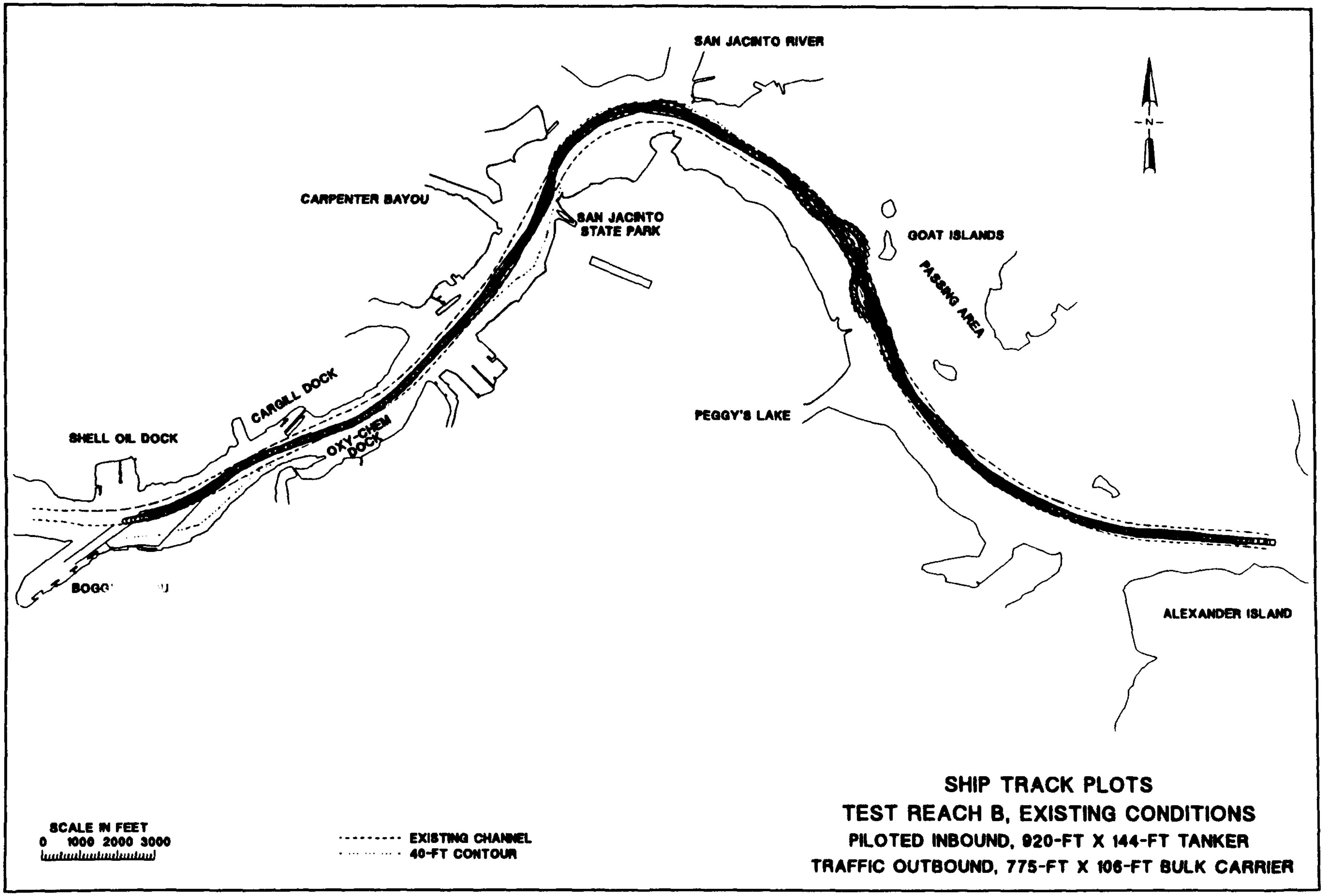
SHIP TRACK PLOTS, PILOT 2
TEST REACH A, PHASE II CONDITIONS
PILOTED OUTBOUND, 971-FT X 140-FT BULK CARRIER
TRAFFIC INBOUND, 1013-FT X 173-FT TANKER

PLATE 30



SHIP TRACK PLOTS, PILOT 3
TEST REACH A, PHASE II CONDITIONS
PILOTED OUTBOUND, 971-FT X 140-FT BULK CARRIER
TRAFFIC INBOUND, 1013-FT X 173-FT TANKER

PLATE 32



SHIP TRACK PLOTS
TEST REACH B, EXISTING CONDITIONS
PILOTED INBOUND, 920-FT X 144-FT TANKER
TRAFFIC OUTBOUND, 775-FT X 106-FT BULK CARRIER

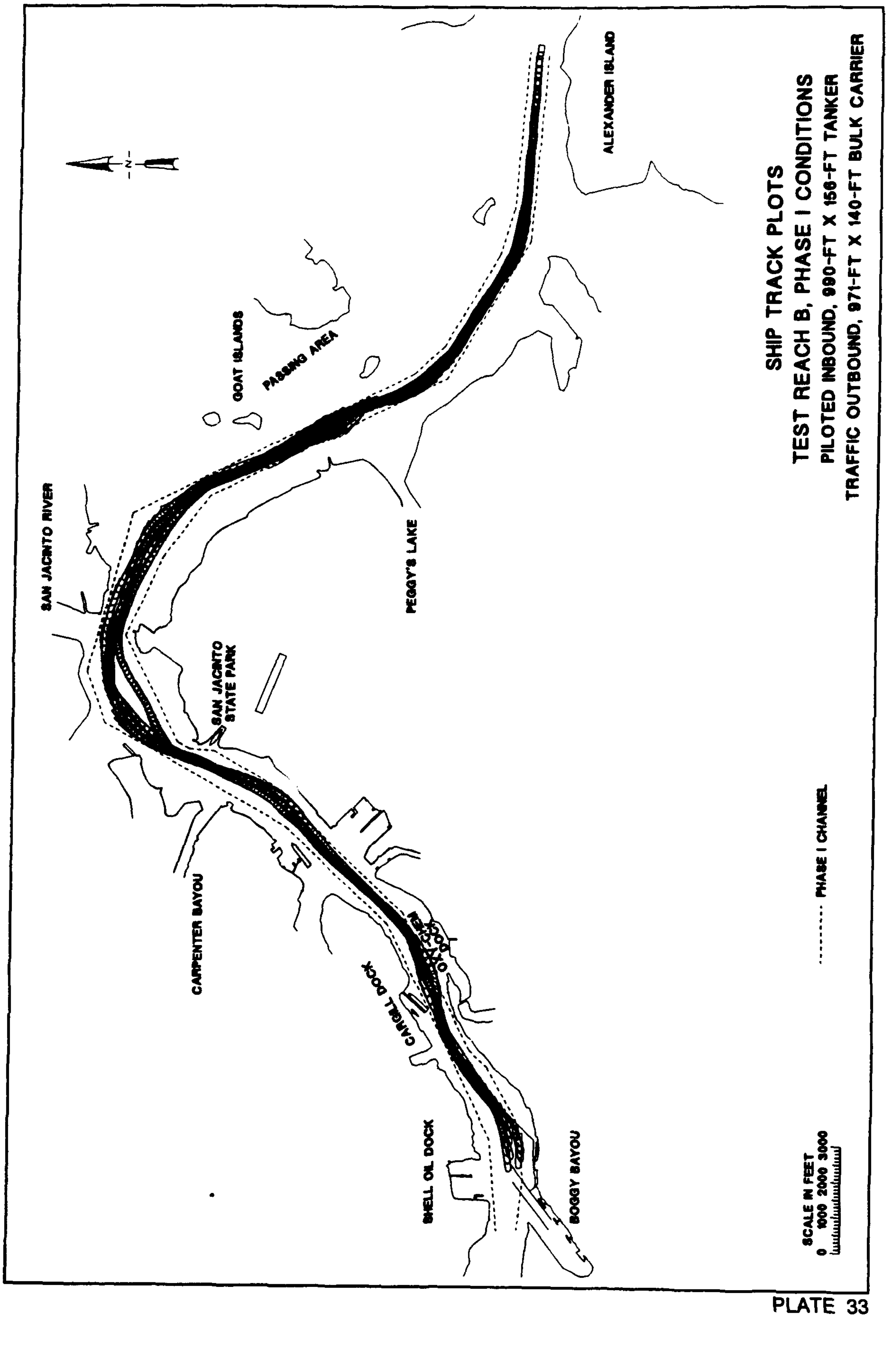
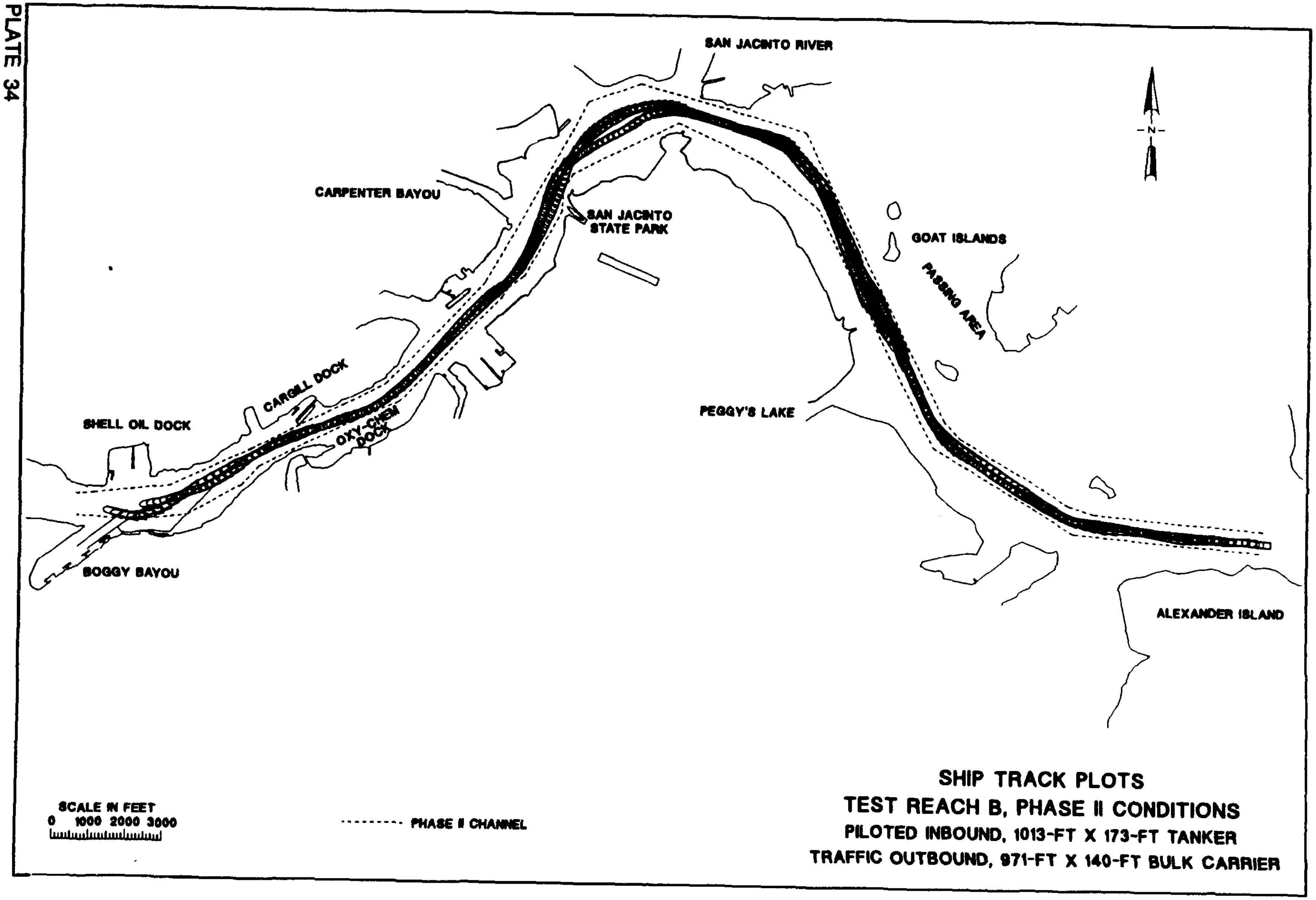
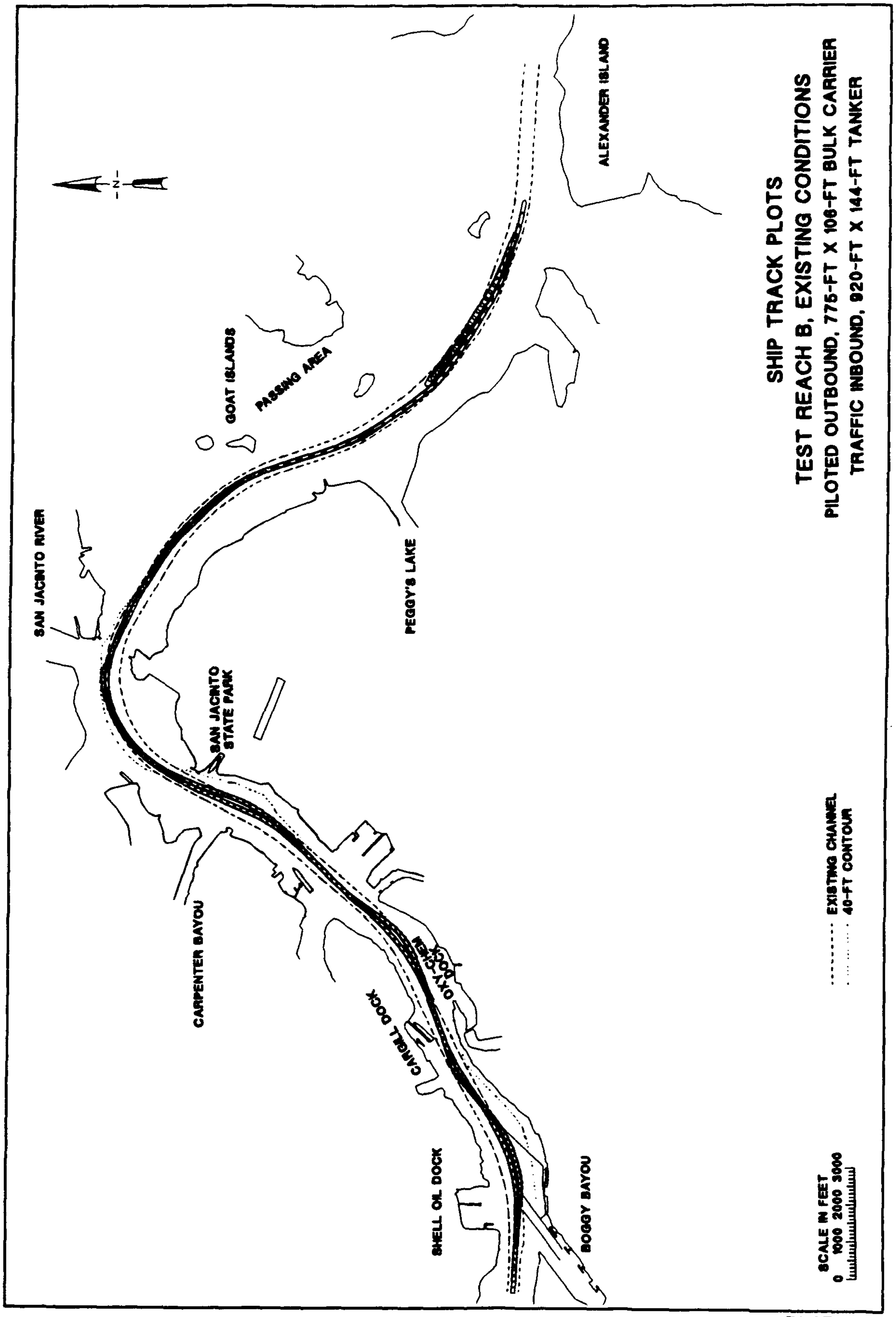

SHIP TRACK PLOTS
TEST REACH B, PHASE I CONDITIONS
PILOTED INBOUND, 990-FT X 156-FT TANKER
TRAFFIC OUTBOUND, 971-FT X 140-FT BULK CARRIER
N
ALEXANDER ISLAND
GOAT ISLANDS
PASSING AREA
SAN JACINTO RIVER
PEGGY'S LAKE
SAN JACINTO STATE PARK
CARPENTER BAYOU
CARGILL DOCK
SHELL OIL DOCK
BOGGY BAYOU
PHASE I CHANNEL
SCALE IN FEET
0 1000 2000 3000

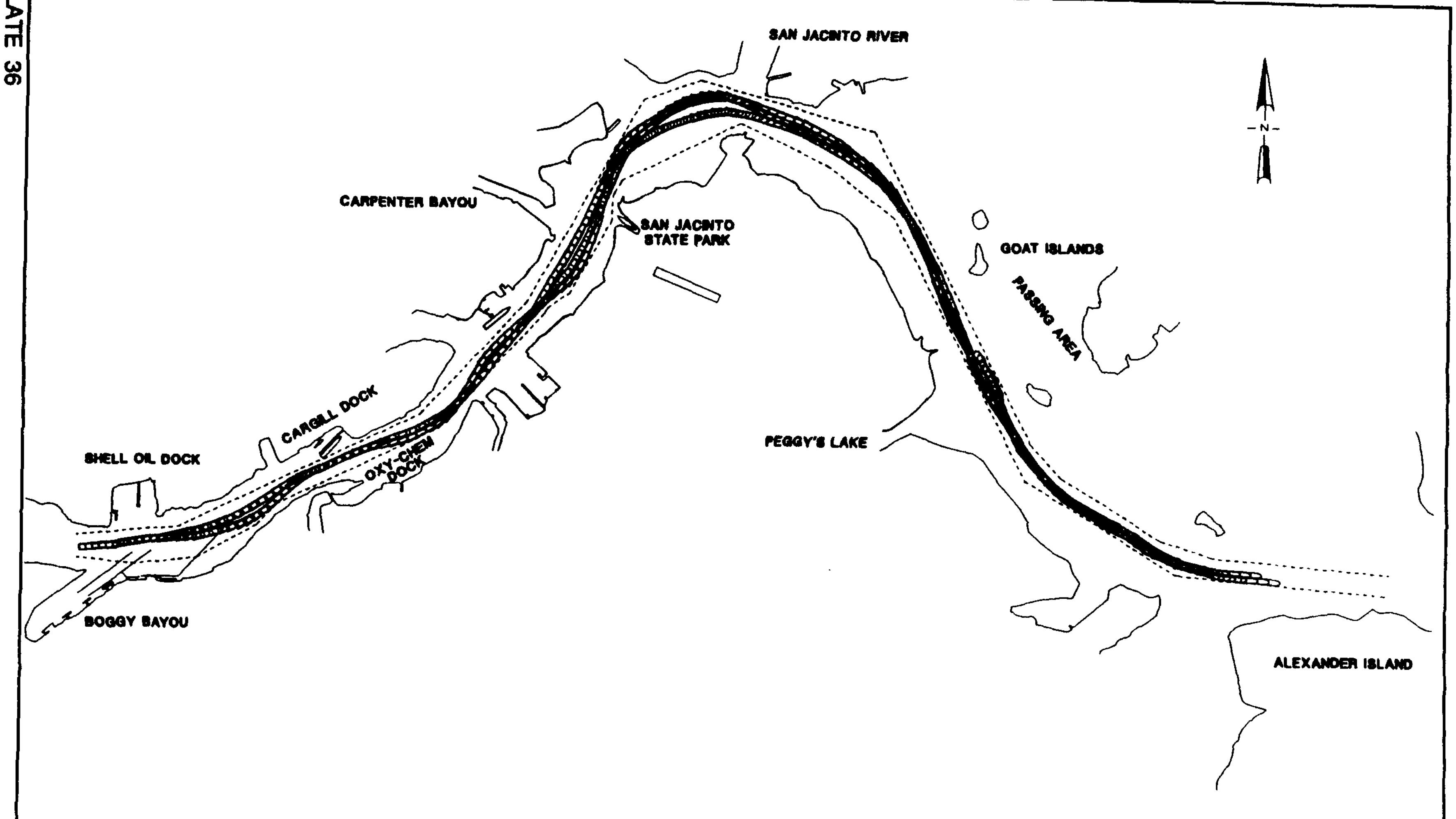
PLATE 34



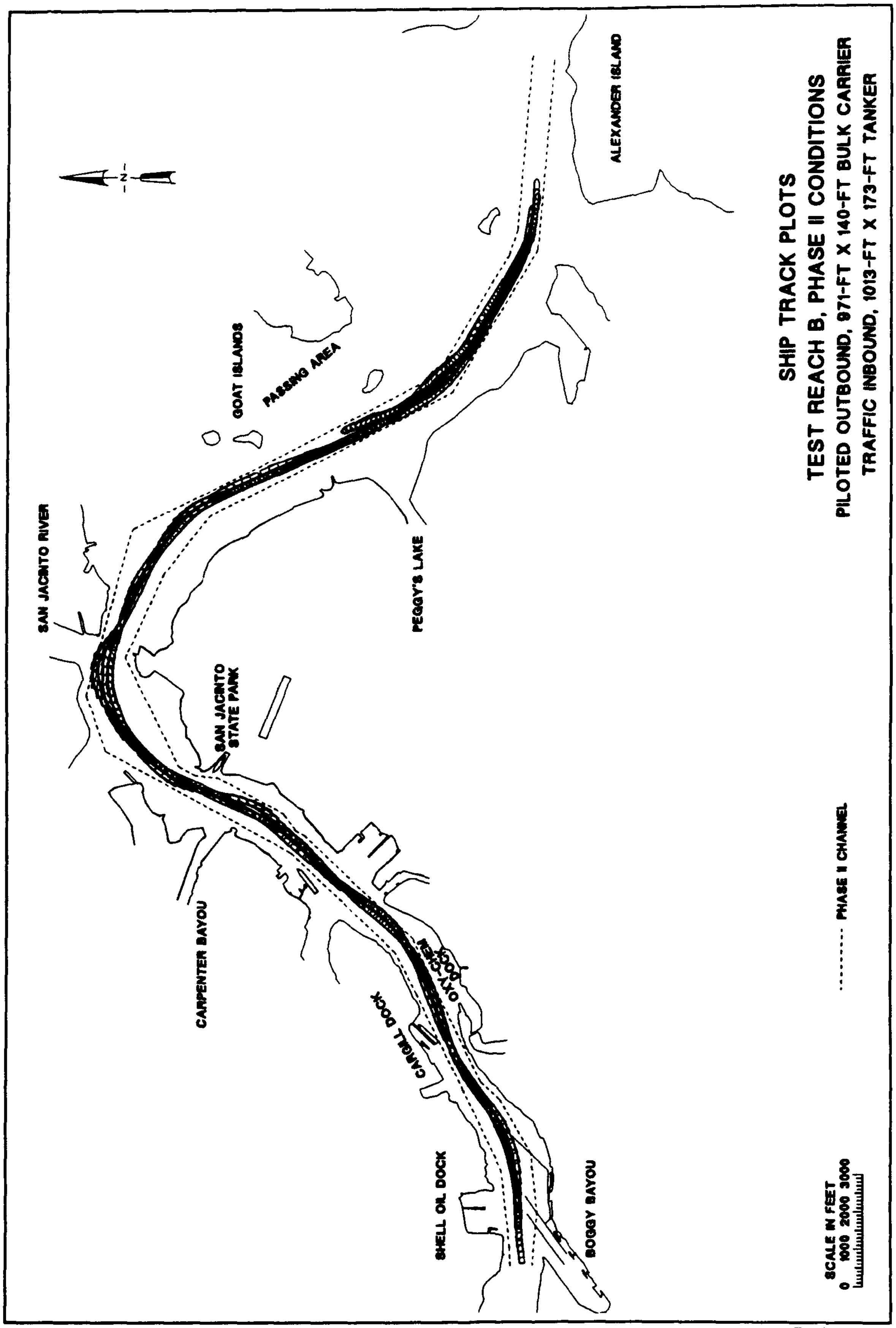
SHIP TRACK PLOTS
TEST REACH B, PHASE II CONDITIONS
PILOTED INBOUND, 1013-FT X 173-FT TANKER
TRAFFIC OUTBOUND, 971-FT X 140-FT BULK CARRIER



SHIP TRACK PLOTS
TEST REACH B, EXISTING CONDITIONS
PILOTED OUTBOUND, 775-FT X 106-FT BULK CARRIER
TRAFFIC INBOUND, 920-FT X 144-FT TANKER

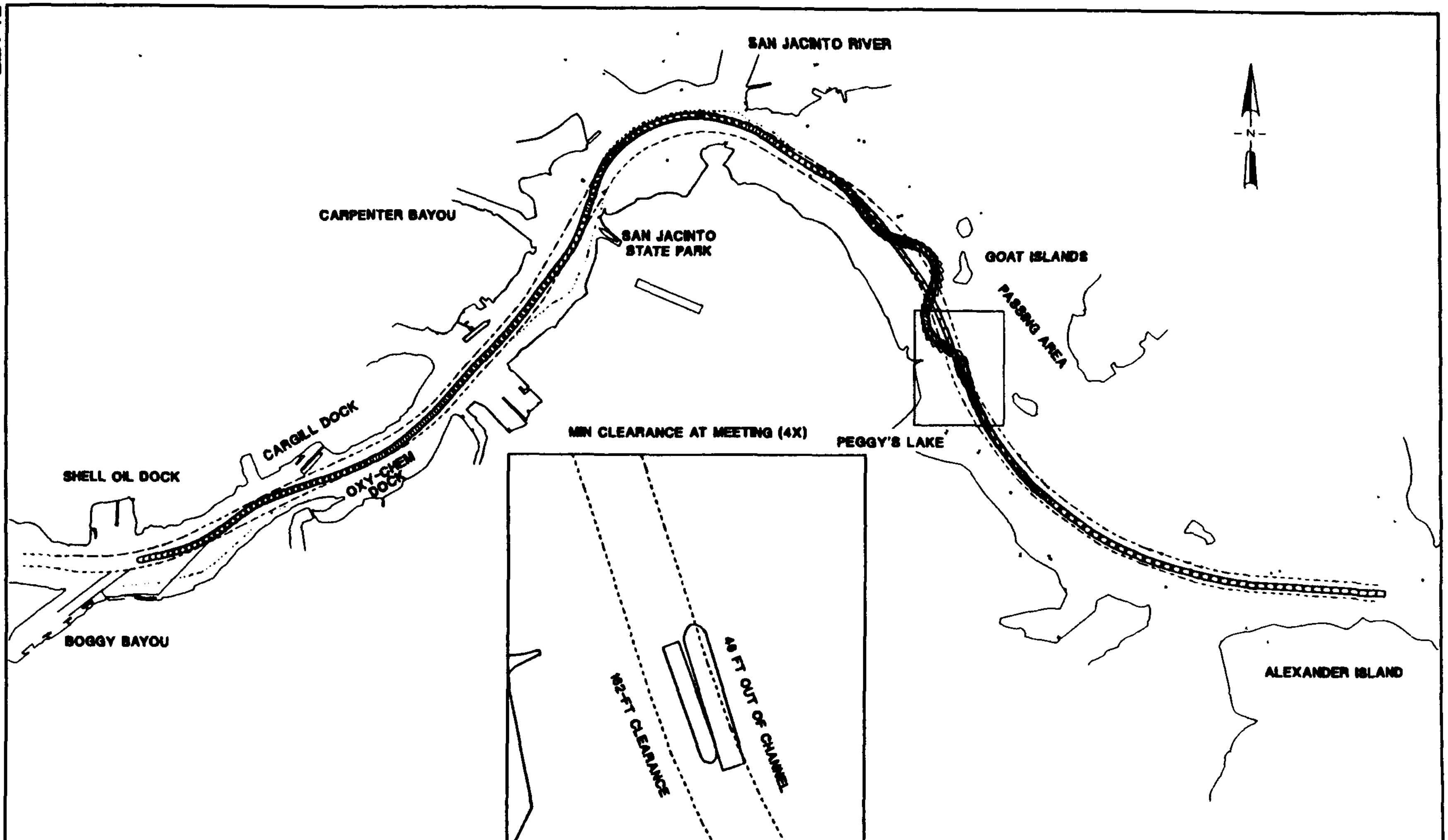


SHIP TRACK PLOTS
TEST REACH B, PHASE I CONDITIONS
PILOTED OUTBOUND, 971-FT X 140-FT BULK CARRIER
TRAFFIC INBOUND, 990-FT X 156-FT TANKER

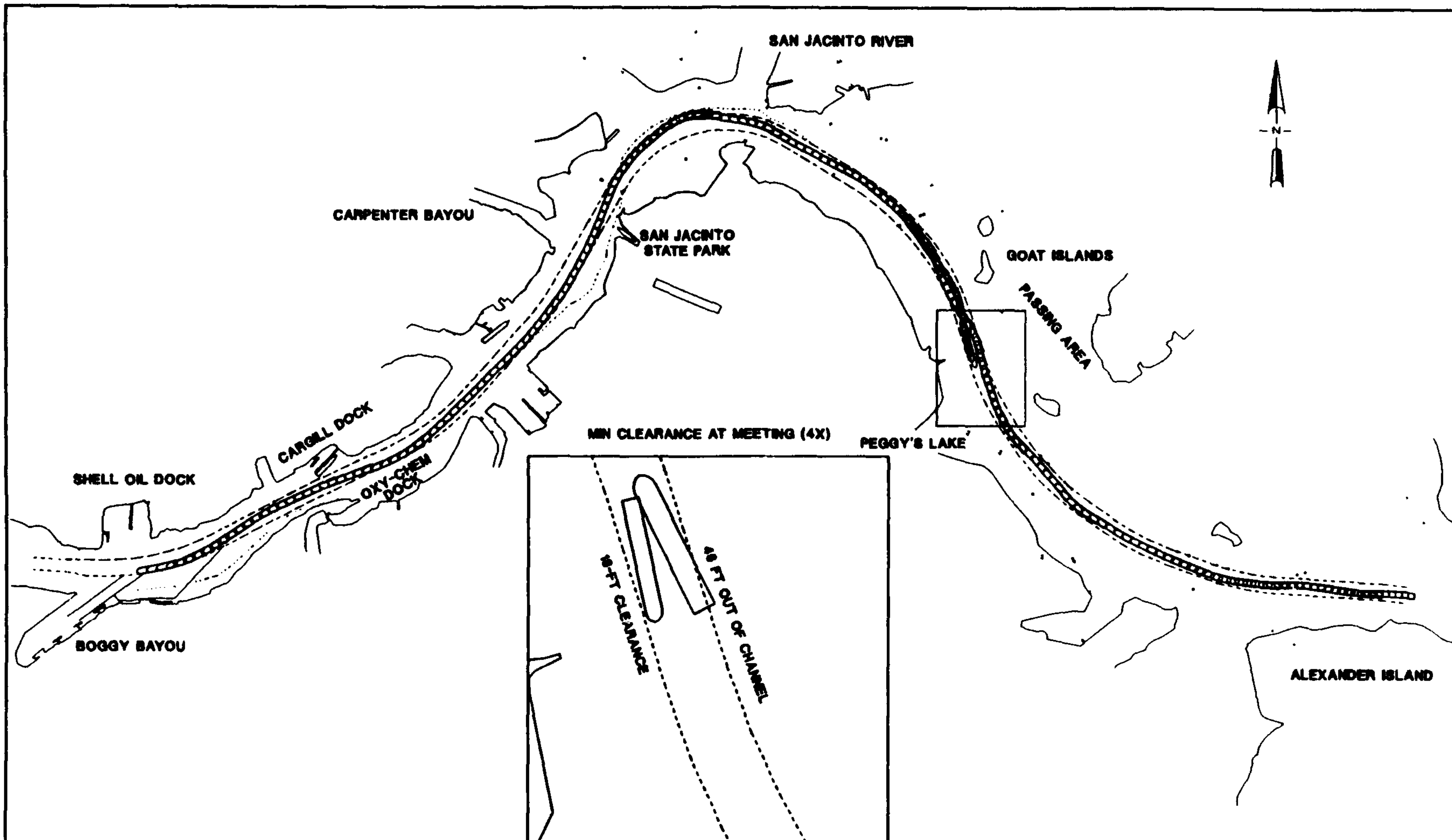


SHIP TRACK PLOTS
TEST REACH B, PHASE II CONDITIONS
PILOTED OUTBOUND, 971-FT X 140-FT BULK CARRIER
TRAFFIC INBOUND, 1013-FT X 173-FT TANKER

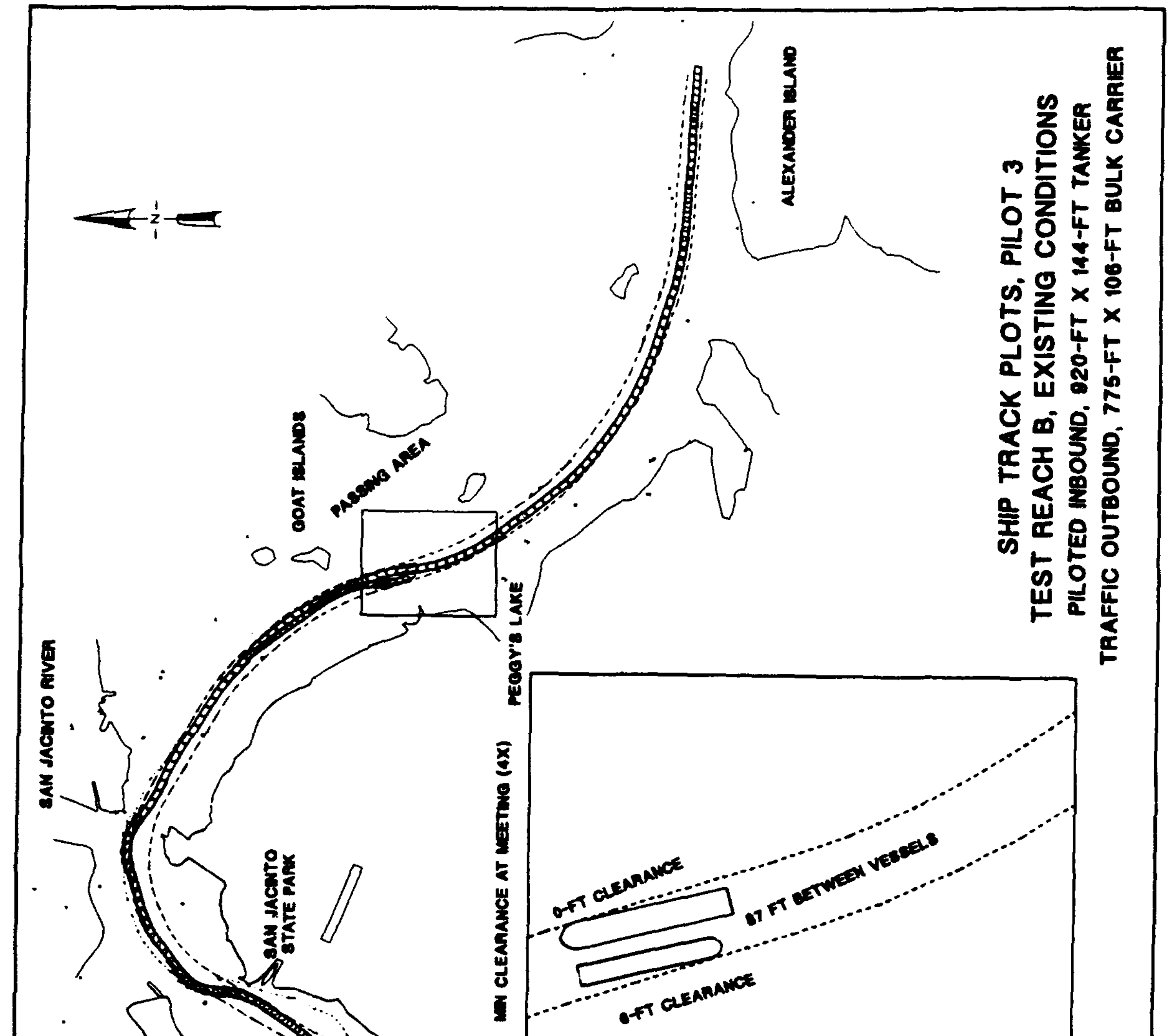
PLATE 37

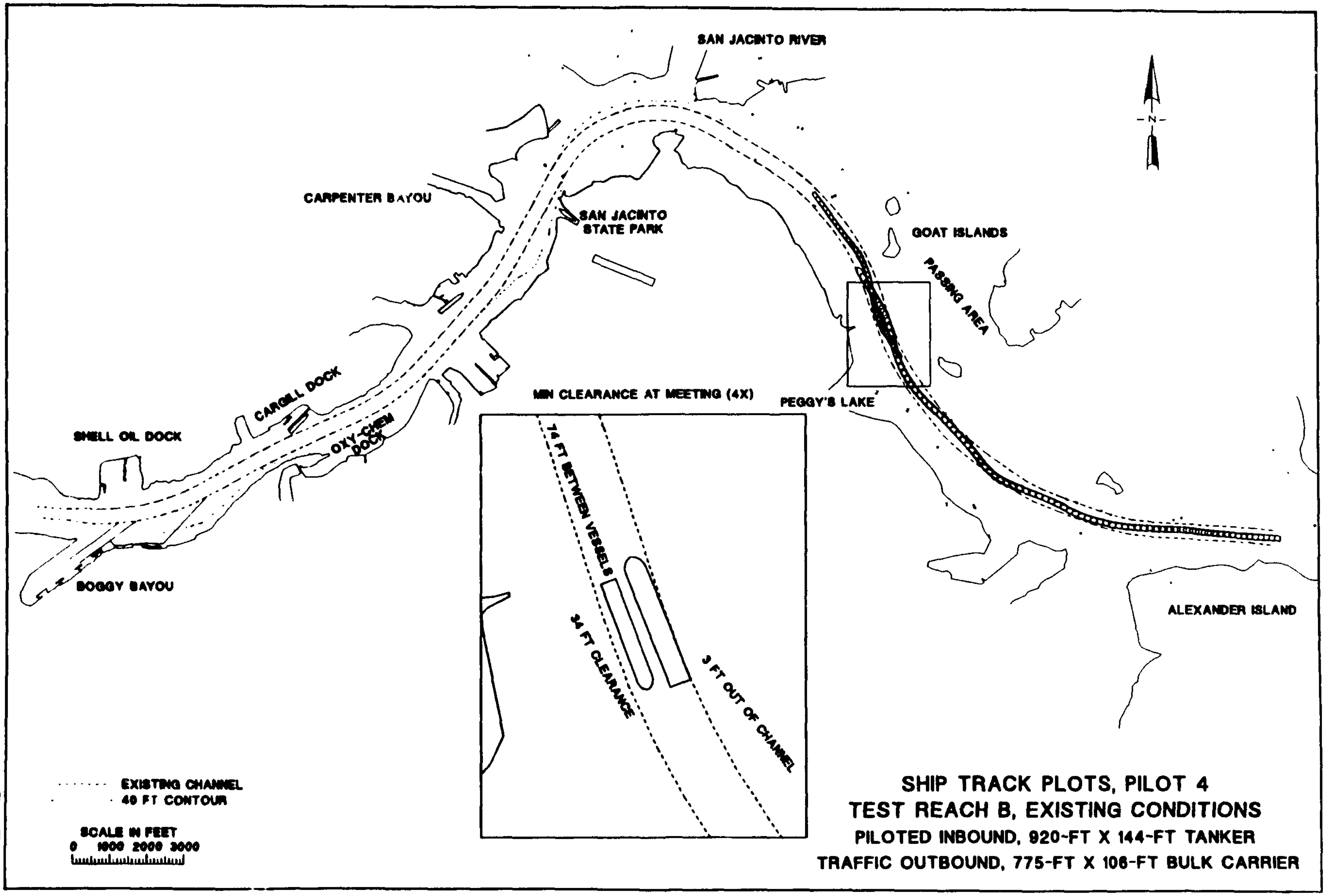


SHIP TRACK PLOTS, PILOT 1
TEST REACH B, EXISTING CONDITIONS
PILOTED INBOUND, 920-FT X 144-FT TANKER
TRAFFIC OUTBOUND, 775-FT X 106-FT BULK CARRIER

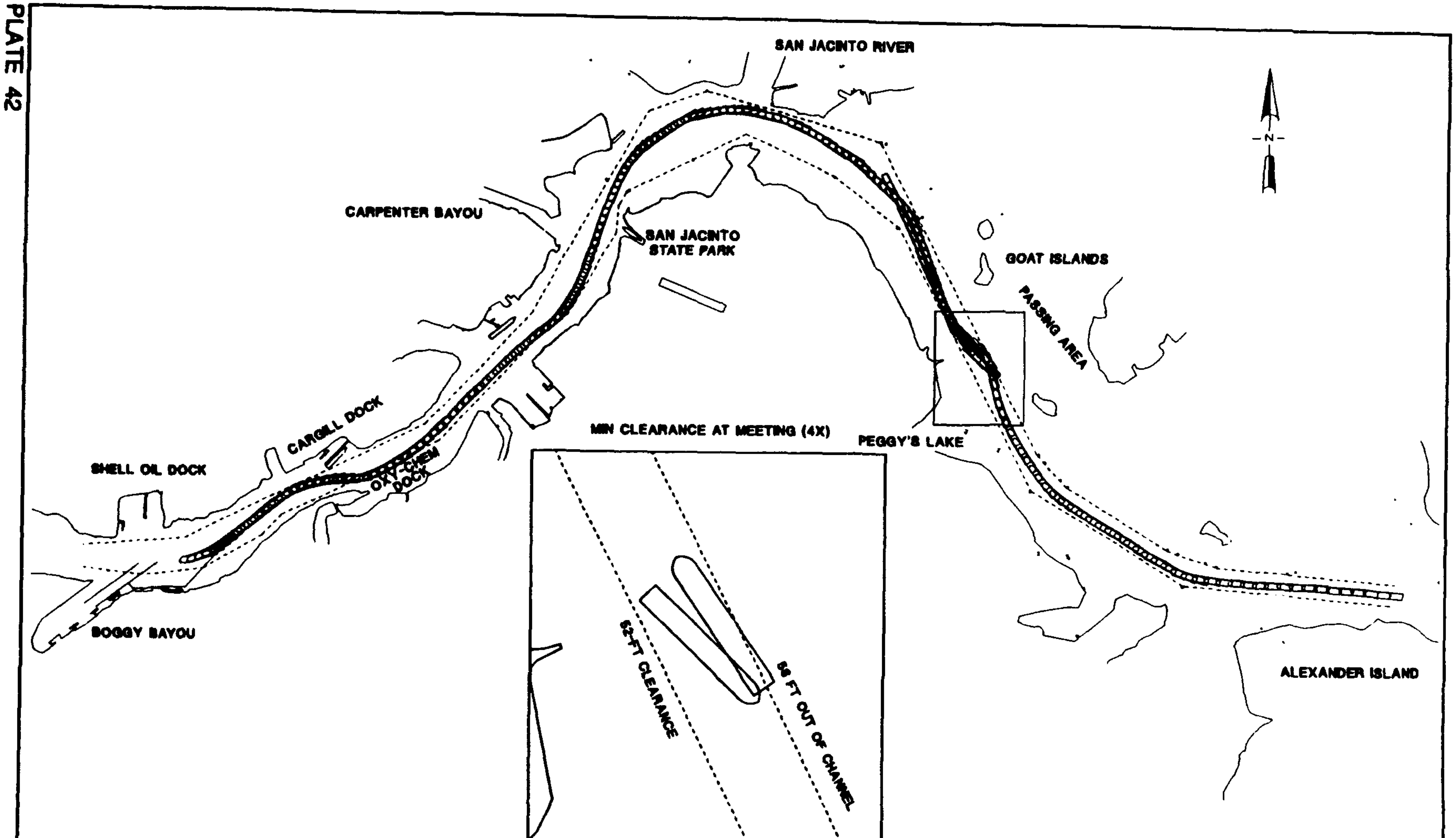


SHIP TRACK PLOTS, PILOT 2
TEST REACH B, EXISTING CONDITIONS
PILOTED INBOUND, 920-FT X 144-FT TANKER
TRAFFIC OUTBOUND, 775-FT X 106-FT BULK CARRIER


SHIP TRACK PLOTS, PILOT 3
TEST REACH B, EXISTING CONDITIONS
PILOTED INBOUND, 920-FT X 144-FT TANKER
TRAFFIC OUTBOUND, 775-FT X 106-FT BULK CARRIER
ALEXANDER ISLAND
GOAT ISLANDS
PASSING AREA
PEGGY'S LAKE
SAN JACINTO RIVER
SAN JACINTO STATE PARK
MIN CLEARANCE AT MEETING (4X)
0-FT CLEARANCE
87 FT BETWEEN VESSELS
6-FT CLEARANCE
CARPENTER BAYOU
OXY-CHEM DOCK
CARGILL DOCK
SHELL OIL DOCK
BOGGY BAYOU
EXISTING CHANNEL
40 FT CONTOUR
SCALE IN FEET
0 1000 2000 3000
N
PLATE 40

