Report 4335

HYDRODYNAMIC STABILITY EVALUATION OF AN 0.088-SCALE SOLID ROCKET BOOSTER MODEL

NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER
Bethesda, Maryland 20034

HYDRODYNAMIC STABILITY EVALUATION OF AN 0.088-SCALE SOLID ROCKET BOOSTER MODEL

by

John F. Campbell

SHIP PERFORMANCE DEPARTMENT
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Naval Ship Research and Development Center

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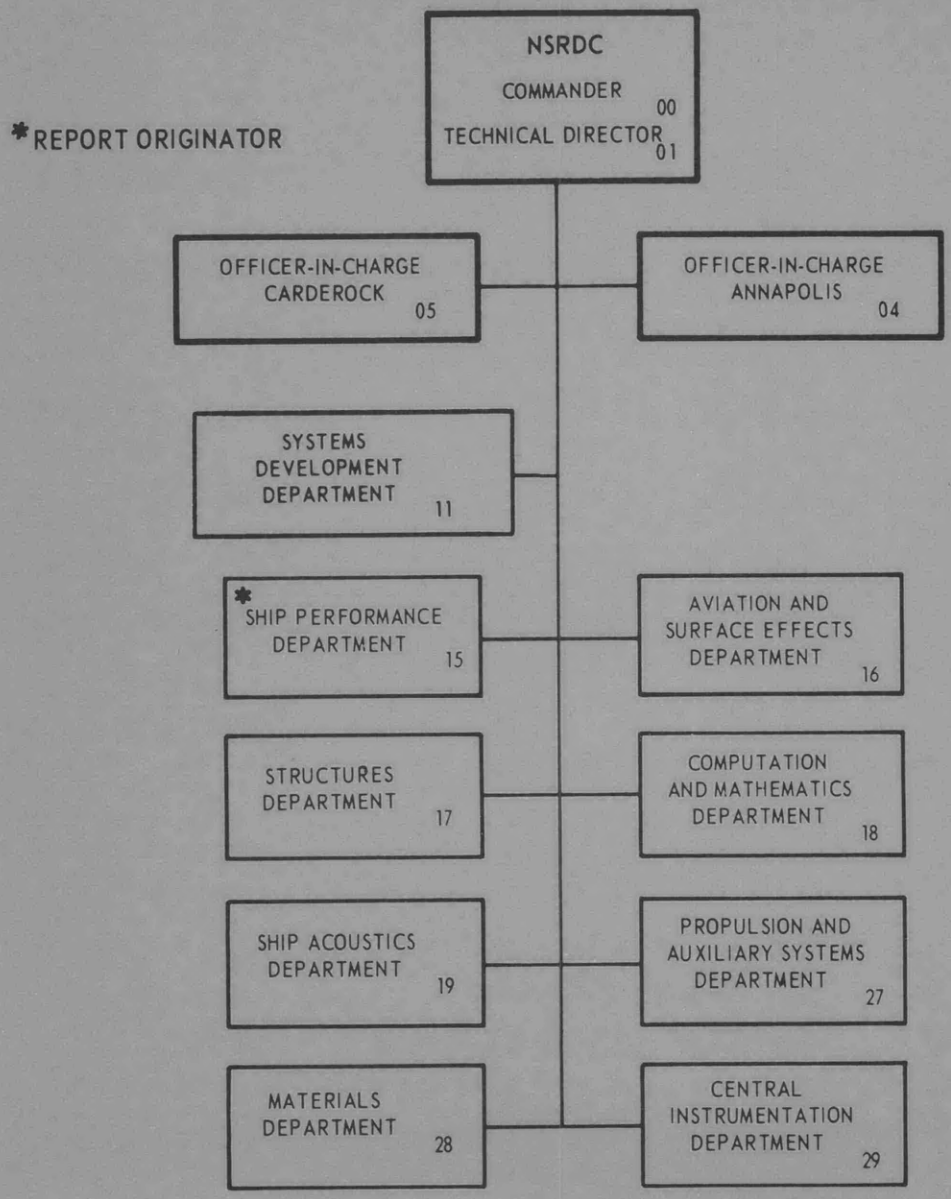

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The free-floating and towing stability of a 0.088-scale Solid Rocket Booster model was experimentally investigated to determine the feasibility of towing a full-scale rocket booster at sea. Equilibrium attitude and towing behavior were examined at various percentages of internal water-fill, sea states, sea directions, towpoint attachments, and towline lengths. Towline tensions were measured, and pitching, rolling, and yawing motions were monitored. Predicted, full-scale values of average and peak towline tension are presented graphically.

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ABSTRACT

The free-floating and towing stability of a 0.088-scale Solid Rocket Booster model was experimentally investigated to determine the feasibility of towing a full-scale rocket booster at sea. Equilibrium attitude and towing behavior were examined at various percentages of internal water-fill, sea states, sea directions, towpoint attachments, and towline lengths. Towline tensions were measured, and pitching, rolling, and yawing motions were monitored. Predicted, full-scale values of average and peak towline tension are presented graphically. Results indicate a stable towing behavior with acceptable towline loads at zero and 10 percent internal water-fill conditions. However, with increasing percentages of water-fill the towing performance is less desirable due to unstable behavior and large towline tensions.

ADMINISTRATIVE INFORMATION

The work described in this report was performed for the National Aeronautics and Space Administration under Purchase Request CC28928A, Naval Ship Research and Development Center Work Unit 1-1548-035.

INTRODUCTION

The Naval Ship Research and Development Center (NSRDC) was requested by the National Aeronautics and Space Administration, Kennedy Space Center (NASA/KSC) to conduct experimental stability evaluations on an 0.088-scale model of a Solid Rocket Booster (SRB) candidate design to establish the feasibility of towing the SRB at sea. The stability characteristics, both free-floating and under tow, were to be examined under controlled-flooding and free-flooding conditions.

The first manned orbital flight of the Space Shuttle will take place in 1978 under the sponsorship of NASA. As presently conceived, the Space Shuttle system will consist of an orbiter, and external propellant droptank, and two parallel-burn solid rocket boosters. The Space Shuttle is the first step in the evolution of a reusable space transportation system. Potentially reusable items are the orbiter and the SRBs. The SRBs are jettisoned and parachuted to the ocean's surface after the system has reached a preselected velocity. For the Space Shuttle system to be economically feasible, methods must be devised to recover the SRBs after splashdown. NASA/KSC has been assigned the responsibility for recovering the SRBs after splashdown.

In support of the KSC responsibility, NSRDC conducted stability experiments of an SRB model in two phases. The first phase focused on the free-floating stability in calm water with various percentages of internal water-fill ranging from zero to 85 percent. The second phase consisted of towing experiments under controlled-flooding and free-flooding conditions

for various towpoint attachments, towline lengths, sea states, and sea directions. Towcable tensions were measured, and rolling, pitching, and yawing motions were monitored.

This report describes the model, the instrumentation system, and the experimental procedures. It presents the free-floating stability results graphically for several internal water-fill percentages between zero and 85 percent. Towcable tensions measured in the towing experiments are presented graphically as a function of speed for all of the model configurations. The towing behavior of the model is described in terms of the effects of variations of each parameter. These results are used to establish conditions for obtaining the best performance when the SRB is towed at sea.

MODEL DESCRIPTION

An overall profile view of the Solid Rocket Booster model appears as Figure 1. The physical characteristics of the model and a corresponding full-scale SRB are identified in Table 1.

TABLE 1 – PHYSICAL CHARACTERISTICS OF THE MODEL AND THE CORRESPONDING FULL-SCALE SRB

	Model	Full-Scale
Linear scale ratio	11.36	1.0
Overall length, feet	11.75	133.5
Nominal diameter, feet	1.0	11.4
Nozzle skirt outside diameter, feet	1.88	21.4
Weight in air, pounds	110.75	162,516
Volume displacement, cubic feet	7.65	11,226
Internal floodable volume, cubic feet	7.30	10,712
Longitudinal center of gravity aft of forward bulkhead, feet	5.54	63.0
Vertical center of gravity below longitudinal centerline, feet	0.0	0.0
Pitch moment of inertia about center of gravity, slug-feet squared	42.17	7,978,004

The SRB model is constructed of 1/16-in. aluminum. The main body consists of four right circular cylindrical sections joined together at inside rib-like flanges. The nosepiece is a conical frustrum joined to the forward cylindrical section at a solid bulkhead. It represents the parachute storage area in the full-scale SRB configuration. The tailpiece, which is a single unit comprising the nozzle and a flared protective skirt, is shown in Figure 2. The open-nozzle throat provides access for water intake to the model interior. The model was sealed at all

