Technical Note N-1196

MOORING SYSTEMS CONCEPTS FOR EXPEDITIONARY LOGISTICS FACILITY OPERATIONS

By

R. C. Towne and W. G. Hatch

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ABSTRACT

The objective of this study was to develop an engineering/operational methodology to assess the feasibility of, and to design as a preliminary concept, the total mooring systems for cargo ships and associated unloading platforms operating in open and sheltered coastal waters. The methodology was to be capable of examining the mooring systems in terms of performance, logistic burden, installation, and operational modes in the context of the Expeditionary Logistics Facility. Mooring concepts are proposed and alternatives identified in terms of the state of the art and advanced technical solutions. Cost effectiveness comparisons are made of the proposed mooring concepts using the methodology developed in the study. Technical barriers and trade-offs are identified; RDT&E developments are recommended.

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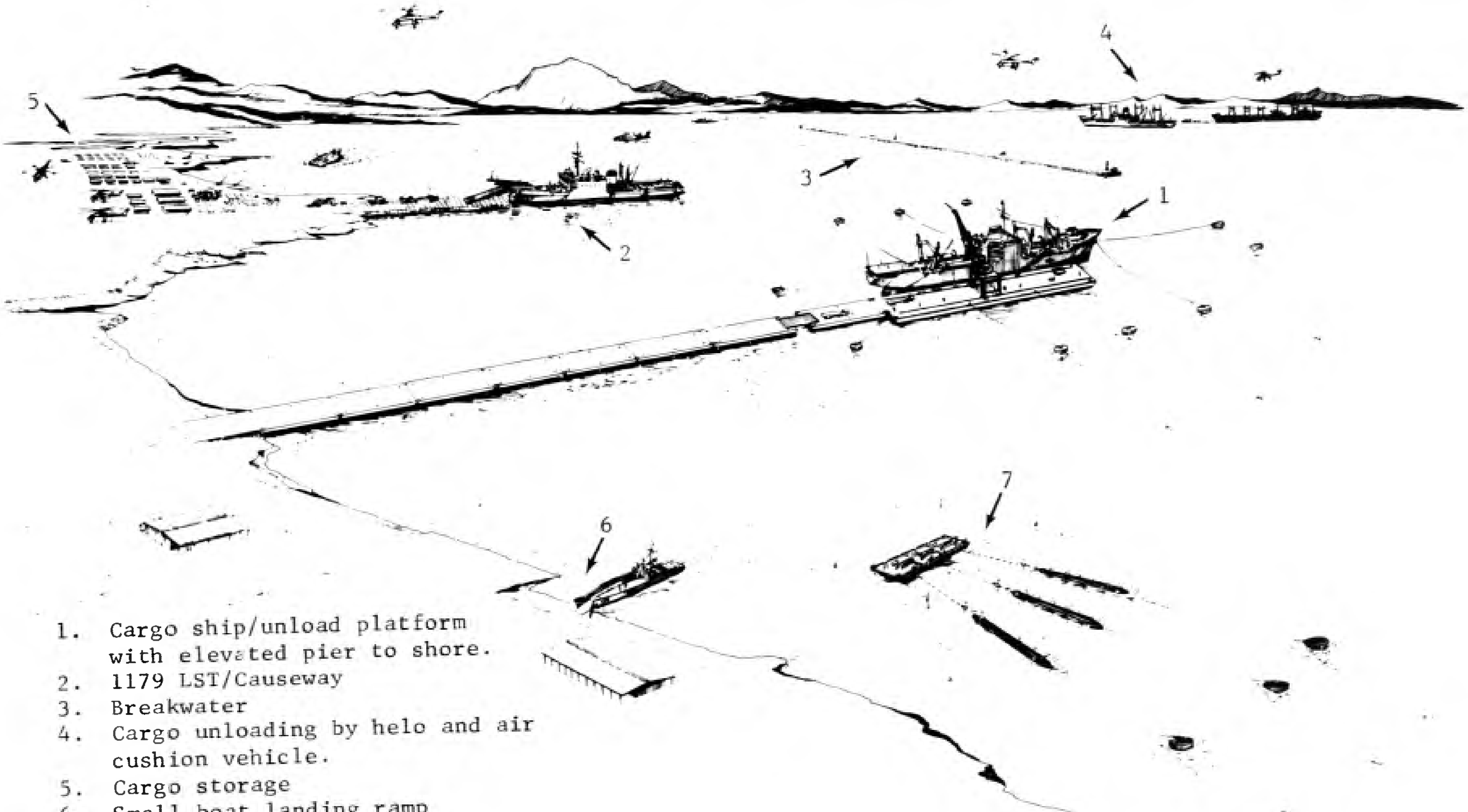
INTRODUCTION

The Navy General Operation Requirement-41 (GOR-41) (Rev. 70) Logistics, asserts the need for the ability to convert coastal waters to a deep-draft ship unloading facility in support of military operations such as those typified in Figure 1. The ability to transfer large quantities of supplies ashore from military or commercial-type cargo ships in short time periods is mandatory.

A logistic transfer complex, which could be installed rapidly and later retrieved, has been proposed by the Naval Facilities Engineering Command (NAVFAC) in a Proposed Technical Approach (PTA) document.[1] The component development necessary to formulize this logistic transfer complex is titled Expeditionary Logistic Facilities (ELF). Project ELF is a combination of components required for the ship-to-shore-over-the-beach transfer and throughput movement of cargo. The principal subsystem components/functions are: cargo handling (cranes, piers/platforms, wharves, moorings, fenders); cargo transfer (shuttle craft and causeways); wave attenuation (mobile breakwaters); cargo storage (beach hardening/stabilization, container storage and materials handling equipment).

A preliminary analysis[2] of the requirements associated with the PTA concept resulted in a listing of 20 primary items or capabilities required for a coastal cargo facility. One of these capabilities was Mooring Systems (item J).[2] A state-of-the-art study[3] outlined the present mooring system capabilities and formulated a development program for the coastal mooring systems. NAVFAC issued a contract[4] in June 1970 with PRC Systems Sciences Co. (PRC)/Frederic R. Harris, Inc. (FRH) to identify and analyse alternative platforms that could function as piers and transporters of port components; additionally the study was to identify connecting causeway alternatives. The Naval Civil Engineering Laboratory (NCEL) was requested to design, in a preliminary sense, the total mooring system configuration and its subsystems to be used in anchoring cargo ships relative to the adapter ship mooring systems proposed by FRH. An engineering and operational methodology was to be developed to compare and assess the feasibility of the mooring systems in support of the ELF.

This report presents: a proposed cargo ship mooring system relative to the FRH adapter ship/mooring systems; a comparison methodology expressed in terms of performance, operational readiness, and survivability of the systems; and proposed critical experiments for ELF mooring components.



1. Cargo ship/unload platform with elevated pier to shore.
2. 1179 LST/Causeway
3. Breakwater
4. Cargo unloading by helo and air cushion vehicle.
5. Cargo storage
6. Small boat landing ramp
7. Fuel storage/dispensing facility.

Figure 1. Expeditionary Logistic Facility

ENVIRONMENTAL CONSTRAINTS

The operational environment is defined[1,3] for this study as:

Operational: (with cargo ship)

Significant wave height	3.5-5.0 feet
Current	4 knots
Wind	30 knots
Tidal range	8 feet

Survival: (without cargo ship)

Significant wave height	14.0-20.0 feet
Current	4 knots
Wind	75 knots

The significant wave height is the average of the highest 1/3 of the waves. The current is tidal and is assumed to run parallel to the shore line. The winds may be local and not necessarily those which generated the existing swell. Table 1 lists wave data relative to sea states based on the Pierson-Moskowitz sea spectrum[5] as used in this report.

MOORING MISSIONS

The operational missions for which moorings and related accessories are required are described below. Only the cargo ship/unloading platform and causeway missions are discussed in this report. Specific criteria are cited and illustrations provided as indicated. The remaining missions, although listed below, are to be covered in a later study.

Cargo Ship

The mooring systems must be able to moor and maneuver those ships pertinent to the military operations,[3] i. e., the Military Sea Transportation Service vessels, the military assault type ships and the commercial shipping. Maneuvering of the ships will include the requirement to control and position the ships alongside an unloading platform or crane, as well as the ability to moor the ship under the environmental constraints.

Unloading Platform

This facility will provide the means of unloading the cargo ships. Several concepts[2,3,4] have been proposed and some typical ship hull concepts are considered separately for the purposes of mooring analysis. Table 2 lists the typical platforms considered by FRH.

Table 1. Sea Spectrum

Sea State	Wind Knots	Wave Height (ft) Avg.	Wave Height (ft) *Signif.	Wave Height (ft) Avg 1/10 Highest	*Signif. Range of Periods (sec)	*Period of Max. Energy of Wave Spectrum	*Avg Period (sec)	*Avg Wave Length (ft)	Min. Fetch (N. Miles)	Min. Duration of Wind (hour)
1	6	0.31	0.50	0.6	0.77-2.43	1.95	1.39	6.57	9	1.6
	8.5	0.60	1.00	1.20	1.09-3.43	2.76	1.96	13.14	10	2.4
	9	0.80	1.20	1.60	1.19-3.76	3.02	2.15	15.76	11	2.5
2	10	0.94	1.50	1.88	1.34-4.21	3.38	2.40	19.70	12	2.6
	12	1.27	2.00	1.54	1.54-4.86	3.90	2.77	26.27	17	3.6
	12.5	1.55	2.50	3.10	1.72-5.43	4.36	3.10	32.84	20	4.3
	13	1.86	3.00	3.72	1.89-5.95	4.78	3.40	39.41	25	4.9
3	13.5	2.17	3.50	4.35	2.04-6.43	5.16	3.67	45.98	30	5.4
	14	2.42	4.00	4.85	2.18-6.87	5.52	3.92	52.54	36	6.1
	15	2.84	4.50	5.68	2.31-7.29	5.86	4.16	59.11	40	6.6
	16	3.15	5.00	6.30	2.44-7.68	6.17	4.38	65.68	50	7.8
4	17	3.74	6.00	7.50	2.67-8.41	6.76	4.80	78.82	55	8.3
	18	4.36	7.00	8.73	2.89-9.09	7.30	5.19	91.95	65	9.2
	19	4.68	7.50	9.36	2.99-9.41	7.56	5.37	98.52	70	9.5
5	20	5.00	8.00	10.00	3.08-9.71	7.81	5.55	105.09	75	10
	21	5.70	9.00	10.30	3.27-10.30	8.28	5.88	118.22	90	11
	22	6.40	10.00	13.00	3.45-10.86	8.73	6.20	131.36	100	12
	24	7.90	12.00	16.00	3.78-11.90	9.56	6.79	157.63	130	14
6	25	8.81	14.00	17.60	4.08-12.85	10.33	7.34	183.90	160	16
	27	10.21	16.00	20.42	4.36-13.74	11.04	7.84	210.17	200	19
	28	11.00	18.00	23.00	4.63-14.57	11.71	8.32	236.45	230	20
	29	12.20	20.00	24.50	4.88-15.36	12.34	8.77	262.72	250	22
7	31	15.33	25.00	32.00	5.45-17.17	13.80	9.80	328.40	315	26
	34	19.00	30.00	38.00	5.97-18.81	15.12	10.74	394.08	420	30
	36	21.00	35.00	44.00	6.45-20.32	16.33	11.60	459.76	500	34
	38	25.00	40.00	50.00	6.90-21.72	17.42	12.40	525.43	600	38

*The Pierson-Moskowitz Sea Spectrum from, "The Frank Close-Fit Ship Motion Computer Program" NSRDC Report 3289, by Frank and Salvesen.

Table 2. Unloading Platform Concepts

Vessel (Class)	Displacement (long tons)		Length (ft)	Beam (ft)	Draft (ft)	
	Full	Light			Full	Light
C8-5-81B Lash	44,428	26,764	772	100	35	24
C5-5-78a Cont., RoRo	27,510	18,110	602	90	33	24
C4-5-1a Mariner	22,630	12,135	564	76	32	19
CC2 Saipan	19,320	14,420	693	77	26	21
LSD 35 Thomaston	11,970	7,320	510	82	19	13
Semi-Submersible catamaran (open-truss)	22,500	------	760	108	30	--
DeLong (Modified)	1,750	------	602	100	6	--
Jack-Up Platform	------	------	600	100	--	--
Pontoon Barge	4,700	------	300	84	7	--
C7 (Modified)	------	------	715	95	22	--
CVA (Modified)	------	------	683	77	22	--
Catamaran (ship hull)	------	------	745	100	22	--
Barge (ship hull)	------	------	705	100	22	--

Causeways

A causeway, as used herein, is a floating or elevated structure composed of end-connected pontoon sections to form a roadway from a ship or unloading platform to shore. It must be capable of being moored under the environmental constraints established for the ELF. These include the tidal current requirements and the ability to survive the storm conditions. Mooring line components may extend 200 feet to both sides of the causeway.

Tankers/Fuel Terminals

Future fuel requirements will necessitate the use of larger tankers. The Military Sea Transport Service (MSTS) has initiated a program to replace T-2 type tankers with new tankers having a 25,000 dwt displacement and a draft of 33 feet. In addition, off-shore storage facilities[3] may be used. This facility may eliminate the tanker mooring requirement by unloading from the tanker, at some distance to sea, into towable containers and moving only the containers to a dispensing barge terminal moored off shore.

Miscellaneous Moorings

Mooring buoys will be needed for anchoring small craft, pontoon barges, or other vessels. The mooring capability will be dependent upon the individual requirements, however modular components should be investigated.

MOORING FORCES

The mooring forces are based on the summation of the various ship loads induced by the current, wind and waves. The effects of ship motion on the mooring forces imposed by waves, i. e., surge, heave and pitch, and the additional effects of shallow water.

(a) The ships and platforms were assumed moored normal to the beach, which presented the maximum area to the currents but minimum area to waves (bow-on waves).

(b) The primary currents, i. e., tidal currents, were assumed to flow parallel to the shoreline.

(c) The ships' drafts were assumed to be less that 80 percent of the water depths.

(d) The winds were assumed to strike the ship/platform from any direction and the wind loads were added vectorially to the current and bow-on wave induced loads.

A computer program, entitled RELMO[6] was developed to study the relative motions of parallel cargo ships and unloading platforms in head-on seas. Computations for heave, surge and pitch motions are in the vertical plane only. The statistical data output is based on the Pierson-Moskowitz sea spectrum shown in Table 1 for a fully developed sea. The program will produce ship motion data relative to irregular waves, i. e., a wave spectrum, or data for regular sinusoidal waves for a large number of wave frequencies. The absolute motions of a moored or unmoored ship may be obtained or the relative motions between two ships can be developed.

Ship mooring data for typical unloading platform hulls and several cargo ships are given in Table 3. Data on the semi-submersible catamaran unloading platform concept[4] were not obtainable from RELMO at this date. The program is planned to produce this data in FY 72. Chapter IV of reference 4 indicates that the motions of a semi-submersible catamaran in a sea state 6 will be considerably less than the single hull adpater platform. Some comparative data[7] of mooring line forces between a ship-form vessel and a semi-submersible vessel was measured in the field. This information indicates that the total effective steady force can be greater for the semi-submersible for the higher wave heights. The measured steady mooring line force for bow and beam were 387 kips and 234 kips respectively for the semi-submersible compared to 116 and 205 kips for the ship hull vessels. It was assumed in reference 4 that the relative motions between a cargo vessel and semi-submersible catamaran adapter platform in a sea state 3 would approximate the absolute motions of the cargo vessel. Absolute motions of some typical cargo ships are presented in Table 4.

Relative motions between the C8 (adapter ship) and a C4 or C5 cargo ship are shown in the graphs in Figures 2 through 13. The relative motions in the graphs are plotted versus the dimensionless term XF/L, where XF is a variable that locates relative positions along the longitudinal axes of the ships (to identify hatch or cargo locations) and L is the length between the ship's after perpendicular and forward perpendicular, Figure 14.* For example, it can be seen that the position 0.85, Figure 2, toward the bow of the ship has the most vertical displacement. The point of reference at the stern of the ships is the after perpendicular, which in the case of the C8 coincides with the stern and in the case of the C4 and C5, the after perpendicular is 24 feet and 21 feet forward of the stern, respectively.

Five representative ships (single hull ships types C8, C5, C4, CC2 and LSD 35) were selected for analysis to develop the mooring force data of Table 3 and to establish mooring hardware components. RELMO[6] was used to develop data for each of the 5 ships in sea states 3 and 6, in 50-foot and 100-foot water depths, and with full and light ship displacements for surge, heave, mooring spring-constants and the associated horizontal and vertical ship velocities and accelerations. Figures 15 through 24 are graphs of the surge and spring-constant data. The associated Pierson-Moskowitz sea spectra for 5-foot and 20-foot significant wave heights are given in Figures 25 through 29. These sea spectra indicate

*Figures 2 through 13 were computed with the point L/2 of each ship in juxtaposition.

the areas of maximum wave energy relative to the wave frequency or period and relative energy contained in the two sea spectra. Also shown on these graphs are the surge response amplitude operators of the individual ships for several mooring spring-constants. Each of the proposed FRH mooring concepts, i. e., systems A, B, C, swing moor, and the NCEL Positive Control Mooring System (PCM) are analysed below.

Figures 15 through 24 show that there is little appreciable effect on reduction of ship surge caused by increasing the mooring spring-constant (or line stiffness) for ship sizes from the C8, (44,428 long tons displacement, 772 feet in length) to the LSD 35 (11,790 long tons displacement, 510 feet in length). Figure 15 shows that no change in surge is effected by increasing the spring constant up to 250,000 pounds per foot in a sea state 3 for the C8 hull. The surge amplitude tends to increase significantly at about a mooring spring-constant of 3,000,000 pounds per foot because of resonance. These data indicate the desirability to maintain a mooring system with a spring constant below 50,000 pounds per foot for all these ships. The effect of changing water depth from 50 feet to 100 feet for the C8 type ship can be seen by comparing the graphs in Figures 15 and 16. The effects in sea state 3 are negligible while the surge amplitude is doubled (from 9 feet to 18 feet) in a sea state 6. The water depth effect varies only slightly for the other ships as can be observed by comparing the graphs for 50-foot and 100-foot water depths for each individual ship. Figures 30 and 31 are graphs showing the relation between wave height and ship surge in 50- and 100-foot water depths for the 5 ship hull adapter vessels using mooring spring-constants of 250,000 and 500,000 pounds per foot. It can be seen that surge is not significant in wave heights up to about 7 feet but the surge values vary considerable for the individual ships above the 7-foot wave height. These data indicate the necessity of designing a mooring system for a specific ship under the specified environmental conditions.

The maximum requirements for deep draft cargo ships and unloading platforms are dependent upon the unloading system to be used, i. e., whether the platform is swing-moored or spread moored and whether the cargo ship is held by tying to the platform or by a separate moor. The maximum forces used to design the moorings, as selected from the data presented above and from reference 3 were 1,200,000 pounds for beam-on loads caused by current and wind forces. Spring constants were maintained below about 90,000 pounds per foot.

The FRH report[4] developed the mooring forces on the adapter ships based on a broadside 2.0 knot current (110,000 pounds) plus a broadside wind force caused by a 30 mile per hour wind (100,000 pounds) resulting in a 210,000 pound mooring force plus the wave forces. The results of the FRH study indicated that there is little to be gained by providing more than a total of 450,000 pounds total resistance in the mooring system based on the FRH specified current, wind, and wave forces. The study results indicated that large increases in the resistance of moorings would produce relatively minor reductions in the ship motions, e. g., increasing the mooring force from 450,000 pounds to 1,800,000 pounds would not change the ship surge, 8.0 feet, in a 6.25 foot, 9 second regular wave, although the sway could be reduced from 8 feet to 4 feet. So the FRH recommended ship moorings are based on the restraint required to hold the ship against the environment and not additional restraint to reduce the ship motions caused by the environment.

MOORING CONCEPTS

The mooring systems proposed in this section are selected to operate with the unloading platforms suggested by the FRH study.[4] Four arrangements for mooring the platforms were outlined by FRH and the hardware for these systems are described below, together with one mooring system proposed to maneuver and moor the deep draft cargo ships. Figure 32 outlines the mooring requirements and system alternatives.

Unloading Platform Mooring

The types of unloading platforms proposed by FRH include several adapter ship or hull-type vessels, a semi-submersible catamaran, and an elevated pier of the DeLong type. Each of the platform types has an option of a floating or an elevated causeway connecting the platform to the beach. Three of the FRH suggested mooring arrangements, Figures 33, 34, and 35 use ground tackle while the fourth, Figure 36, uses a breasting platform. The causeways also require either the conventional ground tackle or piling to hold them in position. The proposed mooring arrangements are basically either a spread moor or a swing-type moor.

To identify specific mooring hardware components, it was necessary to analyze the individual ships which are proposed as unloading platforms (adapter ships) and the cargo ship types which will be unloaded by the cargo handling system. The platforms/ships were studied in the context of the ELF operating environment and operating procedures. For example, the unloading platforms are expected to transfer cargo in a sea state 3, and remain moored in a sea state 6. The cargo ships will remain moored in a sea state 3 while their displacements will vary from the loaded condition to a light condition. The water depths at the site will vary from about 50 feet to 100 feet. These conditions were all assumed to affect the motions of the platforms/ships and conversely the loads on the mooring systems. As previously noted, the FRH proposed platforms (adapter ships) varied considerably in displacement, length, and configuration.

<u>Mooring Concept A</u>. This concept is shown in Figure 33. The mooring system, as generalized by F. R. Harris,[4] has a more idealized energy absorption capability than standard mooring systems. The spring constant of this system tends to become relatively constant once the buoy is submerged and thus provides a large energy absorption capability (large area under the curve when plotting horizontal force versus the horizontal displacement, Figure 37). The mooring lines extend from the deck, under the ship to a bottom sheave on the opposite side and up to a large buoy. The lines are pre-tensioned by means of winches on the ship. This pretensioning partially submerges the buoy. With an adapter vessel equivalent to the size of the C8, moored bow-on to the waves and beam-on to the current, the forces on the vessel are expected to be 150,000 pounds on the

bow/stern lines and 1,200,000 pounds on the beam lines. The hardware components for this system are defined in Table 5, and the major problems or limitations of each component are listed in Figure 38. With the required number of mooring lines, the spring constant of this system is 15,000 pounds per foot on the bow/stern lines and 90,000 pounds per foot on the beam lines. Referring to Figures 15 and 16, the spring constants will be within acceptable values for avoiding resonance. Reference 4 has pointed out certain disadvantages of this system, i. e., the adapter ship would have to be positioned at a draft deeper than any of the cargo ships, about 35 feet, for the cargo ship to clear the mooring lines. Relative motions could cause the mooring lines to strike the cargo vessels' propeller, causing damage to the ship or lines.

NCEL concurs with FRH assessment of the mooring system A disadvantages and in view of the large number of components (Table 5) required to meet the NCEL mooring requirements, agree that this system would not be suitable for ELF operations.

Mooring Concept B. This concept has vertical mooring lines prestressed by constant tension winches on the adapter ship and with the lines anchored to stake piles on the bottom. As the ship moves laterally, under the influence of a forcing function such as waves, wind, or current, the vertical mooring lines develop a horizontal force component which resists the ship motion. The winches will pay out or haul in the lines to maintain the preset tension. This system is shown in Figure 34. The hardware components, required to hold the C8 adapter ship under the imposed environment, are listed in Table 6. The individual components have been analyzed to identify problem areas and these are listed in Figure 39. With the required number of mooring lines, the spring constant of this system is 50,000 pounds per foot. This spring constant will allow the adapter ship to operate at a frequency well below the area of resonance of the ship period and wave period. The mooring winch preset tension is 150,000 pounds; the ship will move 25 feet horizontally to resist the current and move 0.02 feet and 1.3 feet longitudinally to resist the wave force in sea states 3 and 6, respectively.

While this system may be operationally acceptable from a mooring standpoint, it may not be acceptable for pier, causeway, or crane operations. This will depend upon the total system.

Swing Moor Concept. A large, special buoy, equipped with conventional ground tackle, anchors the unloading platform. Reference 4, depicts the platform as an open truss, semi-submersible catamaran. A special attachment between the platform and buoy allows the catamaran to swing freely about the buoy. The cargo ships are secured to the platform and thus the swing mooring must anchor the ships in addition to the platform as illustrated in Figure 35. This concept permits the ships to assume a position which will impose the smallest force on the anchorage. The hardware components for this system are listed in Table 6. The primary limitations of each component are listed in Figure 40. A combination of mooring winches mounted on the unloading platform and auxiliary tugs would be needed to maneuver the cargo ship alongside the unloading platform. See Table 7.

