2 mil

SQF

A Reproduced Copy

OF

Reproduced for NASA

by the

NASA Scientific and Technical Information Facility

(NASA-TM-X-69441) TEST REPORT FOR 120-INCH-DIAMETER SOLID ROCKET BOOSTER (SRB) MODEL TESTS (NASA) ~~96~~ 94 p HC $7.00 CSCL 21H

N74-11599

Unclas
G3/28 22279

JOHN F. KENNEDY
SPACE CENTER

KSC TR-1253

TEST REPORT

FOR

120-INCH-DIAMETER
SOLID ROCKET BOOSTER (SRB)
MODEL TESTS

Conducted at the
Long Beach Naval Shipyard, California

August 1973

JOHN F. KENNEDY SPACE CENTER, NASA

I

TEST REPORT

FOR

120-INCH-DIAMETER
SOLID ROCKET BOOSTER (SRB)
MODEL TESTS

Prepared by:

William C. Jones

W. C. Jones, DD-SED
Space Shuttle Solid Rocket
Booster Retrieval Task Team

Approved by:

L. J. Junker

L. J. Junker, DD-SED
Test Technical Director

i

ABSTRACT

The Space Shuttle Solid Rocket Boosters (SRB's) will be jettisoned to impact in the ocean within a 200-mile radius of the launch site. Tests were conducted at Long Beach, California, using a 120-inch-diameter Titan 3C model to simulate the full-scale characteristics of the prototype SRB during retrieval operations.

The objectives of the towing tests were to investigate and assess the following:

a. floating and towing characteristics of the SRB
b. need for plugging the SRB nozzle prior to tow
c. attach point locations on the SRB
d. effects of varying the SRB configuration
e. towing hardware
f. difficulty of attaching a tow line to the SRB in the open sea.

The model was towed in various sea states using four different types and varying lengths of tow line at various speeds. Three attach point locations were tested.

Test data was recorded on magnetic tape for the tow line loads and for model pitch, roll, and yaw characteristics and was reduced by computer to tabular printouts and X-Y plots. Profile and movie photography provided documentary test data.

The free floating characteristics of the model with the nozzle plugged were very stable with the nose of the model up at a +1-1/2-degree pitch angle. The model positioned its longitudinal axis in the troughs of the sea and experienced heaving motions from the swell of the sea.

The free floating characteristics of the model with the nozzle unplugged were assessed in calm water only. The model ingested water until it stabilized at a nose-up attitude of +7-1/2 degrees. At that time it was determined that subjecting the unplugged model to a sea state would result in taking on more water and cause the SRB to rotate to the spar buoy mode.

The model exhibited stable pitch, roll, and yaw characteristics under tow in all test configurations at tow speeds below 10 knots. Instability in the roll and yaw axes occurred at speeds of 10 to 14 knots with the heavier and longer lengths of wire tow line. The model pitch angle decreased as tow speed increased, and the model plowed significantly at speeds of 10 knots and above. Removal of the nozzle exit cone improved model stability at the higher tow speed.

Analysis of test data indicates that plugging of the nozzle area is necessary for model towing due to the exposure of the nozzle throat area at the higher tow speeds.

All attachment configurations tested provided acceptable towing characteristics with the single center attachment resulting in the smallest tow line load.

PRECEDING PAGE BLANK NOT FILMED

Tow speeds had the most significant effect on tow line loads and model towing characteristics. Using 7-inch-circumference nylon tow line, the tow line loads at the tow vessel increased with speed and ranged from 1500 pounds at 6 knots to 13,500 pounds at 14 knots.

Use of the 7-inch-circumference nylon line produced the smallest tow line loads and produced no increase in line loads as the length was increased. The 1-inch-diameter steel wire, 6-inch-circumference nylon line, and 7-inch-circumference nylon line were optimally sized for towing the model while the 2-inch-diameter steel wire was oversized. To determine the tow line which is best suited for towing the actual Shuttle SRB, scaling of the model load data is required.

Scaling of the model data causes the full scale values for speed and tow line loads to increase as the square root and cube, respectively, of the scale factor, .78. The full scale loads were much higher than the model loads with a difference between them of 15,647 pounds at 14 knots for the 7-inch-circumference nylon tow line. The 1-inch-diameter steel wire is undersized for full scale model towing, while the 7-inch-circumference nylon line would be acceptable at speeds up to 15 knots without exceeding the maximum working load.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (cont'd)

LIST of TABLES

SECTION I

INTRODUCTION

1.1 PURPOSE AND SCOPE

The purpose of this document is to present the test plan and test results of large scale Solid Rocket Booster (SRB) model tests conducted at Long Beach, California. Testing began on March 26, 1973, and was completed on April 5, 1973. The test program utilized a 120-inch-diameter (Titan 3C) model of the Space Shuttle SRB as shown in Figure 1. The model simulated the 142-inch-diameter baseline dated February 2, 1973, with the exception of the flared aft skirt. Tests conducted were: waterborne attitude, waterborne stability, harbor and ocean towing, and attachment at sea.

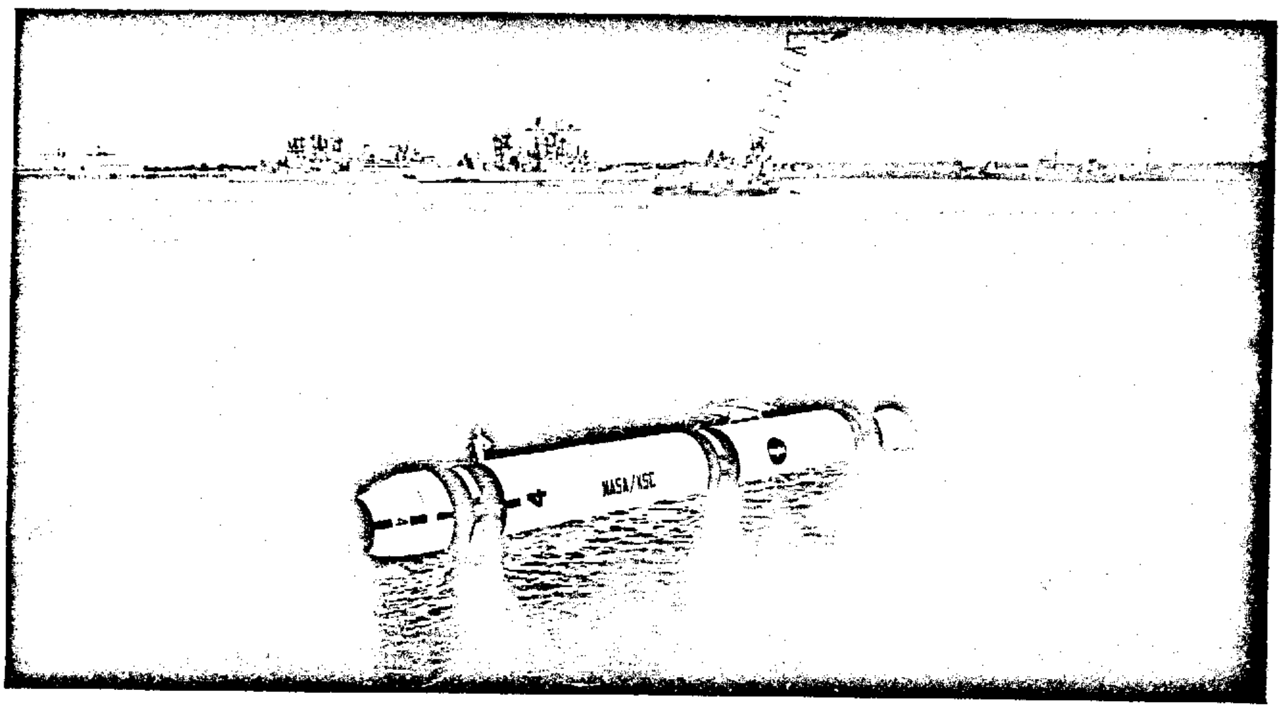

Figure 1. 120-Inch-Diameter SRB Model

The tests were conducted in two phases:

Phase 1 (March 26 to March 30):	Harbor tow tests, stability test, and attitude test
Phase 2 (April 3 to April 5):	Ocean tow tests and attachment at sea test

The purpose of the in-harbor testing was to establish a calm water baseline for acquisition of data and to gain the experience and confidence necessary to conduct the ocean tests. Tests were conducted in the ocean to assess the effects of variable ocean conditions on the SRB.

Test data recorded during the towing tests consisted of tow line loads at the tow vessel and at the model, and pitch, roll, and yaw characteristics of the model. The results of attitude, stability, and attachment tests were documented also.

1.2 MODEL DESCRIPTION

The model was a previously static fired 120-inch-diameter Titan 3C solid rocket booster which was obtained from MSFC. The model consisted of a nose section, segmented body sections, aft support skirt, a 6-degree canted nozzle, and an exit cone extension. The center of gravity of the model simulated the 142-inch-diameter baseline for the Shuttle SRB.

The longitudinal position of the center of gravity (lcg) of the model for the MSFC drop tests was located 435 inches from the aft edge of the structural support skirt and required relocation for the tow tests due to a change in the Shuttle SRB baseline from a 156-inch diameter to a 142-inch diameter. The 142-inch-diameter baseline required locating the lcg at 415 inches (reference aft skirt). This was accomplished by relocating the ballast system.

The ballast system consisted of eight I-beams with associated weights which were moved further aft in the model. An additional 5200 pounds of lead was attached to the beams. All weights were attached symmetrically about the roll axis of the model to maintain the original roll axis cg (see Figure 2).

To simulate the Shuttle SRB after parachute descent and water impact, an open nose fairing was welded to the forward handling fixture of the model (see Figure 3). This structure represented the empty parachute compartment of the Shuttle SRB after the parachutes are deployed.

Three different tow line attachment configurations were tested: two-point bridle, single center, and single side. Towing brackets were added to the model for the two-point bridle and single side configurations; an existing 2-inch shackle on the nose section was used for the single center configuration (see Figures 4, 5, and 6).

A bulkhead plate with an access hatch was installed as a nozzle plug to prevent the SRB from sinking during the tow tests. The assembly was placed between the nozzle and the exit cone extension (see Figure 7).

As part of the data acquisition system, a telemetry package was placed on the model to transmit tow line loads at the model and pitch, roll, and yaw data to the tow vessel. The electronic equipment was placed in waterproof pressurized cannisters which were fastened to gusset plates inside the nose fairing of the model for easy access (see Figure 8). A pitch, roll, and yaw measuring system in the waterproof container was installed at the lcg of the model (see Figure 9). Three antennas were placed around the outside skin of the model at 120-degree intervals (see Figure 10).