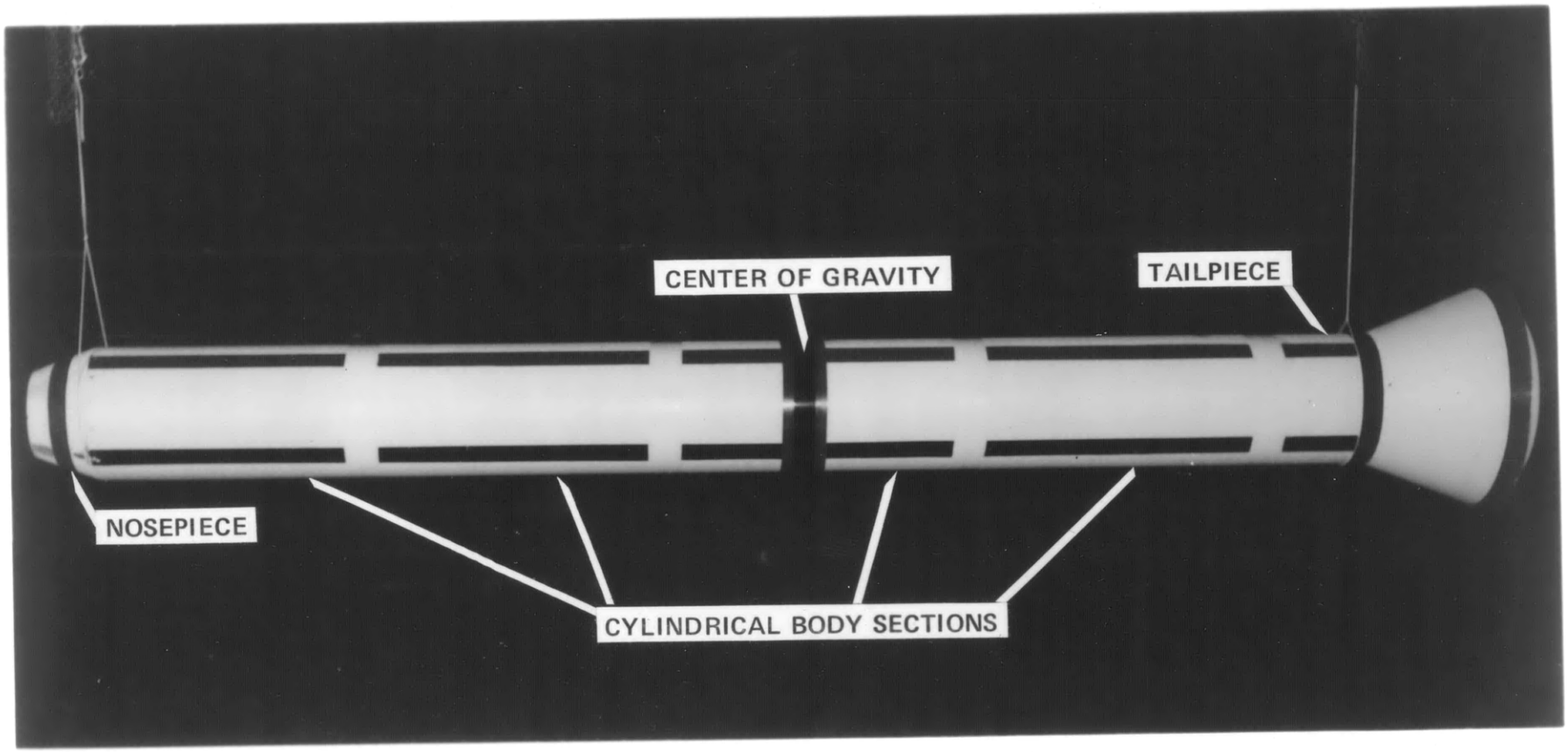

Figure 1 – Overall Profile View of the 0.088-Scale Solid Rocket Booster Model

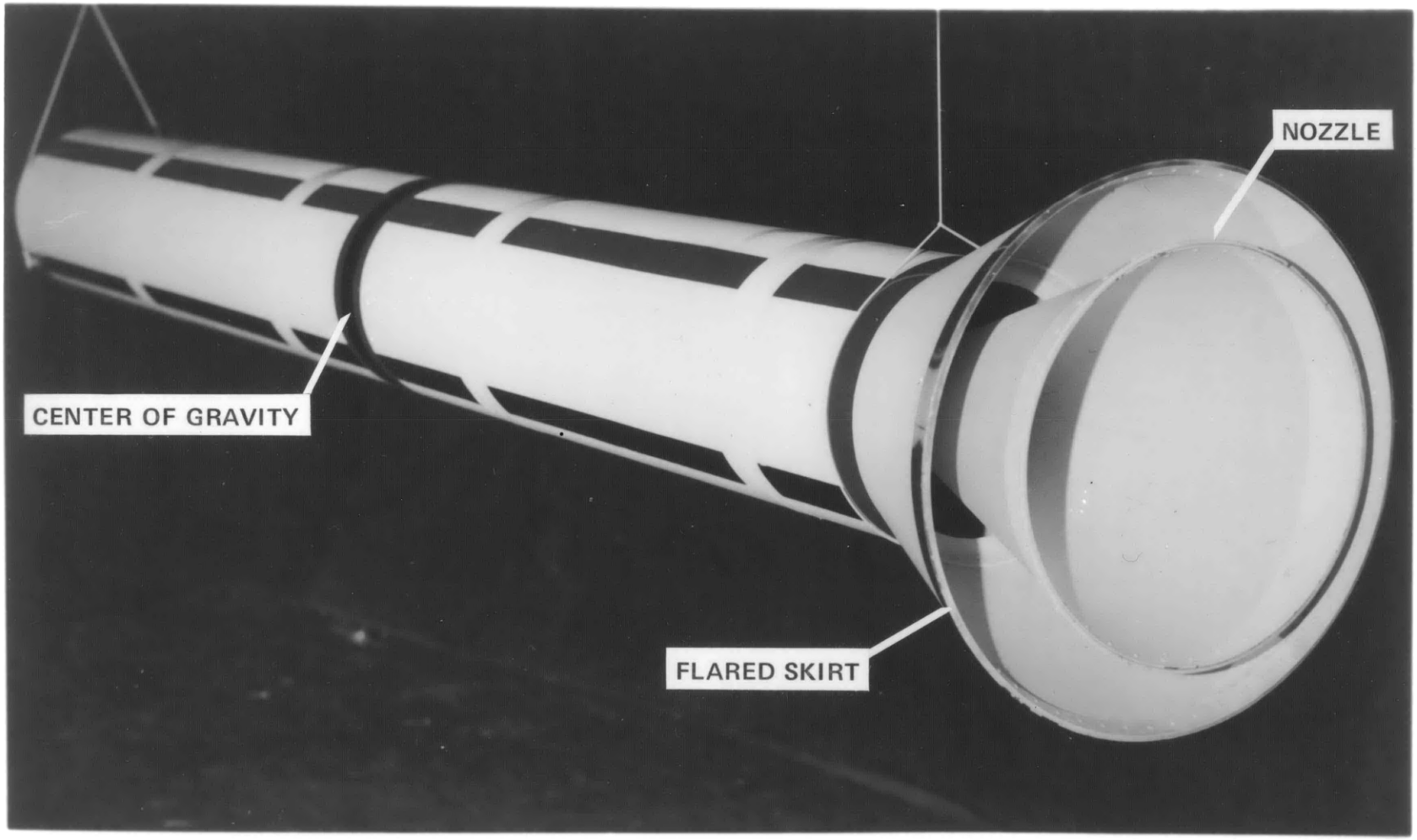

Figure 2 – Quarter Aft View of the 0.088-Scale Solid Rocket Booster Model

external joints to maintain watertight integrity, and the nozzle throat was sealed with a removable polyurethane plug to permit controlled flooding as required.

Both a single towpoint and a bridle arrangement were investigated in the experiments. An eyebolt mounted to the forward bulkhead on the model longitudinal axis (shown in Figure 3) served as the single towpoint. The bridle connection consisted of two aluminum brackets mounted 180 degrees apart on the outside circumference of the forward bulkhead. The bridle ends were attached to the brackets and the towline was attached to the bridle apex.

The SRB model was ballasted to properly scale three static trim parameters: (1) center of gravity (CG) location; (2) total weight in air; and (3) pitch moment of inertia relative to the CG location. The model and full-scale values of these parameters are identified in Table 1.

INSTRUMENTATION

Towline loads and attitude motions of the SRB model were measured by two instrumentation systems. The load measuring system comprised a strain-gage-bridge ring dynamometer and a signal-conditioning control unit. The motion measurement system consisted of a rate gyro assembly mounted in the model and demodulator-integrator circuitry.

The strain-gage bridge-ring dynamometer is a four-active-arm unit with a 200-pound force-measurement capacity. The signal conditioning control unit provides bridge power, calibration voltages, and signal gain. Both strip chart and magnetic tape recorders were provided for tension measurements. The overall system accuracy was ±1 pound.

The rate gyro assembly contained three orthogonally mounted, subminiature, fluid-filled Kearfott rate gyros. Integrating circuitry was provided to obtain relative angular displacements. Strip chart and magnetic tape recorders were used to monitor signals from the gyros. The mean accuracy of this measurement system, taking into account the accuracy and drift rate of the gyros and the accuracy of the integration circuitry, was ±1.5 degrees.

EXPERIMENTAL PROCEDURES

The experimental procedures for the free-floating experiments and the towing exepriments are described below.

FREE-FLOATING EXPERIMENTS

The free-floating stability evaluations in calm water were conducted in the Circulating Water Channel. Free-floating stability was examined for water-fill conditions from zero to 85 percent of the total floodable volume in fill increments of 5 percent. In each case, the model was placed in the water initially either horizontally, nose down, or nose up and the resulting equilibrium attitude was observed.