Table 3. Ship[1] Mooring

Ship	Displacement (long tons) Full Load	Light	Length Overall (ft)	Horizontal Displacement[4] (ft) SS 3 Water Depth 50'	100'	SS 6 50'	100'	Horizontal Velocity[5] (ft/sec) SS 3 Water Depth 50'	100'	SS 6 50'	100'	Force on Mooring System[2] (Kips) SS 3 Water Depth 50'	100'	SS 6 50'	100'	Horizontal Disp 50' wate Mooring Spring Constant 250^k/ft
LSD-35	11,970	7,320	510	.04	.06	4.16	4.20	.04	.05	1.80	1.9	.10	.15	10.4	10.5	11.9
CC-2	19,320	14,420	693	.02	.02	1.69	2.50	.02	.02	.68	1.0	.05	.05	4.2	6.2	8.2
C-4	22,630	12,135	564	.05	.05	4.00	4.03	.04	.04	1.5	1.8	.12	.12	10.0	10.1	47.7
C-5	27,510	18,110	602	.03	.04	3.30	3.62	.03	.03	1.4	1.6	.07	.10	8.2	9.0	15.3
C-8	44,428	26,764	772	.03	.03	.96	1.76	.03	.03	.39	.72	.07	.07	2.4	4.4	2.5

1. Ship Displacement - full load.

2. Mooring Spring Constant - 2,500 lbs/ft.

3. Sea State 6 - 20 ft significant wave height.

4. The data produced by RELMO is limited to ship/platform motions in the vertical plane with head seas only, i. e., heave and pitch, while horizontal displacement represents only surge, and no data is available presently for sway, yaw, or roll.

5. Data for velocities and accelerations are defined as significant values or the average of the 1/3 highest values.

H

Ship[1] Mooring Data

Horizontal Displacement[3,4] (ft) 50' water depth		Horizontal Displacement[3,4] (ft) 100' water depth		Force on Mooring System[3] (Kips) 50' water depth		Force on Mooring System[3] (Kips) 100' water depth	
Mooring Spring Constant $250^k/ft$	Mooring Spring Constant $500^k/ft$	Mooring Spring Constant $250^k/ft$	Mooring Spring Constant $500^k/ft$	$250^k/ft$	$500^k/ft$	$250^k/ft$	$500^k/ft$
11.9	2.5	14.3	2.5	2,980	1,250	3,570	1,800
8.2	2.7	14.1	4.3	2,060	1,350	3,520	2,150
47.7	10.8	45.3	21.0	11,950	5,400	11,350	10,500
15.3	20.3	14.9	29.9	3,820	10,150	3,720	14,950
2.5	9.0	4.0	18.0	625	445	1,000	9,000

B

Table 4. Absolute Ship Motions[1]

Ship	Vertical Displacement (feet)		Vertical Velocity (ft/sec)		Vertical Acceleration ft/sec^2		Horizontal Displacement[4] (feet)		Horizontal Velocity (ft/sec)		Horizontal Acceleration ft/sec^2	
	SS3[2]	SS6[3]	SS3	SS6	SS3	SS6	SS3	SS6	SS3	SS6	SS3	SS6
LSD-35	.38	9.7	.33	5.0	.009	.08	.04	4.0	.04	1.7	.001	.02
CC2	.18	6.6	.14	3.2	.003	.05	.02	1.6	.02	.67	.001	.008
C4	.49	7.5	.42	3.9	.01	.07	.05	3.6	.04	1.5	.001	.02
C5	.36	7.5	.30	3.8	.007	.06	.03	3.2	.03	1.3	.001	.019
C8	.17	3.5	.14	1.8	.004	.03	.03	.96	.03	.39	.001	.005

1. No mooring restraint, 50-foot water depth, motions measured at center of gravity.

2. Sea state 3, significant wave height 5 feet.

3. Sea state 6, significant wave height 20 feet.

4. Horizontal displacement represents only surge.

5. All data represents the average of the 1/3 highest values.

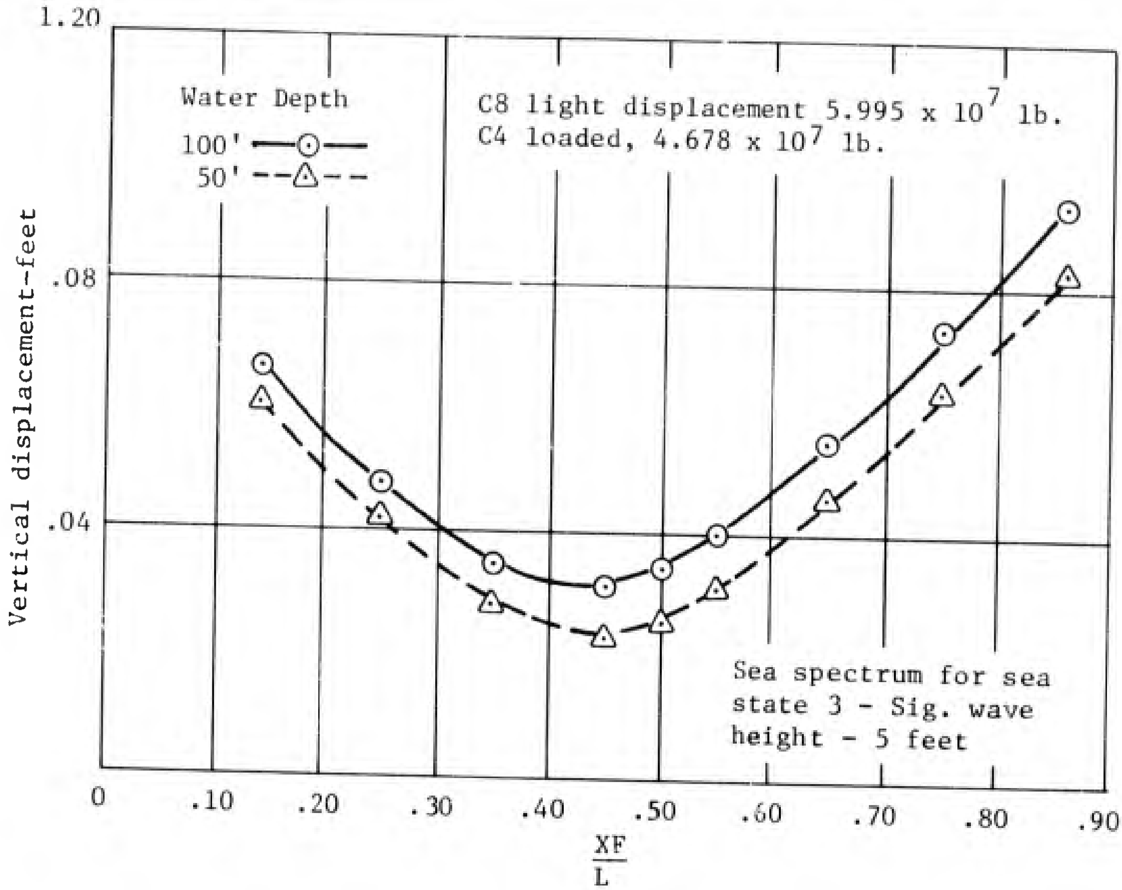


Figure 2. Relative motion (heave) between C8 (light) and C4 (loaded).

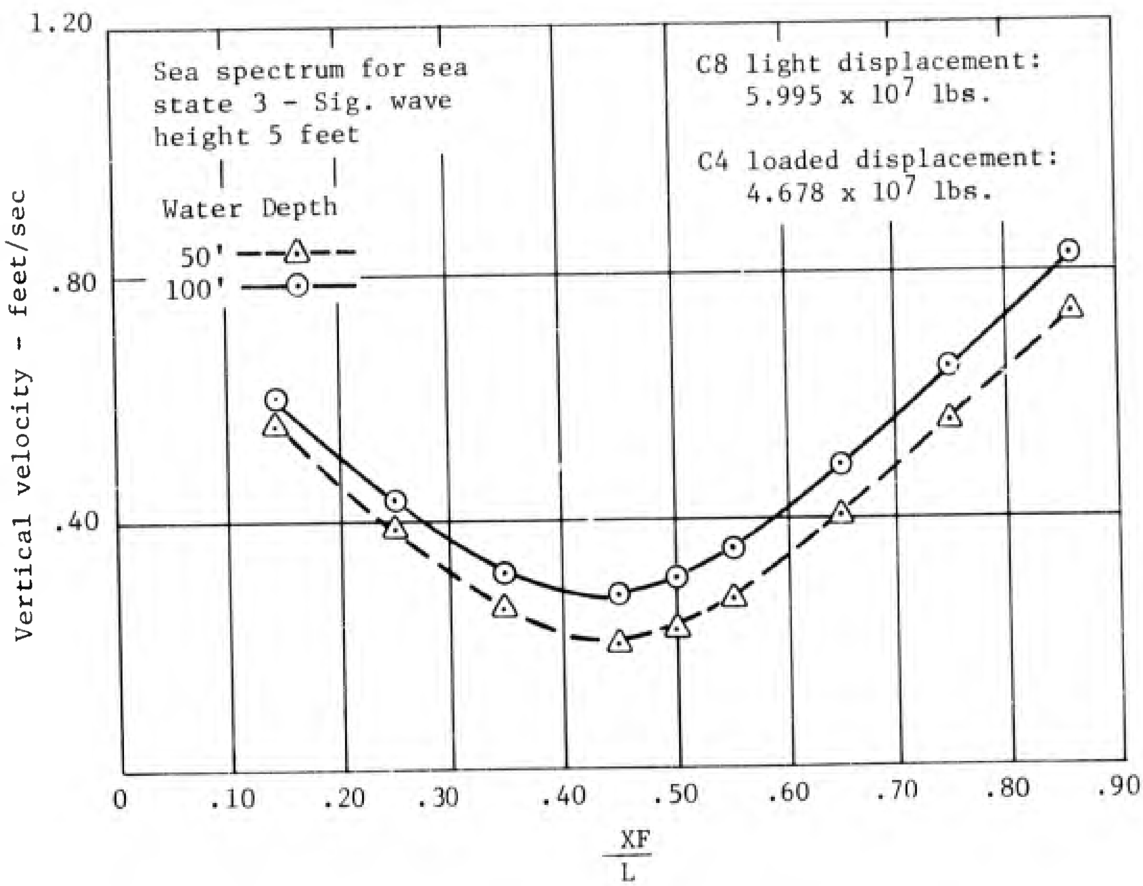


Figure 3. Relative motion (velocity) between C8 (light) and C4 (loaded).

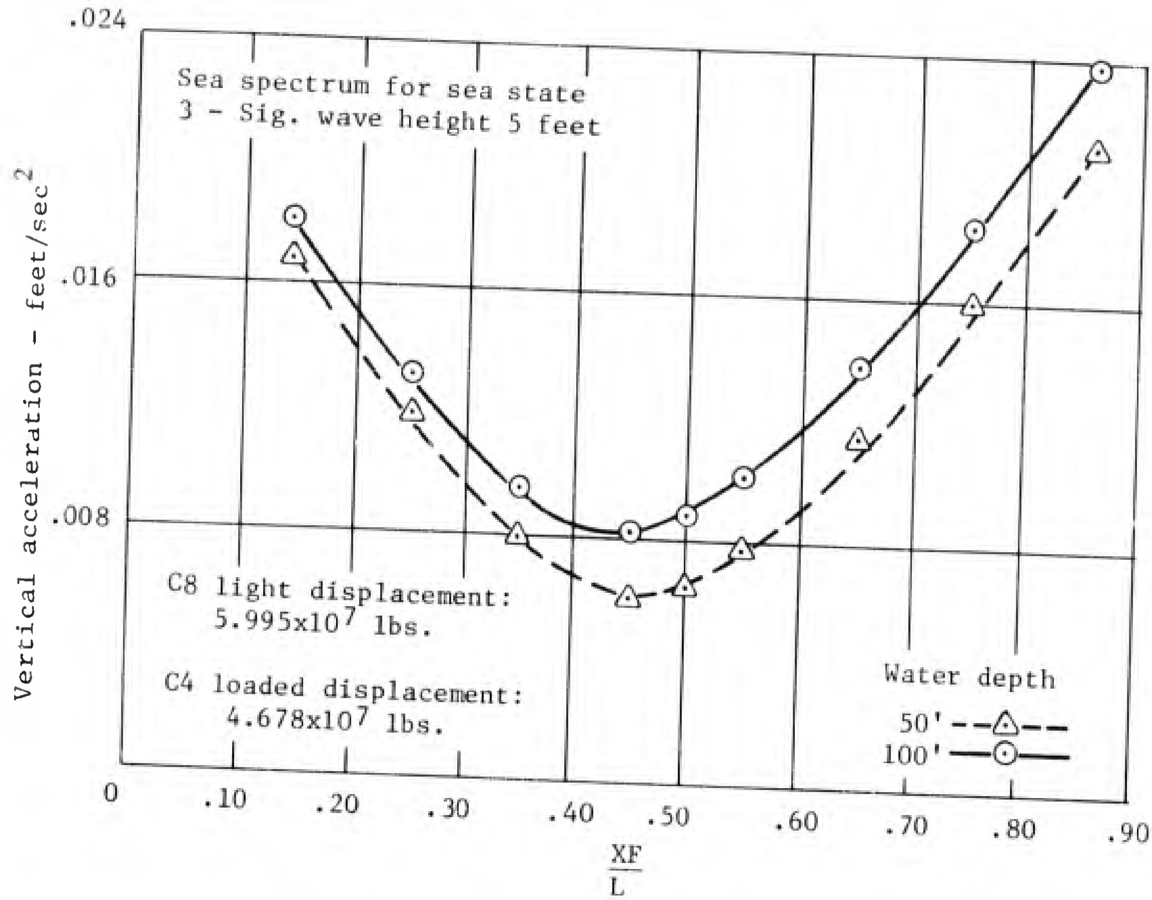


Figure 4. Relative motion (acceleration) between C8 (light) and C4 (loaded).

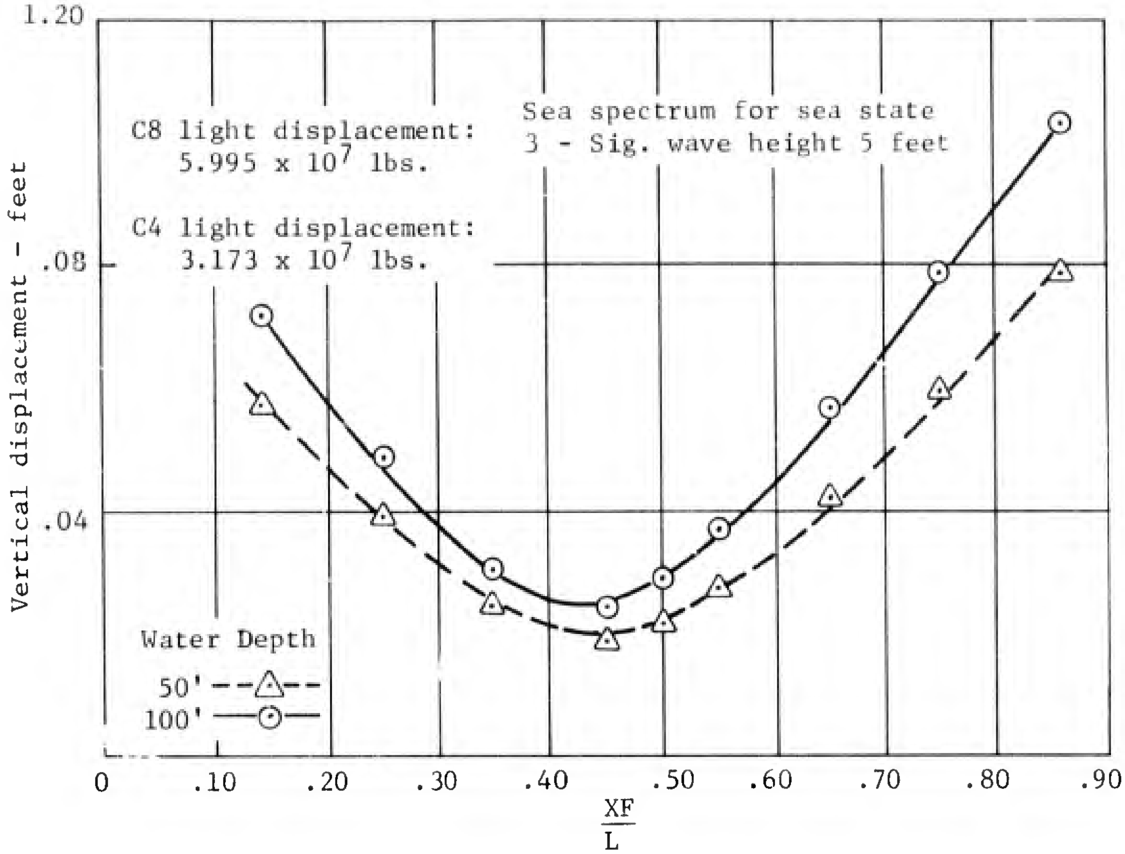


Figure 5. Relative motion (heave) between C8 (light) and C4 (light).

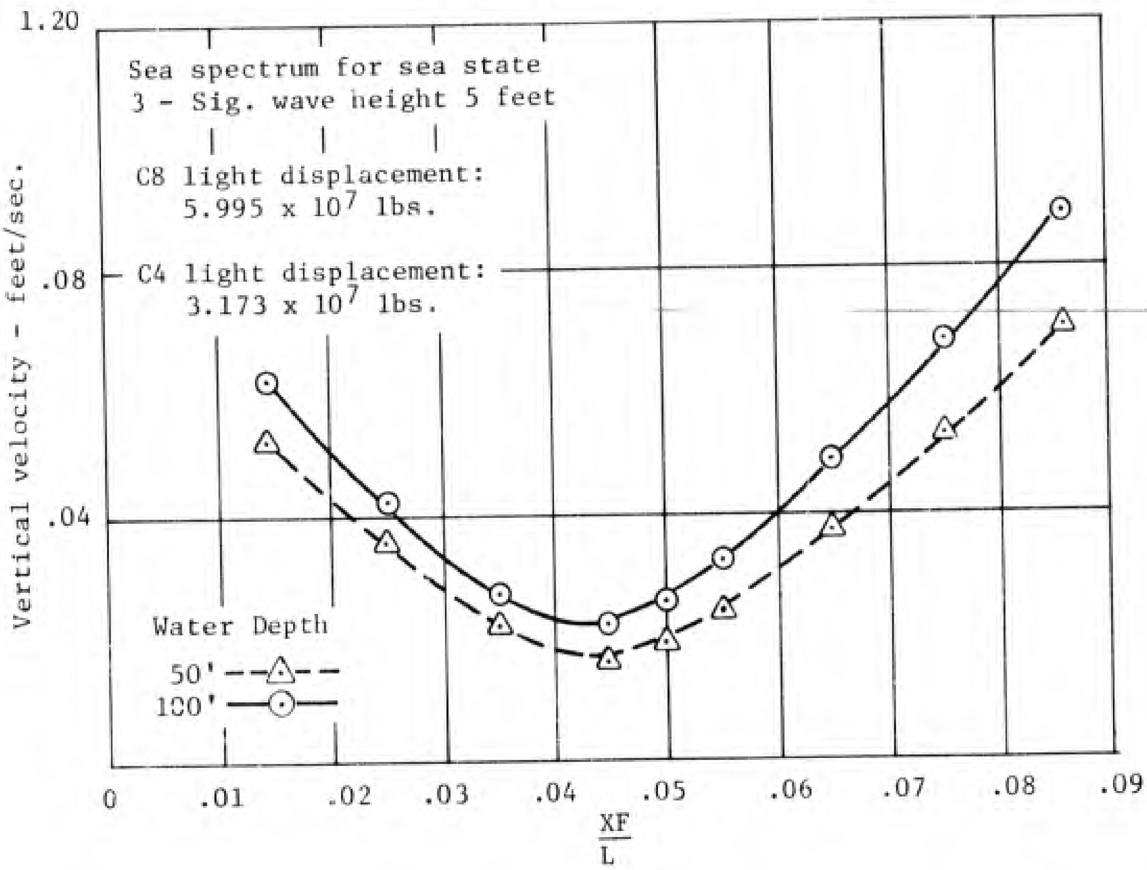


Figure 6. Relative motion (velocity) between C8 (light) and C4 (light).

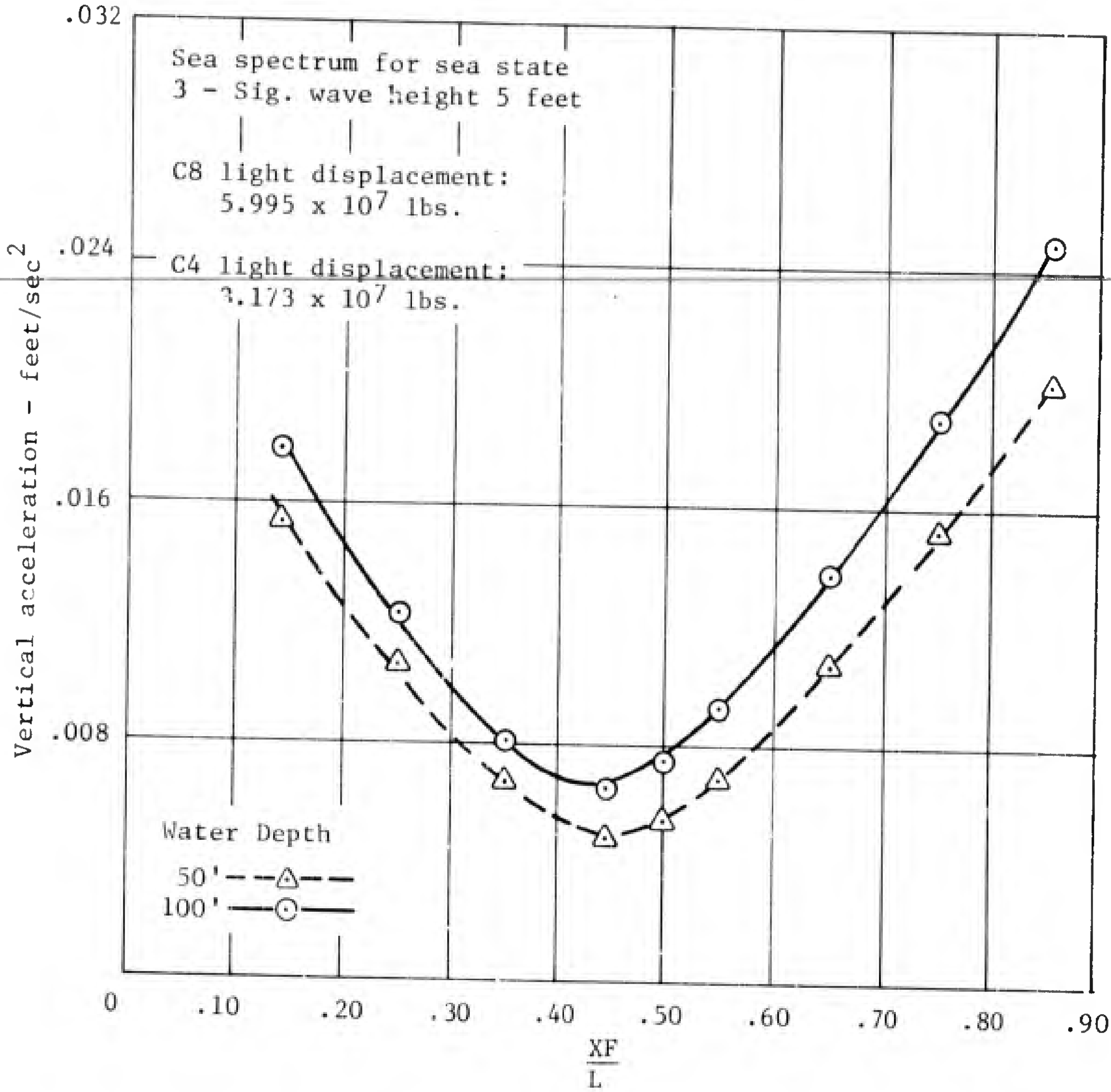


Figure 7. Relative motion (acceleration) between C8 (light) and C4 (light).

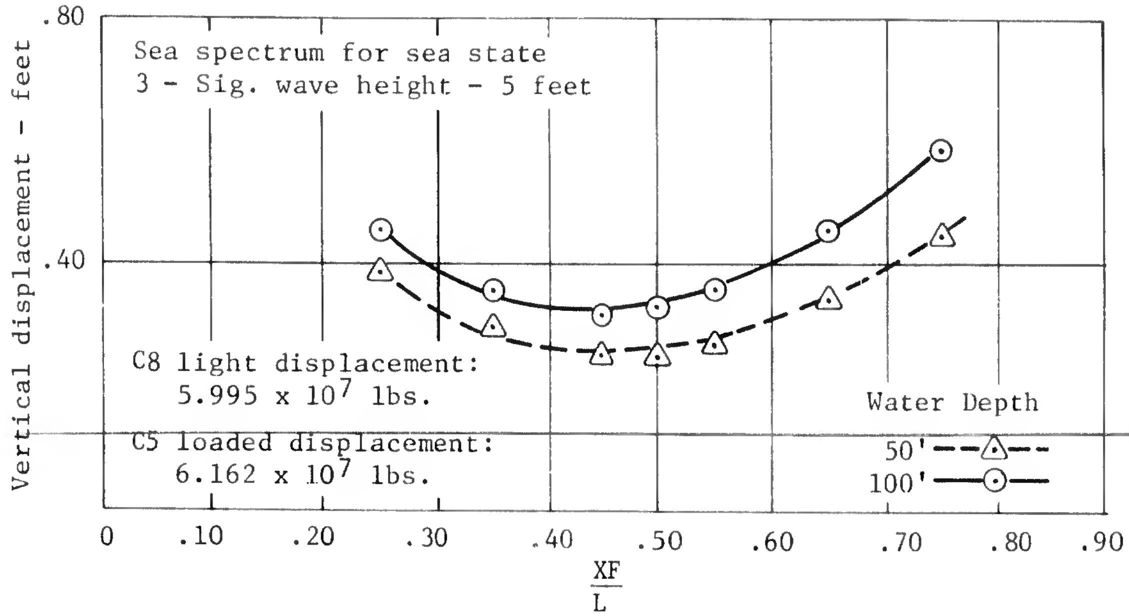


Figure 8. Relative motion (heave) between C8 (light) and C5 (loaded).