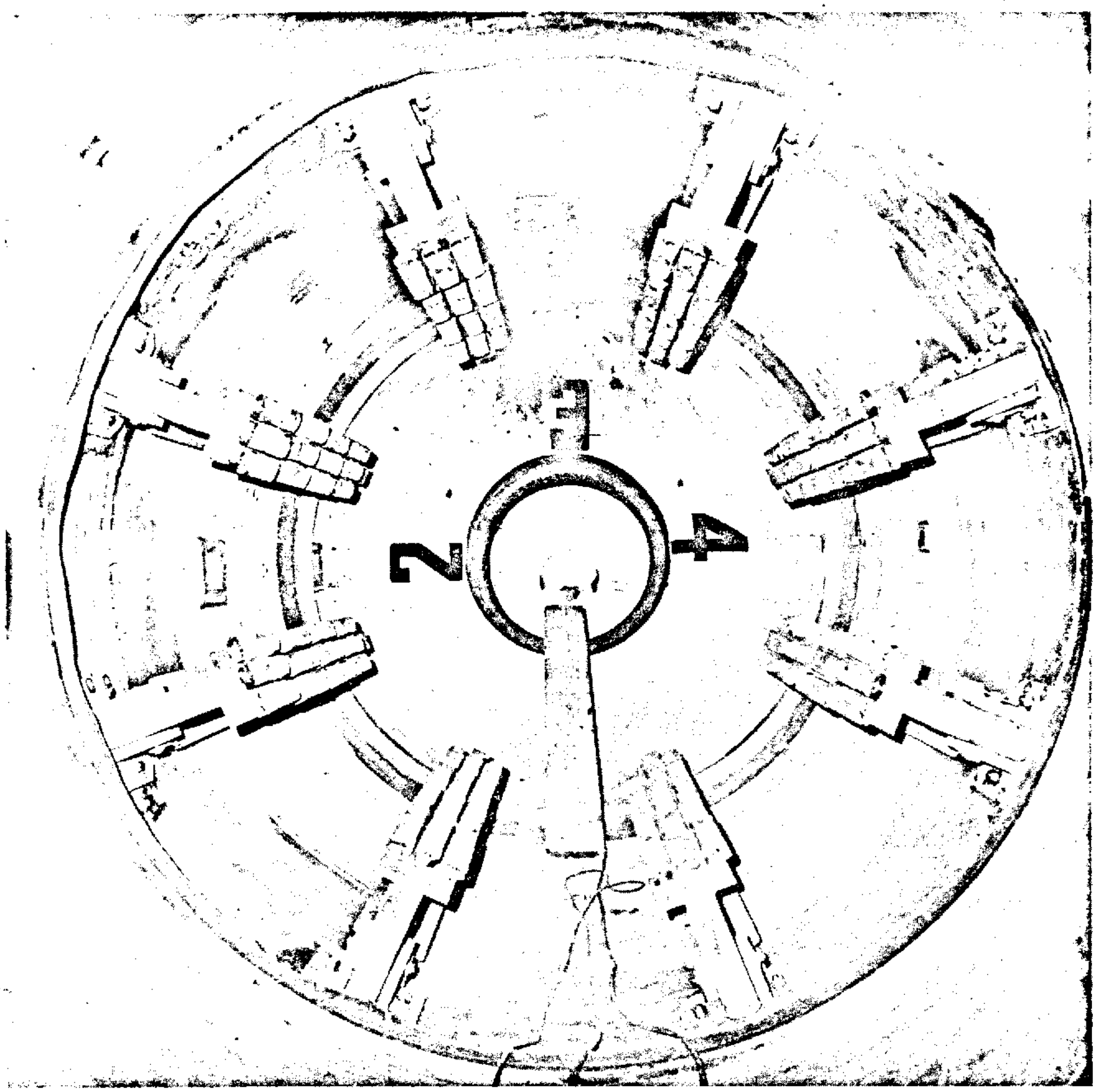

Figure 2. Ballast System Installation

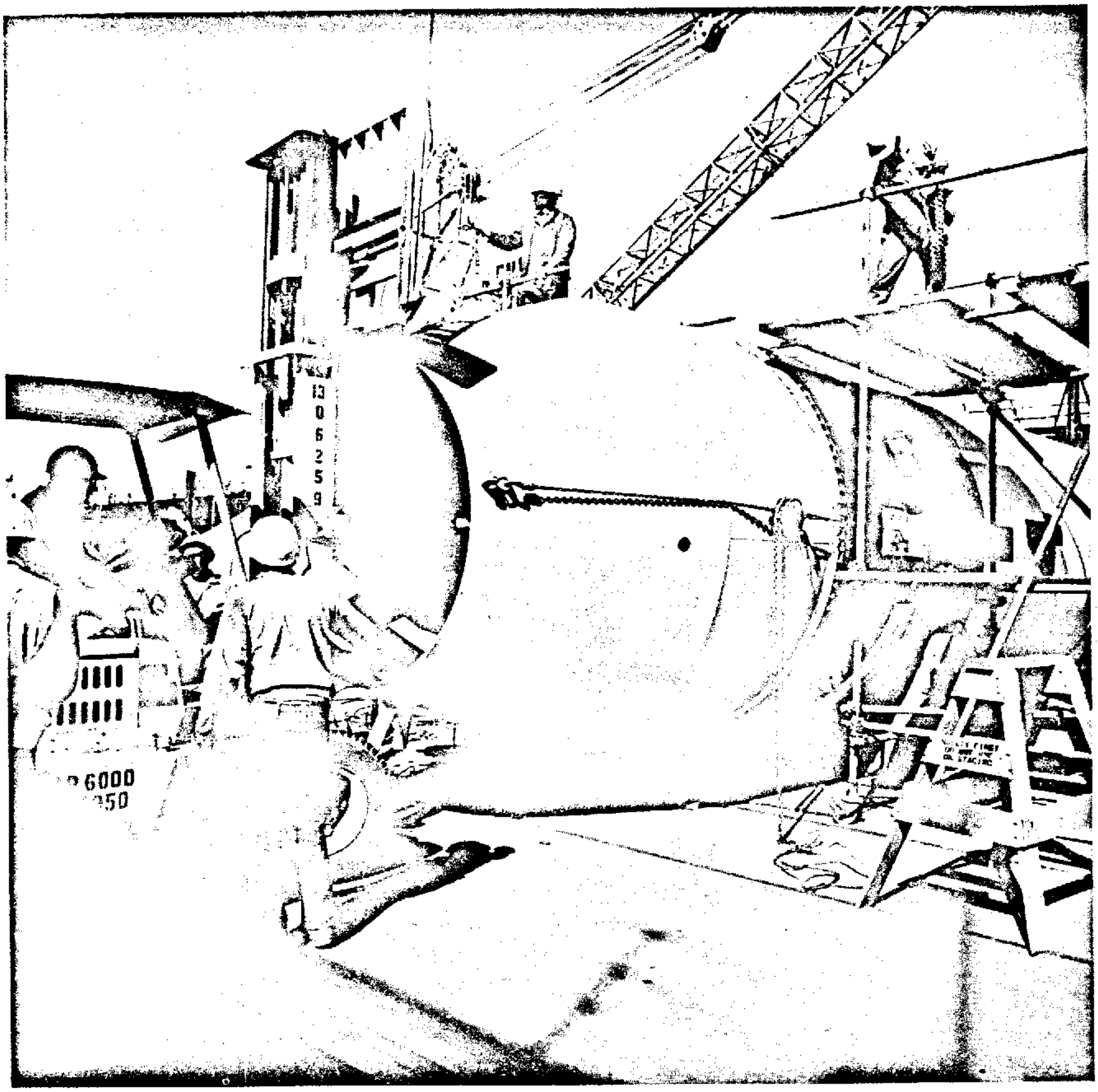

Figure 3. Open Nose Fairing Installation

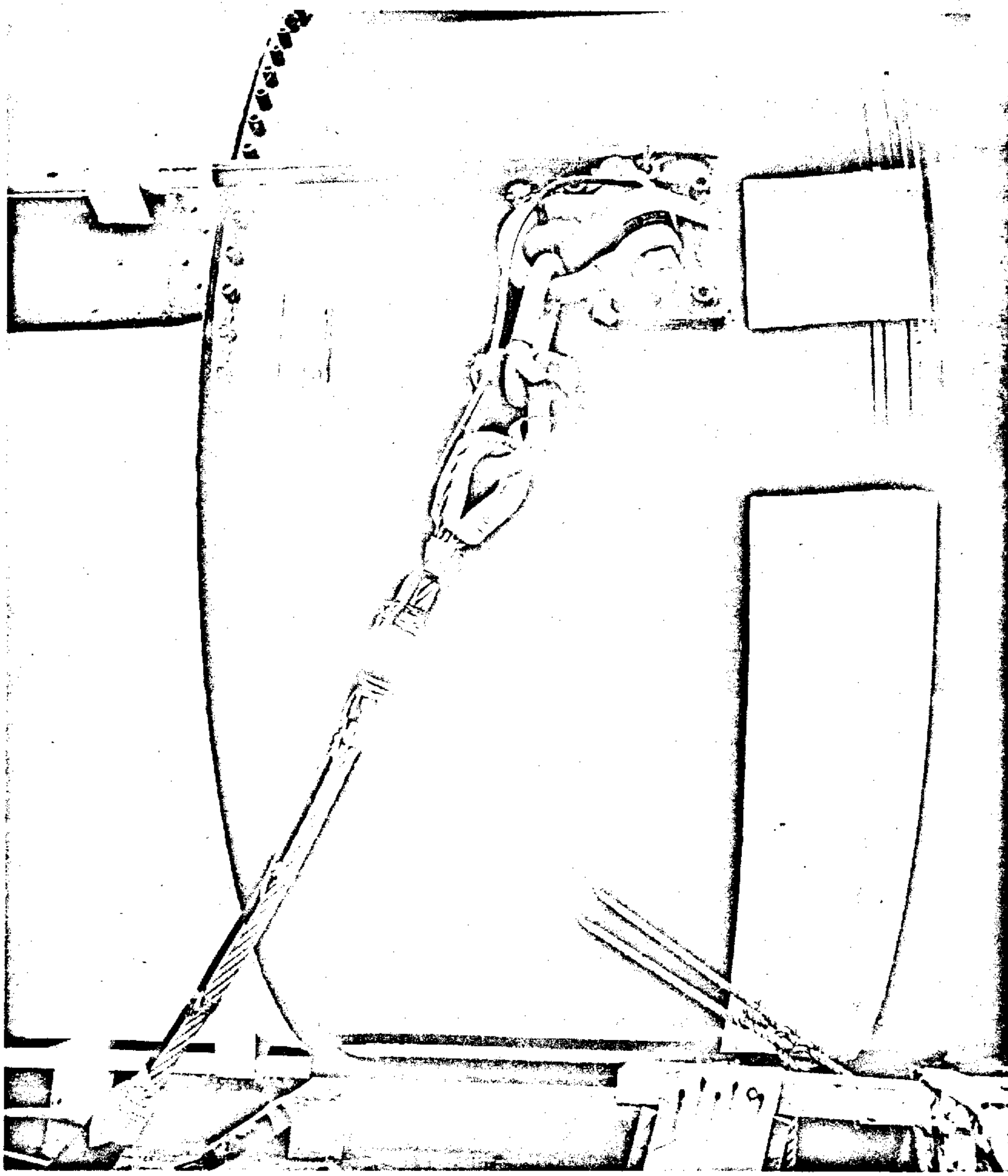

Figure 4. Towing Bracket for Two-Point Bridle Attachment

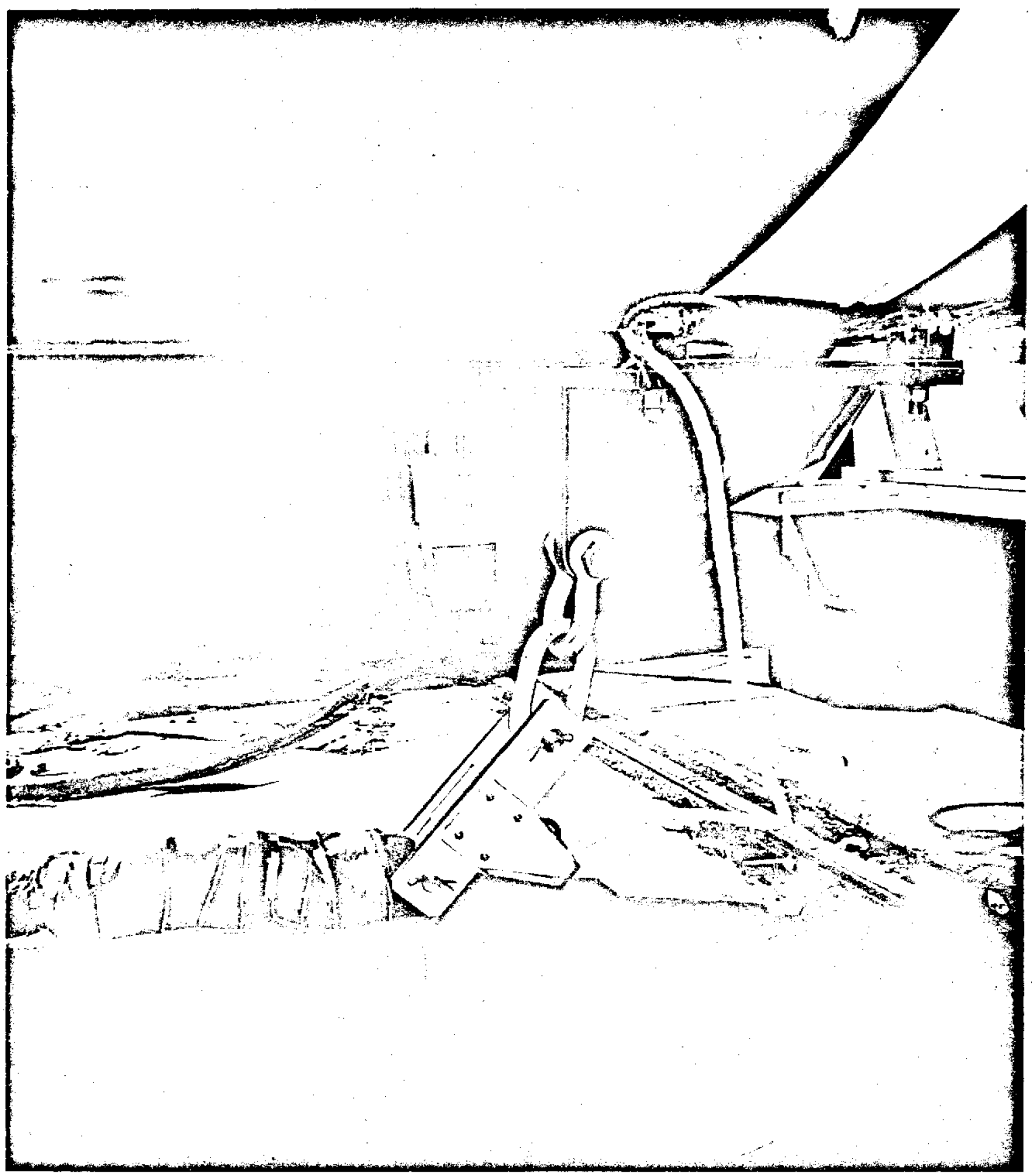

Figure 5. Towing Bracket for Single Side Attachment

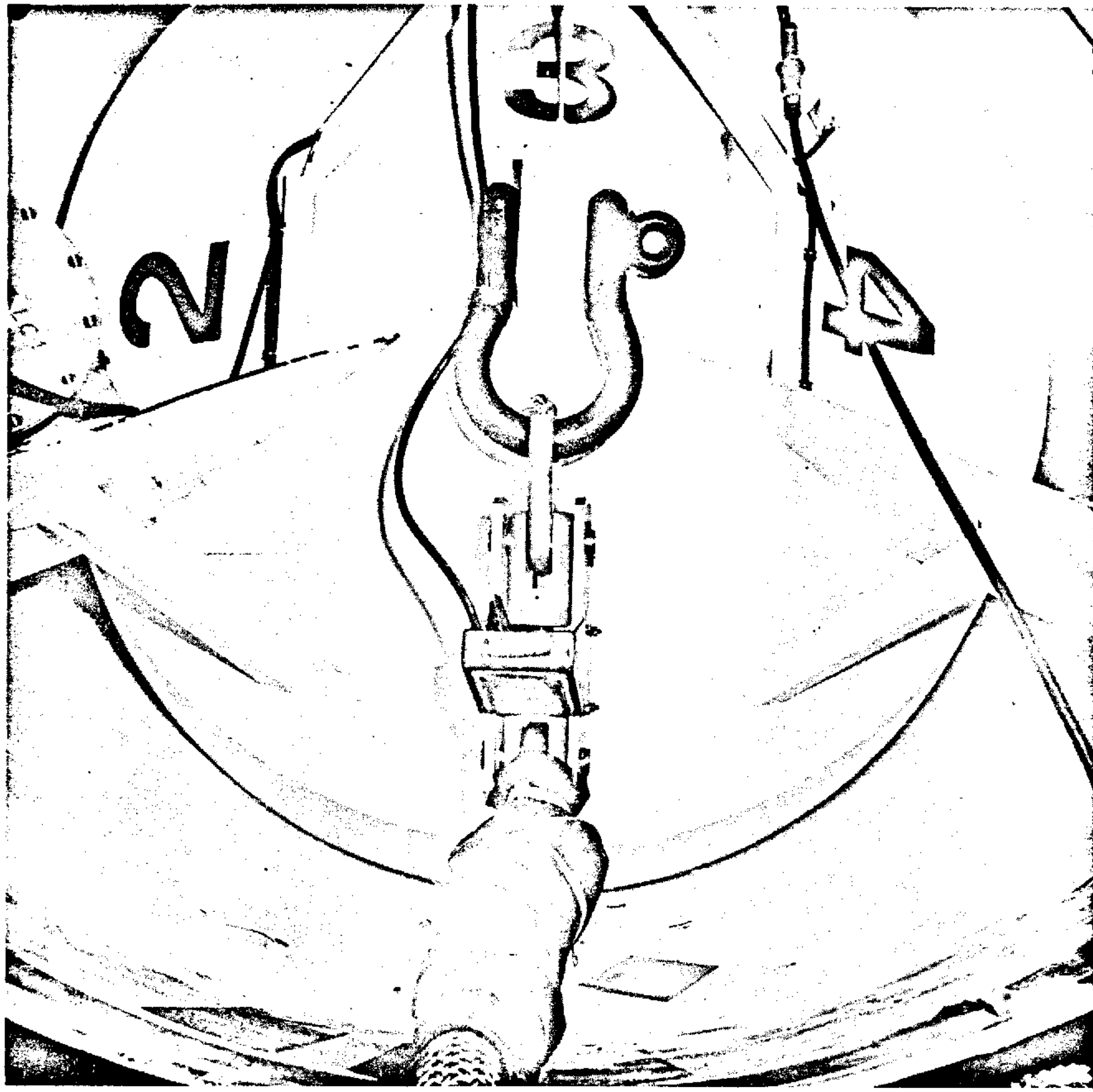

Figure 6. Single Center Attachment

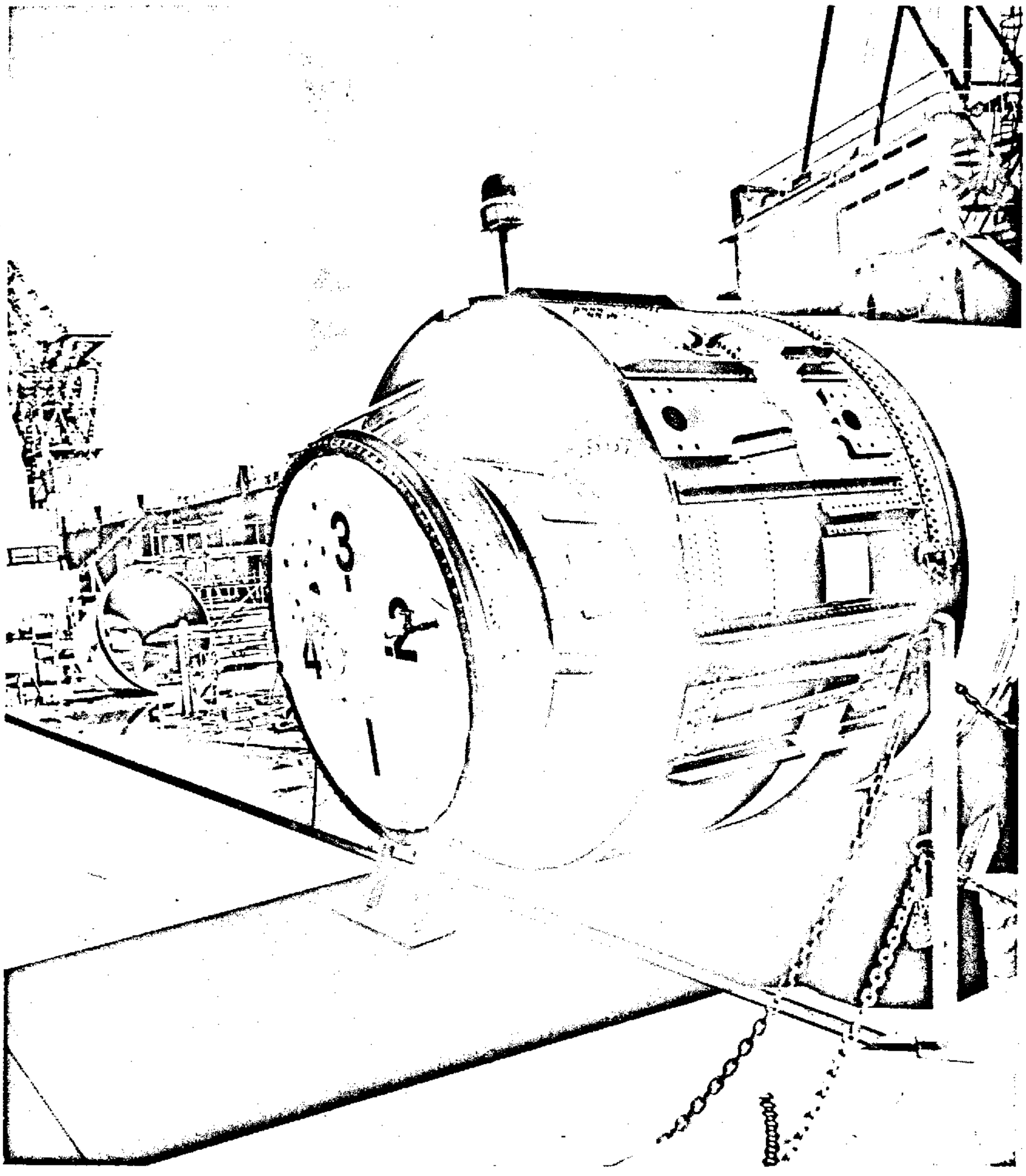

Figure 7. Nozzle Plug Assembly

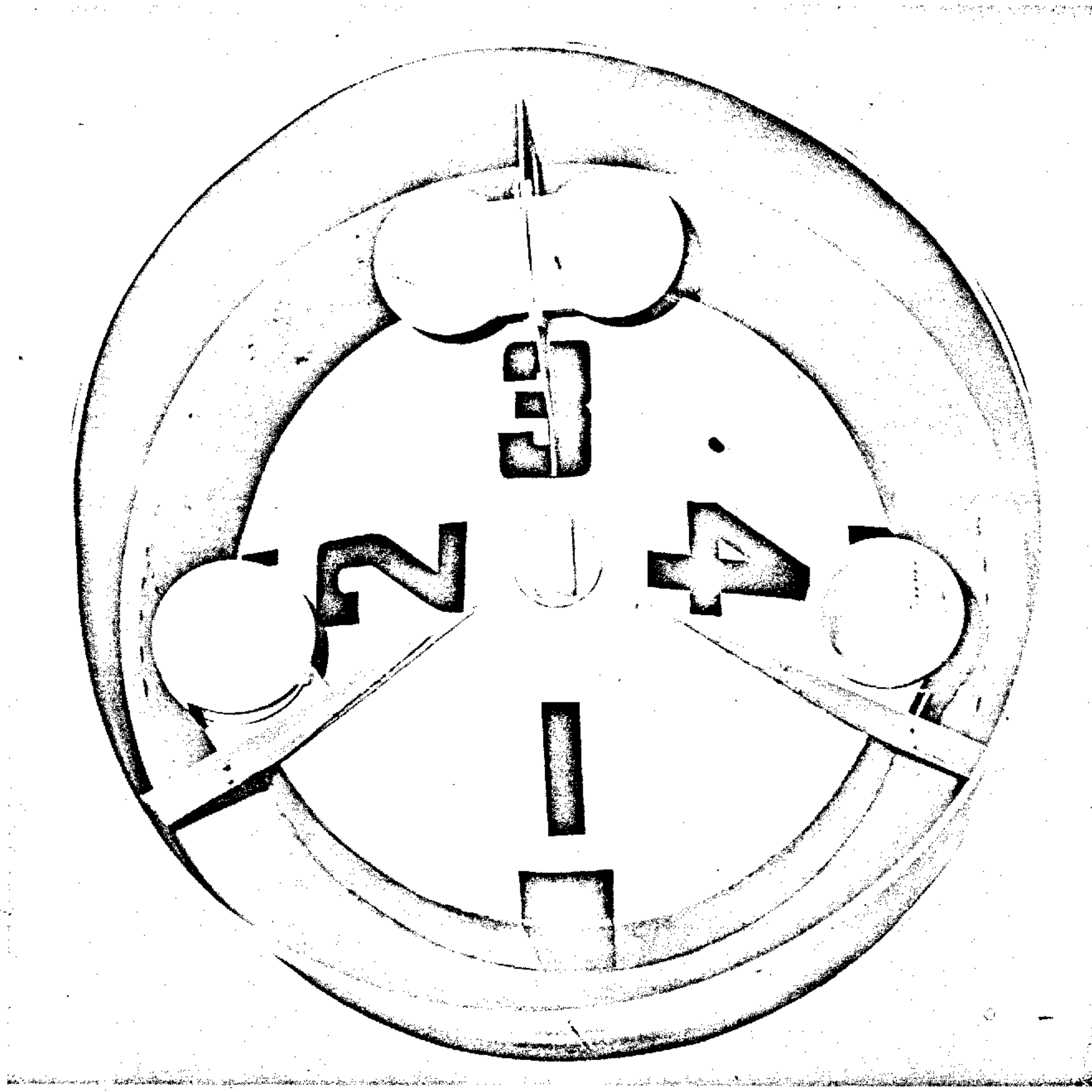

Figure 8. Electronic Equipment Installation in Nose Fairing

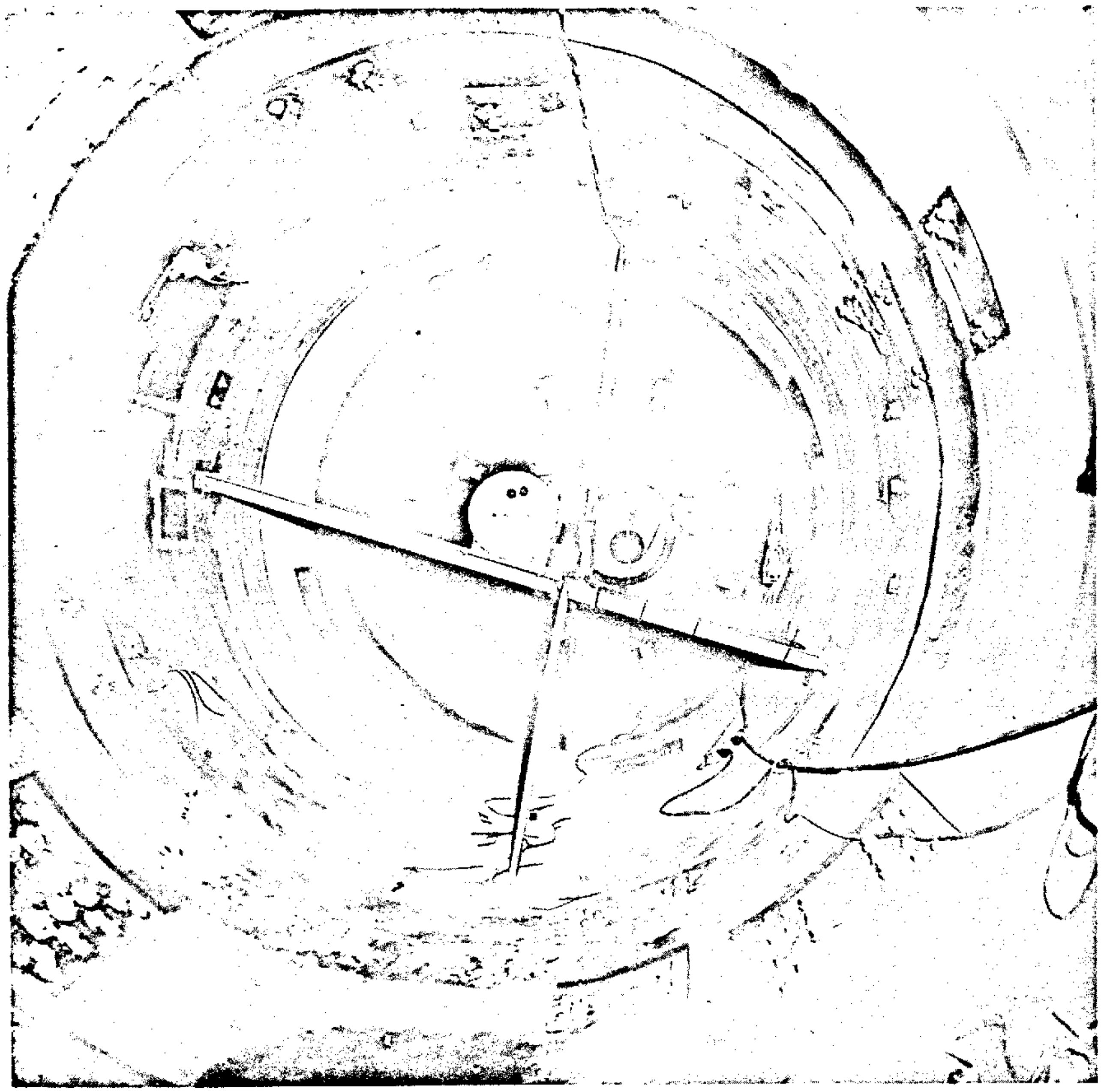

Figure 9. Pitch, Roll, and Yaw Measurement System Installation

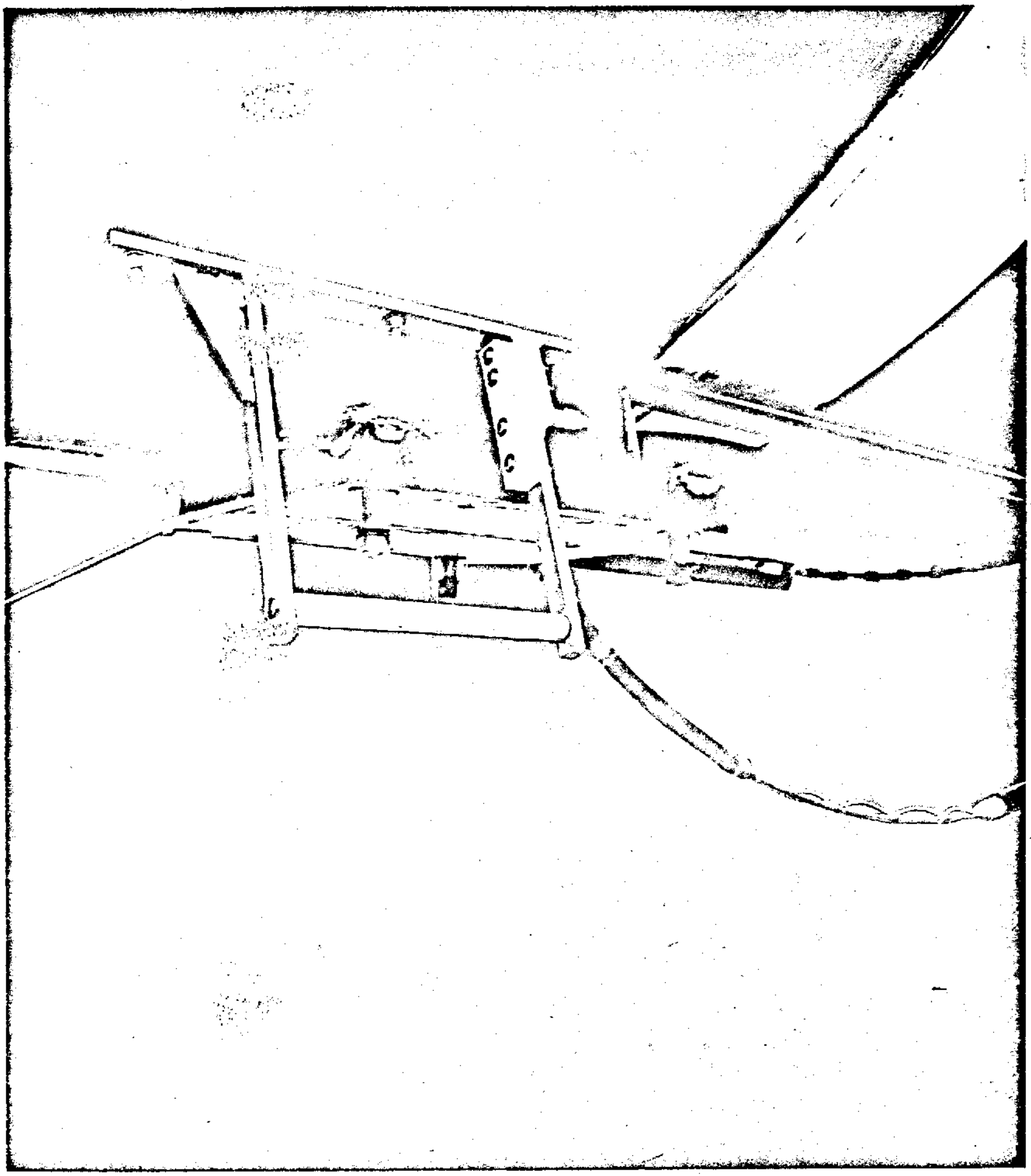

Figure 10. Antenna Installation

Approximately 200 holes which resulted from the removal of MSFC water impact test instrumentation on the model were sealed with nuts, bolts, and RTV sealant. Paint patterns were added to the model for photographic data acquisition.

The dimensions and weight of the modified model were as follows:

Length:	101 feet
Body Diameter:	10 feet
Weight:	93,286 pounds
Longitudinal Postion of Center of Gravity, lcg:	415 inches (reference aft support skirt)

1.3 VESSELS AND TEST HARDWARE

Two types of tow vessels were used during the testing--a U.S. Navy harbor tug (YTB 807) as shown in Figure 11 and a Fleet Ocean Tug (USS Molala, ATF 106) as shown in Figure 12. The YTB 807 was used for the tow operations in the harbor phase of the testing. It produced 1500 shaft horsepower, and its towing equipment consisted of an aft-mounted capstan, H-bitts aft, and miscellaneous securing cleats. Since this vessel does not normally perform astern towing operations, 900 feet of 1-inch-diameter steel tow wire, 600 feet of 6-inch-circumference nylon line, and a storage reel were added to the vessel.

The ATF 106 was used for tow operations in the ocean phase of the testing and is specifically designed for all types of ocean towing. Its towing hardware consisted of an automatic towing machine which maintained a specific tension on the tow cable, capstan, stern rollers, H-bitts, Norman pins, and miscellaneous pad eyes and securing cleats. The ATF 106 carried 5000 feet of 1-inch-diameter and 2100 feet of 2-inch-diameter steel towing cable and 2400 feet of 7-inch-circumference, regular lay nylon tow line.

A 100-foot long, 6-inch circumference braided nylon pendant was attached to the model for the single center and single side attachment configurations. This pendant provided a quick and safe method for connecting and disconnecting the tow line during initial hook-up and while at sea. For the two-point bridle attachment, an 80-foot-long, 3-3/8-inch-circumference nylon pendant was used as part of the bridle.

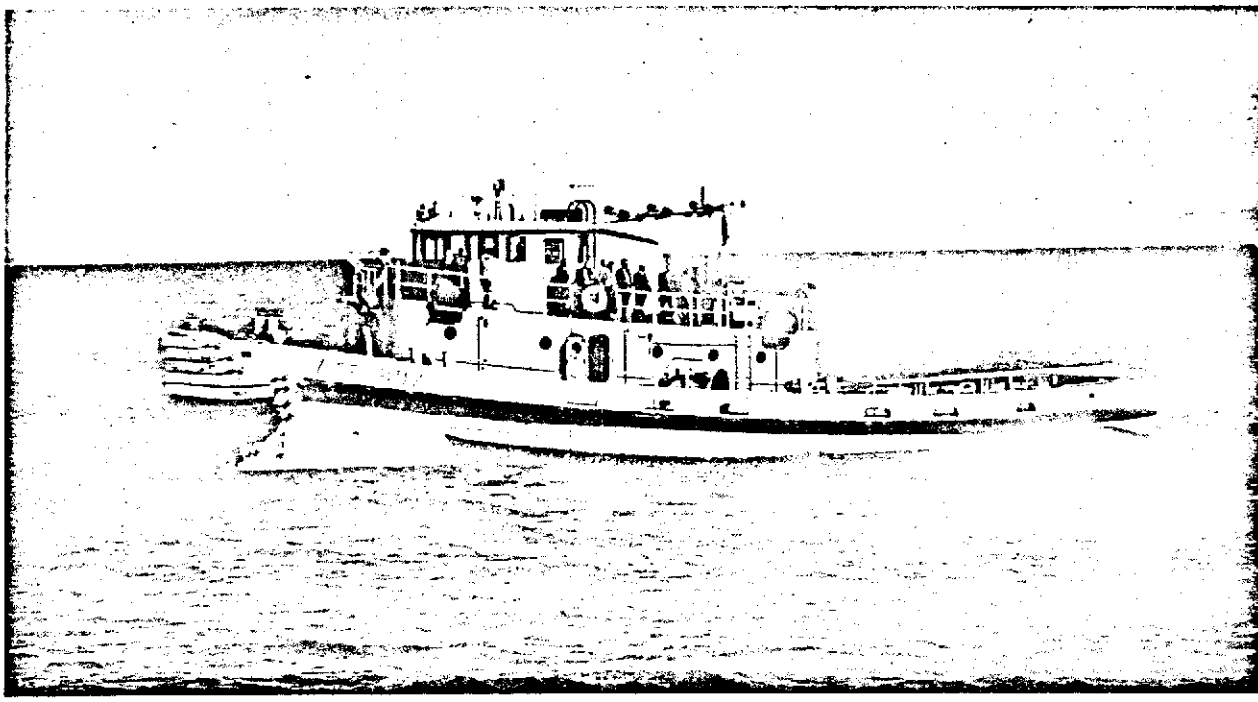

Figure 11. USN Harbor Tug (YTB 807)

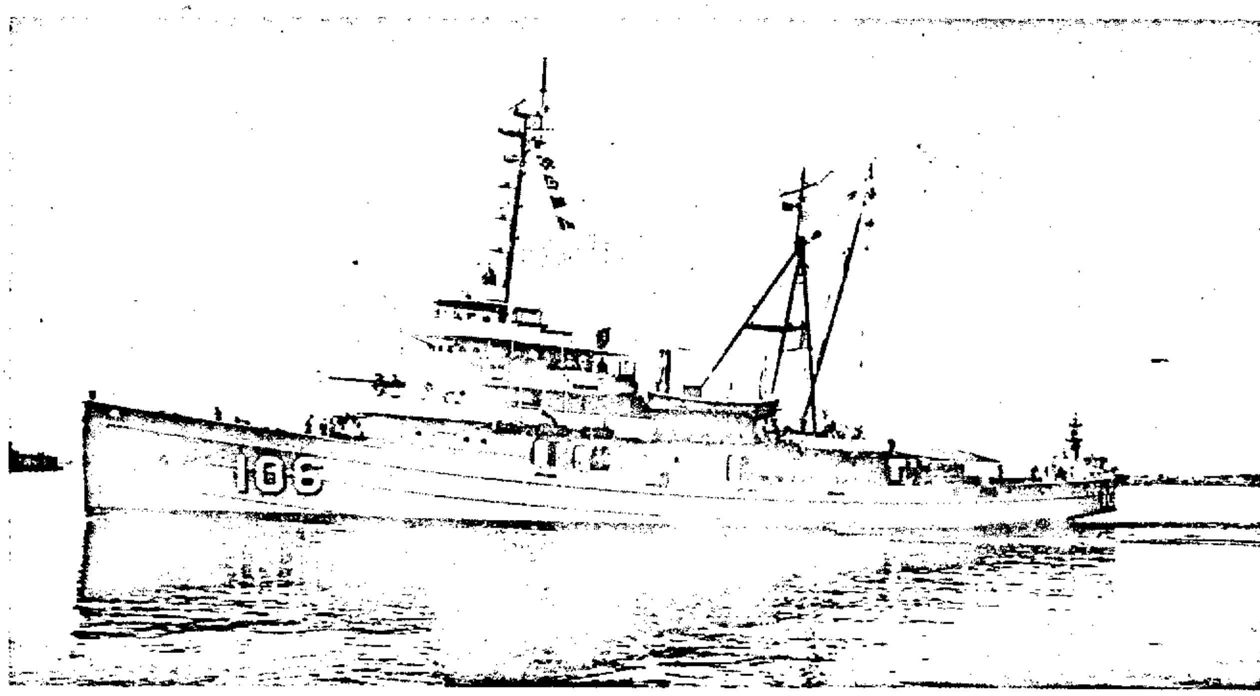

Figure 12. USN Fleet Ocean Tug USS Molala (ATF 106)

A combined carpenter stopper/load cell arrangement was used with the wire tow cables to gather data on tow line loads at the tow vessel (see Figure 13).

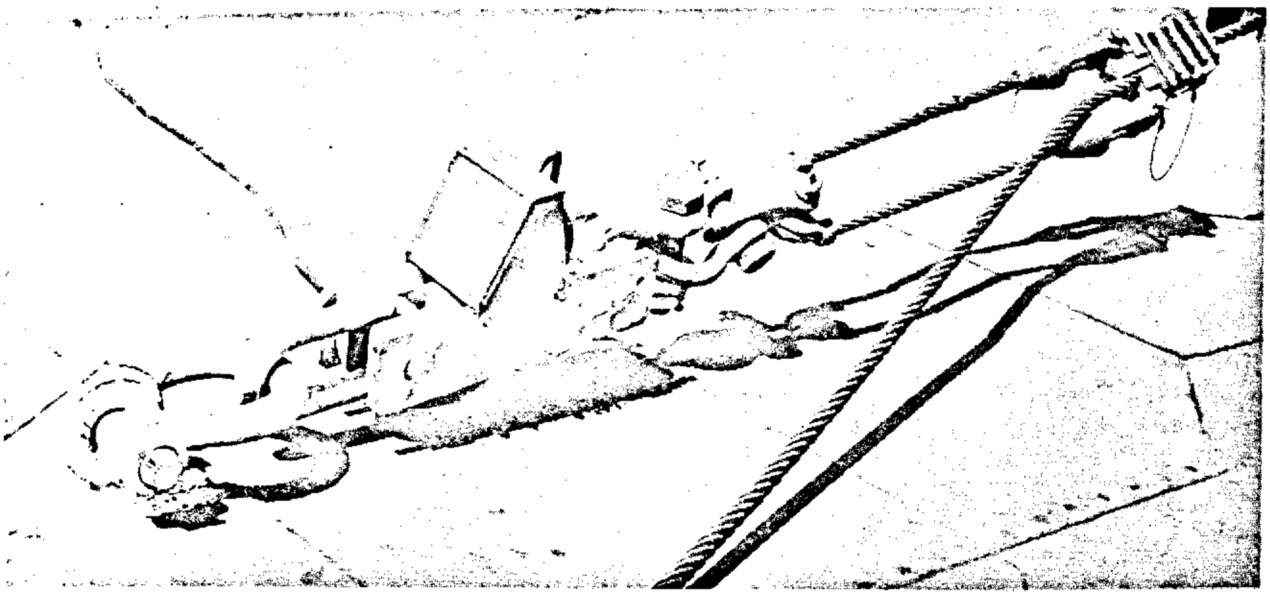

Figure 13. Carpenter Stopper/Load Cell Arrangement

Two 34-foot work boats were used to maneuver the model during docking operations. One work boat was also used in the harbor tow testing as a camera boat for profile photography of the model. A torpedo retriever boat was used in the ocean tow testing as the profile camera boat.

1.4 INSTRUMENTATION AND DATA ACQUISITION SYSTEMS

1.4.1 Instrumentation

The measurement and acquisition system for the tow tests was used to record forces on the tow line at the model and tow vessel and to record the model's pitch, roll, and yaw characteristics. This system consisted of three load cell transducers, two pendulum potentiometers, a rate gyroscope, a radio frequency telemetry link, a strip-chart recorder, and a tape recorder. Measurement components installed on the SRB were in waterproof enclosures and were battery powered. The components installed on the ATF and YTB tow vessels were rack-mounted and used the ship's electrical power.

One or two 0 to 30,000-pound capacity load cells and their associated 50-foot waterproof cables were installed at the model in the tow harness as required for the tow attachment configurations. Two waterproof load cell power supply/signal conditioner containers were installed in the SRB nose fairing. A telemetry transmitter and its separate waterproof enclosed battery container were installed in the nose fairing. The transmitter was connected by 25-foot coaxial cables to three antennas installed 120 degrees apart on the circumference of the nose fairing (see Figure 10).

A waterproof enclosure containing two pendulum potentiometers, one to measure ±45-degree pitch and one to measure ±45-degree roll, and a rate gyroscope to measure yaw rate were installed in the model nose fairing. The data was recorded using the reference system in Figure 14. A 100-foot cable assembly was routed inside the SRB to the forward bulkhead and then routed to interface with the telemetry input connection.

The transmitted data was received by a rack-mounted telemetry receiver on the tow vessel. The data was simultaneously recorded on a tape recorder and a strip-chart recorder. The strip-chart recorder provided real-time readout and a permanent paper record with written annotations (see Figure 15). A master time clock was utilized to time correlate all test data.

A 0 to 30,000-pound capacity load cell was installed in the tow cable at the tow vessel when 1-inch-diameter and 2-inch-diameter steel wire was used for towing. Real-time data from this load cell was available on a meter readout, while simultaneously being recorded on both the strip-chart recorder and the tape recorder. The overall SRB measurement component installation and the tow vessel measurement component installation are shown in Figures 16 and 17, respectively.

A pit log (speedometer) was mounted on the side of each tow vessel to obtain towing speeds during the testing (see Figure 18).

1.4.2 Photographic System

The photographic system consisted of four 24 frames per second motion picture cameras which were used for documentary coverage and to gather data on model pitch, roll, and yaw characteristics. Two engineering cameras, one wide angle and the other telephoto, were located on the tow vessel. Another engineering camera was located on a camera boat to provide profile photography of the model. The engineering data cameras were time syncronized with a master time clock for correlation of the data.

1.5 REFERENCE DOCUMENTS

Test Plan for MSFC/KSC Space Shuttle Solid Rocket Booster Water Recovery Program, 77% Model, December, 1972, DD-SED, John F. Kennedy Space Center, NASA

Qualitative Investigation of Booster Recovery in Open Sea, TR-1195, March 1, 1973, DD-SED, John F. Kennedy Space Center, NASA

Measurement Support Plan and Requirements for 77% SRB Tow Testing, January 10, 1973, IN-MSD, John F. Kennedy Space Center, NASA

Preliminary Photographic Support Plan for SRB Tow Test, December 27, 1972, IS-DOC, John F. Kennedy Space Center, NASA

Test Procedure for Solid Rocket Booster 77% Model Tow Test, January 30, 1973, SO-ENG, John F. Kennedy Space Center, NASA