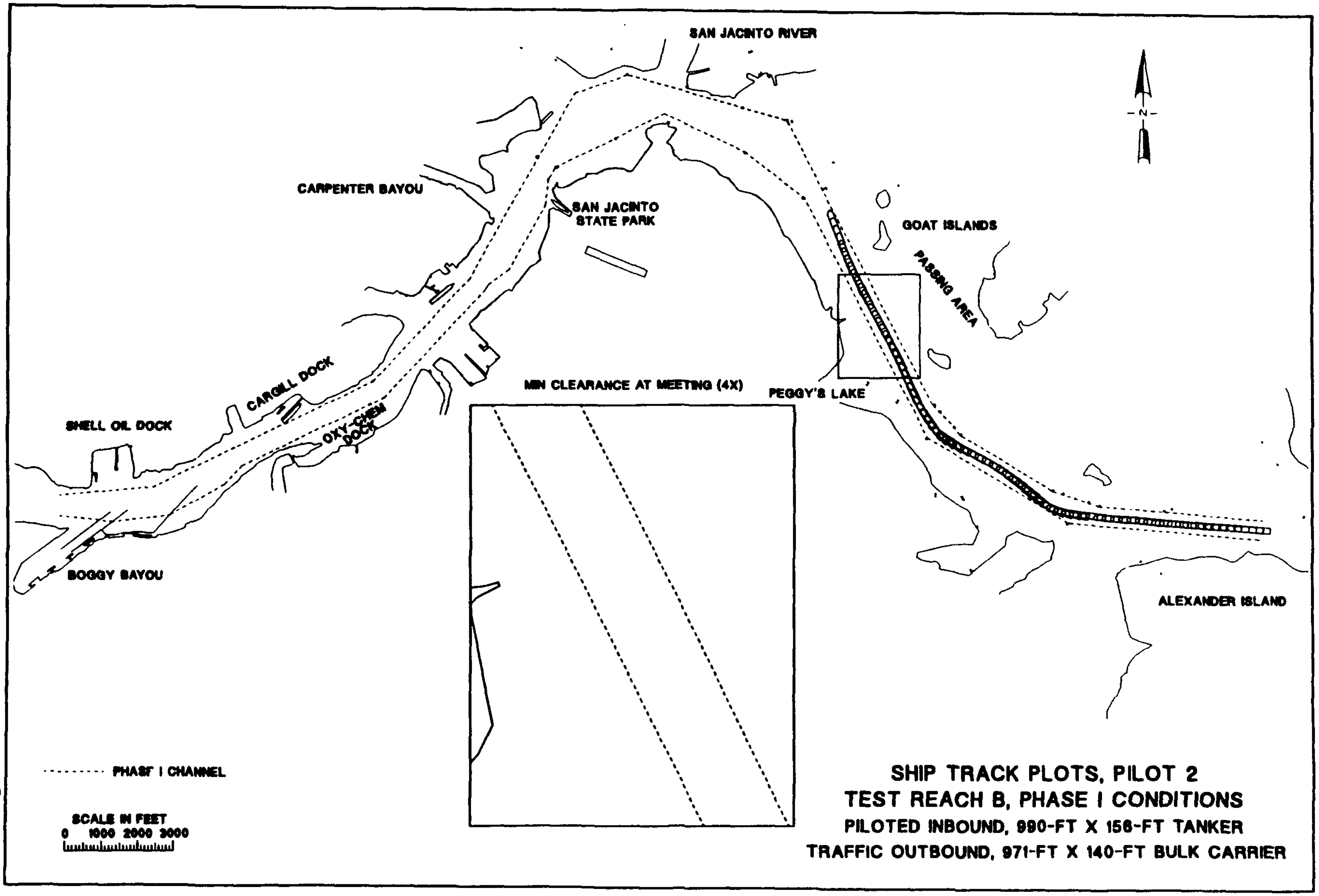


SHIP TRACK PLOTS, PILOT 4
TEST REACH B, EXISTING CONDITIONS
PILOTED INBOUND, 920-FT X 144-FT TANKER
TRAFFIC OUTBOUND, 775-FT X 106-FT BULK CARRIER



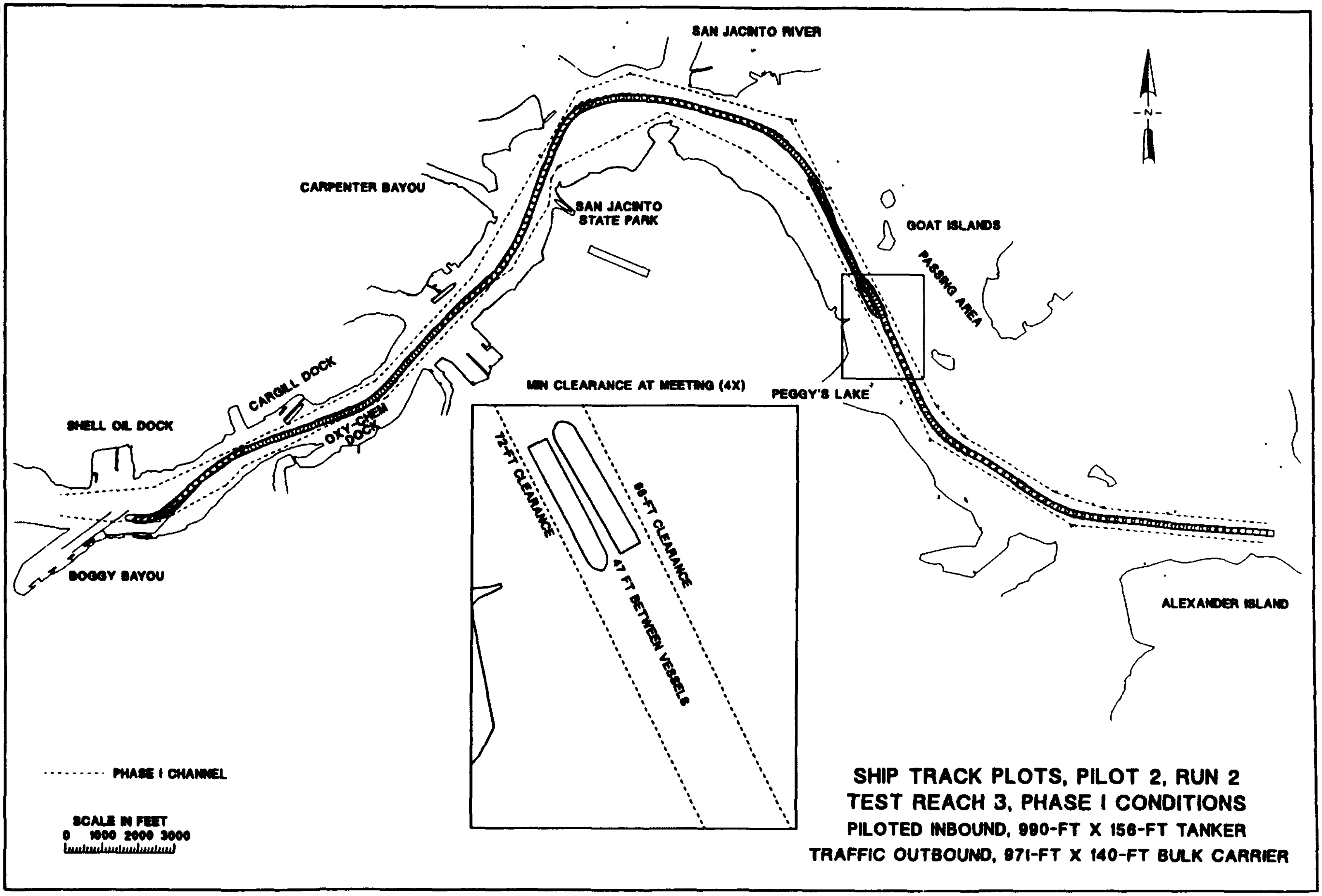
SHIP TRACK PLOTS, PILOT 1
TEST REACH B, PHASE I CONDITIONS
PILOTED INBOUND, 990-FT X 158-FT TANKER
TRAFFIC OUTBOUND, 971-FT X 140-FT BULK CARRIER

PLATE 42

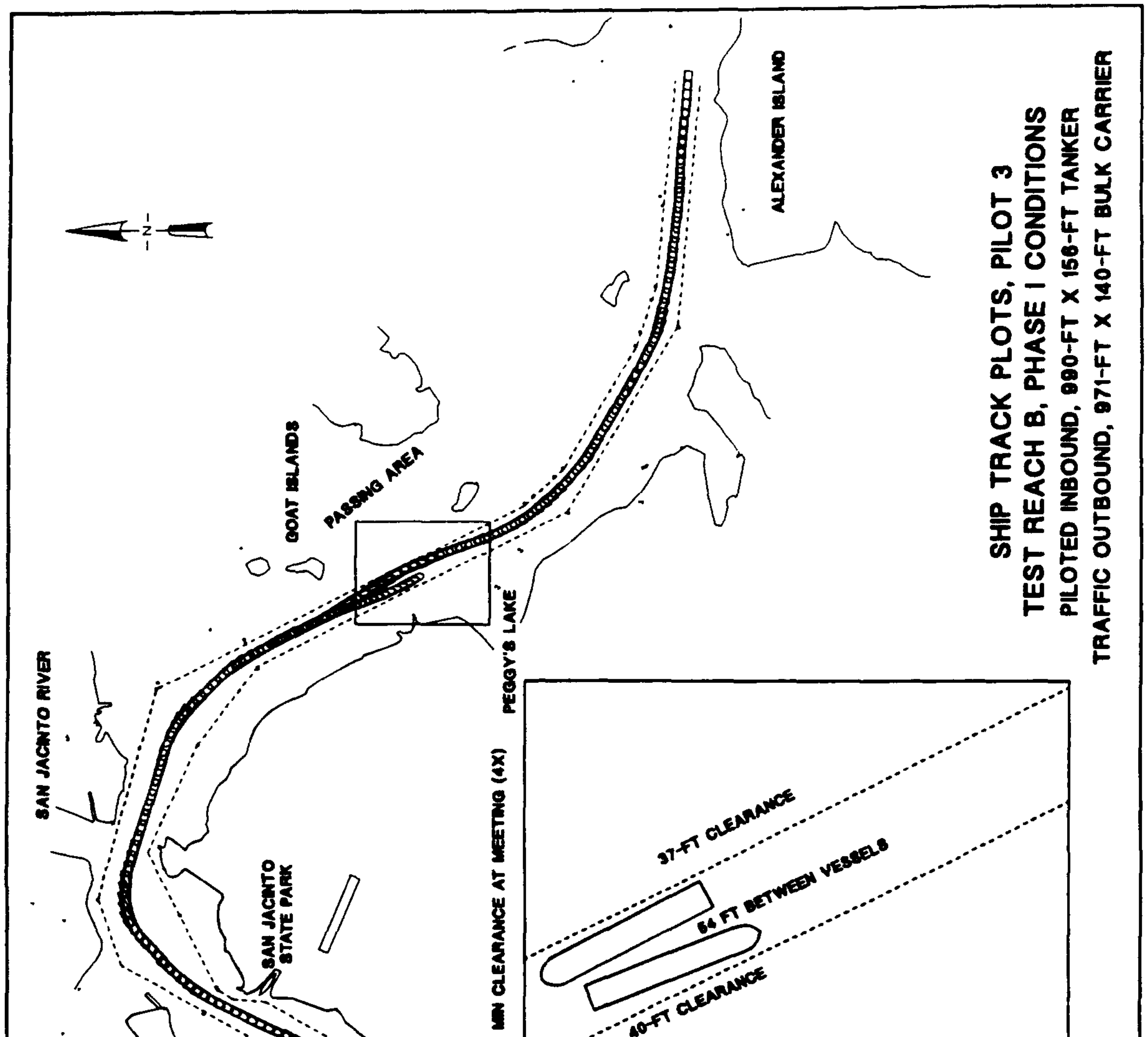


SHIP TRACK PLOTS, PILOT 2
TEST REACH B, PHASE I CONDITIONS
PILOTED INBOUND, 990-FT X 156-FT TANKER
TRAFFIC OUTBOUND, 971-FT X 140-FT BULK CARRIER

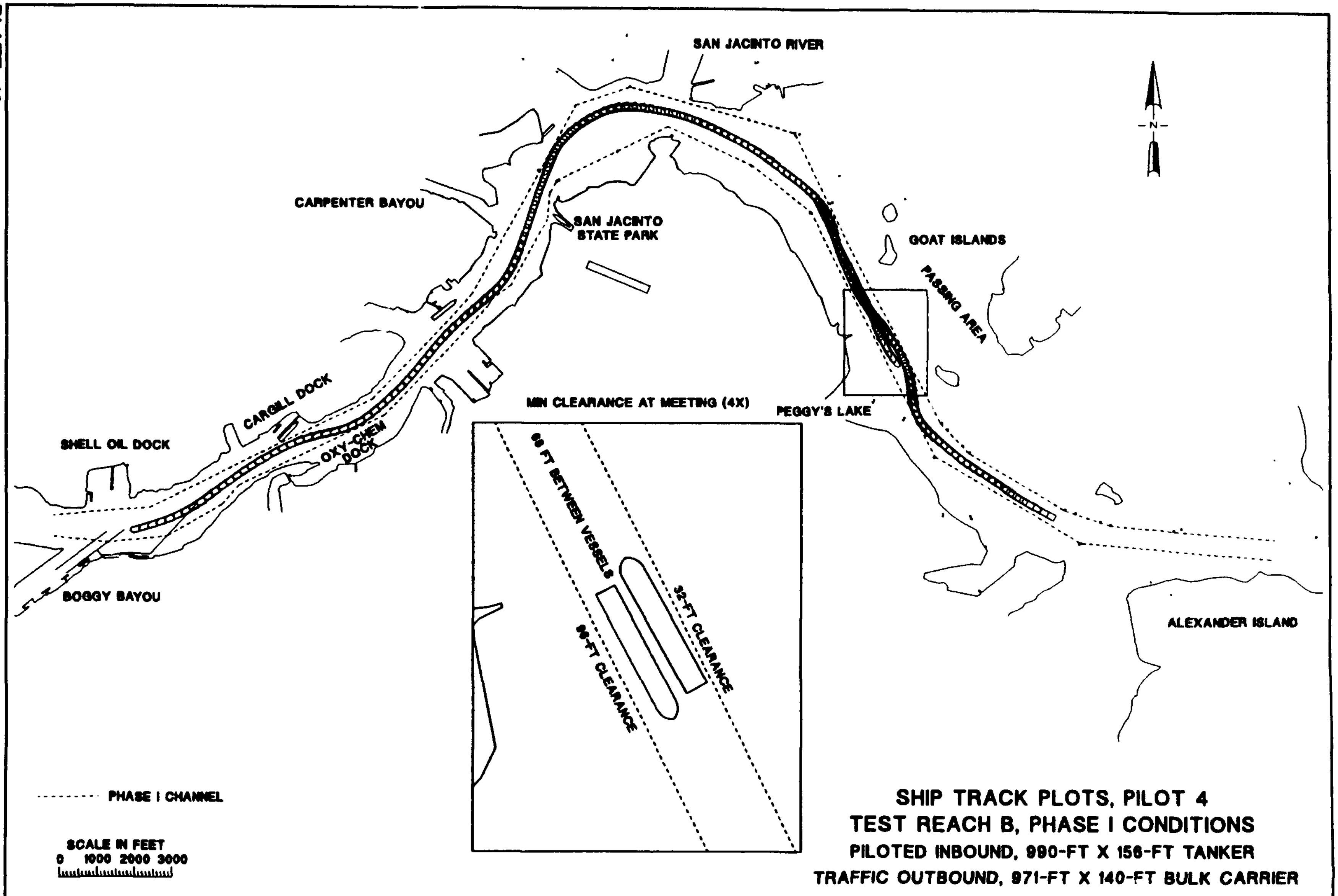
PLATE 44



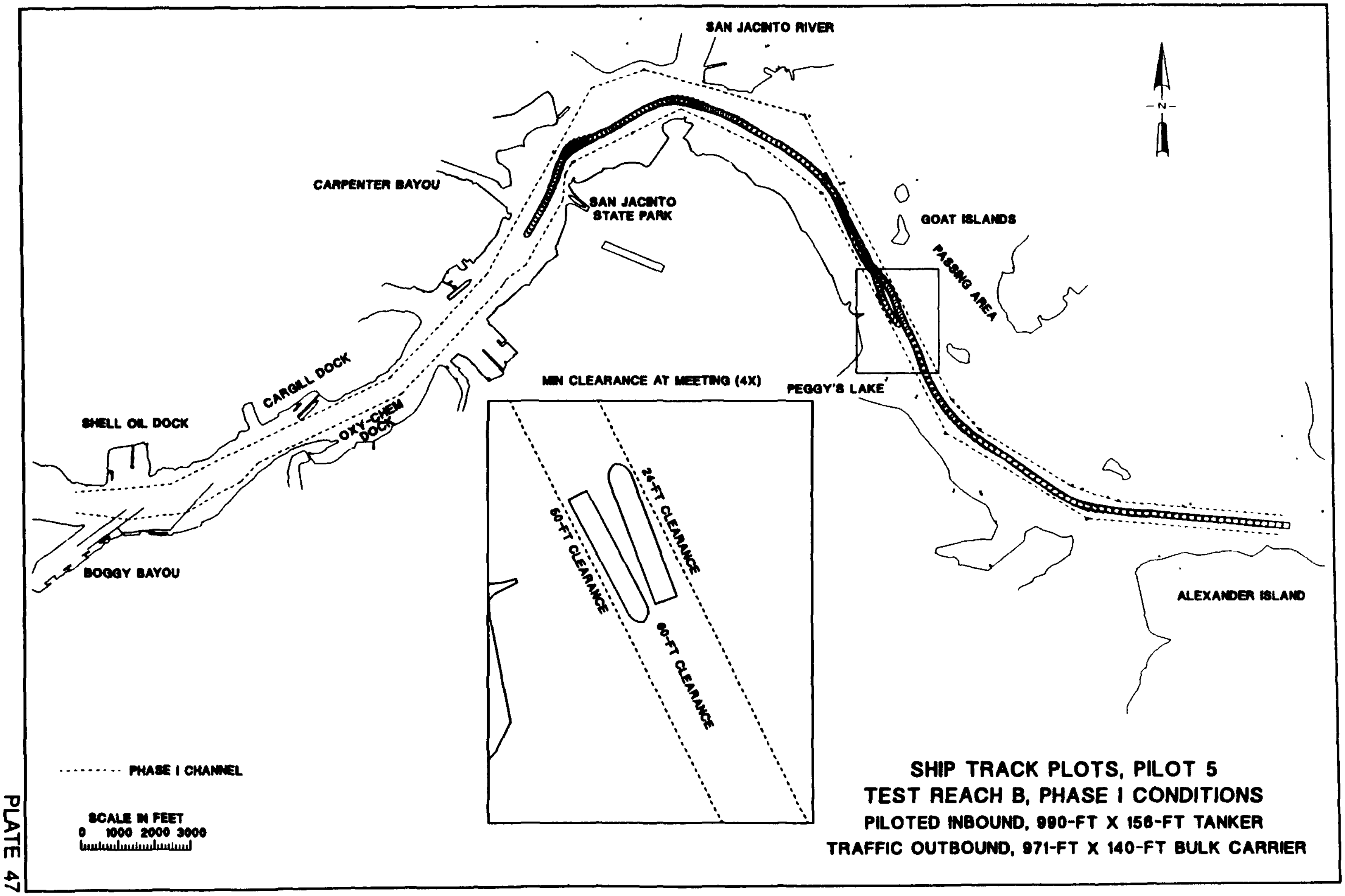
SHIP TRACK PLOTS, PILOT 2, RUN 2
TEST REACH 3, PHASE I CONDITIONS
PILOTED INBOUND, 990-FT X 156-FT TANKER
TRAFFIC OUTBOUND, 971-FT X 140-FT BULK CARRIER



SHIP TRACK PLOTS, PILOT 3
TEST REACH B, PHASE I CONDITIONS
PILOTED INBOUND, 990-FT X 156-FT TANKER
TRAFFIC OUTBOUND, 971-FT X 140-FT BULK CARRIER

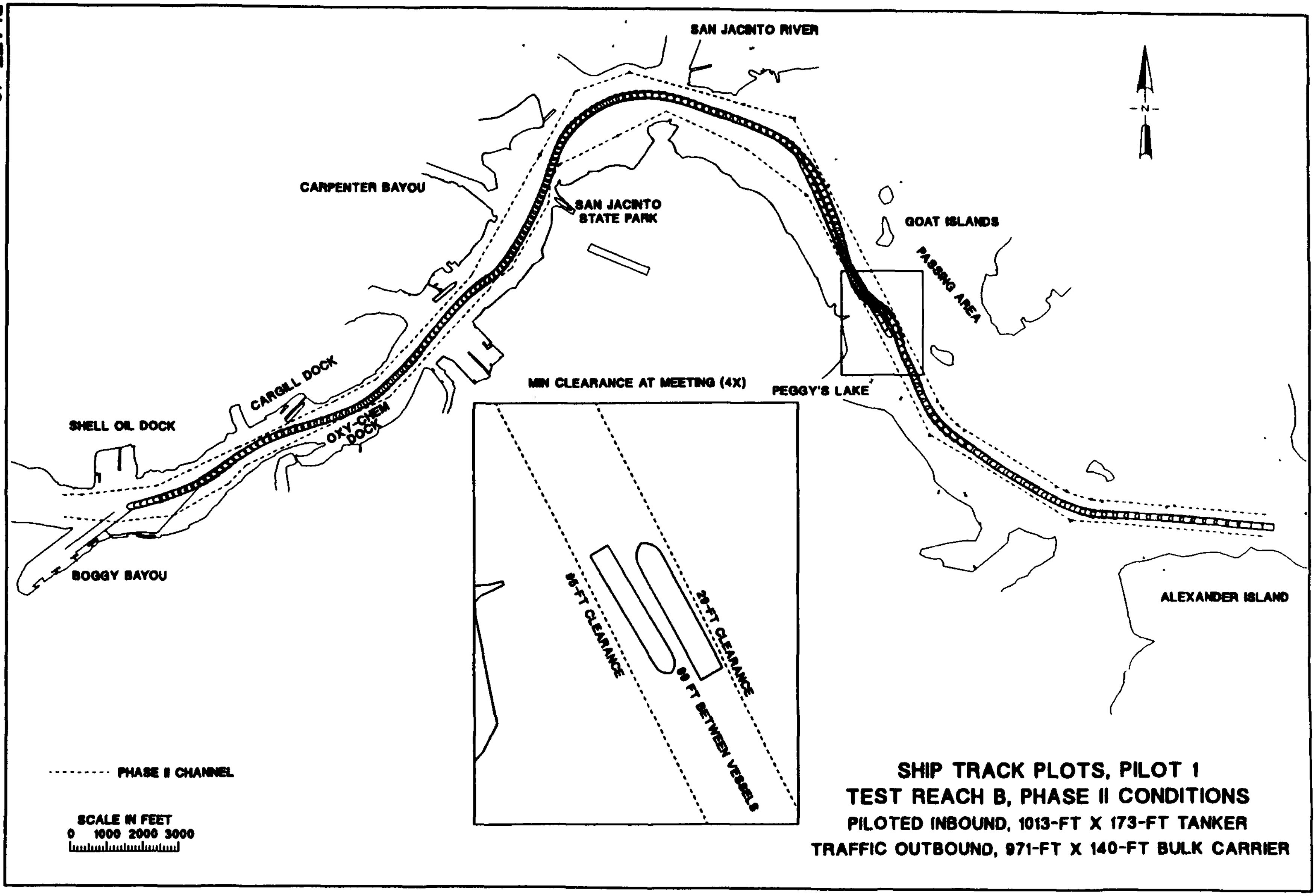


SHIP TRACK PLOTS, PILOT 4
TEST REACH B, PHASE I CONDITIONS
PILOTED INBOUND, 990-FT X 156-FT TANKER
TRAFFIC OUTBOUND, 971-FT X 140-FT BULK CARRIER

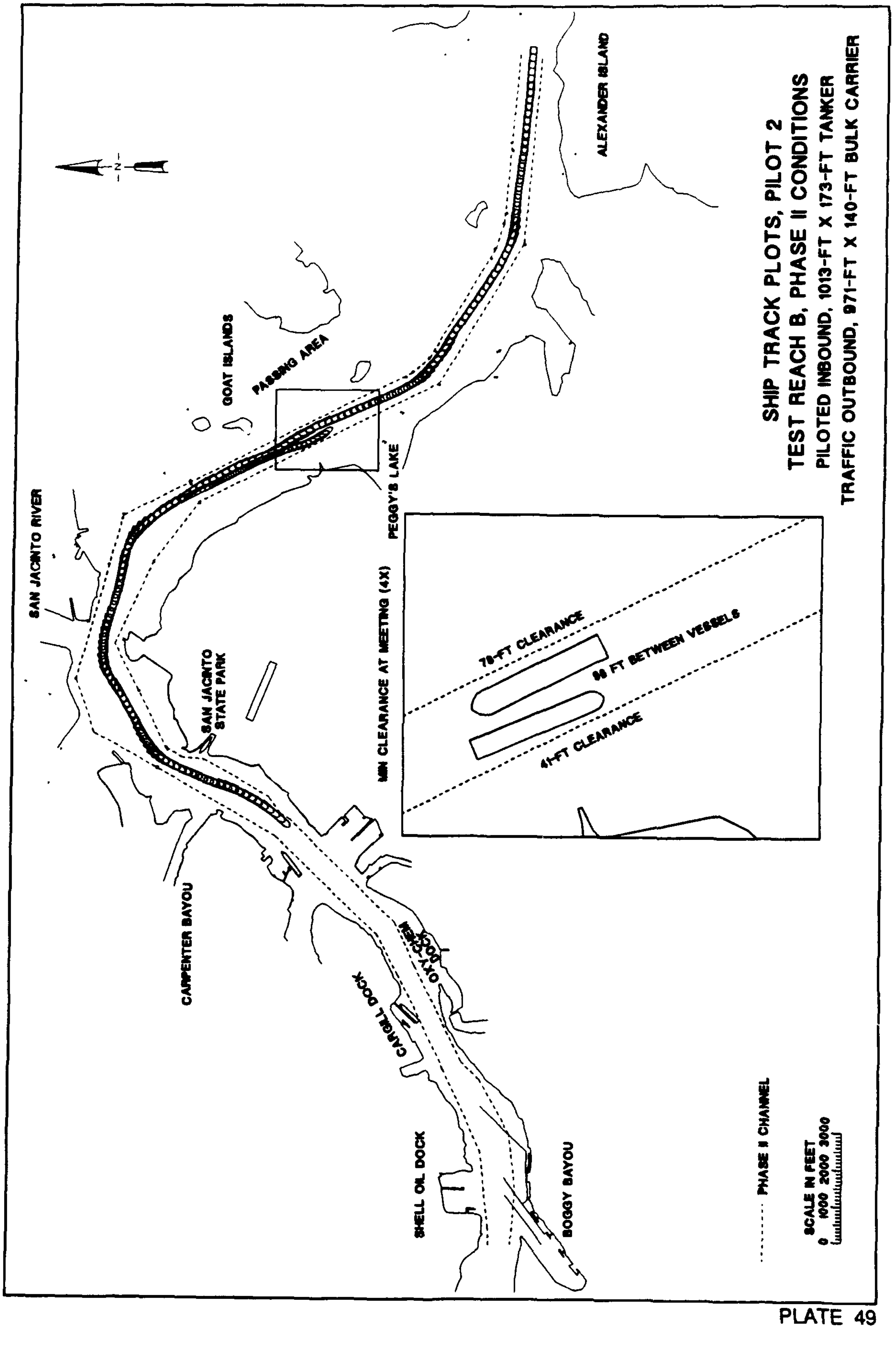


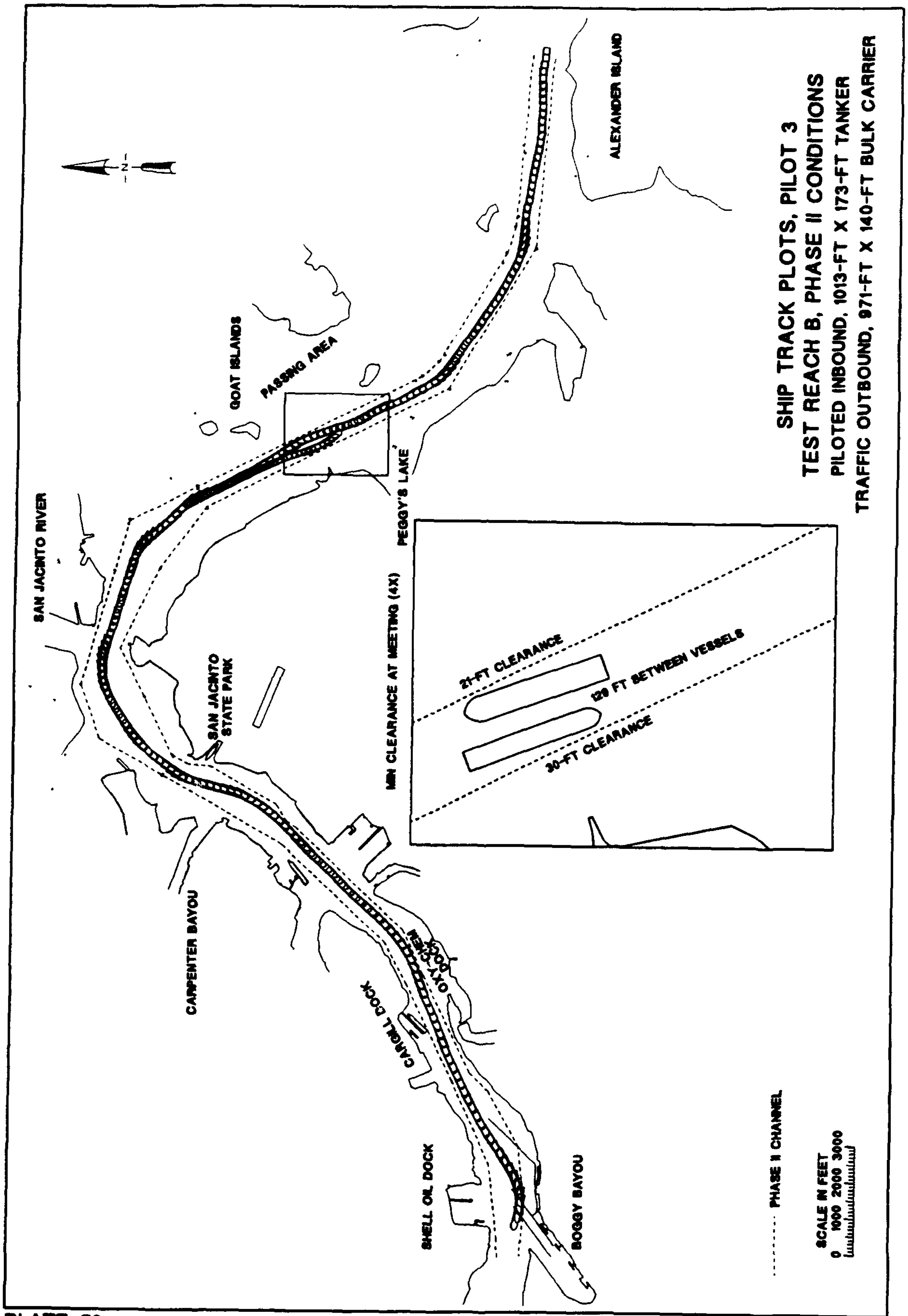
SHIP TRACK PLOTS, PILOT 5
TEST REACH B, PHASE I CONDITIONS
PILOTED INBOUND, 990-FT X 156-FT TANKER
TRAFFIC OUTBOUND, 971-FT X 140-FT BULK CARRIER

PLATE 48

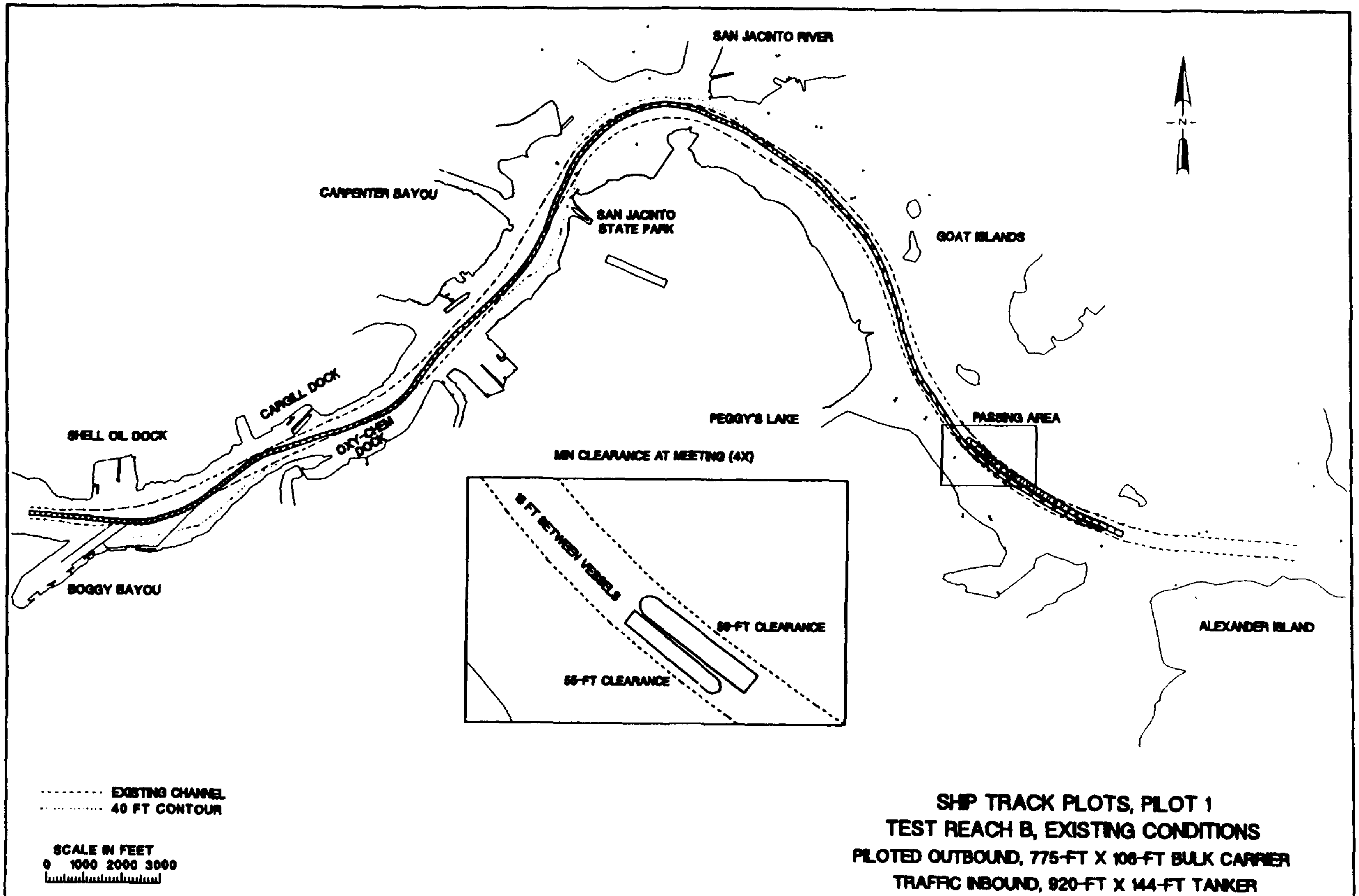


SHIP TRACK PLOTS, PILOT 1
TEST REACH B, PHASE II CONDITIONS
PILOTED INBOUND, 1013-FT X 173-FT TANKER
TRAFFIC OUTBOUND, 971-FT X 140-FT BULK CARRIER

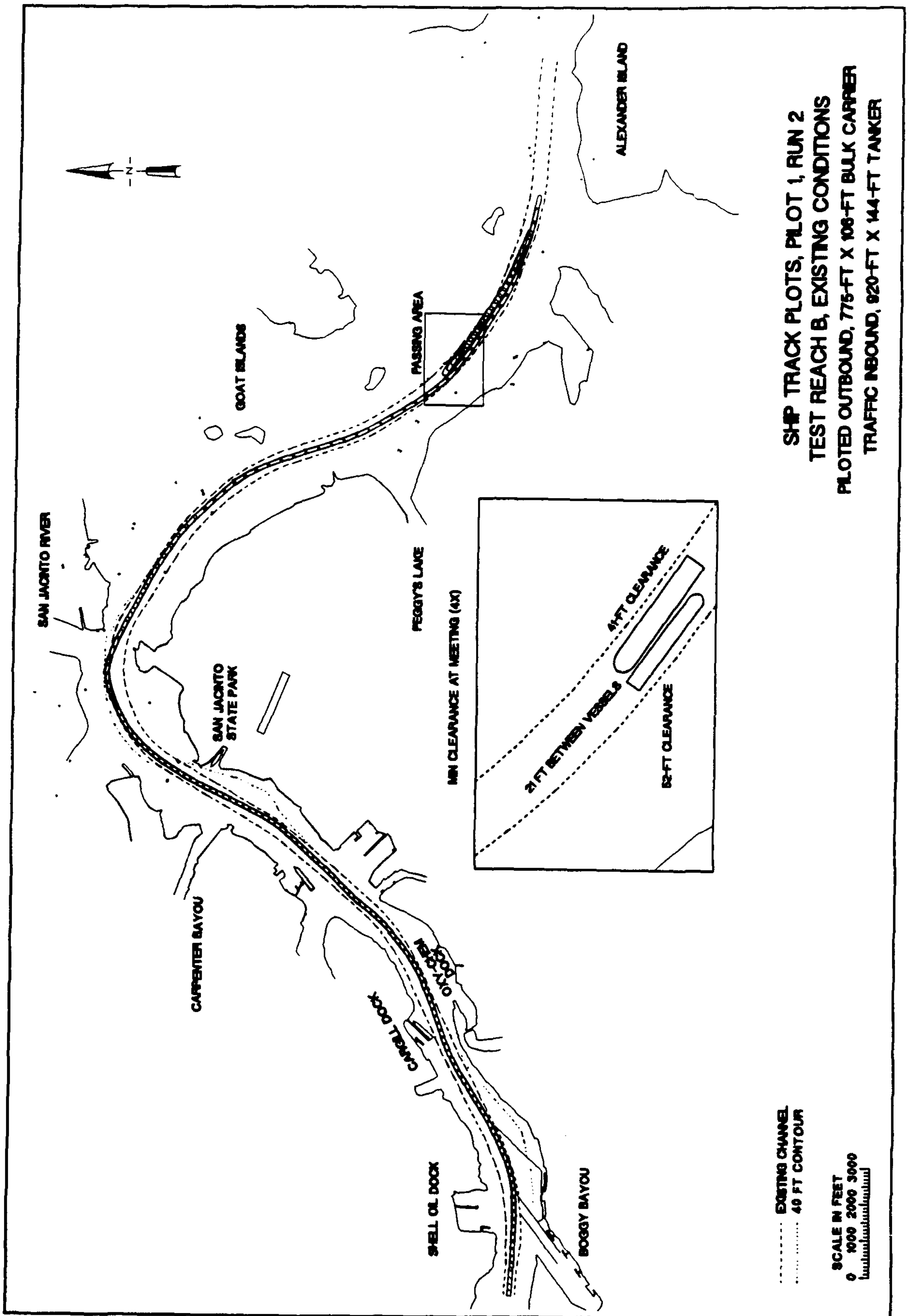

SHIP TRACK PLOTS, PILOT 2
TEST REACH B, PHASE II CONDITIONS
PILOTED INBOUND, 1013-FT X 173-FT TANKER
TRAFFIC OUTBOUND, 971-FT X 140-FT BULK CARRIER
N
ALEXANDER ISLAND
GOAT ISLANDS
PASSING AREA
PEGGY'S LAKE
SAN JACINTO RIVER
SAN JACINTO STATE PARK
MIN CLEARANCE AT MEETING (4X)
78-FT CLEARANCE
98 FT BETWEEN VESSELS
41-FT CLEARANCE
CARPENTER BAYOU
OXY CHEM DOCK
CARGILL DOCK
SHELL OIL DOCK
BOGGY BAYOU
PHASE II CHANNEL
SCALE IN FEET
0 1000 2000 3000



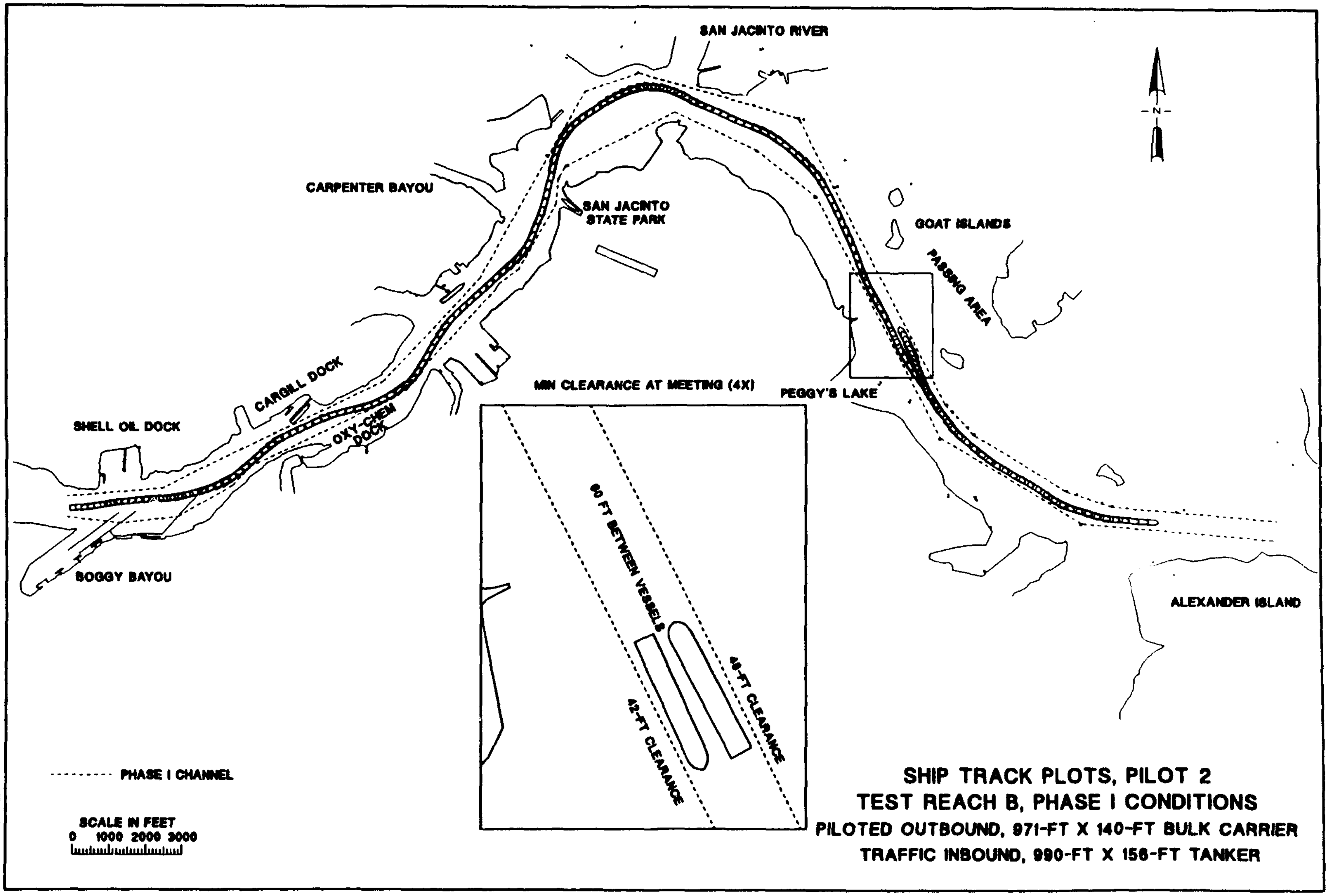
SHIP TRACK PLOTS, PILOT 3
TEST REACH B, PHASE II CONDITIONS
PILOTED INBOUND, 1013-FT X 173-FT TANKER
TRAFFIC OUTBOUND, 971-FT X 140-FT BULK CARRIER