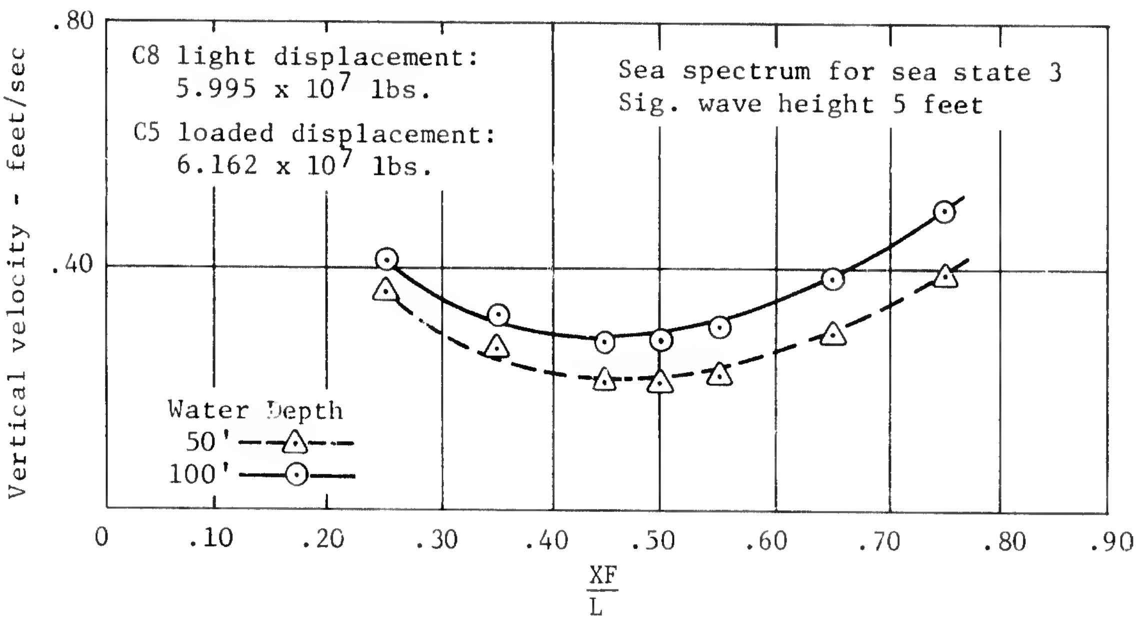


Figure 9. Relative motion (velocity) between C8 (light) and C5 (loaded).

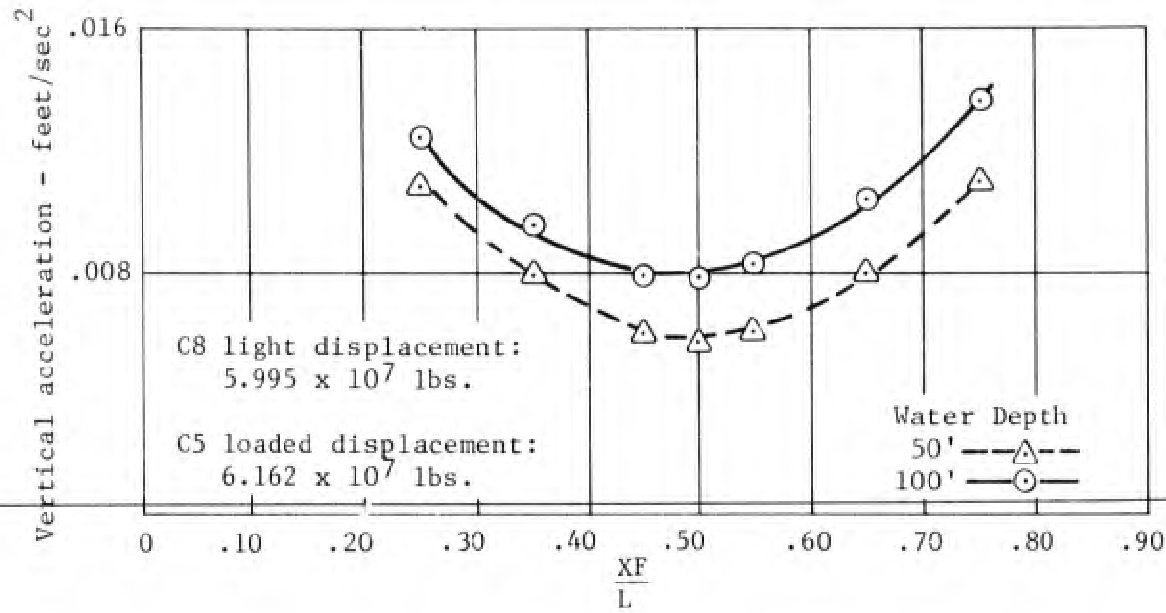


Figure 10. Relative motion (acceleration) between C8 (light) and C4 (loaded).

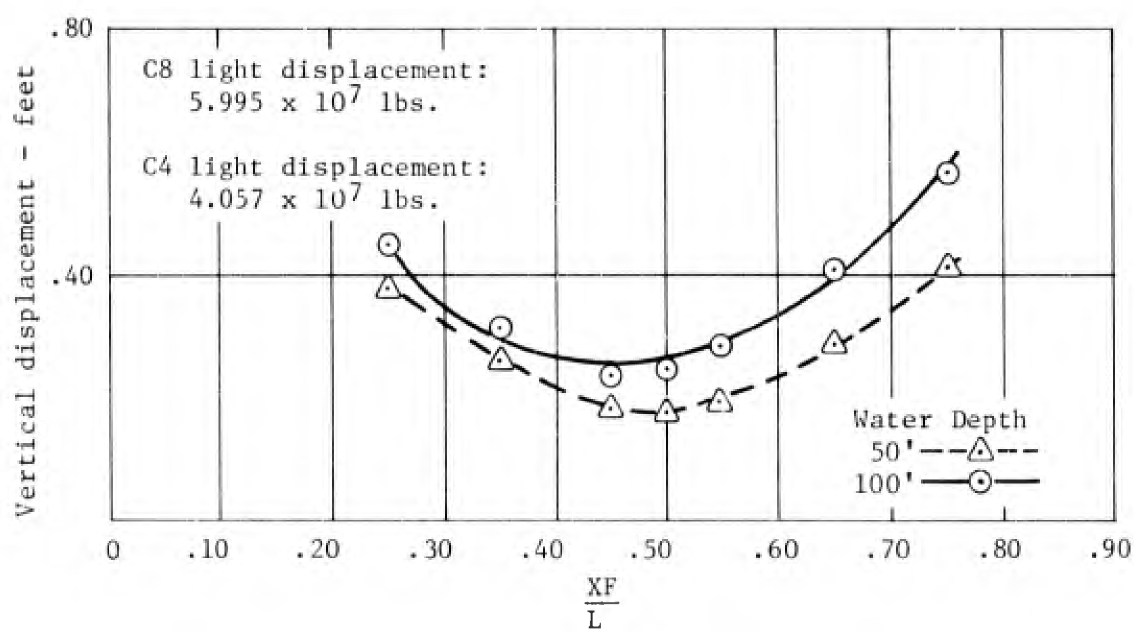


Figure 11. Relative motion (heave) between C8 (light) and C5 (light).

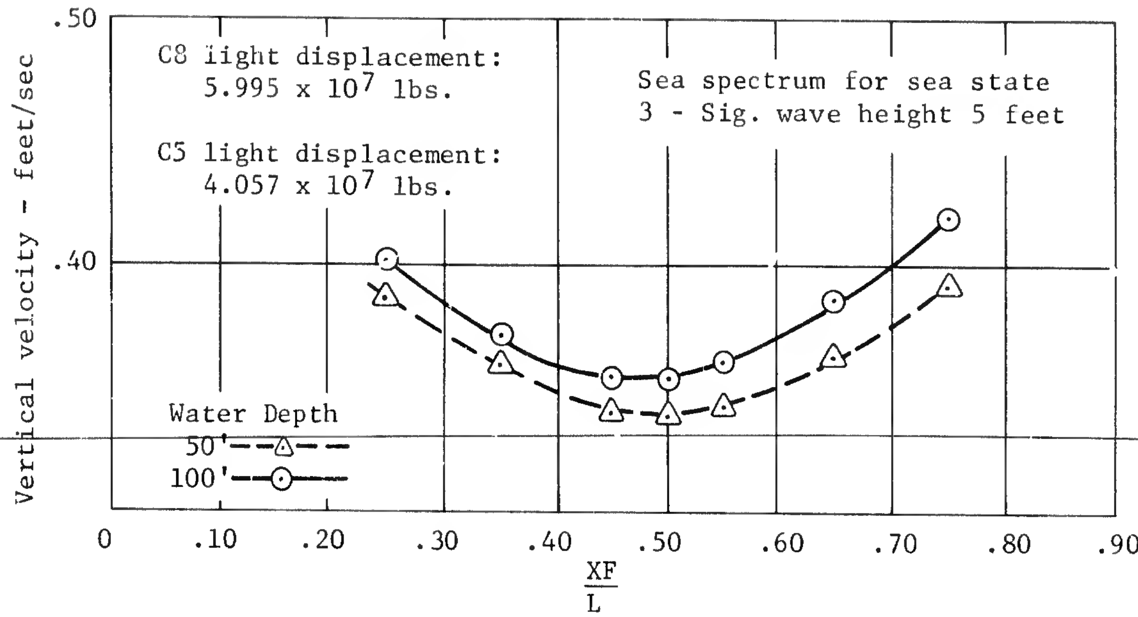


Figure 12. Relative motion (velocity) between
C8 (light) and C5 (light).

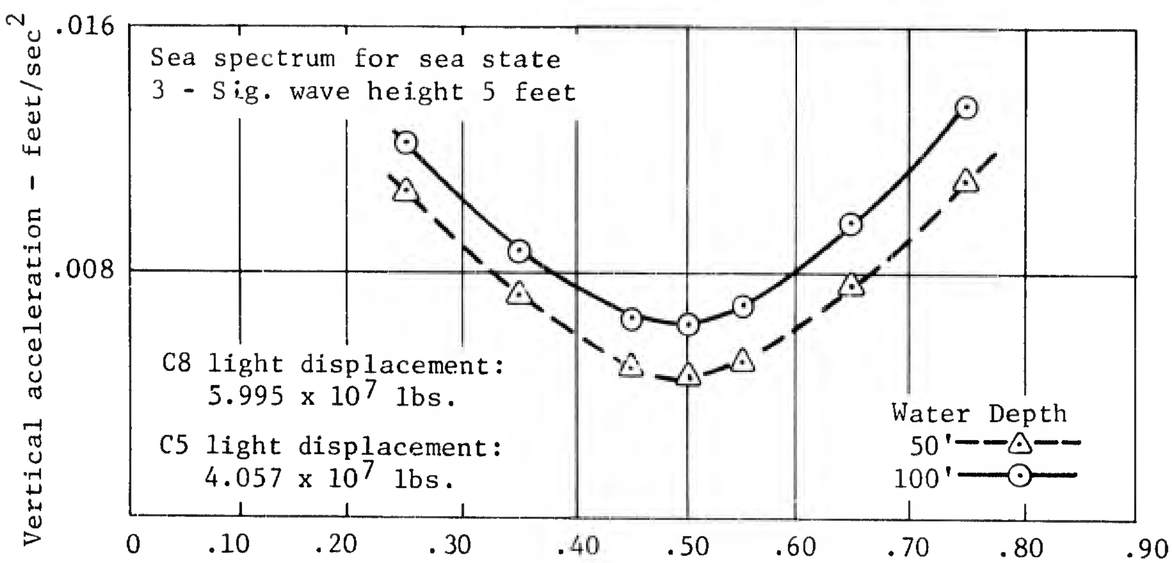
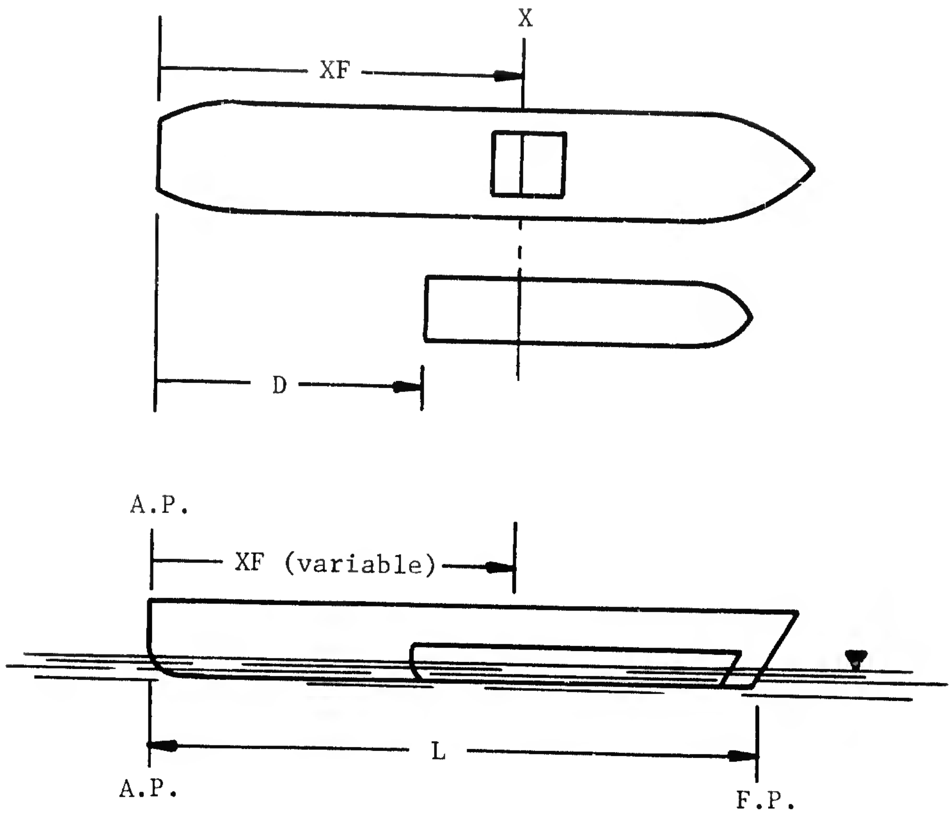


Figure 13. Relative motion (acceleration) between
C8 (light) and C5 (light).



D = Varies with location of cargo shuttle craft alongside cargo ship.

X = Point of measurement of relative motion.

L = Length between the After Perpendicular (A.P.) and the Forward Perpendicular (F.P.)

XF = Distance from A.P. to point of interest in relative motion.

Proposed adapter ship hulls, L:

C8	=	740 feet
C5	=	560 feet
C4	=	520 feet
CC2	=	664 feet
LSD-35	=	500 feet

Distance of A.P. from ship stern:

C8	=	0
C5	=	21 feet
C4	=	24 feet
CC2	=	23 feet
LSD-35	=	0

Figure 14. Location of relative motion measurements.

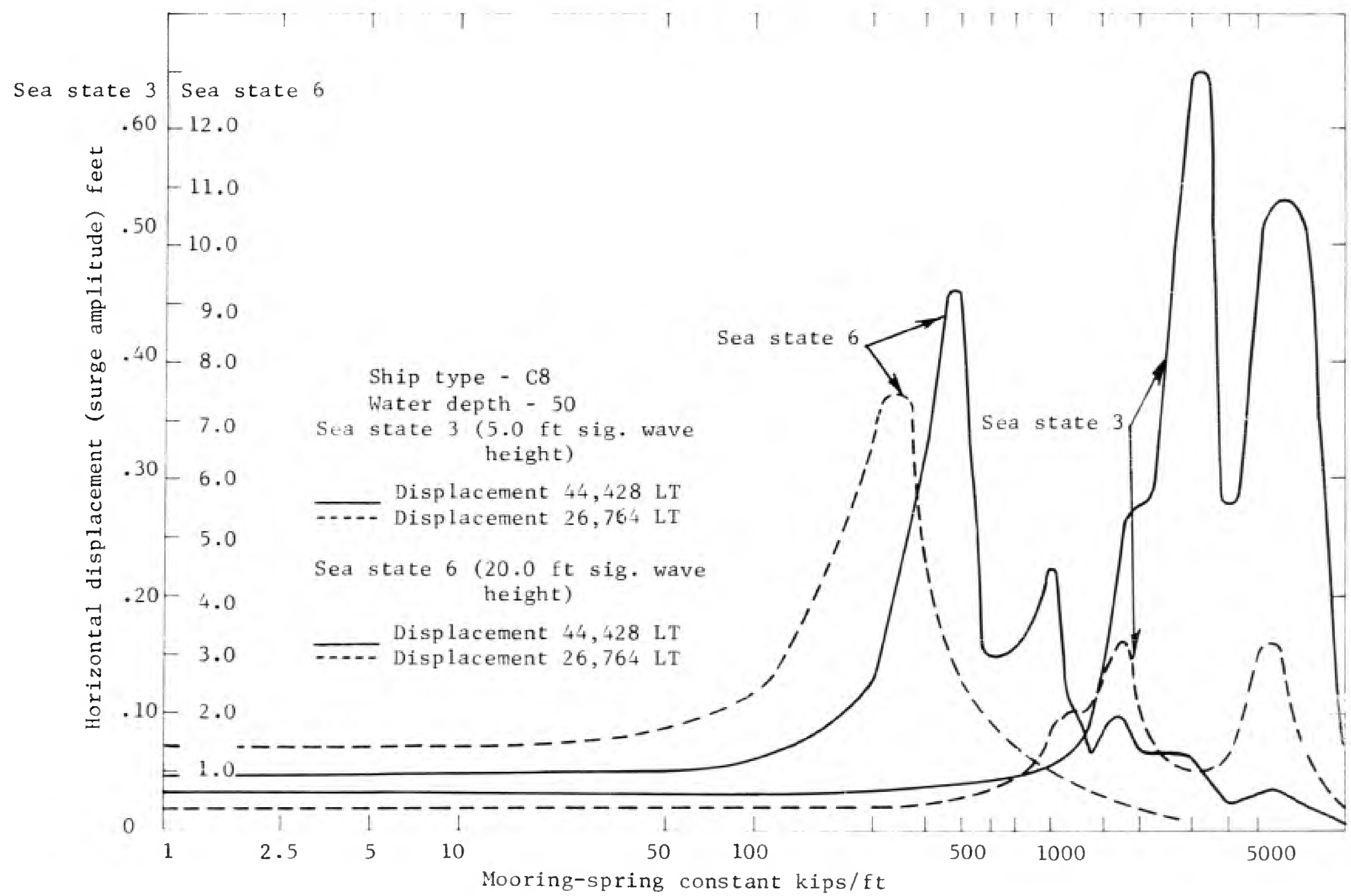


Figure 15. C8 surge with mooring restraint - 50-foot water depth.

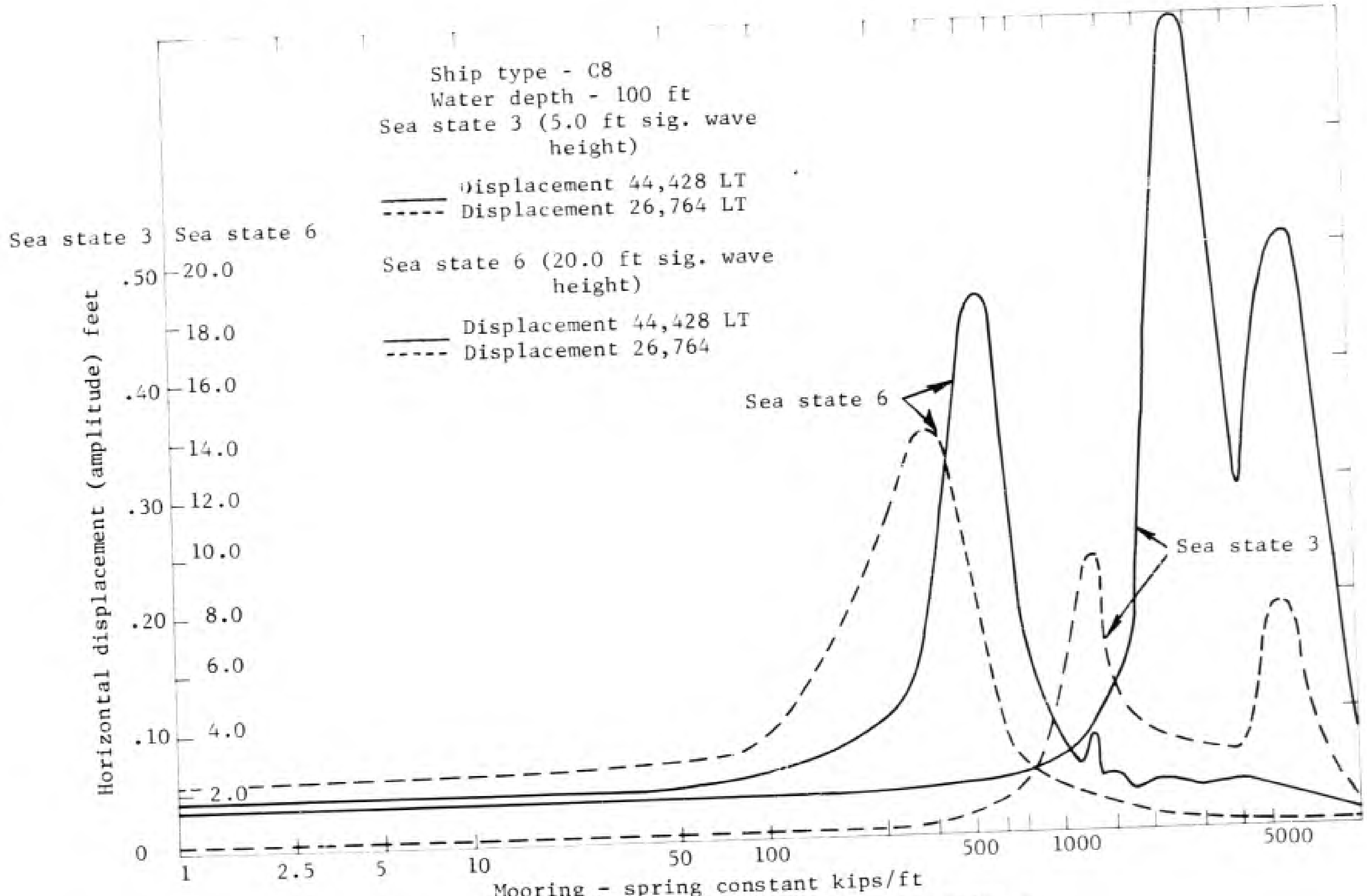


Figure 16. C8 surge with mooring restraint - 100-foot water depth.