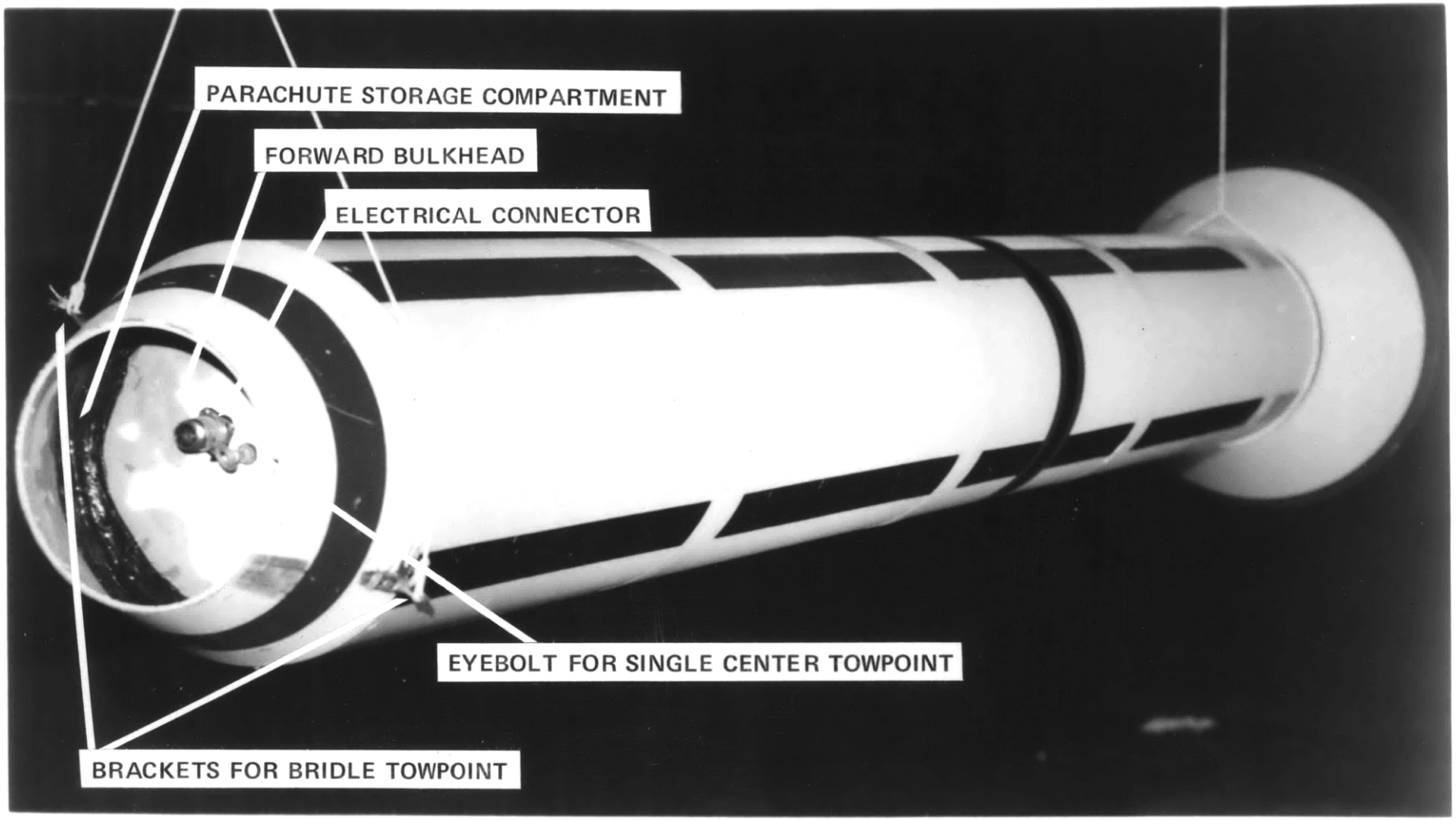

Figure 3 – Quarter Front View of the 0.088-Scale Solid Rocket Booster Model

TOWING EXPERIMENTS

The towing experiments were conducted in the Maneuvering and Seakeeping (MASK) facility with the towing arrangement shown in Figure 4. The model was towed from a single strut extending vertically beneath the carriage to provide a towpoint approximately one foot above the water surface.

The towing parameters investigated are listed in Table 2. In most cases these parameters were independently varied.

TABLE 2 – PARAMETER IDENTIFICATION FOR THE TOWING EXPERIMENTS

Parameter	Model	Full-Scale
Towpoint Attachment	Single Center; Bridle	Single Center; Bridle
Towline Length, feet	23, 46	261.4, 522.8
Towline Type	3/16-in. diameter nylon rope	2 1/4-in. diameter double braided nylon
Water Fill, percent	0, 10, 20, 30, 40, 55, 65, free-flooding	0, 10, 20, 30, 40, 55, 65, free-flooding
Towing Speed, knots	0.7, 1.4, 2.1, 2.8, 3.5, 4.2	2.36, 4.72, 7.08, 9.44 11.80, 14.16
Sea State	Calm Water, 3, 4, 5	Calm Water, 3, 4, 5
Direction of Seas	Head, Bow, Following	Head, Bow, Following

To generate scaled sea-states, a single bank of wavemakers was used. Various directional seas were obtained by varying the angle of the bridge structure, along which the towing carriage travels, relative to the bank of wavemakers. Sea states were represented by scaling the significant wave height, $h_{1/3}$, and the wave period, T, for the maximum energy of a spectrum of random irregular waves (significant wave height is defined as the average height of the highest one-third of a sample of waves). The significant wave height and period were scaled linearly by λ and $\sqrt{\lambda}$, respectively, where λ represents the linear scale ratio of 11.36 for the model. Model and full-scale values of $h_{1/3}$ and T for sea states 3, 4, and 5 are listed in Table 3.

FREE-FLOATING STABILITY RESULTS

The free-floating stability experiments indicated two behavioral patterns. At internal water-fill conditions from zero to 40 percent, the model maintained a relatively horizontal attitude with pitch angles ranging from 1.5 degrees nose-up at zero percent water-fill to 7.5 degrees nose-up at 40 percent. This behavior is graphically illustrated in Figure 5. At internal water-fill conditions from 45 to 85 percent, the model assumed a vertical attitude. Under these conditions, as illustrated in Figure 6, the equilibrium attitude depended on the