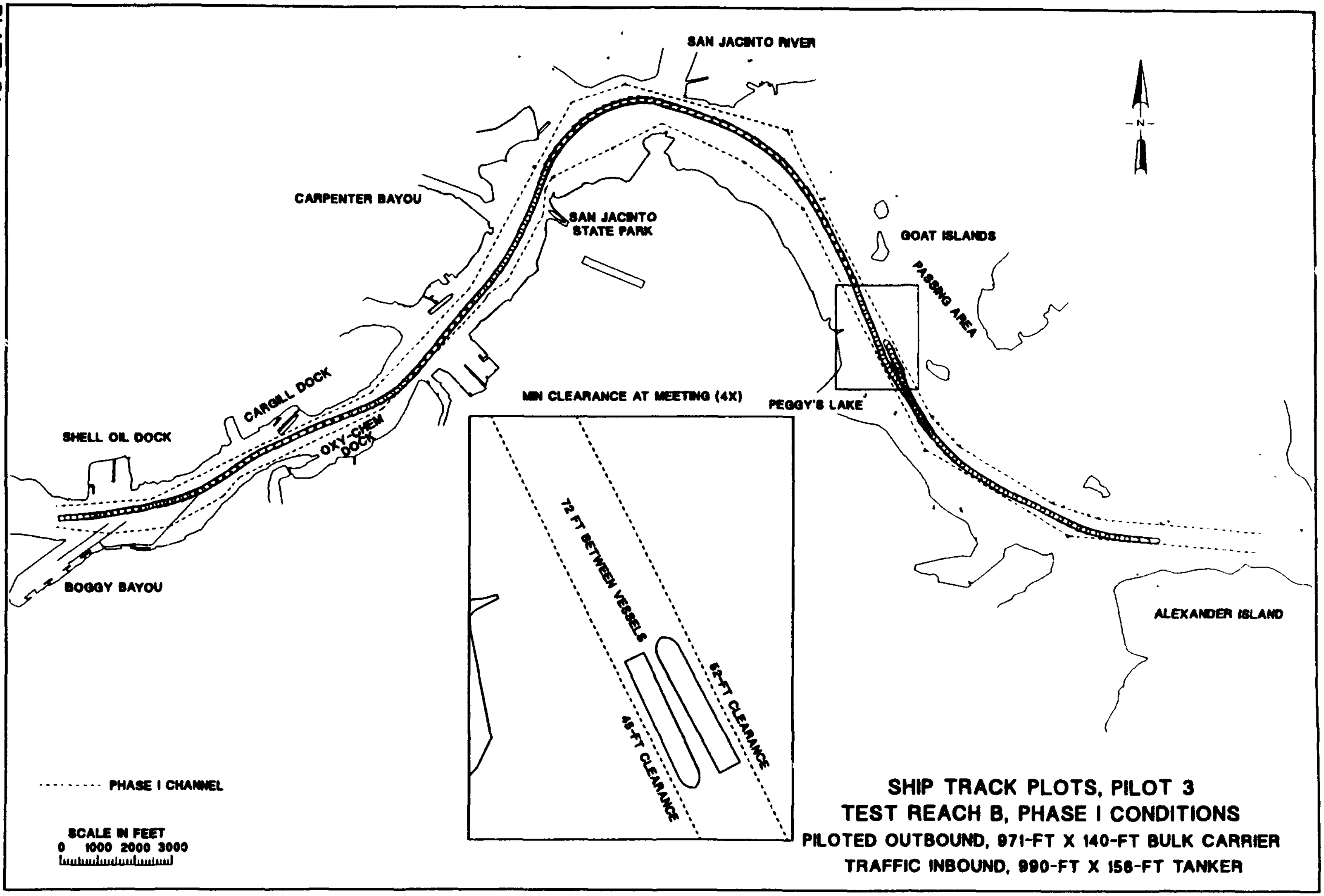
SHIP TRACK PLOTS, PILOT 1
TEST REACH B, EXISTING CONDITIONS
PILOTED OUTBOUND, 775-FT X 106-FT BULK CARRIER
TRAFFIC INBOUND, 920-FT X 144-FT TANKER



SHIP TRACK PLOTS, PILOT 1, RUN 2
TEST REACH B, EXISTING CONDITIONS
PILOTED OUTBOUND, 775-FT X 106-FT BULK CARRIER
TRAFFIC INBOUND, 920-FT X 144-FT TANKER

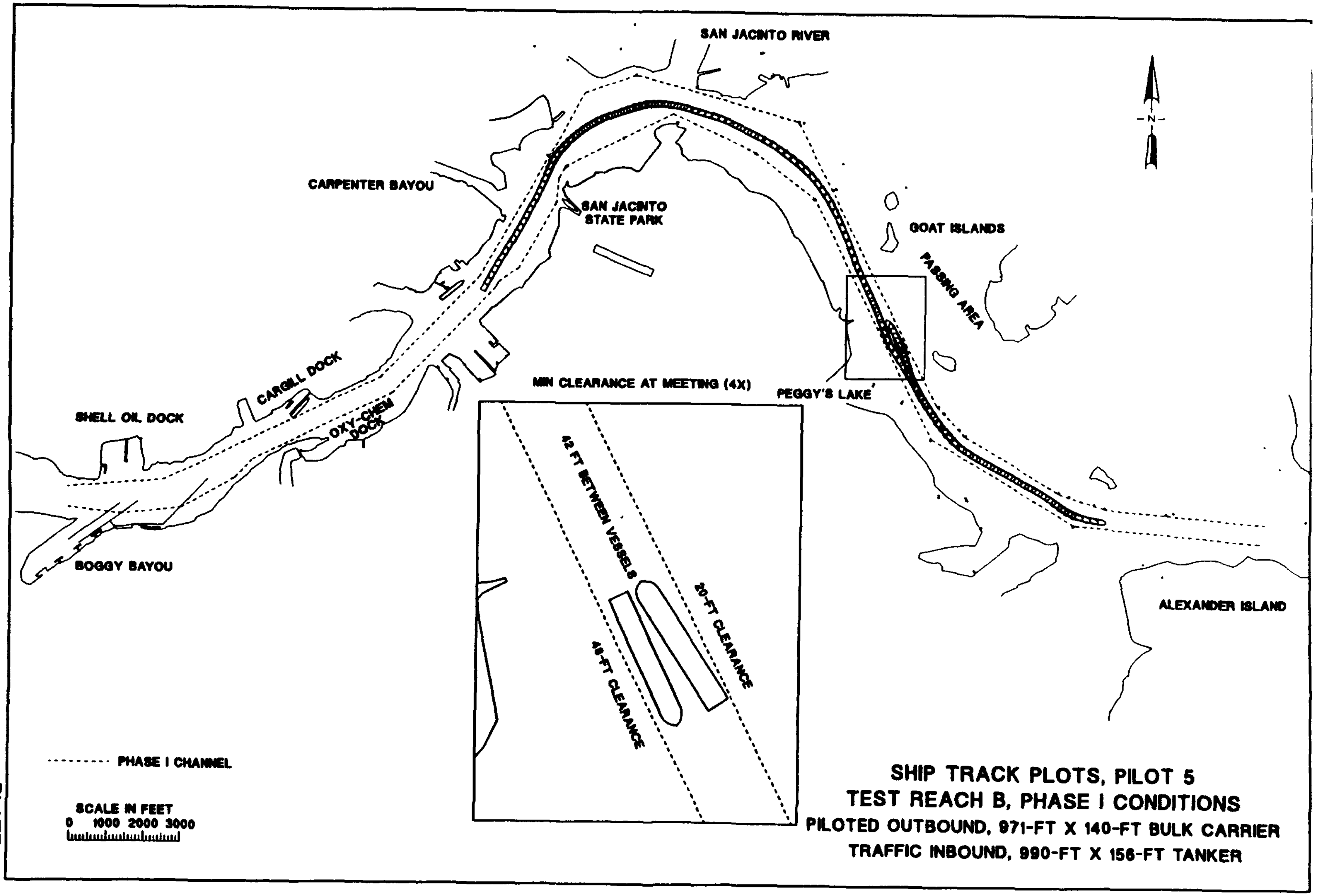


SHIP TRACK PLOTS, PILOT 2
TEST REACH B, PHASE I CONDITIONS
PILOTED OUTBOUND, 971-FT X 140-FT BULK CARRIER
TRAFFIC INBOUND, 990-FT X 156-FT TANKER

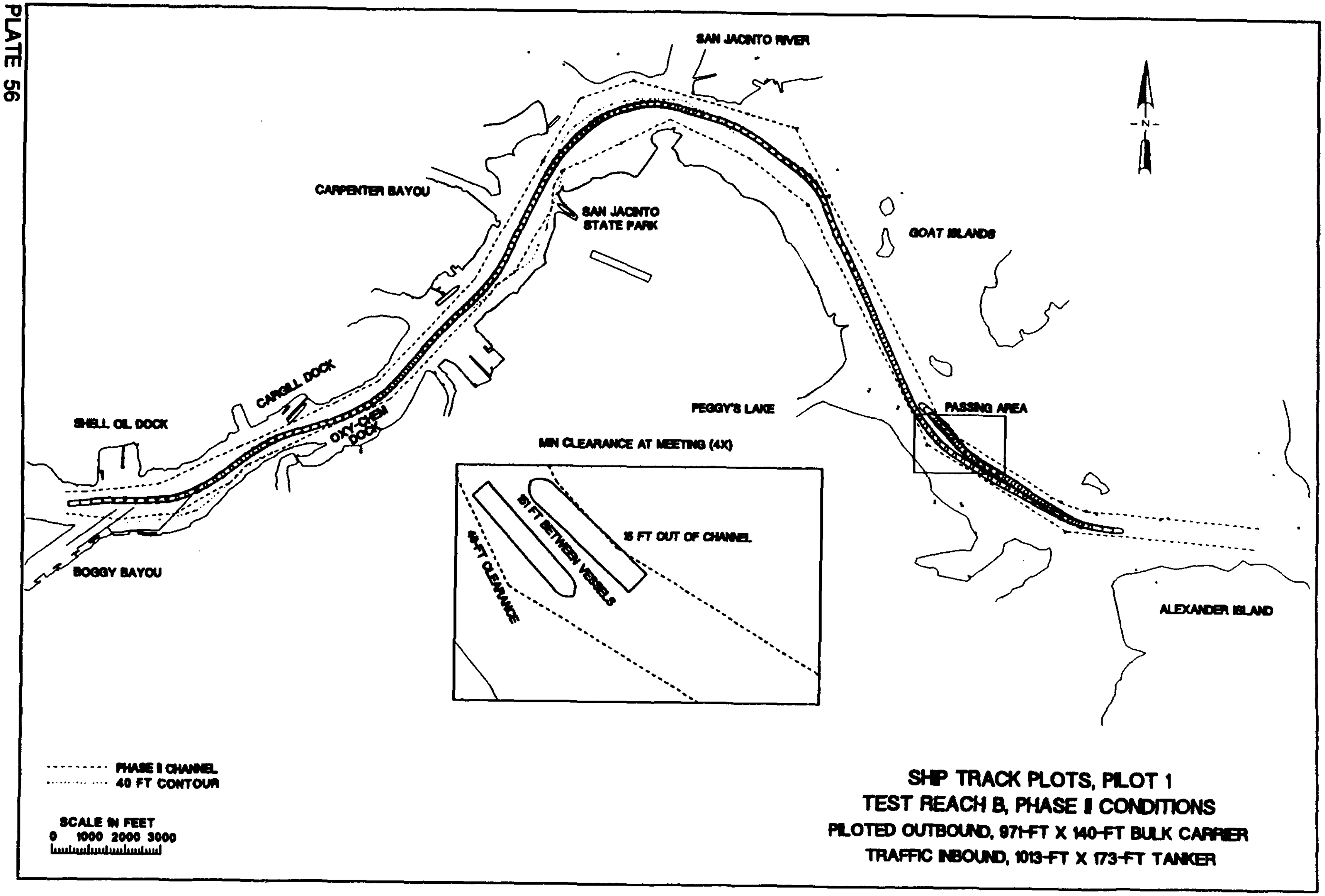


SHIP TRACK PLOTS, PILOT 3
TEST REACH B, PHASE I CONDITIONS
PILOTED OUTBOUND, 971-FT X 140-FT BULK CARRIER
TRAFFIC INBOUND, 990-FT X 158-FT TANKER

PLATE 54

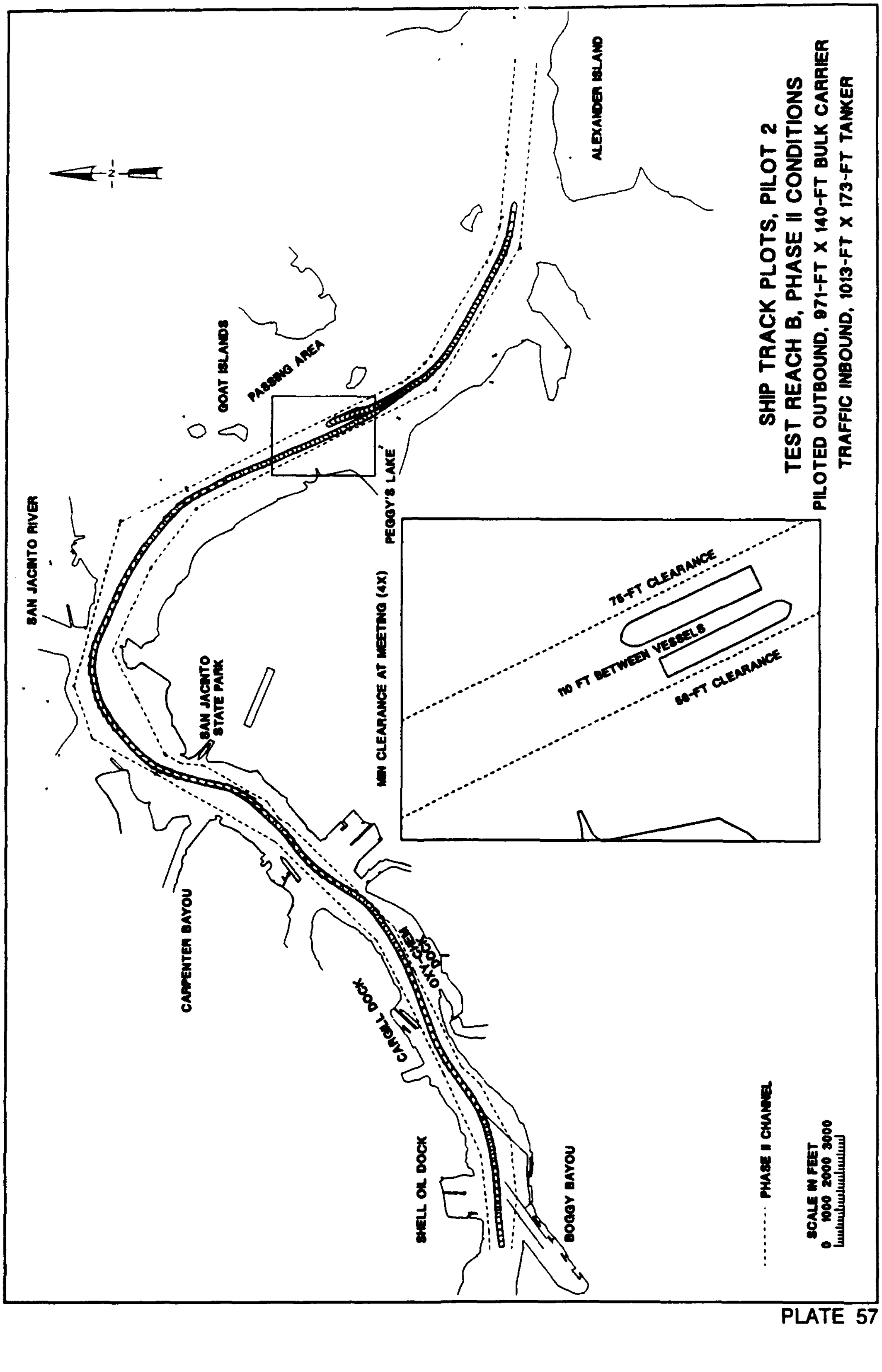


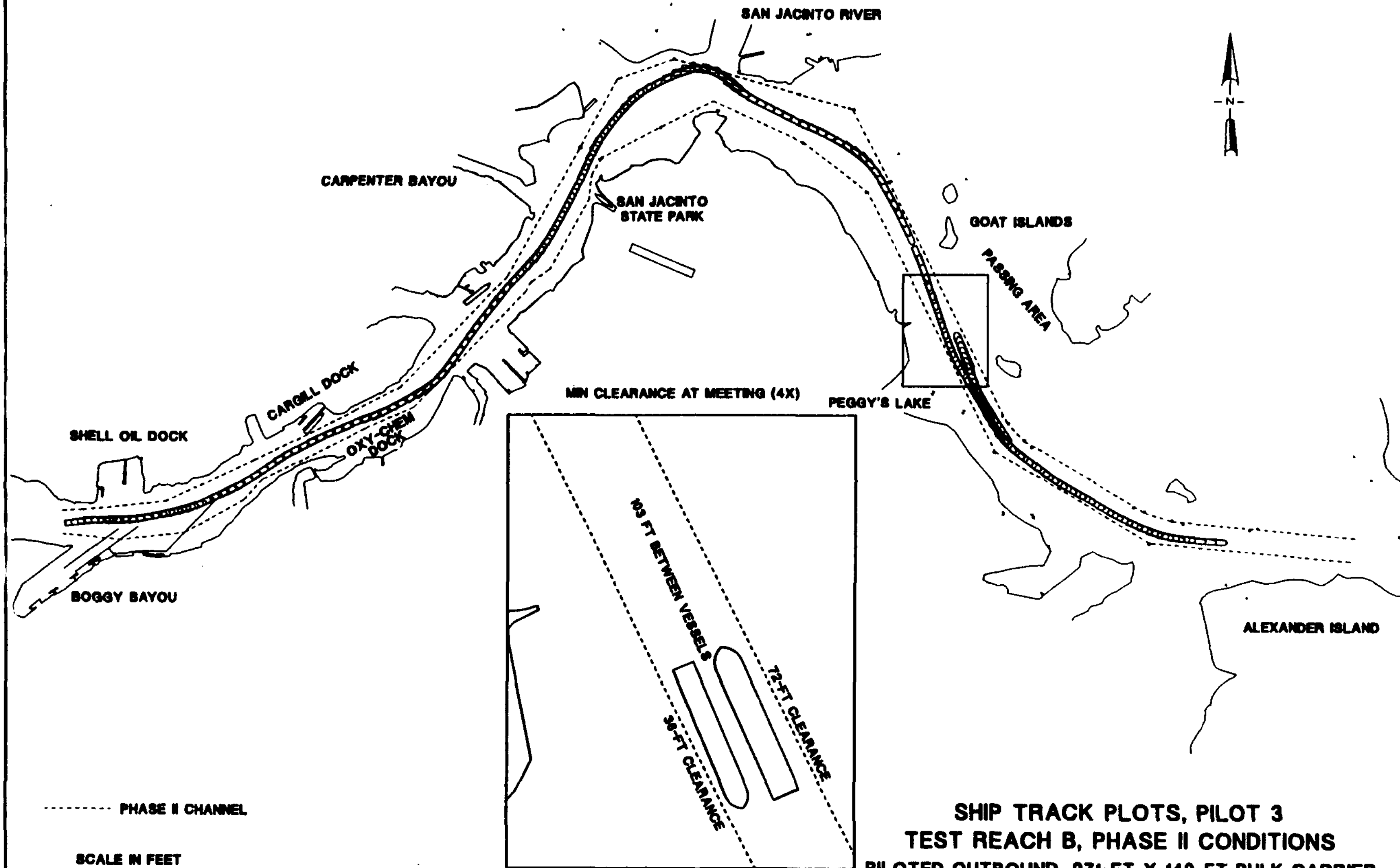
SHIP TRACK PLOTS, PILOT 5
TEST REACH B, PHASE I CONDITIONS
PILOTED OUTBOUND, 971-FT X 140-FT BULK CARRIER
TRAFFIC INBOUND, 990-FT X 156-FT TANKER



SHIP TRACK PLOTS, PILOT 1
TEST REACH B, PHASE II CONDITIONS
PILOTED OUTBOUND, 971-FT X 140-FT BULK CARRIER
TRAFFIC INBOUND, 1013-FT X 173-FT TANKER

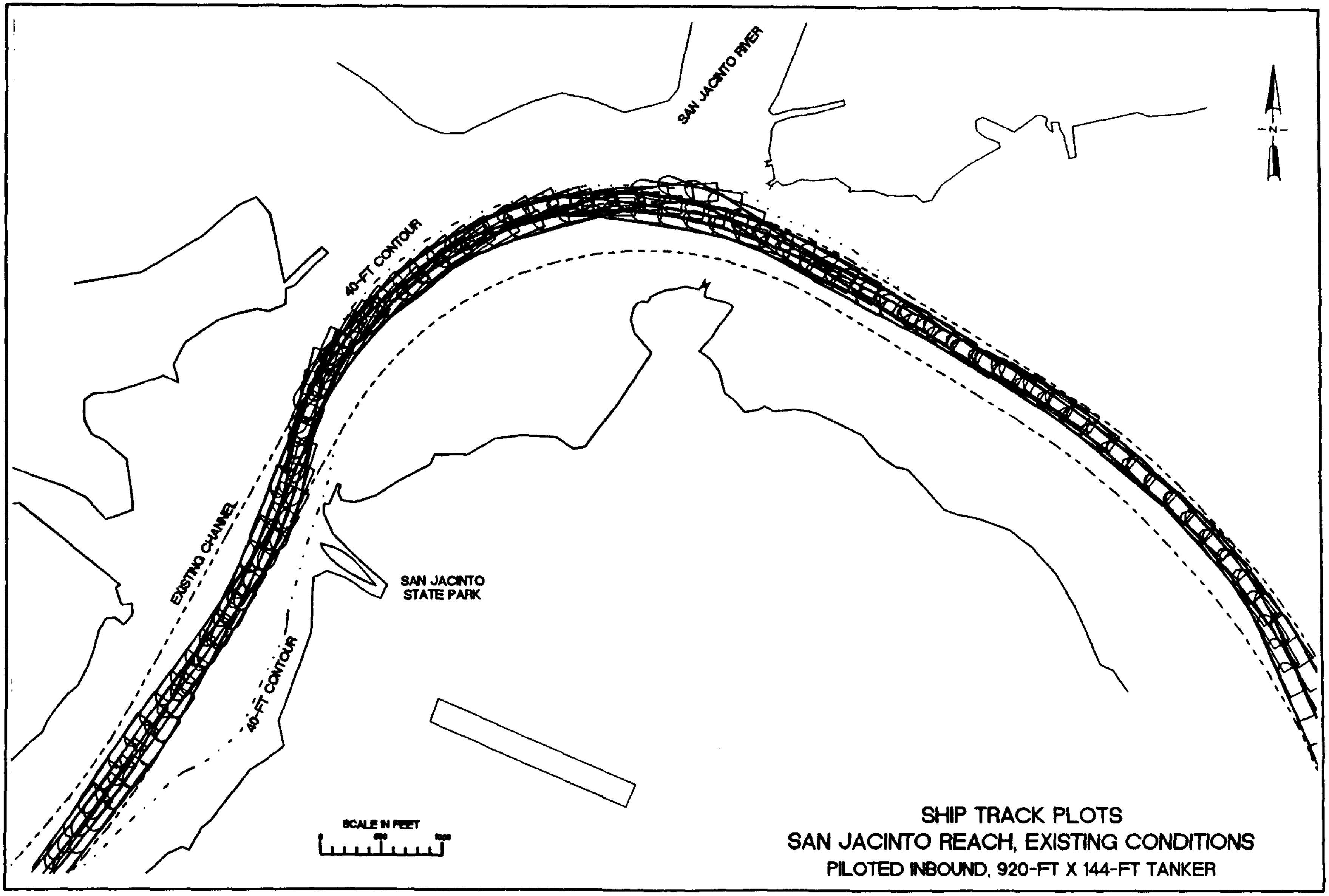
PLATE 56


SHIP TRACK PLOTS, PILOT 2
TEST REACH B, PHASE II CONDITIONS
PILOTED OUTBOUND, 971-FT X 140-FT BULK CARRIER
TRAFFIC INBOUND, 1013-FT X 173-FT TANKER
ALEXANDER ISLAND
GOAT ISLANDS
PASSING AREA
PEGGY'S LAKE
SAN JACINTO RIVER
MIN CLEARANCE AT MEETING (4X)
75-FT CLEARANCE
110 FT BETWEEN VESSELS
56-FT CLEARANCE
SAN JACINTO STATE PARK
CARPENTER BAYOU
OXY-CHEM DOCK
CARGILL DOCK
SHELL OIL DOCK
BOGGY BAYOU
PHASE II CHANNEL
SCALE IN FEET
0 1000 2000 3000
N



SHIP TRACK PLOTS, PILOT 3
TEST REACH B, PHASE II CONDITIONS
PILOTED OUTBOUND, 971-FT X 140-FT BULK CARRIER
TRAFFIC INBOUND, 1013-FT X 173-FT TANKER

PLATE 58



SHIP TRACK PLOTS
SAN JACINTO REACH, EXISTING CONDITIONS
PILOTED INBOUND, 920-FT X 144-FT TANKER

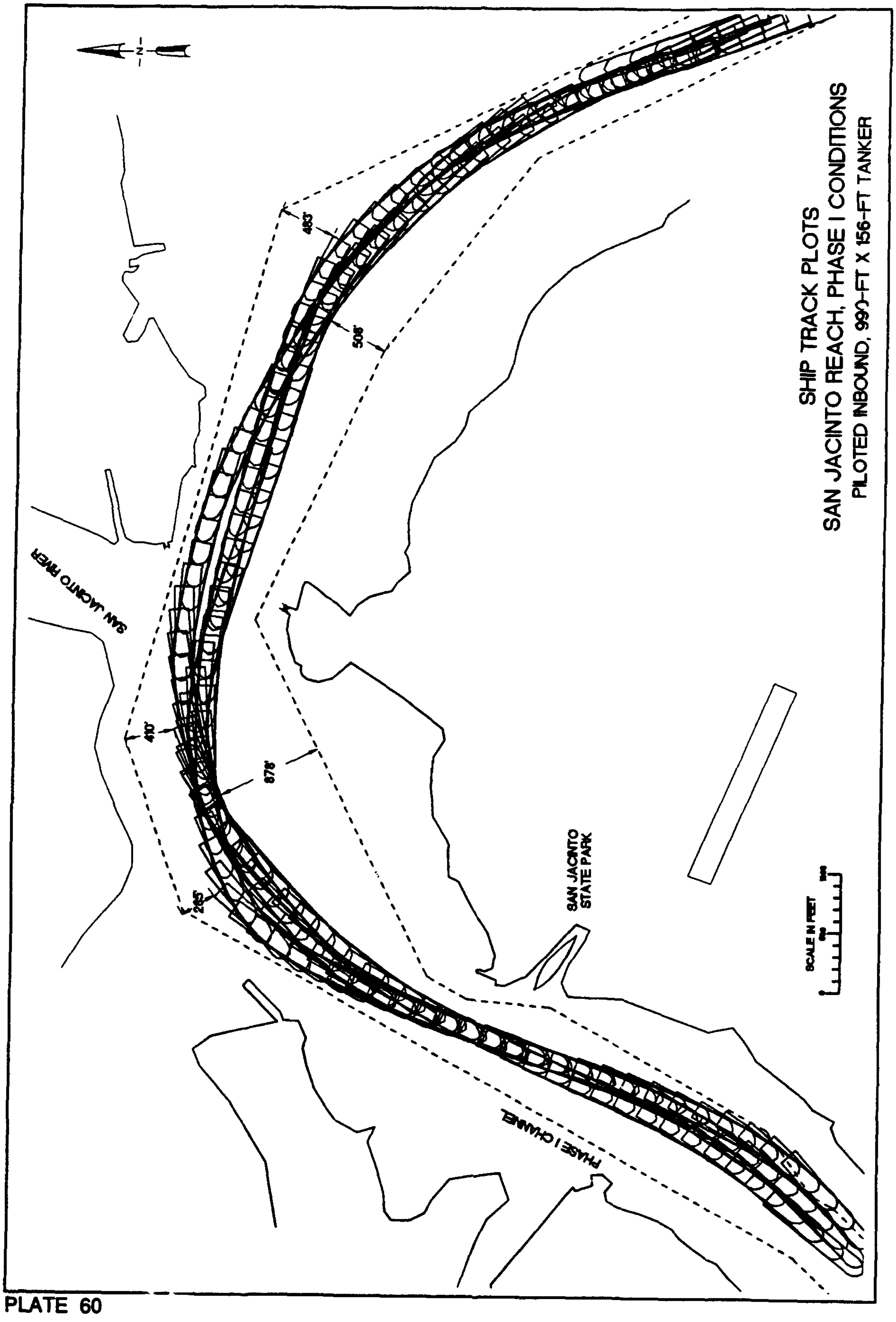
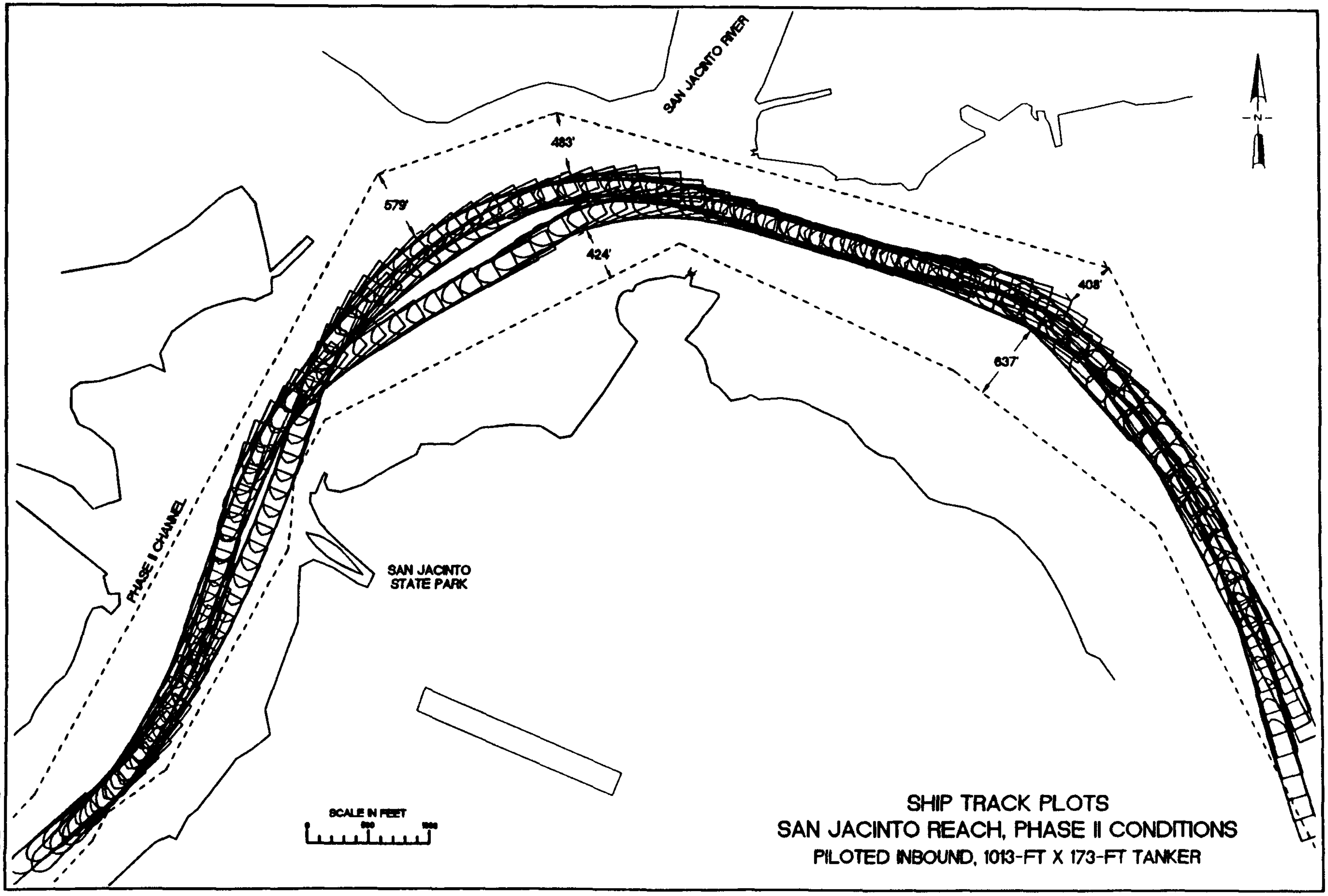
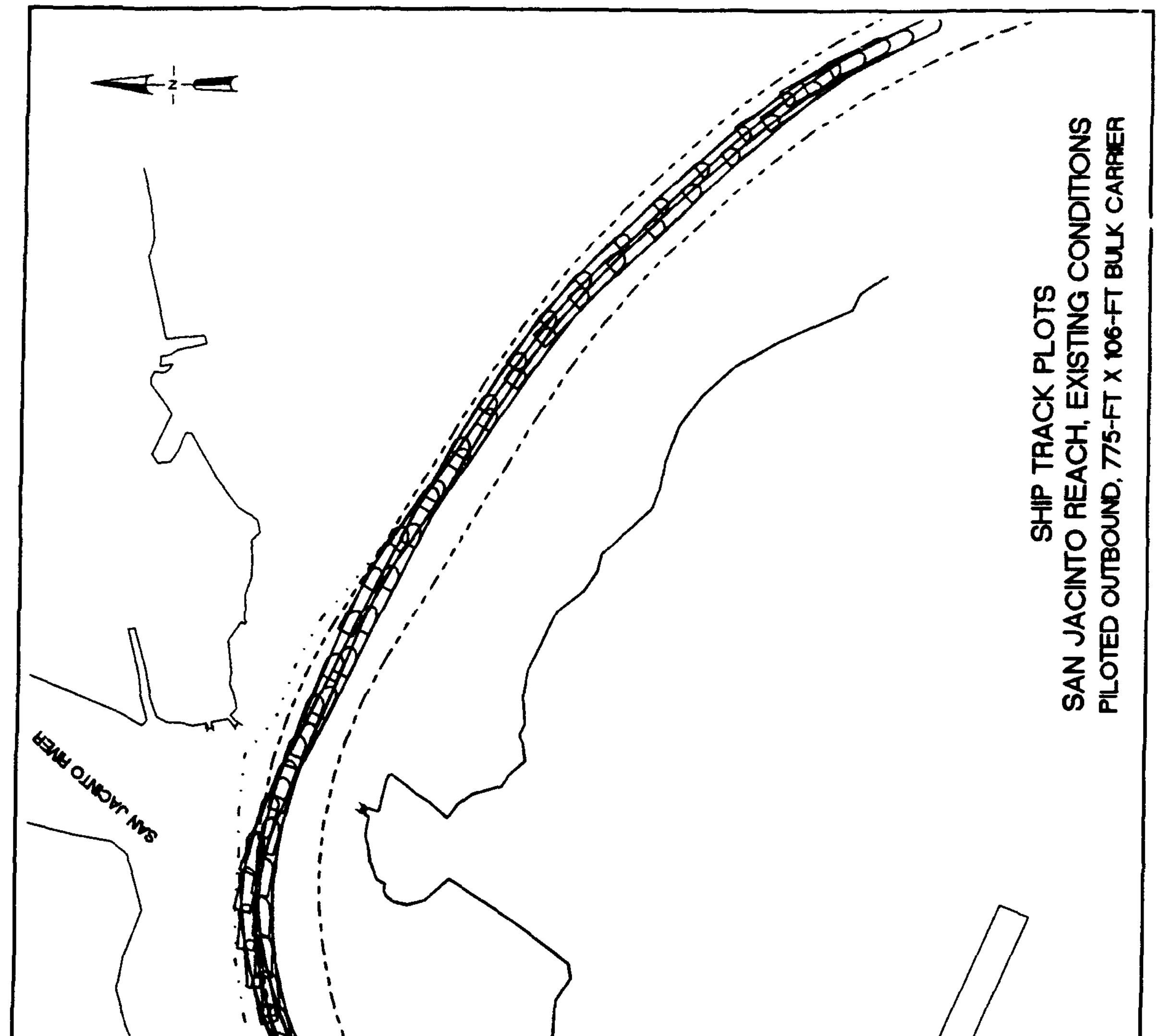

SHIP TRACK PLOTS
SAN JACINTO REACH, PHASE I CONDITIONS
PILOTED INBOUND, 990-FT X 156-FT TANKER
N
SAN JACINTO RIVER
PHASE I CHANNEL
SAN JACINTO STATE PARK
SCALE IN FEET
483'
506'
410'
878'
285'

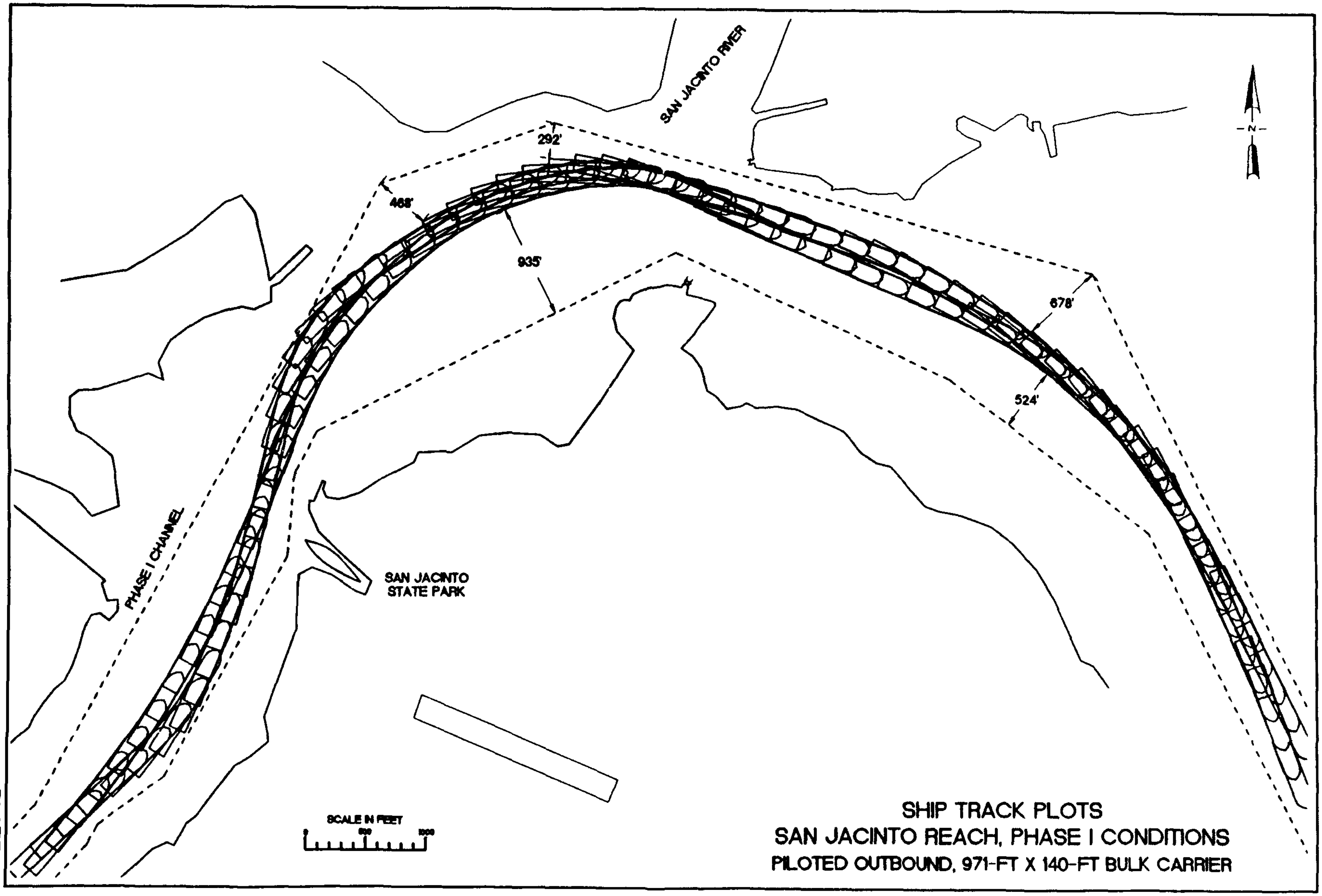
PLATE 60



SHIP TRACK PLOTS
SAN JACINTO REACH, PHASE II CONDITIONS
PILOTED INBOUND, 1013-FT X 173-FT TANKER



SHIP TRACK PLOTS
SAN JACINTO REACH, EXISTING CONDITIONS
PILOTED OUTBOUND, 775-FT X 106-FT BULK CARRIER



SHIP TRACK PLOTS
SAN JACINTO REACH, PHASE I CONDITIONS
PILOTED OUTBOUND, 971-FT X 140-FT BULK CARRIER

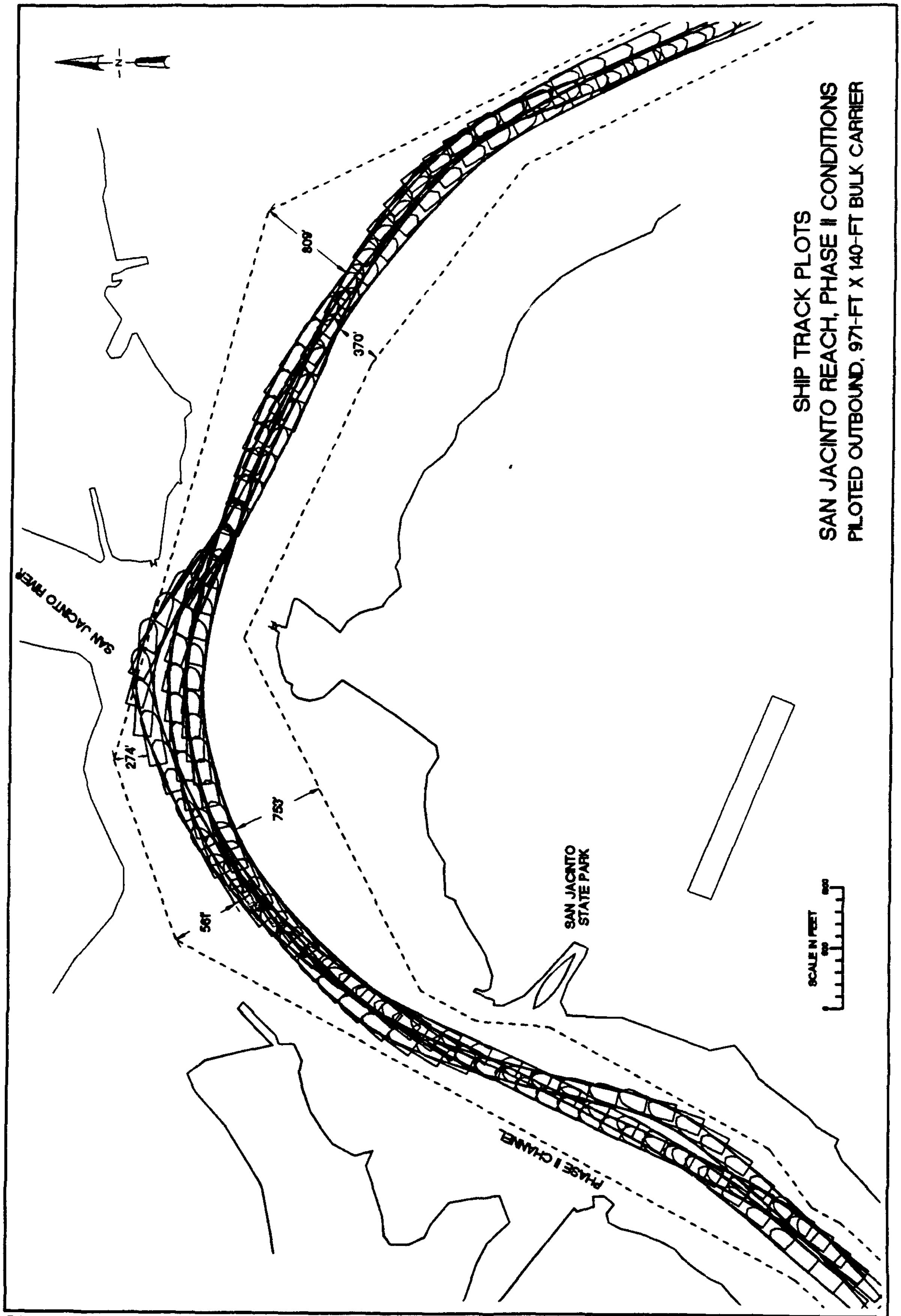
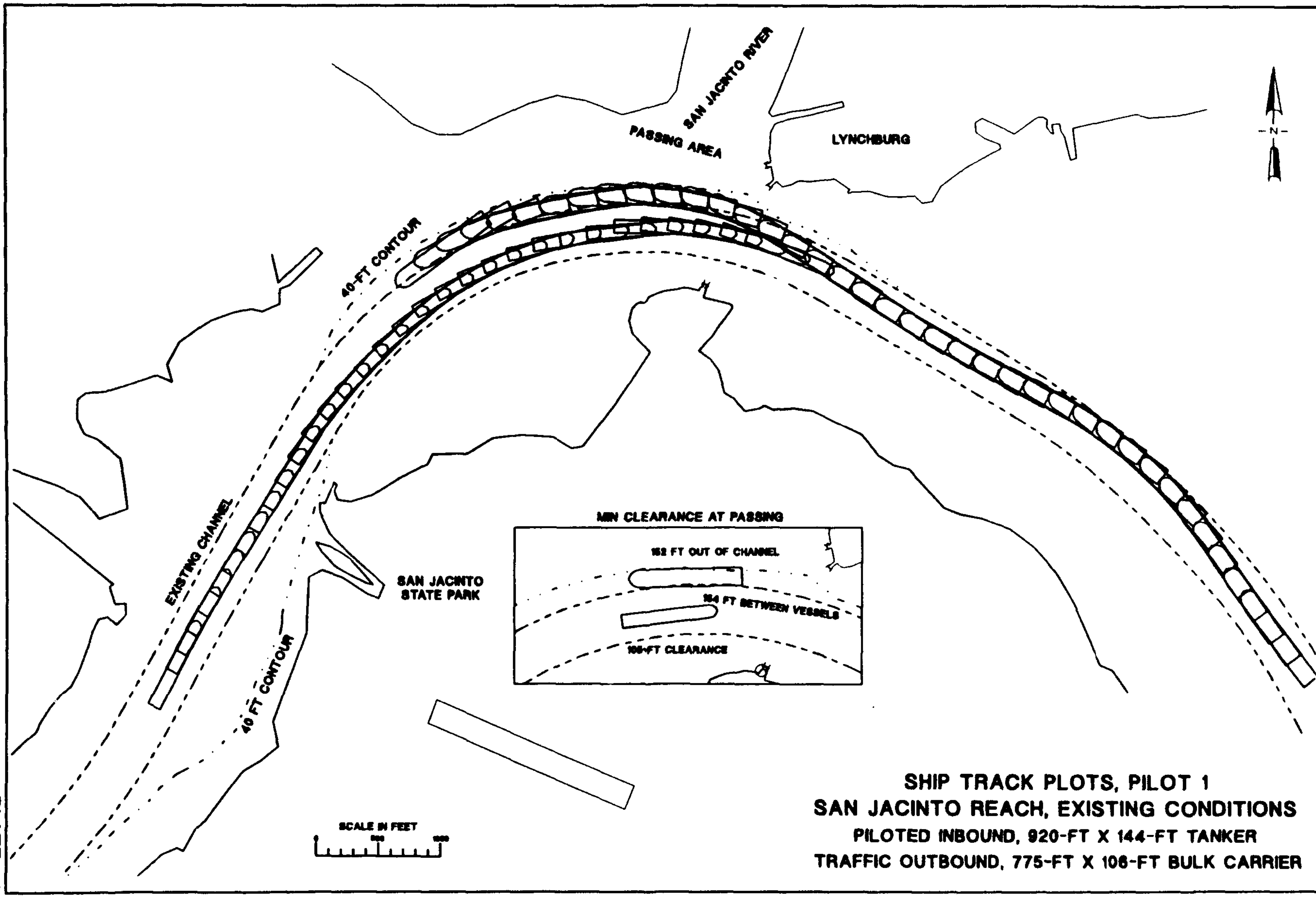