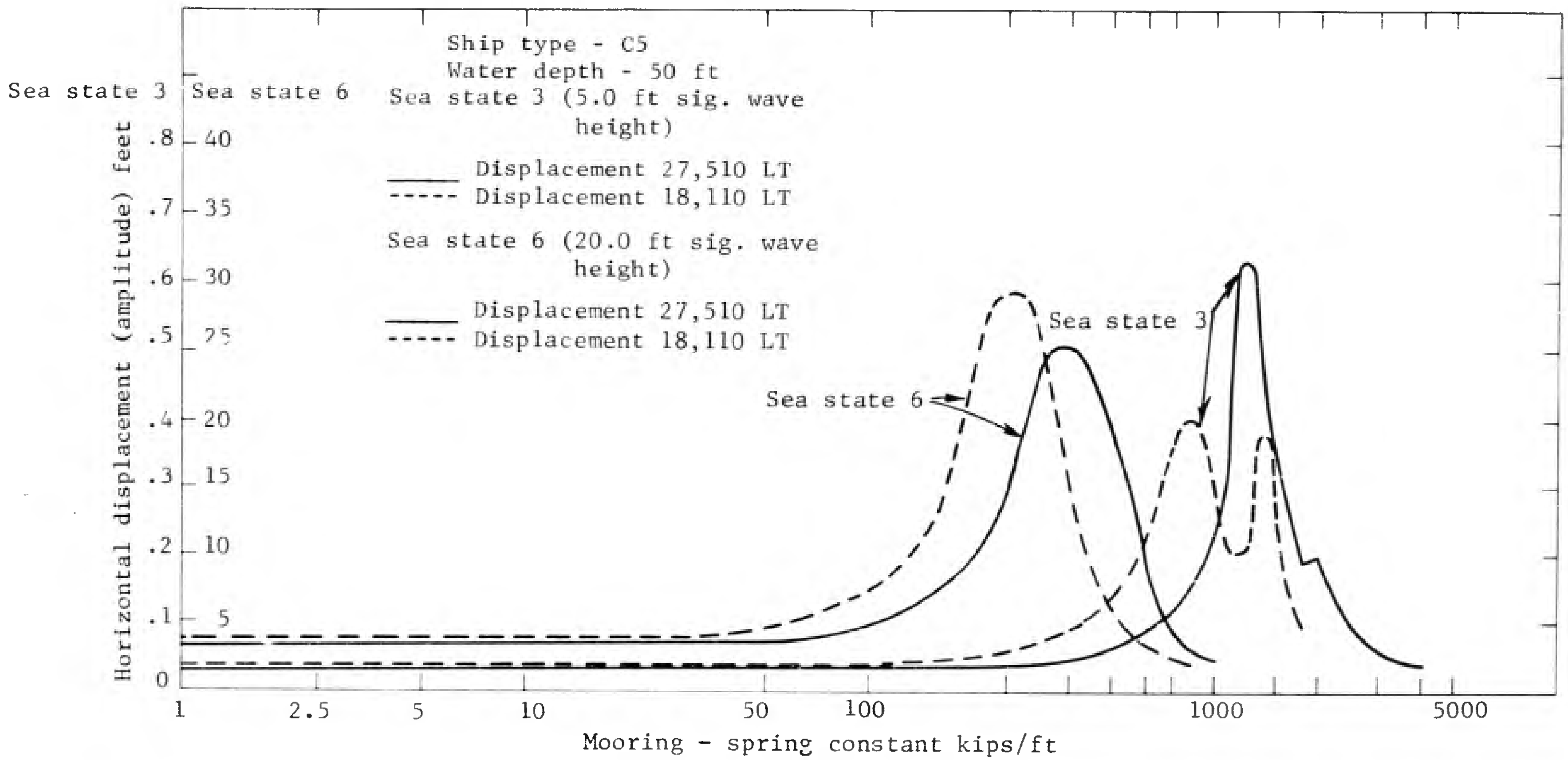


Figure 17. C5 surge with mooring restraint - 50-foot water depth

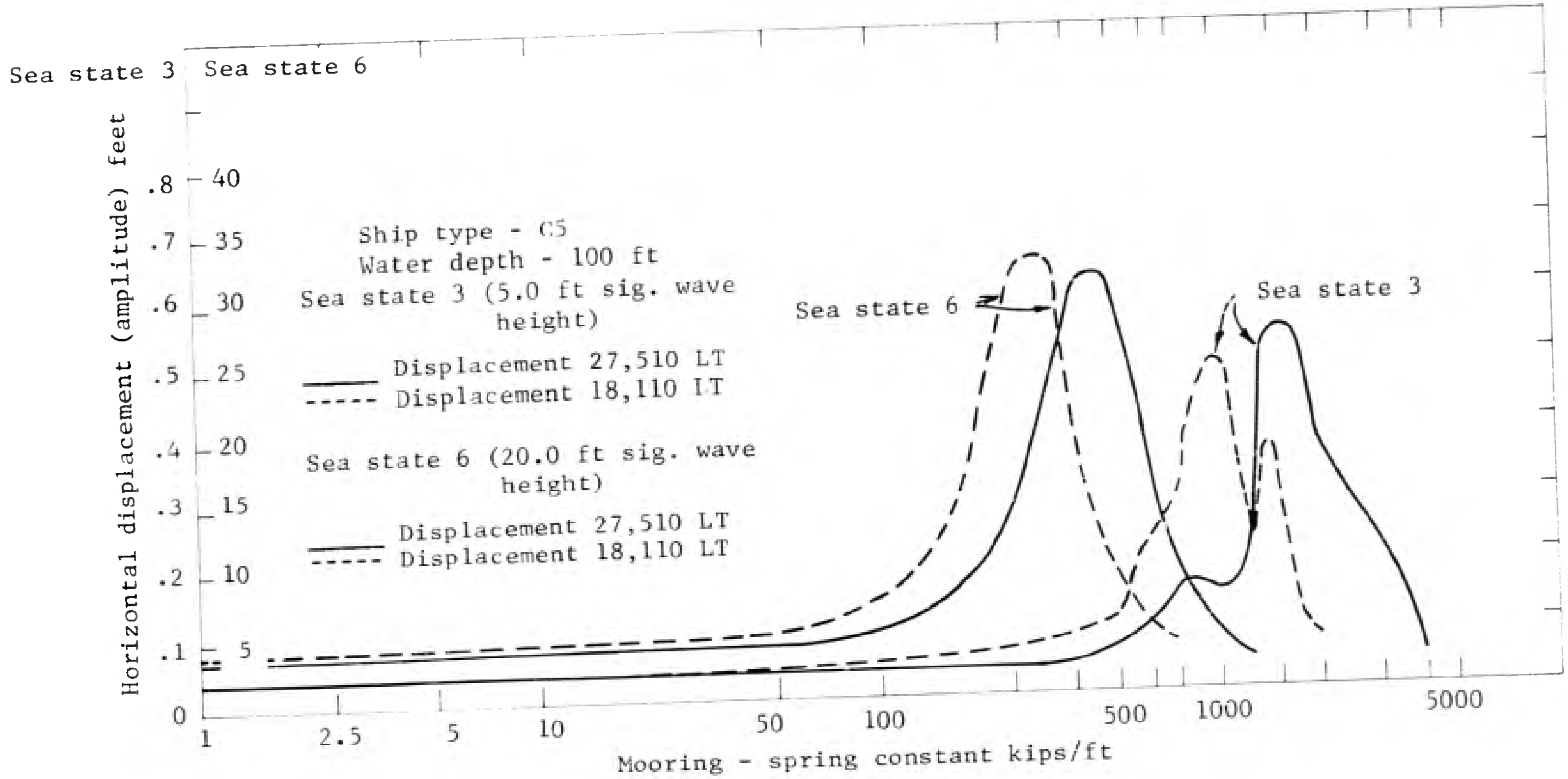


Figure 18. C5 surge with mooring restraint - 100-foot water depth

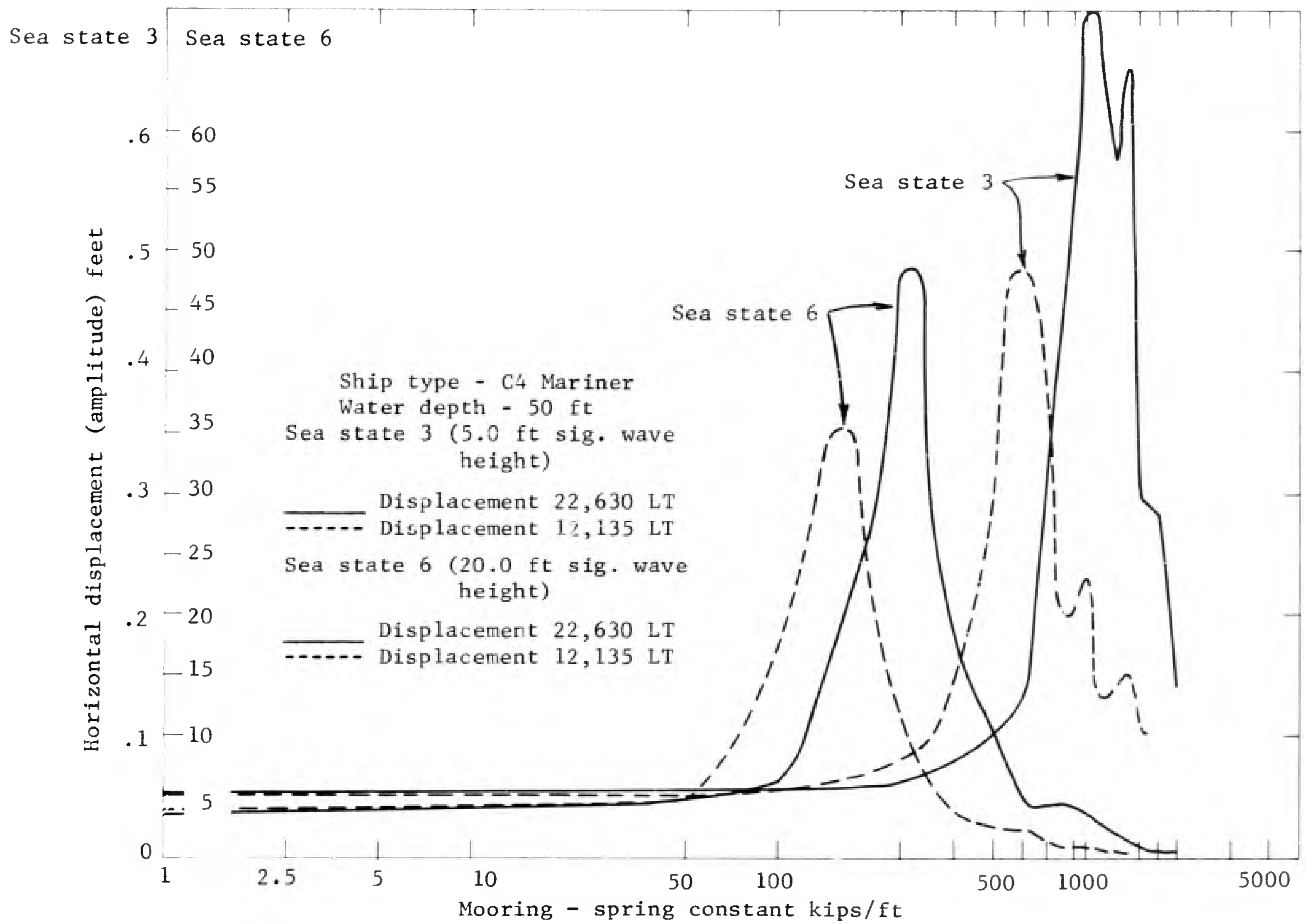


Figure 19. C4 surge with mooring restraint - 50-foot water depth

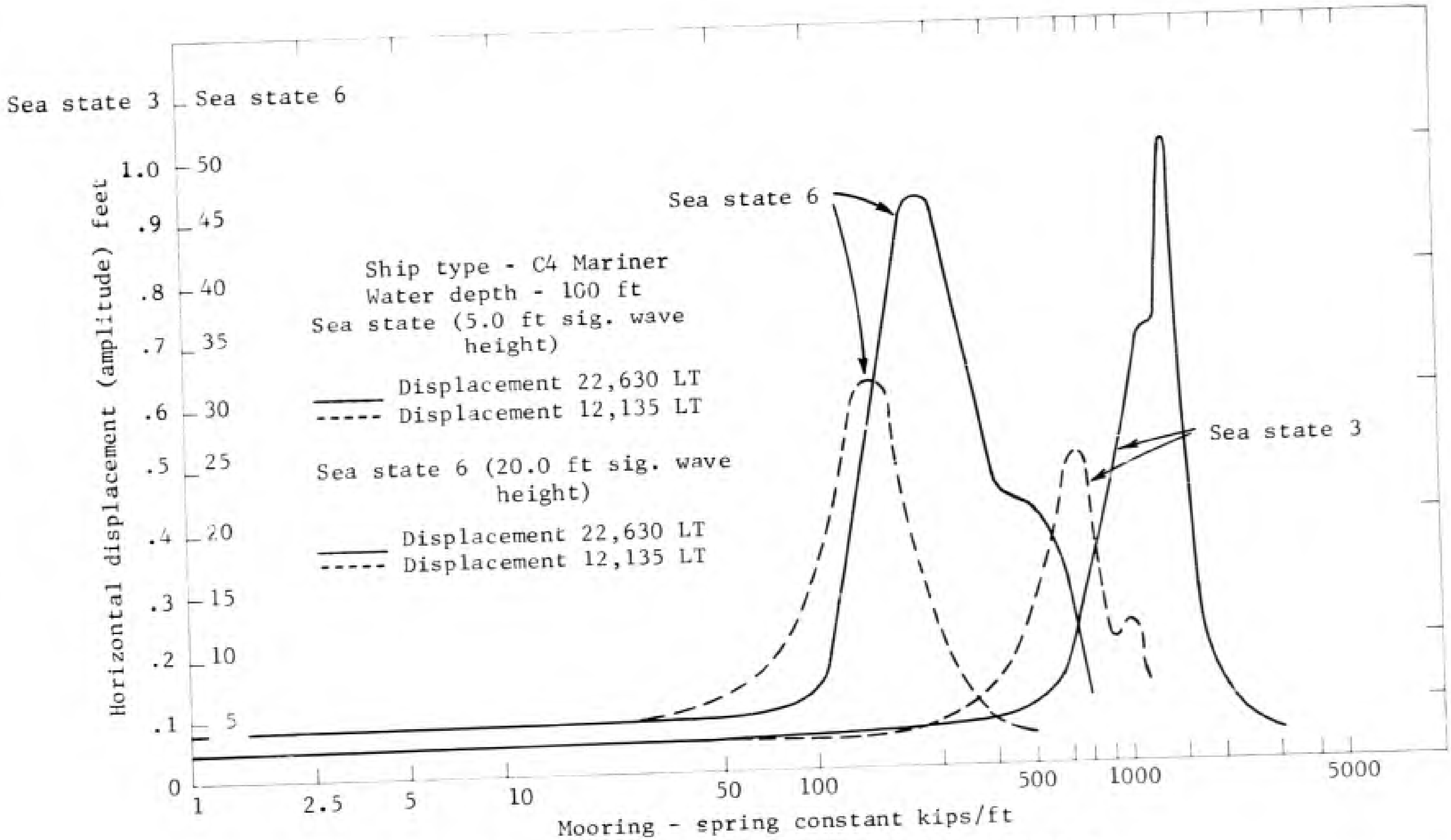


Figure 20. C4 surge with mooring restraint - 100-foot water depth

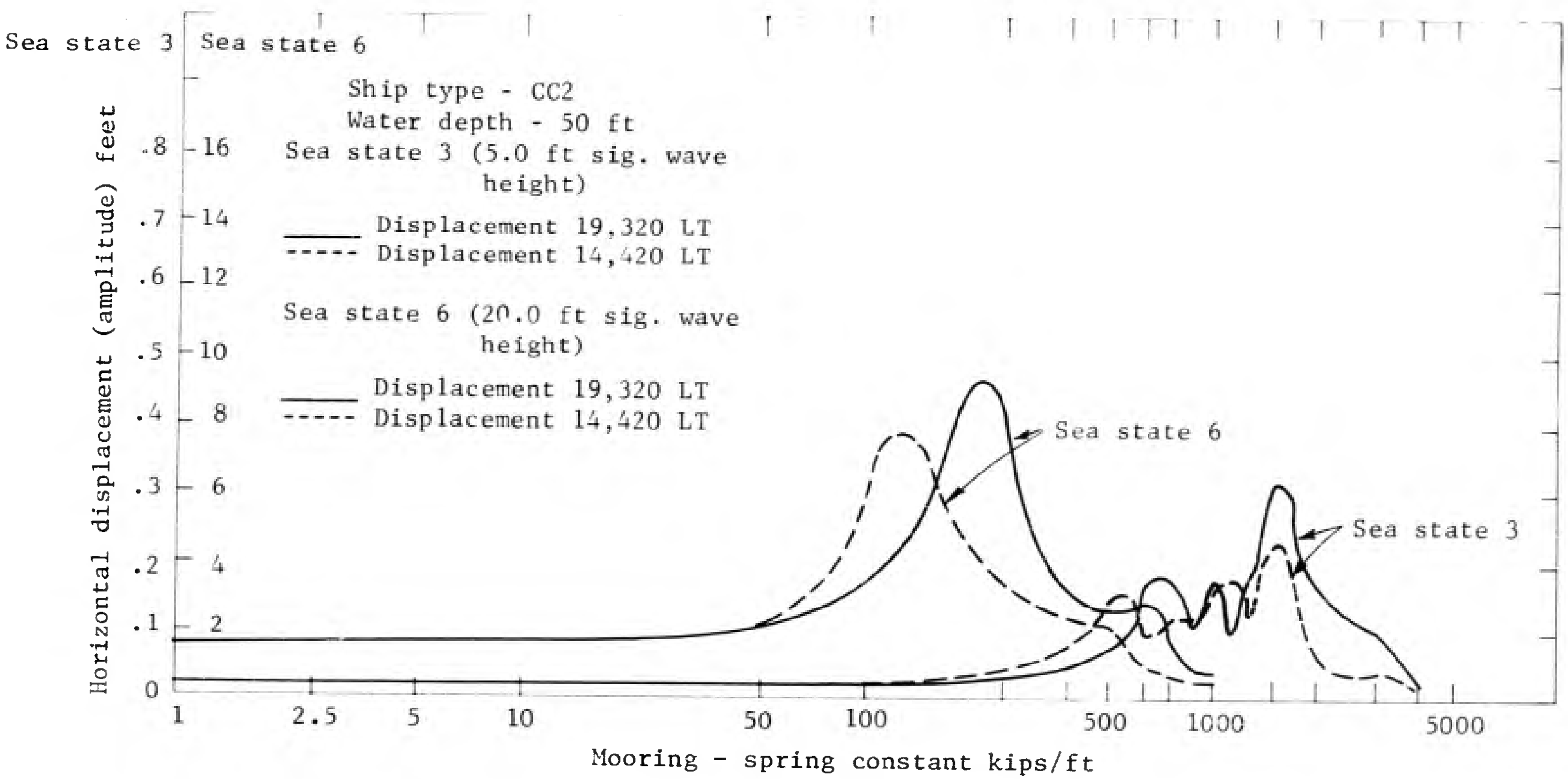


Figure 21. CC2 surge with mooring restraint - 50-foot water depth

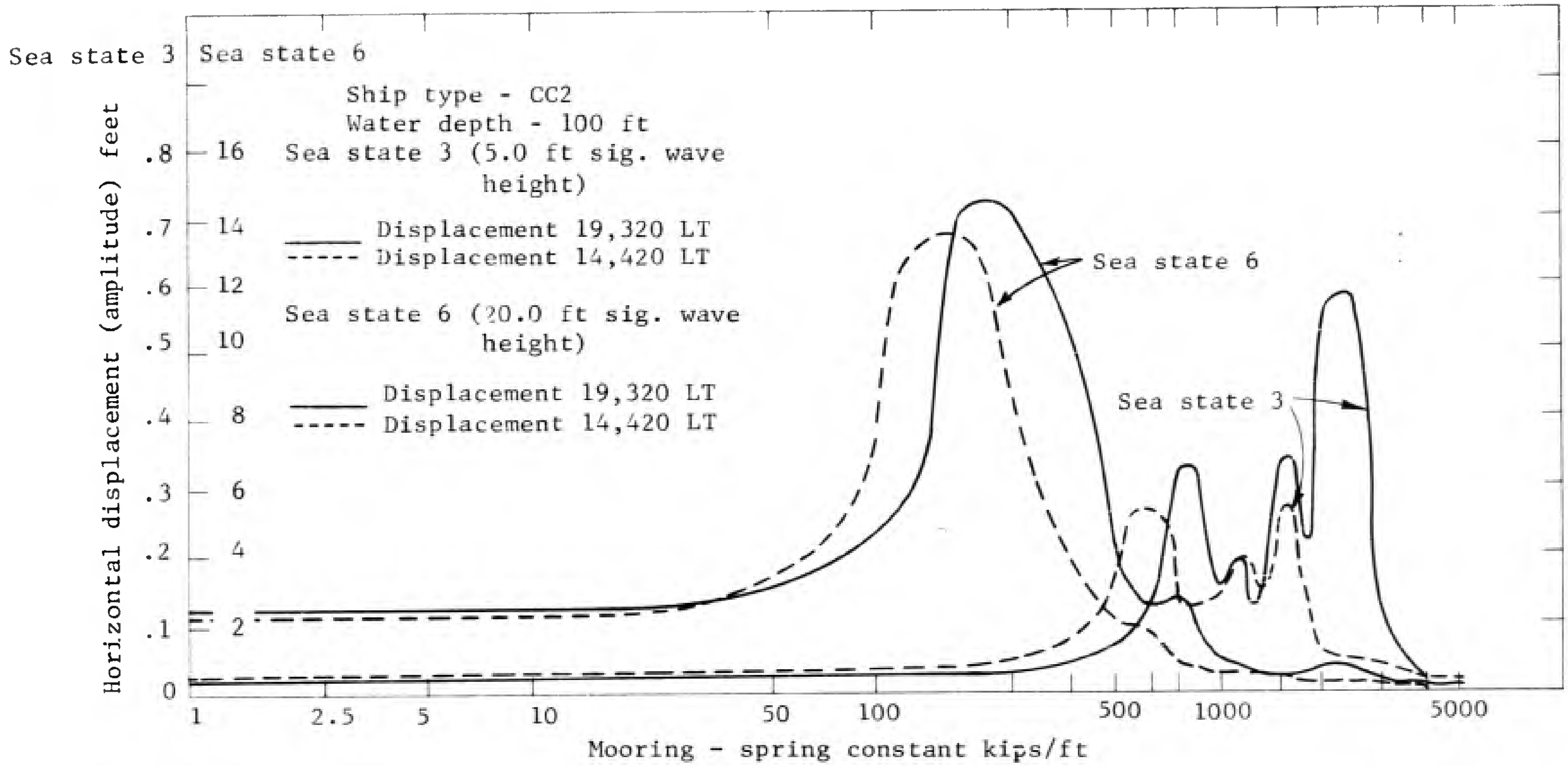


Figure 22. CC2 surge with mooring restraint - 100-foot water depth

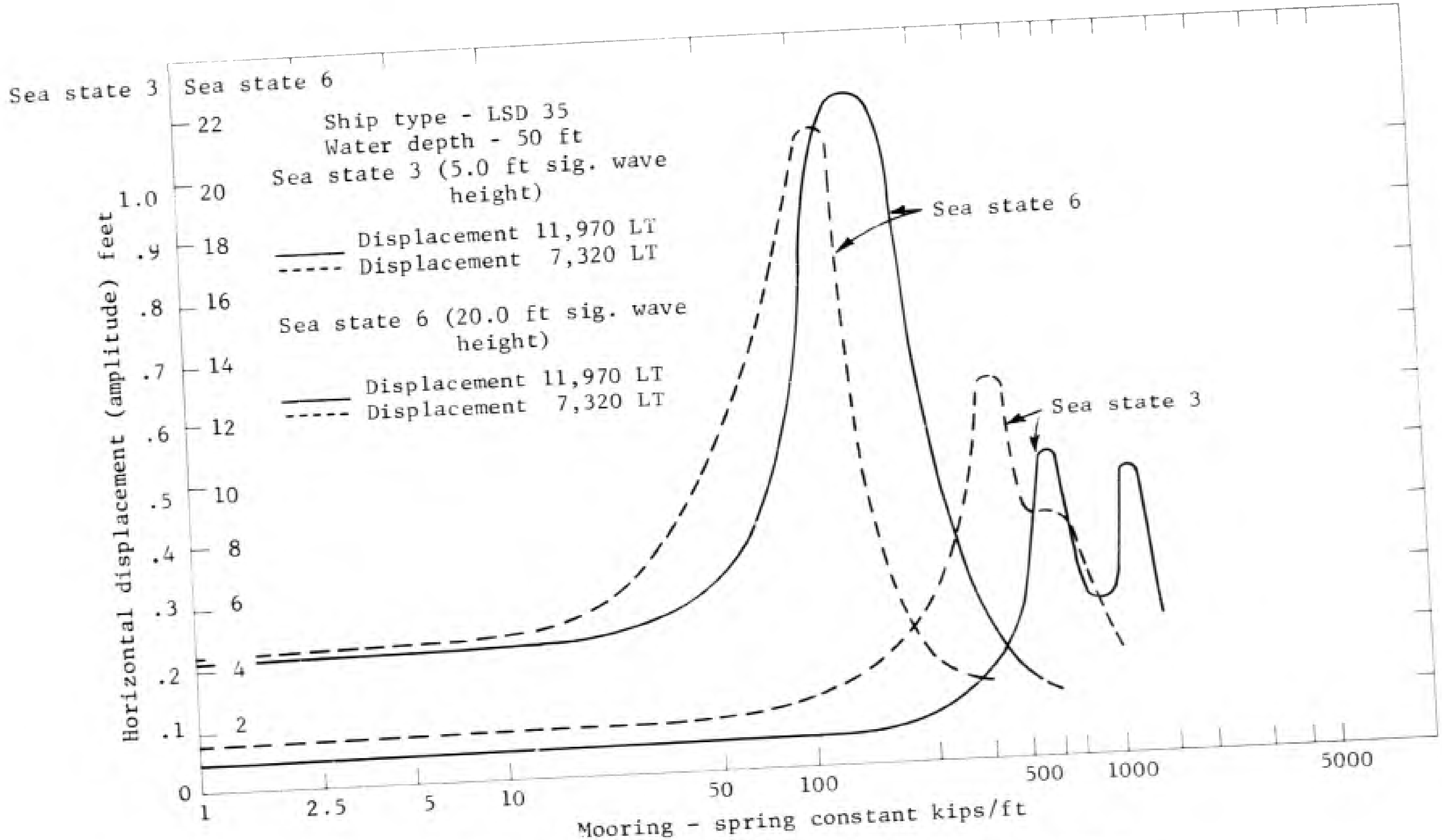


Figure 23. LSD 35 surge with mooring restraint - 50-foot water depth

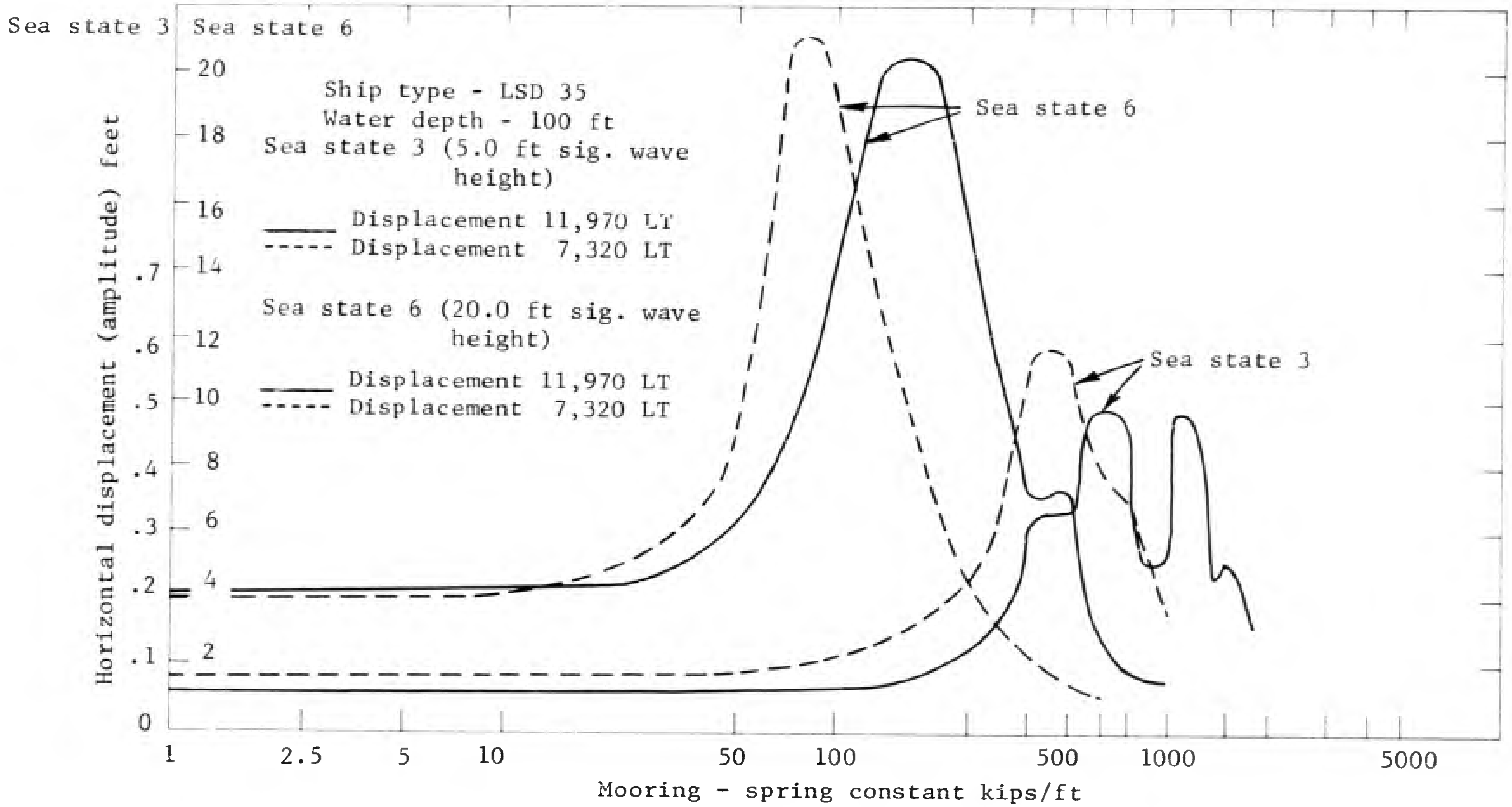