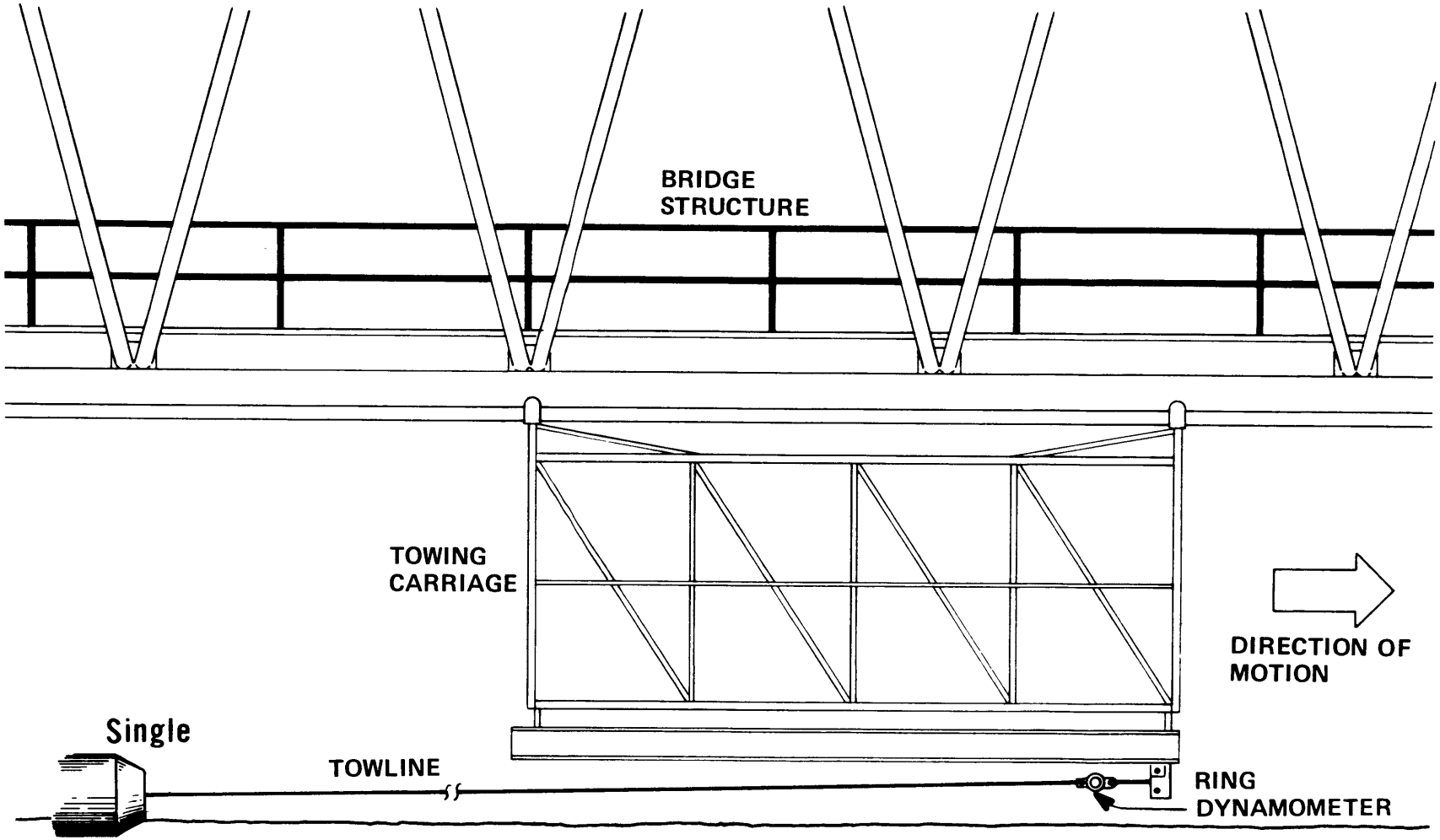

Figure 4 – General Towing Arrangement

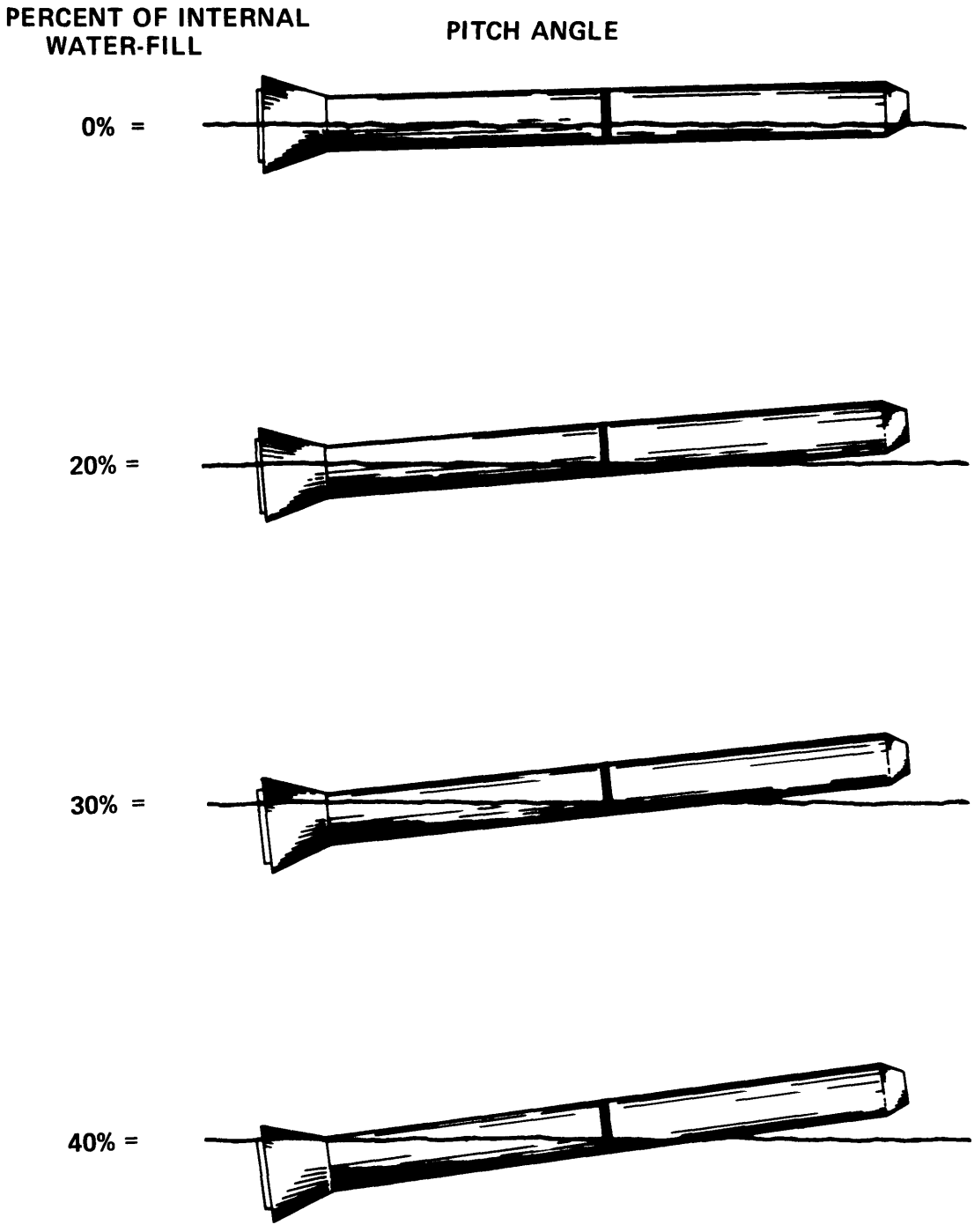

Figure 5 – Free-Floating Attitude of SRB in Calm Water at Water-Fill Conditions from Zero to 40 Percent

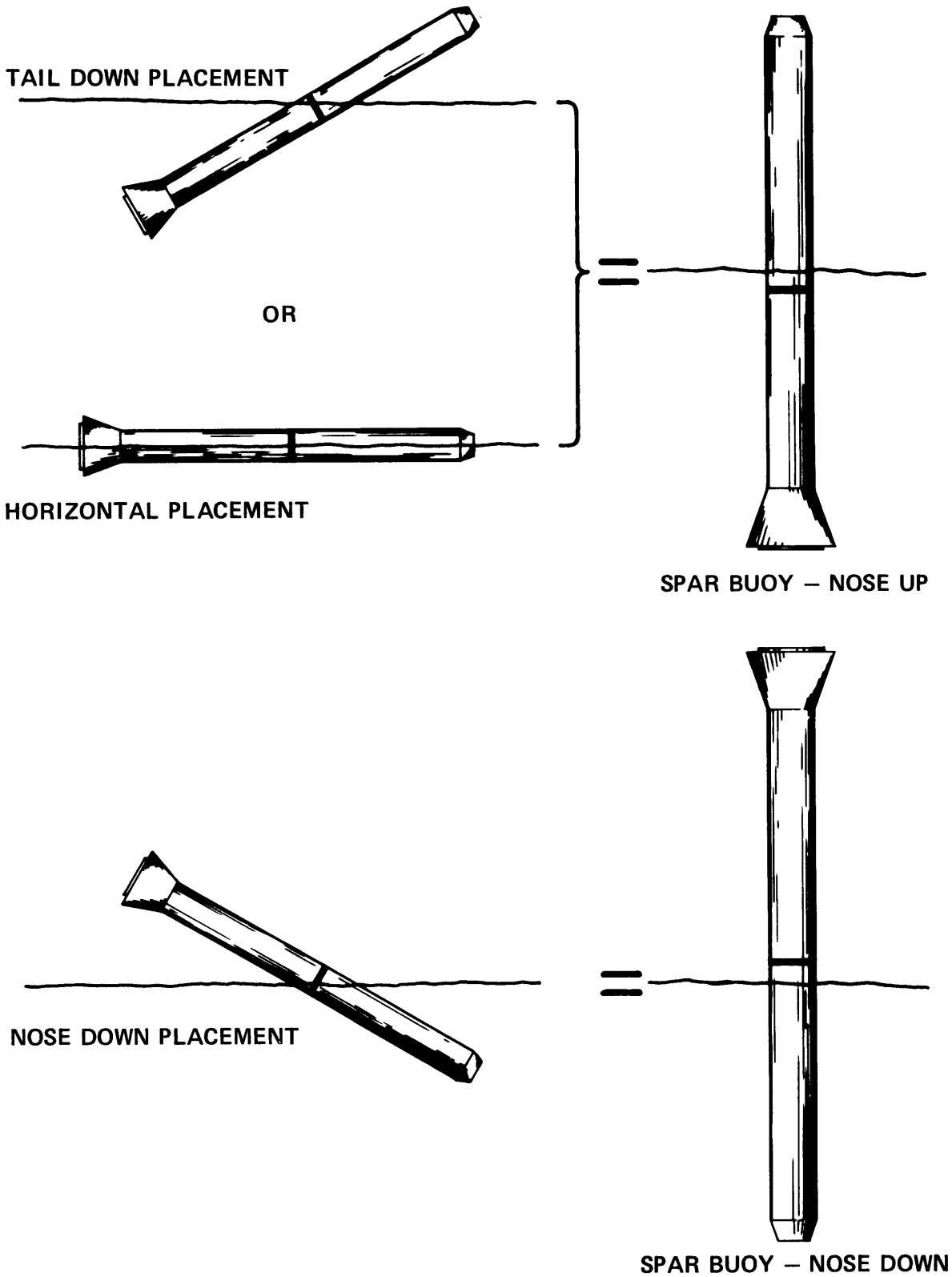

Figure 6 – Free-Floating Attitude of SRB in Calm Water at Water-Fill Conditions from 45 to 85 Percent

TABLE 3 – SIGNIFICANT WAVE HEIGHTS AND PERIODS FOR SEA STATES 3, 4, AND 5

Sea State	Model		Full-Scale	
	$h_{1/3}$, ft	T sec	$h_{1/3}$, ft	T sec
3	0.61	2.2	6.9	7.4
4	0.88	2.6	10.0	8.8
5	1.17	3.0	13.3	10.1

placement of the model in the water. If the model was placed nose-down the resulting attitude was nose-down. However, when placed horizontally or tail down, the model always assumed a nose-up attitude. At 86 percent water-fill the model sank. The overall behavior in the free-floating experiments is graphically summarized in Figure 7.

TOWING RESULTS

The effects of the various experimental parameters on the towline tensions and on the towing stability are discussed below.

TOWLINE TENSION

Predicted full-scale values of average and peak towline tensions for all of the model configurations examined are tabulated in Appendix A. These results are summarized in Figure 8 which graphically presents predicted full-scale average towline tension as a function of speed. For each shaded region in Figure 8, the lower boundaries represent tensions developed in calm water and in a sea state 3 in following seas; the middle portion of the regions represent tensions in sea states 4 and 5 in following seas, and in sea state 3 in head and bow seas; the upper boundaries apply to tensions in sea states 4 and 5 in head and bow seas.

TOWING STABILITY

The following paragraphs describe the towing behavior of the SRB as a function of each parameter variation.

Towline Attachment and Towline Length

Neither towline attachment, single point or bridle, nor towline length had any noticeable effect on towing behavior.