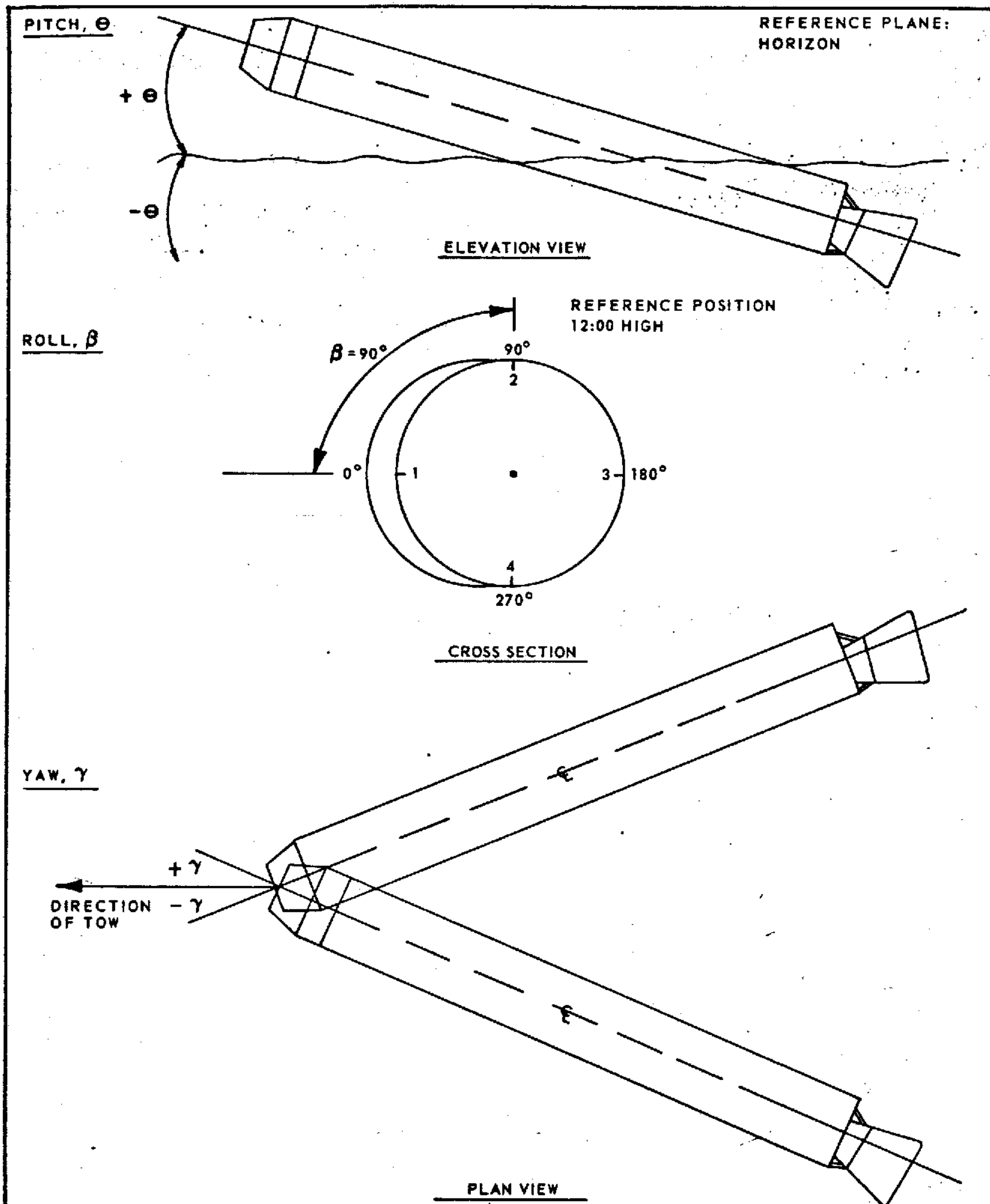

Figure 14. Model Attitude Reference System

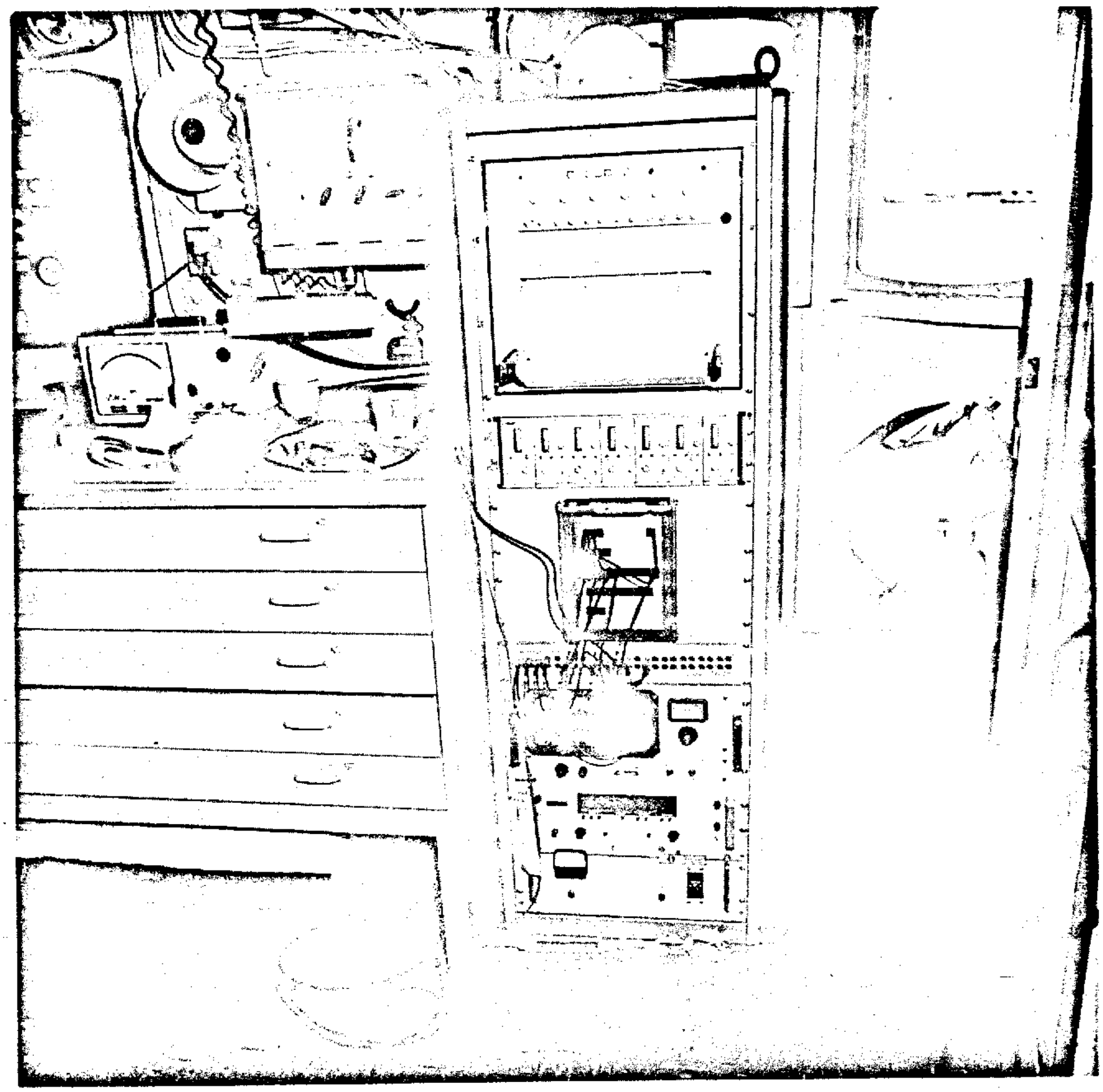

Figure 15. Strip Chart and Magnetic Recorders

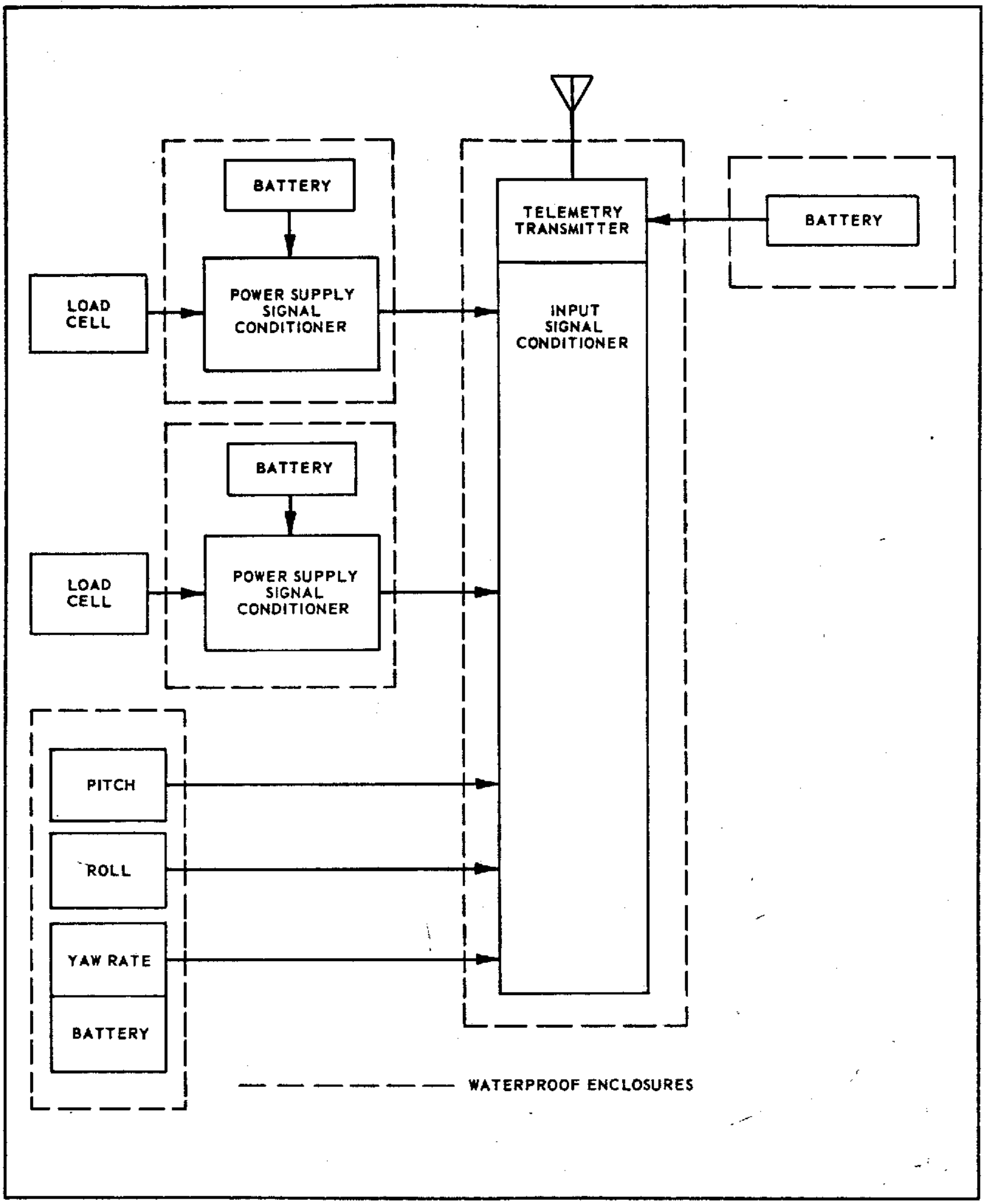

Figure 16. SRB Measurement System Installation

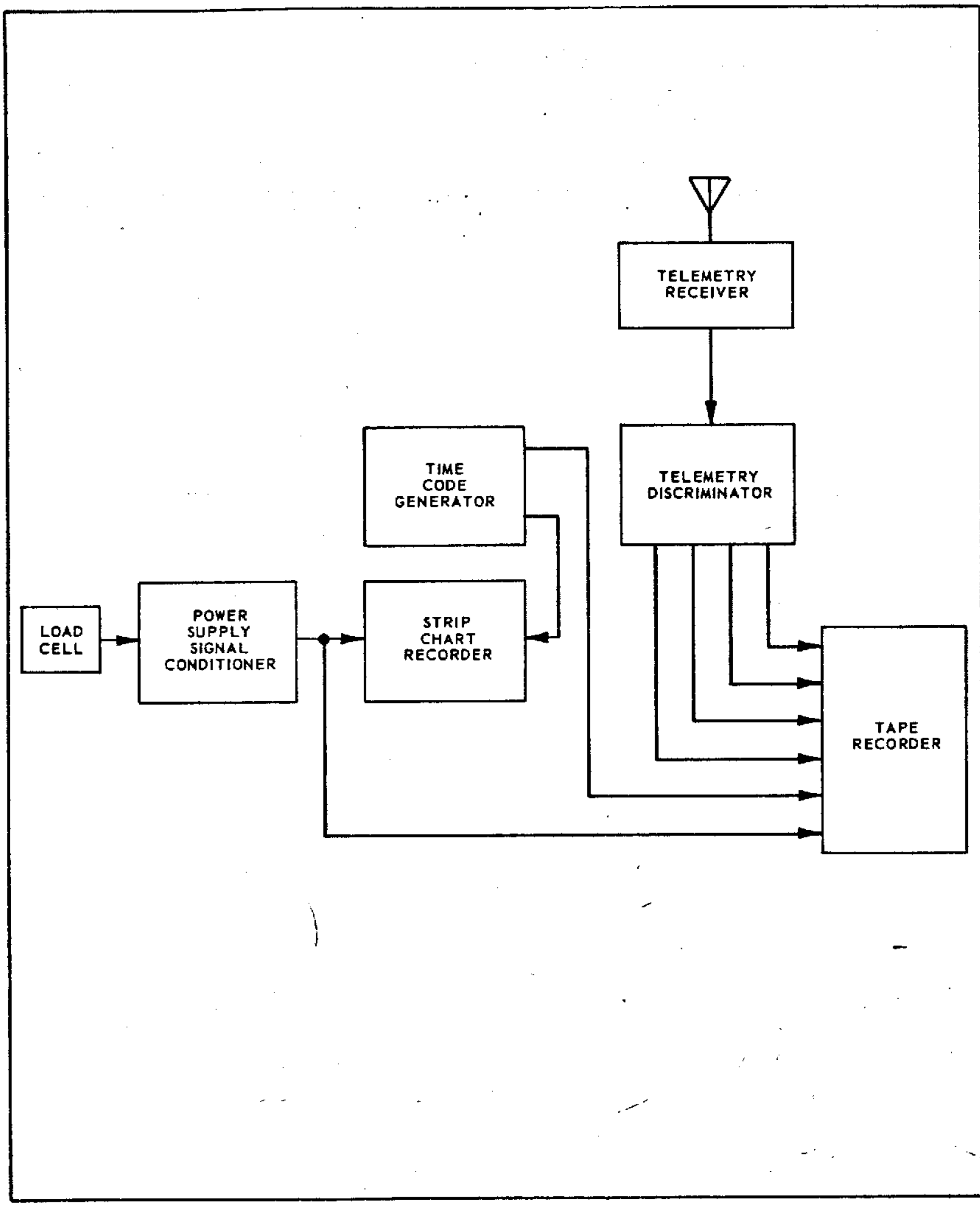

Figure 17. Tow Vessel Measurement System Installation

Figure 18. Speedometer Installation

U.S. Navy Towing Manual, Volumes I and II, NAVSHIPS 0925-000-1000, 1971

Principles of Naval Architecture, John P. Comstock, Ed., The Society of Naval Architects and Marine Engineers, New York, 1967

Water, Air, and Interface Vehicles, Philip Mandel, MIT Press, Cambridge, Massachusetts, 1969

Unclassified Excerpt from "Dynamic Scale Modeling Technics for Mine Countermeasures," Charles Sieber (D.T.M.B.), Proceedings of the 16th Naval Mine Countermeasures, January 30, 1973

John F. Kennedy Space Center, NASA, Drawings:

79K04073	Sling Assembly, 77% SRB Model
79K04074	Wire Rope Assembly, 77% SRB Model
79K04075	Wire Rope Assembly, 77% SRB Model
79K04076	Drouge Assembly, 77% SRB Model
79K04077	Cover Plate Assembly, Nose Cone, 77% SRB Model
79K04078	Nose Cone, 77% SRB Model
79K04083	Wire Rope Assembly, 77% SRB Model
79K04095	Rope Assembly, 77% SRB Model
79K04096	Flounder Plate, 77% SRB Model
79K04097	Nylon Bridle Assembly, 77% SRB Model
79K04098	Tow Installation, 77% SRB Model
79K04099	Adapter Plate, 77% SRB Model
79K04100	Cleat Installation, 77% SRB Model
79K04101	Nozzle Plug Assembly, 77% SRB Model
79K04103	Shackle Plate Assembly, 77% SRB Model
79K04112	Paint Pattern, 77% SRB Model
79K04123	Instrumentation Installation, 77% SRB Model
79K04146	Tow Weldment, 77% SRB Model
79K04166	Support Assembly, Pitch/Roll Instrumentation, 77% SRB Model

SECTION II

TEST OBJECTIVES

The primary objective of the SRB model test program was to determine the characteristics of the SRB floating free and under tow. In addition to assessing the floating and towing characteristics, the following requirements were included as test objectives:

a. Investigate the need for plugging the SRB nozzle prior to towing
b. Assess attach point locations on the SRB for towing
c. Assess effects of SRB configuration variations on towing
d. Assess various towing hardware
e. Assess difficulty of attachment of tow lines at sea.

SECTION III

TEST DESCRIPTION

3.1 HARBOR TOW TESTING

The initial towing tests were accomplished within the outer breakwater at Long Beach, California, (see Figure 19) to determine calm water characteristics and to gain initial test experience in calm water.

Three attachment configurations were used:

a. Two-point bridle

b. Single center

c. Single side

Two types of tow lines were used during the testing: (1) 1-inch-diameter steel cable and (2) 6-inch-circumference nylon line. A nylon pendant of either 3-3/8-inch or 6-inch circumference nylon was attached at the model for all test runs (see Figures 20, 21, and 22). The nozzle remained plugged throughout all tow tests.

A YTB was used to tow the model. Tow speeds, tow line configurations, and model configurations were varied according to the test profile sheets in paragraph 3.1.1.

3.1.1 Test Profile Sheets, Harbor Tests

3.1.1.1 Two-Point Bridle Attachment (See Figure 20)

Test configurations for the two-point bridle attachment tests (Test No. 1 and Test No. 2) using 1-inch-diameter steel cable and 6-inch-circumference nylon line are tabulated below:

1-Inch-Diameter Steel Cable			6-Inch-Circumference Nylon Line		
Test No.	Tow Vessel Speed (knots)	Length of Cable (feet)	Test No.	Tow Vessel Speed (knots)	Length of Cable (feet)
1B	4	200	2A	4	100
1C	4	400	2B	4	200
1D	4	600	2C	4	400
1L	6	200	2D	4	500
1M	6	400	2L	6	200
1N	6	600	2M	6	400
1O	6	800	2N	6	500

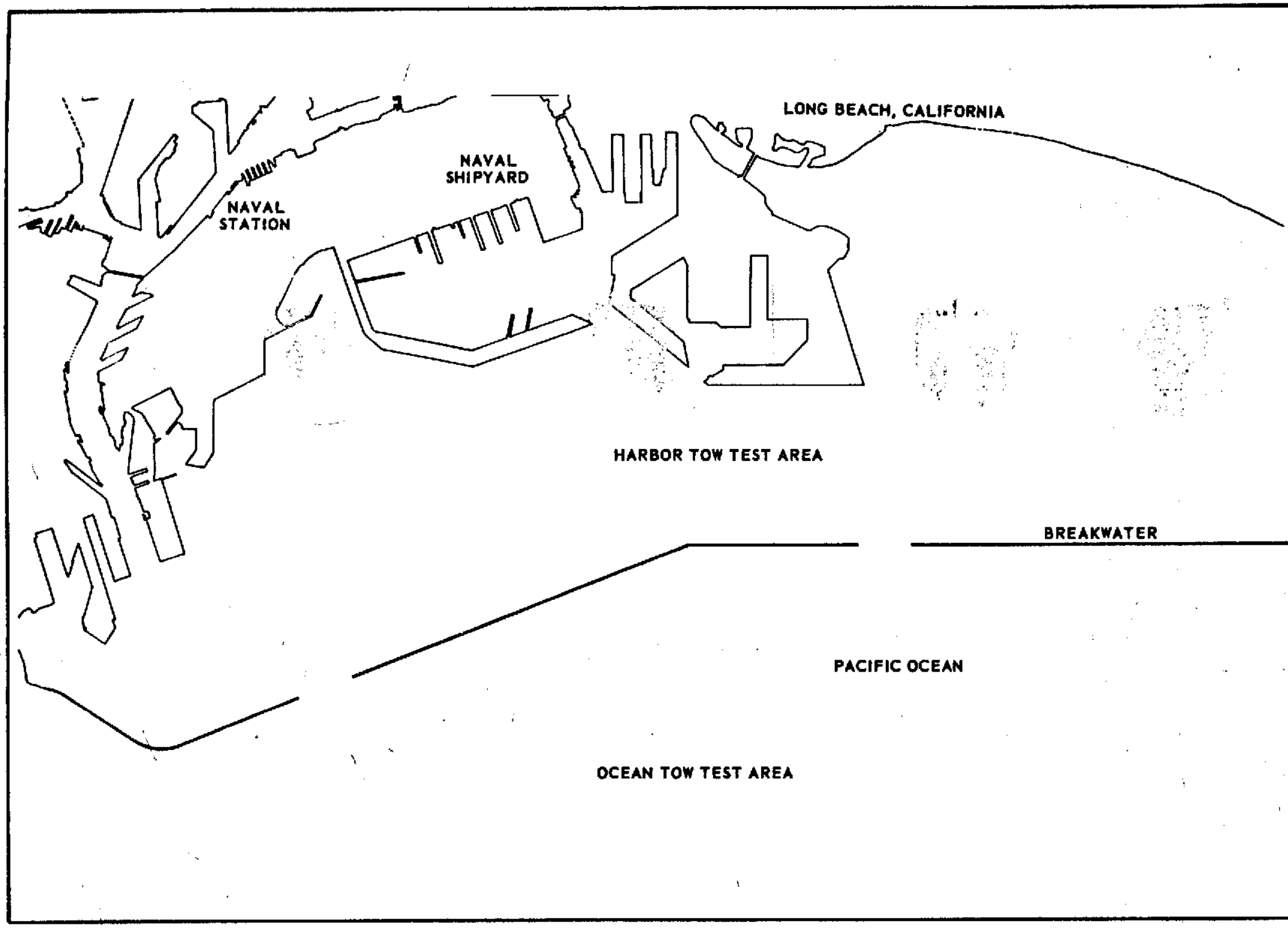

Figure 19. Site Plan

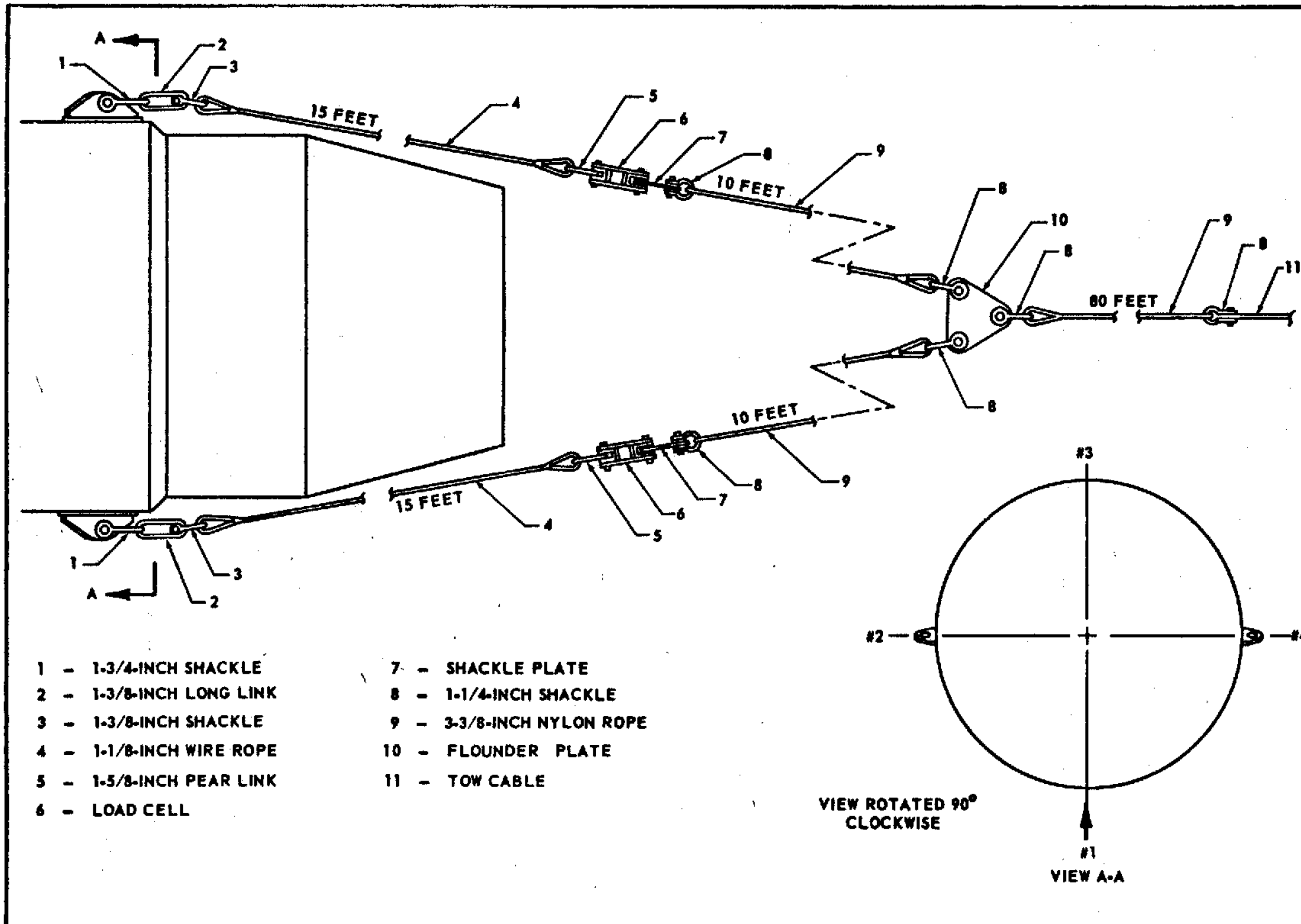

Figure 20. Two-Point Bridle Attachment Configuration

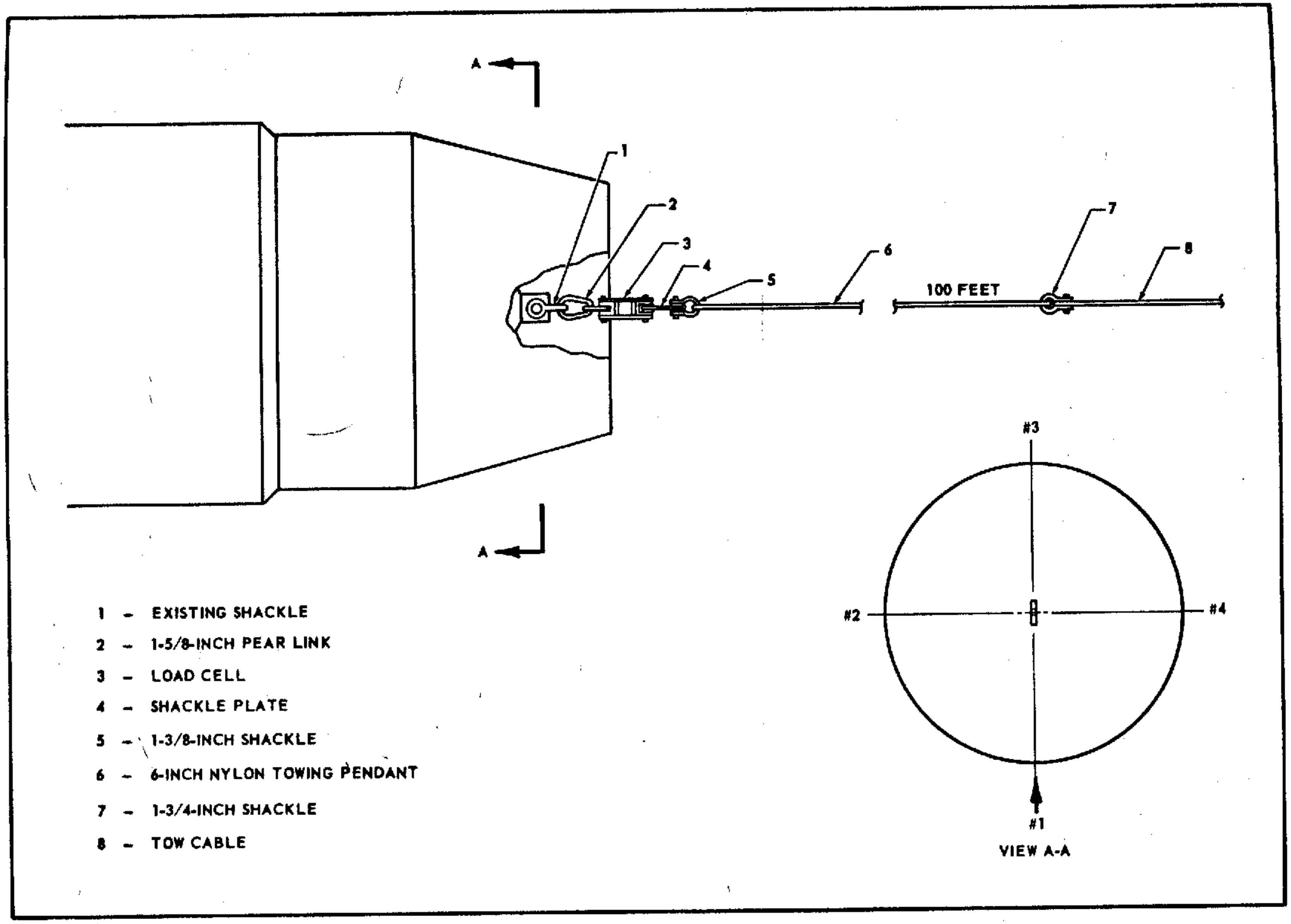

Figure 21. Single Center Attachment Configuration

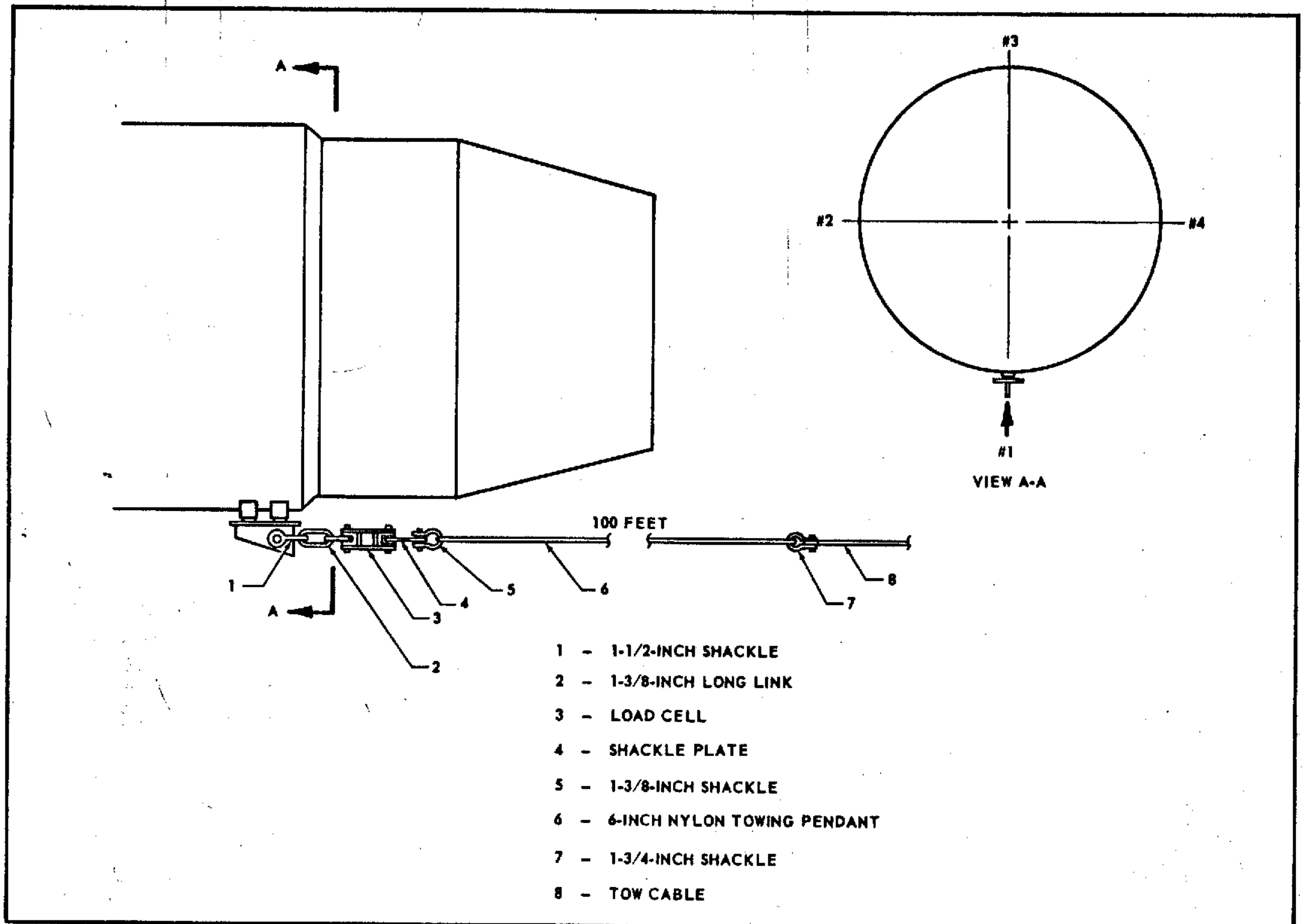

Figure 22. Single Side Attachment Configuration

1-Inch-Diameter Steel Cable			6-Inch-Circumference Nylon Line		
Test No.	Tow Vessel Speed (knots)	Length of Cable (feet)	Test No.	Tow Vessel Speed (knots)	Length of Cable (feet)
1Q	8	400	20	8	400
1R	8	600	2R	8	500
1S	8	800	2V	10	500
1U	10	400			
1V	10	600			
1W	10	800			

3.1.1.2 Single Center Attachment (See Figure 21)

Test configurations for the single center attachment tests with the exit cone attached (Test No. 3 and Test No. 4) using 1-inch-diameter steel cable and 6-inch-circumference nylon line are tabulated below:

1-Inch-Diameter Steel Cable			6-Inch-Circumference Nylon Line		
Test No.	Tow Vessel Speed (knots)	Length of Cable (feet)	Test No.	Tow Vessel Speed (knots)	Length of Cable (feet)
3A-1	4	100	4A	4	100
3B	4	200	4B	4	200
3C	4	400	4C	4	400
3D	4	600	4D	4	500
3L	6	200	4L	6	200
3M	6	400	4M	6	400
3N	6	600	4N	6	500
30	6	800	4Q	8	400
3Q	8	400	4R	8	500
3R	8	600	4V	10	500
3S	8	800			
3U	10	400			
3V	10	600			
3W	10	800			

Test configurations for the single center attachment tests with the exit cone removed (Test No. 7 and Test No. 8) using 1-inch-diameter steel cable and 6-inch-circumference nylon line are tabulated below:

1-Inch-Diameter Steel Cable			6-Inch-Circumference Nylon Line		
Test No.	Tow Vessel Speed (knots)	Length of Cable (feet)	Test No.	Tow Vessel Speed (knots)	Length of Cable (feet)
7A	4	100	8B	4	200
7B	4	200	8D	4	500
7C	4	400	8L	6	200
7E	4	800	8N	6	500
7L	6	200	8R	8	500
7M	6	400	8V	10	500

1-Inch-Diameter Steel Cable		
Test No.	Tow Vessel Speed (knots)	Length of Cable (feet)
7O	6	800
7Q	8	400
7S	8	800
7U	10	400
7W	10	800

3.1.1.3 Single Side Attachment (See Figure 22)

Test configurations for the single side attachment tests (Test No. 5. and Test No. 6) using 1-inch-diameter steel cable and 6-inch-circumference nylon line are tabulated below:

1-Inch-Diameter Steel Cable		
Test No.	Tow Vessel Speed (knots)	Length of Cable (feet)
5A	4	100
5B	4	200
5C	4	400
5D	4	600
5L	6	200
5M	6	400
5N	6	600
5O	6	800
5Q	8	400
5R	8	600
5S	8	800
5U	10	400
5V	10	600
5W	10	800

6-Inch-Circumference Nylon Line		
Test No.	Tow Vessel Speed (knots)	Length of Cable (feet)
6A	4	100
6B	4	200
6C	4	400
6D	4	500
6L	6	200
6M	6	400
6N	6	500
6Q	8	400
6R	8	500
6V	10	500

3.2 OCEAN TESTING

The ocean testing was conducted outside the breakwater at Long Beach in the Pacific Ocean (see Figure 19) to encounter various sea states.