SHIP TRACK PLOTS
SAN JACINTO REACH, PHASE II CONDITIONS
PILOTED OUTBOUND, 971-FT X 140-FT BULK CARRIER
SAN JACINTO RIVER
PHASE II CHANNEL
SAN JACINTO STATE PARK
SCALE IN FEET
N
809'
370'
274'
753'
561'

PLATE 64



SHIP TRACK PLOTS, PILOT 1
SAN JACINTO REACH, EXISTING CONDITIONS
PILOTED INBOUND, 920-FT X 144-FT TANKER
TRAFFIC OUTBOUND, 775-FT X 106-FT BULK CARRIER

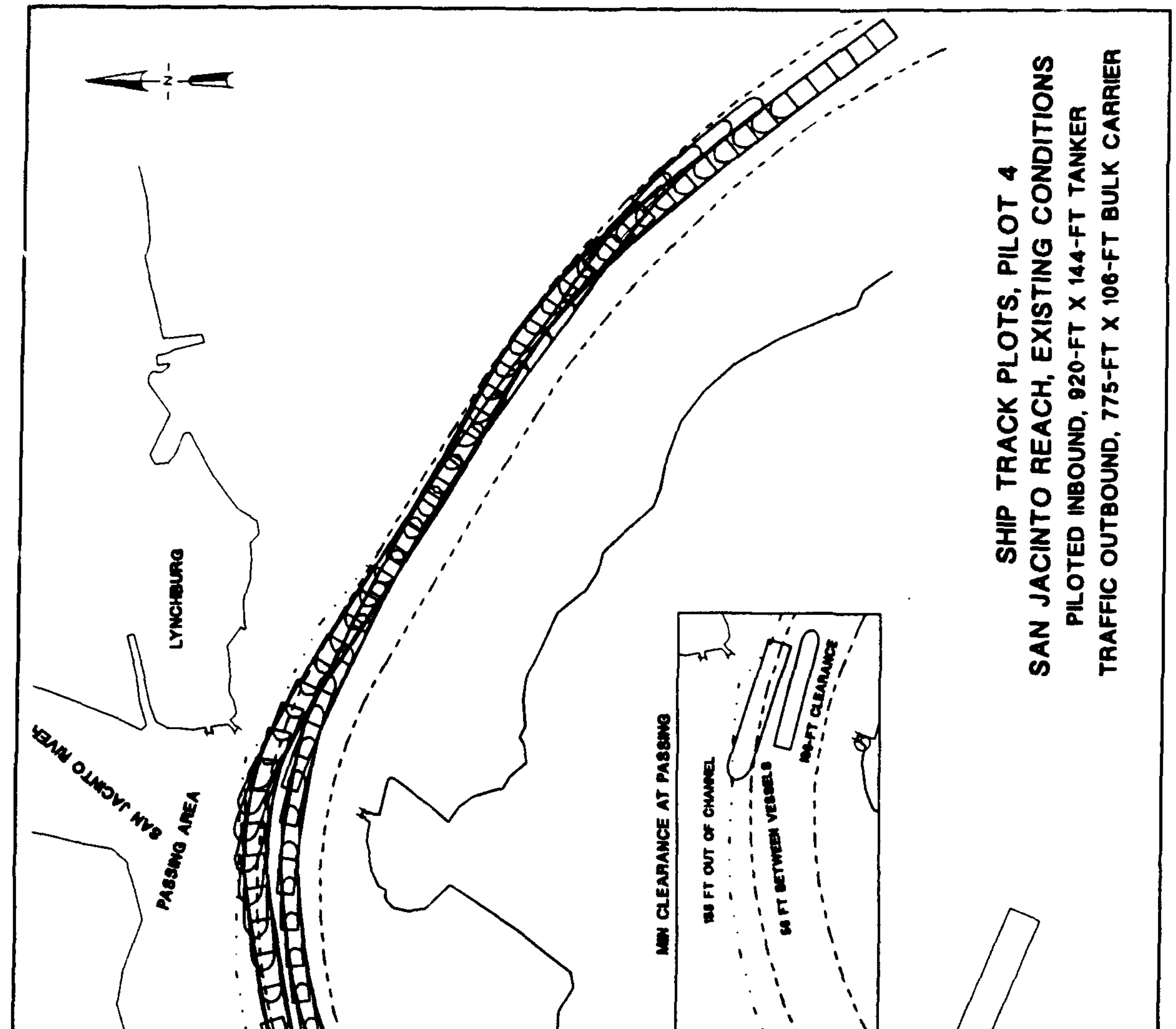
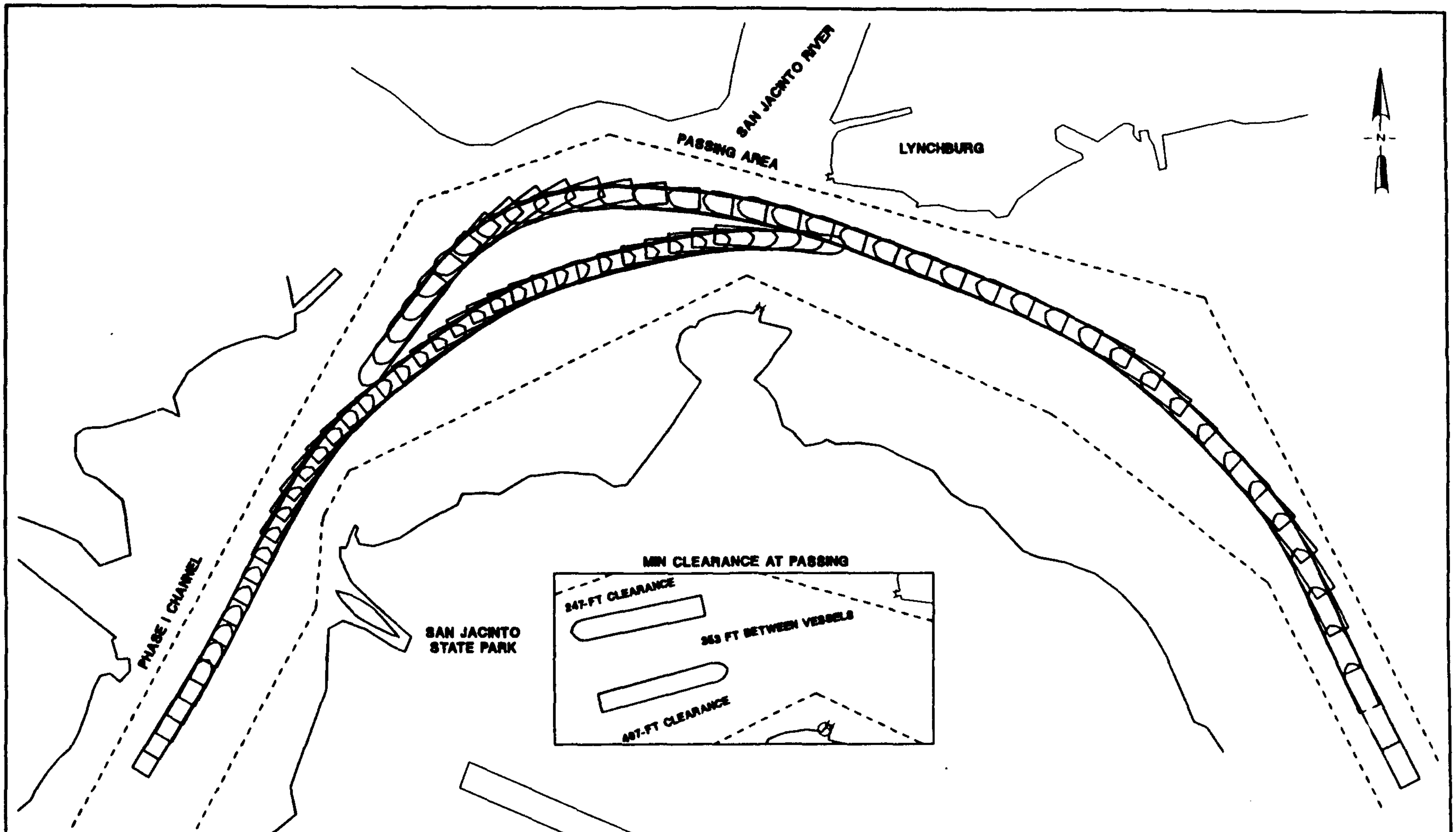
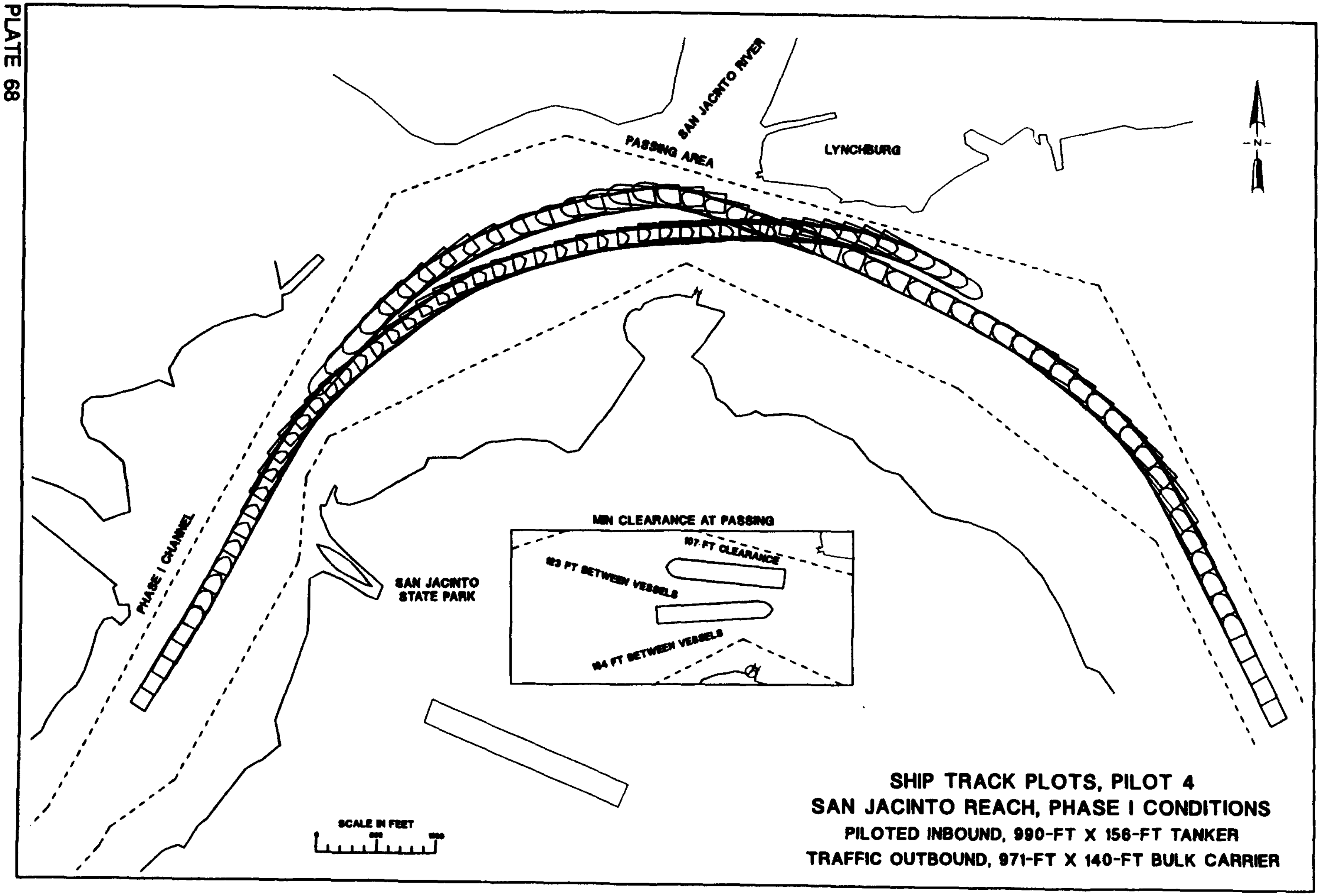

SHIP TRACK PLOTS, PILOT 4
SAN JACINTO REACH, EXISTING CONDITIONS
PILOTED INBOUND, 920-FT X 144-FT TANKER
TRAFFIC OUTBOUND, 775-FT X 106-FT BULK CARRIER
LYNCHBURG
SAN JACINTO RIVER
PASSING AREA
40-FT CONTOUR
40 FT CONTOUR
EXISTING CHANNEL
SAN JACINTO STATE PARK
MIN CLEARANCE AT PASSING
158 FT OUT OF CHANNEL
56 FT BETWEEN VESSELS
106-FT CLEARANCE
SCALE IN FEET
N

PLATE 66

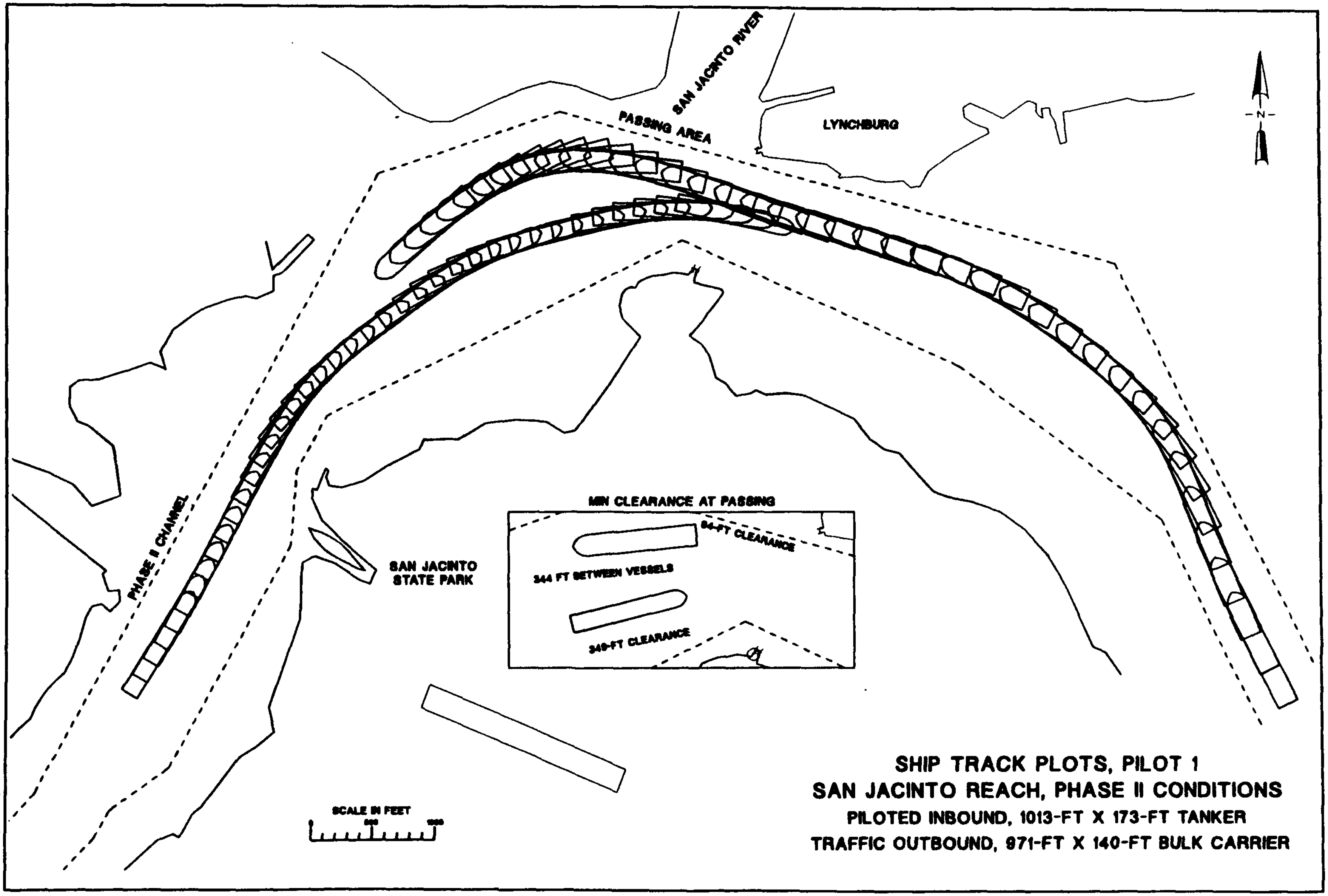


SHIP TRACK PLOTS, PILOT 1
SAN JACINTO REACH, PHASE I CONDITIONS
PILOTED INBOUND, 990-FT X 156-FT TANKER
TRAFFIC OUTBOUND, 971-FT X 140-FT BULK CARRIER

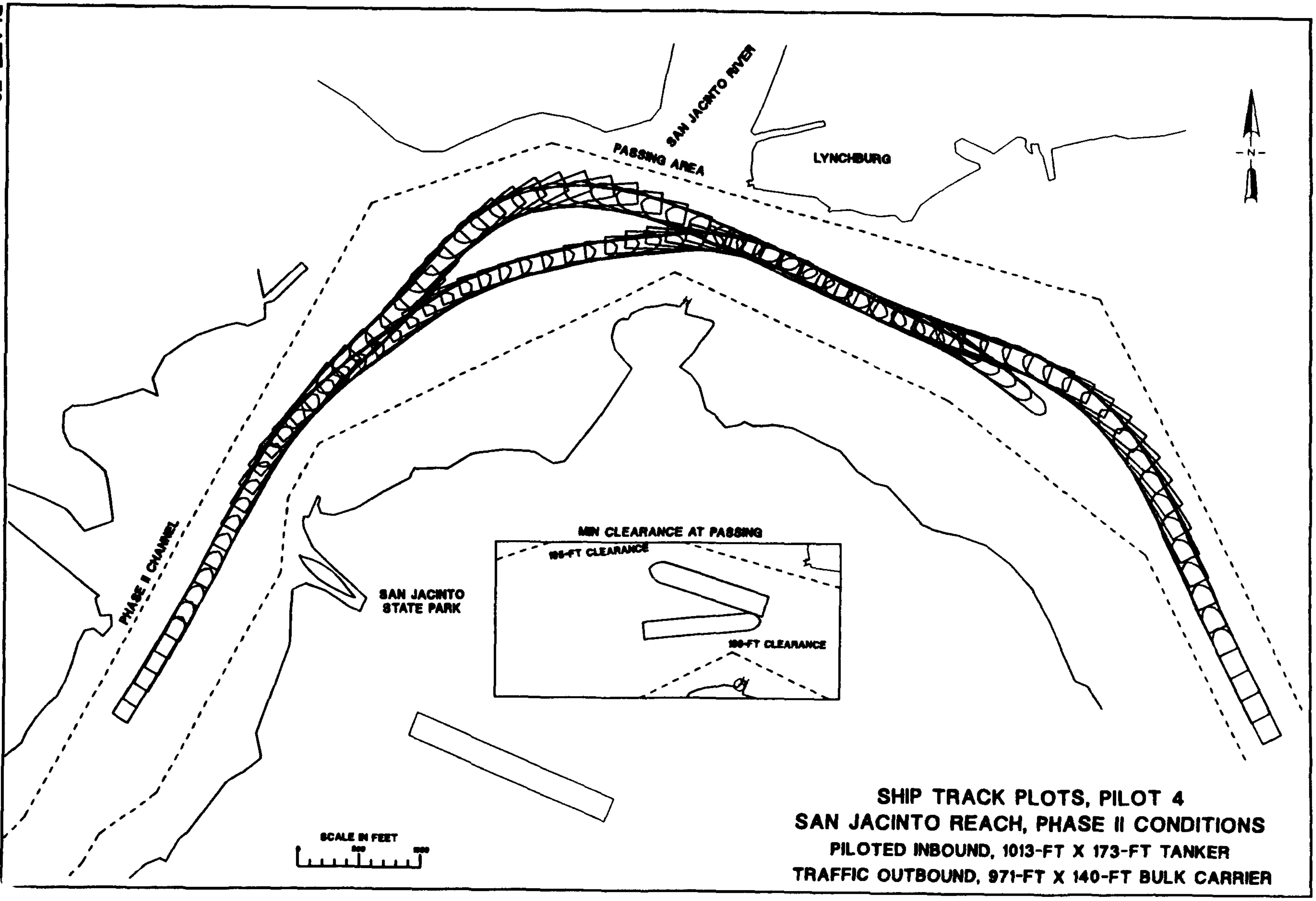


SHIP TRACK PLOTS, PILOT 4
SAN JACINTO REACH, PHASE I CONDITIONS
PILOTED INBOUND, 990-FT X 156-FT TANKER
TRAFFIC OUTBOUND, 971-FT X 140-FT BULK CARRIER

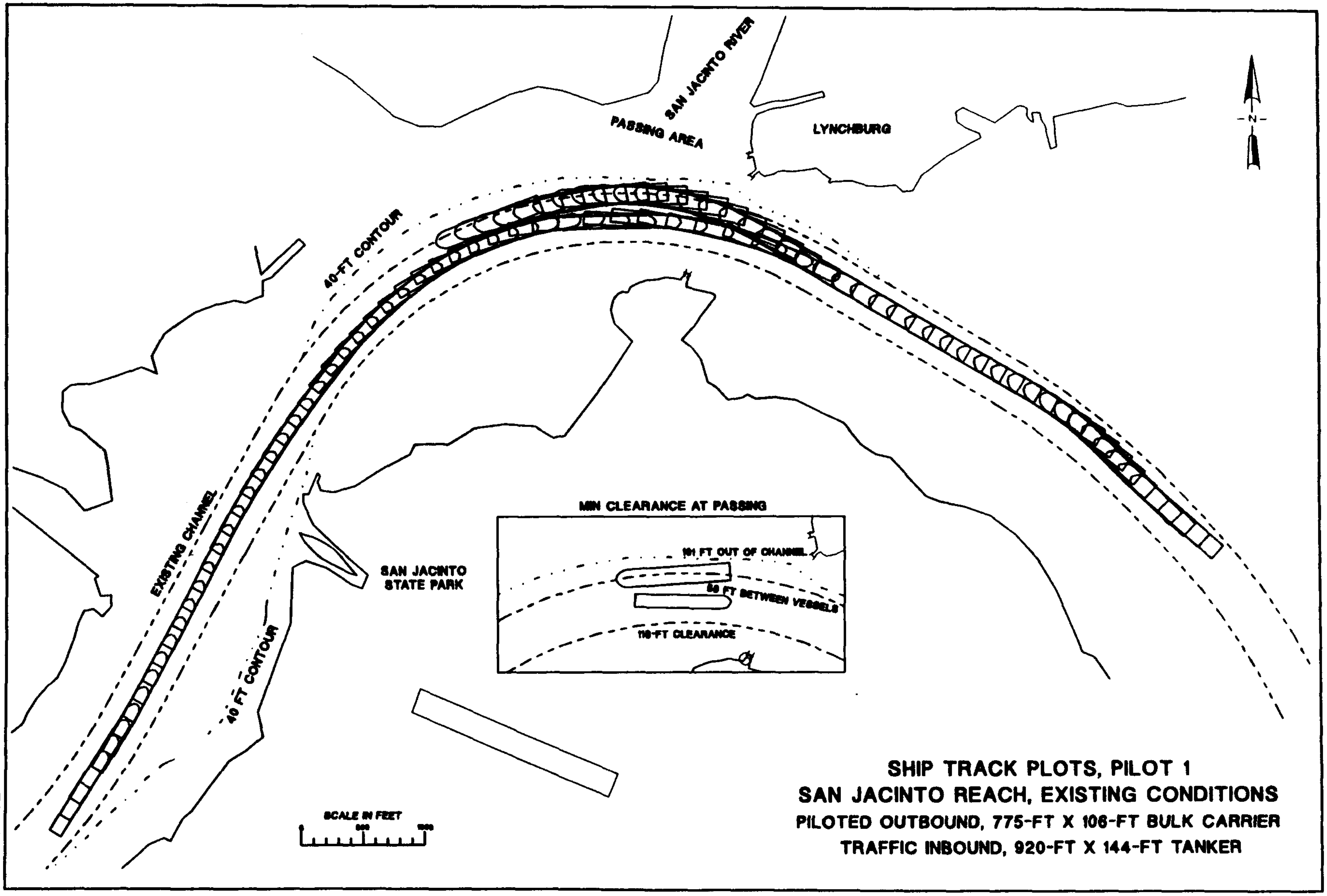
PLATE 68



SHIP TRACK PLOTS, PILOT 1
SAN JACINTO REACH, PHASE II CONDITIONS
PILOTED INBOUND, 1013-FT X 173-FT TANKER
TRAFFIC OUTBOUND, 971-FT X 140-FT BULK CARRIER



SHIP TRACK PLOTS, PILOT 4
SAN JACINTO REACH, PHASE II CONDITIONS
PILOTED INBOUND, 1013-FT X 173-FT TANKER
TRAFFIC OUTBOUND, 971-FT X 140-FT BULK CARRIER



SHIP TRACK PLOTS, PILOT 1
SAN JACINTO REACH, EXISTING CONDITIONS
PILOTED OUTBOUND, 775-FT X 106-FT BULK CARRIER
TRAFFIC INBOUND, 920-FT X 144-FT TANKER

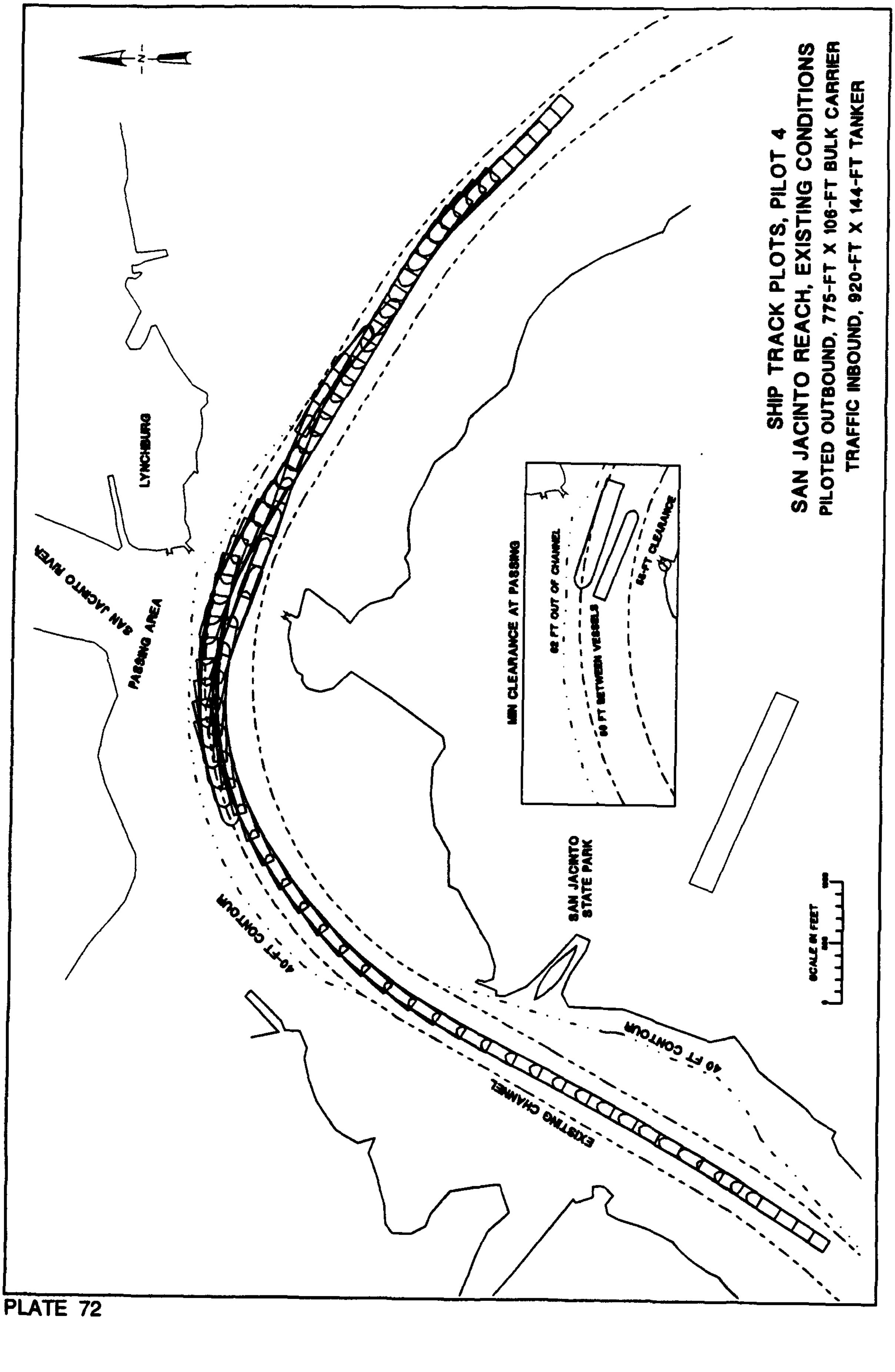
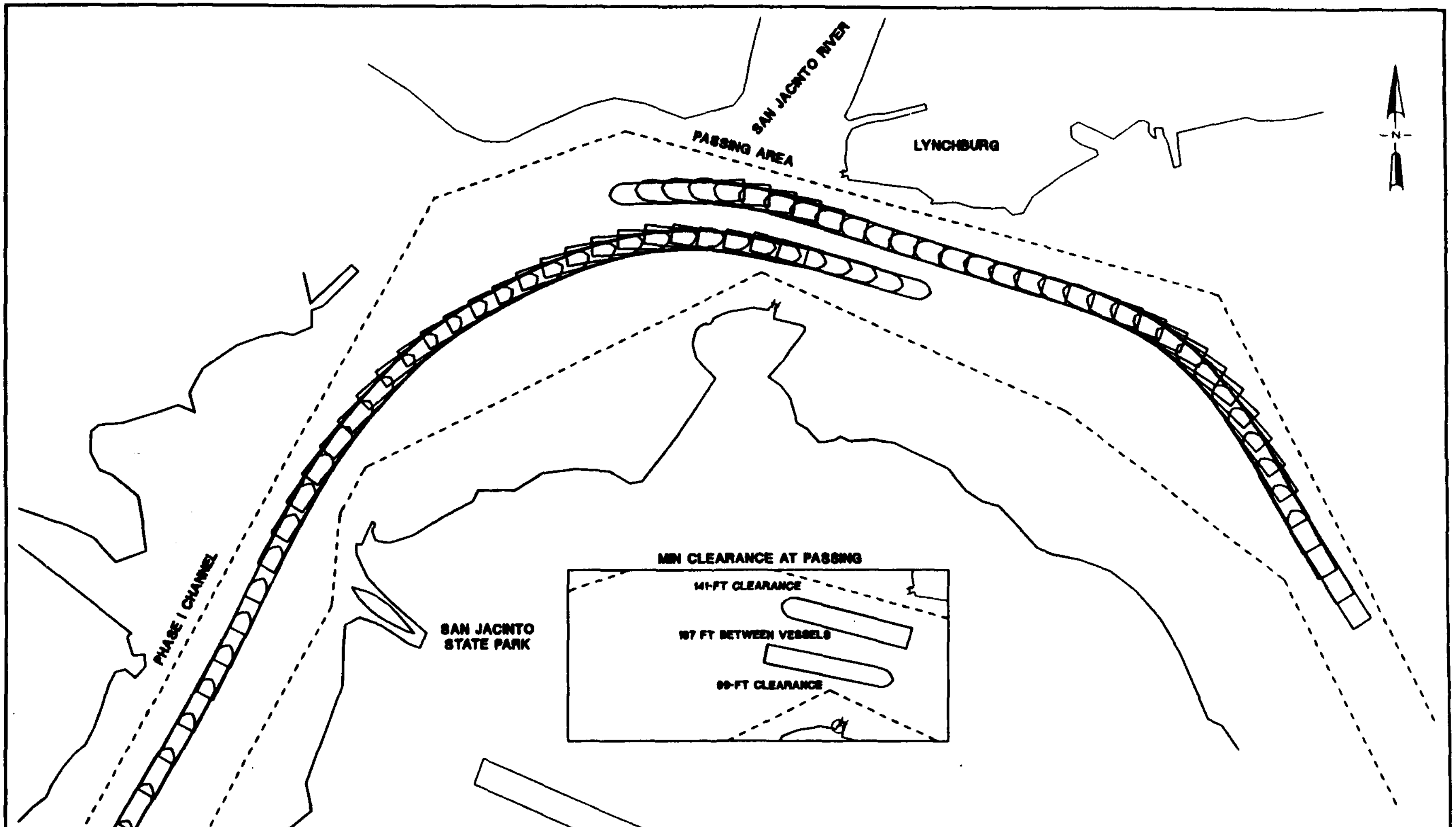
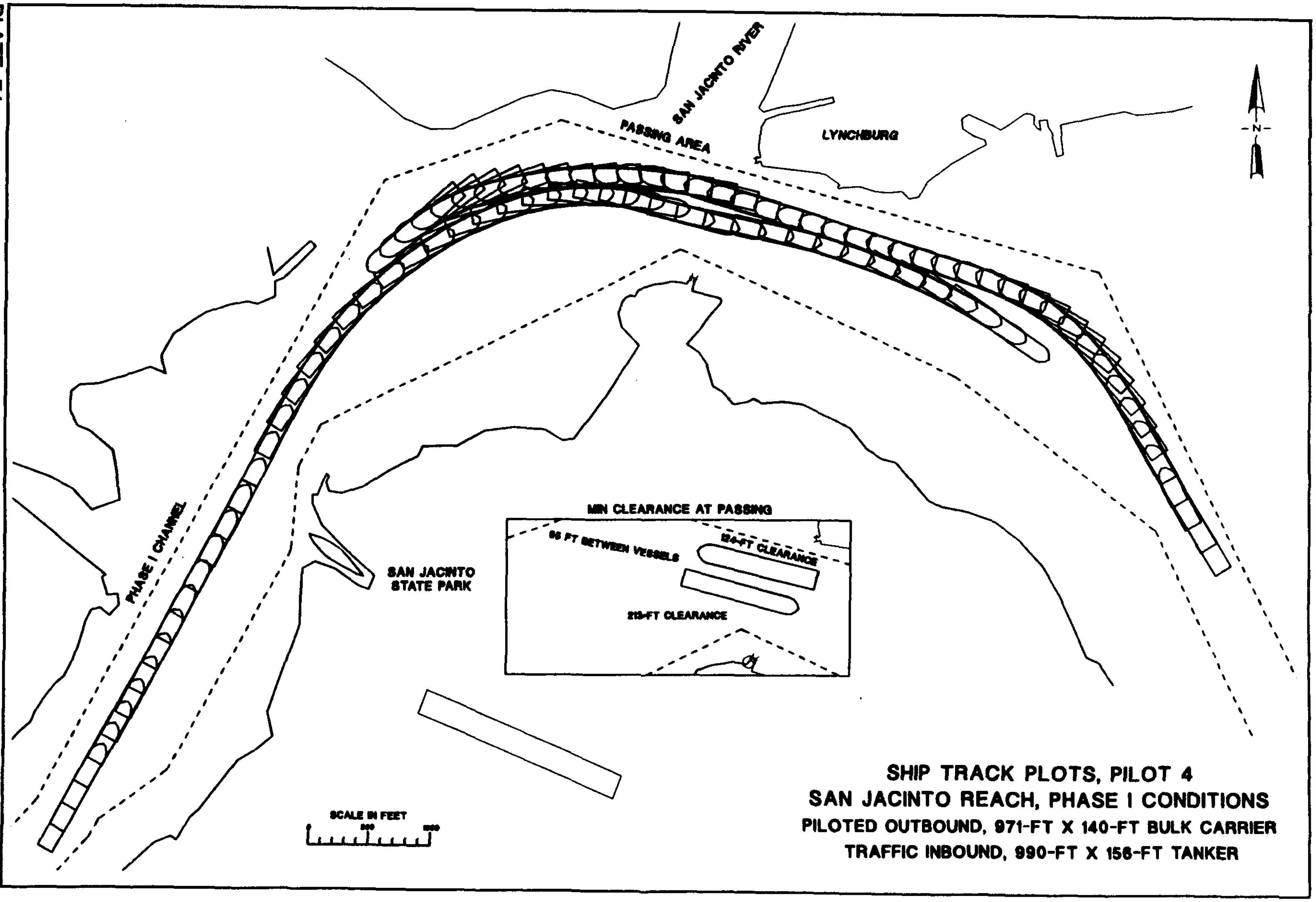

SHIP TRACK PLOTS, PILOT 4
SAN JACINTO REACH, EXISTING CONDITIONS
PILOTED OUTBOUND, 775-FT X 106-FT BULK CARRIER
TRAFFIC INBOUND, 920-FT X 144-FT TANKER
N
LYNCHBURG
SAN JACINTO RIVER
PASSING AREA
MIN CLEARANCE AT PASSING
92 FT OUT OF CHANNEL
56 FT BETWEEN VESSELS
55-FT CLEARANCE
SAN JACINTO STATE PARK
40-FT CONTOUR
40 FT CONTOUR
EXISTING CHANNEL
SCALE IN FEET

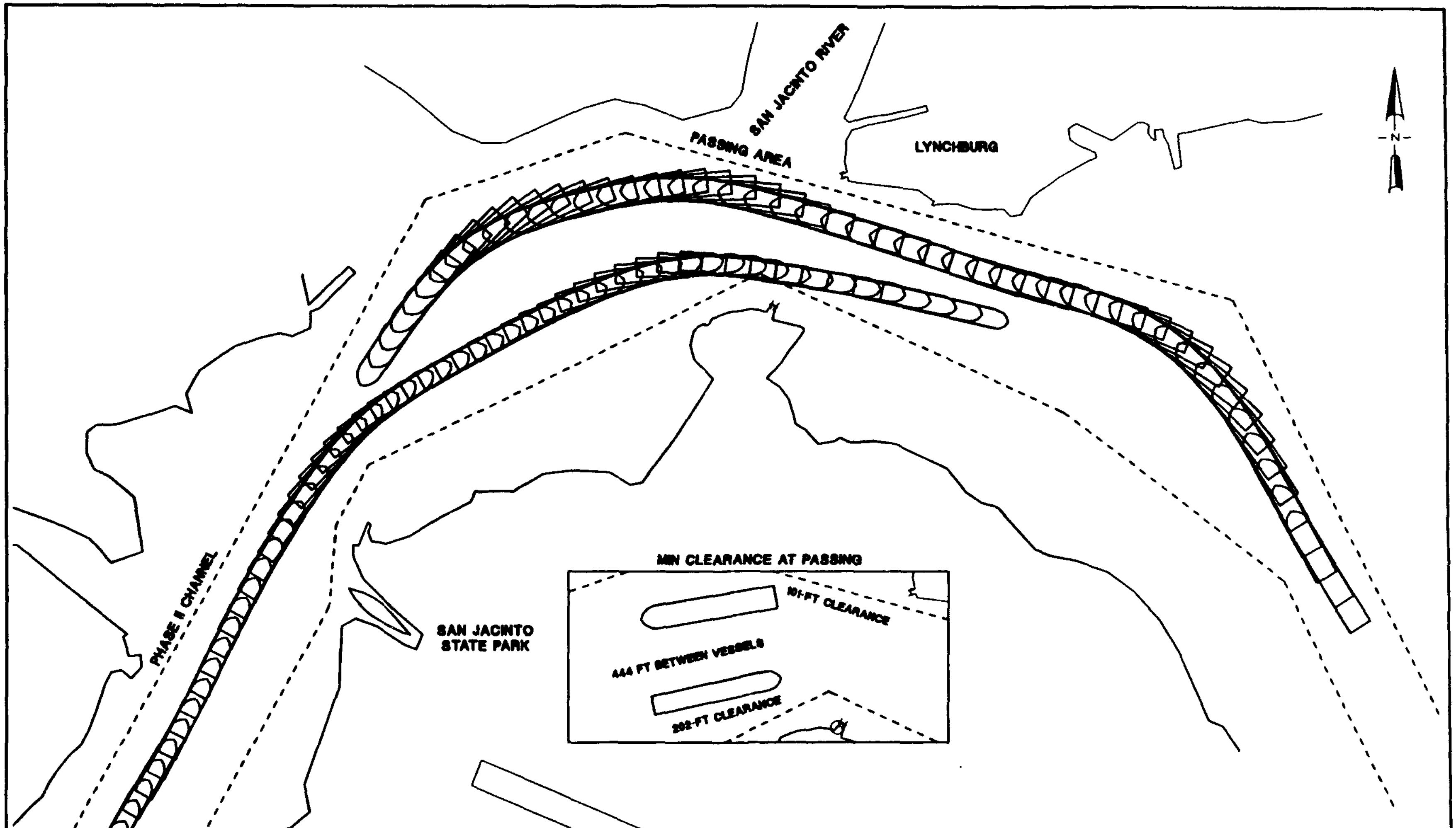
PLATE 72



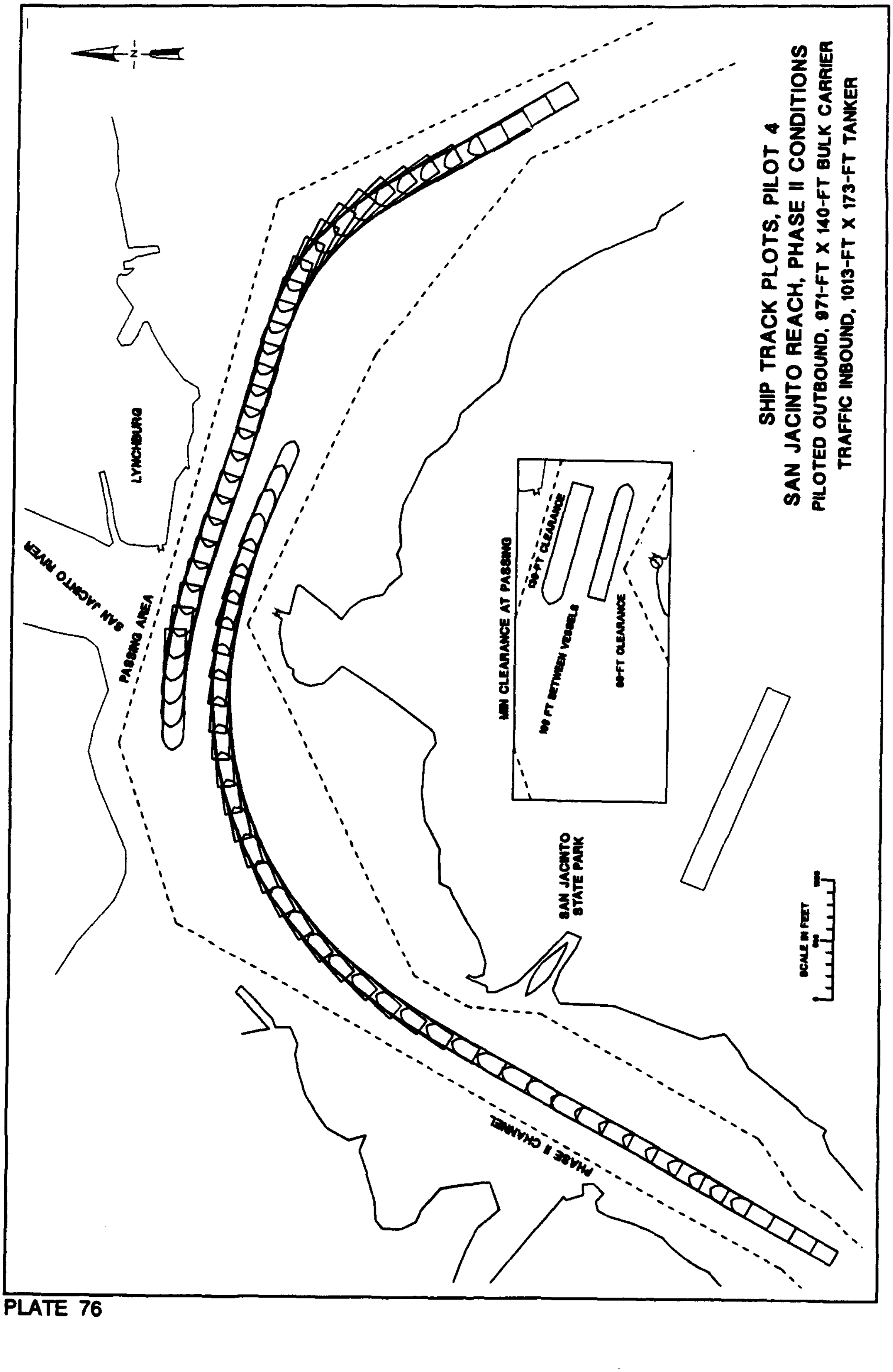
SHIP TRACK PLOTS, PILOT 1
SAN JACINTO REACH, PHASE I CONDITIONS
PILOTED OUTBOUND, 971-FT X 140-FT BULK CARRIER
TRAFFIC INBOUND, 990-FT X 156-FT TANKER