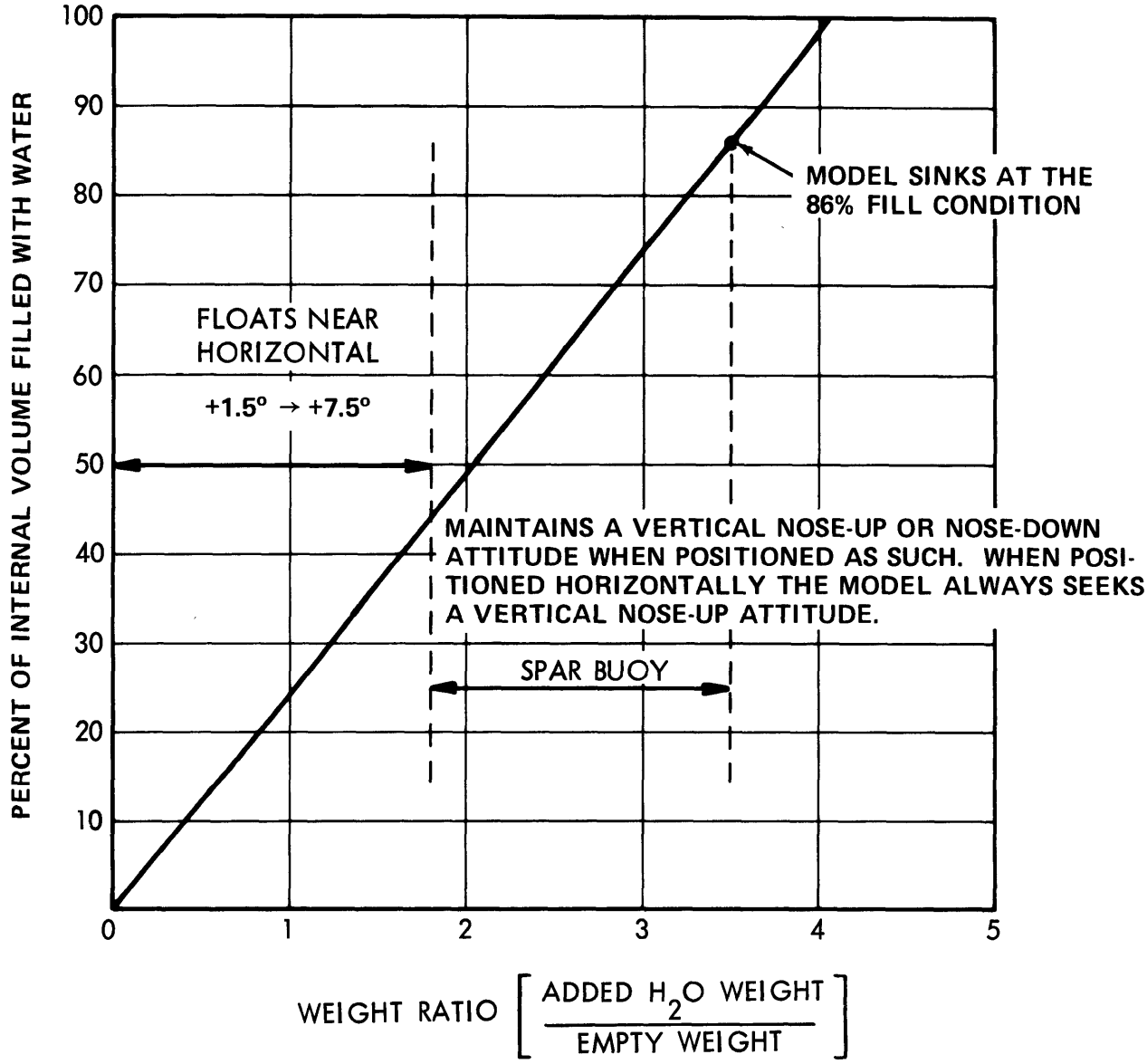

Figure 7 – Controlled Flooding/Free-Floating Stability Summary

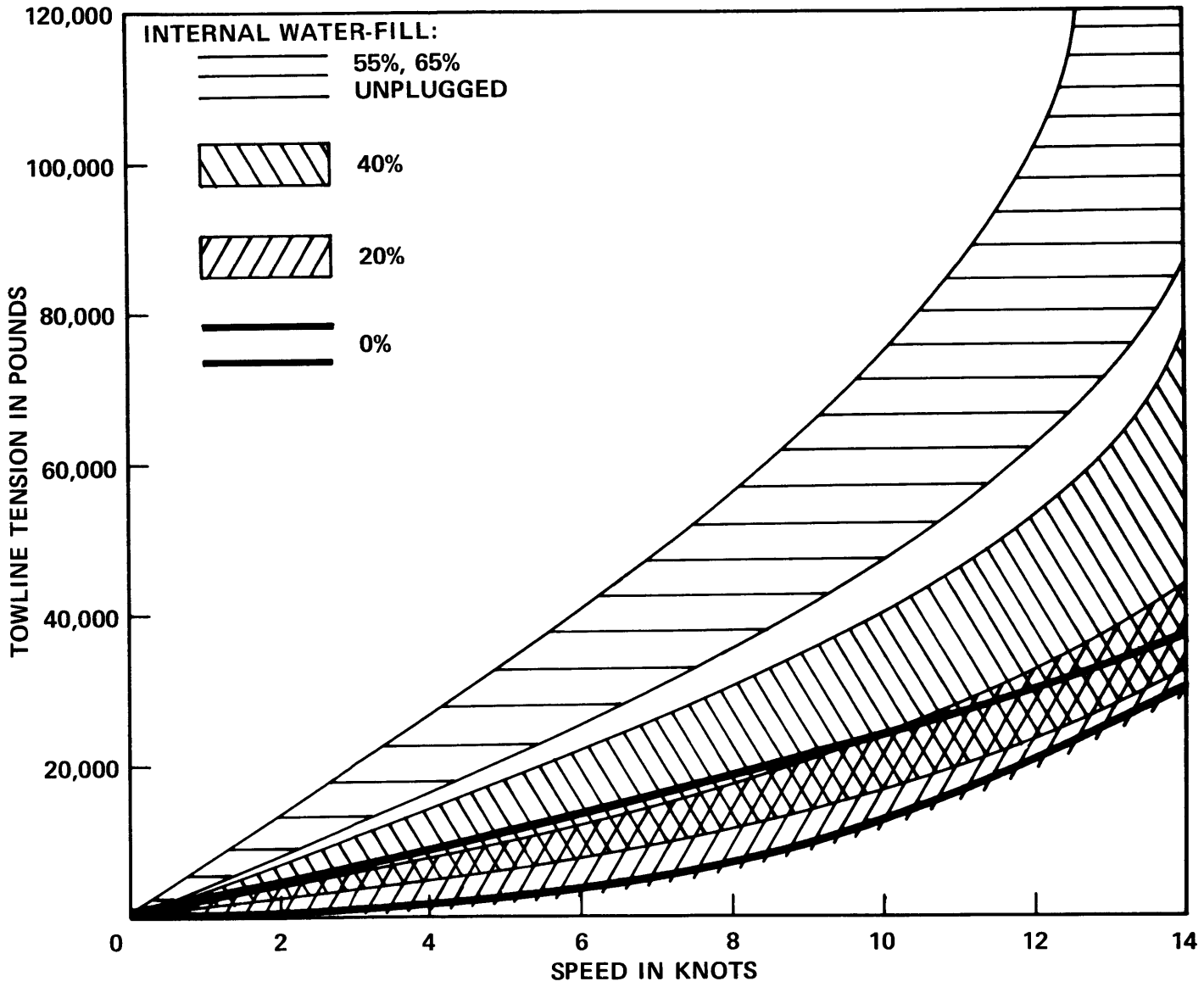

Figure 8 – Predicted Full-Scale Average Towline Tension for Various Internal Water-Fills as a Function of Speed for All Towpoints, Towline Lengths, Sea States, and Direction of Seas

Towing Speed

Increased towing speed had the effect of amplifying any unstable towing behavior. Otherwise towing speed did not significantly affect model stability up to certain limits which were influenced by the water-fill condition. The maximum stable towing speed for the various water-fill conditions is described in the next paragraph.

Internal Water-Fill

The model towed satisfactorily at all internal water-fill conditions except 30 and 40 percent. At zero and 10 percent a stable straight line tow was maintained up to a full-scale speed of 14 knots, the maximum speed investigated. At 20 percent water-fill a straight line tow was maintained up to a speed of 12 knots; above this speed the model would not tow astern. At 30 and 40 percent the behavior was stable up to 10 knots; above this speed the model assumed a large (approximately 45 degrees) nose-down attitude with the flared skirt coming completely out of the water. This resulted in large oscillatory yawing and rolling motions with subsequent large lateral divergent motions. In this condition the horizontal towline angle with respect to the direction of tow oscillated between peak values of approximately ±45 degrees. At internal water-fill conditions of 55 and 65 percent, the SRB again maintained stable straight line tows to 14 knots, but the corresponding towline tensions were approximately double the tensions at any other water-fill condition.

Towline tensions with the nozzle throat unplugged were comparable to the tensions at the 55 and 65 percent water-fill conditions. The towing behavior was stable and a straight line tow was maintained except in bow and following seas at speeds above 12 knots. Under these conditions, the SRB again assumed a nose-down attitude with the nozzle skirt coming completely out of the water with resultant large amplitude rolling, yawing, and lateral divergent motions. With the nozzle throat open, this behavior allowed the model to take on an indeterminate amount of water, particularly in higher sea states, posing the threat of the SRB sinking.

Sea State and Direction of Sea

With increasing sea states, pitching, yawing, and heaving motions increased and the unstable behavior previously noted at water-fill conditions of 30 and 40 percent was amplified.

For a given sea condition, the largest pitching and heaving motions were observed in head seas; these motions were significantly smaller in following seas. In bow seas, yawing motions as well as pitching and heaving were large, with the most erratic behavior occurring at zero and 10 percent water-fill conditions.

CONCLUSIONS

The following conclusions are drawn on the basis of the results of the model experiments.

1. The free-floating attitude of the SRB will change from horizontal to vertical between 40 and 50 percent internal water-fill. The SRB will sink at approximately 86 percent water-fill.

2. The SRB configured with the flared nozzle skirt will maintain an acceptably stable, straight line tow with internal water-fill conditions of zero and 10 percent.

3. The SRB towing performance will be degraded at internal water-fill conditions greater than 30 percent due to unstable towing behavior and large towline tensions.

4. The SRB towing stability will decrease with decreasing submergence of the nozzle skirt.

5. Towing the SRB with the nozzle throat unplugged is not desirable because of the large towing tensions and the unstable behavior in bow and following seas at speeds above 12 knots.