The single center attachment point was utilized throughout the ocean tests. Three types of tow line were used: (1) 1-inch-diameter steel cable, (2) 2-inch-diameter steel cable, and (3) 7-inch-circumference nylon line which were connected to a 6-inch-circumference nylon pendant.

The tow tests were conducted with the model towed at various headings relative to the wave motion. Tests were also performed with the exit cone removed and attached.

An ATF was used to tow the model. Tow speeds, tow line configurations, and model configurations were varied according to the test profile sheets in paragraph 3.2.1.

3.2.1 Test Profile Sheets, Ocean Tests

Test configurations for the single center attachment tests with the exit cone attached (Test Nos. 10, 11, and 13) using 1-inch-diameter steel cable, 2-inch-diameter steel cable, and 7-inch-circumference nylon line, respectively, are tabulated below:

1-Inch-Diameter Steel Cable

Test No.	Tow Vessel Speed (knots)	Length of Cable (feet)
10A-1*	2	100
10H-4	6	1100
10H-5	6	1100
10I-4	6	1400
10I-6	6	1400
10J-1	6	1800
10I-1	6	1400
10H-3	6	1100
10H-1	6	1100
10I-2	6	1400
10G-1	6	800
10M-4	8	1100
10M-5	8	1100
10N-4	8	1400
10N-6	8	1400
10O-1	8	1800
10N-1	8	1400
10M-3	8	1100
10M-1	8	1100
10N-2	8	1400
10L-1	8	800
10Q-4	10	1100
10Q-5	10	1100
10R-4	10	1400
10R-6	10	1400
10S-1	10	1800
10R-1	10	1400
10O-3	10	1100
10O-1	10	1100
10R-2	10	1400
10P-1	10	800
10U-4	12	1100
10U-5	12	1100
10V-4	12	1400
10V-6	12	1400
10W-1	12	1800
10V-1	12	1400
10U-3	12	1100
10U-1	12	1100
10V-2	12	1400
10Y-4	14	1100
10Y-5	14	1100

2-Inch-Diameter Steel Cable

Test No.	Tow Vessel Speed (knots)	Length of Cable (feet)
11A-1	2	100
11F-1	6	400
11G-1	6	800
11M-1	8	1100
11N-1	8	1400
11O-1	8	1800
11Q-1	10	1100
11R-1	10	1400
11S-1	10	1800
11U-1	12	1100
11V-1	12	1400

7-Inch-Circumference Nylon Line

Test No.	Tow Vessel Speed (knots)	Length of Cable (feet)
13A-1	2	100
13C-1	2	400
13F-1	6	400
13G-1	6	800
13H-1	6	1100
13M-1	8	1100
13N-1	8	1400
13Q-1	10	1100
13R-1	10	1400
13U-1	12	1100
13V-1	12	1400

*The number following the hyphen indicates the direction of sea as coded in Figure 23.

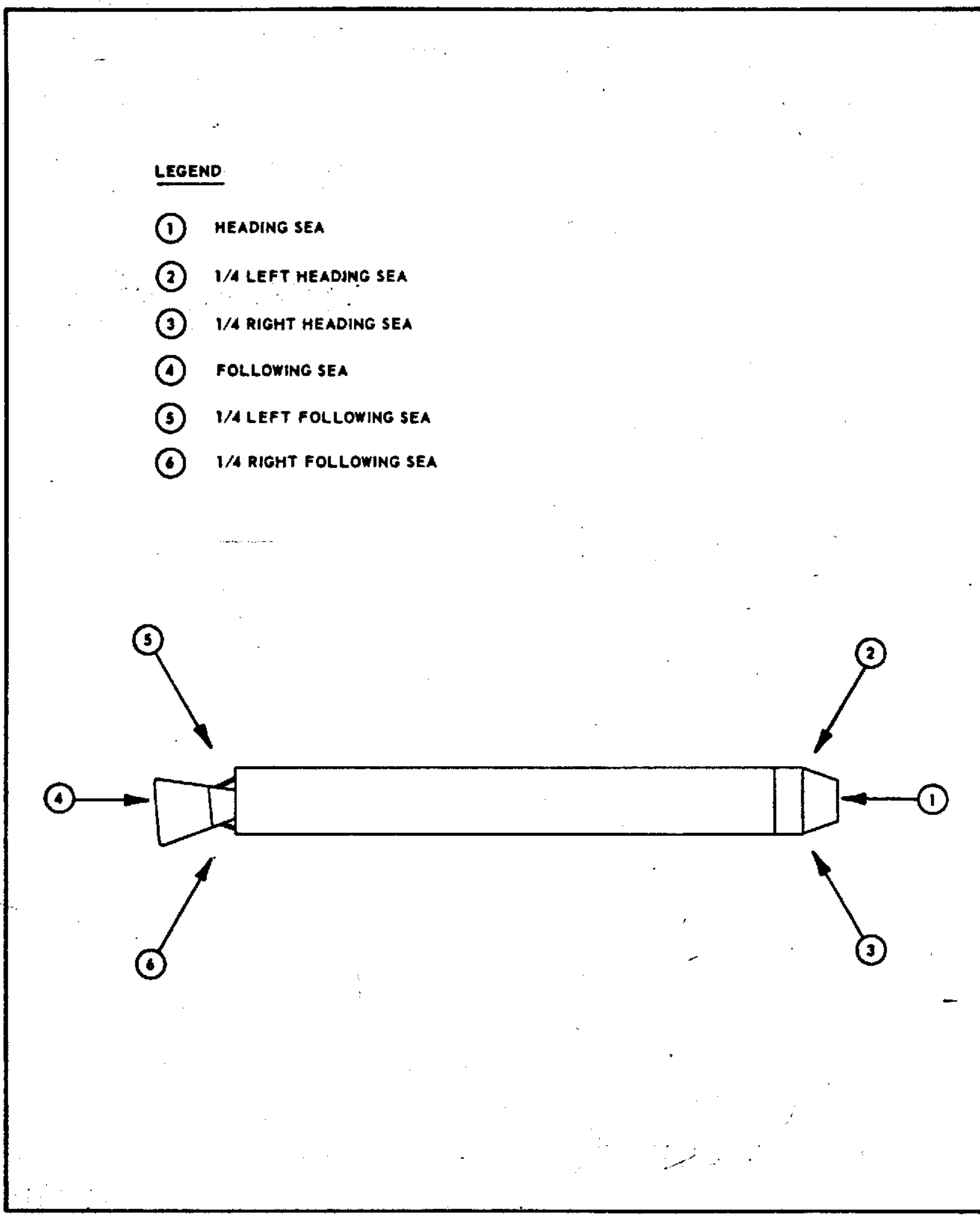

Figure 23. Wave Direction in Relation to SRB

7-Inch-Circumference Nylon Line		
Test No.	Tow Vessel Speed (knots)	Length of Cable (feet)
13Y-1	14	1100
13Z-1	14	1400

Test configurations for the single center attachment tests with the exit cone removed (Test No. 15 and Test No. 16) using 1-inch-diameter steel cable are tabulated below:

1-Inch-Diameter Steel Cable		
Test No.	Tow Vessel Speed (knots)	Length of Cable (feet)
15G-1*	6	800
15H-1	6	1100
15L-1	8	800
15M-1	8	1100
15P-1	10	800
15Q-1	10	1100
15R-1	10	1400
15T-1	12	800
15U-1	12	1100
15V-1	12	1400
15Y-1	14	1100
16A-1	8	100
16B-1	8	300
16C-1	10	100
16D-1	10	300
16E-1	12	100
16F-1	12	300

* The number following the hypen indicates the direction of sea as coded in Figure 23.

3.3 STABILITY TEST

A stability test was conducted during which the model was released to float freely without the tow cable in a sea state 2 condition. The position the model assumed relative to the wave motion and wind, as well as the model pitch, roll, and yaw characteristics were documented by movie cameras.

3.4 ATTITUDE TEST

An attitude test was conducted along dockside in calm water. The model was lowered into the water with the nozzle unplugged and permitted to take on water until an equilibrium position was achieved. The exit cone was pointed downward when the model was placed in the water.

3.5 ATTACHMENT TEST

An attachment-at-sea test was performed in the ocean. The model was cast adrift with the 100-foot nylon pendant attached to the nose and a float attached to the free end of the pendant. A small rubber boat with an outboard motor was deployed from the ATF, and personnel attached a messenger line to the 100-foot nylon pendant. After the messenger line was attached, it was passed to the stern of the ATF where a capstan was used to pull the model closer. When the free end of the 100-foot pendant reached the ship, the 7-inch-circumference nylon tow line was attached, and the ATF proceeded to tow the model at 8 knots.

SECTION IV

TEST RESULTS

4.1 GENERAL

The tow test data recorded on magnetic tape for tow line loads and model pitch, roll, and yaw were reduced by computer to tabular printouts and X-Y plots. Photographic documentation of selected test runs was reduced to provide additional pitch, roll and yaw data.

Table I presents a summary of tow line load data from the load cell(s) for each test run with the attachment configuaration, type of tow cable, model configuration, tow speeds, and tow cable lengths.

Test results are presented and discussed in the following paragraphs:

4.2 Towing Characteristics
4.3 Floating Characteristics
4.4 Nozzle Plugging
4.5 Attachment Configurations
4.6 Tow Speeds
4.7 Tow Lines
4.8 Scaling

4.2 TOWING CHARACTERISTICS

The test results indicate that the model exhibited stable pitch, roll, and yaw characteristics for most towing configurations. Instability in the yaw and roll axes occurred only at the higher tow speeds (10 to 14 knots) and with longer lengths of wire tow line. Removal of the exit cone improved model stability at the higher tow speeds.

The pitch angle of the model at zero tow speed was +1-1/2 degrees, and as two speeds increased, the pitch angle decreased. Figure 24 represents the relationship between tow speed and pitch angle for 7-inch-circumference nylon tow line. These data points were selected because the 7-inch-circumference nylon tow line has a specific gravity of 1.14, and the effects of tow line weight were reduced. The pitch angle decreases as a linear function of speed to 12 knots where the pitch rate increases significantly and the plot becomes curvilinear. A plot of the same relationship shown in Figure 25 for 1-inch-diameter steel wire tow line indicates the same result with the pitch rate increasing above 12 knots.

The change in the pitch rate above 12 knots is a result of the model nose plowing at the higher tow speeds which increases the drag at the nose of the model. In both the 7-inch-circumference nylon line and the 1-inch-diameter steel wire plots the pitch rate began to increase when the model had a pitch angle between -0.80 and -1.0 degree. Figure 26 represents the relationship between model tow speed and average model pitch angle computed from all test runs. Model pitch attitude decreases as tow speed increases with a greater decrease in pitch angle between a tow speed of 12 and 14 knots.

Table I. Tow Line Load Data for Load Cells at the Tow Vessel and at the Model

TEST NO.: 1
Date of Test: March 26, 1973
Towing Cable Attachment: Two-Point Bridle
Type of Cable: 1-Inch Steel Cable (Max. Allowable Load = 21,400 pounds)
Exit Cone: Attached

Test No.	Tow Vessel Speed (knots)	Length of Cable (feet)	Tensile Load at Tug, LC-3				Tensile Load at SRB, LC-1/LC-2			
			Minimum Load (pounds)	Average Load (pounds)	Maximum Load (pounds)	Percent of Maximum Allowable	Minimum Load (pounds)	Average Load (pounds)	Maximum Load (pounds)	Percent of Maximum Allowable
1B	4	200	514	615	997	5	0/0	197/274	459/569	2/3
1C	4	400	816	1032	1297	6	100/569	241/727	426/876	2/4
1D	4	600	936	1180	1357	6	0/508	0/660	0/876	0/4
1L	6	200	2373	3910	5855	27	132/323	1515/1127	2179/2003	10/9
1M	6	400	3400	4060	5100	24	420/1273	843/1611	1600/2154	7/10
1N	6	600	3027	3495	3856	18	816/1010	1052/1349	1328/1547	6/7
1O	6	800	3442	3769	4328	20	426/876	699/1021	1105/1273	5/6
1Q	8	400	5500	6800	8300	39	1500/1212	2330/2005	3100/2667	14/12
1R	8	600	4917	6856	8248	39	1519/1578	2762/2645	3655/3390	17/16
1S	8	800	5738	7703	9468	44	1360/2214	2465/2996	3443/3989	16/19
1U	10	400	5600	9800	13800	64	1100/2214	3200/3971	6000/5571	28/26
1V	10	600	6616	9864	12307	57	2179/2547	4009/3870	5272/5214	25/24
1W	10	800	7666	10745	13696	64	2459/2396	4115/3998	5656/5571	26/26

Table I. Tow Line Load Data for Load Cells at the Tow Vessel and at the Model (cont)

TEST NO.: 2
Date of Test: March 26, 1973
Towing Cable Attachment: Two-Point Bridle
Type of Cable: 6-Inch Circumference Nylon (Max. Allowable Load = 26,500 pounds)*
Exit Cone: Attached

Test No.	Tow Vessel Speed (knots)	Length of Cable (feet)	Tensile Load at SRB, LC-1/LC-2 Minimum Load (pounds)	Average Load (pounds)	Maximum Load (pounds)	Percent of Maximum Allowable
2A	4	100	0/0	-	0/**	-
2B	4	200	0/0	-	0/**	-
2C	4	400	0/0	-	0/**	-
2D	4	500	**/0	-	1086/937	4/3
2L	6	200	426/722	1292/1300	2304/1911	9/7
2M	6	400	718/569	1108/861	1582/1304	6/5
2N	6	500	328/477	758/918	1233/1334	5/5
2Q	8	400	2148/2063	2865/2795	3412/3629	13/14
2R	8	500	848/1151	1738/1821	2707/2939	10/11
2V	10	500	1772/2487	2508/3341	3422/4587	13/17

* LC-3 was not used on nylon line.

** Value was less than 300 pounds.

Table I. Tow Line Load Data for Load Cells at the Tow Vessel and at the Model (cont)

TEST NO.: 3
Date of Test: March 27, 1973
Towing Cable Attachment: Single Center
Type of Cable: 1-Inch Steel Cable (Max. Allowable Load = 21,400 pounds)
Exit Cone: Attached

Test No.	Tow Vessel Speed (knots)	Length of Cable (feet)	Tensile Load at Tug, LC-3: Minimum Load (pounds)	Tensile Load at Tug, LC-3: Average Load (pounds)	Tensile Load at Tug, LC-3: Maximum Load (pounds)	Tensile Load at Tug, LC-3: Percent of Maximum Allowable
3A-1	4	100	*	--	1657	8
3B	4	200	**	--	**	--
3C	4	400	756	1212	1597	7
3D	4	600	575	994	1117	5
3L	6	200	1477	2269	3086	14
3M	6	400	1776	2510	3383	15
3N	6	600	1477	2035	2492	12
3O	6	800	1537	2052	2492	12
3Q	8	400	2314	3535	5504	26
3R	8	600	4092	5652	6791	32
3S	8	800	3442	4207	5034	24
3U	10	400	4740	7785	10512	49
3V	10	600	5093	8074	10744	50
3W	10	800	4505	7475	9700	45

Test No.	Tensile Load at SRB, LC-1: Minimum Load (pounds)	Tensile Load at SRB, LC-1: Average Load (pounds)	Tensile Load at SRB, LC-1: Maximum Load (pounds)	Tensile Load at SRB, LC-1: Percent of Maximum Allowable
3A-1	1041	1668	3229	15
3B	1169	1517	1835	9
3C	816	1051	1392	7
3D	880	1190	1645	8
3L	2054	2987	3776	18
3M	2490	3236	4259	20
3N	3198	3552	3927	18
3O	2676	3354	3655	17
3Q	4767	6160	7991	37
3R	4078	5889	7178	33
3S	4916	5742	6624	31
3U	6420	9660	12478	58
3V	6185	9441	12536	59
3W	5183	7278	10583	49

* Value was less than 300 pounds.
** No data was recorded.

Table I. Tow Line Load Data for Load Cells at the Tow Vessel and at the Model (cont)

TEST NO.: 4
Date of Test: March 27, 1973
Towing Cable Attachment: Single Center
Type of Cable: 6-Inch Circumference Nylon (Max. Allowable Load = 26,500 pounds)*
Exit Cone: Attached

Test No.	Tow Vessel Speed (knots)	Length of Cable (feet)	Tensile Load at SRB, LC-1 Minimum Load (pounds)	Average Load (pounds)	Maximum Load (pounds)	Percent of Maximum Allowable
4A	4	100	328	1490	2645	10
4B	4	200	944	1610	2614	10
4C	4	400	1233	1434	1709	6
4D	4	500	1041	1372	1709	6
4L	6	200	1960	2907	3958	15
4M	6	400	1835	2712	3625	14
4N	6	500	2861	3598	4199	16
4Q	8	400	3746	5218	7004	26
4R	8	500	5094	5880	6712	25
4V	10	500	7237	8485	9376	35

*LC-3 was not used on nylon line.

Table I. Tow Line Load Data for Load Cells at the Tow Vessel and at the Model (cont)

TEST NO.: 5
Date of Test: March 28, 1973
Towing Cable Attachment: Single Side
Type of Cable: 1-Inch Steel (Max. Allowable Load = 21,400 pounds)
Exit Cone: Attached

Test No.	Tow Vessel Speed (knots)	Length of Cable (feet)	Tensile Load at Tug, LC-3				Tensile Load at SRB, LC-1			
			Minimum Load (pounds)	Average Load (pounds)	Maximum Load (pounds)	Percent of Maximum Allowable	Minimum Load (pounds)	Average Load (pounds)	Maximum Load (pounds)	Percent of Maximum Allowable
5A	4	100	876	1320	2195	10	0	392	1041	5
5B	4	200	1417	1827	2195	10	0	167	426	2
5C	4	400	2015	2473	4210	20	0	0	0	0
5D	4	600	2552	2775	3086	14	0	0	0	0
5L	6	200	2195	2856	3856	18	1614	2368	3534	16
5M	6	400	2492	3175	4092	19	2054	2831	4072	19
5N	6	600	2789	3588	4328	20	1423	2266	3014	14
5O	6	800	3501	4002	4857	23	2613	3248	4558	21
5Q	8	400	5386	7365	9525	45	4138	6350	8597	40
5R	8	600	6323	8515	10918	51	3655	6278	9318	44
5S	8	800	4681	6058	7257	34	4379	5847	7265	34
5U	10	400	7723	10545	13812	65	5803	9040	12622	59
5V	10	600	7141	10590	13928	65	5035	10410	13569	63
5W	10	800	5738	9031	11381	53	5597	8873	12019	56

Table I. Tow Line Load Data for Load Cells at the Tow Vessel and at the Model (cont)

TEST NO.: 6
Date of Test: March 28, 1973
Towing Cable Attachment: Single Side
Type of Cable: 6-Inch Circumference Nylon (Max. Allowable Load = 26,500 pounds)*
Exit Cone: Attached

Test No.	Tow Vessel Speed (knots)	Length of Cable (feet)	Tensile Load at SRB, LC-1			
			Minimum Load (pounds)	Average Load (pounds)	Maximum Load (pounds)	Percent of Maximum Allowable
6A	4	100	164	583	1455	5
6B	4	200	68	601	1168	4
6C	4	400	686	1296	2148	8
6D	4	500	1646	4850	9122	34
6L	6	200	589	368	3837	14
6M	6	400	3442	4060	4827	18
6N	6	500	3045	3475	4078	15
6Q	8	400	7353	8590	9548	36
6R	8	500	6214	7236	8222	31
6V	10	500	7672	9048	10468	40

*LC-3 was not used on nylon line.

Table I. Tow Line Load Data for Load Cells at the Tow Vessel and at the Model (cont)

TEST NO.: 7
Date of Test: March 29, 1973
Towing Cable Attachment: Single Center
Type of Cable: 1-Inch Steel (Max. Allowable Load = 21,400 pounds)
Exit Cone: Removed

Test No.	Tow Vessel Speed (knots)	Length of Cable (feet)	Tensile Load at Tug, LC-3				Tensile Load at SRB, LC-1			
			Minimum Load (pounds)	Average Load (pounds)	Maximum Load (pounds)	Percent of Maximum Allowable	Minimum Load (pounds)	Average Load (pounds)	Maximum Load (pounds)	Percent of Maximum Allowable
7A	4	100	30	410	1057	5	0	0	0	0
7B	4	200	0	0	0	0	0	0	0	0
7C	4	400	756	1048	1357	6	*	-	*	-
7E	4	800	1056	1468	2254	11	*	-	*	-
7L	6	200	1297	1858	2552	12	328	860	1423	7
7M	6	400	2015	2720	4328	20	197	823	1551	7
7O	6	800	876	2343	4564	21	230	1860	4469	21
7Q	8	400	3501	4856	6090	28	1424	2887	4259	20
7S	8	800	3442	4358	5386	25	2459	3622	4678	22
7U	10	400	3915	6883	10048	47	3260	5998	9232	43
7W	10	800	4681	8563	9177	43	4289	6762	9088	42

* No data was recorded.

Table I. Tow Line Load Data for Load Cells at the Tow Vessel and at the Model (cont)

TEST NO.: 8
Date of Test: March 29, 1973
Towing Cable Attachment: Single Center
Type of Cable: 6-Inch Circumference Nylon (Max. Allowable Load = 26,500 pounds)*
Exit Cone: Removed

Test No.	Tow Vessel Speed (knots)	Length of Cable (feet)	Tensile Load at SRB, LC-1			
			Minimum Load (pounds)	Average Load (pounds)	Maximum Load (pounds)	Percent of Maximum Allowable
8B	4	200	**	-	**	-
8D	4	500	33	60	132	0.5
8L	6	200	165	723	1137	4
8N	6	500	686	1340	2054	8
8R	8	500	2428	2965	3867	15
8V	10	500	4078	5587	6683	25

*LC-3 was not used on nylon line.
**No data was recorded.

Table I. Tow Line Load Data for Load Cells at the Tow Vessel and at the Model (cont)

TEST NO.: 10
Date of Test: April 4, 1973
Towing Cable Attachment: Single Center
Type of Cable: 1-Inch Steel Cable (Max. Allowable Load = 21,400 pounds)
Exit Cone: Attached

Test No.	Tow Vessel Speed (knots)	Length of Cable (feet)	Tensile Load at Tug, LC-3				Tensile Load at SRB, LC-1			
			Minimum Load (pounds)	Average Load (pounds)	Maximum Load (pounds)	Percent of Maximum Allowable	Minimum Load (pounds)	Average Load (pounds)	Maximum Load (pounds)	Percent of Maximum Allowable
10A-1*	2	100	30	201	333	2	**	--	**	--
10H-4	6	1100	1656	2604	2790	13	33	453	1105	5
10H-5	6	1100	2433	3213	4092	19	296	956	1771	8
10I-4	6	1400	3324	4192	4799	22	524	1437	2521	12
10I-6	6	1400	3797	4675	5621	26	524	1665	2583	12
10J-1	6	1800	3679	4520	5562	26	848	1739	3442	16
10I-1	6	1400	2900	4000	6400	30	810	2060	5000	23
10H-3	6	1100	2314	4021	5386	25	0	1803	3321	16
10H-1	6	1100	3300	4015	4600	21	1200	2110	2900	14
10I-2	6	1400	4210	4650	5269	25	686	1431	2892	14
10G-1	6	800	3856	4249	4975	23	880	1654	2521	12
10M-4	8	1100	2314	3570	4505	21	751	1944	3412	16
10M-5	8	1100	2552	3276	4446	21	557	1453	2738	13
10N-4	8	1400	3205	4941	7374	34	2397	4423	7324	34
10N-6	8	1400	3915	5753	7665	36	1582	3570	5685	27
10O-1	8	1800	5914	7410	11090	52	2179	3990	8251	39
10N-1	8	1400	5000	6400	8100	38	2400	3700	5800	27
10M-3	8	1100	3797	4733	5562	26	1898	2956	4469	21
10M-1	8	1100	4400	5472	6400	30	1700	3030	3900	18
10N-2	8	1400	5152	5710	6733	31	2273	3256	4319	20
10L-1	8	800	4033	4476	5152	24	2117	2822	3686	17
10Q-4	10	1100	3561	6710	9468	44	1487	4476	7295	34
10Q-5	10	1100	4387	6048	8829	41	1360	3033	5863	27
10R-4	10	1400	3400	6440	10400	49	1700	4770	8500	40
10R-6	10	1400	4328	7380	10918	51	1200	4525	7961	37

Table I. Tow Line Load Data for Load Cells at the Tow Vessel and at the Model (cont)

TEST NO.: 10 (Cont'd)
Date of Test: April 4, 1973
Towing Cable Attachment: Single Center
Type of Cable: 1-Inch Steel Cable (Max. Allowable Load = 21,400 pounds)
Exit Cone: Attached

Test No.	Tow Vessel Speed (knots)	Length of Cable (feet)	Tensile Load at Tug, LC-3: Minimum Load (pounds)	Tensile Load at Tug, LC-3: Average Load (pounds)	Tensile Load at Tug, LC-3: Maximum Load (pounds)	Tensile Load at Tug, LC-3: Percent of Maximum Allowable	Tensile Load at SRB, LC-1: Minimum Load (pounds)	Tensile Load at SRB, LC-1: Average Load (pounds)	Tensile Load at SRB, LC-1: Maximum Load (pounds)	Tensile Load at SRB, LC-1: Percent of Maximum Allowable
10S-1	10	1800	8306	10000	12597	59	4648	6630	11789	55
10R-1	10	1400	7200	10200	11400	53	4600	6700	10800	50
10Q-3	10	1100	5973	7580	9119	43	3801	6025	7817	37
10Q-1	10	1100	6265	8100	10300	48	3381	5216	7730	36
10R-2	10	1400	4505	6116	7433	35	1929	3803	5391	25
10P-1	10	800	6090	7631	9932	46	3137	5077	7933	37
10U-4	12	1100	5973	8141	10048	47	3045	5411	7933	37
10U-5	12	1100	5445	9184	13928	65	1960	6394	11071	52
10V-4	12	1400	7500	11600	16100	75	5000	10260	13800	64
10V-6	12	1400	6849	11028	16127	75	4588	9050	14144	66
10W-1	12	1800	9700	12750	15600	73	6800	10281	14900	70
10V-1	12	1400	8190	11930	14100	66	7140	9183	15640	73
10U-3	12	1100	8539	10085	12423	58	6039	8631	10985	51
10U-1	12	1100	9800	11730	14000	65	5500	8743	11600	54
10V-2	12	1400	9642	12075	14448	68	6186	9096	12220	57
10Y-4	14	1100	8539	12747	16417	77	5749	10048	14029	66
10Y-5	14	1100	6148	12800	17633	82	3137	11222	15495	72

*Number following the hyphen indicates direction of sea as coded in Figure 23.
**No data was recorded.

Table I. Tow Line Load Data for Load Cells at the Tow Vessel and at the Model (cont)

TEST NO.: 11
Date of Test: April 3, 1973
Towing Cable Attachment: Single Center
Type of Cable: 2-Inch Steel (Max. Allowable Load = 82,500 pounds)
Exit Cone: Attached

Test No.	Tow Vessel Speed (knots)	Length of Cable (feet)	Tensile Load at Tug, LC-3				Tensile Load at SRB, LC-1			
			Minimum Load (pounds)	Average Load (pounds)	Maximum Load (pounds)	Percent of Maximum Allowable	Minimum Load (pounds)	Average Load (pounds)	Maximum Load (pounds)	Percent of Maximum Allowable
11A-1*	2	100	1116	1310	1477	2	**	--	**	--
11F-1	6	400	1896	2218	2433	3	1360	1793	2335	3
11G-1	6	800	5210	5854	6382	8	815	1716	2583	3
11M-1	8	1100	6200	7013	8000	10	3500	4567	6200	8
11N-1	8	1400	8829	9420	10570	13	4916	5957	6799	8
11O-1	8	1800	11400	12600	13200	16	6400	7666	8600	10
11Q-1	10	1100	8500	10346	13000	16	6000	8356	12000	15
11R-1	10	1400	11671	13057	14564	18	8366	10318	12593	15
11S-1	10	1800	15300	18700	21000	25	11500	14744	18900	23
11U-1	12	1100	9900	12800	15100	18	7000	10620	13700	17
11V-1	12	1400	21004	23834	26524	32	13110	18519	23646	29

* Number following the hyphen indicates direction of sea as coded in Figure 23.

** No data was recorded.

Table I. Tow Line Load Data for Load Cells at the Tow Vessel and at the Model (cont)

TEST NO.: 13
Date of Test: April 3, 1973
Towing Cable Attachment: Single Center
Type of Cable: 7-Inch Circumference Nylon (Max. Allowable Load = 27,500 pounds)*
Exit Cone: Attached

Test No.	Tow Vessel Speed (knots)	Length of Cable (feet)	Tensile Load at SRB, LC-1			
			Minimum Load (pounds)	Average Load (pounds)	Maximum Load (pounds)	Percent of Maximum Allowable
13A-1**	2	100	***	-	***	-
13C-1	2	400	***	-	***	-
13F-1	6	400	976	1595	2023	7
13G-1	6	800	1392	1672	1960	7
13H-1	6	1100	912	1082	1360	5
13M-1	8	1100	2366	3340	4408	16
13N-1	8	1400	2984	3351	4198	15
13Q-1	10	1100	4438	5013	5500	20
13R-1	10	1400	4468	4845	5803	21
13U-1	12	1100	7730	8621	9836	36
13V-1	12	1400	7178	8539	10181	37
13Y-1	14	1100	12421	15501	20414	74
13Z-1	14	1400	9922	11705	12909	47

*LC-3 was not used on nylon line.
**Number following the hyphen indicates direction of sea as coded in Figure 23.
***No data was recorded.