SHIP TRACK PLOTS, PILOT 4
SAN JACINTO REACH, PHASE I CONDITIONS
PILOTED OUTBOUND, 971-FT X 140-FT BULK CARRIER
TRAFFIC INBOUND, 990-FT X 156-FT TANKER

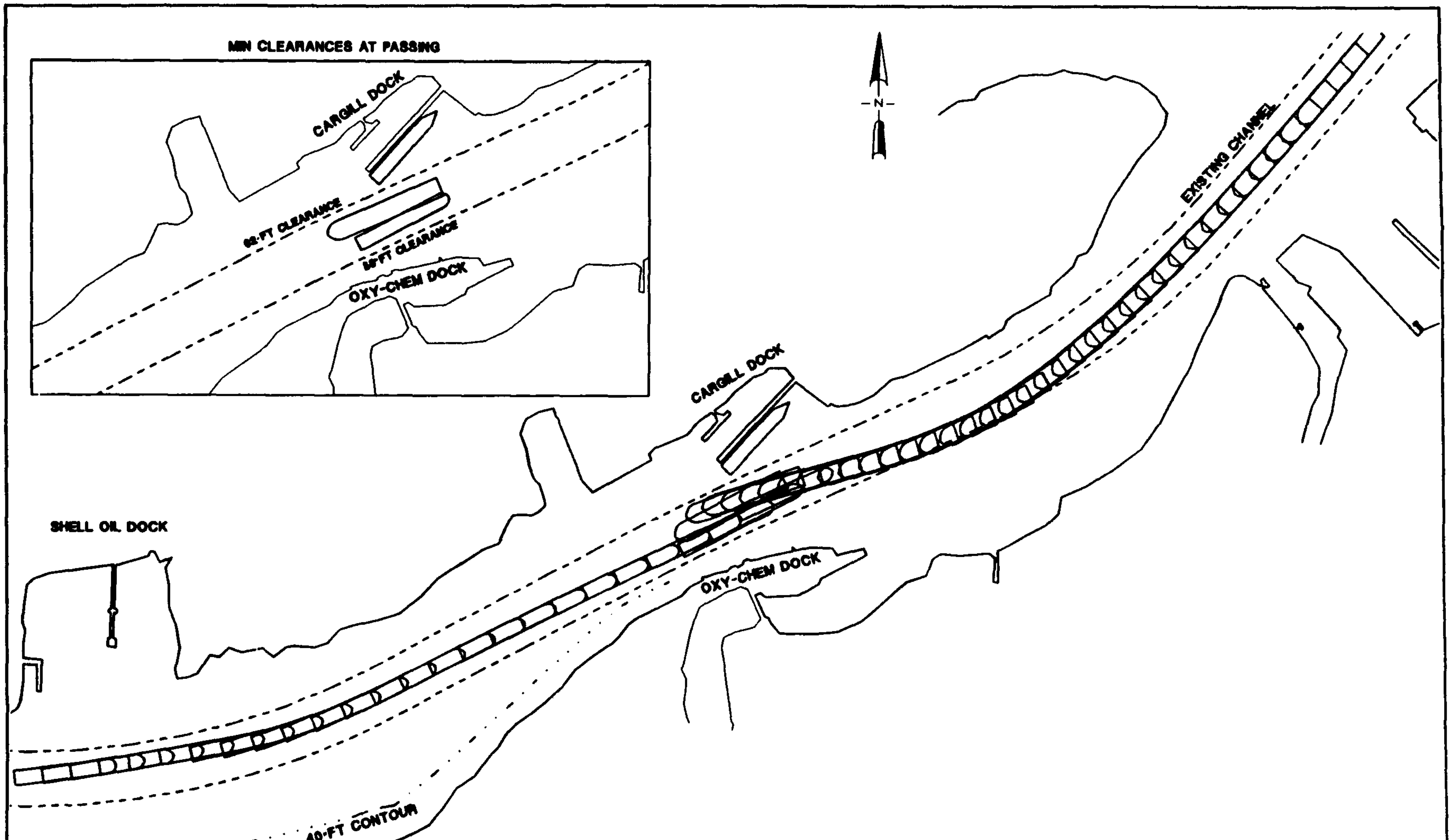


SHIP TRACK PLOTS, PILOT 1
SAN JACINTO REACH, PHASE II CONDITIONS
PILOTED OUTBOUND, 971-FT X 140-FT BULK CARRIER
TRAFFIC INBOUND, 1013-FT X 173-FT TANKER



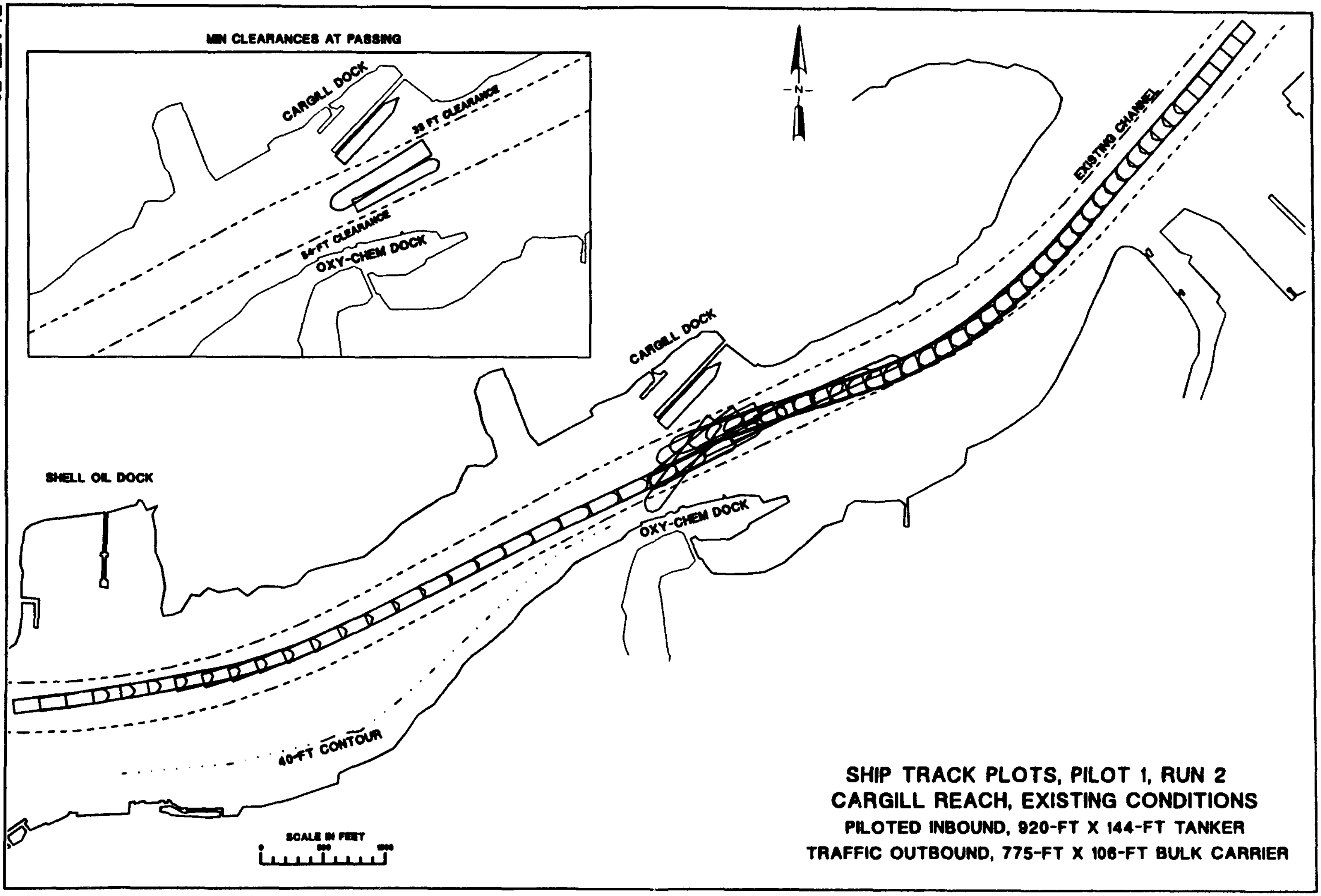
SHIP TRACK PLOTS, PILOT 4
SAN JACINTO REACH, PHASE II CONDITIONS
PILOTED OUTBOUND, 971-FT X 140-FT BULK CARRIER
TRAFFIC INBOUND, 1013-FT X 173-FT TANKER
N
LYNCHBURG
SAN JACINTO RIVER
PASSING AREA
MIN CLEARANCE AT PASSING
SAN JACINTO
STATE PARK
SCALE IN FEET
PHASE II CHANNEL

PLATE 76

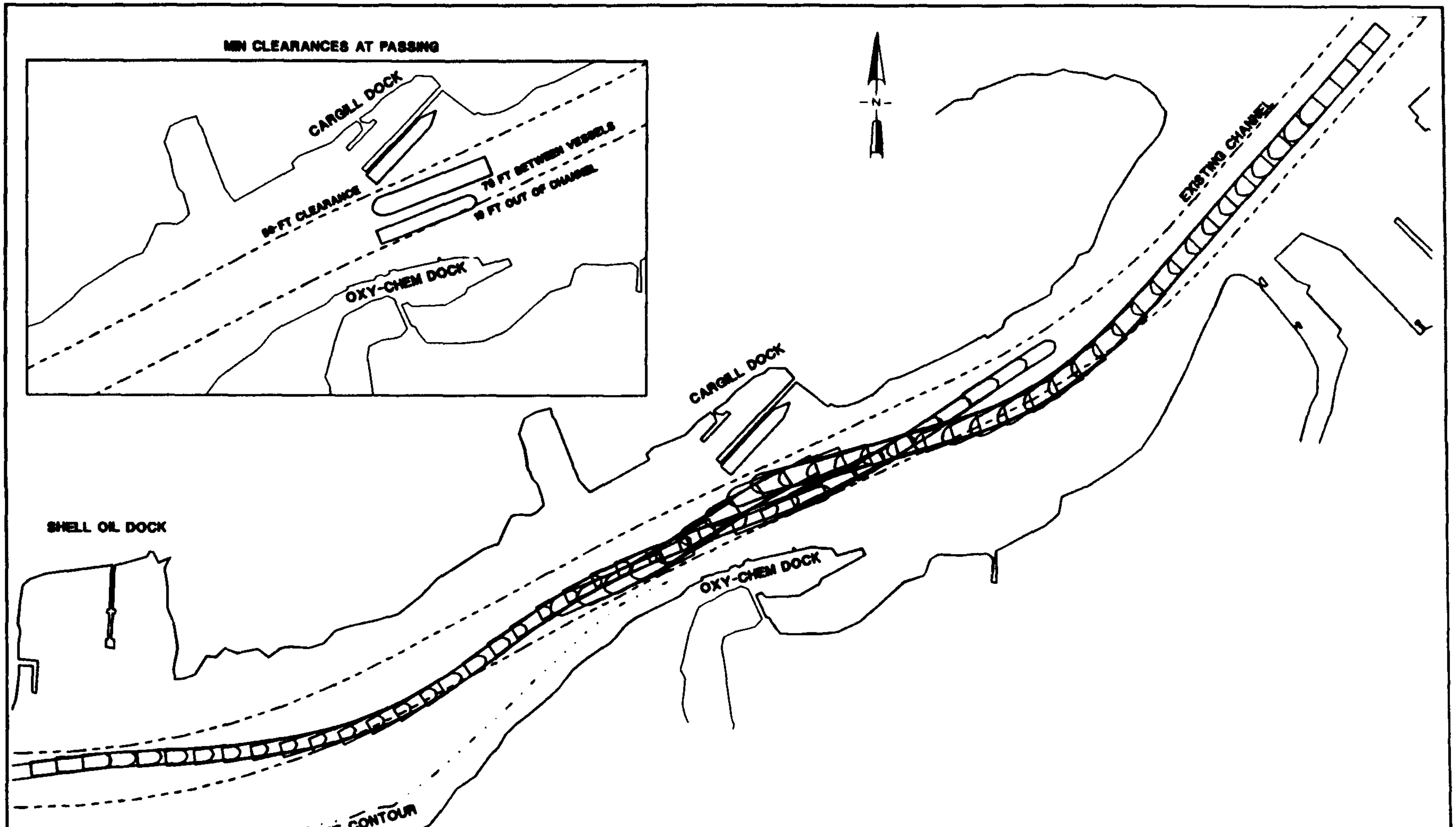


SHIP TRACK PLOTS, PILOT 1
CARGILL REACH, EXISTING CONDITIONS
PILOTED INBOUND, 920-FT X 144-FT TANKER
TRAFFIC OUTBOUND, 775-FT X 106-FT BULK CARRIER

PLATE 78



SHIP TRACK PLOTS, PILOT 1, RUN 2
CARGILL REACH, EXISTING CONDITIONS
PILOTED INBOUND, 920-FT X 144-FT TANKER
TRAFFIC OUTBOUND, 775-FT X 106-FT BULK CARRIER



SHIP TRACK PLOTS, PILOT 2
CARGILL REACH, EXISTING CONDITIONS
PILOTED INBOUND, 920-FT X 144-FT TANKER
TRAFFIC OUTBOUND, 775-FT X 106-FT BULK CARRIER

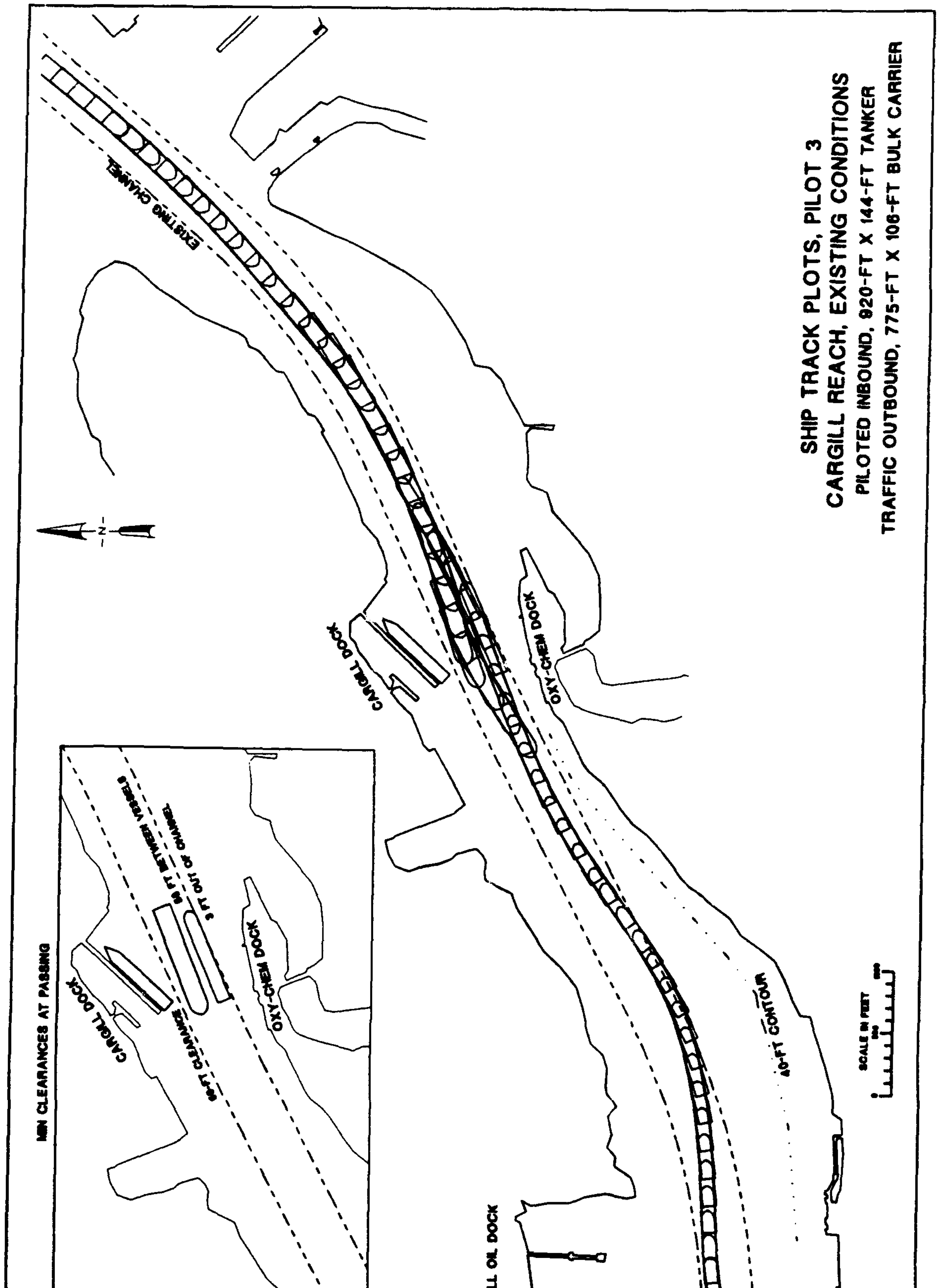
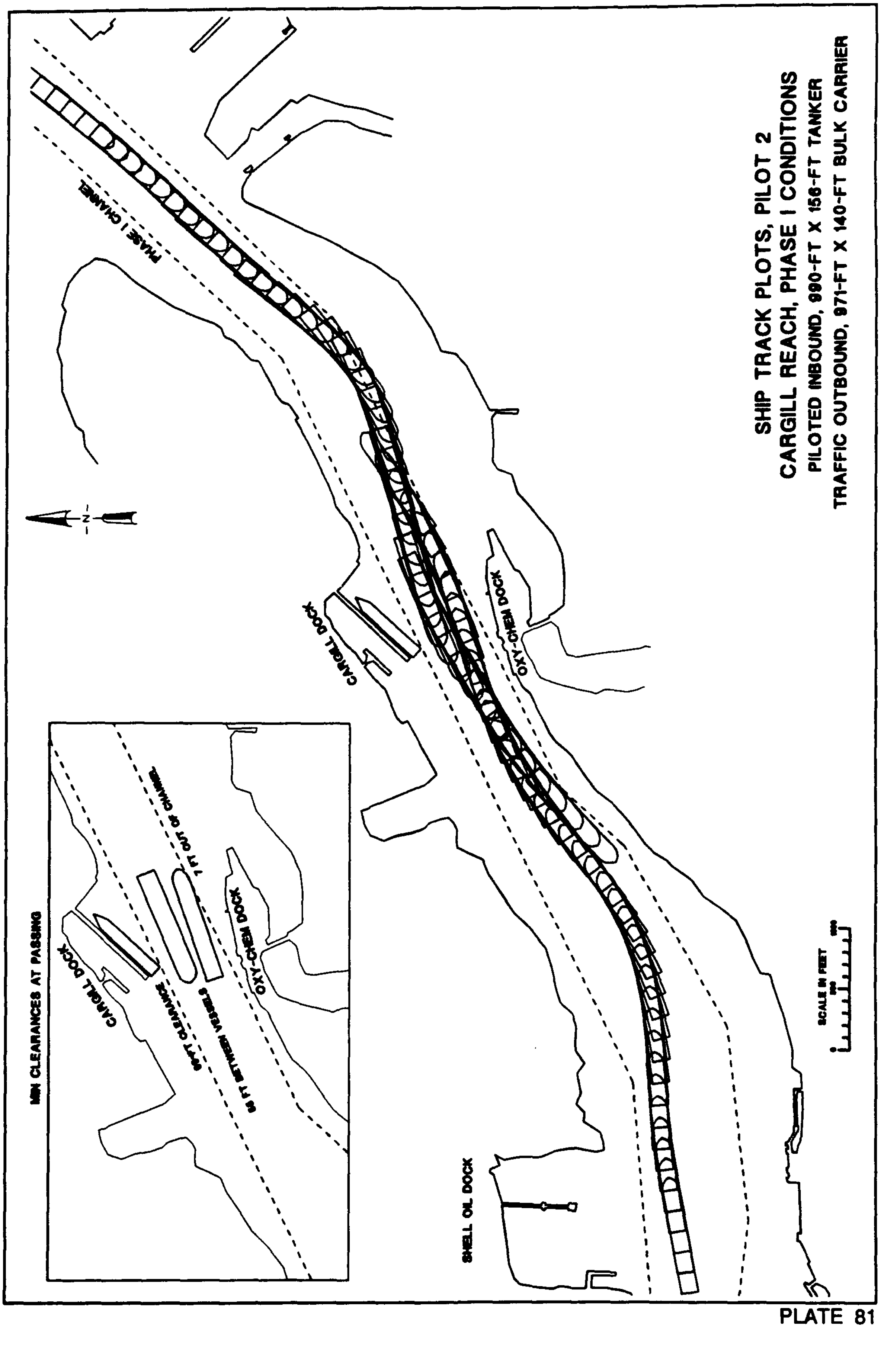

SHIP TRACK PLOTS, PILOT 3
CARGILL REACH, EXISTING CONDITIONS
PILOTED INBOUND, 920-FT X 144-FT TANKER
TRAFFIC OUTBOUND, 775-FT X 106-FT BULK CARRIER
EXISTING CHANNEL
CARGILL DOCK
OXY-CHEM DOCK
SHELL OIL DOCK
40-FT CONTOUR
SCALE IN FEET
N
MIN CLEARANCES AT PASSING
CARGILL DOCK
OXY-CHEM DOCK
60-FT CLEARANCE
86 FT BETWEEN VESSELS
3 FT OUT OF CHANNEL

PLATE 80


SHIP TRACK PLOTS, PILOT 2
CARGILL REACH, PHASE I CONDITIONS
PILOTED INBOUND, 990-FT X 156-FT TANKER
TRAFFIC OUTBOUND, 971-FT X 140-FT BULK CARRIER
PHASE I CHANNEL
CARGILL DOCK
OXY-CHEM DOCK
SHELL OIL DOCK
N
SCALE IN FEET
MIN CLEARANCES AT PASSING
80-FT CLEARANCE
7 FT OUT OF CHANNEL
56 FT BETWEEN VESSELS

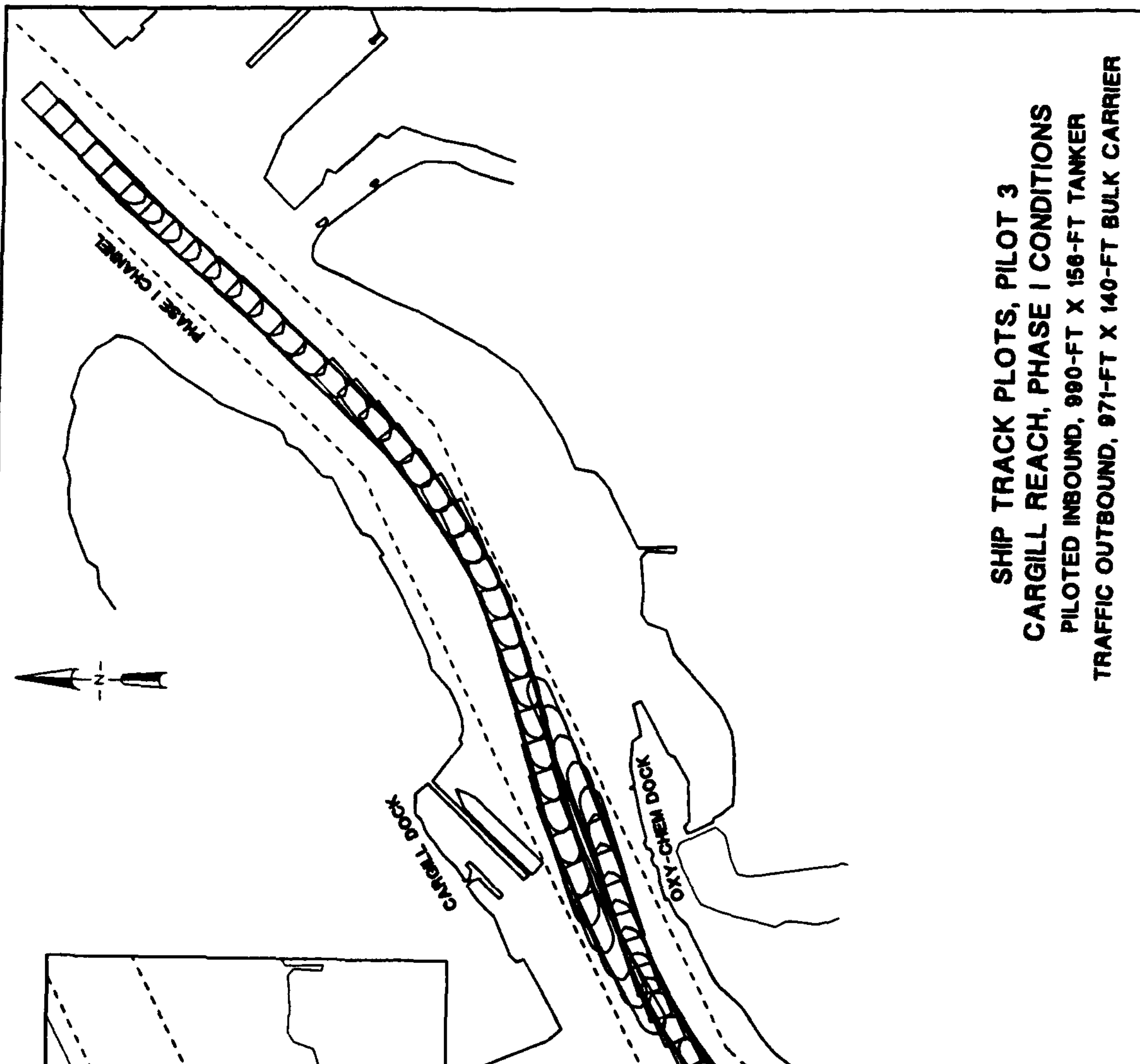
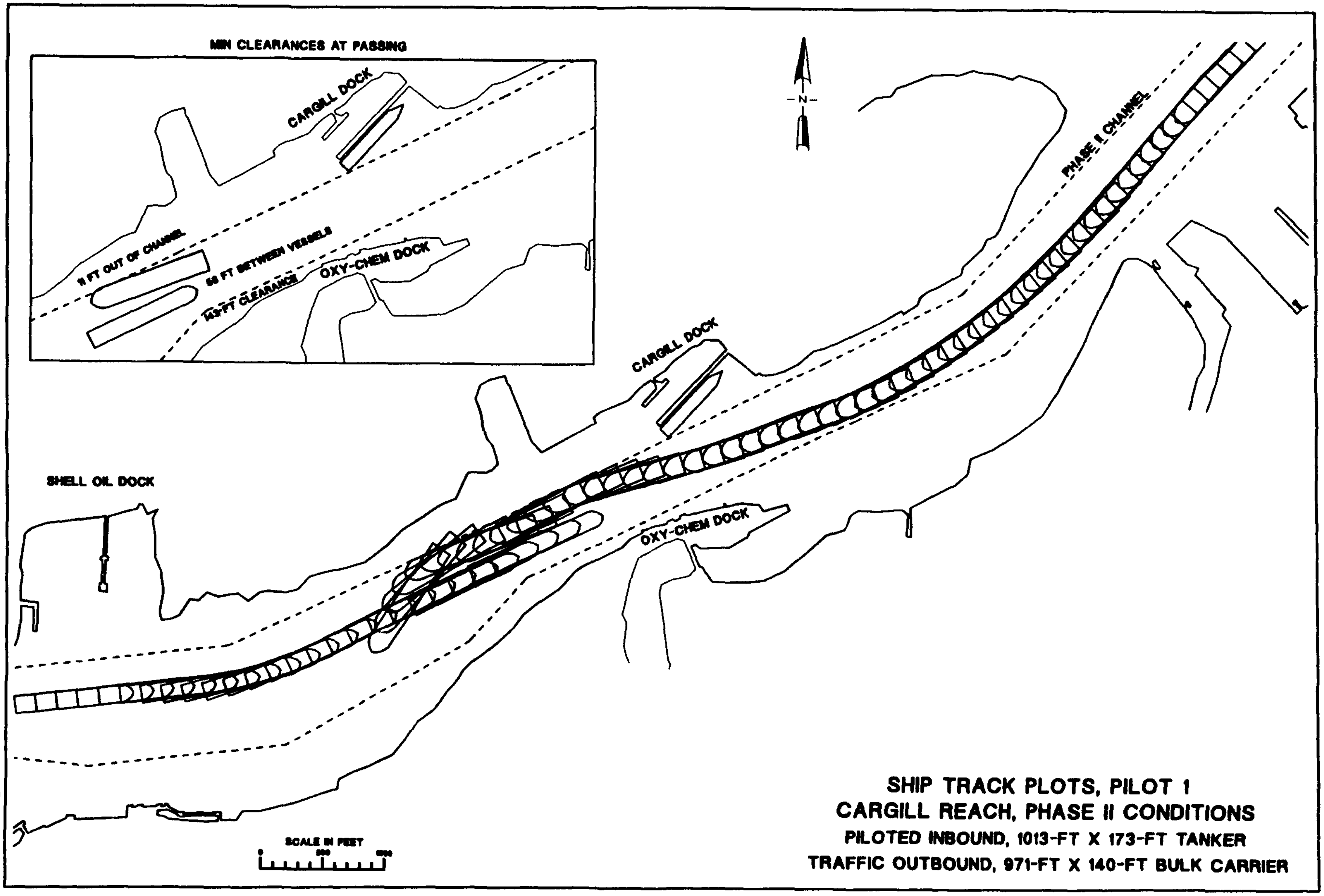
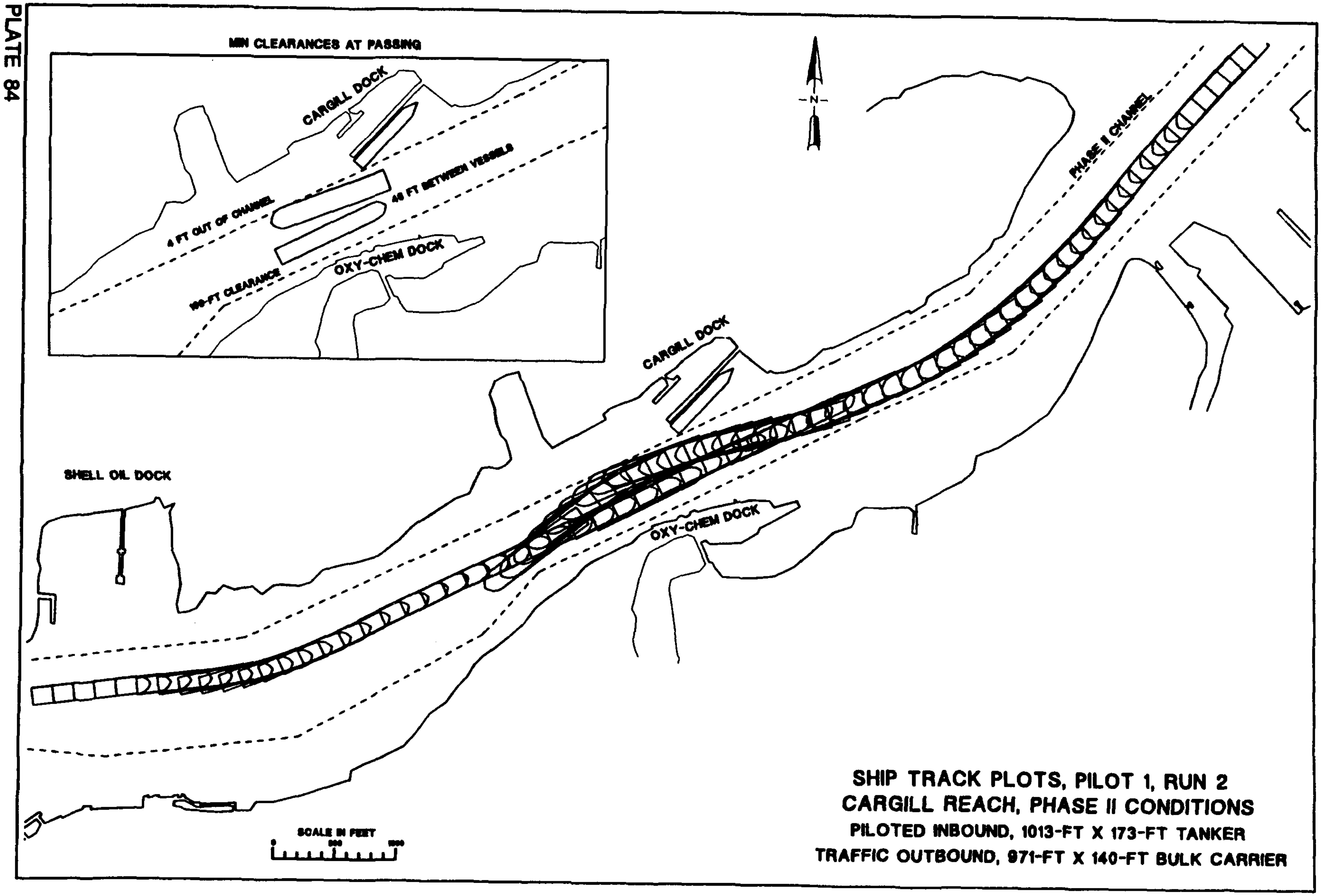

SHIP TRACK PLOTS, PILOT 3
CARGILL REACH, PHASE I CONDITIONS
PILOTED INBOUND, 990-FT X 156-FT TANKER
TRAFFIC OUTBOUND, 971-FT X 140-FT BULK CARRIER
PHASE I CHANNEL
CARGILL DOCK
OXY-CHEM DOCK
SHELL OIL DOCK
N
SCALE IN FEET
MIN CLEARANCES AT PASSING
CARGILL DOCK
OXY-CHEM DOCK
42-FT CLEARANCE

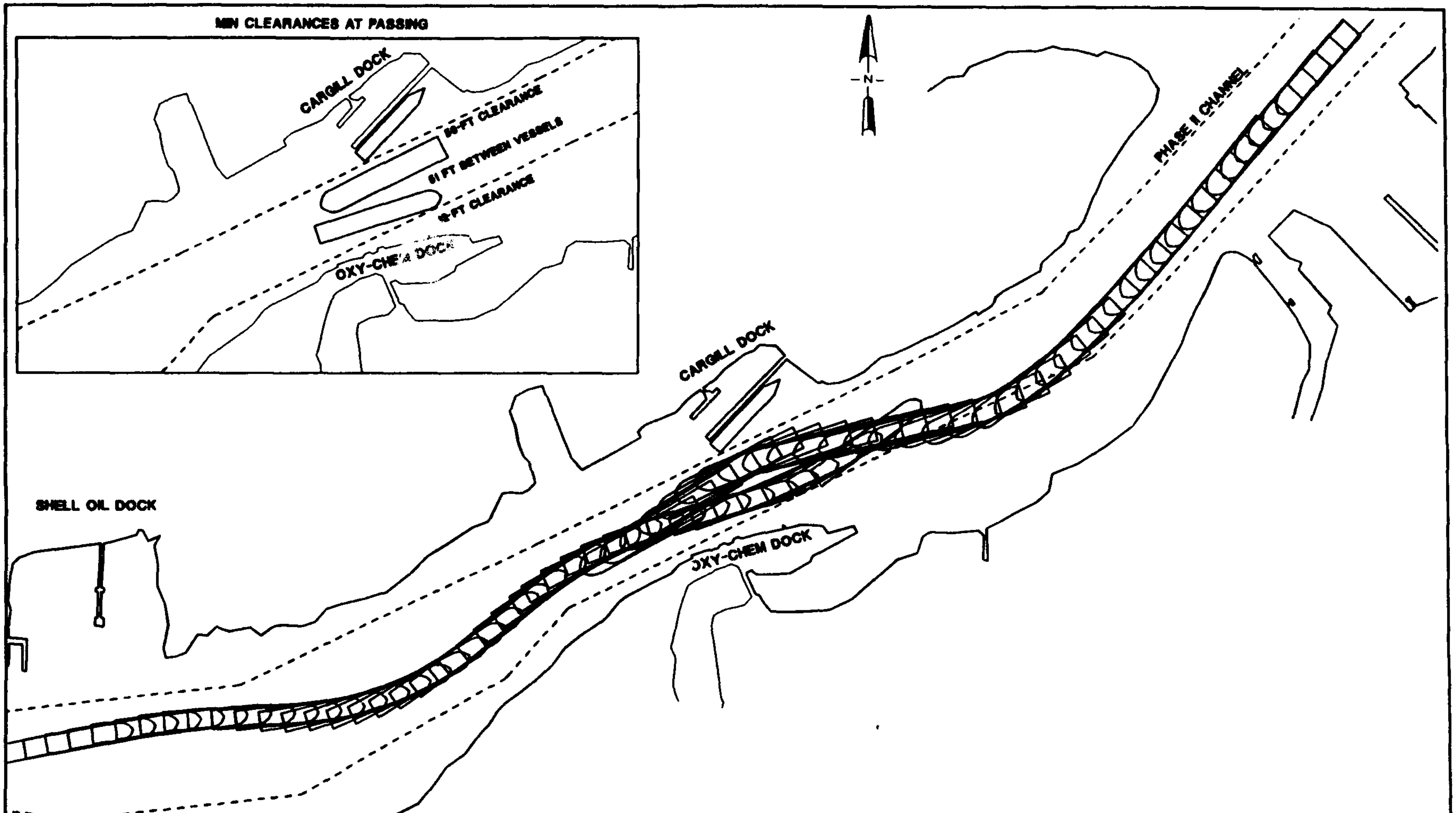
PLATE 82



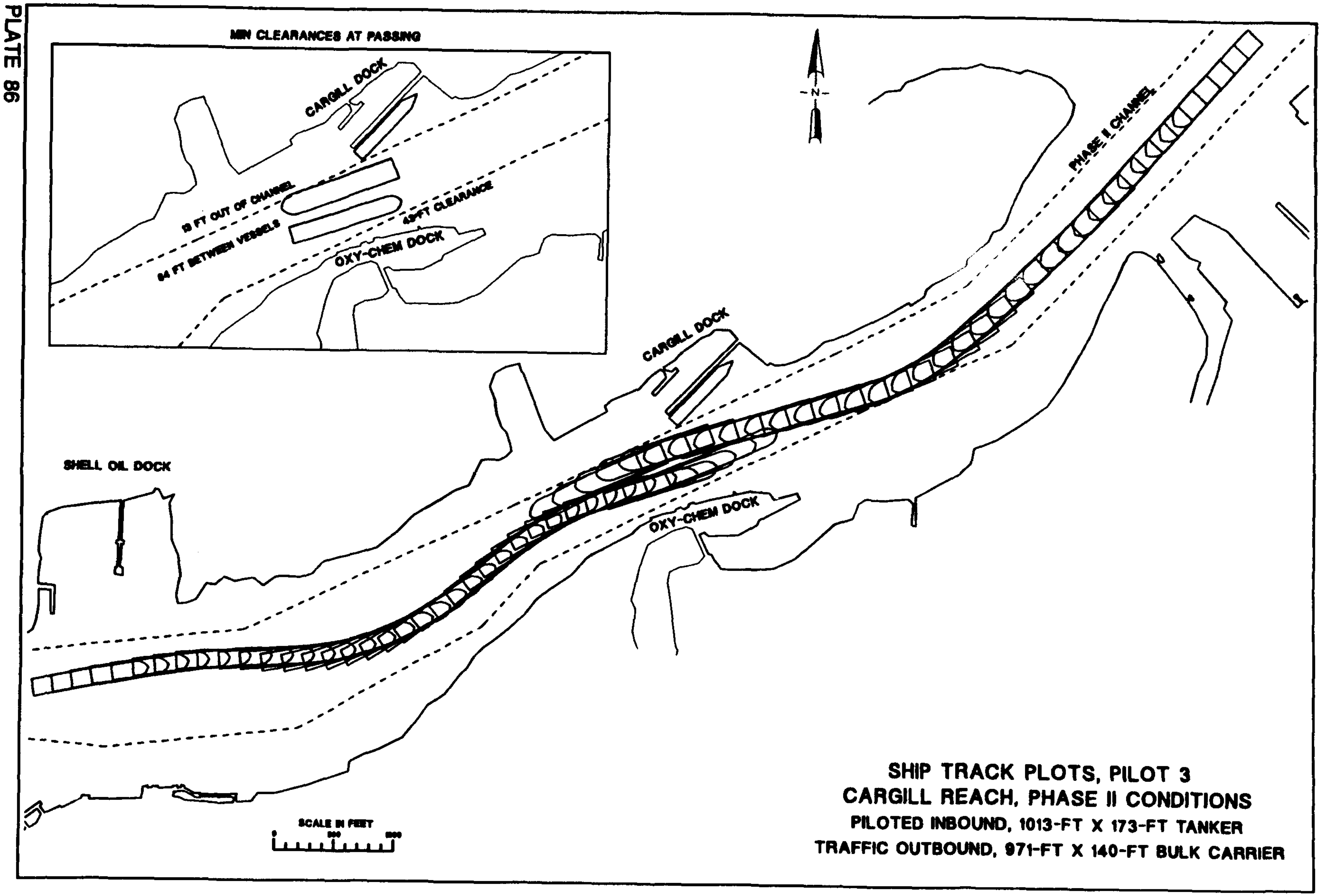
SHIP TRACK PLOTS, PILOT 1
CARGILL REACH, PHASE II CONDITIONS
PILOTED INBOUND, 1013-FT X 173-FT TANKER
TRAFFIC OUTBOUND, 971-FT X 140-FT BULK CARRIER



SHIP TRACK PLOTS, PILOT 1, RUN 2
CARGILL REACH, PHASE II CONDITIONS
PILOTED INBOUND, 1013-FT X 173-FT TANKER
TRAFFIC OUTBOUND, 971-FT X 140-FT BULK CARRIER