Figure 24. LSD 35 surge with mooring restraint - 100-foot water depth

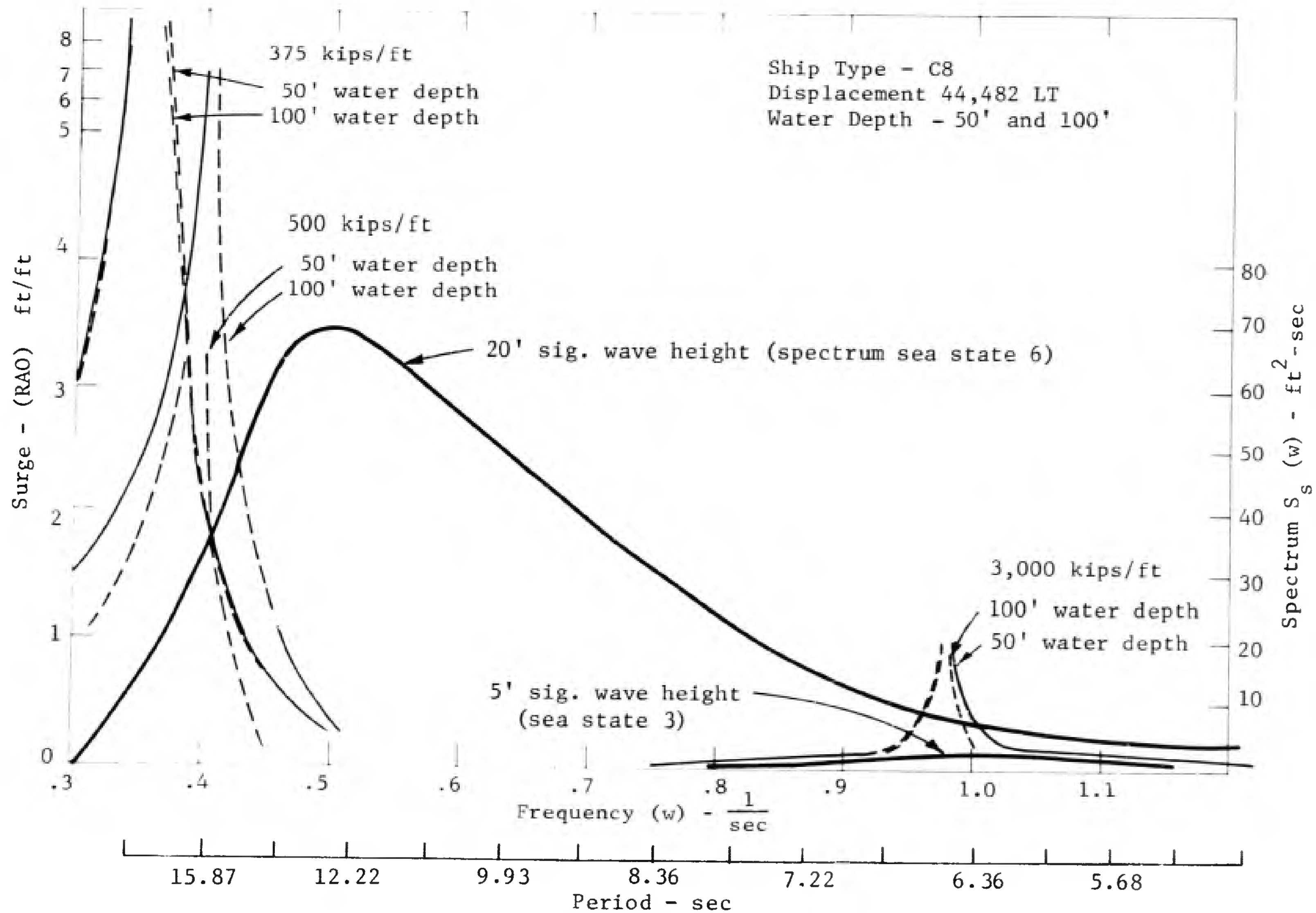


Figure 25. C8 surge response amplitude operator (RAO): 50- and 100-foot water

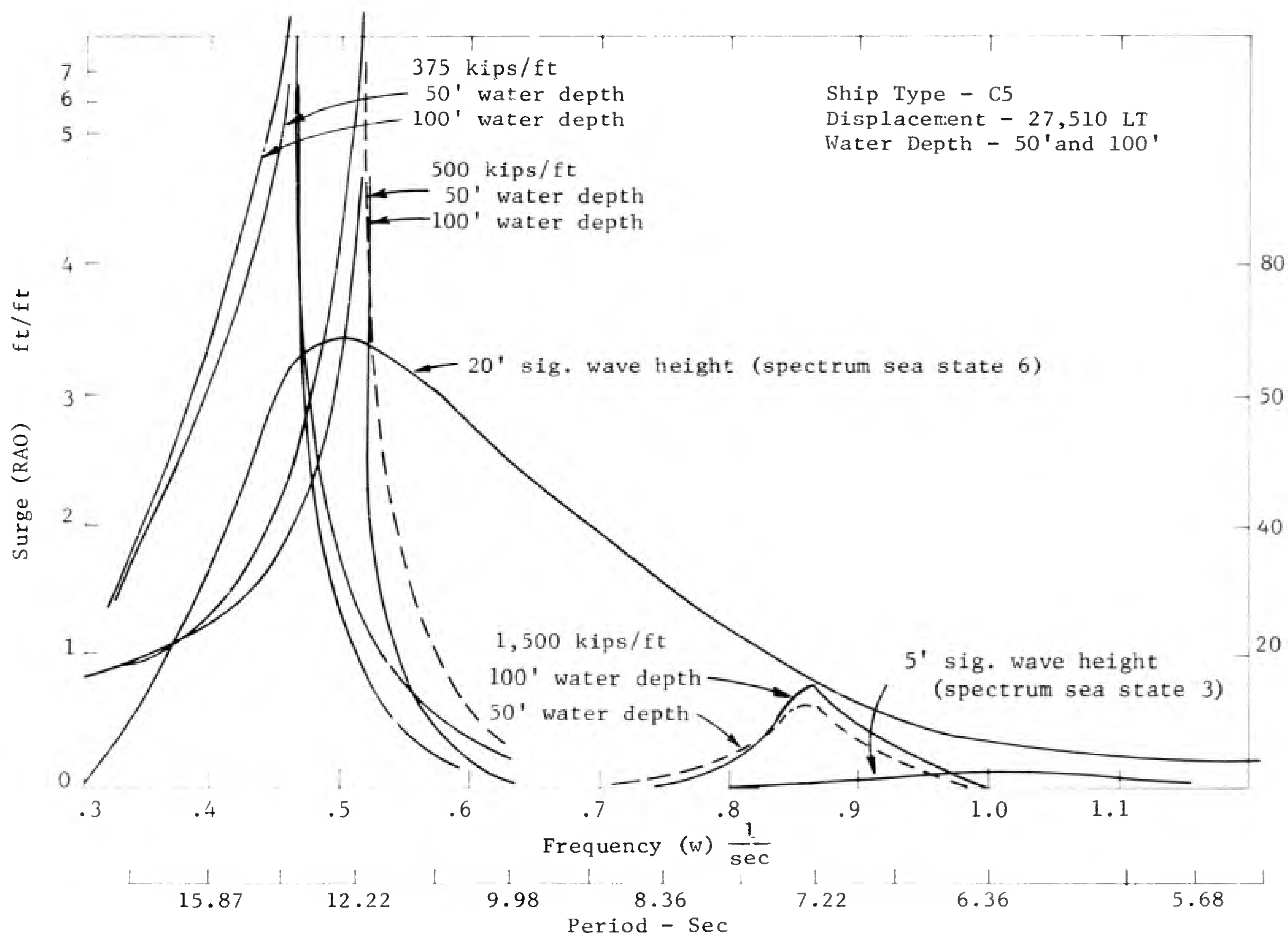


Figure 26. C5 surge response amplitude operator (RAO): 50- and 100-foot water

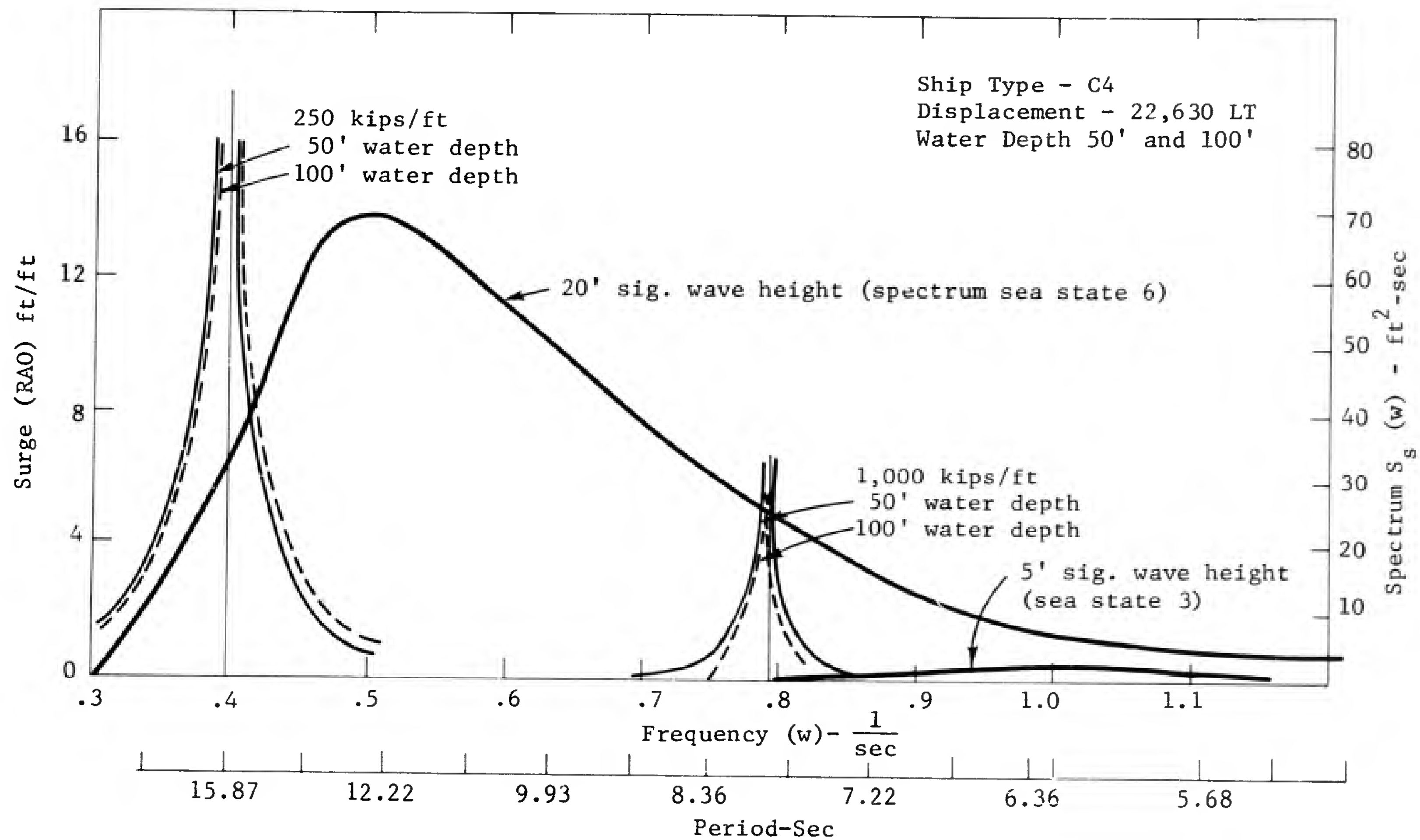


Figure 27. C4 surge response amplitude operator (RAO): 50- and 100-foot water

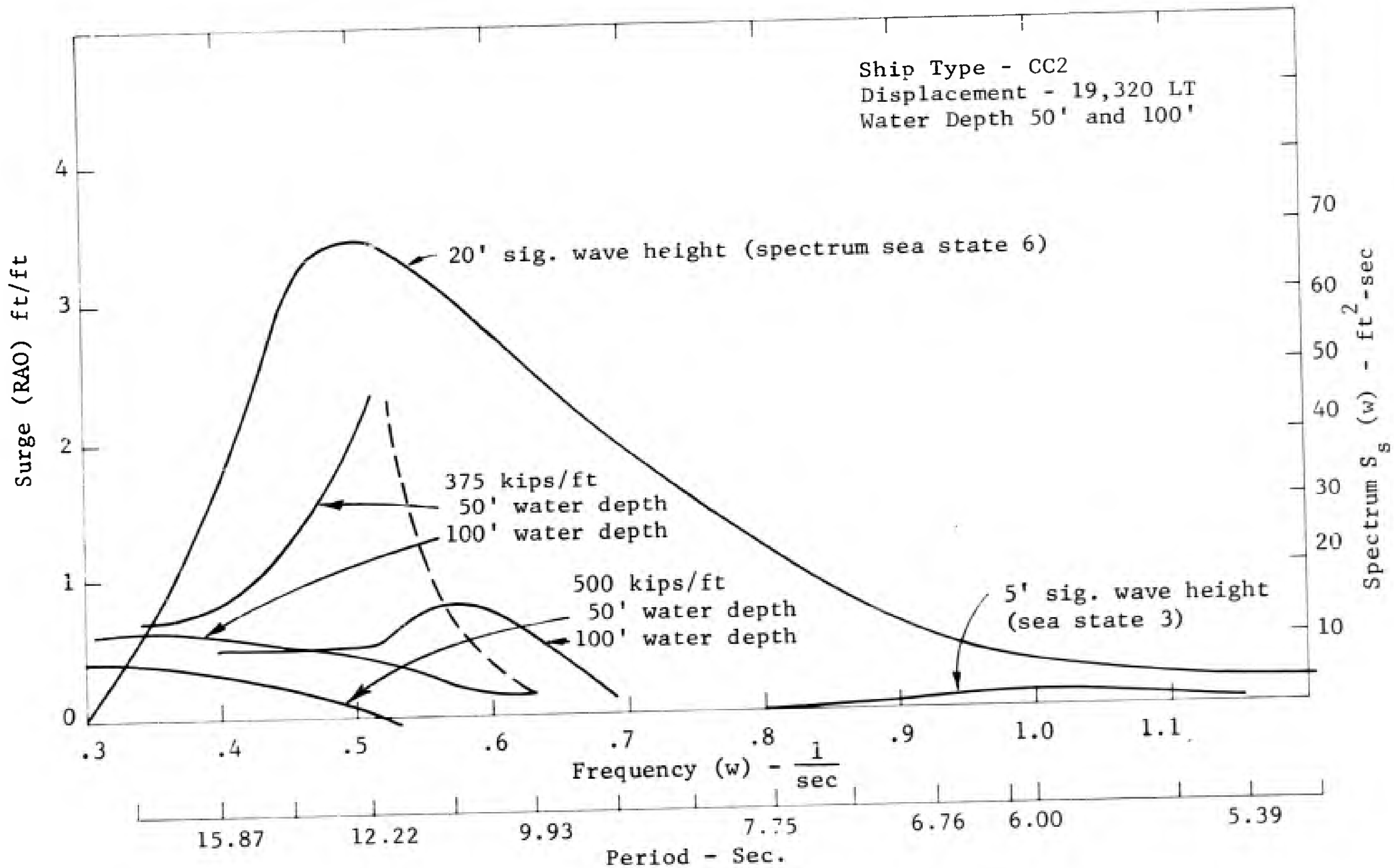


Figure 28. CC2 surge response amplitude operator (RAO): 50- and 100-foot water depth

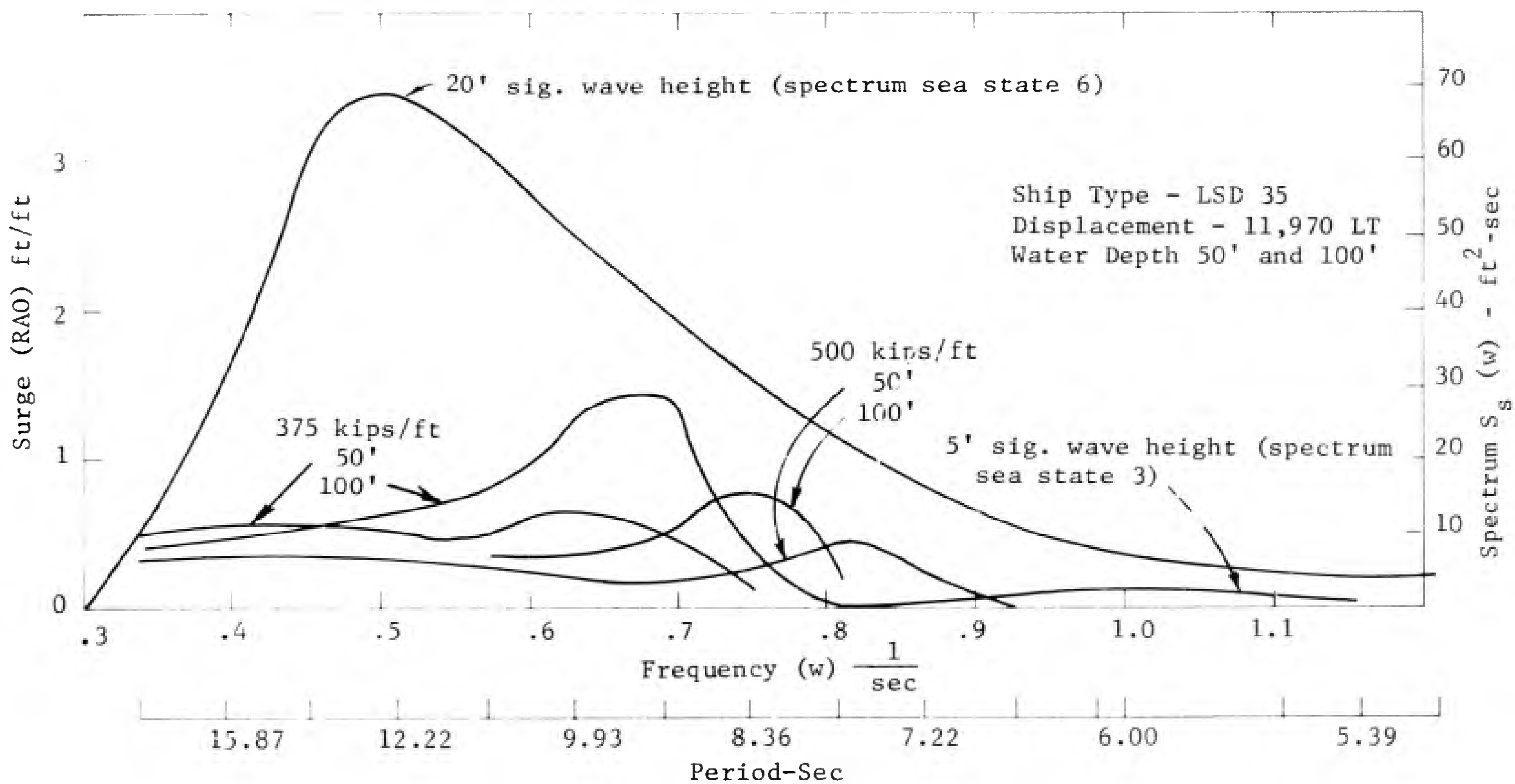


Figure 29. LSD 35 surge response amplitude operator (RAO): 50- and 100-foot water depth

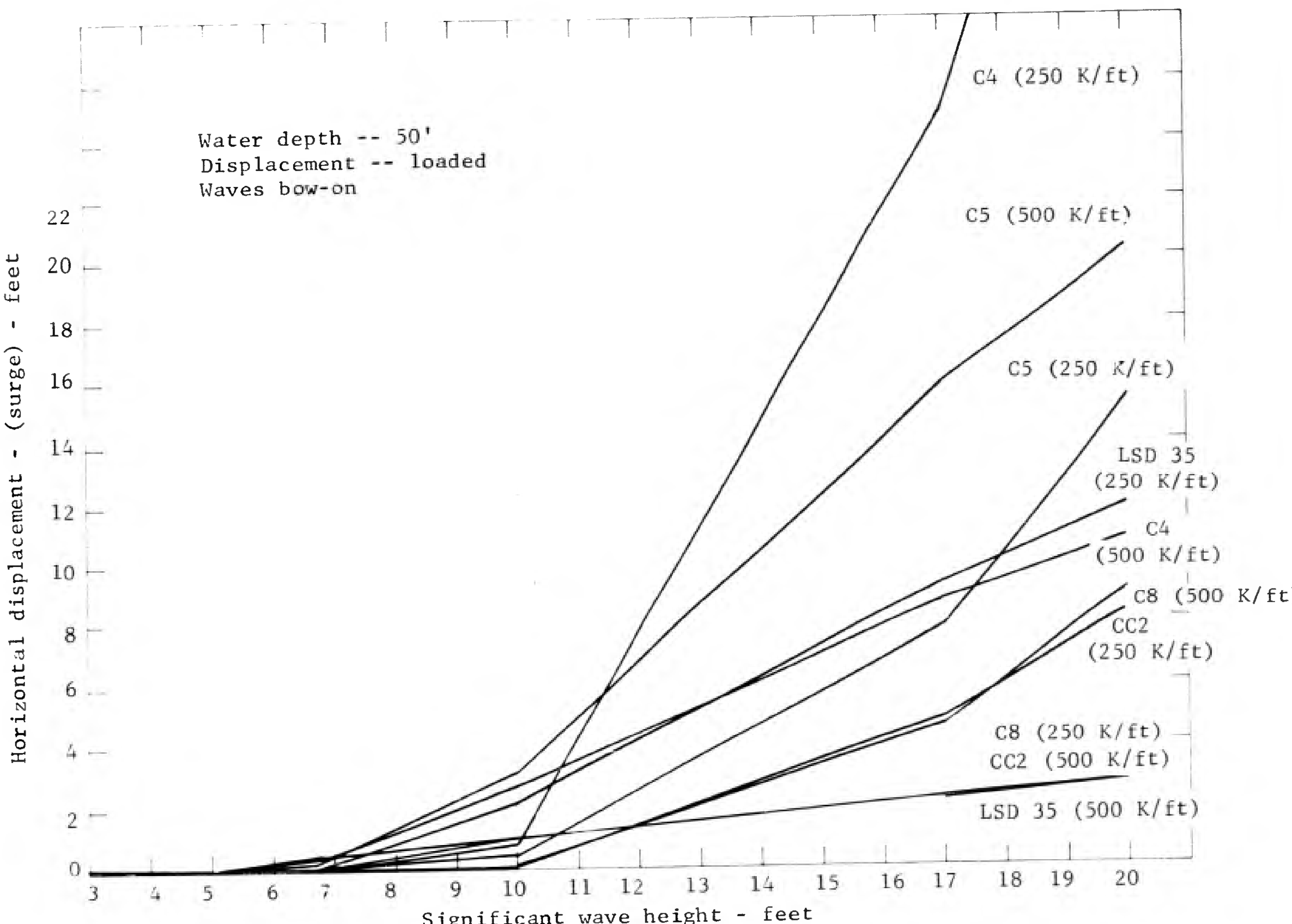


Figure 30. Relation between significant wave height and surge; 50-foot water depth.