Table I. Tow Line Load Data for Load Cells at the Tow Vessel and at the Model (cont)

TEST NO.: 15
Date of Test: April 5, 1973
Towing Cable Attachment: Single Center
Type of Cable: 1-Inch Steel (Max. Allowable Load = 21,400 pounds)
Exit Cone: Removed

Test No.	Tow Vessel Speed (knots)	Length of Cable (feet)	Tensile Load at Tug, LC-3				Tensile Load at SRB, LC-1			
			Minimum Load (pounds)	Average Load (pounds)	Maximum Load (pounds)	Percent of Maximum Allowable	Minimum Load (pounds)	Average Load (pounds)	Maximum Load (pounds)	Percent of Maximum Allowable
15G-1*	6	800	1896	2423	3027	14	32	436	1072	5
15H-1	6	1100	1417	1750	2313	11	230	733	1104	5
15L-1	8	800	2789	3565	4210	20	621	1446	2179	10
15M-1	8	1100	2968	3508	4210	20	1455	2138	3168	15
15P-1	10	800	4748	6575	8596	40	2085	4137	6828	32
15Q-1	10	1100	3323	5242	7316	34	1929	4166	6214	29
15R-1	10	1400	3791	6323	9003	42	1897	4306	7672	36
15T-1	12	800	6382	8511	10975	51	4198	6809	9749	46
15U-1	12	1100	5855	7336	9409	44	4588	6557	9404	44
15V-1	12	1400	8189	10250	12597	59	5685	8028	10842	51
15Y-1	14	1100	7199	11950	17518	82	5390	10420	17193	80

* Number following the hyphen indicates direction of sea as coded in Figure 23.

Table I. Tow Line Load Data for Load Cells at the Tow Vessel and at the Model (cont)

TEST NO.: 16
Date of Test: April 5, 1973
Towing Cable Attachment: Single Center
Type of Cable: 1-Inch Steel (Max. Allowable Load = 21,400 pounds)
Exit Cone: Removed
Aft Skirt Structural Supports: Removed

Test No.	Tow Vessel Speed (knots)	Length of Cable (feet)	Tensile Load at Tug, LC-3: Minimum Load (pounds)	Tensile Load at Tug, LC-3: Average Load (pounds)	Tensile Load at Tug, LC-3: Maximum Load (pounds)	Tensile Load at Tug, LC-3: Percent of Maximum Allowable	Tensile Load at SRB, LC-1: Minimum Load (pounds)	Tensile Load at SRB, LC-1: Average Load (pounds)	Tensile Load at SRB, LC-1: Maximum Load (pounds)	Tensile Load at SRB, LC-1: Percent of Maximum Allowable
16A-1*	8	100	2075	3403	5034	23	**	1890	4108	19
16B-1	8	300	1116	1920	2849	13	783	1740	3014	14
16C-1	10	100	3086	4986	7082	33	1803	3936	5862	27
16D-1	10	300	3974	5981	7082	33	2953	4553	6214	29
16E-1	12	100	4328	6385	10918	51	3533	6598	11330	53
16F-1	12	300	6674	9810	13812	65	5246	8498	13253	62

* Number following the hyphen indicates direction of sea as coded in Figure 23.

** Value was less than 300 pounds.

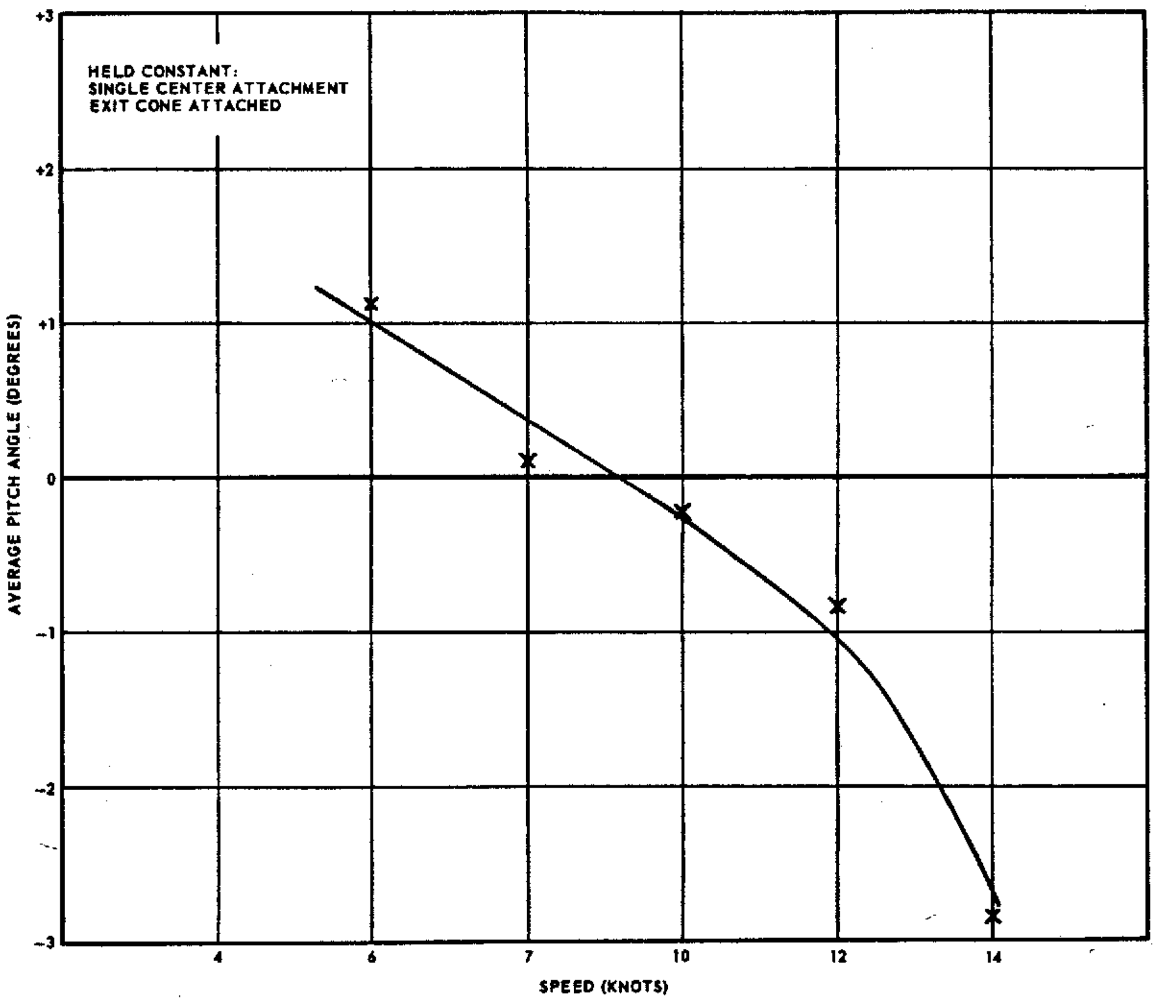

Figure 24. Tow Speed Versus Model Pitch Angle for 7-Inch-Circumference Nylon Line

Figure 25. Tow Speed Versus Model Pitch Angle for 1-Inch-Diameter Steel Wire

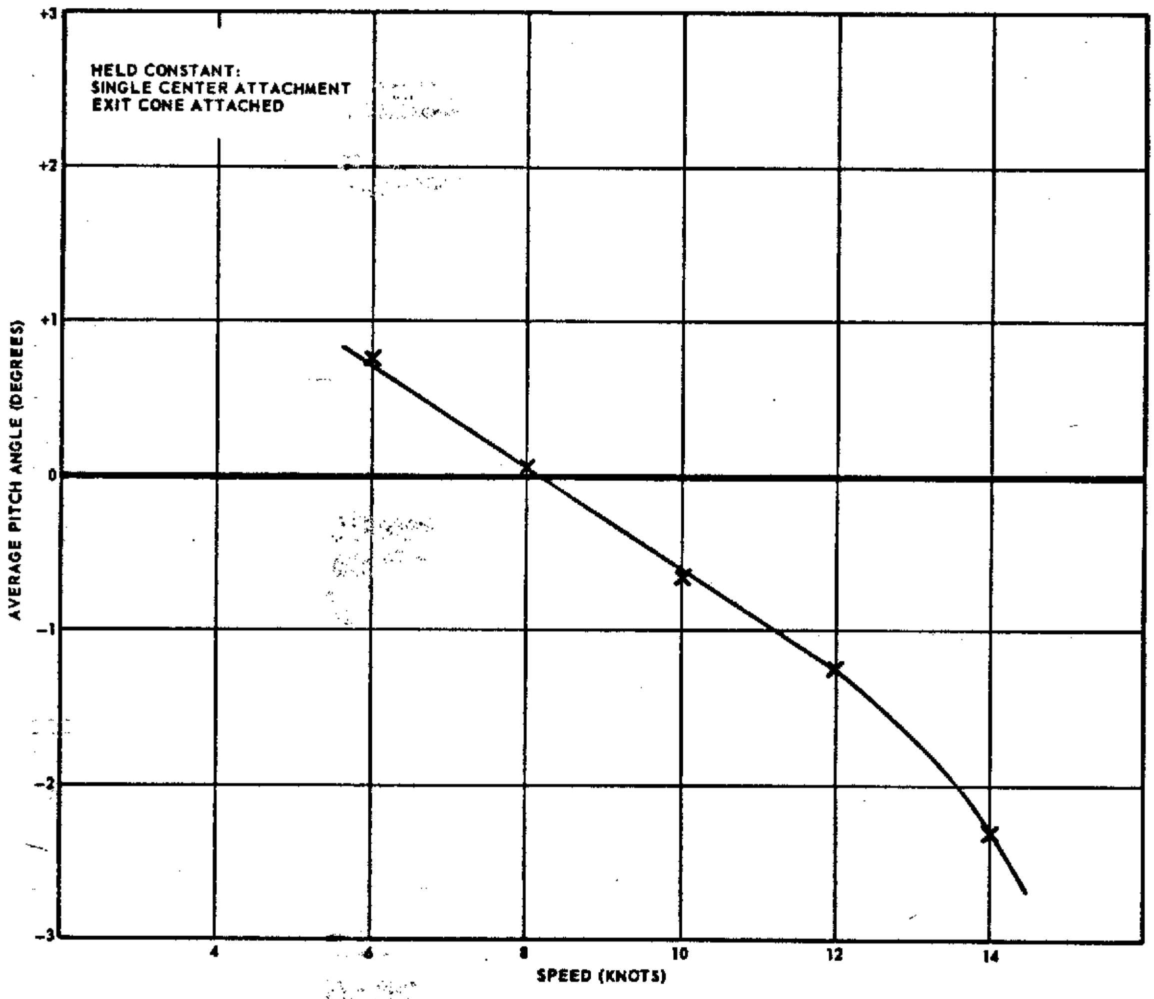

Figure 26. Tow Speed Versus Average Model Pitch Angle for All Test Runs

Removal of the nozzle exit cone decreased the model pitch angle slightly as shown in Figure 27 which represents data recorded during Test No. 15. This reduction was attributed to the loss of the upward planing forces on the aft of the model from the exit cone.

The model was extremely stable in the roll and yaw axes for all tests conducted at tow speeds below 10 knots. The model floated with the exit cone pointed down and the #3 position up at zero tow speed, and as speed increased, water pressure on the exit cone forced the model to roll clockwise or counterclockwise and stabilize. Figure 28 represents tow speed versus model roll position for the conditions stated. As speed was increased, the model rolled from the 180-degree position high to 360-degree position high with the exit cone pointed upward. The exit cone created a "rudder effect," which caused the model to yaw in the same direction as the exit cone cant.

Model instability was primarily a function of tow speed. The type and length tow line also influenced model towing characteristics to a lesser extent. As the speed was increased, the model increased its yaw angle and started rolling due to skin friction, similar to a water wheel. The rolling occurredwhen the model had yawed about 7 degrees from the direction of tow. The speed at which the instability occurred varied with the test configurations as shown in Figure 29. Using 1-inch-diameter steel wire, the model started rolling at 13 knots with 1100 feet of tow cable and at 10 knots with 1400 feet of tow cable. The 2-inch-diameter steel wire produced the worst unstable conditions with yaw angles up to 17 to 18 degrees and roll rates up to 13 rev/min. Using 7-inch-circumference nylon tow line (1100 and 1400 feet long), the model did not begin rolling until the tow speed was increased to 14 knots.

To further investigate the effects of the exit cone on towing stability, the exit cone was removed during Test Nos. 7, 8, 15, and 16. The model stability at the higher tow speeds and longer line lengths was significantly improved; no roll was experienced and a maximum yaw angle of 4 degrees was recorded.

4.3 FLOATING CHARACTERISTICS

To determine the floating characteristics of the model, tests were performed with the nozzle plugged and unplugged. With no water in the casing and the nozzle plugged, the model floated at a +1-1/2-degree pitch angle. The #3 position was up and the canted nozzle was down in the water (see Figure 30).

During the stability test, the model was cast afloat in a sea state 2 condition and gusting winds. The model aligned itself in the trough of the waves, perpendicular to the direction of the wind. In this position the model was very stable with no erratic pitch and no roll or yaw. The model heaved about 1 to 2 feet as it rode the swells, but the movement was smooth with no erratic motion.

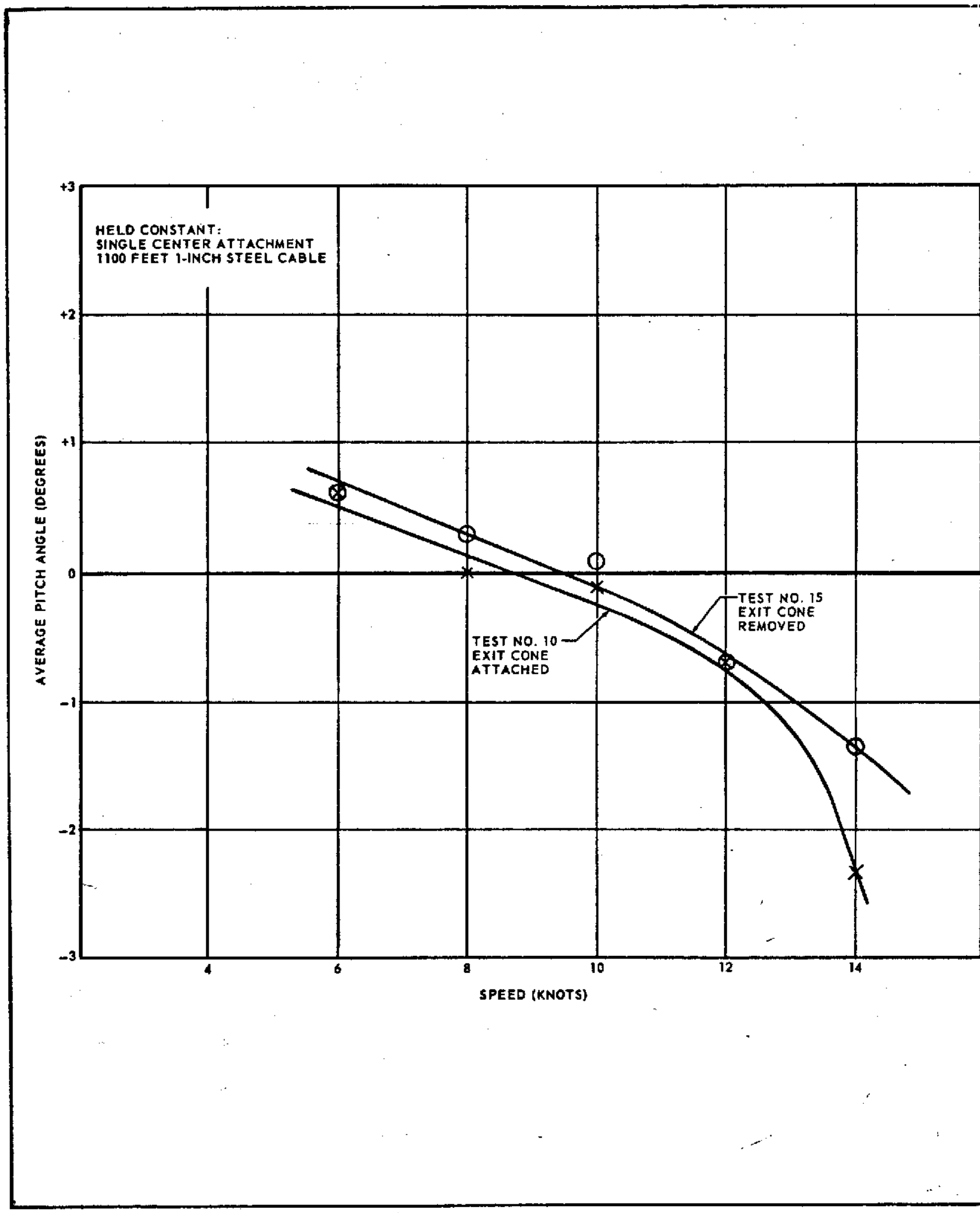

Figure 27. Tow Speed Versus Model Pitch Angle with Exit Cone Attached and Removed

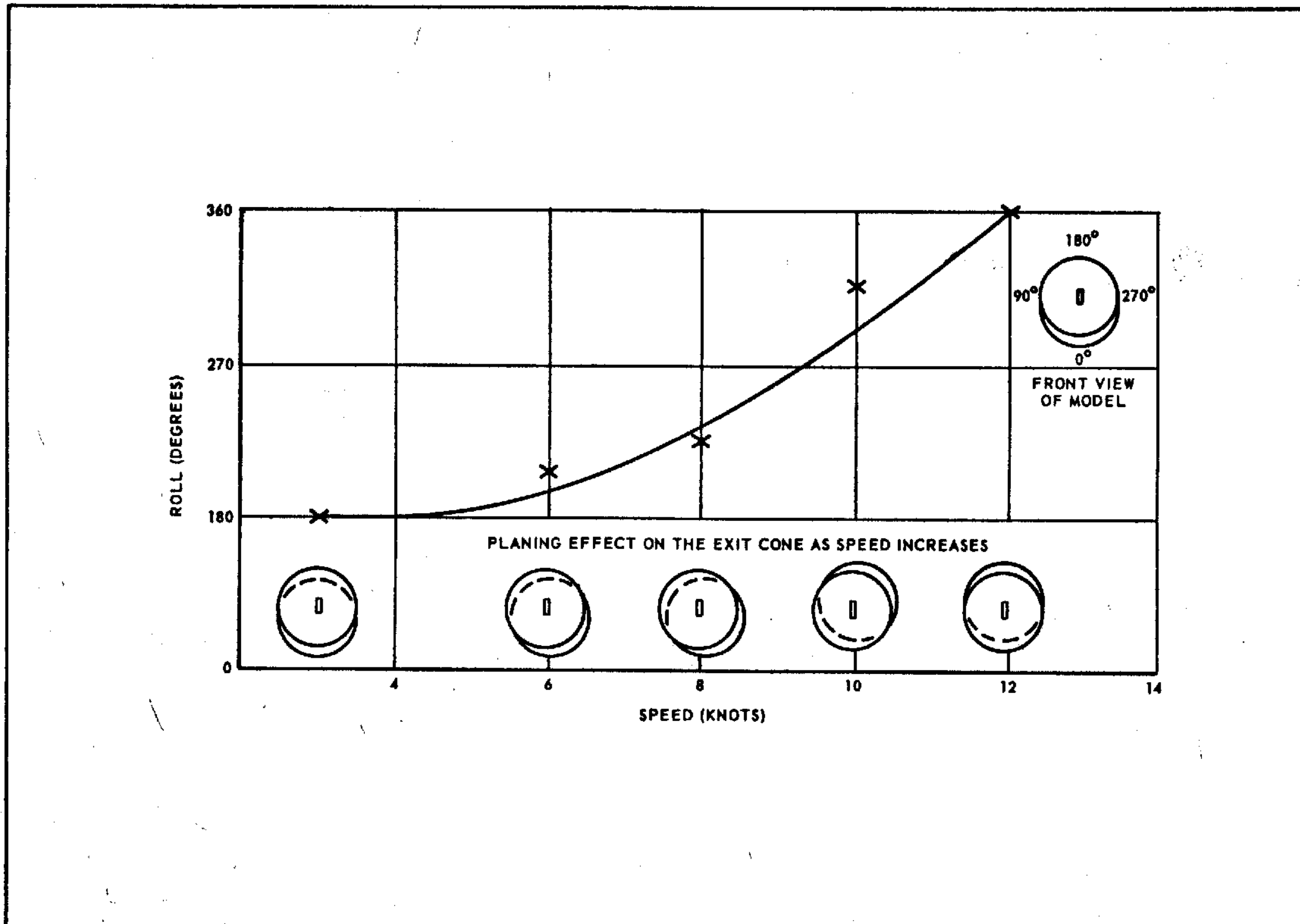

Figure 28. Tow Speed Versus Model Roll Position for Test Nos. 10H1, 10M1, 10Q1, and 10U1

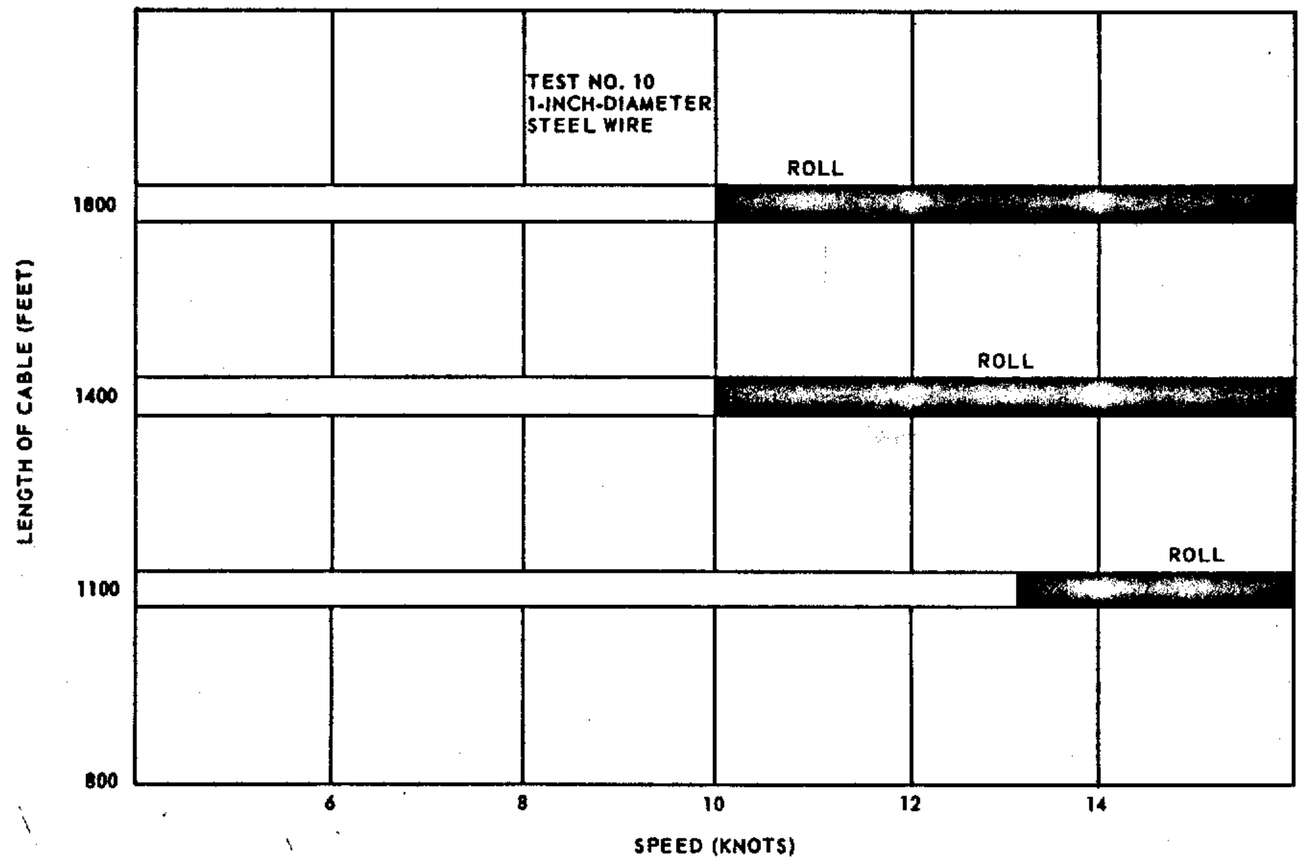

Figure 29. Instability as Related to Tow Speed and Test Configuration (sheet 1 of 3)

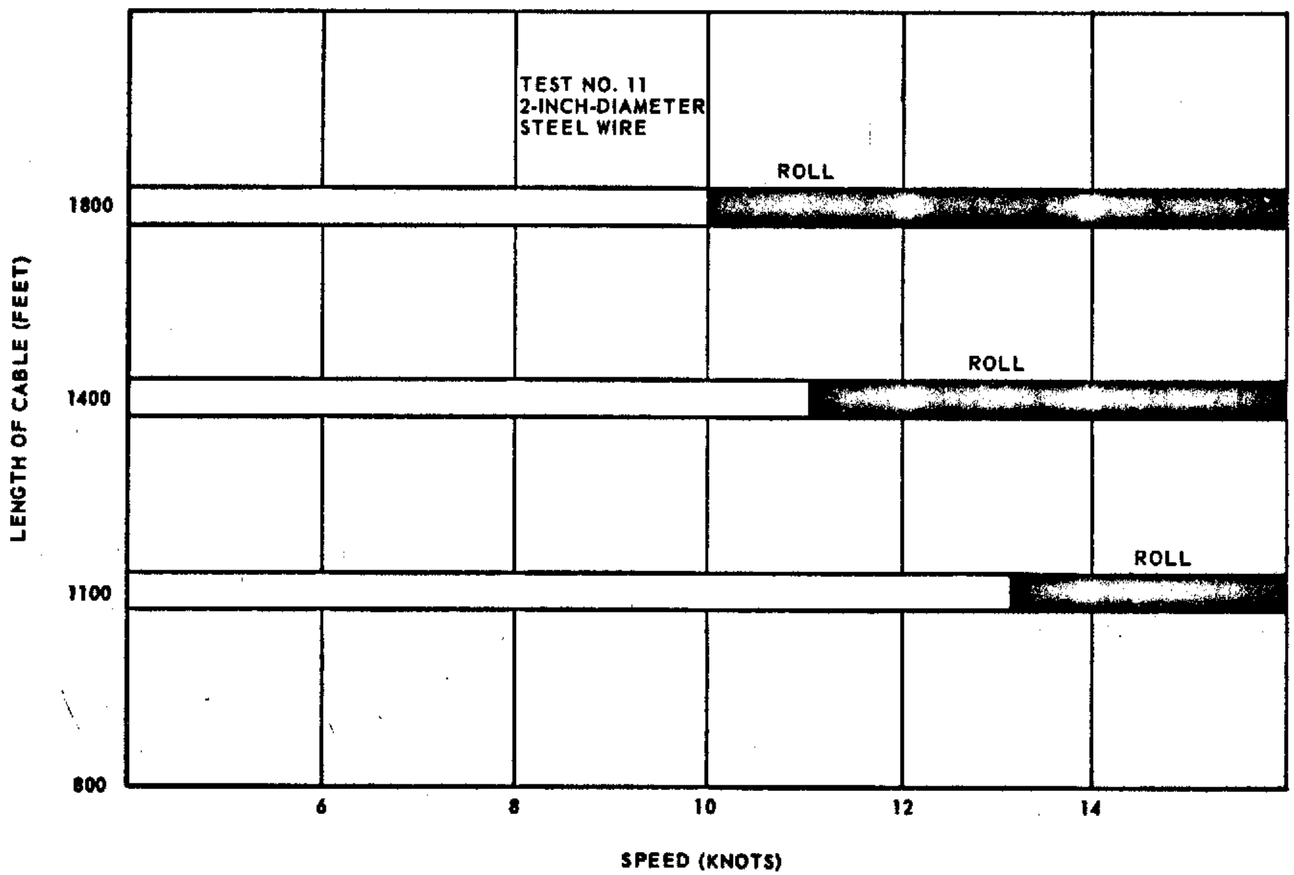

Figure 29. Instability as Related to Tow Speed and Test Configuration (sheet 2 of 3)

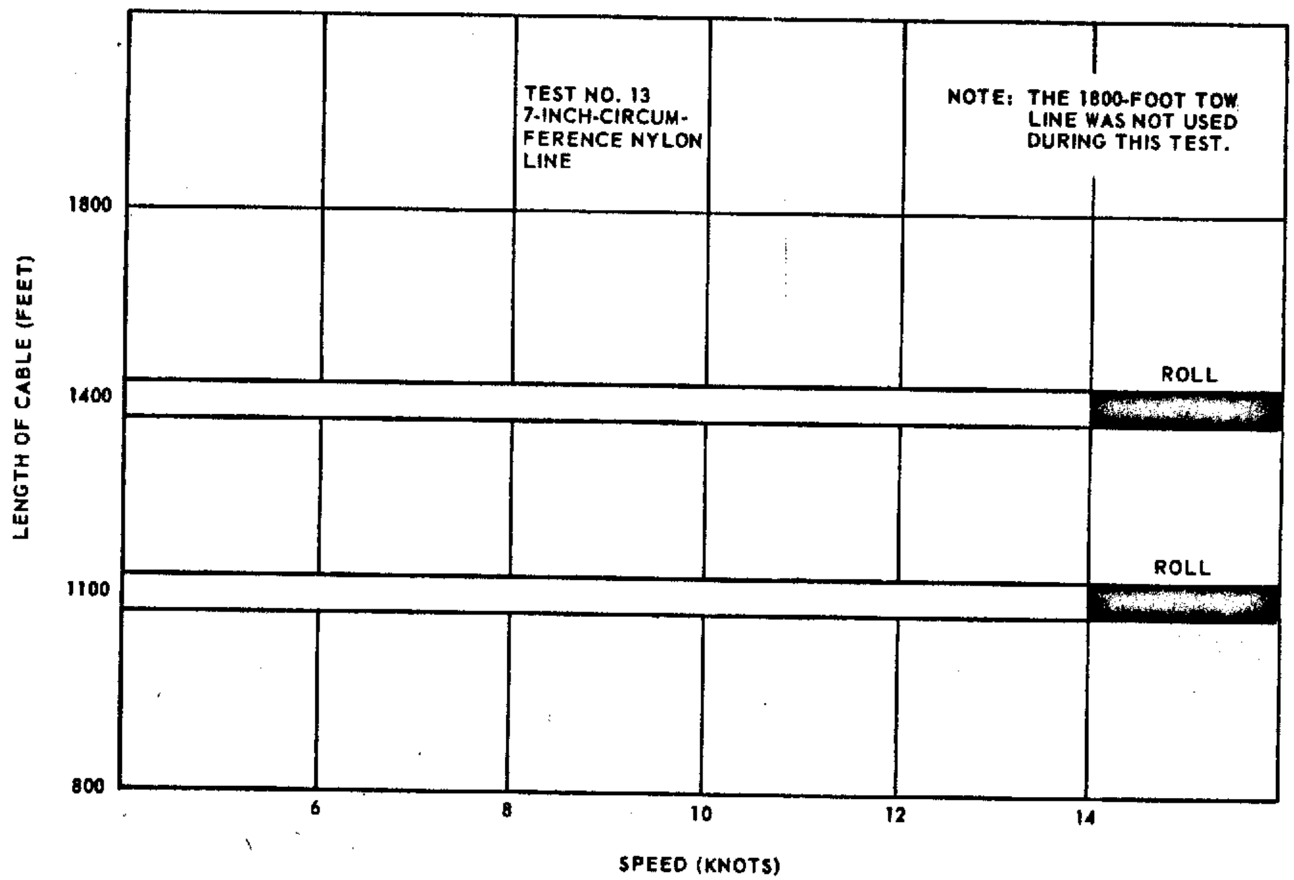

Figure 29. Instability as Related to Tow Speed and Test Configuration (sheet 3 of 3)

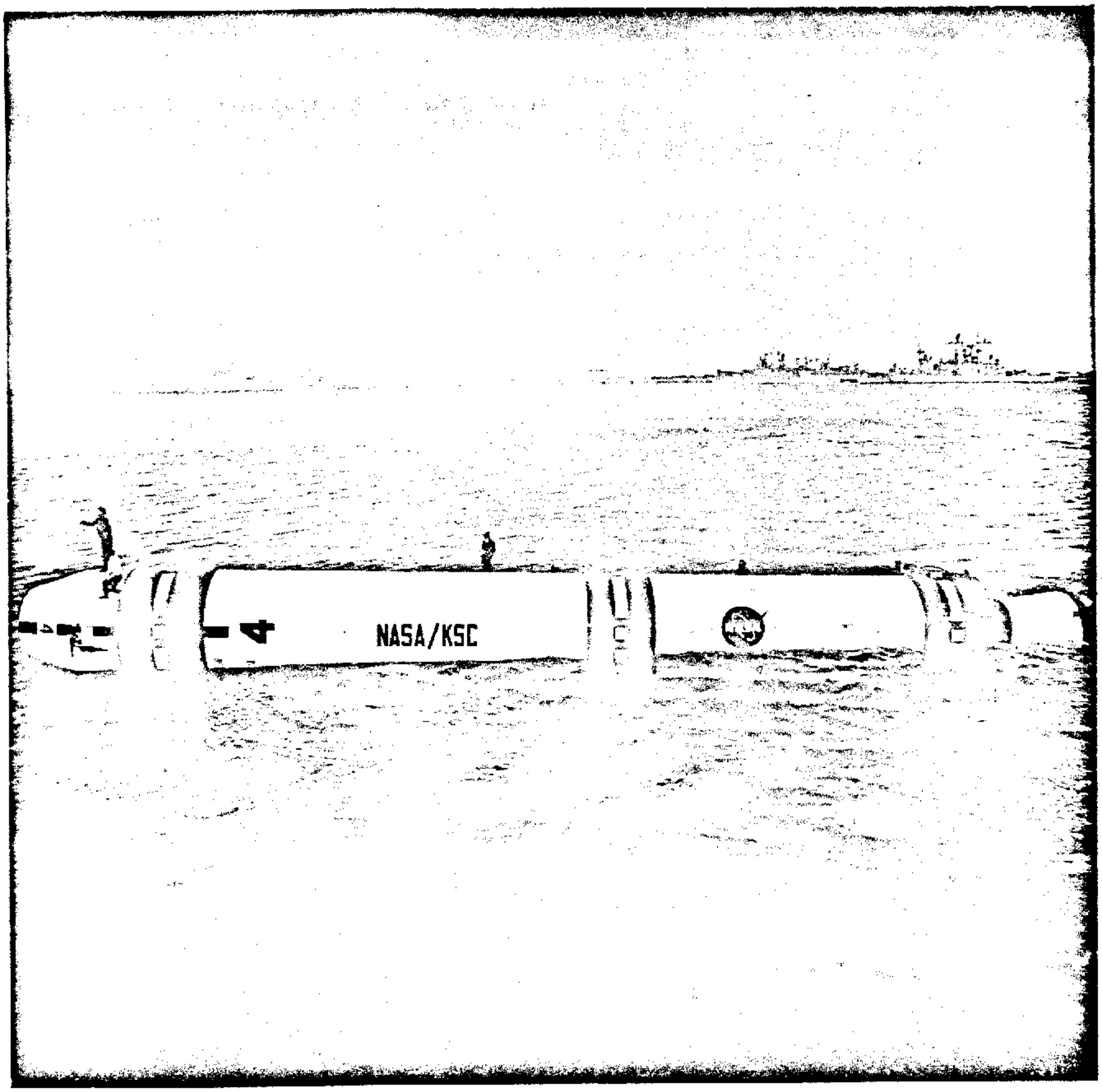

Figure 30. Free-Floating SRB Model

The attachment at sea test, which was conducted in a sea state 1 condition, resulted in a model floating attitude similar to the stability test, except for reduced model heave. A time span of 30 minutes was required to approach the free-floating model, attach the tow line, and commence towing. The use of a nylon pendant and float provided a good method for attaching the tow line while keeping a safe distance between the model and the tow vessel.