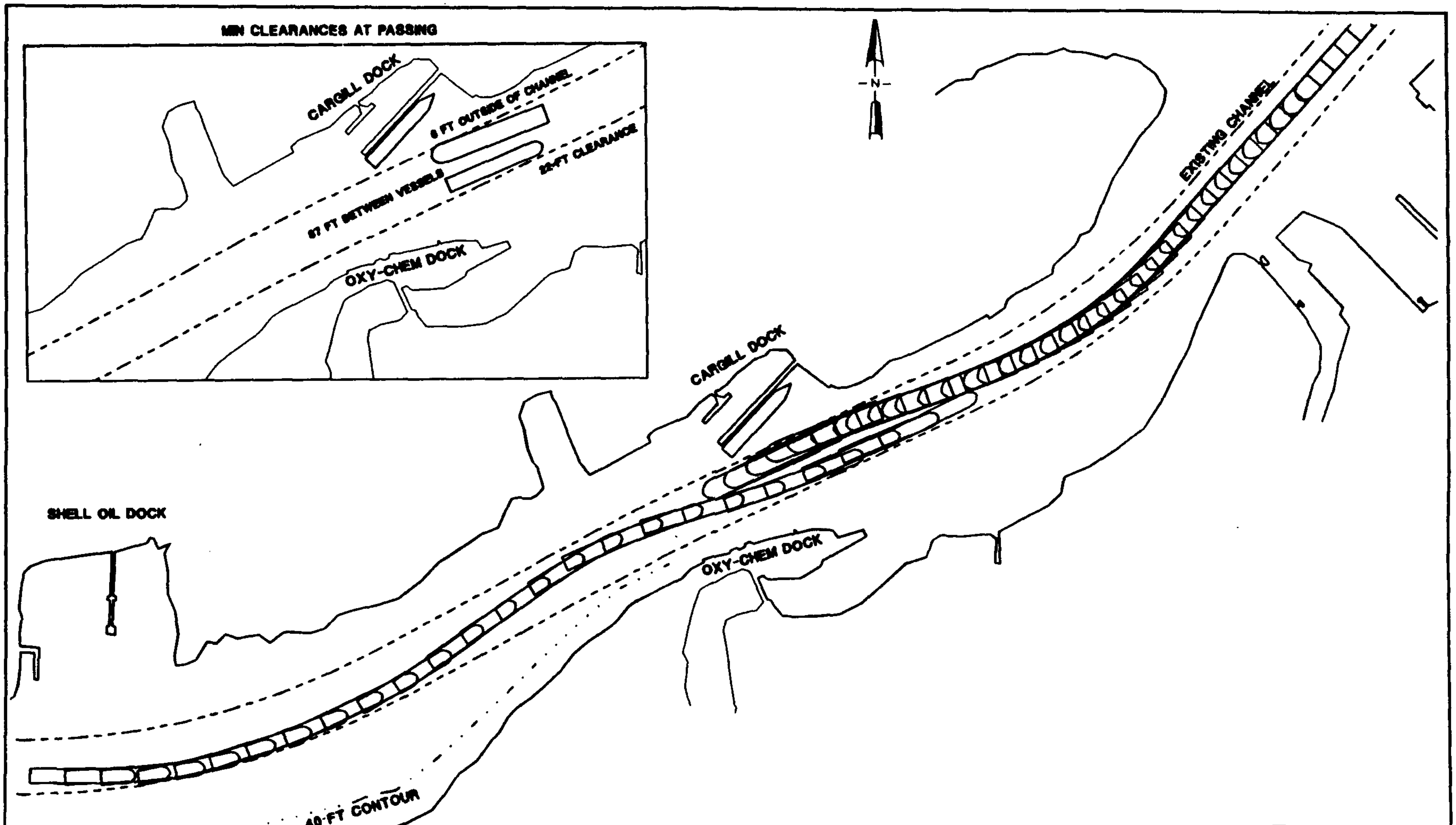


SHIP TRACK PLOTS, PILOT 2
CARGILL REACH, PHASE II CONDITIONS
PILOTED INBOUND, 1013-FT X 173-FT TANKER
TRAFFIC OUTBOUND, 971-FT X 140-FT BULK CARRIER

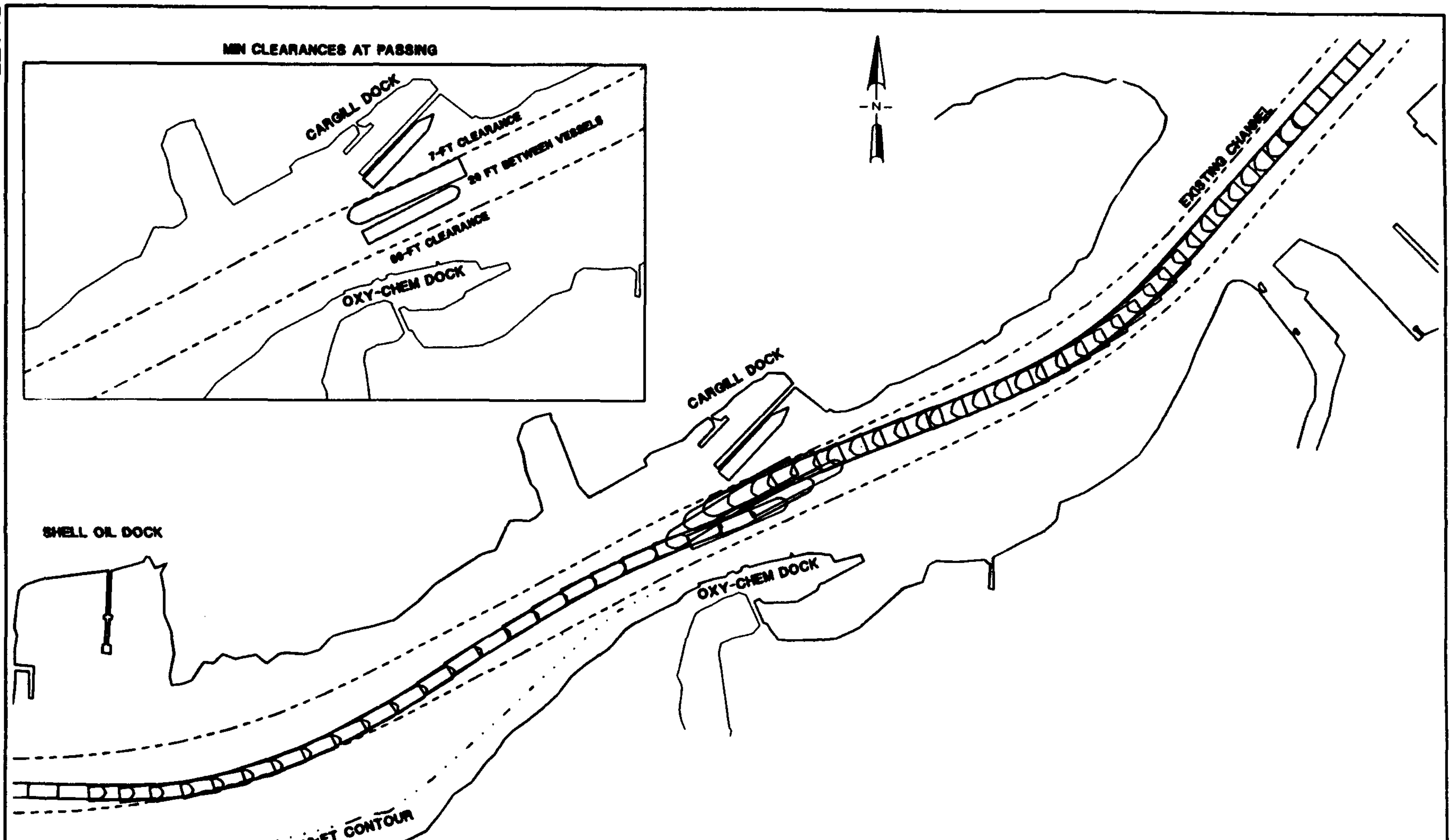


SHIP TRACK PLOTS, PILOT 3
CARGILL REACH, PHASE II CONDITIONS
PILOTED INBOUND, 1013-FT X 173-FT TANKER
TRAFFIC OUTBOUND, 971-FT X 140-FT BULK CARRIER

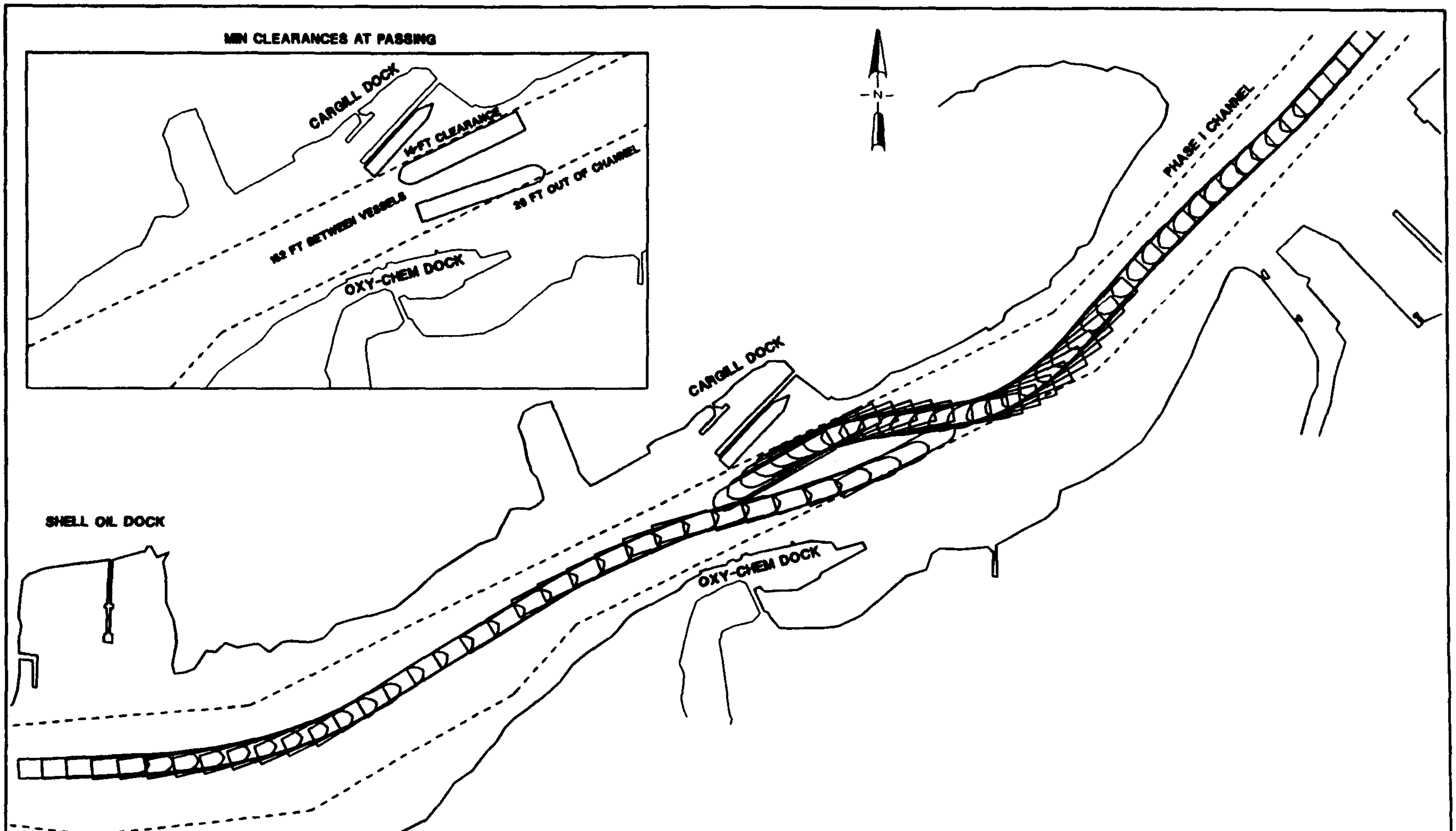
PLATE 86



SHIP TRACK PLOTS, PILOT 2
CARGILL REACH, EXISTING CONDITIONS
PILOTED OUTBOUND, 775-FT X 106-FT BULK CARRIER
TRAFFIC INBOUND, 920-FT X 144-FT TANKER

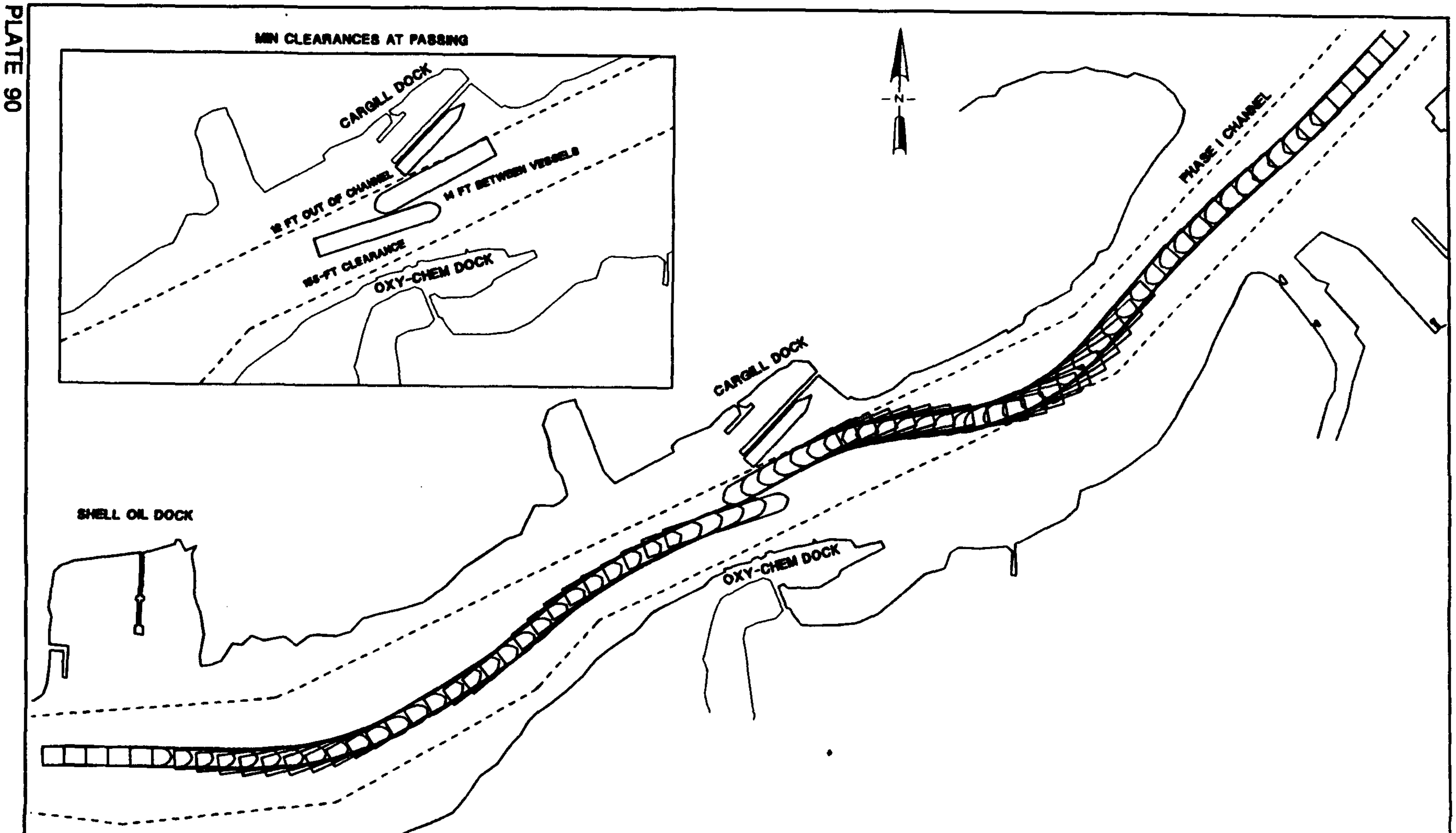


SHIP TRACK PLOTS, PILOT 3
CARGILL REACH, EXISTING CONDITIONS
PILOTED OUTBOUND, 775-FT X 106-FT BULK CARRIER
TRAFFIC INBOUND, 920-FT X 144-FT TANKER

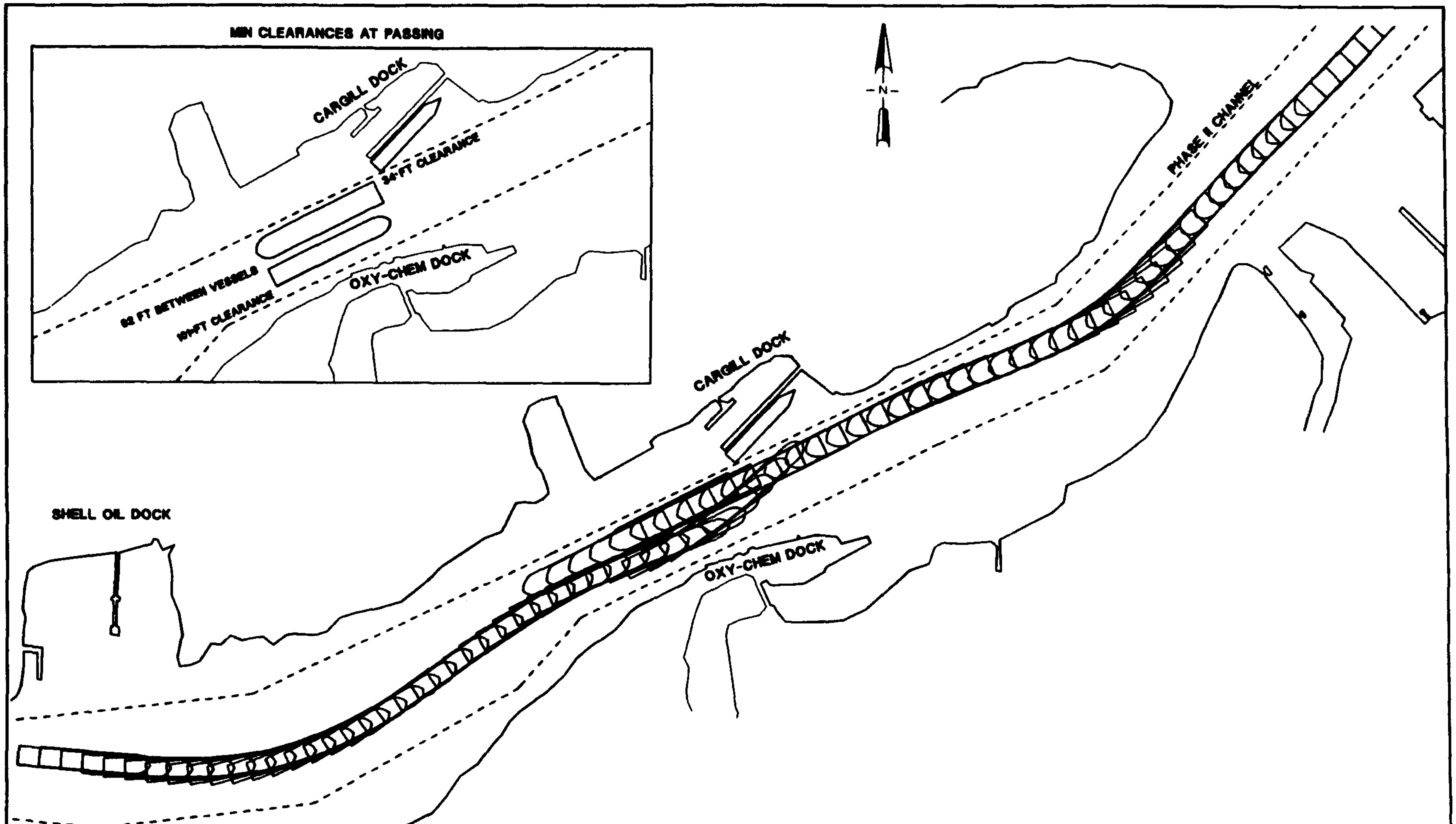


SHIP TRACK PLOTS, PILOT 2
CARGILL REACH, PHASE I CONDITIONS
PILOTED OUTBOUND, 971-FT X 140-FT BULK CARRIER
TRAFFIC INBOUND, 990-FT X 156-FT TANKER

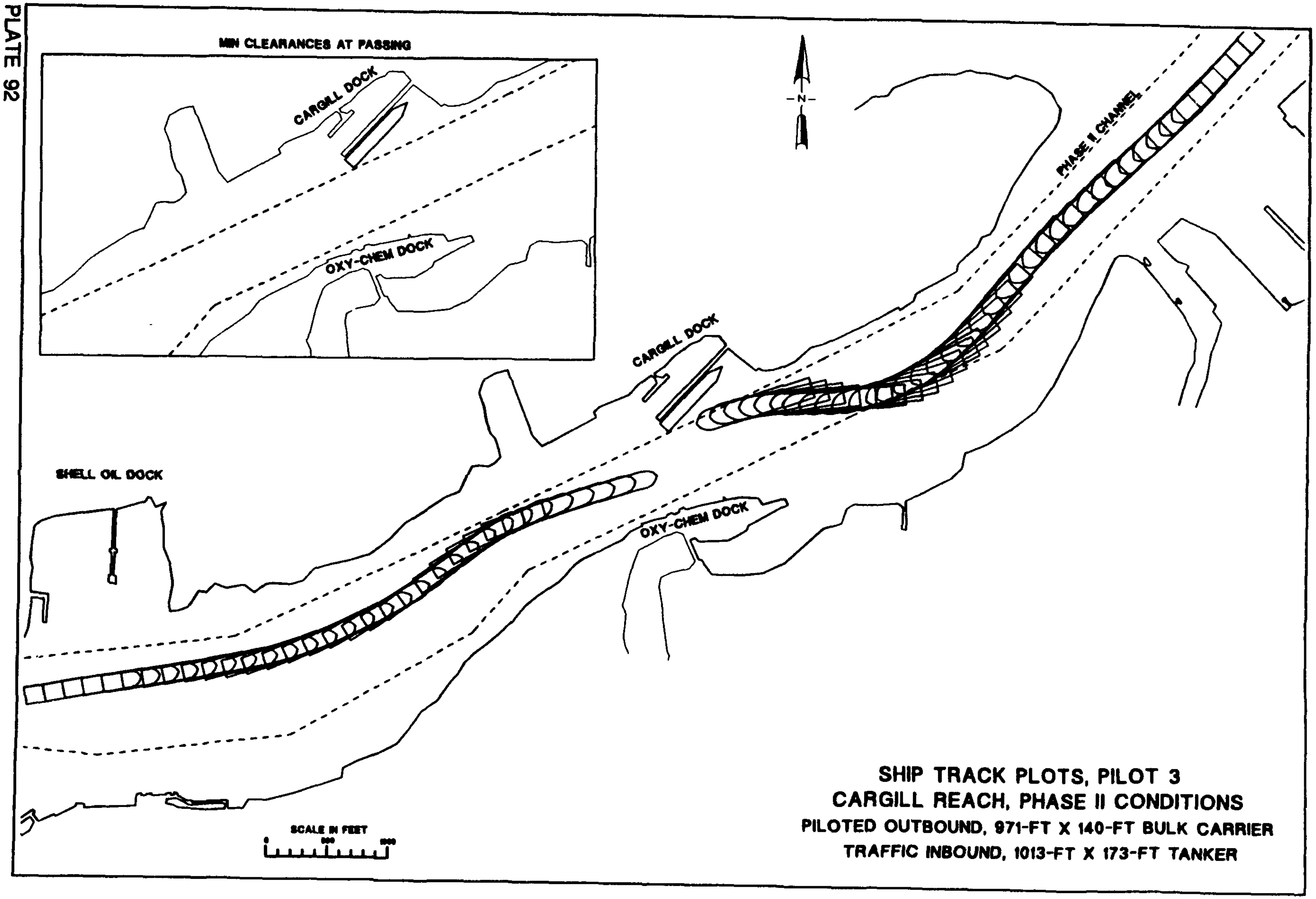
PLATE 89



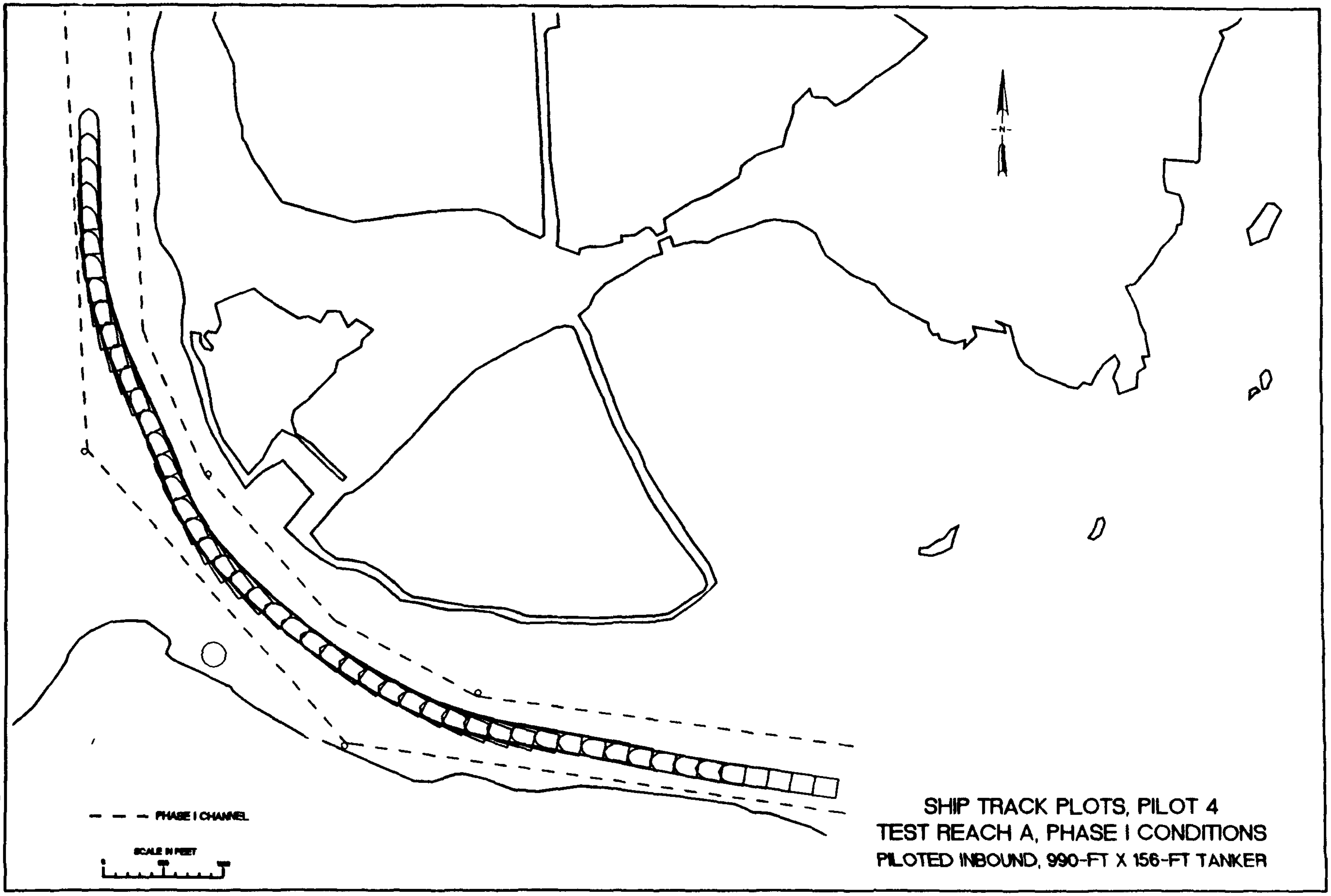
SHIP TRACK PLOTS, PILOT 3
CARGILL REACH, PHASE I CONDITIONS
PILOTED OUTBOUND, 971-FT X 140-FT BULK CARRIER
TRAFFIC INBOUND, 990-FT X 156-FT TANKER



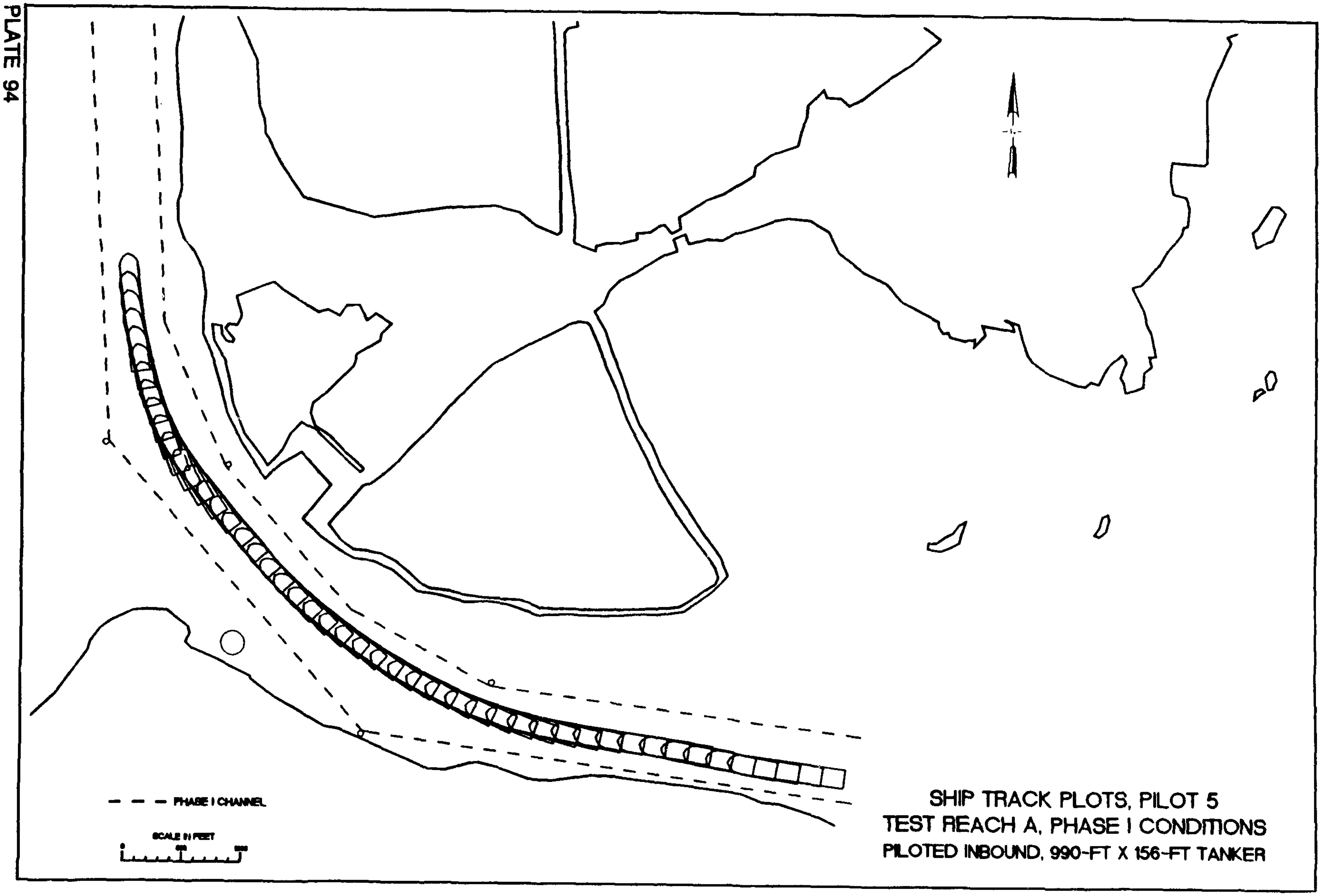
SHIP TRACK PLOTS, PILOT 1
CARGILL REACH, PHASE II CONDITIONS
PILOTED OUTBOUND, 971-FT X 140-FT BULK CARRIER
TRAFFIC INBOUND, 1013-FT X 173-FT TANKER



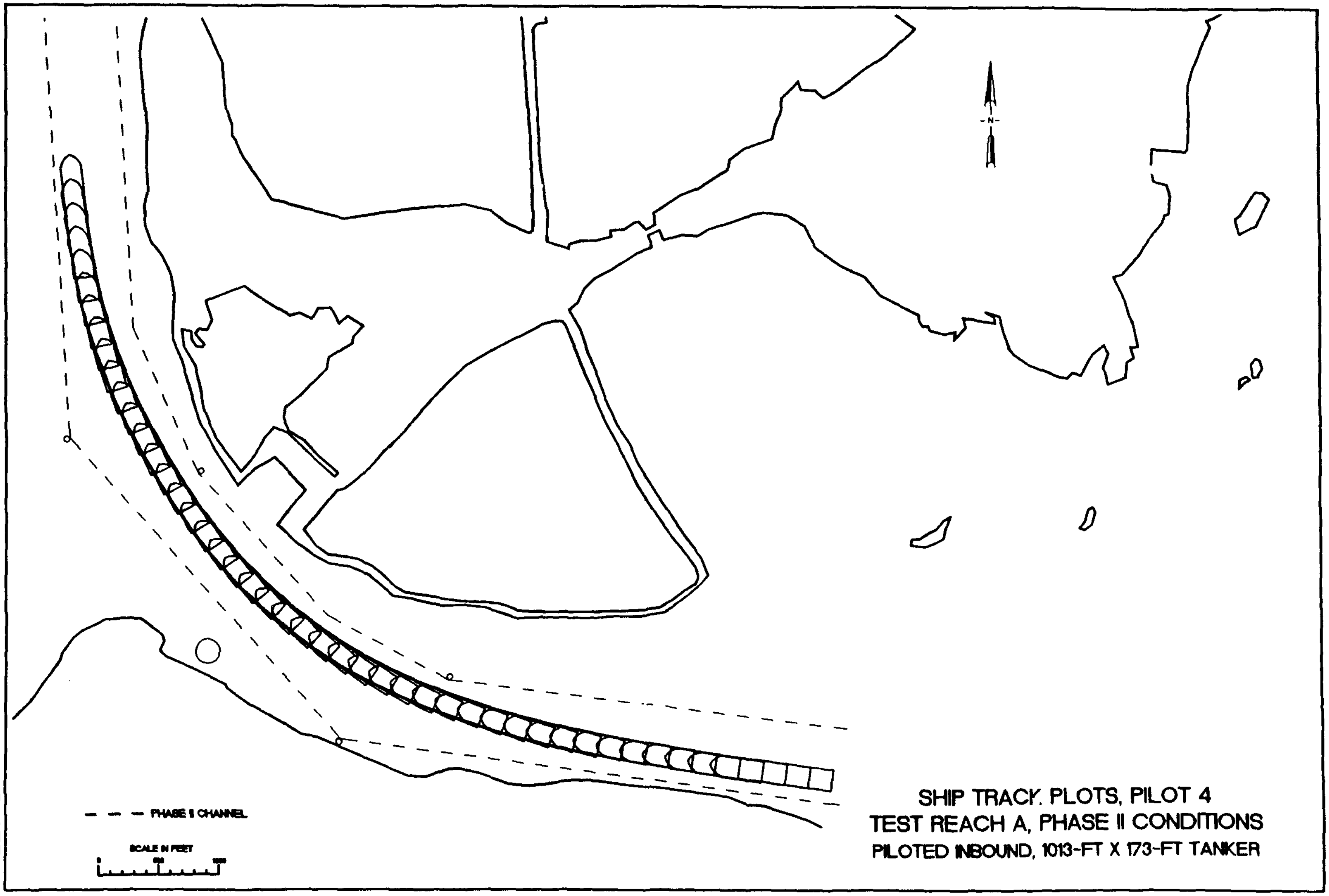
SHIP TRACK PLOTS, PILOT 3
CARGILL REACH, PHASE II CONDITIONS
PILOTED OUTBOUND, 971-FT X 140-FT BULK CARRIER
TRAFFIC INBOUND, 1013-FT X 173-FT TANKER



SHIP TRACK PLOTS, PILOT 4
TEST REACH A, PHASE I CONDITIONS
PILOTED INBOUND, 990-FT X 156-FT TANKER



SHIP TRACK PLOTS, PILOT 5
TEST REACH A, PHASE I CONDITIONS
PILOTED INBOUND, 990-FT X 156-FT TANKER



SHIP TRACK PLOTS, PILOT 4
TEST REACH A, PHASE II CONDITIONS
PILOTED INBOUND, 1013-FT X 173-FT TANKER

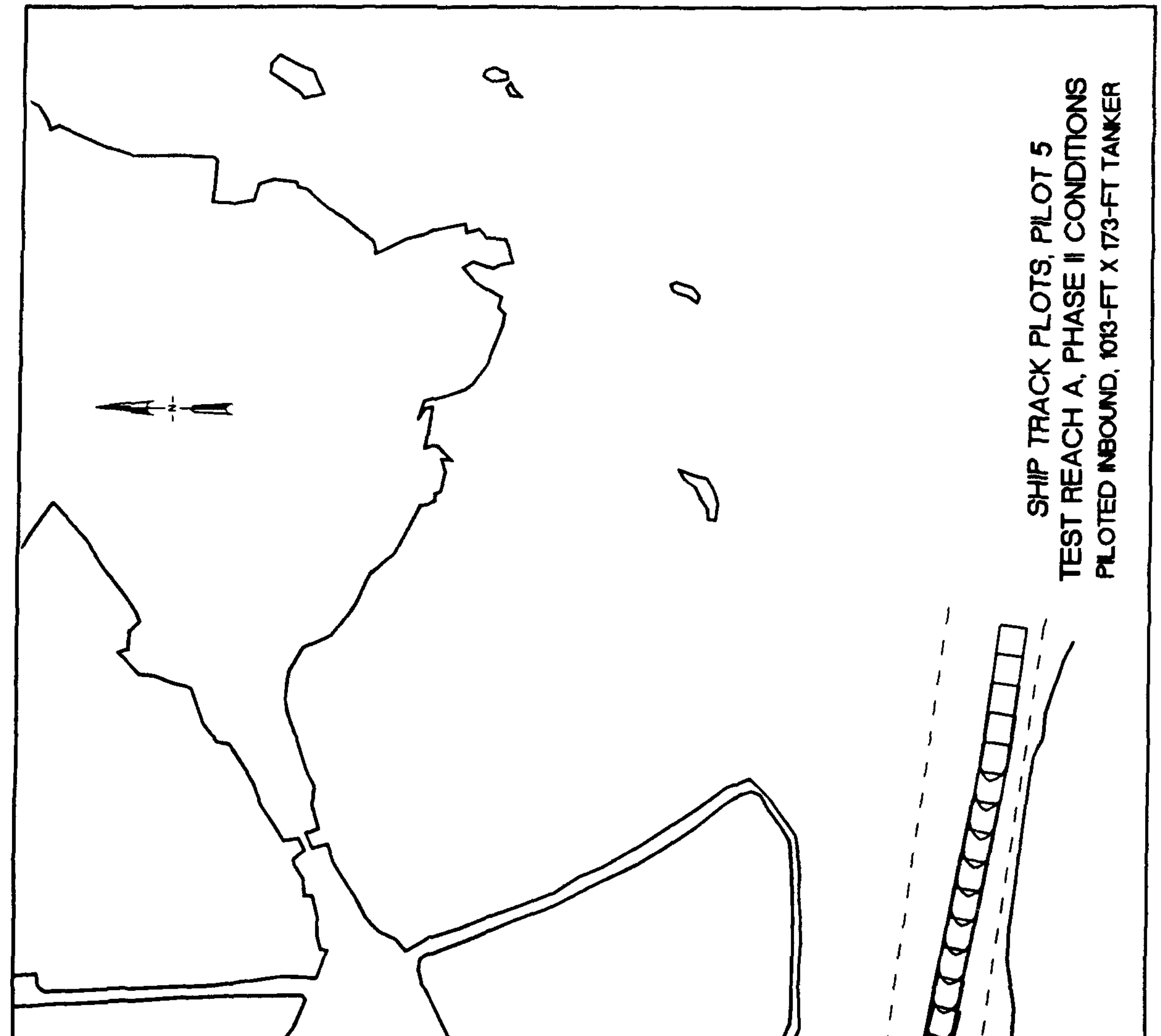
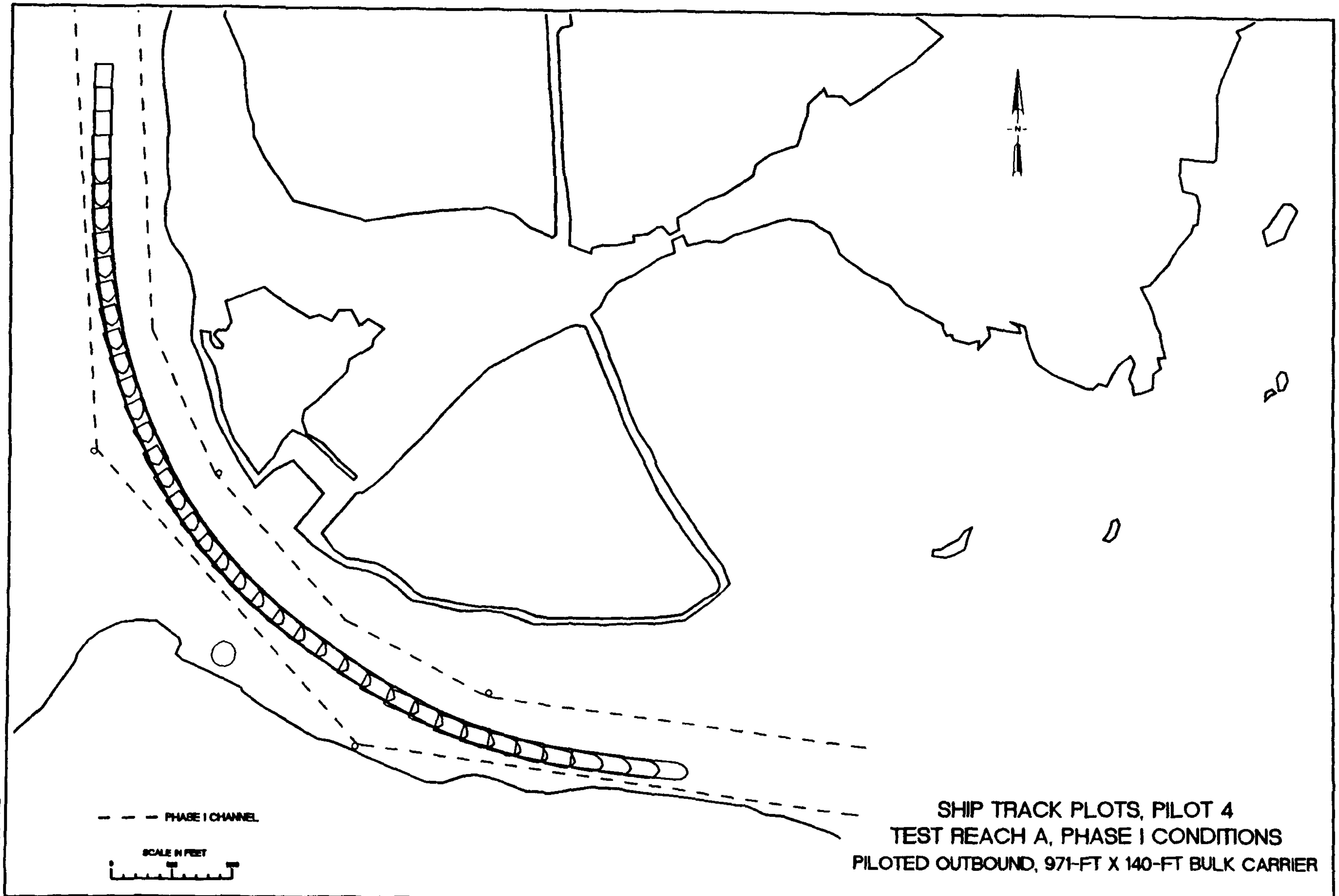
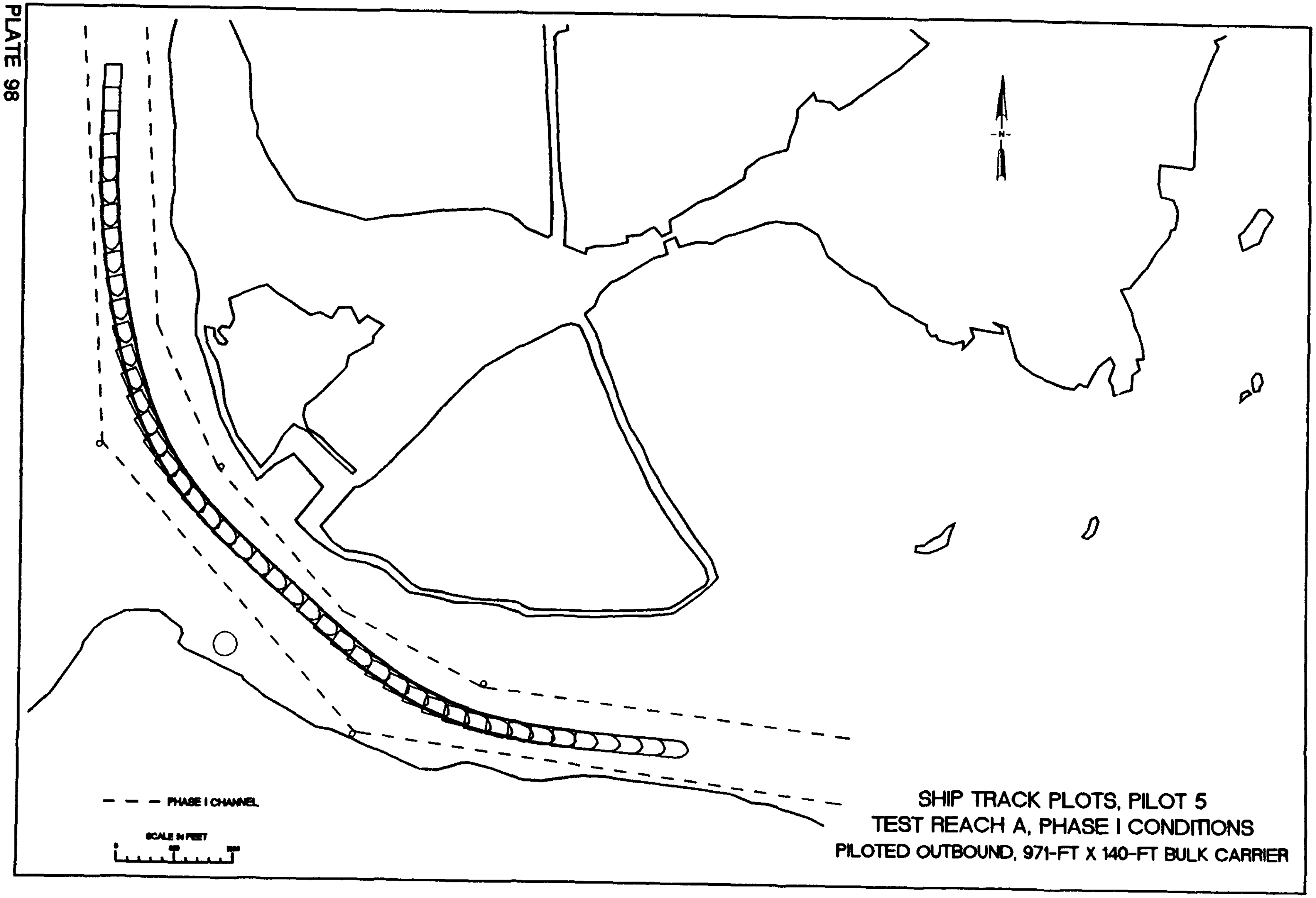