APPENDIX A

PREDICTED FULL-SCALE VALUES OF AVERAGE AND PEAK TOWLINE TENSIONS

TABLE A1 – PREDICTED FULL-SCALE VALUES OF AVERAGE AND PEAK TOWLINE TENSIONS IN CALM WATER WITH THE SINGLE-CENTER TOWPOINT

216.4 FEET TOWLINE LENGTH			
Volume of Internal Water, percent	Towing Speed knots	Average Tensions, lb	Peak Tensions, lb
0	2.36	--	--
	4.72	2,935	2,935
	7.08	6,603	8,804
	9.44	13,207	17,608
	11.80	21,277	24,946
	14.16	29,348	36,685
10	2.36	--	--
	4.72	1,467	1,467
	7.08	7,337	8,804
	9.44	13,027	13,027
	11.80	24,946	24,946
	14.16	30,816	30,816
20	2.36	--	--
	4.72	2,935	4,402
	7.08	5,870	7,337
	9.44	14,674	14,674
	11.80	22,011	22,011
	14.16	26,413	26,413
30	2.36	--	--
	4.72	2,935	2,935
	7.08	7,337	7,337
	9.44	14,671	16,142
	11.80	20,543	22,011
	14.16	23,479	24,946
40	2.36	734	734
	4.72	5,870	7,337
	7.08	27,147	27,881
	9.44	11,739	14,674
	11.80	19,076	24,946
	14.16	36,685	61,631

522.8 FEET TOWLINE LENGTH			
Volume of Internal Water, percent	Towing Speed knots	Peak Tensions, lb	Average Tensions, lb
0	2.36	0	0
	4.72	1,467	1,467
	7.08	4,402	5,870
	9.44	11,739	13,207
	11.80	16,875	19,076
	14.16	16,413	29,348
10	2.36	0	0
	4.72	1,467	2,935
	7.08	4,402	5,870
	9.44	11,006	11,739
	11.80	20,544	20,544
	14.16	25,680	26,413
20	2.36	0	0
	4.72	1,467	1,467
	7.08	4,402	4,402
	9.44	14,674	14,674
	11.80	20,544	20,544
	14.16	23,479	23,479
30	2.36	1,467	1,467
	4.72	2,935	2,935
	7.08	4,402	4,402
	9.44	11,739	13,207
	11.80	16,875	17,609
	14.16	35,218	48,425
40	2.36	2,201	2,201
	4.72	7,337	7,337
	7.08	16,141	27,881
	9.44	13,207	55,762
	11.80	26,413	32,283

TABLE A2 – PREDICTED FULL-SCALE VALUES OF AVERAGE AND PEAK TOWLINE TENSIONS IN CALM WATER WITH THE BRIDLE TOWPOINT

261.4 FEET TOWLINE LENGTH			
Volume of Internal Water, percent	Towing Speed, knots	Average Tensions, lb	Peak Tensions, lb
0	2.36	734	734
	4.72	2,935	2,935
	7.08	6,603	8,804
	9.44	12,473	16,142
	11.80	20,544	20,544
	14.16	26,413	35,218
10	2.36	734	734
	4.72	2,935	2,935
	7.08	5,870	7,337
	9.44	11,739	14,674
	11.80	23,479	26,413
	14.16	29,348	30,816
20	2.36	2,935	2,935
	4.72	5,870	5,870
	7.08	8,804	8,804
	9.44	19,076	19,076
	11.80	27,881	27,881
	14.16	30,816	30,816
30	2.36	4,402	4,402
	4.72	8,804	8,804
	7.08	11,739	11,739
	9.44	19,076	19,076
	11.80	24,946	24,946
	14.16	29,348	29,348
40	2.36	4,402	4,402
	4.72	8,804	8,804
	7.08	13,206	14,674
	9.44	17,609	17,609
	11.80	24,946	30,816
	14.16	52,827	102,719
55	2.36	14,674	17,609
	4.72	19,076	20,544
	7.08	29,348	32,283
	9.44	40,425	51,359
	11.80	77,773	82,175
	14.16	117,372	120,328

522.8 FEET TOWLINE LENGTH			
Volume of Internal Water, percent	Towing Speed, knots	Average Tensions, lb	Peak Tensions, lb
0	2.36	734	734
	4.72	2,935	2,935
	7.08	7,337	8,804
	9.44	13,206	14,674
	11.80	20,544	22,011
	14.16	27,881	32,283
10	2.36	1,467	1,467
	4.72	4,402	4,402
	7.08	7,337	8,804
	9.44	13,206	14,674
	11.80	23,478	23,478
	14.16	29,348	29,348
20	2.36	734	734
	4.72	3,668	3,668
	7.08	7,337	7,337
	9.44	16,142	16,142
	11.80	23,478	23,478
	14.16	27,881	27,881
30	2.36	734	734
	4.72	5,136	5,136
	7.08	8,804	8,804
	9.44	16,142	19,076
	11.80	22,011	23,478
	14.16	36,685	70,436

TABLE A3 – PREDICTED FULL-SCALE VALUES OF AVERAGE AND PEAK TOWLINE TENSIONS IN HEAD SEAS AT A SEA STATE 4 WITH THE SINGLE-CENTER TOWPOINT

261.4 FEET TOWLINE LENGTH			
Volume of Internal Water, percent	Towing Speed, knots	Average Tensions, lb	Peak Tensions, lb
0	2.36	1,467	2,935
	4.72	4,402	8,804
	7.08	8,804	16,142
	9.44	17,609	32,283
	11.80	23,478	42,555
	14.16	29,348	45,490
20	2.36	2,935	8,804
	4.72	7,337	14,674
	7.08	11,739	17,609
	9.44	17,609	29,348
	11.80	26,413	39,620
	14.16	29,348	39,620
40	2.36	2,935	11,739
	4.72	14,674	24,946
	7.08	29,348	36,685
	9.44	58,696	73,371
	11.80	36,686	64,566
	14.16	66,033	143,806
55	2.36	14,674	35,218
	4.72	20,544	39,620
	7.08	32,283	46,957
	9.44	61,631	76,305
	11.80	88,045	105,654
522.8 FEET TOWLINE LENGTH			
0	2.36	734	1,467
	4.72	2,935	5,870
	7.08	8,804	17,608
	9.44	14,674	22,011
	11.80	23,479	29,348
	14.16	29,348	44,022
20	2.36	1,467	2,935
	4.72	5,870	8,804
	7.08	11,739	14,674
	9.44	17,609	23,479
	11.80	26,413	32,283
	14.16	29,348	36,685
40	2.36	2,935	4,402
	4.72	17,609	23,479
	7.08	20,544	36,685
	9.44	14,674	23,479
	11.80	33,750	41,087
	14.16	51,359	88,045

TABLE A4 – PREDICTED FULL-SCALE VALUES OF AVERAGE AND PEAK TOWLINE TENSIONS IN HEAD SEAS AT A SEA STATE 5 WITH THE SINGLE-CENTER TOWPOINT

261.4 FEET TOWLINE LENGTH			
Volume of Internal Water, percent	Towing Speed, knots	Average Tensions, lb	Peak Tensions, lb
0	2.36	1,467	5,870
	4.72	8,804	19,076
	7.08	14,674	36,685
	9.44	19,076	42,555
	11.80	29,348	58,696
	14.16	32,283	61,631
20	2.36	5,870	13,207
	4.72	10,272	22,011
	7.08	14,674	29,348
	9.44	20,544	41,087
	11.80	26,413	49,892
	14.16	36,685	73,371
40	2.36	7,337	17,609
	4.72	13,206	26,413
	7.08	11,739	23,479
	9.44	17,608	29,348
	11.80	24,946	51,359
	14.16	88,045	120,328
522.8 FEET TOWLINE LENGTH			
0	2.36	734	1,467
	4.72	7,337	11,739
	7.08	13,207	22,011
	9.44	17,609	29,348
	11.80	23,479	41,087
	14.16	29,348	39,620
20	2.36	2,935	5,870
	4.72	5,870	14,674
	7.08	13,207	23,479
	9.44	19,076	32,283
	11.80	23,479	36,685
	14.16	36,685	48,425
40	2.36	2,935	5,870
	4.72	17,609	27,881
	7.08	8,804	14,674
	9.44	29,348	70,436
	11.80	24,946	35,218
	14.16	51,359	110,056

TABLE A5 -- PREDICTED FULL-SCALE VALUES OF AVERAGE AND PEAK TOWLINE TENSIONS IN HEAD SEAS AT A SEA STATE 3 WITH THE BRIDLE TOWPOINT

261.4 FEET TOWLINE LENGTH			
Volume of Internal Water, percent	Towing Speed, knots	Average Tensions, lb	Peak Tensions, lb
0	2.36	1,467	2,935
	4.72	3,668	7,337
	7.08	8,804	14,674
	9.44	16,142	29,348
	11.80	22,011	35,218
	14.16	26,413	41,087
20	2.36	4,402	7,337
	4.72	8,804	14,674
	7.08	13,207	20,544
	9.44	20,544	27,881
	11.80	27,881	35,218
	14.16	36,685	45,490
55	2.36	14,674	36,685
	4.72	23,479	32,283
	7.08	36,685	48,425
	9.44	55,762	70,436
522.8 FEET TOWLINE LENGTH			
40	2.36	2,935	4,402
	4.72	10,272	13,207
	7.08	11,739	16,142
	9.44	16,142	20,544
	11.80	26,413	39,620
	14.16	58,696	76,305

TABLE A6 – PREDICTED FULL-SCALE VALUES OF AVERAGE AND PEAK TOWLINE TENSIONS IN HEAD SEAS AT A SEA STATE 4 WITH THE BRIDLE TOWPOINT