In the attitude test, the model was placed in the water at dockside with the nozzle unplugged and the #3 position up (see Figure 31). Water filled the casing until the nozzle area became submerged, and the air remaining inside the model was trapped. The model stabilized in 1 minute and 15 seconds at a +7-1/2-degree pitch angle with the #3 position up. The air escaping from the model prior to stabilization imparted a small forward velocity to the model. The preliminary results from the MSFC drop tests indicated that after the model impacted the water and stabilized, it achieved a 5- to 7-degree positive pitch angle. These values compare closely with the attitude test results with the variation resulting from the different lcg location and different water entry conditions. The MSFC model (156-inch baseline) lcg was 20 inches farther forward than on the tow test model. The lcg being located farther forward would reduce the model pitch angle.

Figure 32 represents a cross-section of the model floating in the water with the nozzle plugged and unplugged.

4.4 NOZZLE PLUGGING

To determine the requirement for a nozzle plugging system, the pitch characteristics of the model were analyzed. From the section on towing characteristics, it was determined that pitch angle was a function of tow speed, tow line, model configuration, and sea state. The pitch angle decreased as the tow speed and tow line length and weight increased; while the sea state caused the model pitch angle to oscillate.

The average pitch angle for each test run was determined by the tow speed and tow line and model configurations, and the range of pitch values was determined by the sea state conditions during the test run. The tabulation below lists the greatest average negative pitch values and range based on the data reduced for three types of tow line used in the testing.

Test No.	Type of Tow Line	Maximum Average Negative Angle	Sea State	Range	Maximum Decrease in Pitch Angle
10	1-inch-diameter steel	-1.2°	3	6.4°	5.5°
11	2-inch-diameter steel	-2.75°	1	2.3°	5.4°
13	2-inch-circumference nylon	-3.6°	1	2.2°	6.2°

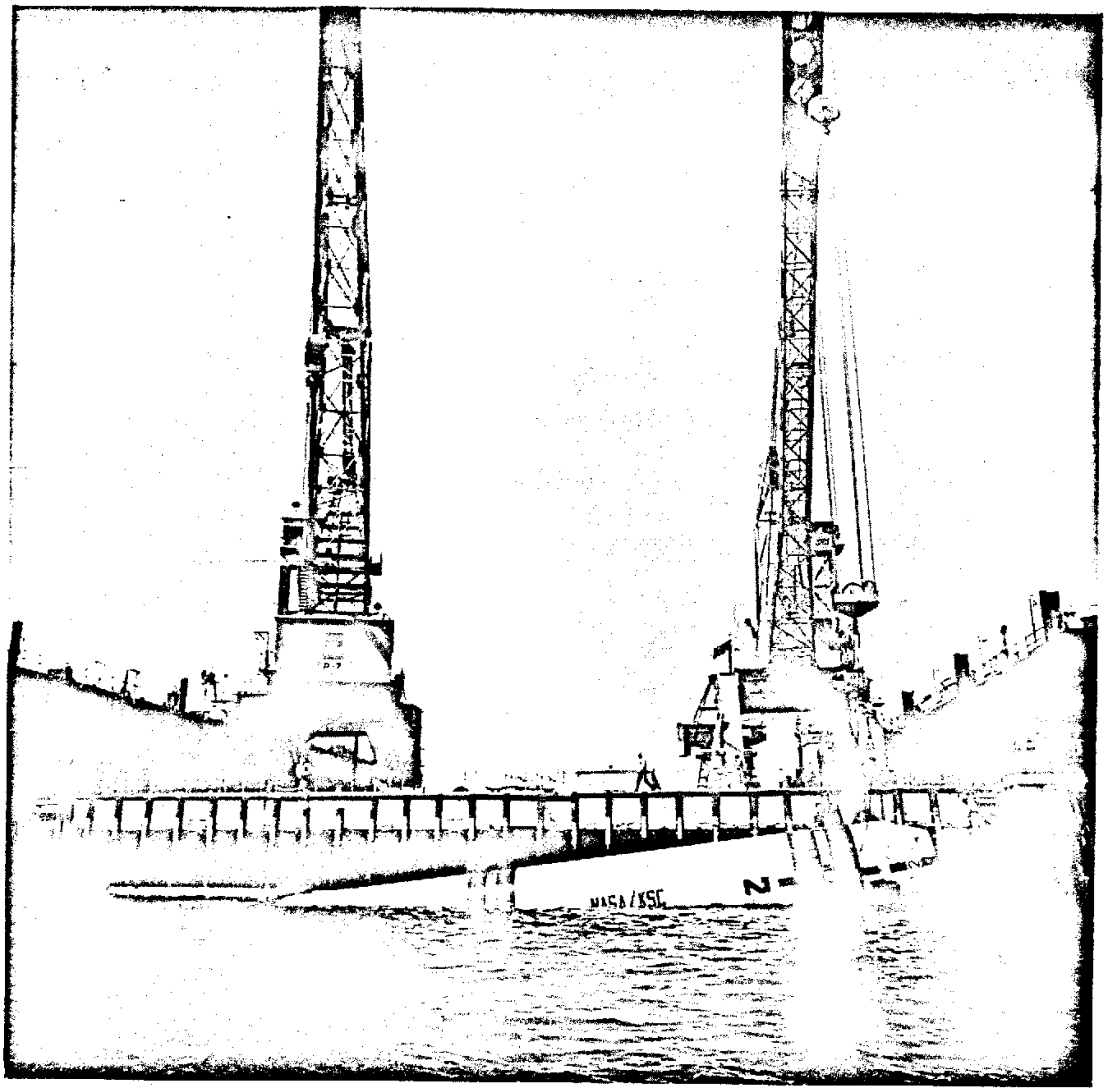

Figure 31. Attitude Test at Dockside

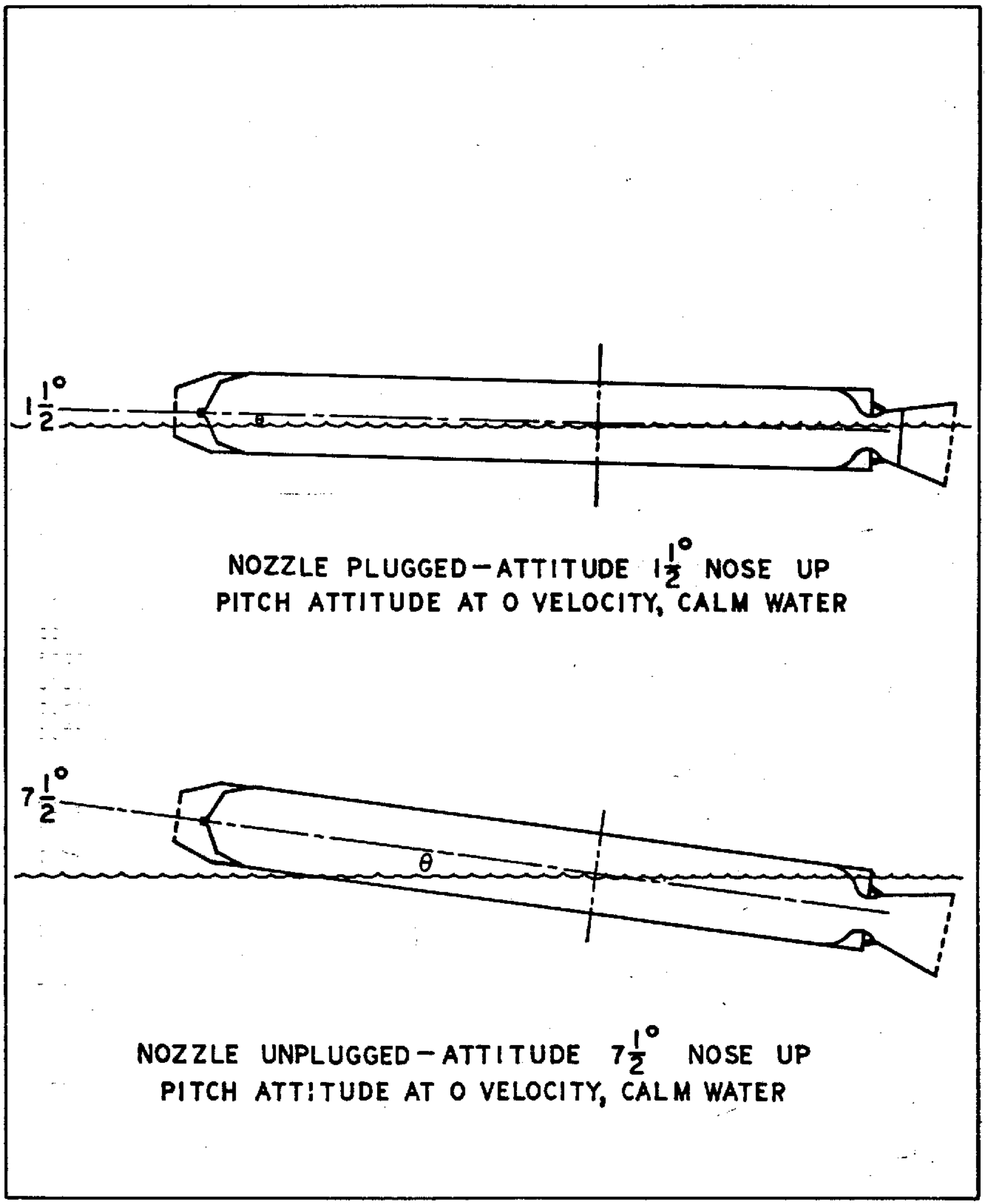

Figure 32. Pitch Attitude of Model While Floating

Since the nozzle was plugged during all tow tests, some assumptions must be made concerning model pitch characteristics when the model is floating with the nozzle unplugged. Hypothetically, the model pitch characteristics for the plugged and unplugged nozzle configurations will be considered relatively close. The model with the unplugged nozzle floated at a pitch angle of +7-1/2 degrees. If the model pitch decreases by 4 degrees due to a high tow speed, the model with the unplugged nozzle would float at a +3-1/2-degree pitch angle as shown in Figure 33. The nozzle area would be at the water/air interface and water could enter the model. If a pitch oscillation of ±2 degrees is added for the sea state effects, then the nozzle area would come out of the water, and the model would start to take on water. This condition would either result in the model sinking, or tow line tensile loading would increase to the point which would cause the model to assume a "spar bouy" mode thereby making towing operations very difficult.

Another factor which must be considered is the potential changes in sea state during towing operations which could produce even greater SRB pitch angles than those experienced during the testing. The highest sea state experienced during the testing was a sea state 3 (3- to 5-foot waves) during Test No. 10, and the criteria for SRB recovery is that it shall be accomplished in a sea state 5.

4.5 ATTACHMENT CONFIGURATIONS

The three attachment configurations for towing the SRB were: (1) two-point bridle, (2) single center, and (3) single side. All test configurations were used in the harbor testing; however, only the single center attachment was used in the ocean testing. Originally, all attachment configurations were to be used in both harbor and ocean phases of the testing, but during the harbor phase, sea conditions reached sea state 3 and provided sufficient data for attachment configurations relative to sea states.

Use of the same attachment point for the ocean testing also provided more data points under constant conditions for analysis of other factors, i.e., types of tow line and lengths, which affected tow line loads and model towing characteristics.

Figures 34 and 35 present the relationship between attachment configurations and tow line loads at the tow vessel for equivalent speed ranges. The line loads using the single center attachment were significantly smaller than the other attachment configurations. Loads experienced using the two-point bridle and single side attachments were approximately the same.

The lower line loads with the single center attachment could have resulted from the tow cable attachment for the single center being located at the forward tip of the model while the other attachments were located 11 feet aft, creating a larger drag profile. This is especially true for the wire tow lines whose direction of pull was not parallel to the direction motion but at a downward angle determined by catenary of the wire (see Figure 36).

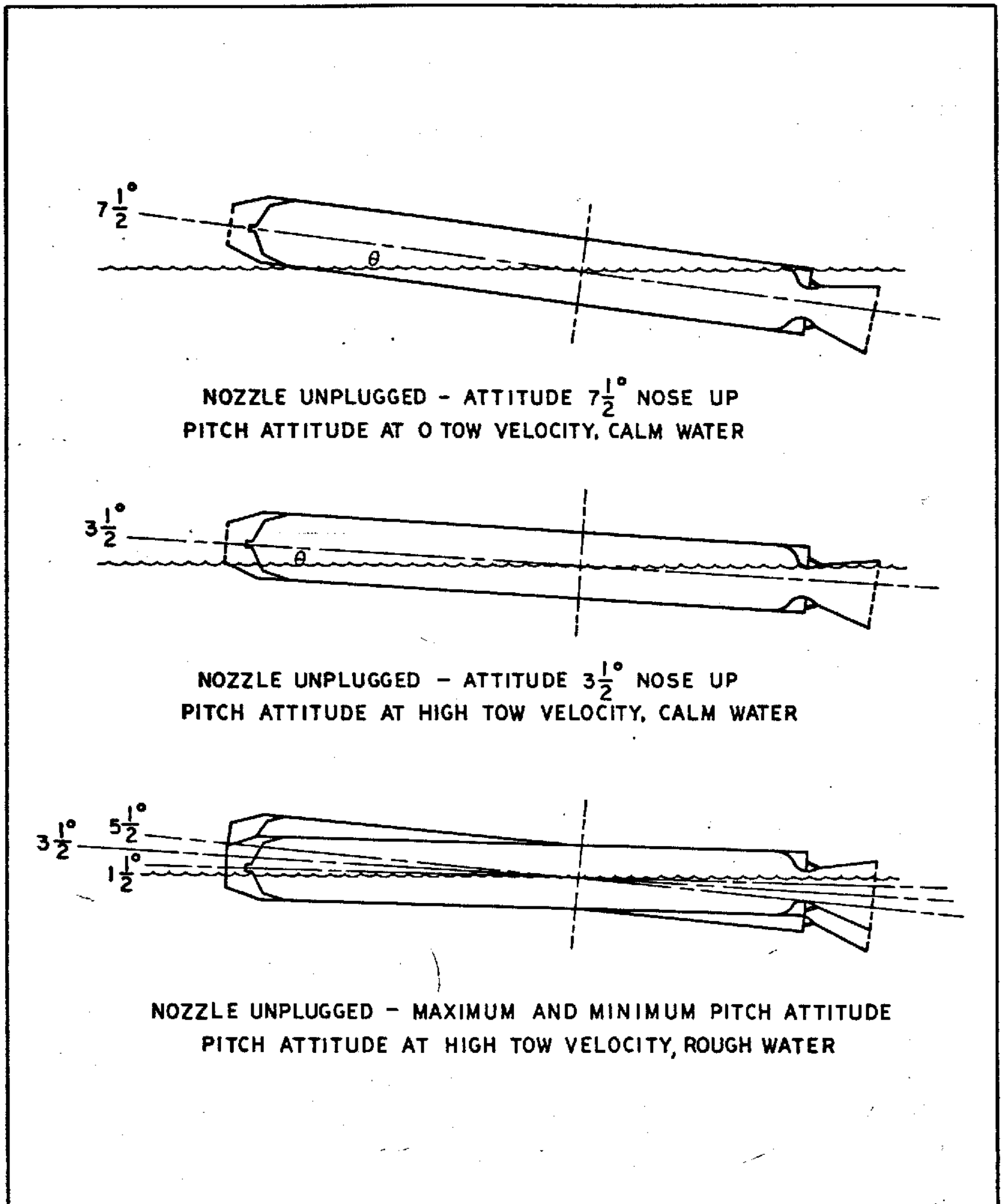

Figure 33. Pitch Angle of Model

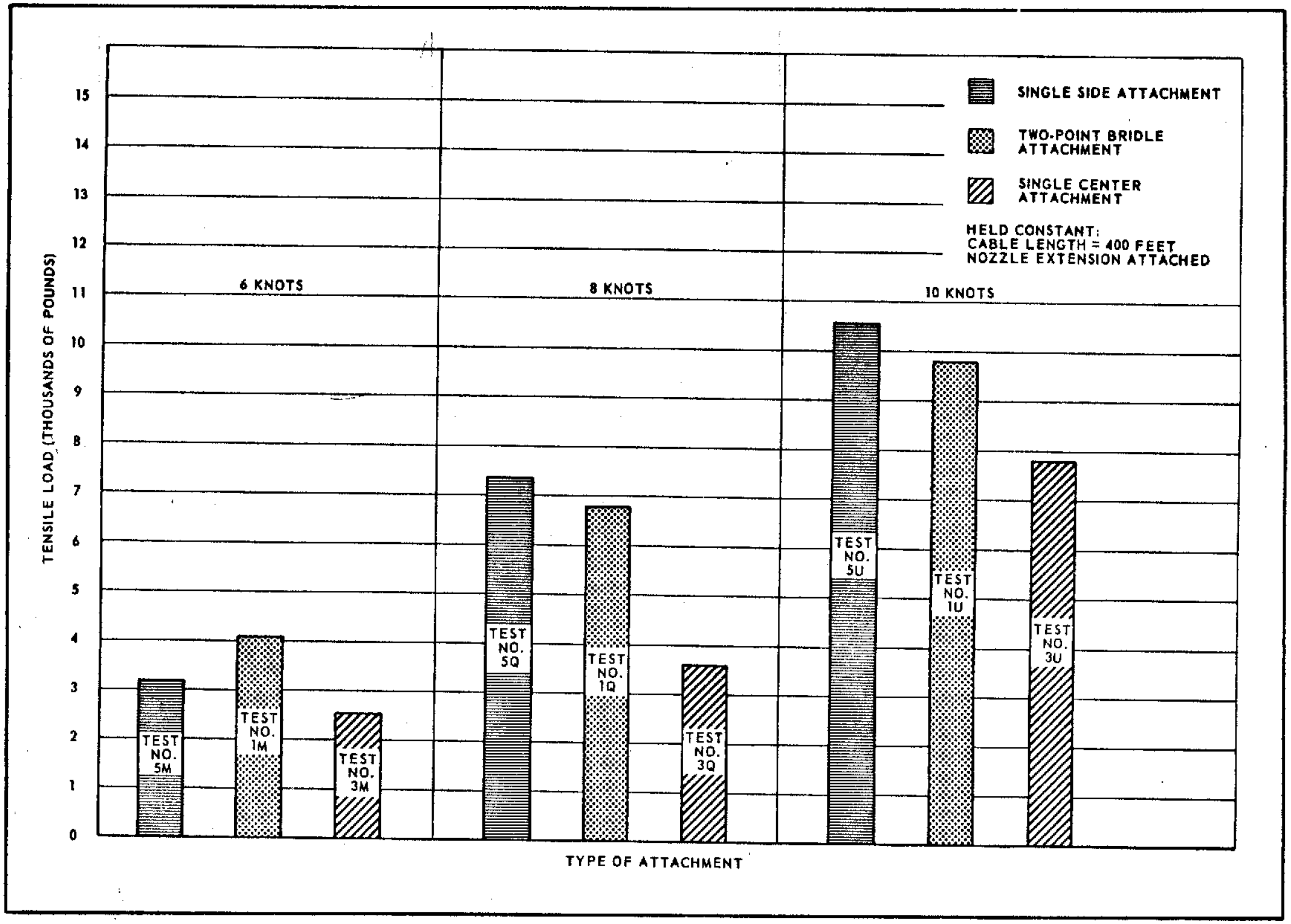

Figure 34. Type of Attachment Versus Average Tensile Load at the Tug Using 400 Feet of 1-Inch-Diameter Steel Wire

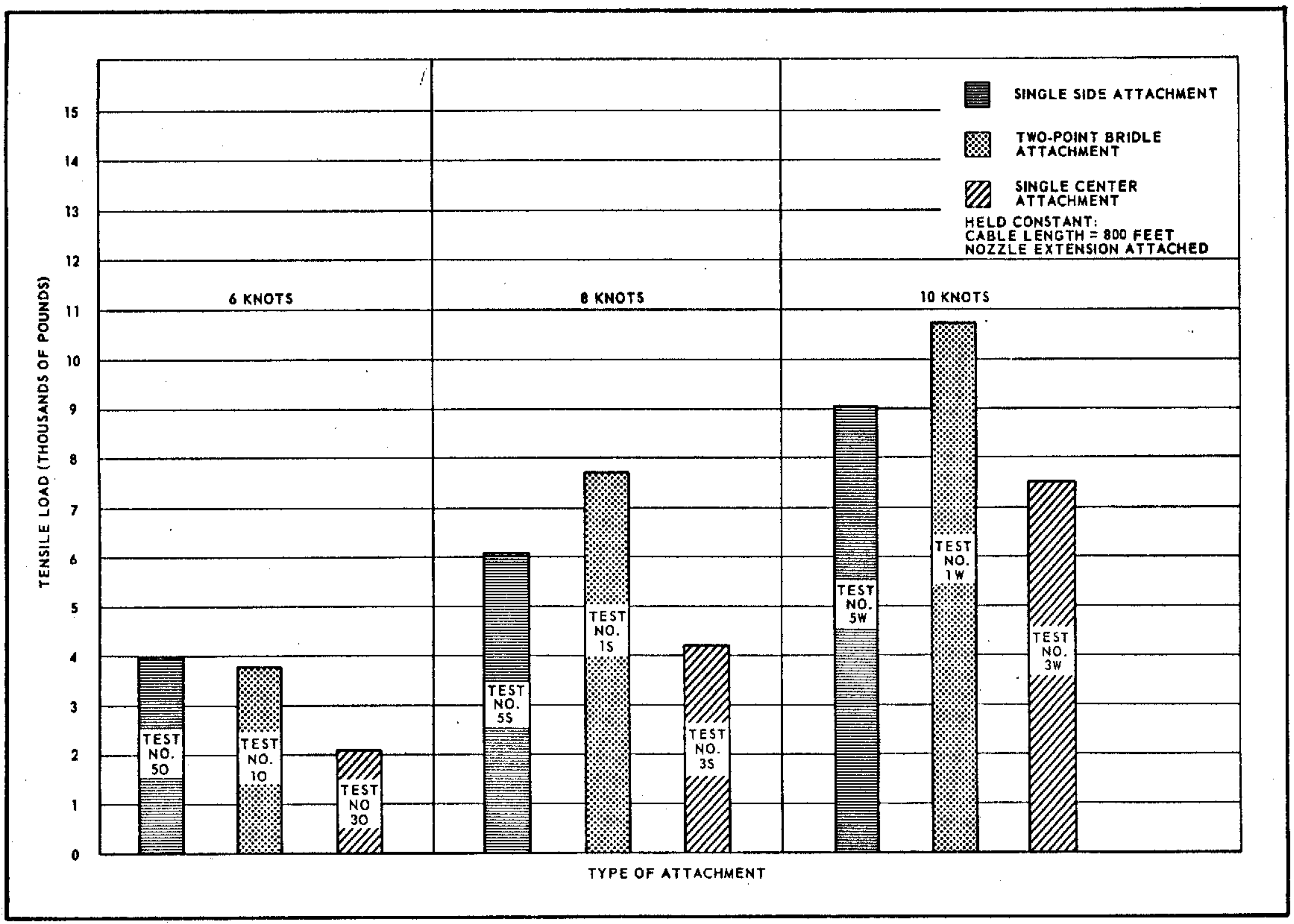

Figure 35. Type of Attachment Versus Average Tensile Load at the Tug Using 800 Feet of 1-Inch-Diameter Steel Wire

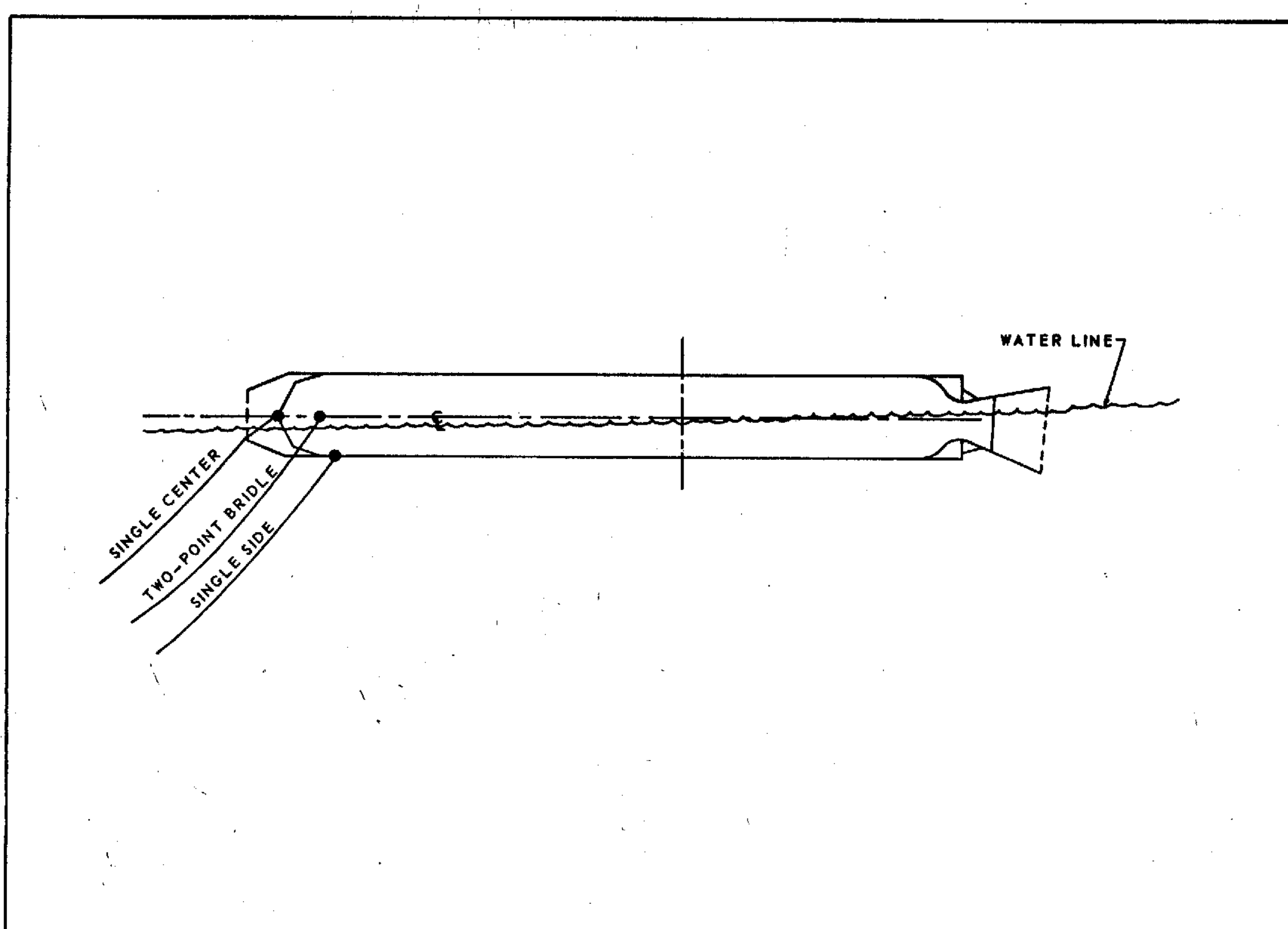

Figure 36. Tow Line Attachment Locations

4.6 TOW SPEEDS

Tow speed had the most significant effect on tow line loading and model towing characteristics. Figure 37 represents the relationship between tow speeds and average line load at the tow vessel for Test No. 10 using 800, 1100, 1400, and 1800 feet of tow line. Tow line loads increased as an exponential function of the tow speed up to 8 knots with an essentially linear region from 8 knots to 14 knots. A linear regression line developed to describe this relationship is presented below:

$$Y = -4186.5 + 1330.9X$$

where

X = tow speed, knots
Y = load at tow vessel, pounds

which has a correlation coefficient of 96 percent with the range of 6 to 14 knots. In Figure 38 the tow speed versus average load at the model is shown for 7-inch-circumferance nylon line. Again the load increases exponentially up to 10 knots and then becomes essentially linear up to 14 knots.