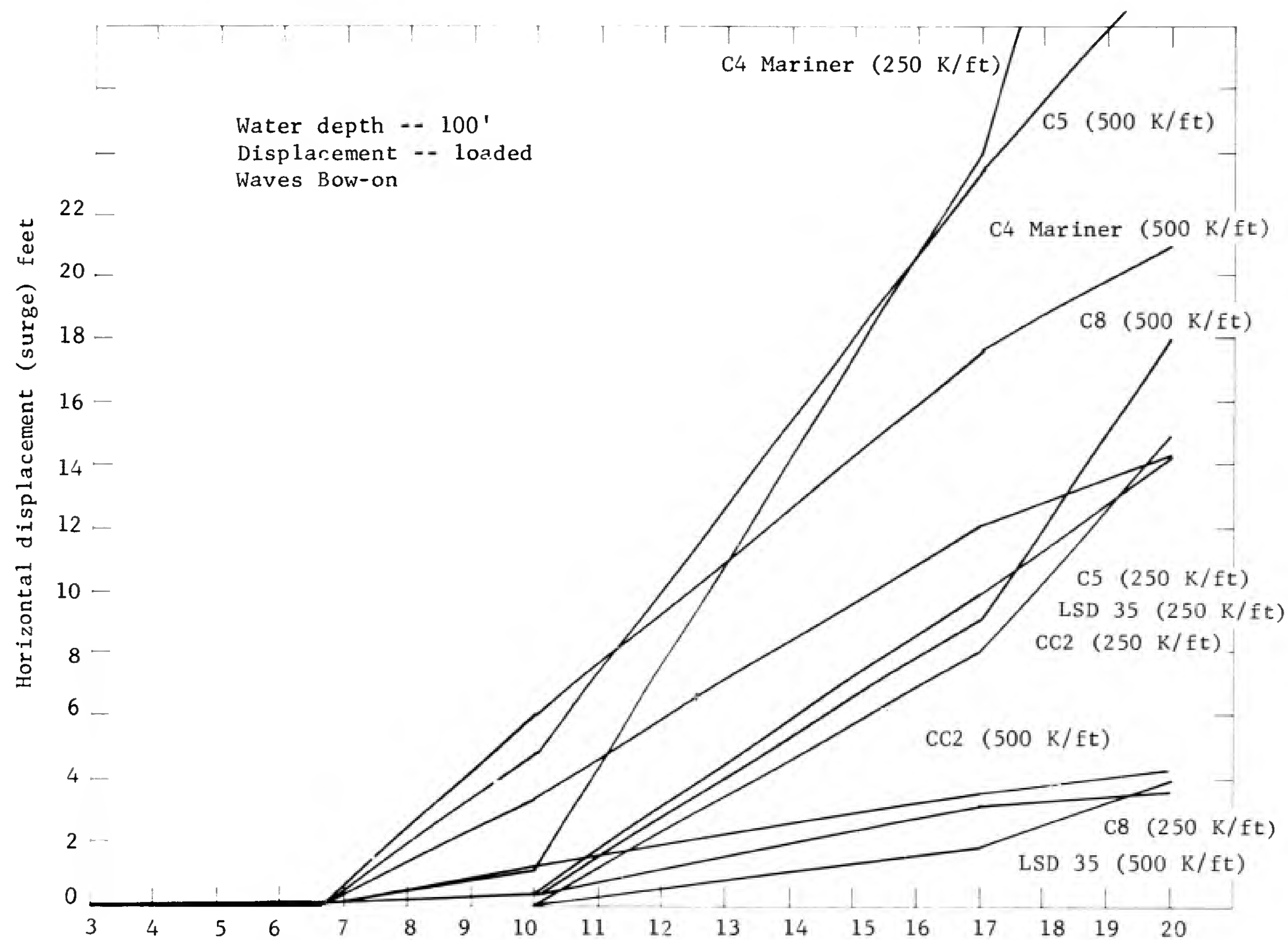
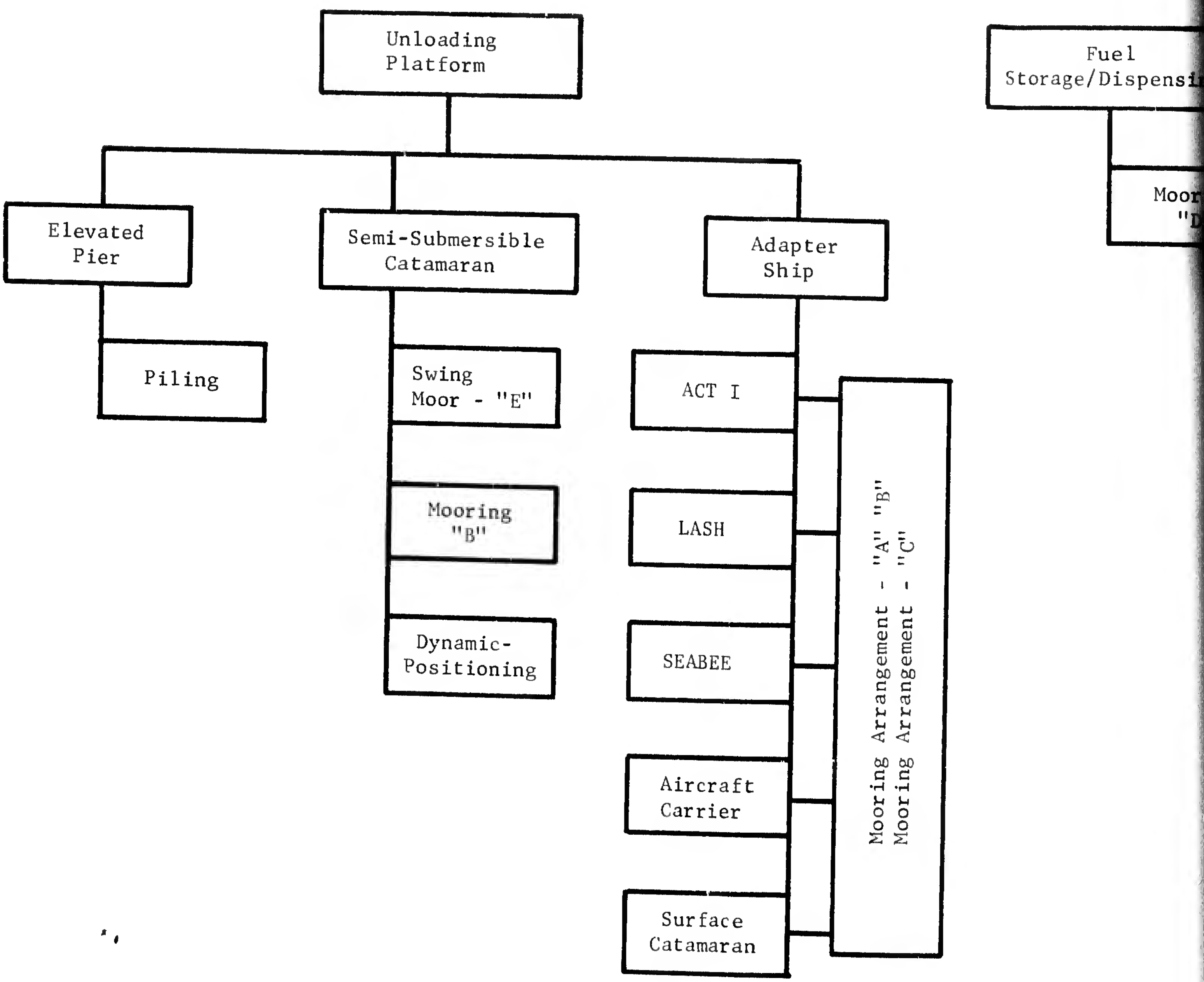


Figure 31. Relation between significant wave height and ship surge; 100-foot water depth.



Unloading Platform
Elevated Pier
Piling
Semi-Submersible Catamaran
Swing Moor - "E"
Mooring "B"
Dynamic-Positioning
Adapter Ship
ACT I
LASH
SEABEE
Aircraft Carrier
Surface Catamaran
Mooring Arrangement - "A" "B"
Mooring Arrangement - "C"
Fuel Storage/Dispensi
Moor

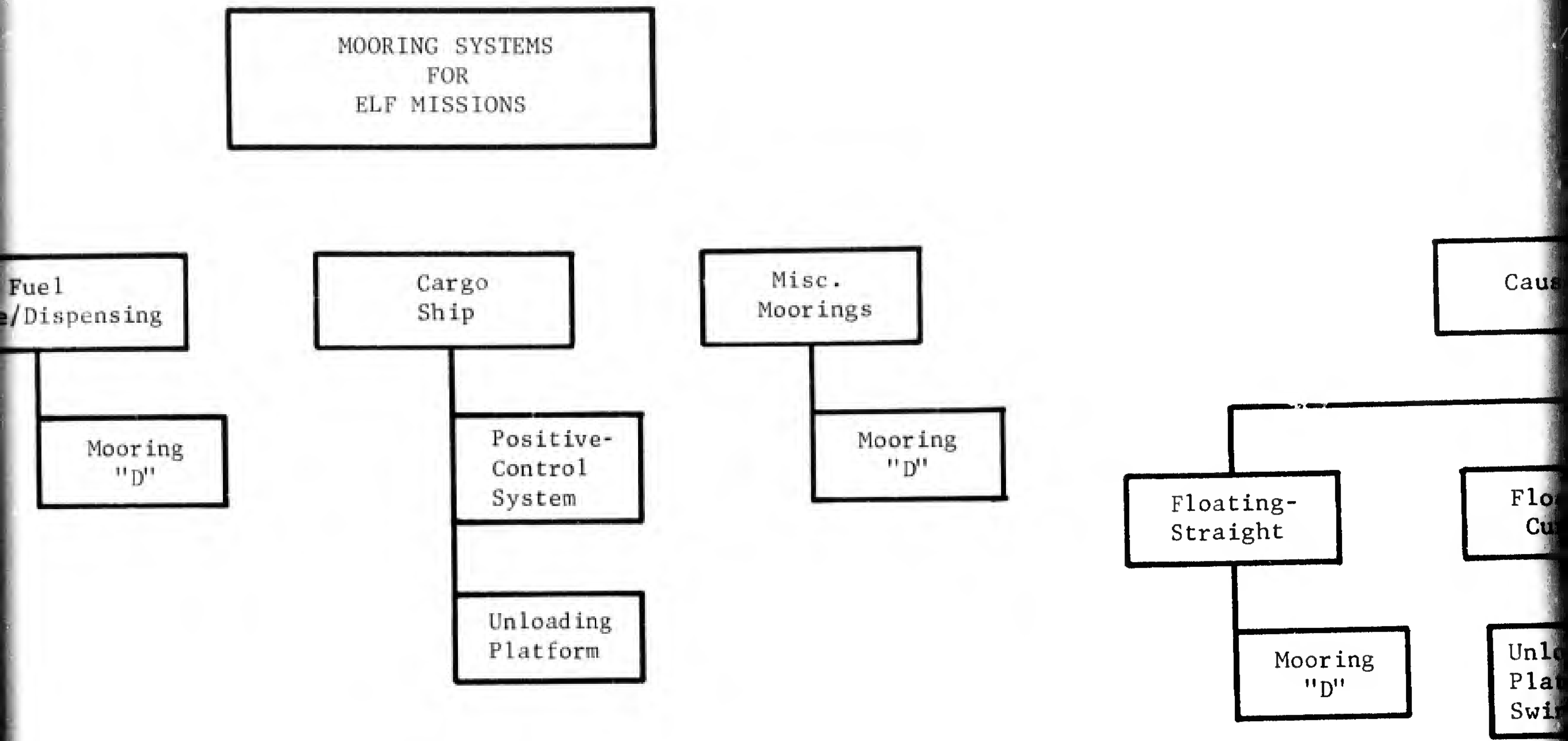
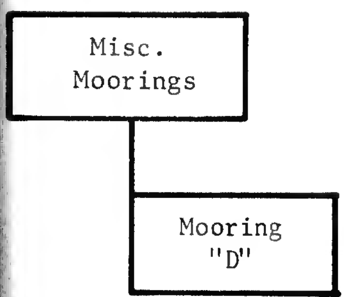
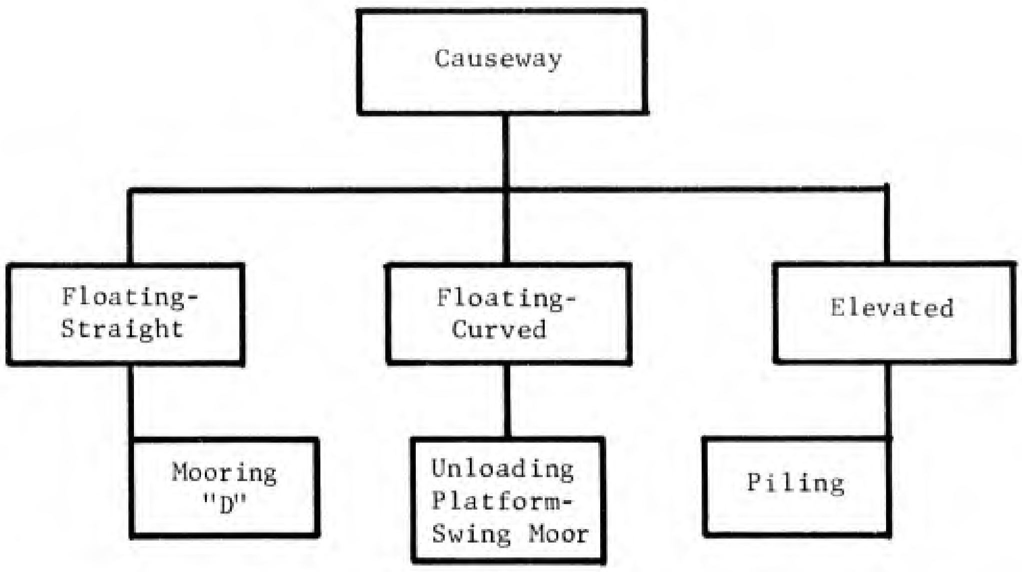

MOORING SYSTEMS
FOR
ELF MISSIONS
Fuel
e/Dispensing
Mooring
"D"
Cargo
Ship
Positive-
Control
System
Unloading
Platform
Misc.
Moorings
Mooring
"D"
Floating-
Straight
Mooring
"D"

Figure 32


Misc.
Moorings
Mooring
"D"


Causeway
Floating-
Straight
Floating-
Curved
Elevated
Mooring
"D"
Unloading
Platform-
Swing Moor
Piling

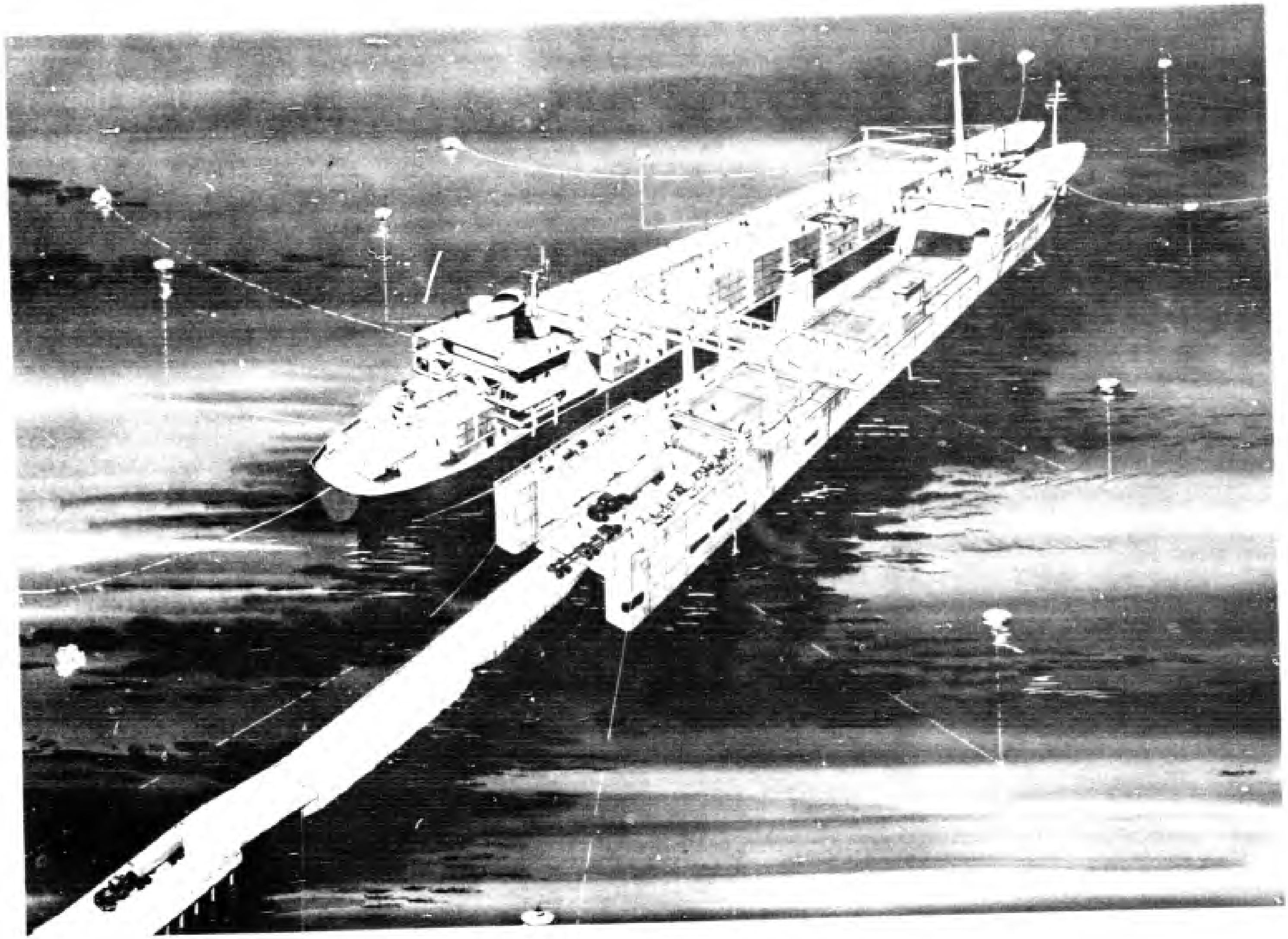


Figure 33. Mooring System "A"

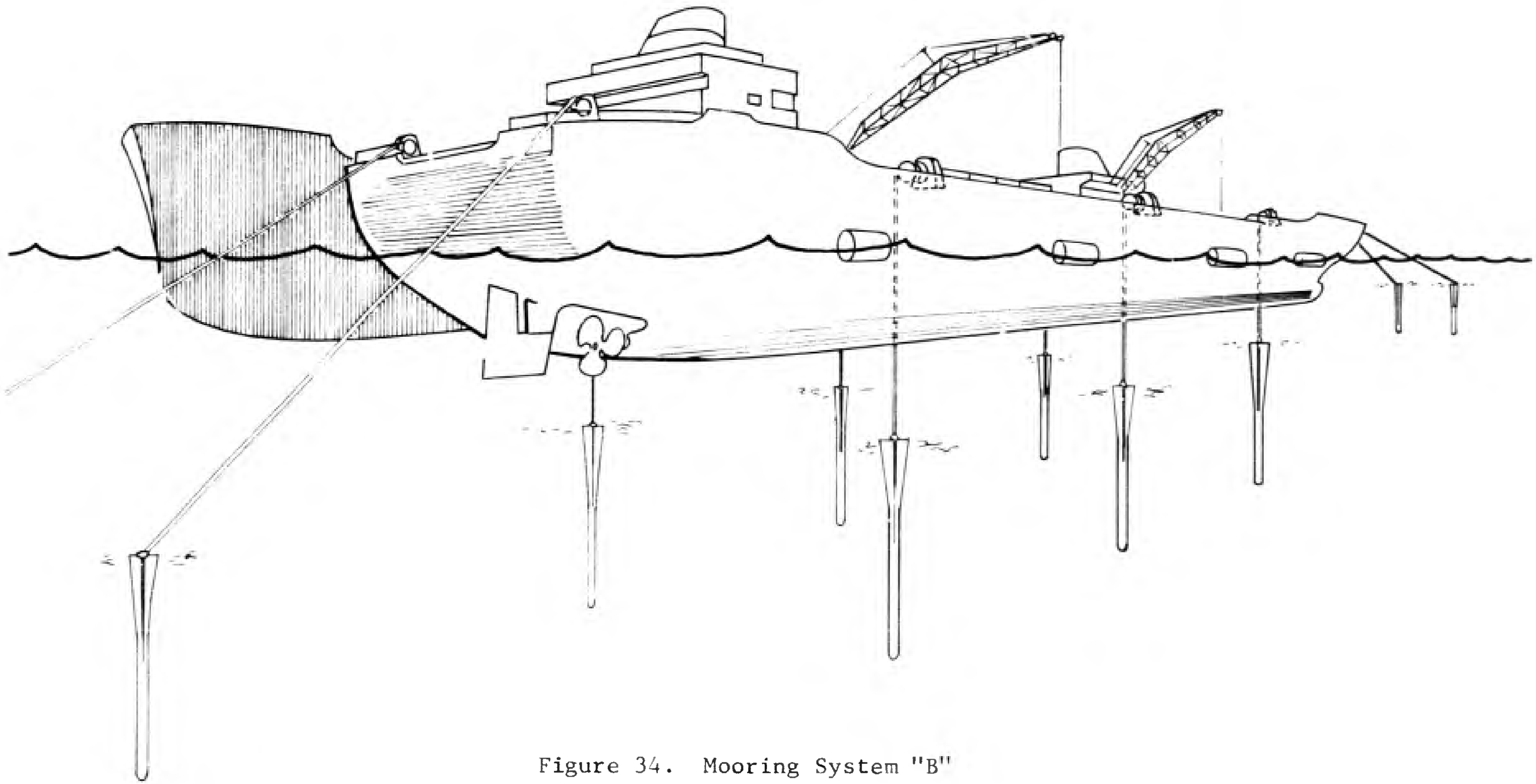


Figure 34. Mooring System "B"

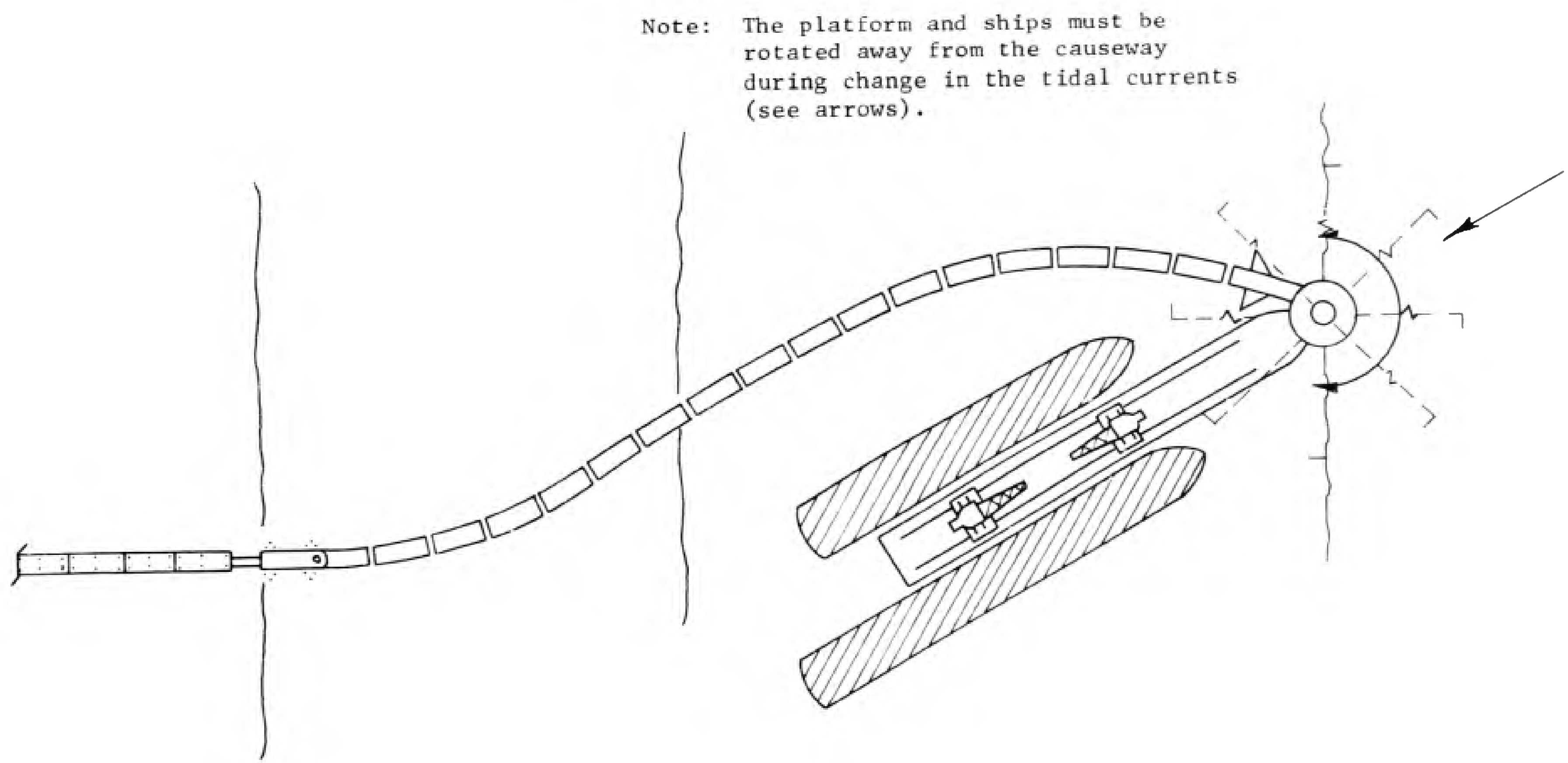


Figure 35. Swing moored unloading platform with two cargo ships.