261.4 FEET TOWLINE LENGTH			
Volume of Internal Water, percent	Towing Speed, knots	Average Tensions, lb	Peak Tensions, lb
0	2.36	1,467	2,935
	4.72	5,869	10,272
	7.08	11,739	29,348
	9.44	16,142	32,283
	11.80	22,011	35,218
	14.16	29,348	45,490
20	2.36	4,402	8,804
	4.72	10,272	13,206
	7.08	17,609	26,413
	9.44	23,478	30,816
	11.80	29,348	41,087
	14.16	32,283	44,022
55	2.36	20,543	41,087
	4.72	24,946	44,022
	7.08	36,685	48,425
	9.44	61,631	76,305
522.8 FEET TOWLINE LENGTH			
0	2.36	1,467	1,467
	4.72	2,935	5,870
	7.08	11,739	17,609
	9.44	19,076	23,479
	11.80	23,479	35,218
	14.16	30,816	41,087
20	2.36	1,467	2,935
	4.72	7,337	10,272
	7.08	11,739	19,076
	9.44	17,609	26,413
	11.80	22,011	29,348
	14.16	29,348	35,218
40	2.36	4,402	5,870
	4.72	11,739	14,674
	7.08	10,272	13,207
	9.44	19,076	24,946
	11.80	26,413	33,750
	14.16	68,968	101,251
65	4.72	29,348	41,807
	7.08	41,087	51,359
	9.44	58,696	66,033
	11.80	99,794	121,795

TABLE A7 -- PREDICTED FULL-SCALE VALUES OF AVERAGE AND PEAK TOWLINE TENSIONS IN HEAD SEAS AT A SEA STATE 5 WITH THE BRIDGE TOWPOINT

261.4 FEET TOWLINE LENGTH			
Volume of Internal Water, percent	Towing Speed, knots	Average Tensions, lb	Peak Tensions, lb
0	2.36	1,467	5,870
	4.72	8,804	26,413
	7.08	14,674	30,816
	9.44	22,011	51,359
	11.80	26,413	52,827
	14.16	30,816	58,696
20	2.36	4,402	14,674
	4.72	10,272	26,413
	7.08	16,141	29,348
	9.44	23,479	36,685
	11.80	29,348	41,087
	14.16	36,685	52,827
55	2.36	19,076	29,348
	4.72	26,413	46,957
	7.08	41,087	61,631
522.8 FEET TOWLINE LENGTH			
0	2.36	1,467	2,935
	4.72	5,870	14,674
	7.08	11,739	19,076
	9.44	17,609	26,413
	11.80	26,413	41,087
	14.16	29,348	44,022
20	2.36	2,935	5,870
	4.72	7,337	14,674
	7.08	13,207	19,076
	9.44	17,069	23,479
	11.80	26,413	35,218
	14 16	32,283	45,489
40	2.36	7,337	11,739
	4.72	13,207	19,076
	7.08	14,674	26,413
	9.44	32,283	39,620
	11.80	52,827	67,501
	14.16	61,631	79,240
65	4.72	38,153	61,631
	7.08	49.892	68,968
	9.44	66,033	80,708
	11.80	99,784	146,741

TABLE A8 – PREDICTED FULL-SCALE VALUES OF AVERAGE AND PEAK TOWLINE TENSIONS IN FOLLOWING SEAS AT A SEA STATE 3 WITH THE SINGLE-CENTER TOWPOINT

261.4 FEET TOWLINE LENGTH			
Volume of Internal Water, percent	Towing Speed, knots	Average Tensions, lb	Peak Tensions, lb
0	4.72	5,870	14,674
	7.08	10,272	24,946
	9.44	14,674	26,413
	11.80	22,011	29,348
	14.16	29,348	41,087
20	4.72	11,739	20,544
	7.08	14,674	32,283
	9.44	20,544	39,620
	11.80	27,881	35,218
	14.16	29,348	35,218
40	4.72	16,142	32,283
	7.08	32,283	54,294
	9.44	60,164	90,979
	11.80	24,946	54,294
	14.16	61,631	82,174
522.8 FEET TOWLINE LENGTH			
0	4.72	8,802	20,538
	7.08	13,203	23,472
	9.44	20,538	39,609
	11.80	24,939	38,142
	14.16	35,208	45,477
20	4.72	7,335	14,670
	7.08	16,269	20,538
	9.44	17,604	29,340
	11.80	26,406	40,944
	14.16	38,142	54,279
40	4.72	11,736	23,472
	7.08	11,736	19,071
	9.44	16,137	44,010
	11.80	20,538	29,340
	14.16	71,883	99,756

TABLE A9 – PREDICTED FULL-SCALE VALUES OF AVERAGE AND PEAK TOWLINE TENSIONS IN FOLLOWING SEAS AT A SEA STATE 4 WITH THE SINGLE-CENTER TOWPOINT

261.4 FEET TOWLINE LENGTH			
Volume of Internal Water, percent	Towing Speed, knots	Average Tensions, lb	Peak Tensions, lb
0	4.72	8,804	17,609
	7.08	17,609	20,544
	9.44	14,674	26,413
	11.80	26,413	54,294
	14.16	29,348	38,153
20	4.72	7,337	20,544
	7.08	19,076	39,620
	9.44	19,076	20,544
	11.80	29,348	41,087
	14.16	29,348	54,294
40	4.72	16,142	35,218
	7.08	33,750	67,500
	9.44	36,685	79,240
	11.80	32,283	64,566
	14.16	45,490	74,838
UNPLUGGED	9.44	24,946	48,425
	11.80	24,947	49,892
522.8 FEET TOWLINE LENGTH			
0	4.72	2,934	8,802
	7.08	10,269	19,071
	9.44	20,538	36,675
	11.80	23,472	36,675
	14.16	30,807	41,076
20	4.72	2,934	17,604
	7.08	11,736	26,406
	9.44	17,604	23,472
	11.80	24,939	48,411
	14.16	29,340	58,680
40	4.72	14,670	23,472
	7.08	26,406	45,477
	9.44	33,741	61,614
	11.80	26,406	49,878
	14.16	58,680	105,624
UNPLUGGED	9.44	51,345	77,751
	11.80	61,614	120,294

TABLE A10 – PREDICTED FULL-SCALE VALUES OF AVERAGE AND PEAK TOWLINE TENSIONS IN FOLLOWING SEAS AT A SEA STATE 5 WITH THE SINGLE-CENTER TOWPOINT

261.4 FEET TOWLINE LENGTH			
Volume of Internal Water, percent	Towing Speed, knots	Average Tensions, lb	Peak Tensions, lb
0	4.72	8,804	17,609
	7.08	11,739	20,544
	9.44	16,142	26,413
	11.80	24,946	48,425
	14.16	32,283	44,022
20	4.72	5,870	20,544
	7.08	14,674	35,218
	9.44	26,413	55,762
	11.80	24,946	39,620
	14.16	29,348	44,022
40	4.72	23,479	51,359
	7.08	29,348	64,566
	9.44	35,218	70,436
	11.80	30,816	66,033
	14.16	66,033	108,588
522.8 FEET TOWLINE LENGTH			
0	4.72	5,868	14,670
	7.08	13,203	33,741
	9.44	17,604	36,675
	11.80	23,472	38,142
	14.16	29,340	46,944
20	4.72	2,934	11,736
	7.08	13,203	29,340
	9.44	17,604	29,340
	11.80	26,406	44,010
	14.16	35,208	61,614
40	4.72	16,137	35,208
	7.08	32,274	57,213
	9.44	26,406	35,208
	11.80	26,406	39,609
	14.16	58,680	89,487

TABLE A11 – PREDICTED FULL-SCALE VALUES OF AVERAGE AND PEAK TOWLINE TENSIONS IN FOLLOWING SEAS AT A SEA STATE 3 WITH THE BRIDLE TOWPOINT

261.4 FEET TOWLINE LENGTH			
Volume of Internal Water, percent	Towing Speed, knots	Average Tensions, lb	Peak Tensions, lb
0	4.72	2,934	8,802
	7.08	16,137	33,741
	9.44	17,604	29,340
	11.80	26,406	55,746
	14.16	29,340	61,614
20	4.72	5,868	19,701
	7.08	11,736	33,741
	9.44	19,701	26,406
	11.80	27,873	39,609
	14.16	29,340	39,609
522.8 FEET TOWLINE LENGTH			
0	4.72	5,868	11,736
	7.08	10,269	22,005
	9.44	14,670	20,538
	11.80	22,005	27,873
	14.16	24,939	30,807
20	4.72	5,868	11,736
	7.08	10,269	20,538
	9.44	17,604	38,142
	11.80	26,406	44,010
	14.16	30,807	58,680
40	4.72	8,802	17,604
	7.08	32,274	44,010
	9.44	22,005	58,680
	11.80	26,406	39,609
	14.16	66,015	115,893

TABLE A12 – PREDICTED FULL-SCALE VALUES OF AVERAGE AND PEAK TOWLINE TENSIONS IN FOLLOWING SEAS AT A SEA STATE 4 WITH THE BRIDLE TOWPOINT

261.4 FEET TOWLINE LENGTH			
Volume of Internal Water, percent	Towing Speed knots	Average Tensions, lb	Peak Tensions, lb
0	4.72	2,934	23,472
	7.08	23,472	46,944
	9.44	24,939	49,878
	11.80	24,939	39.609
	14.16	32,274	39,609
20	4.72	8,802	19,071
	7.08	13,203	27,873
	9.44	20,538	38,142
	11.80	27,873	49,878
	14.16	29,340	49,878
UNPLUGGED	9.44	58,680	117,360
	11.80	80,685	139,365
	14.16	88,020	176,040
522.8 FEET TOWLINE LENGTH			
0	4.72	4,401	10,269
	7.08	13,203	29,340
	9.44	17,604	36,675
	11.80	27,873	52,812
	14.16	30,807	60,147
20	4.72	7,335	13,203
	7.08	11,736	32,274
	9.44	17,604	23,472
	11.80	26,406	49,878
	14.16	33,741	44,010
40	4.72	14,670	23,472
	7.08	29,340	36,675
	9.44	55,746	61,614
	11.80	26,406	44,010
	14.16	70,416	111,492
UNPLUGGED	7.08	10,269	19,071
	9.44	54,279	76,284
	11.80	79,218	110.025