The relationship between tow speed and line loads at the tow vessel are shown in Figure 39 for 2-inch-diameter steel wire. Tensile load data for tow line lengths of 1100, 1400, and 1800 feet are shown to reflect the effect of the heavy weight of the tow line on the tow line loads. The plots have a steeper slope at the longer tow line lengths. For the speed range of 8 to 12 knots, the 1100-foot plot shows line loads in essentially a linear relationship with tow speed. The 1400-foot plot indicates an exponential increase in load versus speed from 10 knots up to 12 knots which is probably a result of the extreme roll and yaw at 11 knots which became more severe as speed was increased.

The 1800-foot plot has approximately the same slope as the 1400-foot plot, but higher load values from 3000 to 6000 pounds were experienced. Again extreme roll and yaw occurred when the tow speed reached 9 knots which could have caused the exponential increase in the speed versus load plot.

Figure 40 represents a typical relationship between tow line loads and speeds for a tow relative to a heading sea and a following sea. The heading sea produced the highest loads with an average difference between heading and following seas of 2070 pounds.

In Figure 41 the difference in the tow line loading at the tow vessel and model are shown for 1-inch-diameter steel wire. The loads at the tow vessel were the highest with the average difference between the two of 2543 pounds. As speed increased, the difference between the loading at the tow vessel and at the model increased. The range of tow line loads is also shown with the variation increasing as the tow speed increases.

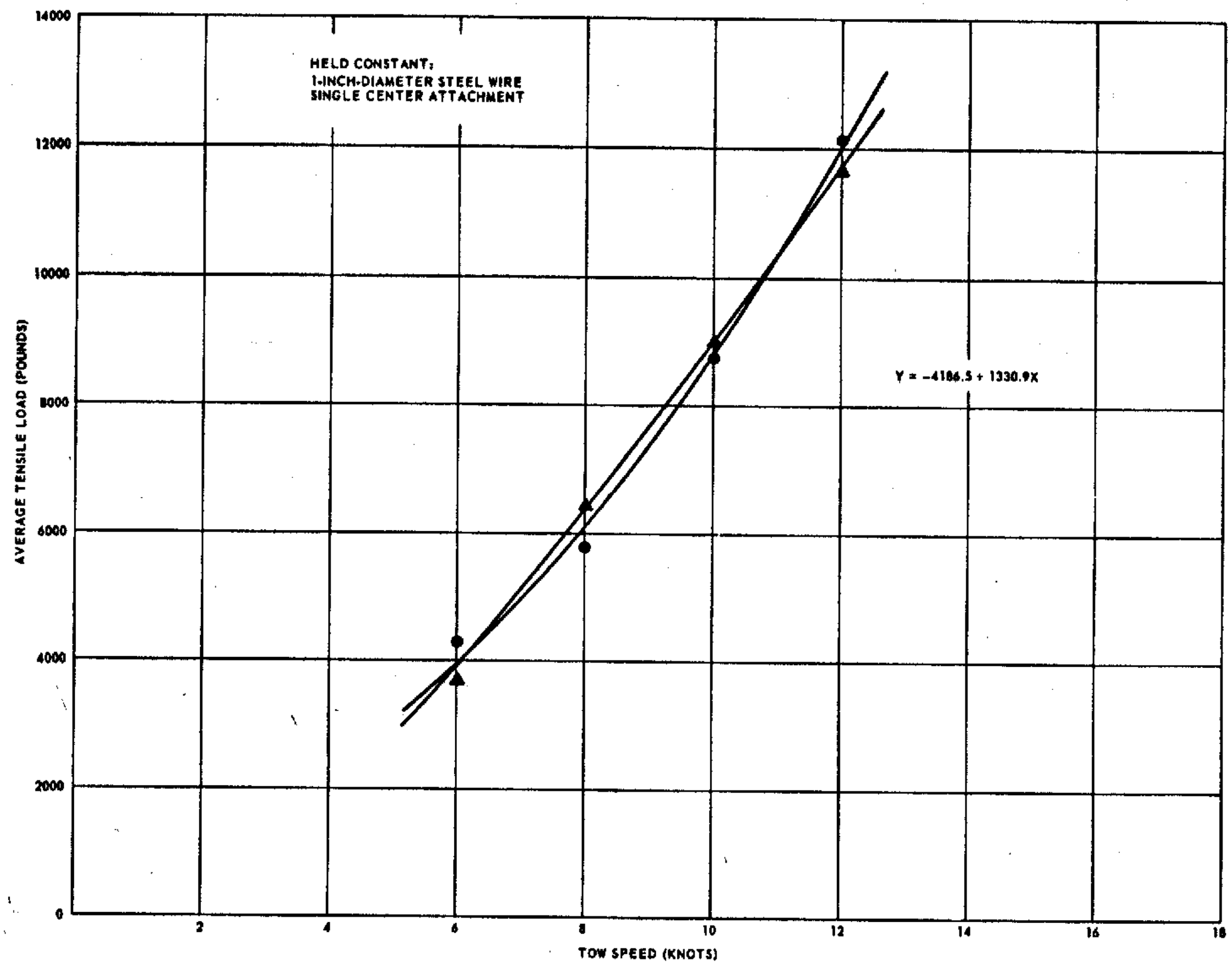

Figure 37. Tow Speed Versus Average Load at Tow Vessel Using 800, 1100, 1400, and 1800 Feet of Tow Line

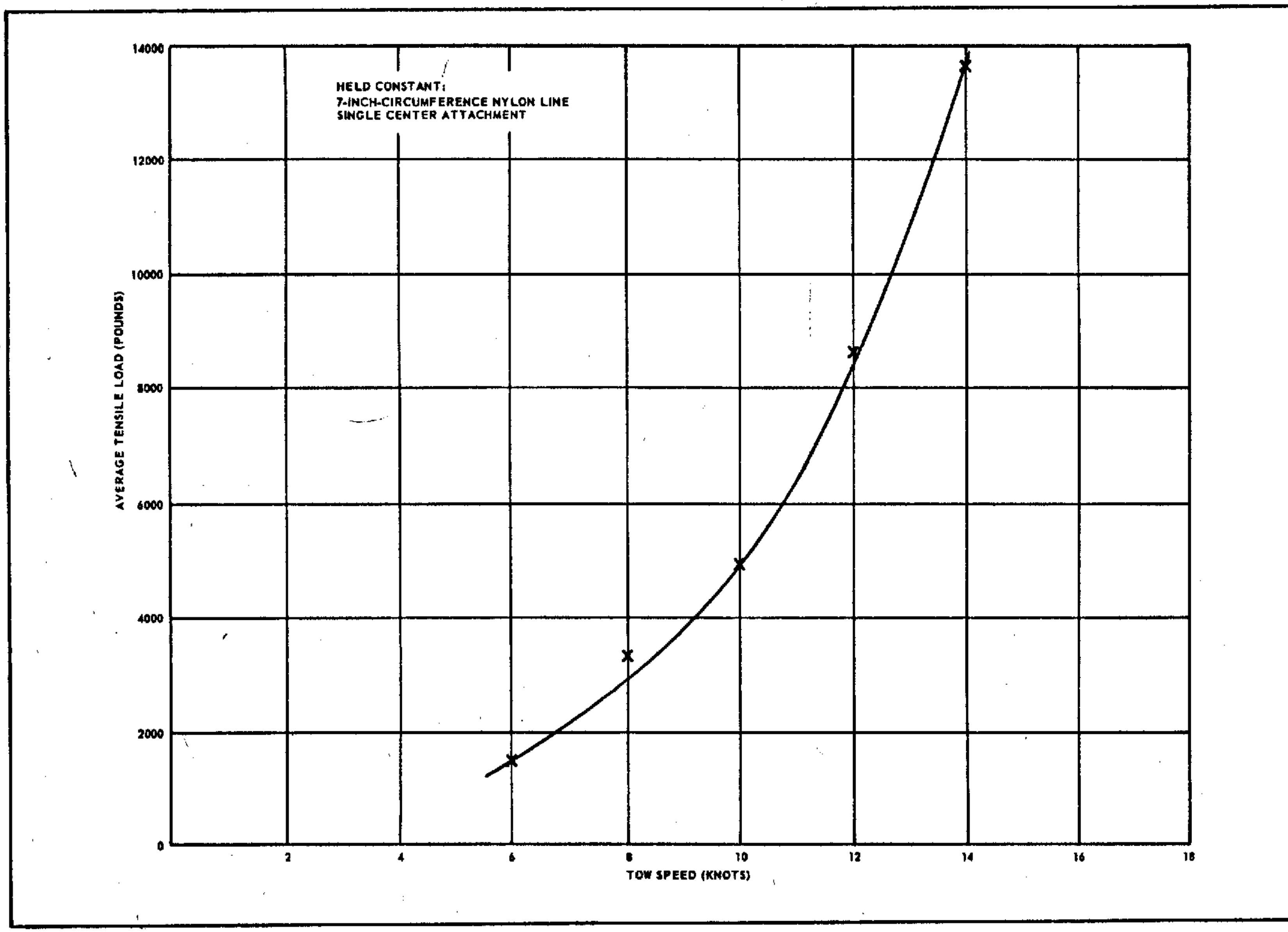

Figure 38. Tow Speed Versus Average Load at Model Using 800, 1100, and 1400 Feet of Nylon Line

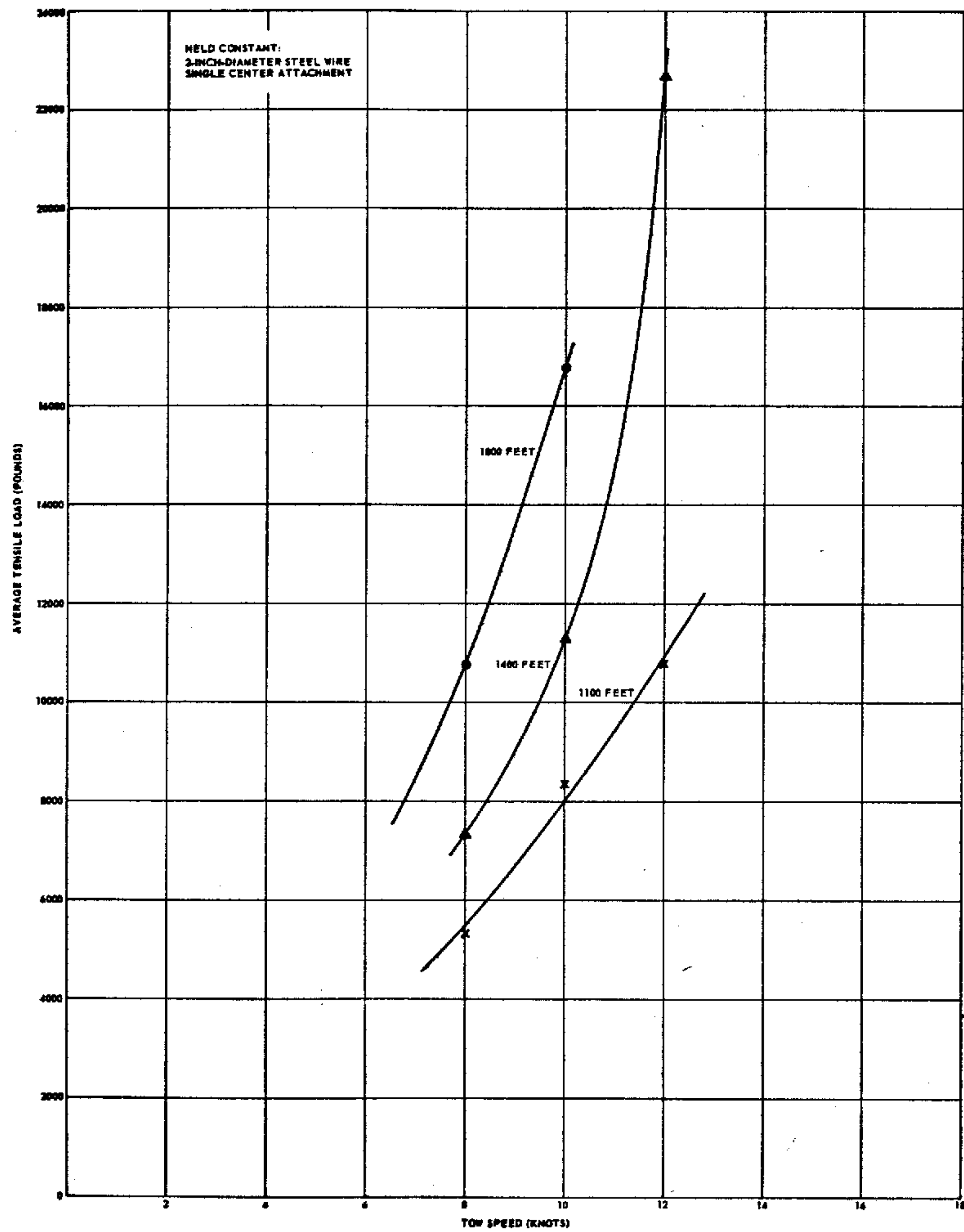

Figure 39. Tow Speed Versus Average Load at Tow Vessel Using 2-Inch-Diameter Steel Wire

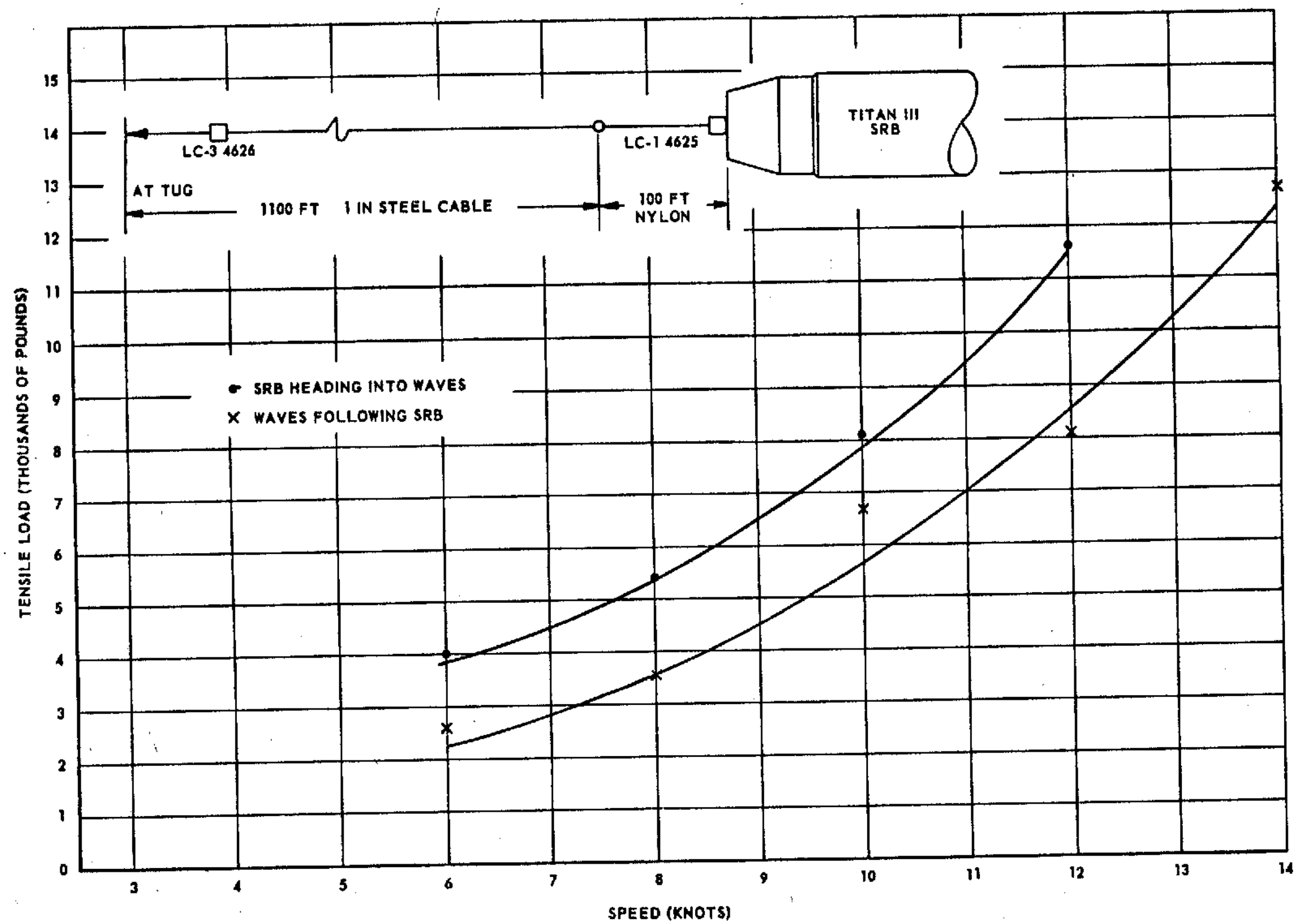

Figure 40. Tensile Load at the Tug as a Function of Wave and SRB Relative Motion

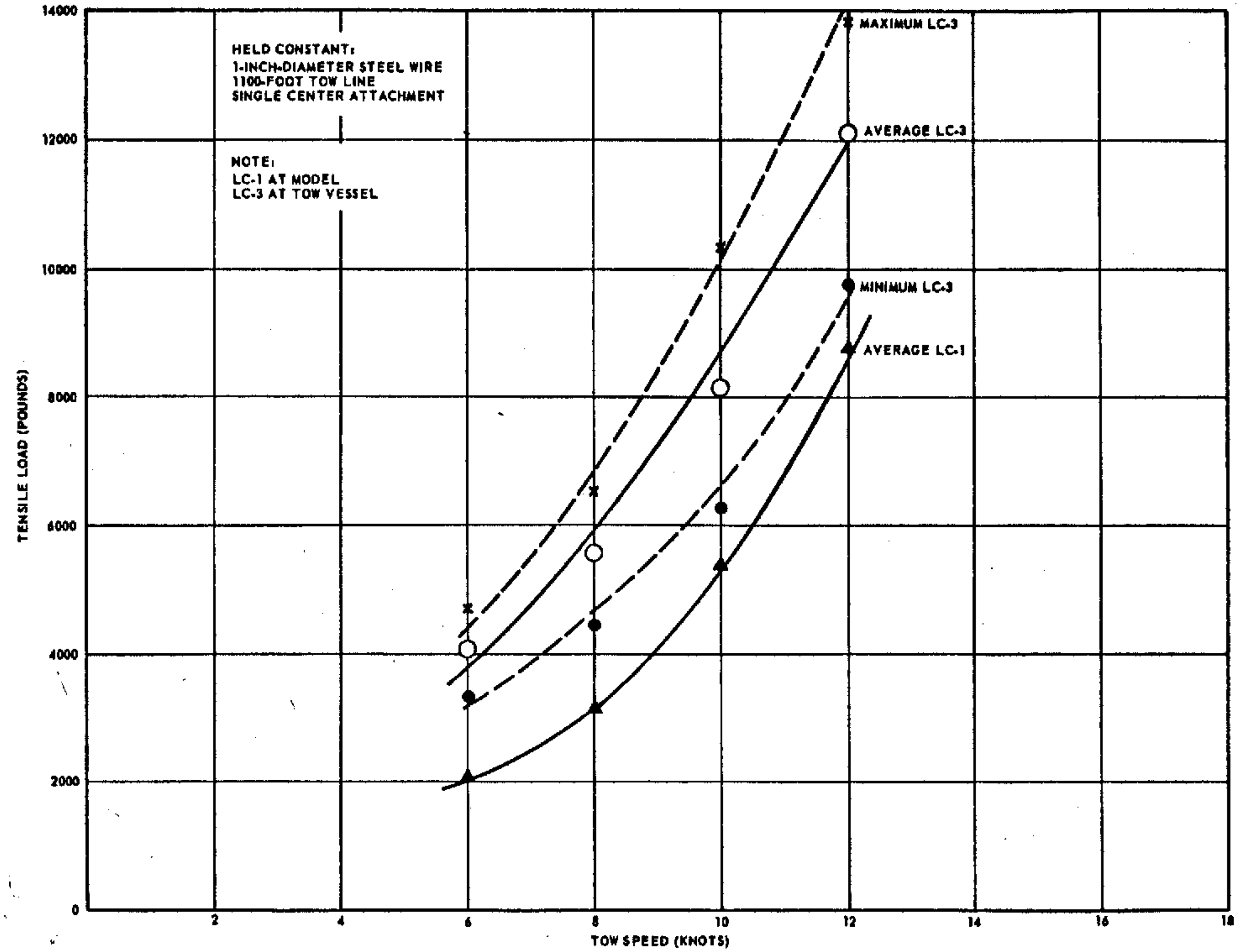

Figure 41. Tow Speed Versus Tow Line Loads at Tow Vessel and at Model

4.7 TOW LINES

Four types of tow lines were used during the tow tests: (1) 1-inch-diameter steel wire, (2) 2-inch-diameter steel wire, (3) 6-inch-circumference braided nylon line, and (4) 7-inch-circumference twisted nylon line. Table II presents the specification data for the tow lines and the maximum allowable load for each which was calculated using the following equation and a 4 to 1 safety factor:

$$\text{Maximum Allowable Load} = \frac{\text{Tensile Breaking Force, Pounds}}{4}$$

The maximum allowable load limit was not exceeded for any of the tow lines used in ocean testing as shown in Figure 42. Eighty-two percent of the maximum allowable load was the highest value achieved in Test No. 10 while using 1100 feet of 1-inch-diameter steel wire and towing at 14 knots. The 1-inch-diameter steel wire and 7-inch-circumference nylon line were optimally sized for towing a model of the size used in this test program, but it is necessary to consider scaling factors in considering the use of these tow lines for the full scale SRB. The 2-inch-diameter steel wire was oversized for its application in towing the model because the maximum load recorded during the tests was only 32 percent of its maximum allowable working load.

Average tow line load at the model versus tow speed was plotted for the 1-inch-diameter steel wire, 2-inch diameter steel wire, and 7-inch-circumference nylon line (Figures 43 and 44) to study the effect of the tow line itself on tow line loads. Tow line length was held constant at 1100 feet in Figure 43 and 1400 feet in Figure 44.

Table II

Tow Cable Data

Size	Material	Type	Force to Break (pounds)	Maximum Allowable Load (pounds)	Weight (lb/ft)
1-inch-diameter	Steel	6 x 37 IWRC*	85,600	21,400	1.5(in water)
2-inch-diameter	Steel	6 x 37 IWRC*	330,000	82,500	5.8(in water)
6-inch-circumference	Nylon	Braided	106,000	26,500	0.95(in air)
7-inch-circumference	Nylon	Regular right hand lay	110,000	27,500	1.3(in air)

*IWRC=Independent Wire Rope Core

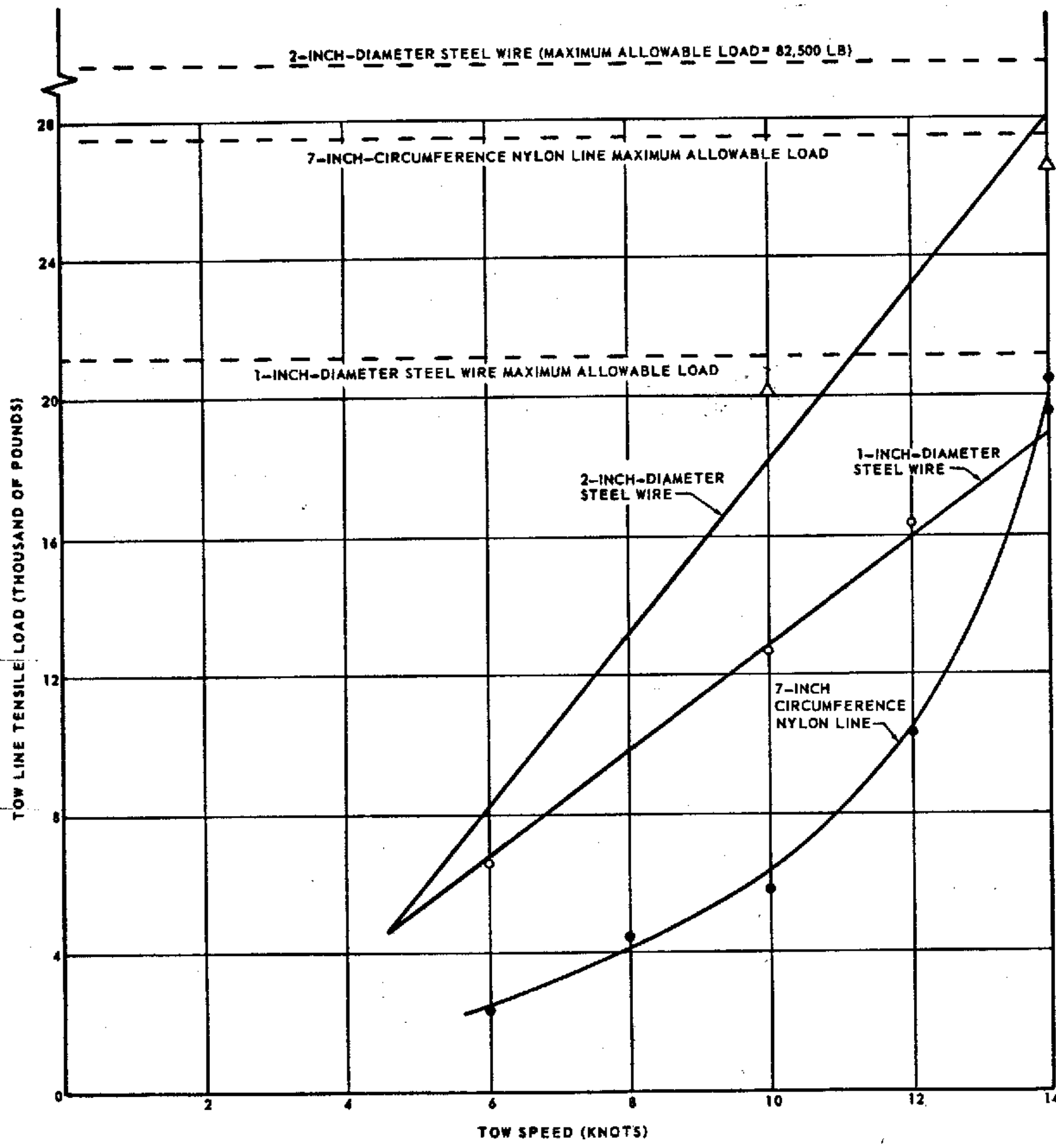

Figure 42. Tow Speed Versus Maximum Tow Line Load for 1- and 2-Inch-Diameter Steel Wire at Tow Vessel and for 7-Inch-Circumference Nylon Line at Model

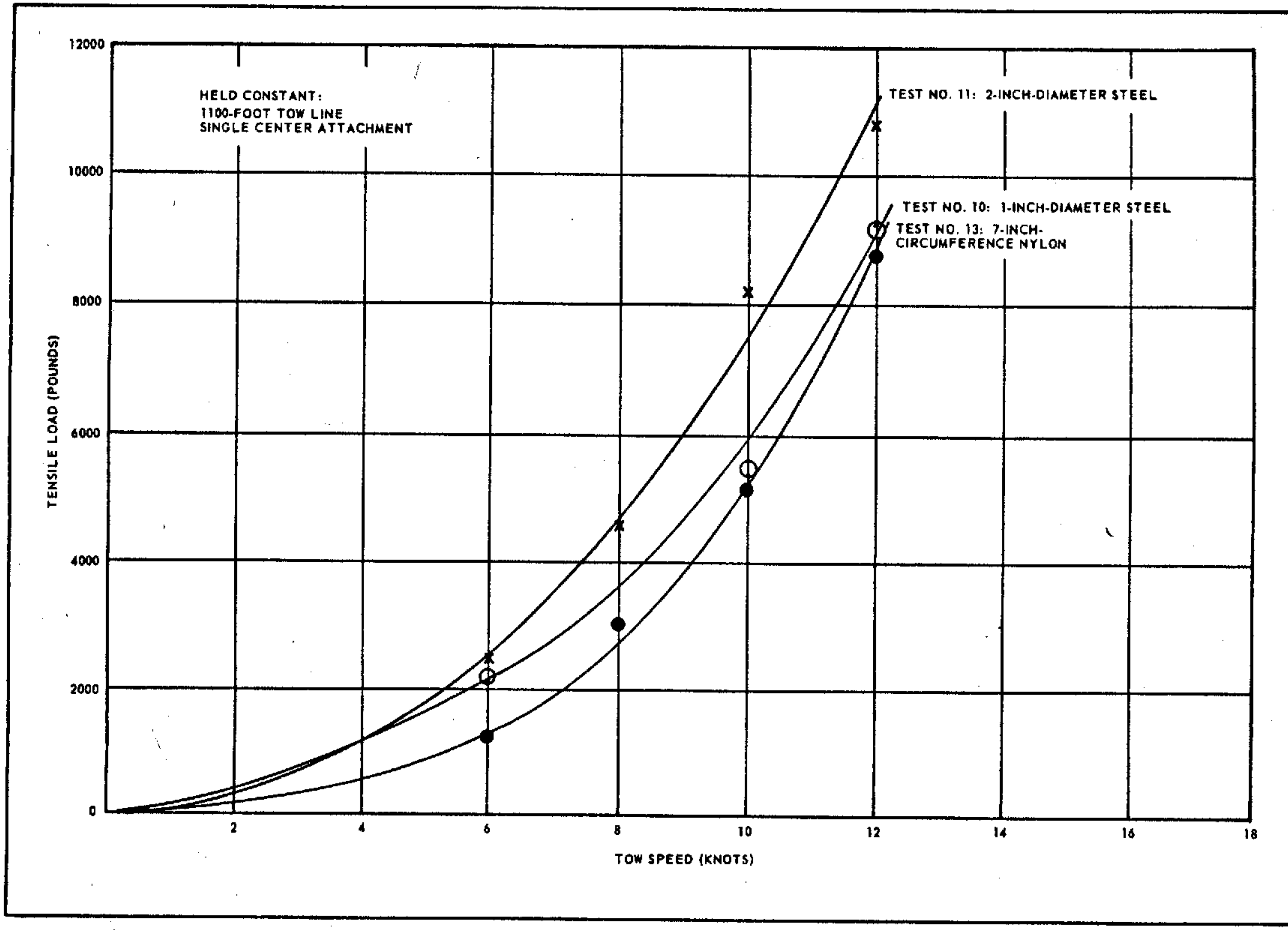

Figure 43. Type of Tow Line Versus Average Loads at Model Using 1100-Foot Tow Line

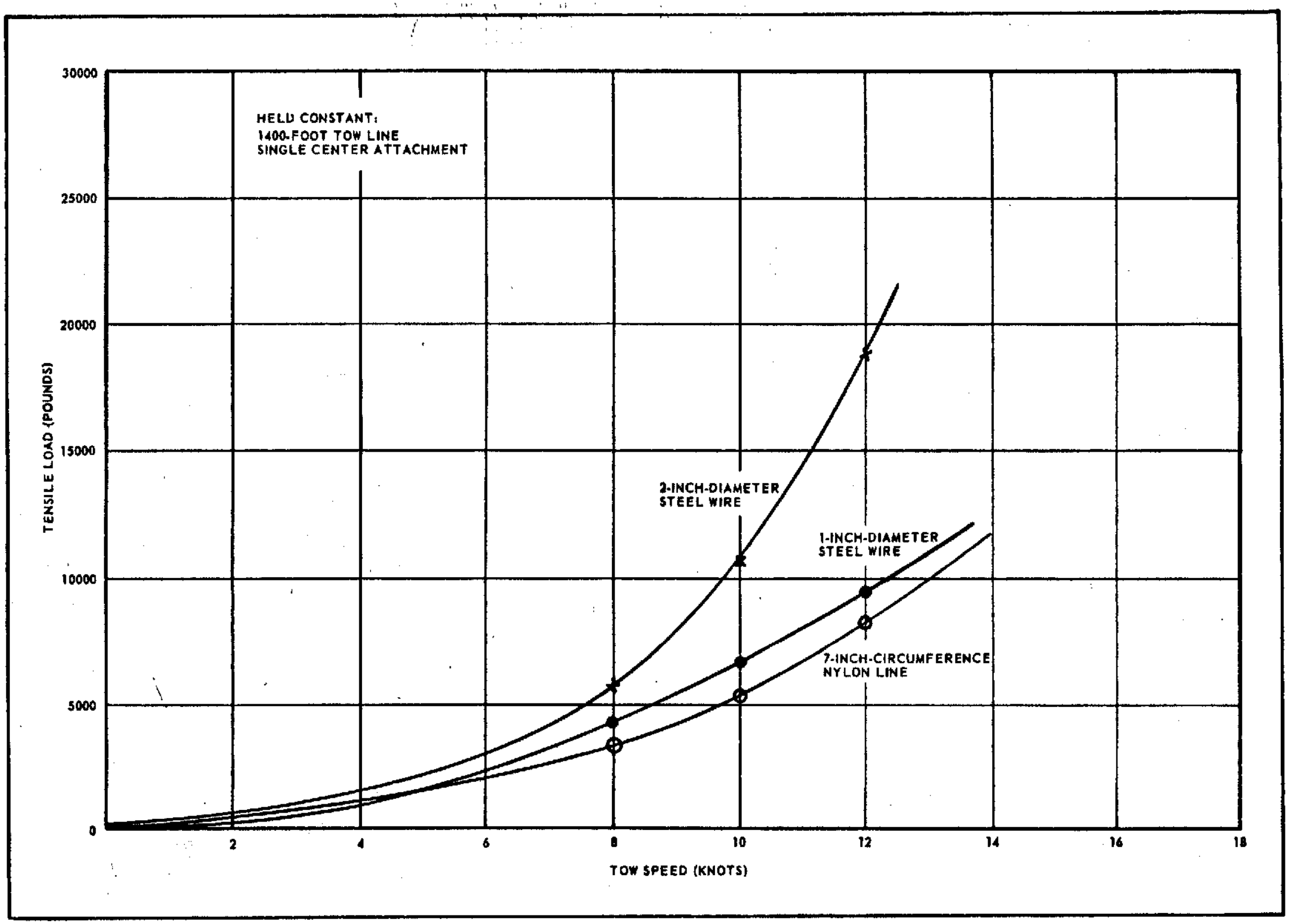

Figure 44. Type of Tow Line Versus Average Loads at Model Using 1400-Foot Tow Line

The 2-inch-diameter steel wire plot in Figures 43 and 44 produced tow line loads at equivalent speeds significantly greater than the other lines. The 2-inch-diameter steel wire plot in Figure 44 became extremely divergent at 8 knots with the tow line 100 percent greater than that exhibited by the other lines at 12 knots. This extreme increase in tow line load for the 2-inch-diameter steel wire at 1400 feet can be attributed to the increased downward (negative) pitch angle of the model produced by the longer, heavier tow line. The 1-inch-diameter steel wire and the 7-inch-circumference nylon plots are very close for both the 1100-foot and 1400-foot lines with the 7-inch-circumference nylon producing the smallest effect on the tow line loads.