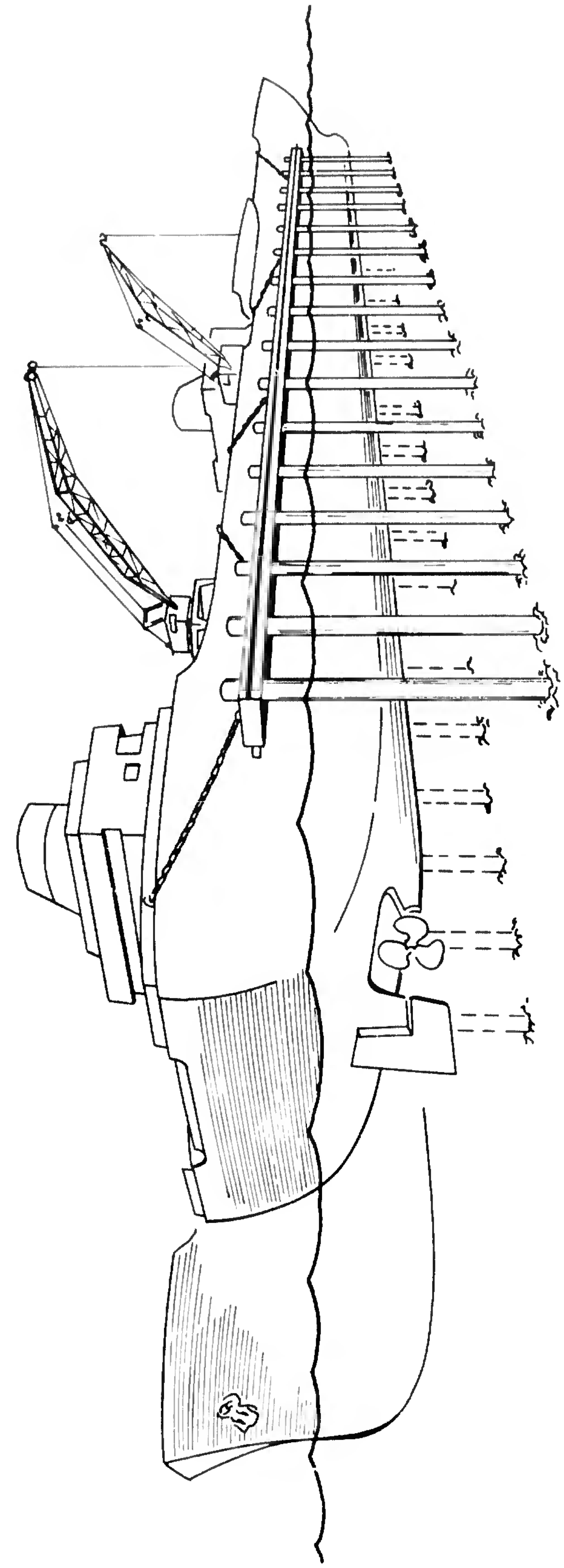


Figure 36. Mooring System "C"

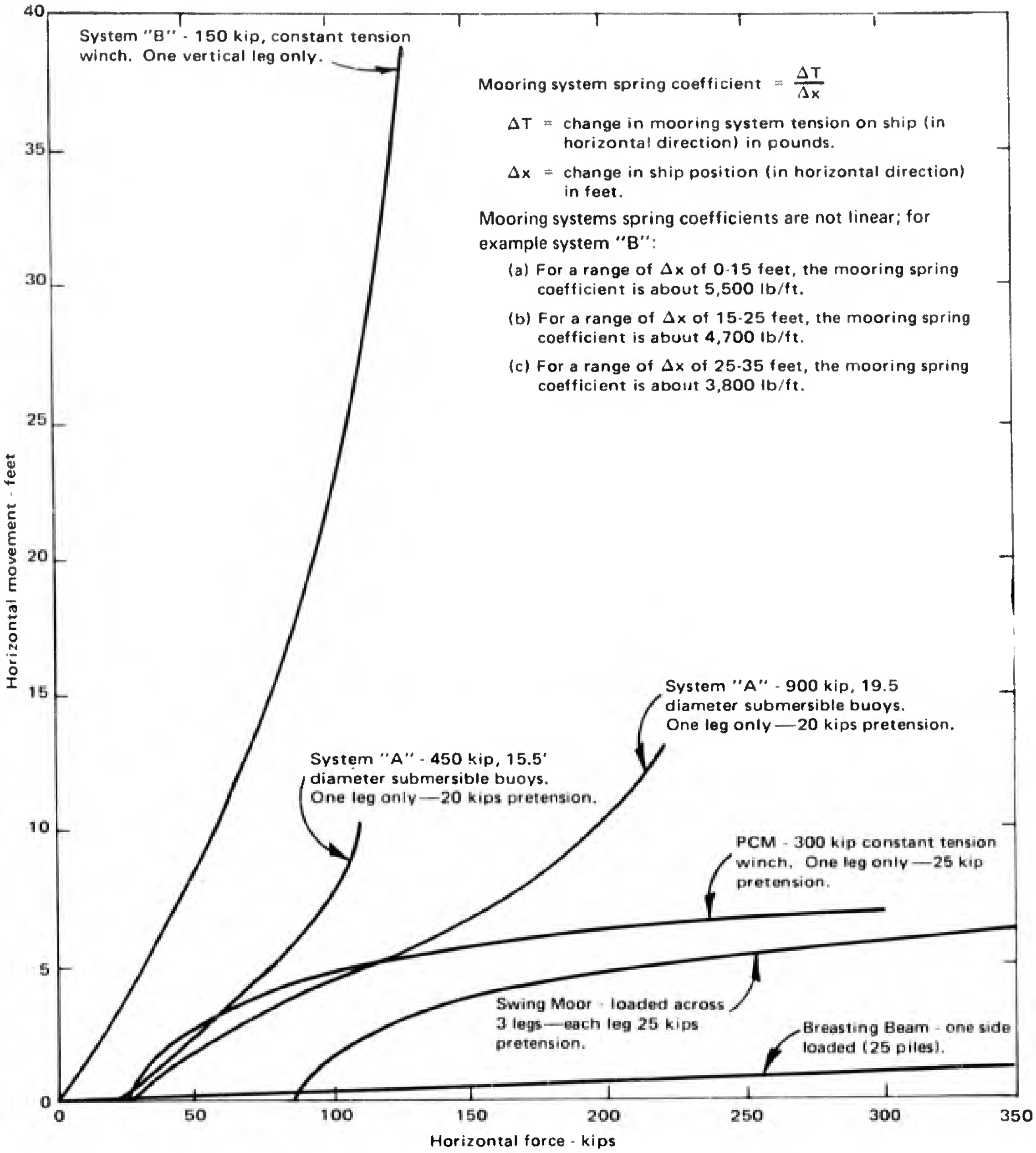
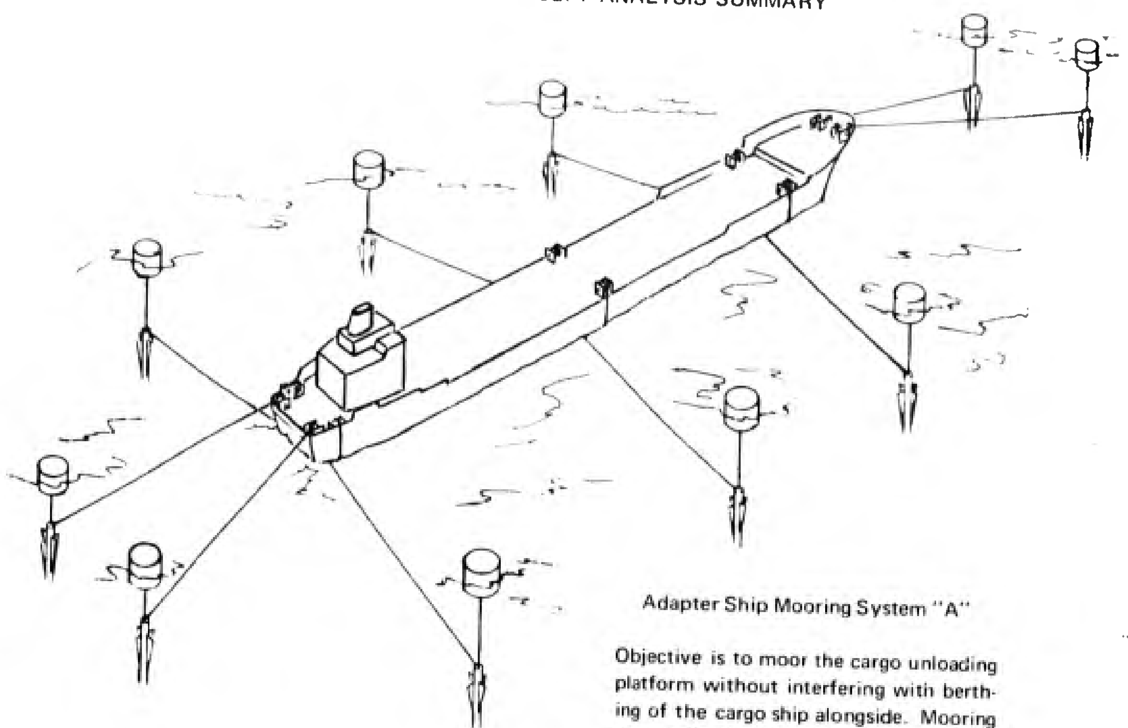


Figure 37. Energy absorption capability of mooring concepts.

PROJECT "ELF" CONCEPT ANALYSIS SUMMARY



Adapter Ship Mooring System "A"

Objective is to moor the cargo unloading platform without interfering with berthing of the cargo ship alongside. Mooring system "A," using state of the art hardware, will accomplish the purpose at a system cost of about $245,000. Platform motion in the sea state 6 criteria will be 9 feet in surge, 3.5 feet in heave.

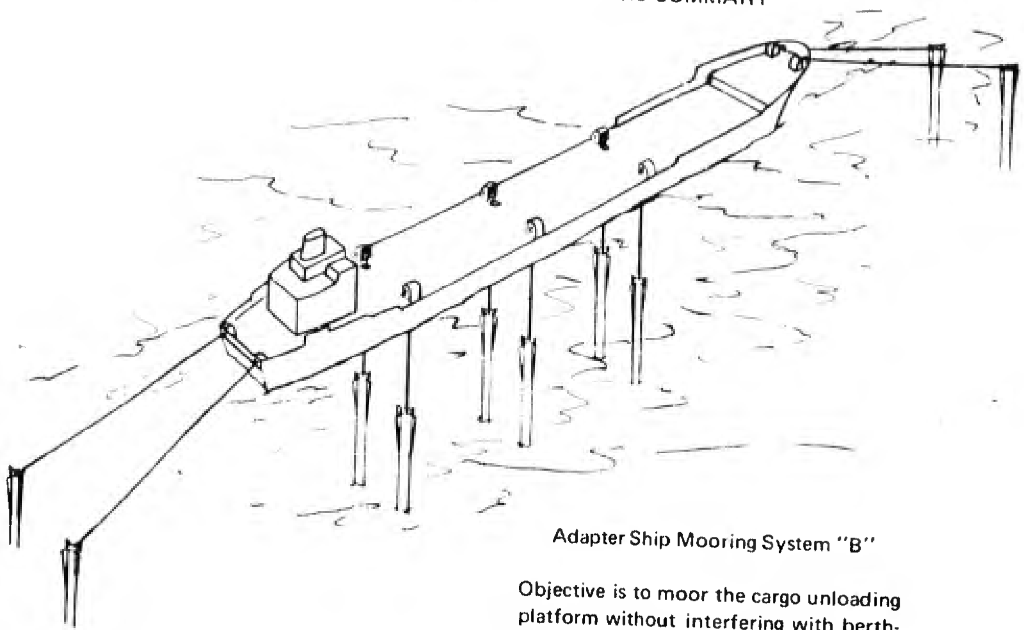
Element	Pacing Problem
1. Anchor—stake pile	11. Burial into hard bottom
	12. Anchor installation in open sea, wave motion
	13. Anchor placement or alignment
	14. Alternate for hard bottom—drilled-in anchor
2. Wire rope	21. Corrosion, wear of wire and fittings
3. Buoy, mooring-tension	31. Corrosion, wear of fittings
	32. Wave/buoy motion
4. Installation equipment	41. Performance of tasks in open seas, wave motions

Experiment

111. Prototype test of stake pile and development of explosive anchor or drilled-in anchors
121. Development and prototype test of installation equipment
131. Operational test of prototype
141. Conduct engineering analysis and prototype test to establish operational procedures
211. Engineering analysis and prototype test to establish wire rope specifications and limitations
311. Cathodic protection analysis
321. Engineering analysis of interaction of buoy, waves, and line tensions
411. Prototype test of hardware to establish operational limitations and procedures

Figure 38. Adapter ship Mooring System A.

PROJECT "ELF" CONCEPT ANALYSIS SUMMARY



Adapter Ship Mooring System "B"

Objective is to moor the cargo unloading platform without interfering with berthing the cargo ship alongside. Mooring system "B," using state of the art hardware, will accomplish the purpose at a system cost of about $1,822,000. Platform motion in the sea state 6 criteria will be 9 feet in surge, 3.5 feet in heave.

Element	Pacing Problem
1. Stake pile	11. Burial in hard bottom 12. Anchor installation in open sea, wave motion 13. Anchor placement or alignment 14. Alternate for hard bottom, drilled-in anchor
2. Wire rope	21. Corrosion, wear of wire and fittings
3. Winch, mooring, constant-tension	31. Continuous operation of winch 32. Unloading platform motion restriction required for cargo unloading operation
4. Installation equipment	41. Performance of tasks in open seas, wave motions

Experiment

111. Prototype test of stake pile to test capacity versus repetitive vertical loads
121. Development and prototype test of installation equipment
131. Operational test of prototype
141. Engineering analysis and prototype test to establish operational procedures

211. Engineering analysis and prototype test to establish failure causes

311. Prototype test of hardware
321. Engineering analysis of cargo unloading/platform motion requirements

411. Prototype test of hardware to establish operational limitations and procedures

Figure 39. Adapter ship Mooring System B.

Table 5. Mooring Components for Unloading Platform

C8 Adapter Ship

Max. Bow-on Force - 150,000 lb.

Max. Beam-on Force - 1,200,000 lb.

Mooring "A"		
Equipment	Cost ($K)	Weight (Kips)
Stake pile, 16" x 3/8" x 100' 16 ea.	14.4	104.8
Buoys, 16 ea. steel, 19.5' dia. rubber 13' dia.	 156.0 512.0	 156.0 184.0
Wire rope, 3" dia., 400' 16 ea.	49.6	96.6
Accessories, (sheaves, fittings)	20.0	64.0
Hardware Buoys: steel rubber	 240.0 596.0	 421.5 449.5
Installation (15 men) 10 days	5.0	
Total steel rubber	$245.0 $601.0	421.5 449.5

Table 6. Mooring Components for Unloading Platform

Semi-Submersible plus Two Cargo Ships

Max. Bow-on Force - 228,000 lb.
Max. Beam-on Force - 1,200,000 lb.

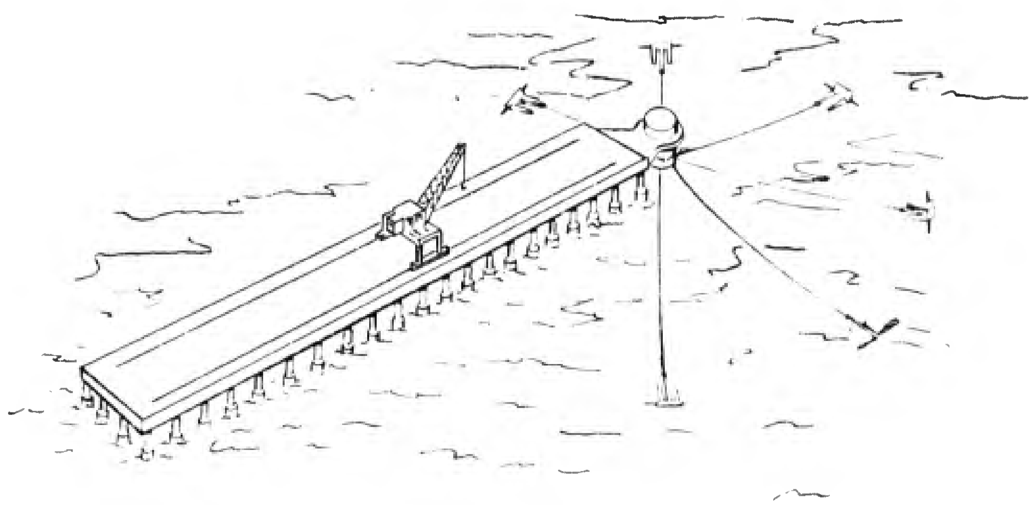
Swing Moor

Equipment	Cost ($K)	Weight (K)
Anchors, 20,000# STATO, 16 ea.	124.0	320
Chain, 3-in. dielock, 370-ft leg, 8 ea.	65.0	192
Chain, 2 3/4-in. dielock, 90-ft leg, 8 ea.	19.0	54
Accessory gear, joining links, etc.	2.0	2
Buoy, special, 35-ft dia., 1 ea.	150.0	150
Hardware	360.0	718
Installation (10 men) 10 days	2.0	
Total	$362.0	718

Mooring "B"

Equipment	Cost ($K)	Weight (K)
Stake pile, 16" ϕ x 3/8 x 30' 12 ea.	7.2	24.0
Wire rope, 1 1/2" ϕ, 300-ft. 12 ea.	7.2	14.4
Fittings	2.6	2.6
Winch, constant-tension 150,000#, 12 ea.	1,180.0	600.0
Hardware	1,817.0	641.0
Installation (15 men) 10 days	5.0	
Total	$1,822.0	641.0

If a floating causeway is attached to the swing-moor as shown in Figure 34, then four additional mooring legs will be needed to compensate for the forces on the causeway. This would increase the total cost to $420,000 and the weight to 861,000 pounds.



Adapter Ship Swing Moor

Objective is to moor the cargo unloading platform without interfering with berthing the cargo ship alongside. The swing moor system, using state of the art hardware, will accomplish the purpose at a system cost of about $511,700. This system must survive a sea state 6 wave environment.

Element	Pacing Problem
1. Anchor	11. Burial into hard ocean bottom
	12. Alternate for hard bottom; drilled-in anchor, explosive anchor
2. Chain	21. Corrosion, wear of chain & fittings
3. Buoy	31. Logistics, design, operation

Experiment

111. Development and prototype test of explosive anchor or drilled-in anchors

121. Conduct engineering analysis and prototype tests to establish operational alternate

211. Cathodic protection development as determined by engineering analysis

311 Engineering analysis and prototype test to determine operational limitations

Figure 40. Adapter ship Swing Moor.

Table 7. Mooring Components for Cargo Ship

Max. bow-on force - 150,000 lb.
Max. beam-on force - 1,200,000 lb.

Positive Control Mooring

Equipment	Total Cost ($K)	Weight (Kips)
Anchors, ea. 20,000# STATO, 10 ea.	77.5	200
Chain, 600-ft leg, 12 ea., 3-in dielock	180.0	535
Accessory gear (links, etc)	1.5	2
Winch, mooring, constant-tension, 10 ea. 300k capacity	1,500.0	600
Buoy, mooring winch, 10 ea. 30-ft dia.	200.0	500
Wire rope, 2 1/2-in. dia., 12,000 ft.	500.0	1,200
Generator, switch control, 10 ea. 440v, 60 cyc, dc, 3 phase	100.0	100
Hardware Total	2,109.0	3,137
Installation (10 men) 1 week	20.0	
Total	$2,109.0	3,137

Unloading Platform

Cargo ship tied to unloading platform. Check unloading platform for mooring system.

Equipment	Cost ($K)	Weight (Kips)
Winch, mooring 50k cap., 10 ea.	1,300	600
Wire rope 12,000 feet	500	1,200
Tug, 2,500 hp 2 ea.	*	-----
Total	1,800	1,800

*Cost to lease tug is about $6,000 per day.

Mooring Concept C. This system has a breasting platform on each side of the adapter ship, as shown in Figure 36. The platforms are supported by high strength steel pipe piles driven into the ocean bottom. Twenty-five piles grouped into 5 breasting dolphins of 5 piles each are used in each breasting platform to resist the specified environmental operating conditions imposed by ELF. The spring constant of one breasting platform is 304,000 pounds per foot. Table 8 lists the hardware components for this system and Figure 41 contains a list of technical limitations of the components.

This system, while being technically adequate, is not considered to be practical in the ELF environment and operations. The fender system is very stiff and in operation would cause damage to the ship or require excessively large fenders. The system operation, at maximum load, depends upon ship/mooring fender contacting uniformily to prevent local failure of the ship hull or mooring fender. Also the spring constant of 304,000 pounds per foot is in the range which would tend to produce resonance of the ship in a sea state 6, as shown in Figures 15 through 18.

Cargo Ship Maneuvering/Mooring

The handling of the large deep-draft cargo ships presents two primary problems, first the maneuvering of the ships into the mooring position and second the actual mooring of the ship. The FRH study[4] has indicated that the cargo ships and unloading platforms need to be moored bow-on to the tidal currents when these currents are in excess of 1.5 knots. This orientation being necessitated by the mooring forces developed by the currents. However, reference 8 indicates that for cargo unloading purposes the ships should be moored beam-on to the currents and bow-on to the waves. Reasoning for this orientation being that the motion most critical to cargo transfer is roll, and roll motion is minimized when the ships are moored heading into the waves. The systems used to maneuver and moor the cargo ships will be required to consider and alleviate these problems.