TABLE A13 – PREDICTED FULL-SCALE VALUES OF AVERAGE AND PEAK TOWLINE TENSIONS IN FOLLOWING SEAS AT A SEA STATE 5 WITH THE BRIDLE TOWPOINT

261.4 FEET TOWLINE LENGTH			
Volume of Internal Water, percent	Towing Speed, knots	Average Tensions, lb	Peak Tensions, lb
0	4.72	1,467	29,340
	7.08	19,071	39,609
	9.44	23,472	46,944
	11.80	26,406	45,477
	14.16	26,406	42,543
20	4.72	2,934	26,406
	7.08	17,604	32,274
	9.44	23,472	44,010
	11.80	32,274	64,548
	14.16	29,340	45,477
40	4.72	8,802	26,406
	7.08	16,137	35,208
	9.44	27,873	41,076
	11.80	23,472	41,076
	14.16	67,482	105,624
522.8 FEET TOWLINE LENGTH			
0	4.72	7,335	14,670
	7.08	14,670	29,340
	9.44	23,472	46,944
	11.08	29,340	61,614
	14.16	32,274	64,548
20	4.72	2,934	14,670
	7.08	13,203	27,873
	9.44	20,538	36,675
	11.08	29,340	61,614
	14.16	36,675	66,015
40	4.72	17,604	20,538
	7.08	35,208	64,548
	9.44	29,340	64,548
	11.08	46,944	89,487
	14.16	73,350	96,822

TABLE A14 – PREDICTED FULL-SCALE VALUES OF AVERAGE AND PEAK TOWLINE TENSIONS IN BOW SEAS AT A SEA STATE 3 WITH THE SINGLE-CENTER TOWPOINT

Volume of Internal Water, percent	Towing Speed, knots	Average Tensions, lb	Peak Tensions, lb
261.4 FEET TOWLINE LENGTH			
40	2.36	4,401	7,335
	4.72	16,137	17,604
	7.08	41,076	42,543
	9.44	23,472	29,340
	11.80	44,010	49,878
	14.16	88,020	140,832
522.8 FEET TOWLINE LENGTH			
0	2.36	4,401	4,401
	4.72	7,335	8,802
	7.08	13,203	19,071
	9.44	19.071	23,472
	11.80	24,939	30,807
	14.16	32,274	39,609
40	2.36	2,934	4,401
	4.72	13,203	14,670
	7.08	10,269	11,736
	9.44	19,071	22,005
	11.80	38,142	57,213
	14.16	126,162	168,705

TABLE A15 – PREDICTED FULL-SCALE VALUES OF AVERAGE AND PEAK TOWLINE TENSIONS IN BOW SEAS AT A SEA STATE 4 WITH THE SINGLE-CENTER TOWPOINT

261.4 FEET TOWLINE LENGTH			
Volume of Internal Water, percent	Towing Speed, knots	Average Tensions, lb	Peak Tensions, lb
0	2.36	2,934	8,802
	4.72	10,269	20,538
	7.08	14,670	26,406
	9.44	20,538	33,741
	11.80	29,340	52,812
	14.16	35,208	48,411
20	2.36	2,934	8,802
	4.72	8,802	14,670
	7.08	11,736	22,005
	9.44	20,538	29,340
	11.80	26,406	35,208
	14.16	61,614	88,020
40	2.36	5,868	10,269
	4.72	19,071	26,406
	7.08	41,076	48,411
	9.44	67,482	82,152
	11.80	58,680	82,152
	14.16	102,690	176,040
UNPLUGGED	7.08	38,142	52,812
	9.44	58,680	73,350
	11.80	95,355	117,360
	14.16	139,365	161,370
522.8 FEET TOWLINE LENGTH			
0	2.36	2,934	2,934
	4.72	7,335	10,269
	7.08	13,203	23,472
	9.44	20,538	27,873
	11.80	24,939	35,208
	14.16	33,741	46,944
20	2.36	4,401	4,401
	4.72	11,736	16,137
	7.08	14,670	19,071
	9.44	19,071	23,472
	11.80	27,873	32,274
	14.16	38,142	51,345

TABLE A16 – PREDICTED FULL-SCALE VALUES OF AVERAGE AND PEAK TOWLINE TENSIONS IN BOW SEAS AT A SEA STATE 5 WITH THE SINGLE-CENTER TOWPOINT

Volume of Internal Water, percent	Towing Speed, knots	Average Tensions, lb	Peak Tensions, lb
261.4 FEET TOWLINE LENGTH			
0	2.36	4,401	14,670
	4.72	10,269	20,538
	7.08	14,670	33,741
	9.44	20,538	41,076
	11.80	29,340	58,680
	14.16	33,741	63,081
20	2.36	2,934	8,802
	4.72	8,802	20,538
	7.08	14,670	26,406
	9.44	20,538	36,675
	11.80	30,807	44,010
	14.16	70,416	93,888
UNPLUGGED	9.44	61,614	77,751
	11.80	96,822	126,162
	14.16	137,898	183,375
522.8 FEET TOWLINE LENGTH			
0	2.36	2,934	4,401
	4.72	8,802	19,071
	7.08	13,203	24,939
	9.44	20,538	38,142
	11.80	29,340	41,076
	14.16	35,208	42,543
20	2.36	4,401	5,868
	4.72	7,335	17,604
	7.08	13,203	23,472
	9.44	23,472	33,741
	11.80	39,340	38,142
	14.16	61,614	79,218

TABLE A17– PREDICTED FULL-SCALE VALUES OF AVERAGE AND PEAK TOWLINE TENSIONS IN BOW SEAS AT A SEA STATE 3 WITH THE BRIDLE TOWPOINT

261.4 FEET TOWLINE LENGTH			
Volume of Internal Water, percent	Towing Speed, knots	Average Tensions, lb	Peak Tensions, lb
0	2.36	2,934	2,934
	4.72	5,868	13,203
	7.08	11,736	20,538
	9.44	19,071	27,873
	11.80	27,873	39,609
	14.16	33,741	52,812
522.8 FEET TOWLINE LENGTH			
0	4.72	4,401	8,802
40	2.36	2,934	2,934
	4.72	10,269	13,203
	7.08	14,670	20,538
	9.44	26,406	35,208
	11.80	39,609	55,746
	14.16	66,015	83,619

TABLE A18 – PREDICTED FULL-SCALE VALUES OF AVERAGE AND PEAK TOWLINE TENSIONS IN BOW SEAS AT A SEA STATE 4 WITH THE BRIDLE TOWPOINT

261.4 FEET TOWLINE LENGTH			
Volume of Internal Water, percent	Towing Speed, knots	Average Tensions, lb	Peak Tensions, lb
0	2.36	2,934	7,335
	4.72	8,802	17,604
	7.08	14,670	32,274
	9.44	22,005	44,010
	11.80	26,406	49,878
	14.16	30,807	44,010
20	2.36	1,467	5,868
	4.72	8,802	16,137
	7.08	11,736	20,538
	9.44	19,071	29,340
	11.80	27,873	39,609
	14.16	45,477	58,680
40	2.36	2,934	5,868
	4.72	16,137	74,939
	7.08	17,604	32,274
	9.44	29,340	73,350
	11.80	51,345	61,614
	14.16	73,350	102,690
UNPLUGGED	4.72	14,670	23,472
	7.08	36,675	45,477
	9.44	67,482	80,685
	11.80	90,954	105,624
	14.16	146,700	176,040
522.8 FEET TOWLINE LENGTH			
0	4.72	4,401	8,802
	7.08	10,269	17,604
	9.44	17,604	29,340
	11.80	22,005	35,208
	14.16	29,340	38,142
20	2.36	1,467	4,401
	4.72	5,868	11,736
	7.08	8,802	14,670
	9.44	17,604	23,472
	11.80	26,406	32,274
	14.16	44,010	58,680
40	2.36	2,934	7,335
	4.72	11,736	17,604
	7.08	39,609	44,010
	9.44	20,538	36,675
	11.80	44,010	64,548
	14.16	70,416	79,218

TABLE A19 – PREDICTED FULL-SCALE VALUES OF AVERAGE AND PEAK TOWLINE TENSIONS IN BOW SEAS AT A SEA STATE 5 WITH THE BRIDLE TOWPOINT

261.4 FEET TOWLINE LENGTH			
Volume of Internal Water, percent	Towing Speed, knots	Average Tensions, lb	Peak Tensions, lb
0	2.36	1,467	7,335
	4.72	10,269	20,538
	7.08	16,137	32,274
	9.44	23,472	44,010
	11.80	24,939	42,543
	14.16	29,340	42,543
20	2.36	1,467	8,802
	4.72	10,269	19,071
	7.08	13,203	24,939
	9.44	19,071	29,340
	11.80	26,406	41,076
	14.16	45,477	64,548
40	2.36	5,868	11,736
	4.72	20,538	20,538
	7.08	8,802	26,406
	9.44	41,076	55,746
	11.80	63,081	80,685
	14.16	71,883	99,756
UNPLUGGED	4.72	26,406	45,477
	7.08	36,675	57,213
	9.44	64,548	80,685
	11.80	102,690	126,162
	14.16	130,563	154,035
522.8 FEET TOWLINE LENGTH			
0	2.36	1,467	1,467
	4.72	5,869	10,269
	7.08	13,203	19,071
	9.44	16,137	29,340
	11.80	22,005	33,741
	14.16	29,340	44,010
20	2.36	1,467	2,934
	4.72	7,335	17,604
	7.08	11,736	17,604
	9.44	17,604	24,939
	11.80	27,873	32,274
	14.16	48,411	64,548
40	2.36	1,467	2,934
	4.72	17,604	20,538
	7.08	41,076	48,411
	9.44	22,005	88,020
	11.80	58,680	79,218
	14.16	64,548	82,152

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