To determine the relationship between tow line lengths and tow line loads, Figures 45, 46, and 47 were developed. These graphs indicate that tow line loads increase as line length is increased for the wire tow lines, but tow line loads were not affected by line length for the nylon line. The 2-inch-diameter steel wire produced the greatest increase in line load per unit length which was to be expected since the 2-inch-diameter steel wire weight is four times as great as the 1-inch-diameter steel wire (see Table II). This is also illustrated in Figures 43 and 44 which show a significant increase in line loads for the 2-inch-diameter steel wire for only a 300-foot increase in tow line length. Instability in the roll and yaw axes occurred at a lower speed with 1400 feet of tow line which also added to the increased loading on the 2-inch-diameter steel wire tow line (see Figure 29).

4.8 SCALING

Model scaling techniques allow the use of small models to predict the performance of full scale vessels which are costly and often unavailable for testing. The 120-inch-diameter model used in this test program simulated the 142-inch-diameter baseline dated February 2, 1973, except for configuration differences in the nose and tail sections. The model had an empty nose frustum while the SRB baseline reflects removal of the entire nose cone, leaving a blunt front section. The model had a short, straight support skirt with a 6-degree canted nozzle while the SRB baseline has a full flared support skirt. The length over diameter (L/D) ratios for the model and SRB are 10.1 and 10.9, respectively.

The scale factors for the model and SRB baseline are as follows:

	Model/SRB
Length:	1212 in./1553 in. = 0.7804
Diameter:	120 in./142 in. = 0.845
Weight:	93,286 lb/147,384 lb = 0.6329

The length scale factor is most important in determining the full scale values of tow line loads since both frictional drag and residuary drag are a function of vessel length. A scale factor of 78 percent or its reciprocal 1.282 (λ) will be used for the tow line calculations. The tow line load at the model is a combination of both frictional (viscous) forces and residuary (wave-making and eddy currents) forces or in equation form:

$$R_T = R_F + R_R$$

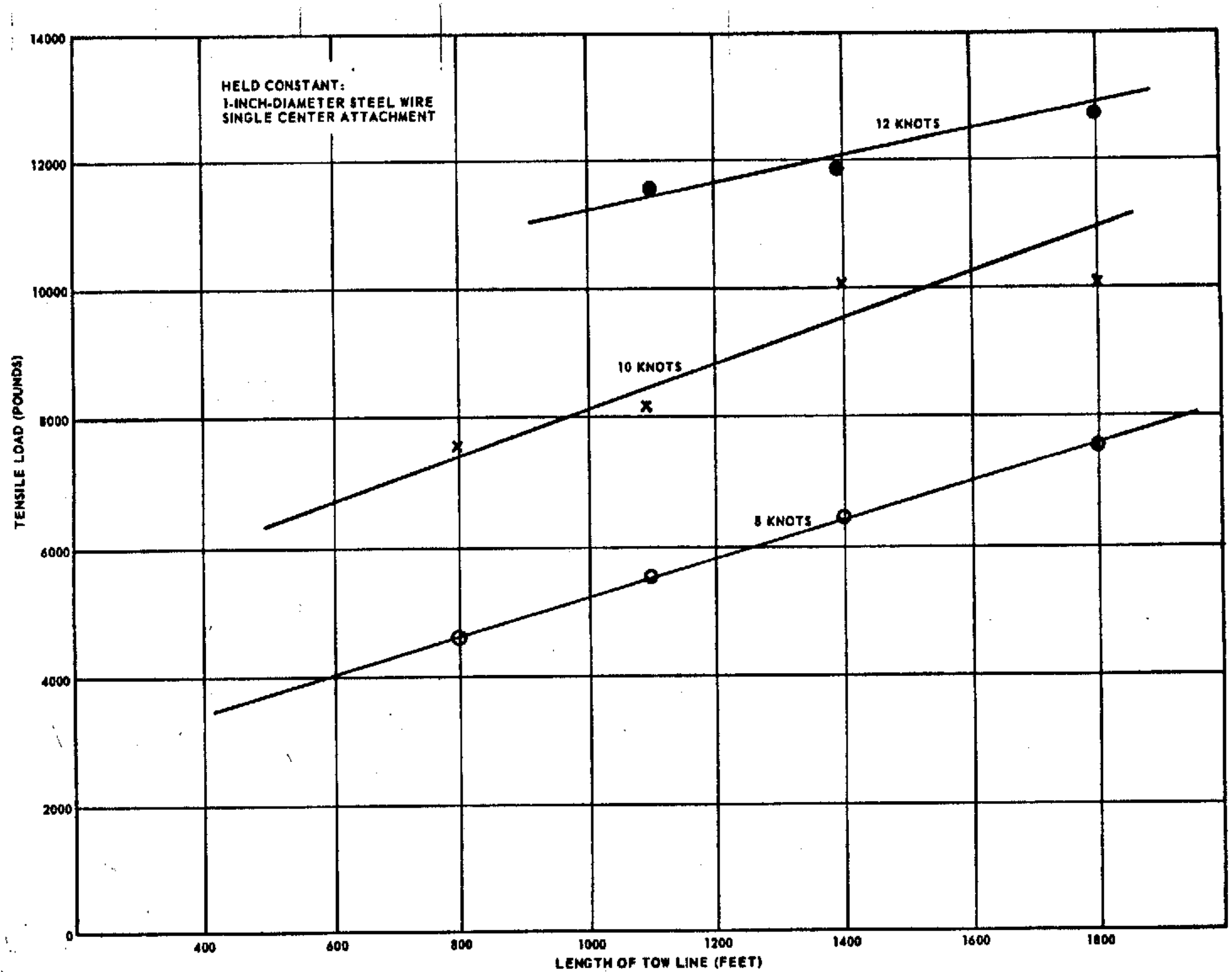

Figure 45. Tow Line Length Versus Average Load at Tow Vessel Using 1-Inch-Diameter Steel Wire

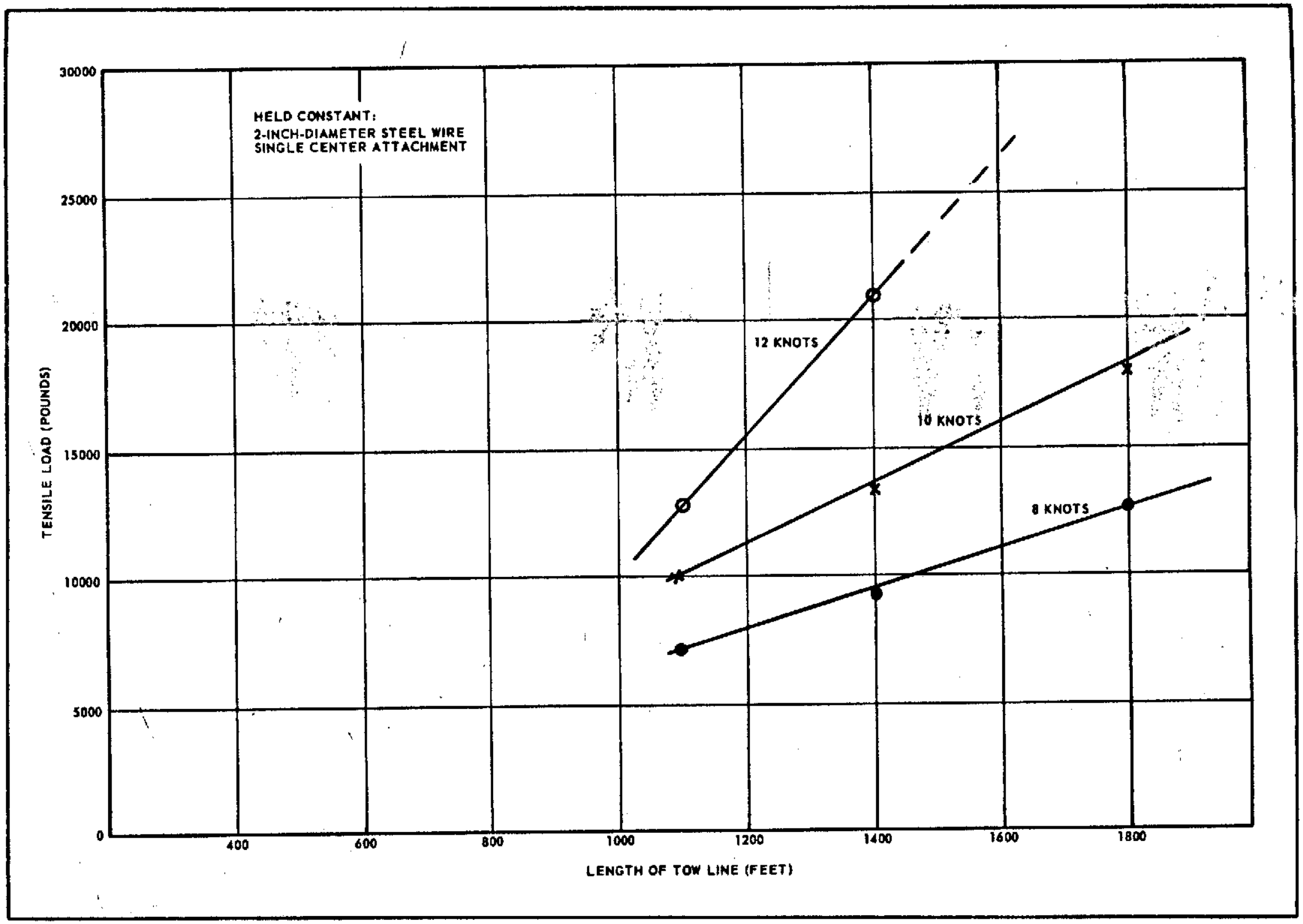

Figure 46. Tow Line Length Versus Average Load at Tow Vessel Using 2-Inch-Diameter Steel Wire

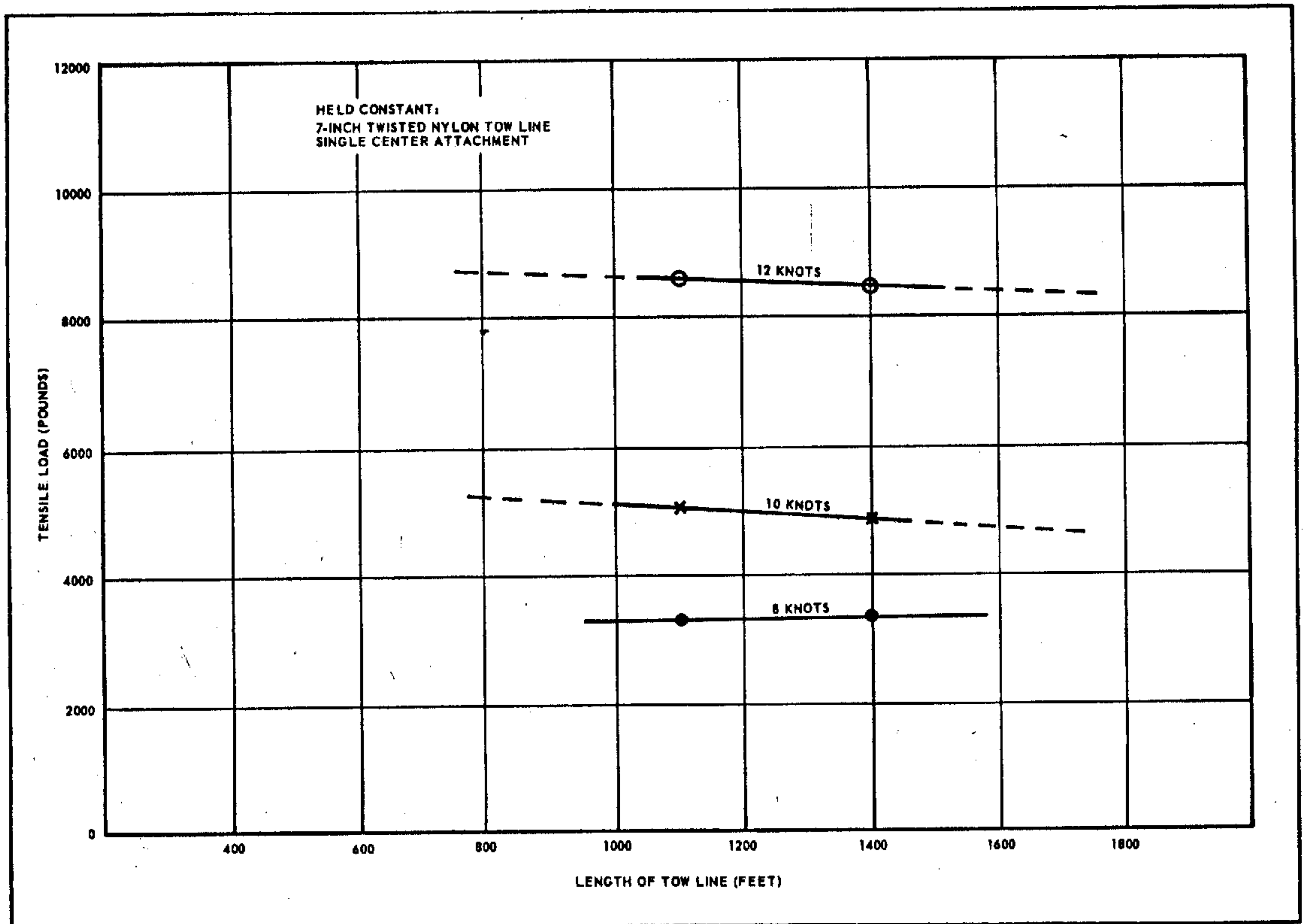

Figure 47. Tow Line Length Versus Average Load at Model

The frictional force (R_F) is a function of Reynold's number, $R_n = \frac{vL}{\nu}$, where

R_n = Reynold's number

$v = \frac{(\text{speed in knots})(6080)}{(3600)}$

L = length of vessel

ν = kinematic viscosity of sea water at 68°F = $1.14 \times 10^{-5}\,ft^2/sec$

and for this test program the Reynold's numbers for the model are in the 10^7 to 10^8 range which means that the frictional force (R_F) is very small as compared with the total load measured on the tow line. This is true for the full scale SRB also; therefore, frictional forces will not be considered in the scaling of tow line loads, and $R_T = R_R$.

The residuary forces, R_R, are a function of the Froude number,

$$F_n = \frac{v}{\sqrt{gL}}$$

where:

v = velocity of tow
g = gravitation constant
L = length of vessel

At corresponding speeds of

$$\left(\frac{v^2}{gL}\right)_{model} = \left(\frac{v^2}{gL}\right)_{SRB}$$

or

$$v_{SRB} = (\lambda)^{1/2} v_{model}$$

the residuary forces are proportional to the cube of the scale factor:

$$\frac{R_{RS}}{R_{RM}} = \left(\frac{L_S}{L_M}\right)^3 = \lambda^3.$$

Using these equations, speed and load values were calculated for the model and the SRB prototype as listed in Tables III and IV and plotted in Figures 48 and 49.

Table III

Model Versus Full Scale Loads (Pounds)

$R_M \times \lambda^3$	=	R_{SRB}
2×10^3 pounds x 2.107		4.214×10^3 pounds
4		8.429
6		12.643
8		16.858
10		21.072
12		25.287
14		29.501
16		33.716
18		37.930
20		42.145
22		46.359
24		50.574
26		54.788
28		59.003
30		63.217

Table IV

Corresponding Speeds (Knots)

$V_{model} \times \lambda^{1/2}$	=	V_{SRB}
2.0 knots x 1.132		2.264 knots
4.0		4.529
6.0		6.794
8.0		9.052
10.0		11.323
12.0		13.587
14.0		15.851

To further examine the scaling and tow line loads, the model and full scale values were plotted in Figure 50 for average tow line loads at the model versus tow speed using 7-inch-circumference nylon line. Full scale tow loads were plotted for the corresponding full scale tow speed as determined in Tables III and IV. The full scale loads were much higher than the model loads at equivalent speeds with the difference between them of approximately 15,647 pounds at 14 knots using 7-inch-circumference nylon tow line. Test No. 13 was selected for scaling purposes because nylon tow line has the least effect on tow line loads, and the use of wire tow lines would have scaled up loads caused by the tow line itself which is already at full scale. Examination of Figure 50 with respect to the sizing of tow lines reveals that the 7-inch-circumference nylon line would be acceptable for towing the full scale SRB at speeds to 15 knots without exceeding the maximum working load.

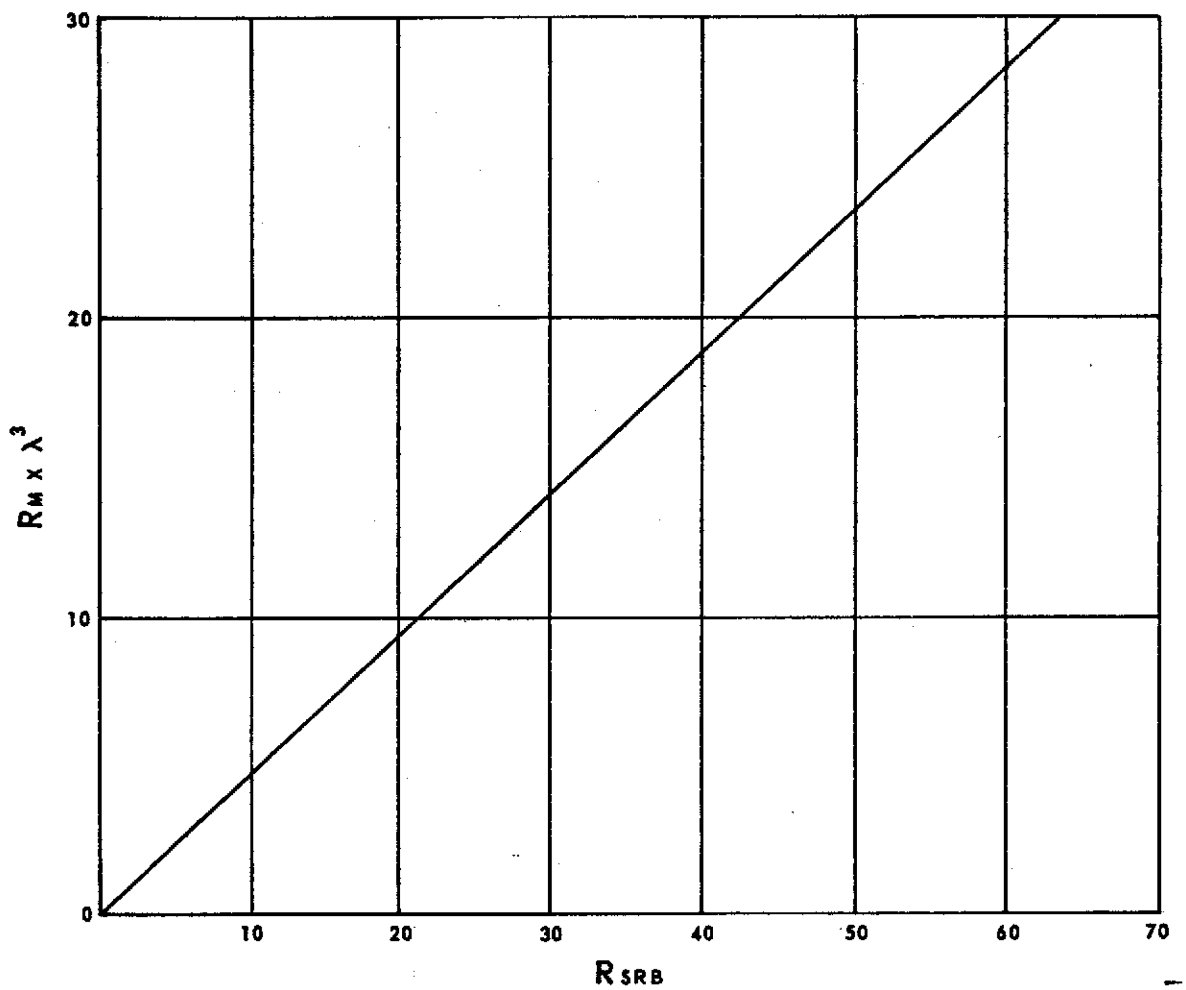

Figure 48. Model Versus Full Scale Loads

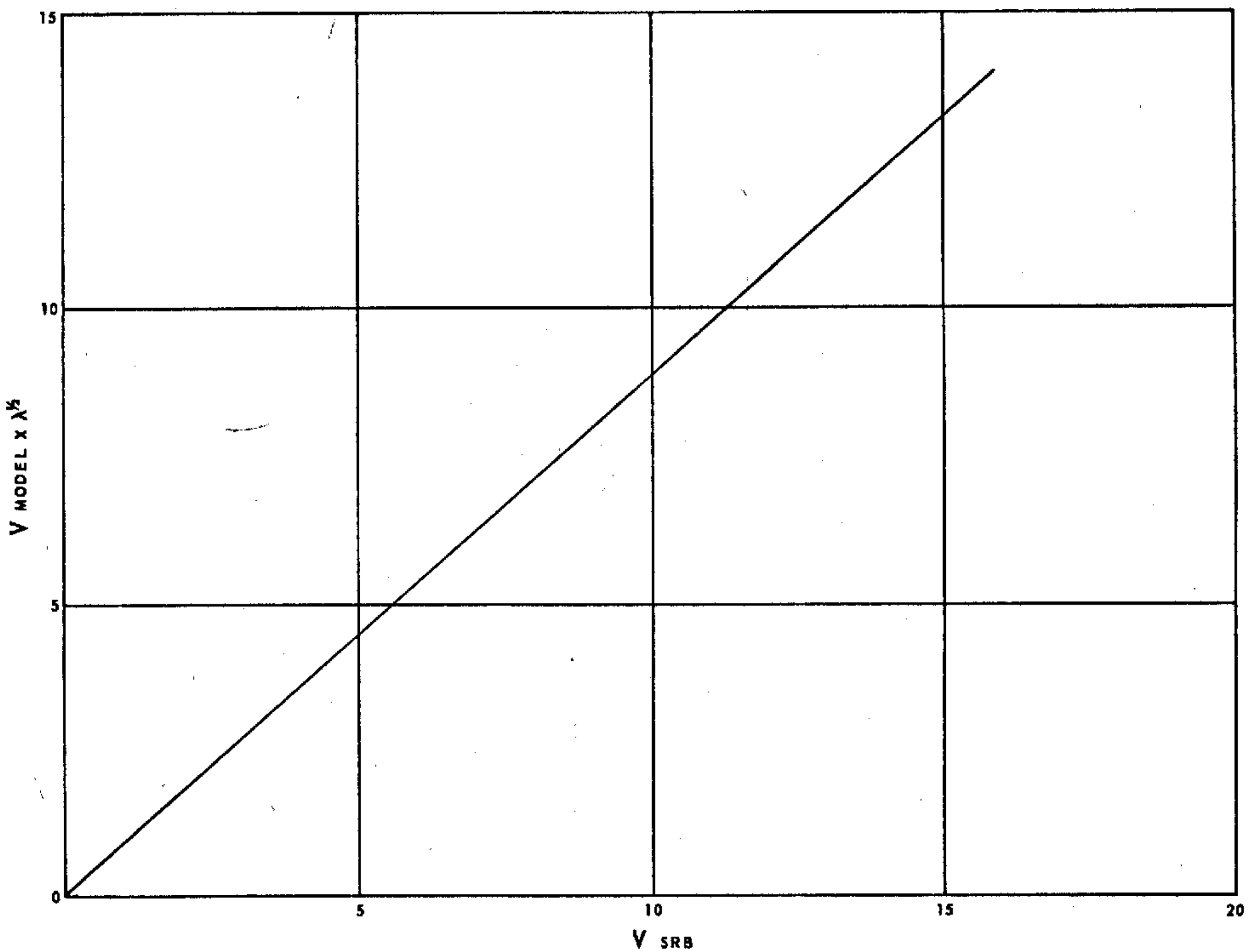

Figure 49. Model and Full Scale Corresponding Speeds

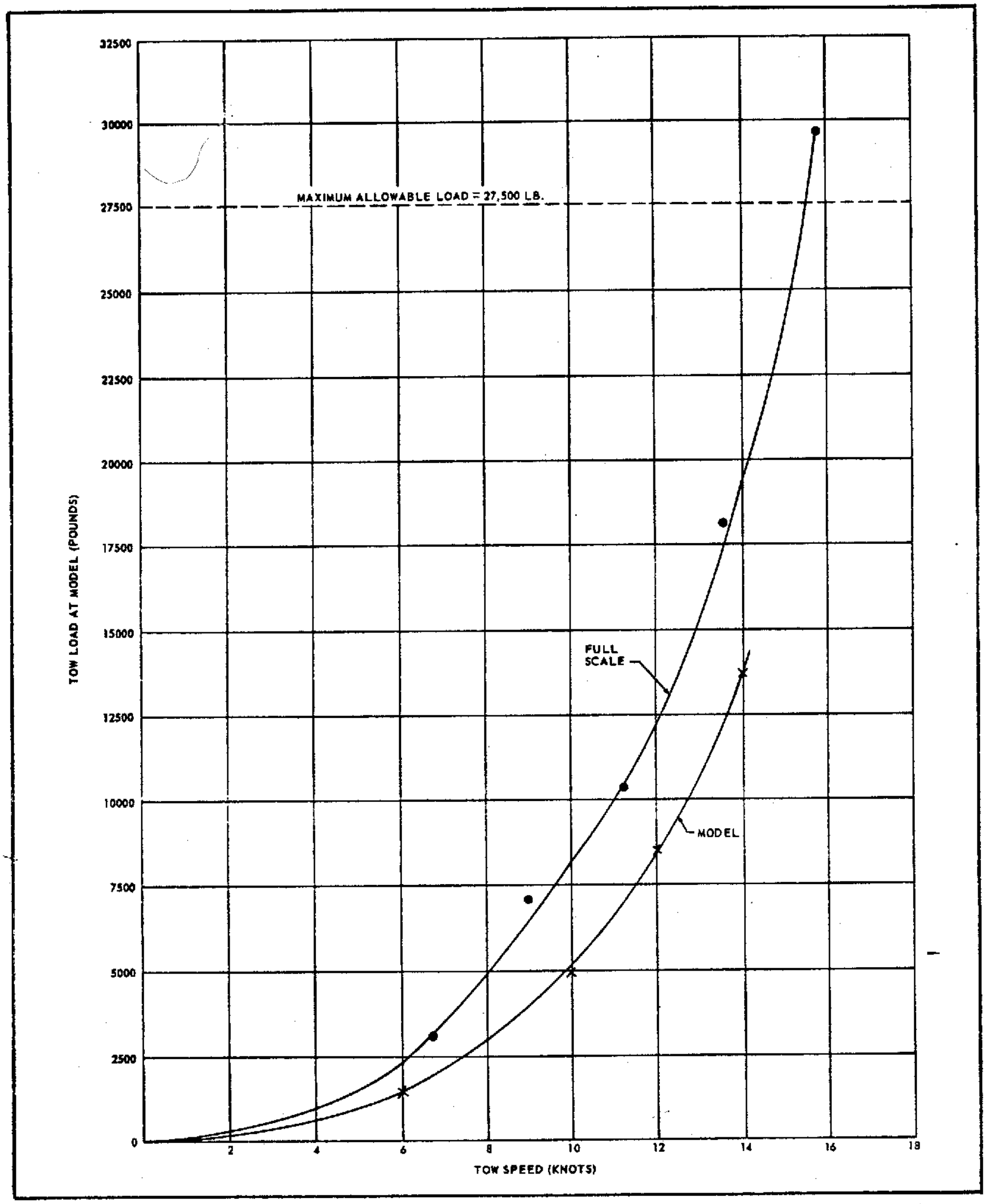

Figure 50. Model and Full Scale Tow Line Loads Versus Tow Speeds Using 7-Inch-Circumference Nylon Line