SHIP TRACK PLOTS, PILOT 5
TEST REACH A, PHASE II CONDITIONS
PILOTED INBOUND, 1013-FT X 173-FT TANKER
PHASE II CHANNEL
SCALE IN FEET

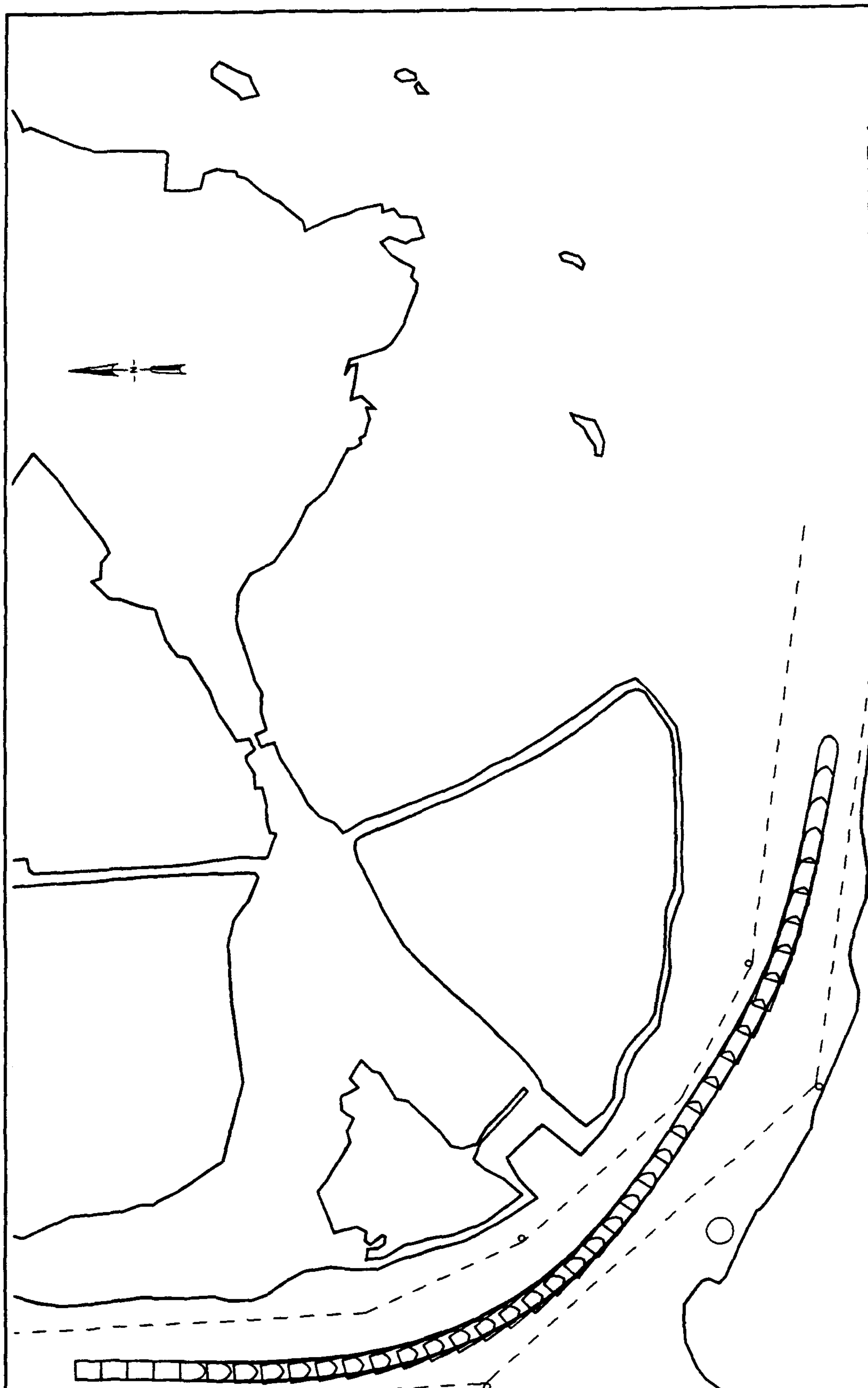
PLATE 96



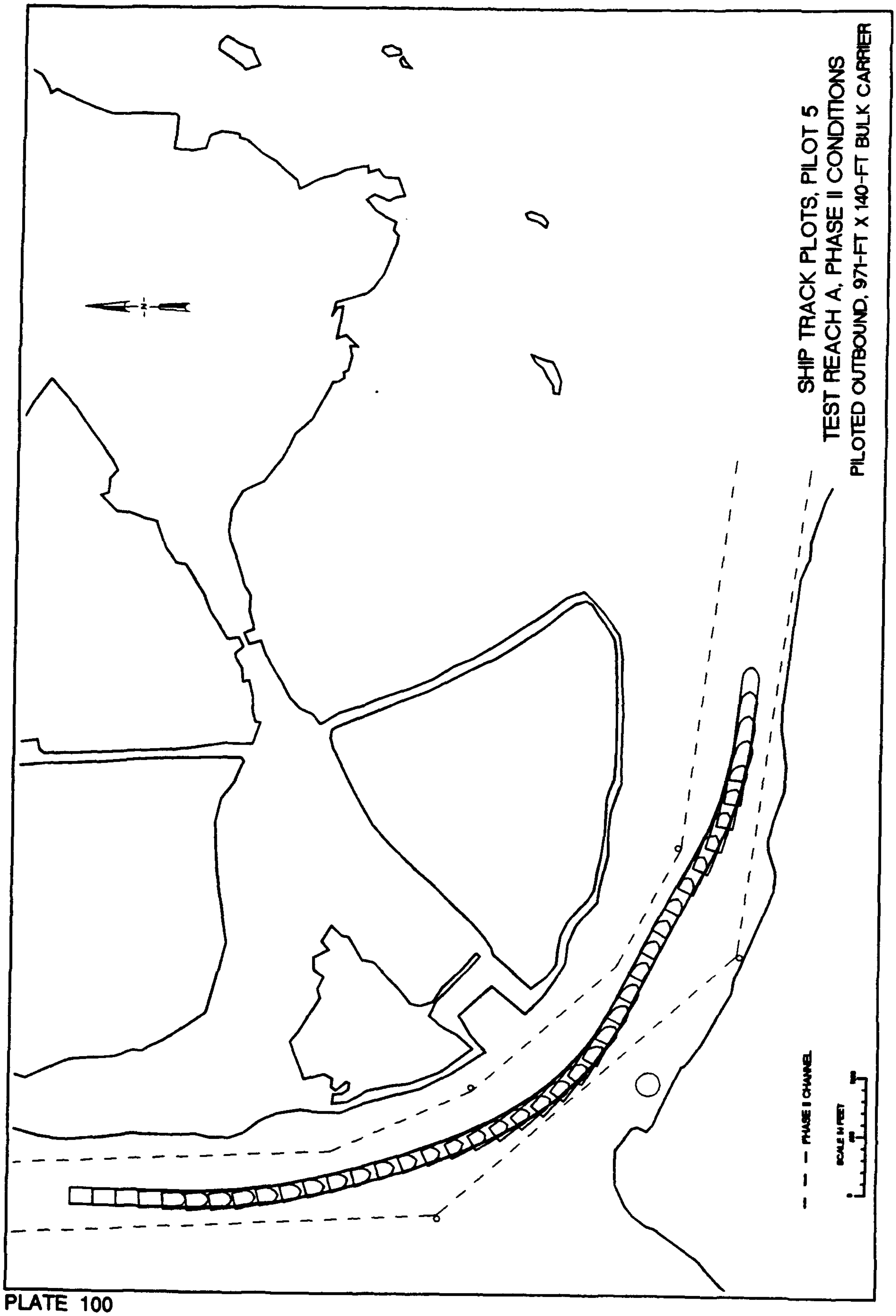
SHIP TRACK PLOTS, PILOT 4
TEST REACH A, PHASE I CONDITIONS
PILOTED OUTBOUND, 971-FT X 140-FT BULK CARRIER



SHIP TRACK PLOTS, PILOT 5
TEST REACH A, PHASE I CONDITIONS
PILOTED OUTBOUND, 971-FT X 140-FT BULK CARRIER

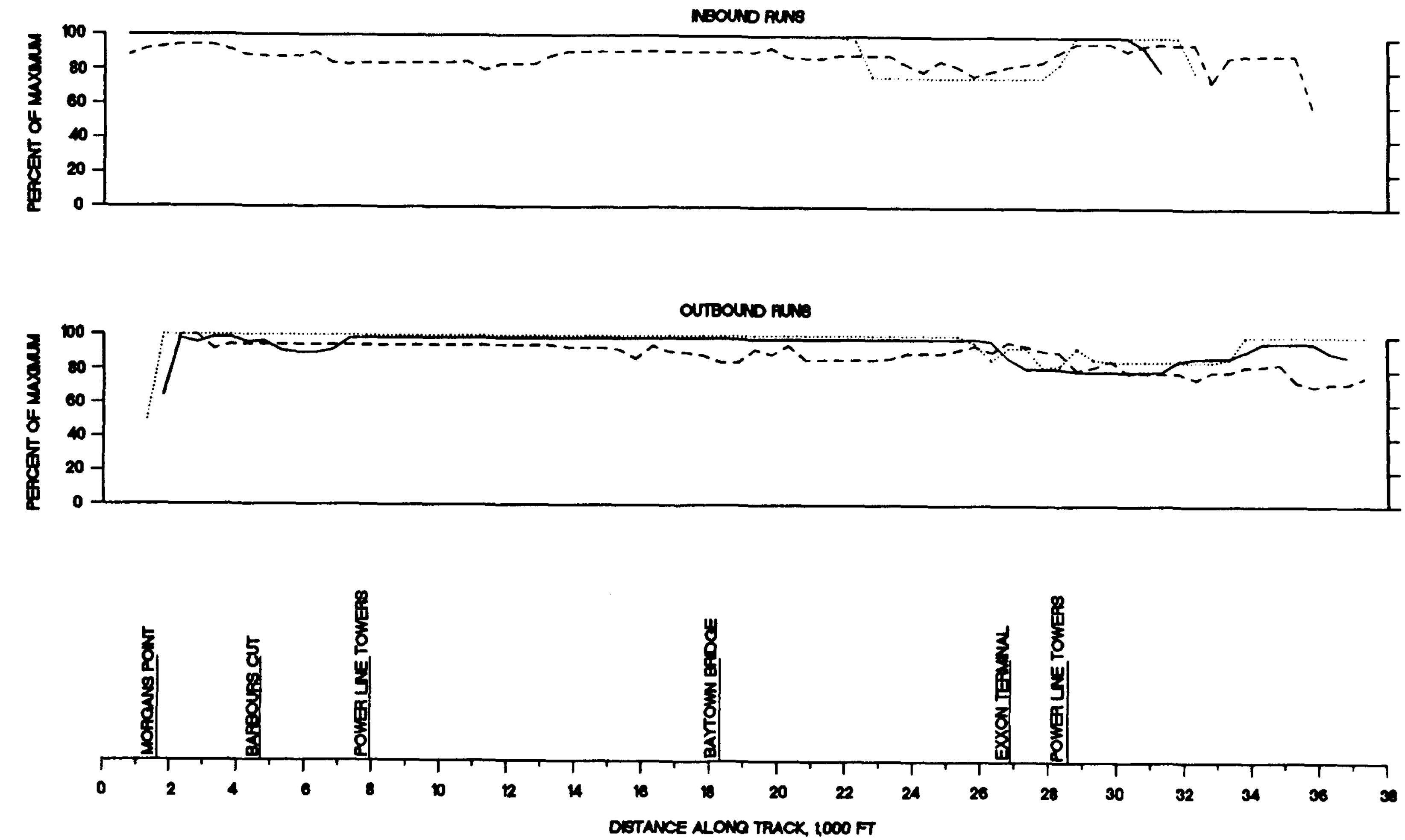


SHIP TRACK PLOTS, PILOT 4
TEST REACH A, PHASE II CONDITIONS
PILOTED OUTBOUND, 971-FT X 140-FT BULK CARRIER



SHIP TRACK PLOTS, PILOT 5
TEST REACH A, PHASE II CONDITIONS
PILOTED OUTBOUND, 971-FT X 140-FT BULK CARRIER

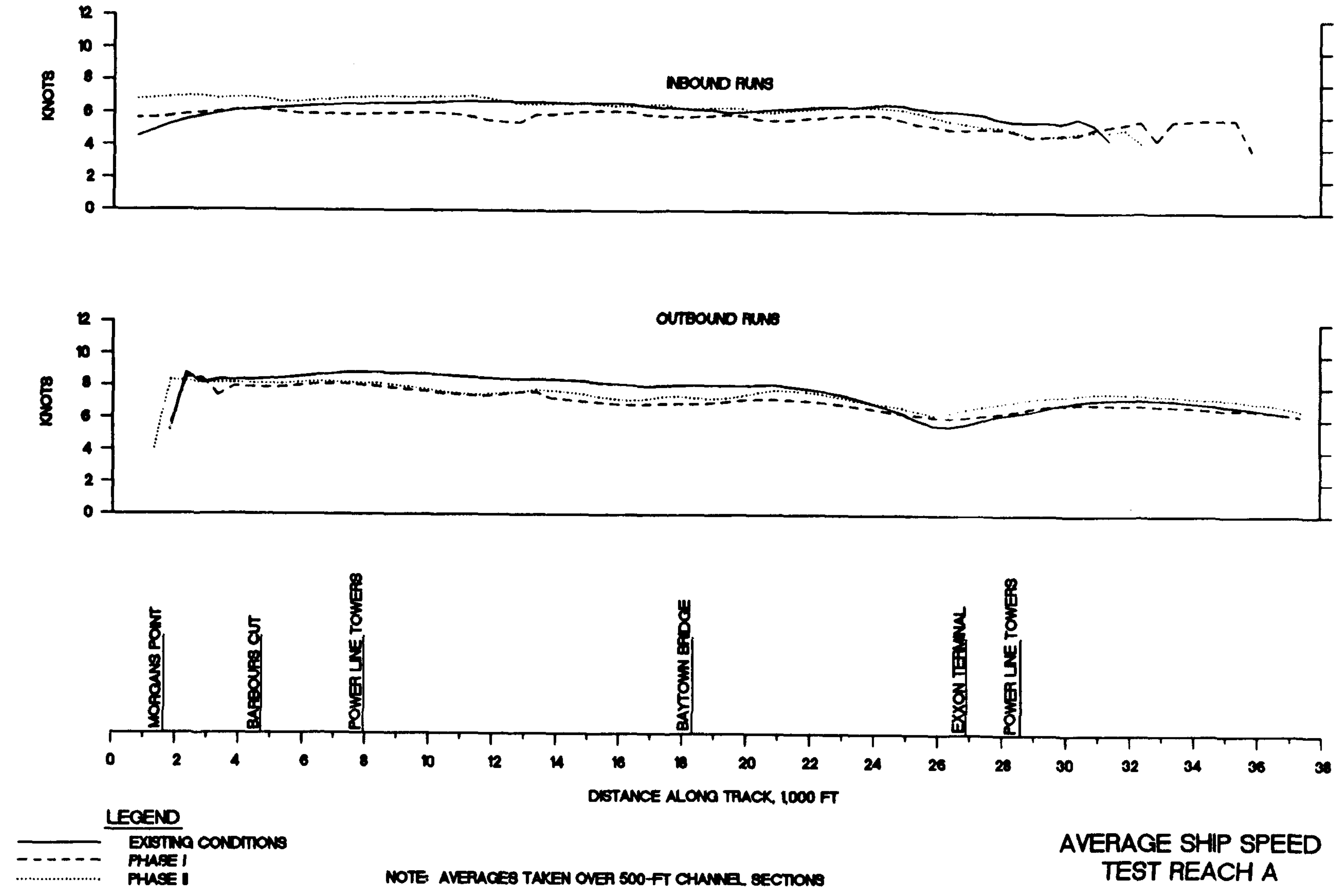
PLATE 100



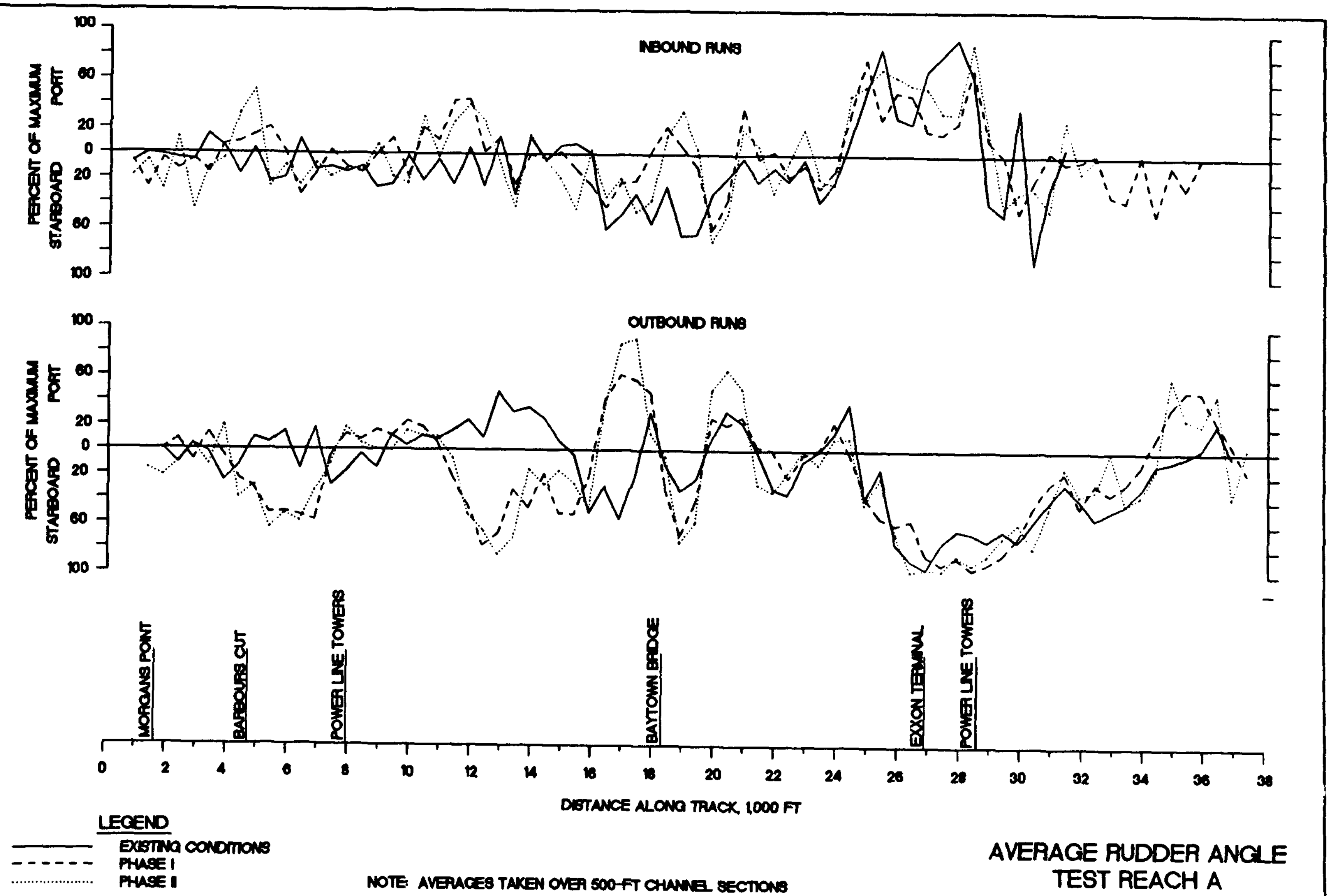
LEGEND
EXISTING CONDITIONS
PHASE I
PHASE II

NOTE: AVERAGES TAKEN OVER 500-FT CHANNEL SECTIONS

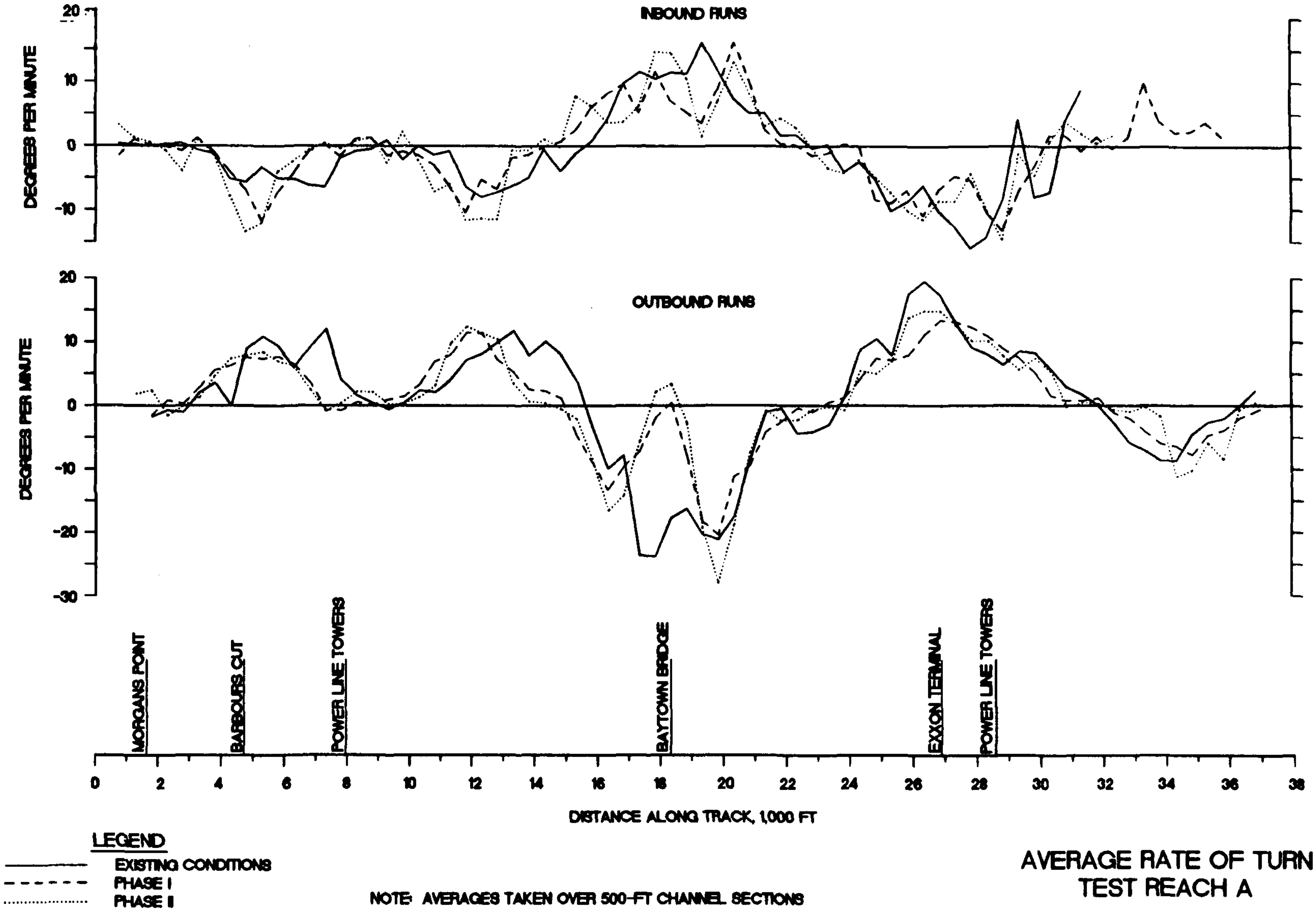
AVERAGE ENGINE RPM
TEST REACH A



AVERAGE SHIP SPEED
TEST REACH A



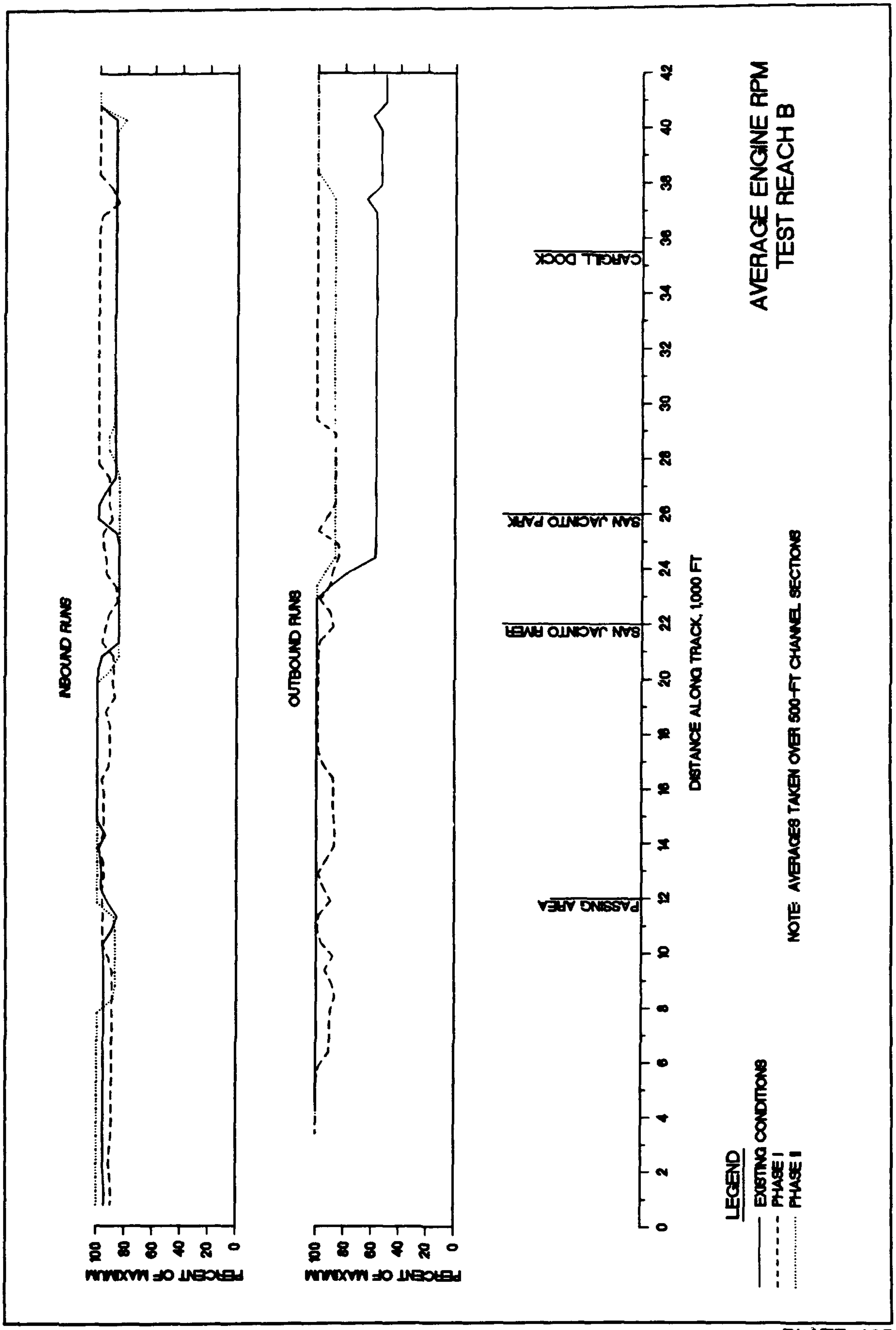
AVERAGE RUDDER ANGLE
TEST REACH A



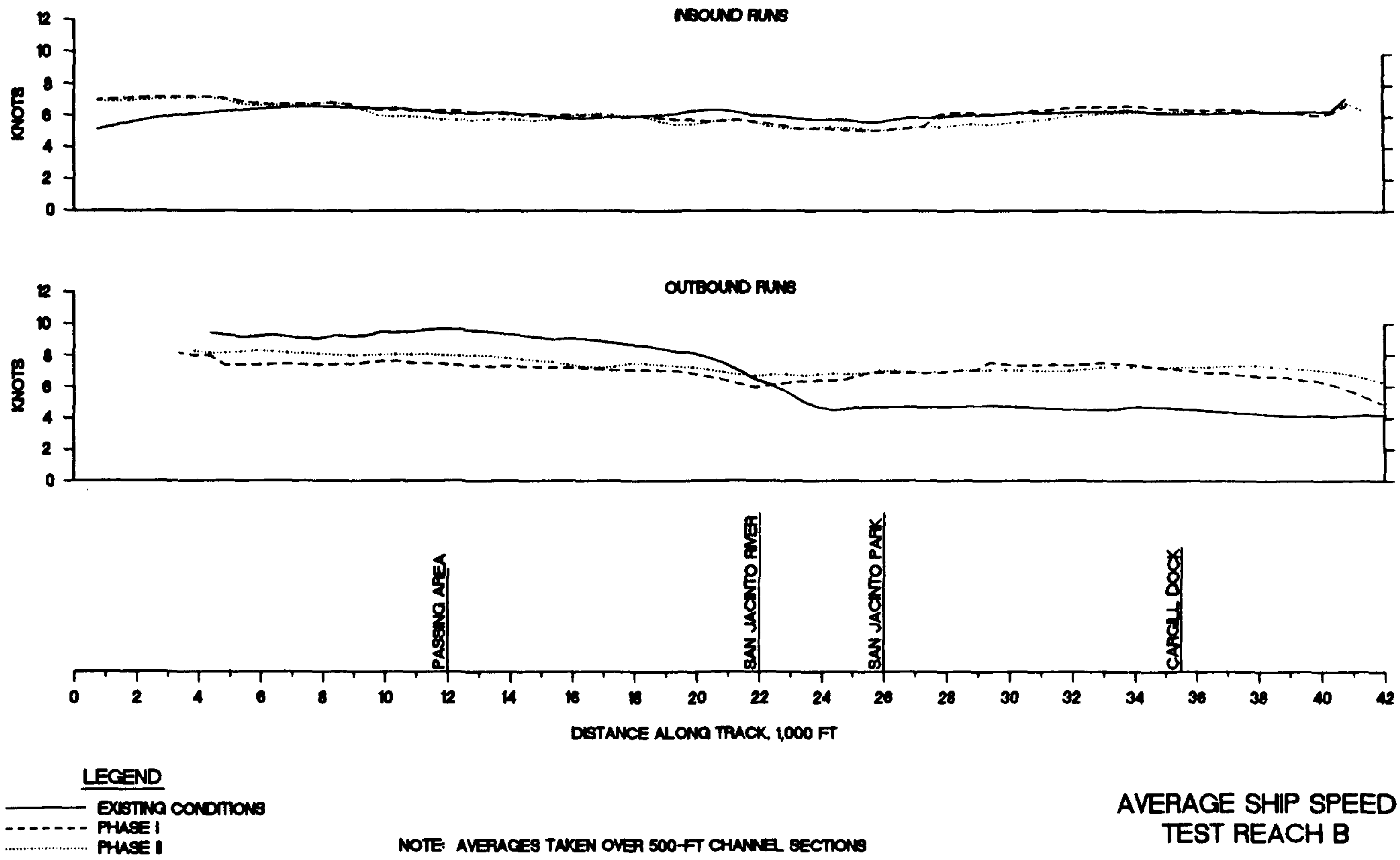
NOTE: AVERAGES TAKEN OVER 500-FT CHANNEL SECTIONS

AVERAGE RATE OF TURN
TEST REACH A

PLATE 104

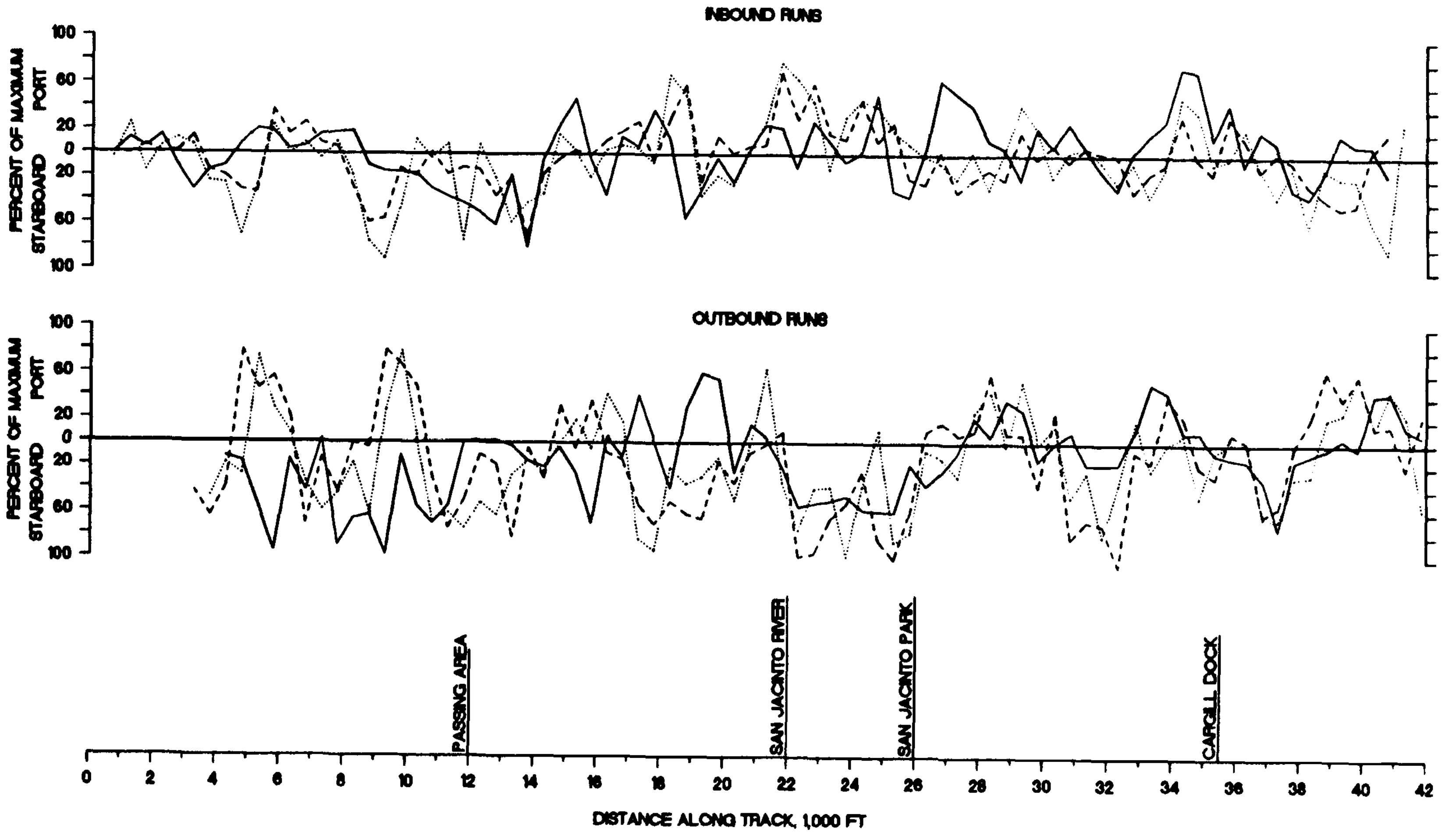


AVERAGE ENGINE RPM
TEST REACH B
INBOUND RUNS
OUTBOUND RUNS
PERCENT OF MAXIMUM
100
80
60
40
20
0
DISTANCE ALONG TRACK, 1,000 FT
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
38
40
42
PASSING AREA
SAN JACINTO RIVER
SAN JACINTO PARK
CARGILL DOCK
LEGEND
EXISTING CONDITIONS
PHASE I
PHASE II
NOTE: AVERAGES TAKEN OVER 500-FT CHANNEL SECTIONS



NOTE: AVERAGES TAKEN OVER 500-FT CHANNEL SECTIONS

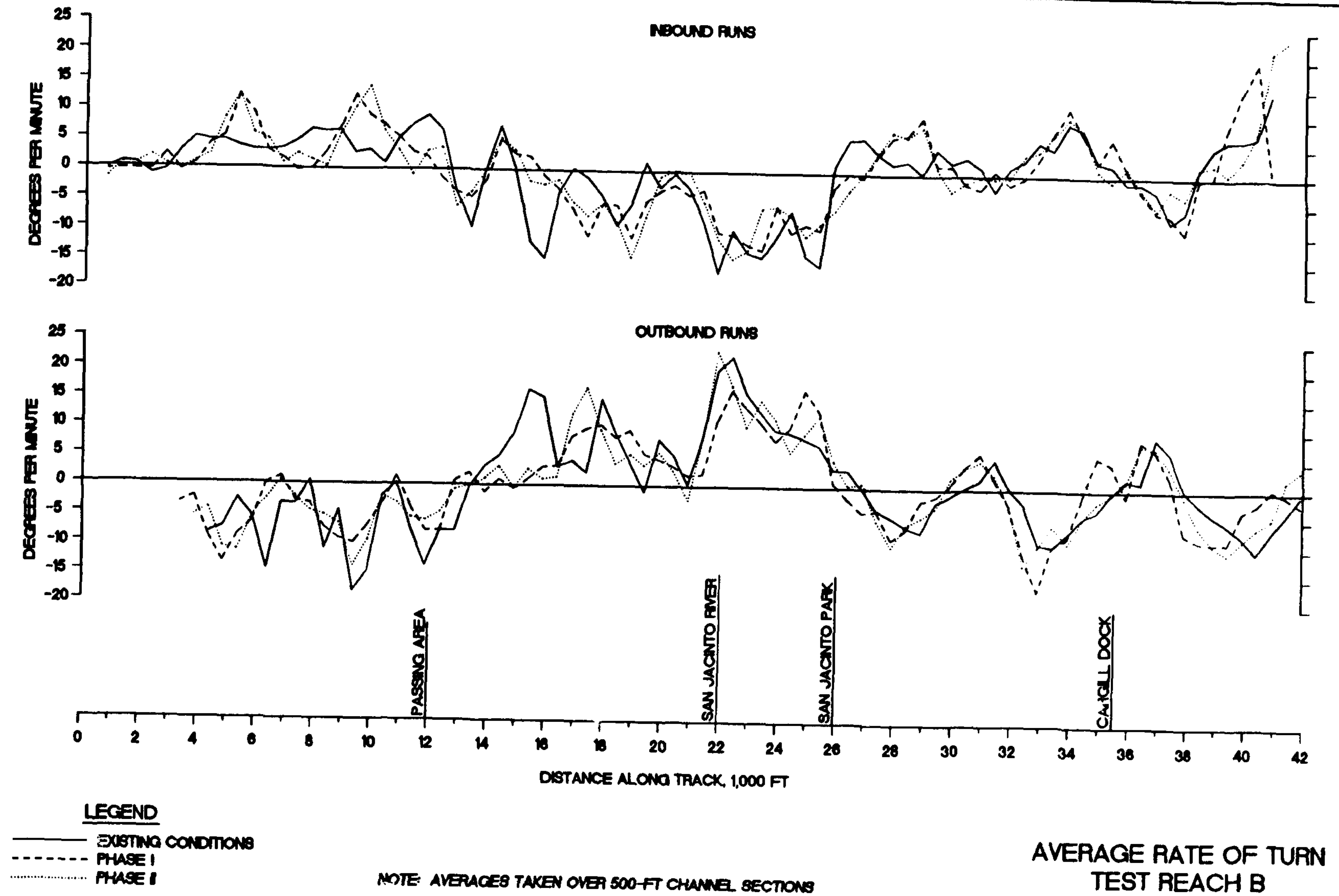
AVERAGE SHIP SPEED
TEST REACH B



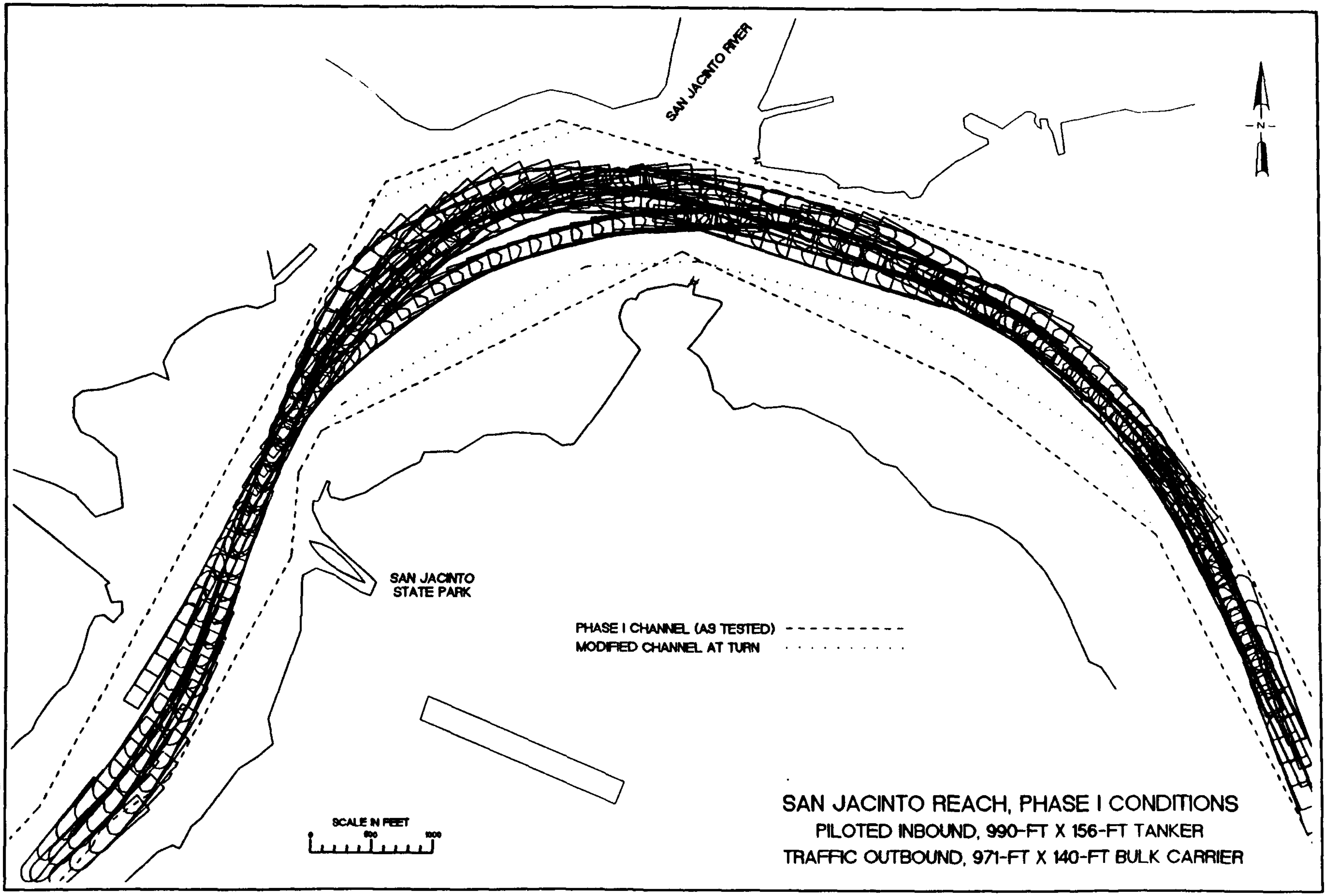
LEGEND
EXISTING CONDITIONS
PHASE I
PHASE II

NOTE: AVERAGES TAKEN OVER 500-FT CHANNEL SECTIONS

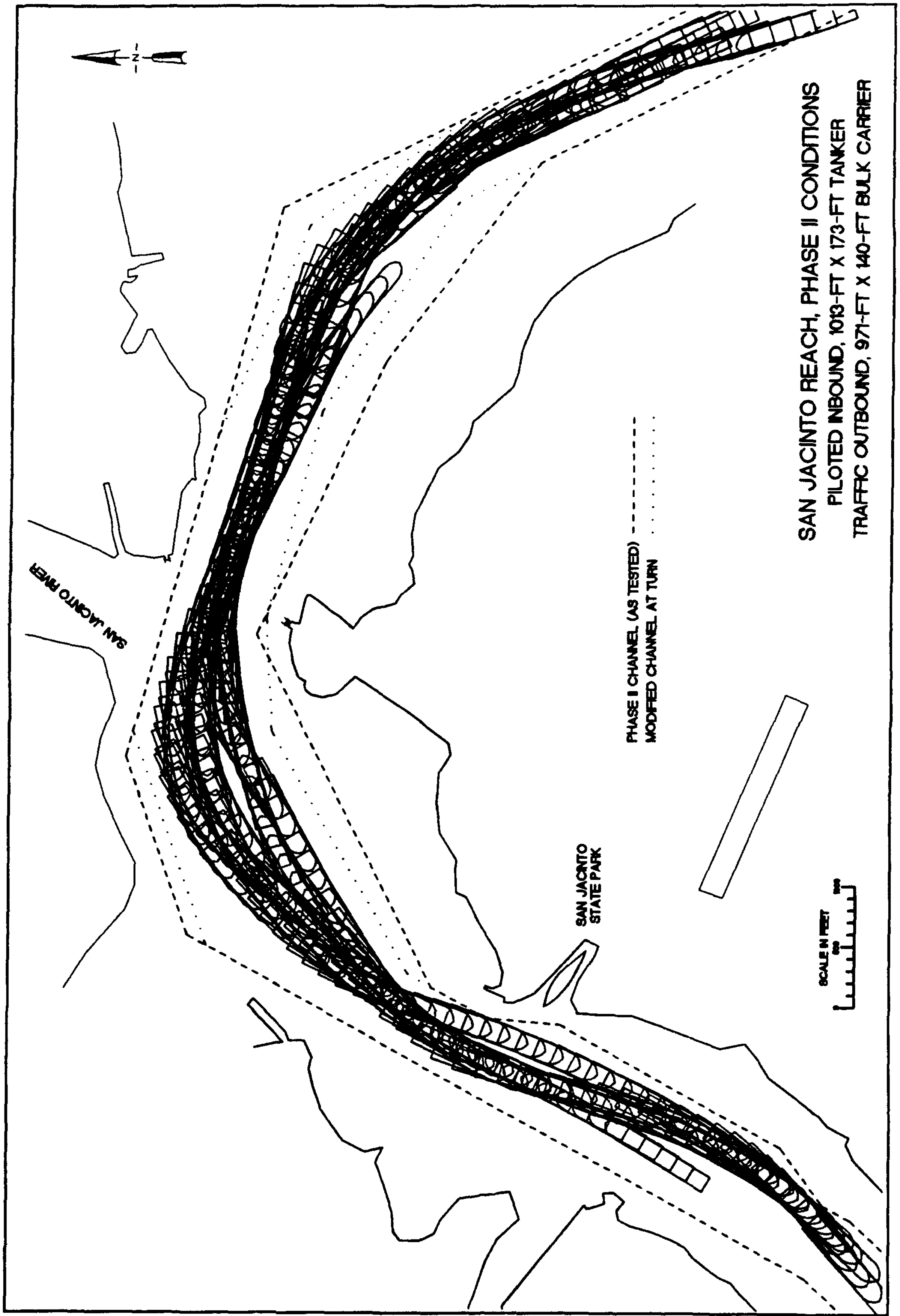
AVERAGE RUDDER ANGLE
TEST REACH B



AVERAGE RATE OF TURN
TEST REACH B



SAN JACINTO REACH, PHASE I CONDITIONS
PILOTED INBOUND, 990-FT X 156-FT TANKER
TRAFFIC OUTBOUND, 971-FT X 140-FT BULK CARRIER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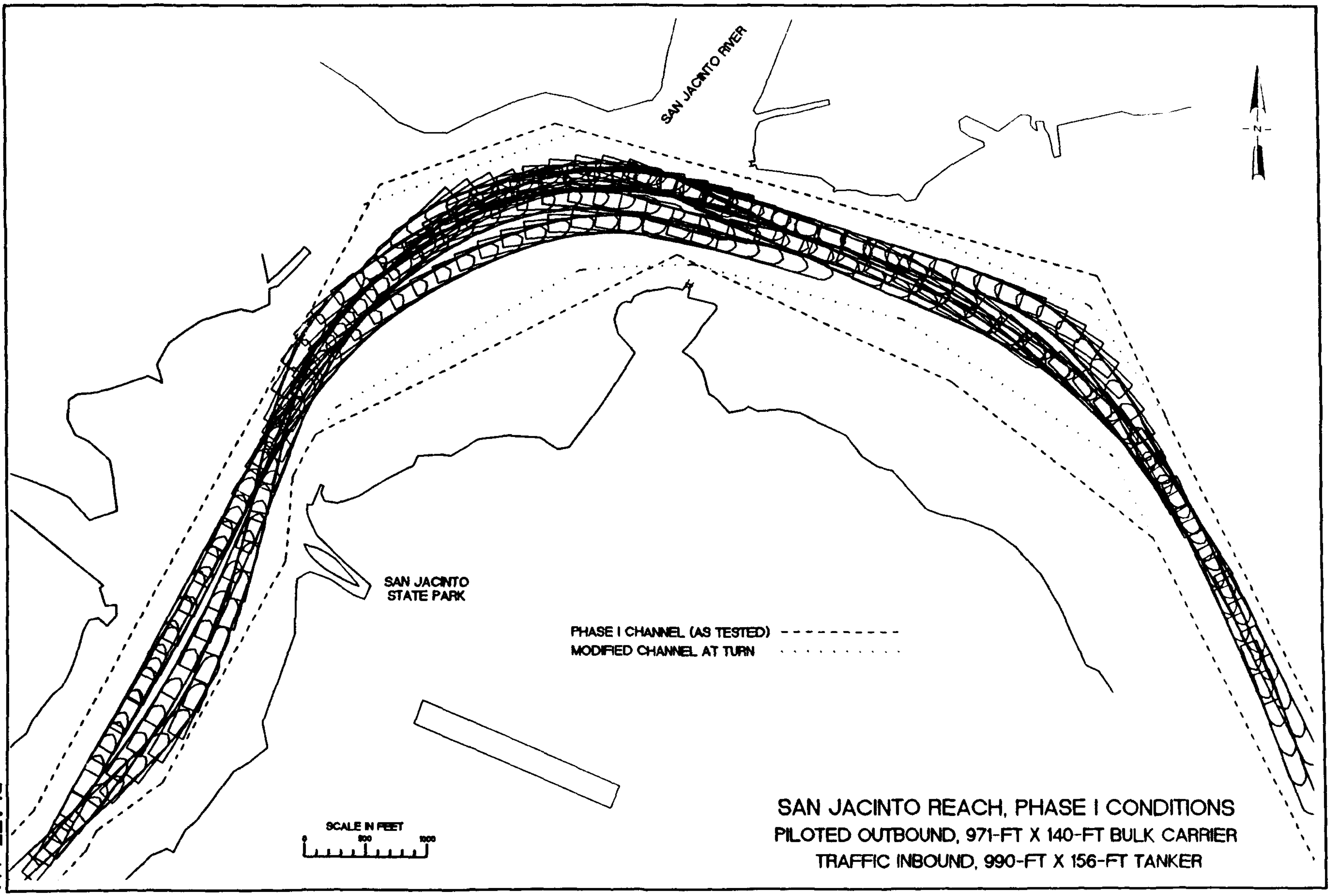
SAN JACINTO REACH, PHASE II CONDITIONS
PILOTED INBOUND, 1013-FT X 173-FT TANKER
TRAFFIC OUTBOUND, 971-FT X 140-FT BULK CARRIER
PHASE II CHANNEL (AS TESTED)
MODIFIED CHANNEL AT TURN
SAN JACINTO RIVER
SAN JACINTO STATE PARK
SCALE IN FEET

PLATE 110



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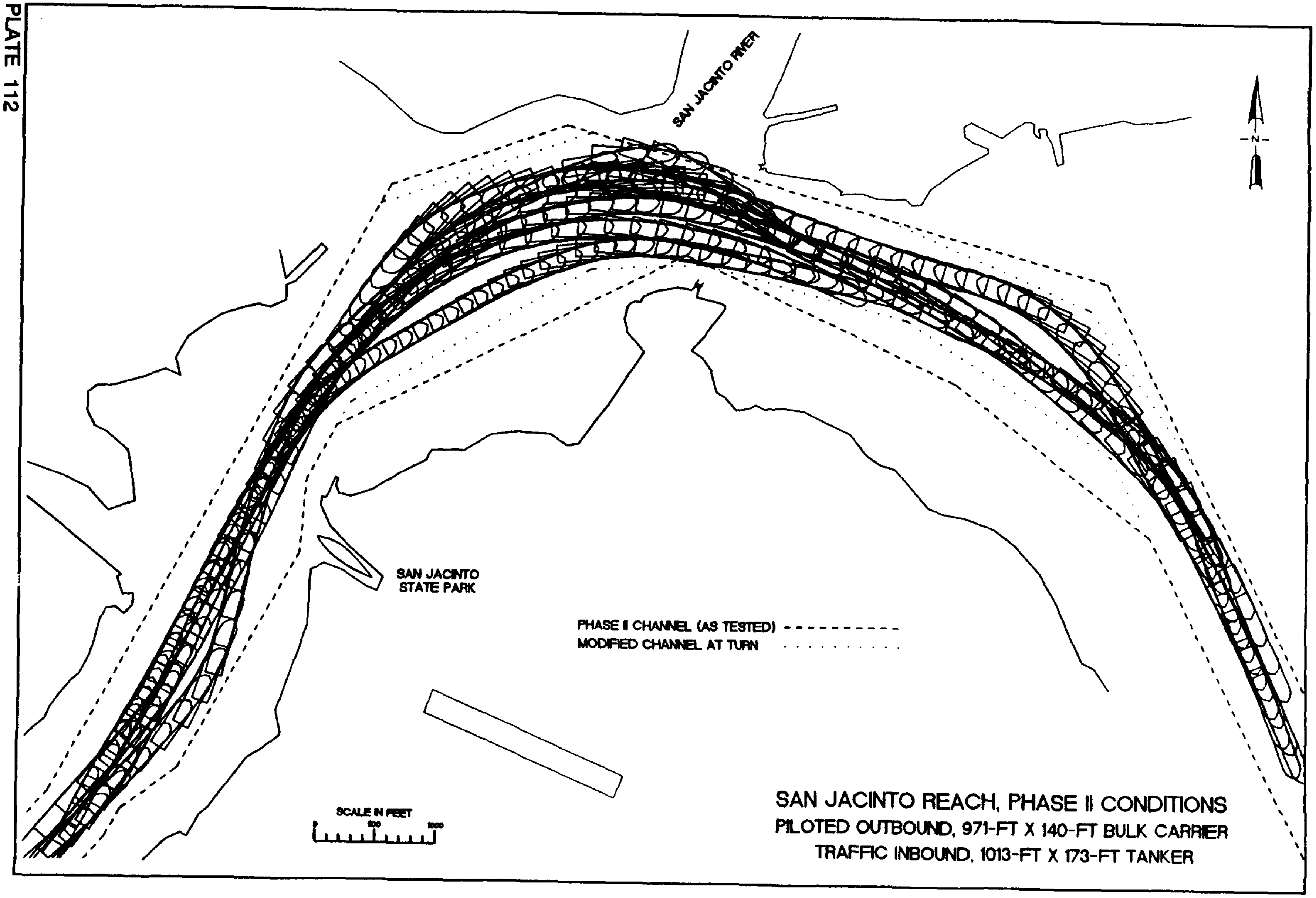
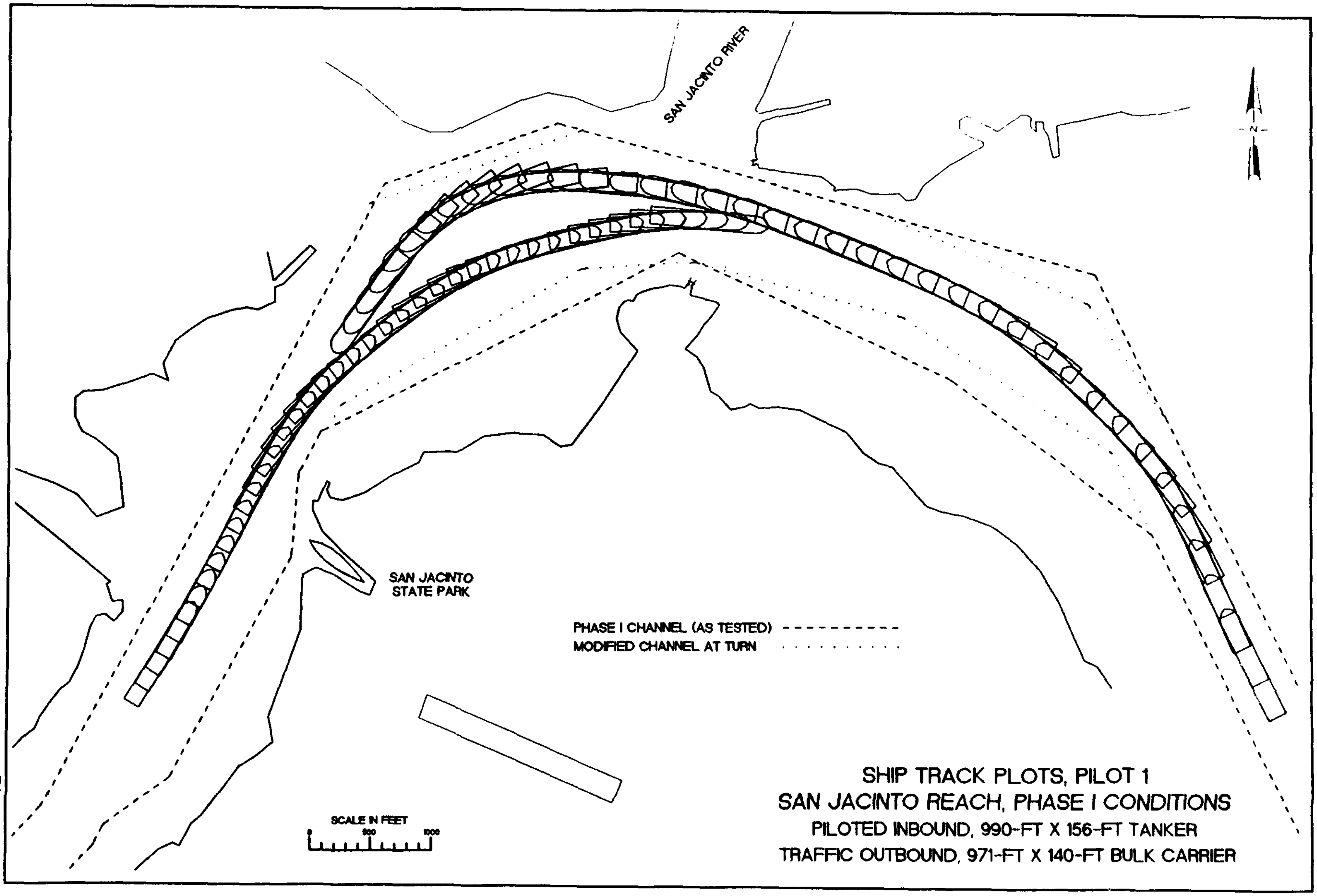
TRAFFIC INBOUND, 990-FT X 156-FT TANKER



SAN JACINTO REACH, PHASE II CONDITIONS
PILOTED OUTBOUND, 971-FT X 140-FT BULK CARRIER
TRAFFIC INBOUND, 1013-FT X 173-FT TANKER

PLATE 112



SHIP TRACK PLOTS, PILOT 1
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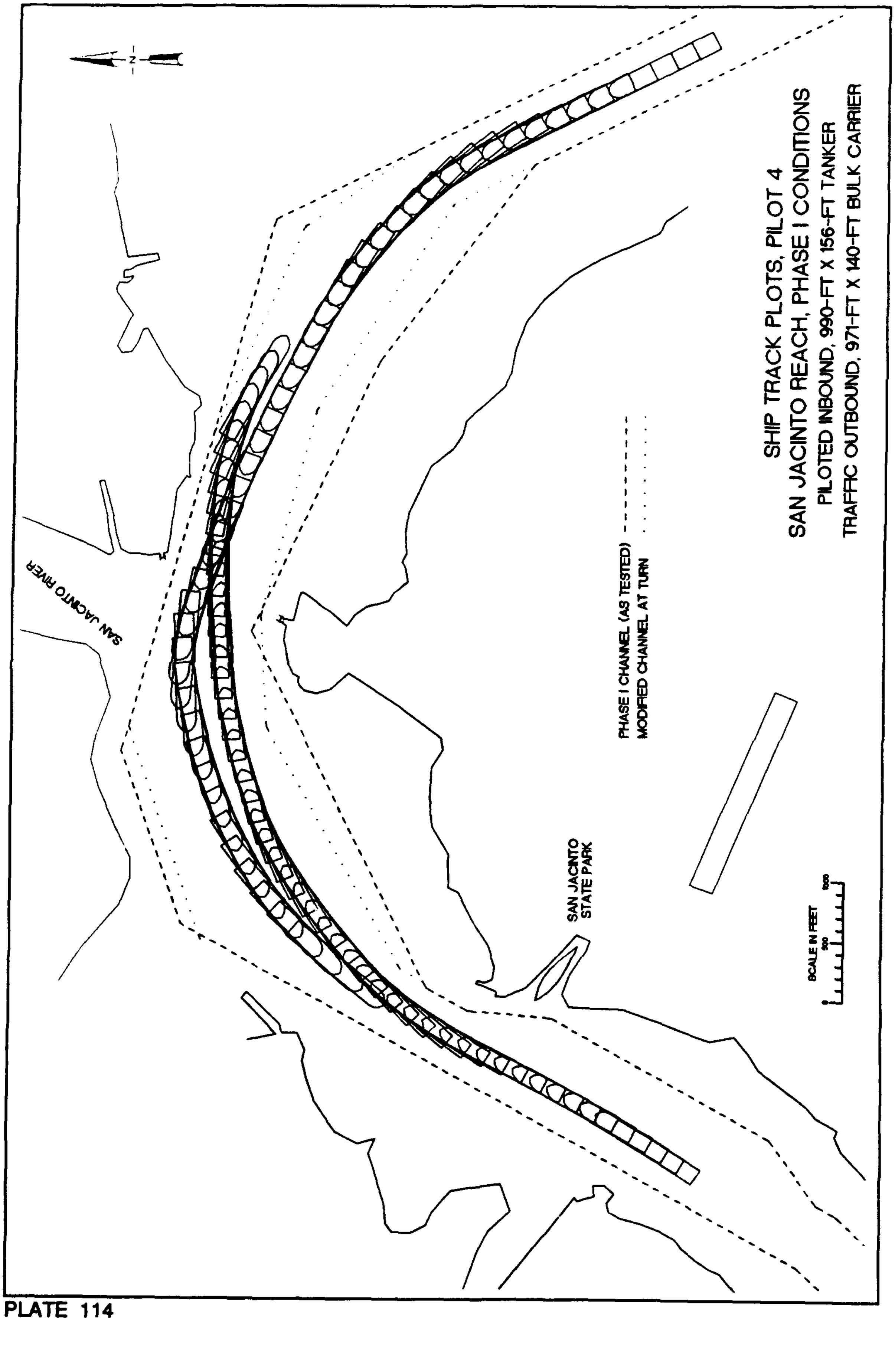
PILOTED INBOUND, 990-FT X 156-FT TANKER
TRAFFIC OUTBOUND, 971-FT X 140-FT BULK CARRIER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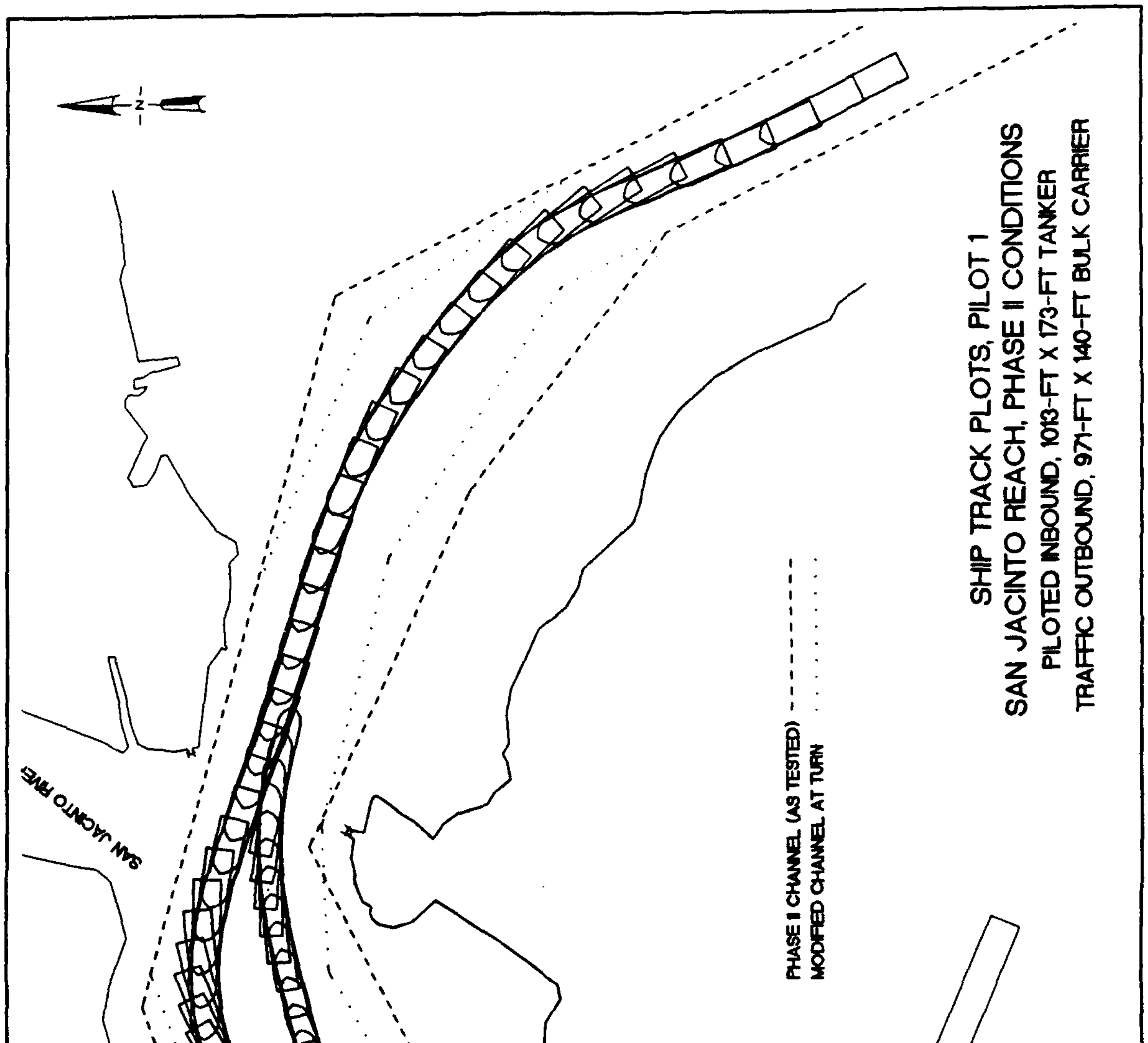
SAN JACINTO REACH, PHASE I CONDITIONS
PILOTED INBOUND, 990-FT X 156-FT TANKER
TRAFFIC OUTBOUND, 971-FT X 140-FT BULK CARRIER
PHASE I CHANNEL (AS TESTED)
MODIFIED CHANNEL AT TURN
SAN JACINTO RIVER
SAN JACINTO STATE PARK
SCALE IN FEET
N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SAN JACINTO REACH, PHASE II CONDITIONS
PILOTED INBOUND, 1013-FT X 173-FT TANKER
TRAFFIC OUTBOUND, 971-FT X 140-FT BULK CARRIER
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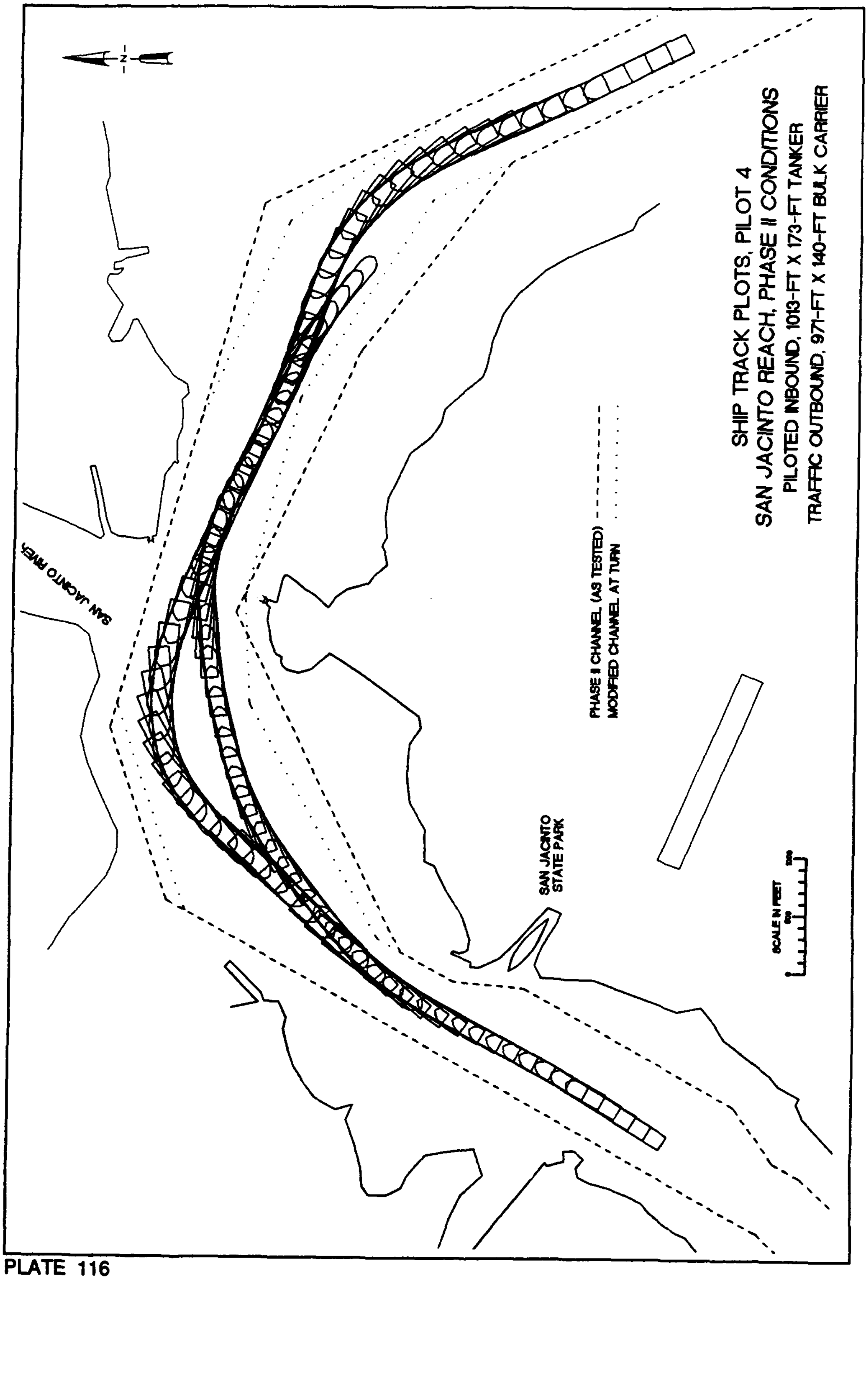
SCALE IN FEET
N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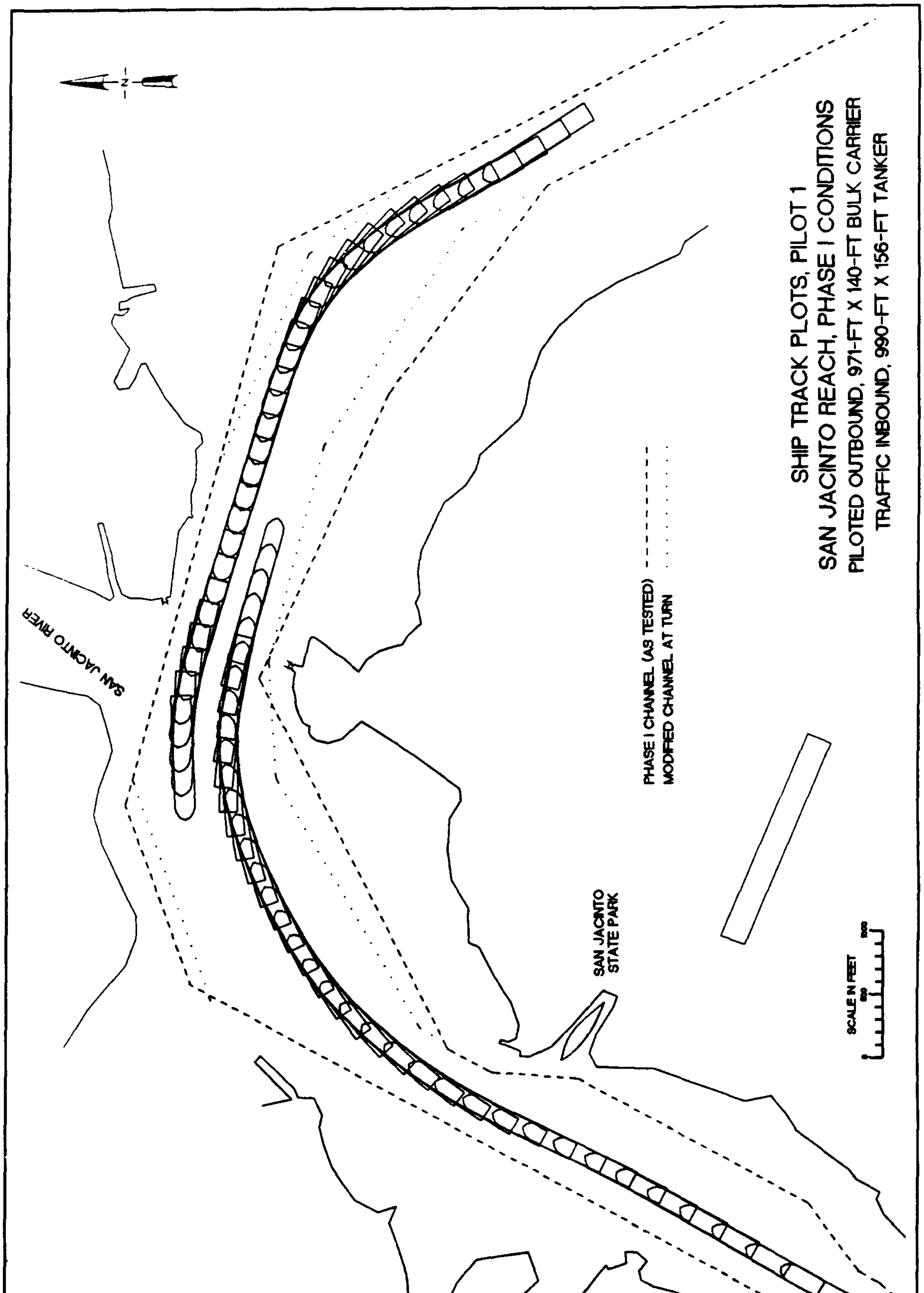
SAN JACINTO REACH, PHASE II CONDITIONS
PILOTED INBOUND, 1013-FT X 173-FT TANKER
TRAFFIC OUTBOUND, 971-FT X 140-FT BULK CARRIER
PHASE II CHANNEL (AS TESTED)
MODIFIED CHANNEL AT TURN
SAN JACINTO RIVER
SAN JACINTO STATE PARK
SCALE IN FEET
N

PLATE 116



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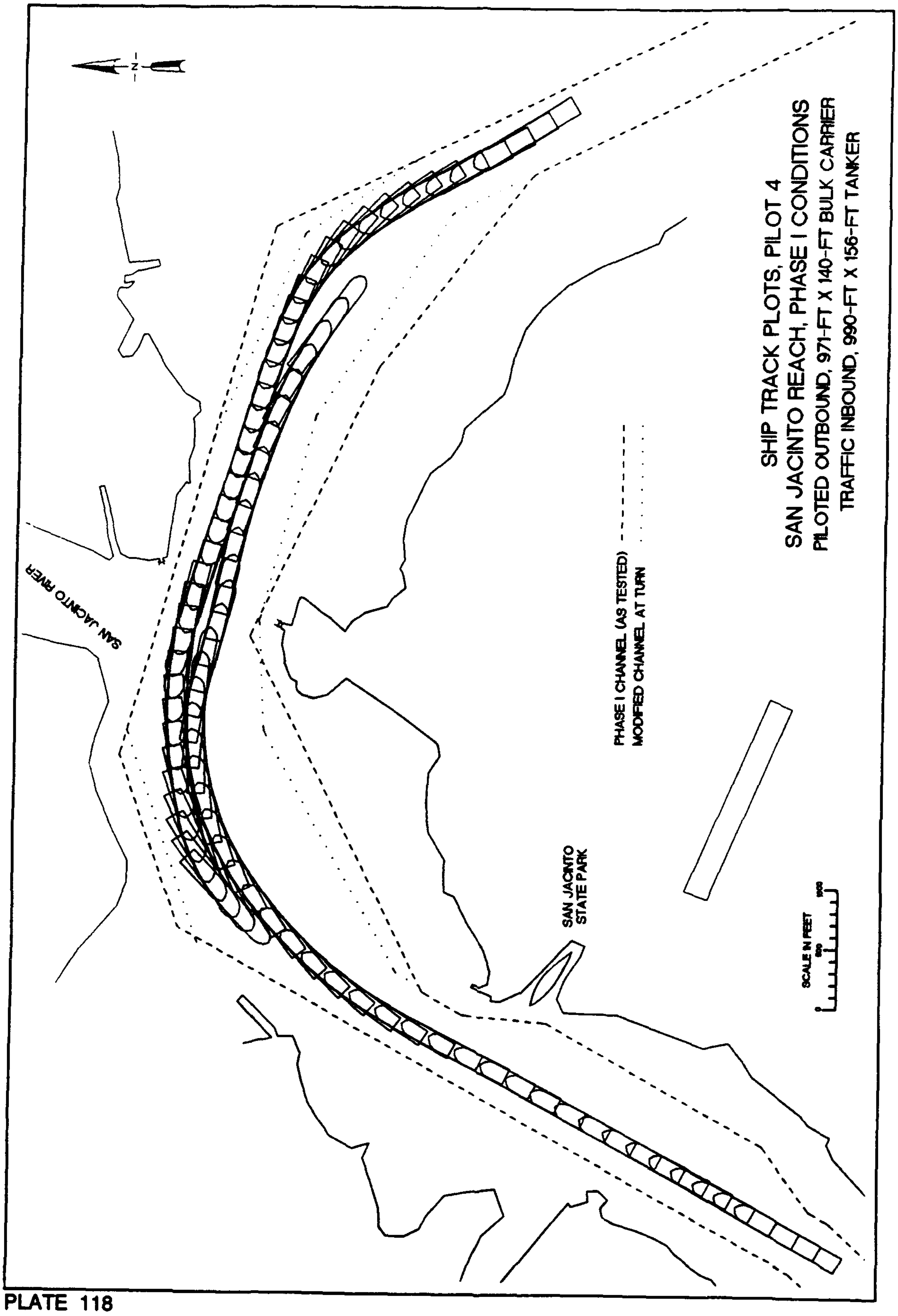
PILOTED OUTBOUND, 971-FT X 140-FT BULK CARRIER
TRAFFIC INBOUND, 990-FT X 156-FT TANKER



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SAN JACINTO REACH, PHASE I CONDITIONS
PILOTED OUTBOUND, 971-FT X 140-FT BULK CARRIER
TRAFFIC INBOUND, 990-FT X 156-FT TANKER
PHASE I CHANNEL (AS TESTED)
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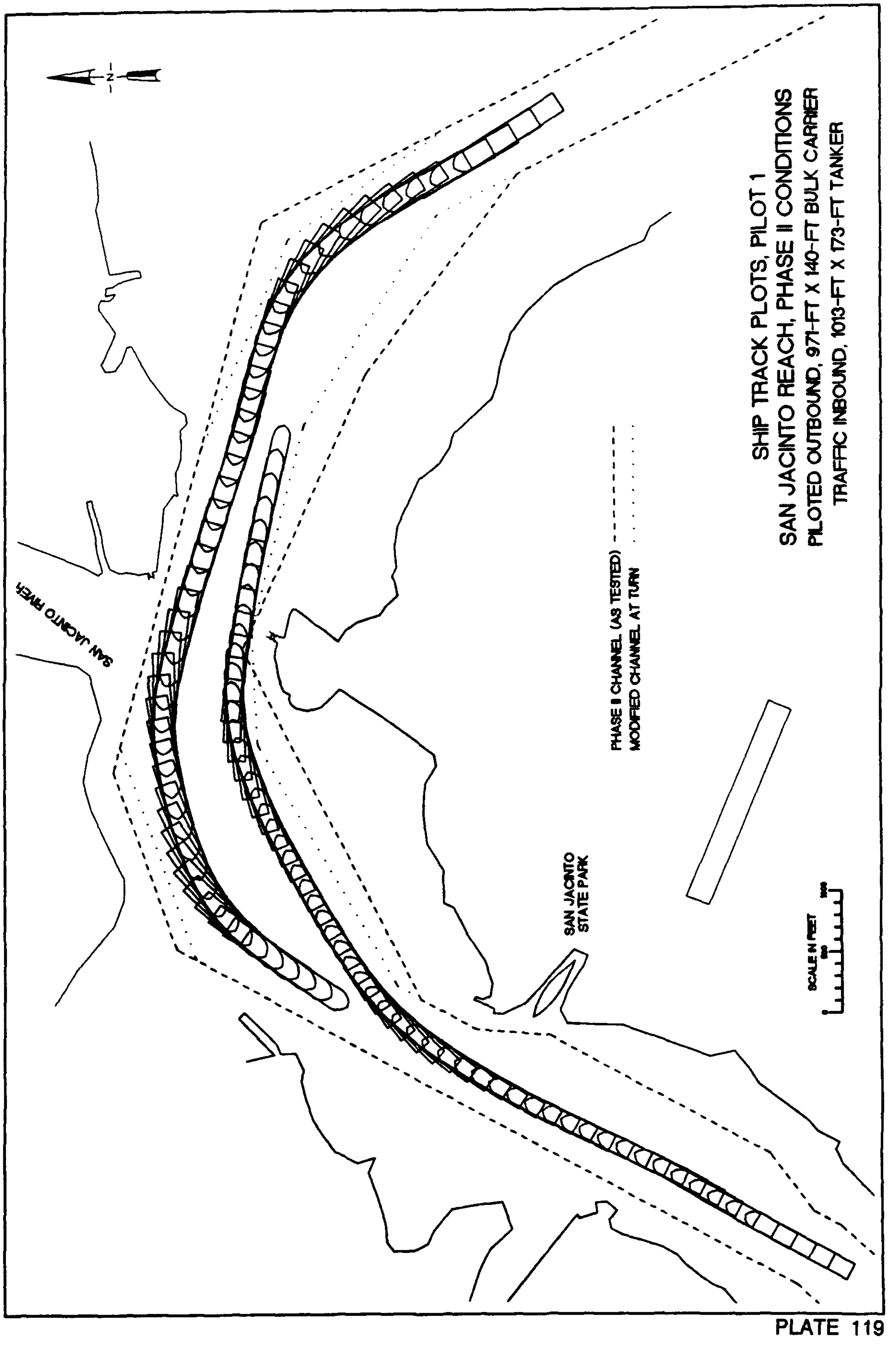
SAN JACINTO STATE PARK
SCALE IN FEET
N



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PILOTED OUTBOUND, 971-FT X 140-FT BULK CARRIER
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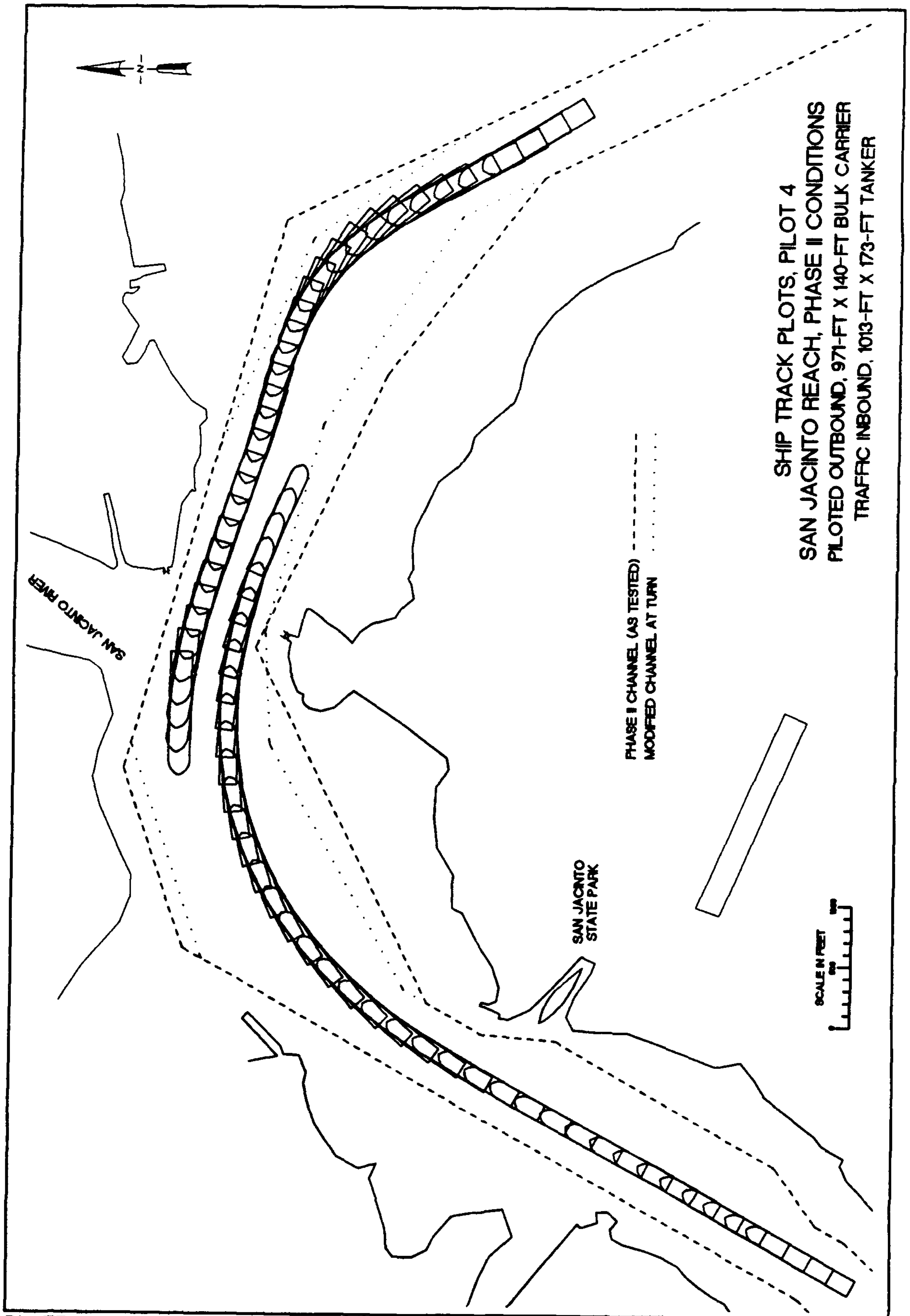
N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SHIP TRACK PLOTS, PILOT 4
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PILOTED OUTBOUND, 971-FT X 140-FT BULK CARRIER
TRAFFIC INBOUND, 1013-FT X 173-FT TANKER
PHASE II CHANNEL (AS TESTED)
MODIFIED CHANNEL AT TURN
SAN JACINTO RIVER
SAN JACINTO
STATE PARK
SCALE IN FEET

PLATE 120

REPORT DOCUMENTATION PAGE

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13. ABSTRACT *(Maximum 200 words)*

The Houston/Galveston Navigation Channels are located along the Gulf of Mexico Coast in eastern Texas. These channels include the Entrance Channel, the Bar Channels (Bolivar Roads Area), Galveston Channel, the Texas City Channel, the Gulf Intercoastal Waterway (GIWW), and the Houston Ship Channel (HSC), which branches off the Bolivar Roads Channel, traverses Galveston Bay, and ends in Houston.

The HSC consists of approximately 65 miles of improved deep-draft channels. The present channel is 400 ft wide and 40 ft deep at mean low tide for most of the channel distance. The project design calls for the channel to be improved in two phases. The Phase I channel is to be 530 ft wide and 45 ft deep, and the Phase II channel is to be 600 ft wide and 50 ft deep. A navigation study was conducted for the Houston/Galveston Navigation Channels, including a real-time ship simulation of the project area, to determine a cost-effective channel design for safe navigation. The Texas City Channel and the section of the HSC past Boggy Bayou are not included in the improvement project.

The HSC is designed for two-way deep-draft traffic. The capability of large loaded vessels to meet and pass is the primary factor in determining safe channel width. In the highly restricted channel, both bank and ship interaction effects are significant factors in conducting bow-on meeting and passing maneuvers. Prototype

(Continued)

14. SUBJECT TERMS

Deep-draft navigation	Navigation channels
Galveston	Ship-ship interaction
Houston	Ship simulation

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data and data from a physical model were used to provide guidance in simulating this maneuver. Other considerations in channel design include several sharp turns, strong currents in certain areas, shallow-draft traffic, location of docks and moored vessels, turning basin operations, overtaking area, and channel marking. Hydrodynamic modeling of the bay was a key element of the study and provided currents for the navigation design.