Cargo Ship Maneuvering. The first problem includes overcoming the loads on the ship caused by the design current, wave, and wind forces, relatively shallow water operation and slow maneuvering ship speeds necessary to control dock velocities. Depending upon the mooring setup, there are three methods for bringing the ship to moor.

First, a mooring arrangement may allow the ship to approach the moor under its own power; second, tugs may be used to push the ship into the moor; and third, auxiliary mooring winches may be used to control the ship movement. For the ship to accomplish self-mooring, a mooring arrangement is required which could always be approached head-on into the major forces of current, wind, and wave. The arrangement could not contain an unloading platform or fixed moor, such as a breasting platform, because of the uncontrolled docking forces which would be inherent in a self-moor system.

The second method employing tugs requires the availability of a large amount of horsepower or number of tugs at the site. This is estimated by FRH[4] to be at least four 2,500 SHP tugs. However, reference 4 also estimates that tugs can berth ships in waves only to about 4 feet in height and remove them in waves up to about 6 feet. In addition the tugs would not be able to maneuver the ships broadside to currents greater than 1.5 knots. So with the stated 4-knot current requirement,[1,3] the mooring/unloading platform system could not be fixed in the normal position, i. e., causeway/platform perpendicular to the shore line and normal to the tidal currents.

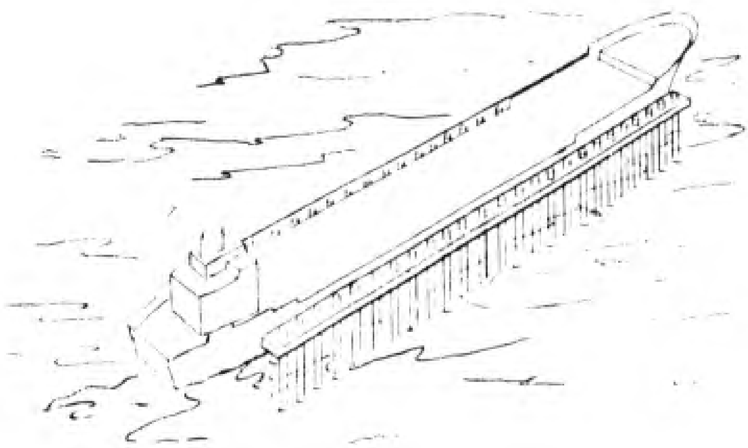
Table 8. Mooring Components for Unloading Platform

C8 Adapter Ship

Max. Bow-on Force - 150,000 lb.
Max. Beam-on Force - 1,200,000 lb.

Mooring "C"		
Equipment	Cost ($K)	Weight (Kips)
Piling, steel, 54" dia. x 120', 50 ea.	$560.0	3,510
Fittings, Accessories	32.0	345
Fenders	156.0	200
Hardware	748.0	4,055
Installation (30 men) 20 days	20.0	
Total	$768.0	4,055

PROJECT "ELF" CONCEPT ANALYSIS SUMMARY



Adapter Ship Mooring System "C"

Objective is to moor the cargo unloading platform without interfering with berthing the cargo ship alongside mooring system "C," using state of the art hardware, will cost about $588,700.

Element	Pacing Problem
1. Piling	11. Burial into hard bottom
	12. Piling placement or alignment
2. Fender	21. Forces/control, wear
3. Installation equipment	31. Performance of tasks in open seas, wave motions

Experiment

111. Engineering analysis and prototype test of installation hardware
121. Engineering tests to establish operational procedures
211. Development and prototype test
311. Prototype tests of hardware to establish operational limitations and procedures

Figure 41. Adapter ship Mooring System C.

The third method using mooring winches requires several preset mooring buoys with large mooring winches. This system, shown in concept in Figure 42, would provide positive control for maneuvering the ships into position alongside the unloading platform. Docking velocities would be controlled by the buoy/winch system and the unloading platform could be positioned perpendicular to the shore line. This Positive Control Mooring (PCM) system would be composed of mooring modules, each capable of holding about 300,000 pounds. Each module would include a constant-tension, remote-controlled winch mounted in a large mooring buoy. The purpose of the constant-tension capability in the mooring system concept is twofold. First it is primarily for maneuvering the ships. It will permit a fixed tension (for example, 20,000 pounds) to be set on one winch as a restraining force on the ship while a higher tension (for example, 25,000 pounds) is set on a second opposing winch to maneuver the ship into a desired position. The first winch, holding 20,000 pounds, will pay out automatically because of the higher tension in the second winch and will permit easy and positive control of the ship. Second, the constant-tension capability will permit quick and accurate pretensioning of a mooring line once the ship has been maneuvered into position. The mooring line is then locked off by the winch directly to the anchorage. It will be possible to use the mooring system to orient the ships (and floating unloading platform, if used) into a heading which will produce the smallest current, wind, and wave forces on the system. A description of the operation of this concept is presented in Appendix A. STATO anchors preset to 300,000 pounds would be used on each mooring leg. A complete system, to handle one cargo ship on each side of the unloading platform, would require 10 to 12 modular units as shown in Figure A-1. Table 8 lists the hardware which would be required for this system; technical limitation of the components are listed in Figure 43. Mooring handling equipment will be needed to preset the anchors and to install the buoys. Also this equipment will be needed to transfer the heavy mooring lines from the mooring winches to the ship.

Cargo Ship Mooring. The cargo ship may be moored by securing to a swing or spread type moor which then requires that the unloading facility be brought to the ship and a ship-to-shore shuttle established. In a second method the ship is tied to the unloading platform which has been provided with a mooring system, as shown in Figure 35. The cargo is transferred to the unloading platform and carried ashore via a connecting causeway system. In this method the platform mooring system must be capable of anchoring both the platform and the cargo ship. A third method uses a mooring system, e. g., the Positive Control Mooring (PCM) system, for the cargo ship, as shown in Figure 42, and a separate mooring system for the unloading platform, such as the FRH mooring concept system B, shown in Figure 34.

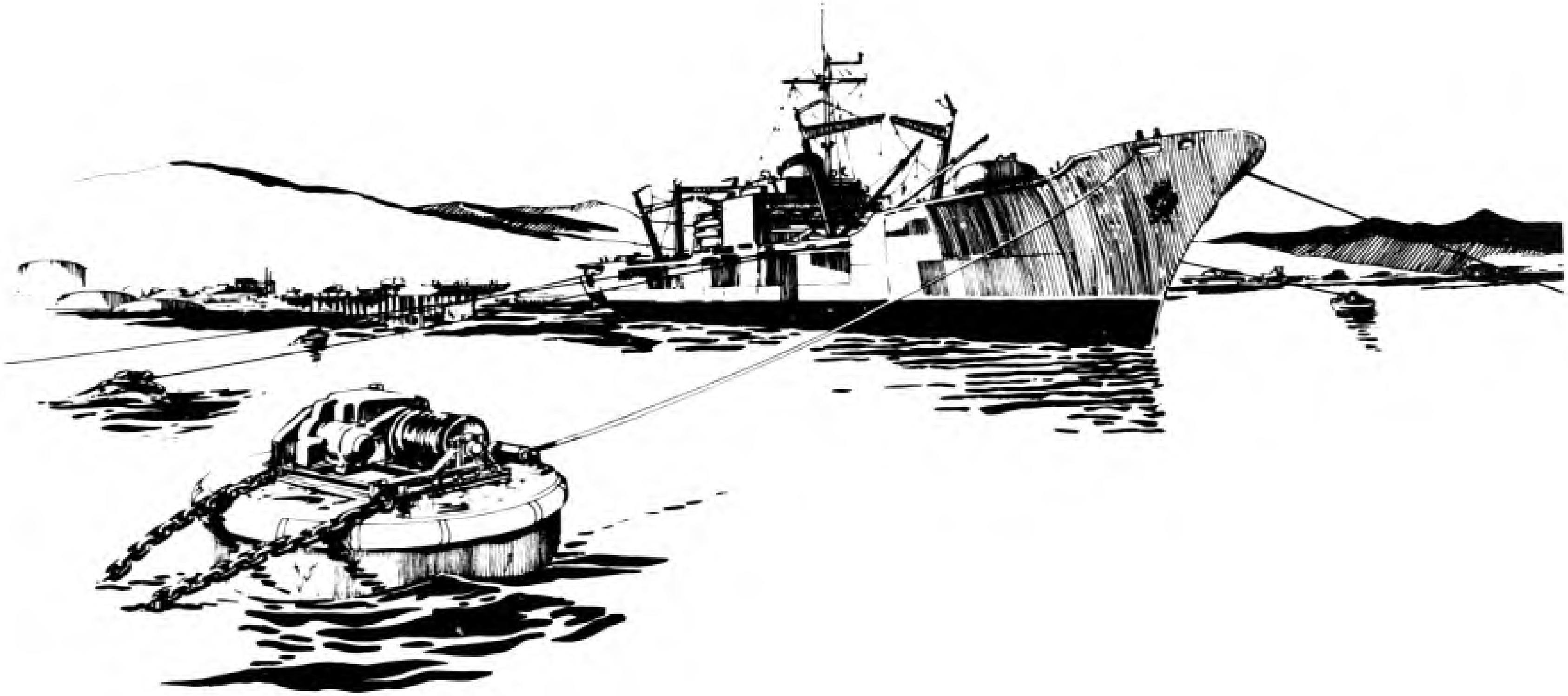
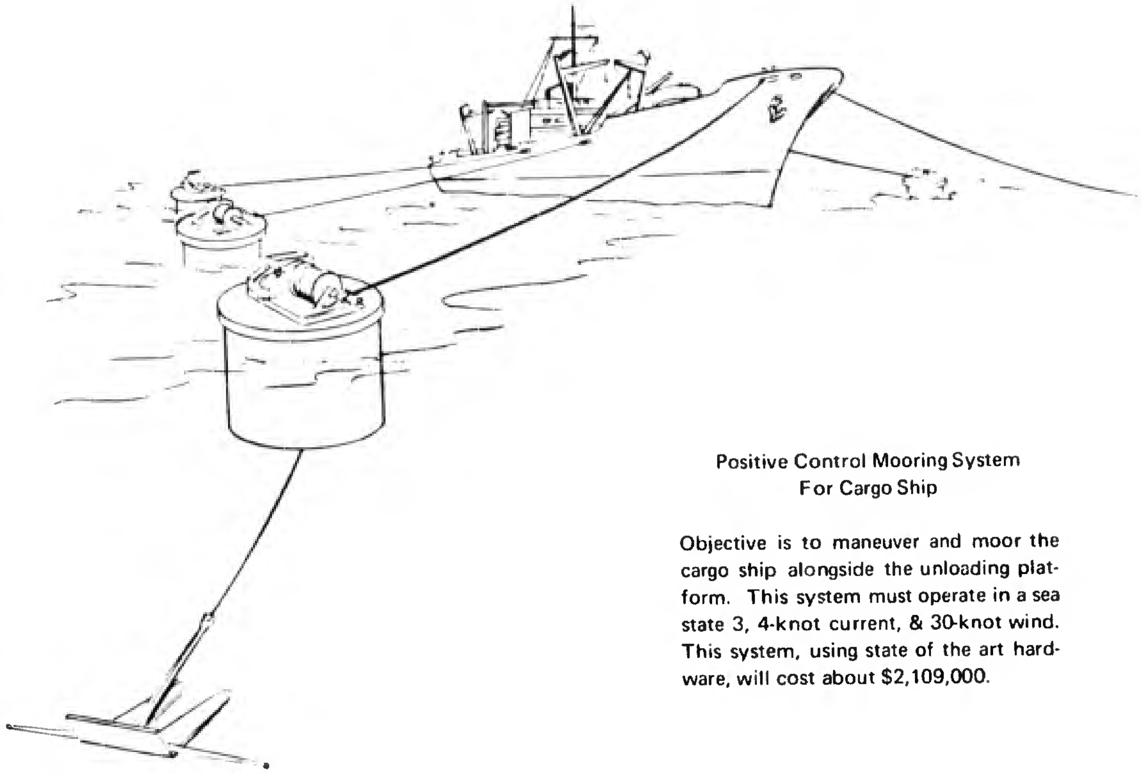


Figure 42. Positive Control Mooring System

PROJECT "ELF" CONCEPT ANALYSIS SUMMARY



Positive Control Mooring System
For Cargo Ship

Objective is to maneuver and moor the cargo ship alongside the unloading platform. This system must operate in a sea state 3, 4-knot current, & 30-knot wind. This system, using state of the art hardware, will cost about $2,109,000.

Element	Pacing Problem	Experiment
1. Anchor—20,000 STATO	11. Burial into hard bottom	111. Development and engineering analysis of alternatives
	12. Anchor installation in open sea, wave motions	121. Prototype test of hardware to establish operational limitations
	13. Alternate for hard bottom—drilled-in anchor, explosive anchor	131. Development and prototype test of alternate anchor
2. Chain—3" Ø Dielock	21. Corrosion, wear of chain & fittings	211. Cathodic protection analysis
3. Wire rope—2-1/2" Ø	31. Corrosion, wear, kinking of wire & fittings during operation	311. Engineering analysis and prototype test to establish wire rope specifications and limitations
4. Winch--300,000#, constant tension	41. Operation from buoy in marine milieu	411. Prototype test of hardware to determine operational limitations
5. Buoy—mooring, 20' Ø	51. Stability in open sea with winch operating	511. Prototype test of hardware to establish operation procedures and limitations
6. Installation equipment	61. Ability to handle anchors, accessory gear and pre-set anchors, ability to handle mooring lines to cargo ship	611. Prototype test of equipment to establish procedures

Figure 43. Positive Control Mooring System for cargo ship.

Dynamic Positioning. This is a "mooring" system for holding a vessel in a relatively fixed position by the use of controlled application of thrust. The system depends upon locating the vessel relative to a fixed point on the ocean bottom, or to other established reference points. The vessel can be held in position if a propulsion system with adequate thrust and control is available. Automatic control, which is more responsive and accurate than manual control, should be provided. Many ships have a dynamic positioning capability[3,4,8] and more are being built for operation in deep water. Ship position control relative to a fixed location is about 2 to 3 percent of the water depth. An estimate of the horsepower requirement for dynamic positioning is 0.25 to 0.50 times the ship's displacement tonnage. Estimated costs for the propulsive unit is $150 per horsepower, which compares unfavorably with most conventional mooring systems for initial costs. This estimated cost is for an outboard type propulsion system with 360 degrees directional control of the thrust. This type unit requires less horsepower than a fixed thruster unit because of the ability to apply thrust in the proper direction. For a 32,000 LT displacement, this would be 8,000 to 16,000 horsepower, with associated costs of $1,200,000 to $2,400,000. Additional horsepower (approximately 32,000 hp) would be required if the adapter ship was moored beam on to a 4-knot current, or if the cargo ship was to be moored by the adapter ship. Problems begin to appear in the outboard type system when the horsepower requirements become very large, thus increasing propeller sizes to the point that directional response is slowed. The major problems with dynamic positioning are its high operational risk compared to a conventional anchor system when working near the beach, plus the large horsepower requirements and associated problems. A total cost for a dynamic positioning system capable of holding an adapter ship beam-on to a 4-knot current is estimated to be $7,200,000. Technical limitations of the components are listed in Figure 44.

Miscellaneous Moorings. The ELF will require other mooring systems for more conventional operations such as mooring small boats, fuel platforms, causeways, and temporary ship buoys. These conventional mooring systems, i. e., anchors, ground tackle and buoy, are listed under the title "mooring D" in Figure 32, and will require a modular design. These modular component systems will be formulated at a later date when the requirements have been specified.

MOORING SYSTEM ANALYSIS

A methodology was formulated as an approach to a system of measurements for determining the relative effectiveness of each mooring system under the same set of predefined and preselected parameters. To evaluate the various mooring system concepts, system parameters were established to measure the applicability of each concept to the mooring missions. The system parameters (Operational Readiness, Mission Performance, Survivability) and characteristics are defined in Appendix B. Tables listing suggested weighting values for each parameter and characteristic together with comparative examples are also contained in Appendix B.

PROJECT "ELF" CONCEPT ANALYSIS SUMMARY

Dynamic Positioning Mooring System

Objective is to moor the cargo unloading platform without interfering with berthing the cargo ship alongside. Dynamic positioning equipment using state of the art hardware will cost about $2,250,000.

Element	Pacing Problem
1. Engine, 2,500 hp	11. Mounting on adapter ship
	12. System control
2. Tail section/propeller	21. Control/clearance
3. Automatic control system	31. Directional control/reaction time/installation of control points

Experiment

111. Design analysis
121. Prototype tests to determine system capabilities
211. Design analysis and prototype test
311. Prototype test of hardware to establish system limitations

Figure 44. Dynamic positioning mooring system.

All of the adapter ship, single hull-type unloading platforms were considered collectively with regard to mooring forces. The catamaran, ship hull and open truss, were considered separately from each other. All types of elevating barges were considered as similar, while the floating barge platform was considered separately. This resulted in 5 categories of mooring missions for analysis. However because of the absence of sufficient data for the semi-submersibles, catamarans and elevated piers, only the adapter, single hull platforms were analyzed at this time. Data is required on these craft relative to wave spectrum/ mooring force in shallow water, with the craft standing dead in the water.

An evaluation of the missions for which the mooring systems must perform indicates that the importance of each mooring system's characteristic varies for different operational situations. The operational situations include 5 missions and four sea state conditions, e. g., sea states 1, 3, 5, and 6. In a sea state 1, all systems were expected to be functional and the Operational Capabilities were weighted uniformily. Sea state 3 is the basic environmental constraint for the mooring systems, therefore this situation was weighted more heavily than sea states 1, 5 and 6 (i. e., 0.55 compared to 0.05, 0.25, and 0.15, Table B-7). Operation in a sea state 5 was desirable but not a stated requirement, therefore, the capability of a system to survive or to perform in this situation is weighted more heavily than the operational readiness parameter. Again the mooring systems are required to survive in a 20-foot significant wave (sea state 6), therefore, the capability to survive is weighted more heavily than the capability for the system to be installed in this situation.

Operational Readiness

To establish the relative effectiveness of each mooring system within the operational constraints, weighting factors and numercial values were assigned for each mission parameter and each system characteristic. The weighting factors for the importance of the mission parameter to the operation vary from 0 to 1, while the assigned value for each system characteristic may vary from 0 to 10. All weighting factors and assigned numerical values were normalized to permit a relative comparison to be made between the numerical values computed for each mooring system concept.

The overall system effectiveness is a summation of the products of the weighting factors and assigned numerical values for each characteristic, as demonstrated in Figure B-12, Appendix B. The larger numerical value represents the better system.

Tables B-1 through B-6, Appendix B, contain the input data, i. e., weighting factors for the mission parameters: Operational Readiness, Mission Performance and Survivability, and the assigned numerical values for the individual system characteristics. It should be remembered that the system comparisons presented in Appendix B are for the adapter ship, single hull-type platform, and do not include, at this time, the other unloading platform types for lack of data.

Appendix B ranking results are summarized below. Total effectiveness includes cost and risk as well as mission parameters whereas mooring effectiveness included only the mission parameters.

Mooring System	Ranking	
	Mooring Effectiveness	Total Effectiveness
A	4	1
B	3	3
C-Pile Beam	5	4
Swing Moor	1	2
Dynamic Positioning	2	5

Sensitivity Analysis

The relative sensitivity of a mooring system's effectiveness to its characteristics was investigated in Appendix B, Table B-14. Sensitivity is a measure of the amount of improvement in a system's effectiveness which could be realized by improving a particular characteristic. For example, in Table B-14, an increase of 0.13 (5.5 percent of effectiveness for sea state 3 operation) effectiveness would be realized if the control capability of System B were improved so as to be equal to system A. Again from Table B-14, System C-Pile Beam, would be improved by 0.10 in effectiveness if its system response were improved to the level of the Swing Moor System.

The sensitivity analysis identified the system characteristics which have the most influence on the effectiveness ranking and points out those system limitations which, if improved, would present the most overall benefit.

System Study Model

In order to evaluate the mooring systems as a total system operation, operational and engineering "paper" models were prepared. These models provide a method of identifying the engineering hardware and operational procedures to be used for each mooring system and point out areas of operational/hardware uncertainties and direction for R&D efforts to realize the proposed concepts. They permit the identification of choices between state of the art and advanced technical solutions, also technical barriers may become more readily apparent. The operational model presents a chronological description of a mooring system from arrival at the site, through emplacement, operation, and retrieval. The engineering model contains a technical description of the equipments required for the mooring system. An outline of these models is contained in Appendix A with an example of their use.

DISCUSSION

Relative motions between a ship and an unloading platform are a primary problem in the transfer of cargo. One means of restraining a ship's motion is to adjust its mooring system, i. e., increase the number of lines or size of lines and their stiffness until the vessel stops moving or the motion reaches an acceptable state for cargo handling. By using a relatively large platform (large displacement) to unload the cargo ships, the absolute surge and heave motions of the platform will be small, initially, e. g., less than .03 and 2.0 feet surge for a C8 hull in 50-ft and 100-ft depths, respectively in a sea state 3 as shown in Figures 15 and 16. But, by examining Figures 15 and 16, it can be seen that these surge motions cannot be practically reduced further by stiffening the mooring lines, e. g., the mooring spring constant would have to be in excess of 10,000,000 pounds per foot instead of 1,000 pounds per foot in order to reduce the surge below the .03 foot motion. Similarly, the force required to eliminate the heave of a ship in a sea state 3 having the displacement of a C8 hull (44,428 long tons) would be about 20,000,000 pounds. As the mooring lines become increasingly stiffer, a ship's natural period of motion can be reduced to a point in which it coincides with the wave frequency and resonance occurs. At resonance, the ship motions increase rapidly as shown at frequencies of 0.4 and 0.98 in Figure 25. So the mooring system's primary advantage lies in its ability to hold the ship from drifting away under the wind, current, and wave forces, and not in reducing or eliminating all motion.

The relative heave motion between a C8 and a C4, shown in Figure 2, varies from about 0.03 foot to 1.0 foot in a sea state 3. This motion may be tolerated in pallet cargo handling operations, but may not be permissible in container movement because of the problems of extraction from a cell, accurate positioning of the container, or impacting on a deck. The container may withstand a force up to 2 g's (a velocity of about 5 feet per second) but this motion may be further aggravated when combined with other motions such as pitch and roll and could result in uncontrollable pendulation motions of a load on a long crane line. These pendulation motions are under investigation by NCEL.

If it is necessary to reduce a ship's motions (or relative motions), it appears that some other method besides mooring lines will be required. As indicated above, motions may be reduced by using greater displacement. The large ship tends to be less effected in a sea state 3 than smaller ship and unloading platform motions and not strive to restrict the motions. A third solution would be to provide the unloading crane with a motion compensating capability. A fourth method would be a breakwater which would reduce the wave motion to an acceptable value.

The mooring system will be dependent upon the type of unloading platform selected. If the selected unloading platform requires a spread moor-type system, then several critical components for the possible mooring systems will be similar. For example, Systems A, B, and PCM all use components such as constant-tension winches, mooring lines, large buoys and stake piles. By purchasing these critical items, evaluation tests can be conducted covering the operational capabilities of all three systems. For System A, the constant-tension winches would be used as conventional winches and the large buoys would be used as the buoyant float. For System B the constant-tension winches and stake piles would be used and not the buoys. For the Positive Control Mooring (PCM) system, the constant-tension winches would be mounted on the large buoys and the stake piles (or conventional anchors) would be used to hold the buoys. All three equipments would not be required; reduced sizes could be used to test the practicality and technical limitations of the components. A proposed program for conducting critical experiments on three ELF mooring systems has been prepared.[13]

The unloading platform concept which uses an elevated pier rather than a floating platform presents slightly different mooring problems. The platform mooring component in this case is composed of piling supporting the pier. The mooring loads on the piling will result from a combination of forces, such as those that may be induced by winds, waves, and currents on the cargo ship when it is tied directly to the pier. Dolphins may be used as an auxiliary mooring component to alleviate or to reduce the mooring loads on the elevated pier. However, the use of dolphins is considered undesirable from an operational viewpoint relative to ELF equipment/installation time criteria.

RELMO[6] (at this date) does not develop data on ship sway and yaw caused by waves striking the ship at an angle to the bow. These motions will be of special concern when the cargo ship is moored to an elevated pier (such as the DeLong concept) with the longitudinal axis of the pier positioned perpendicular to the shore line. Ship surge motions computed by RELMO for a sea state 3 (bow-on to waves) are shown in Figures 17 and 18 (.04 feet with mooring line restraint below 90,000 lb/ft). The FRH report[4] estimates ship sway (6.25 ft wave height, 6 to 15 second period) to range from 8 feet to 22 feet amplitude caused by incident waves at 45 degrees from the bow. Mooring lines will not be capable of significantly reducing this motion. Therefore the elevated pier with fendering system will be required to withstand the forces induced by the sway/yaw motions of the cargo ship. With the design current/wind forces of 1,200,000 pounds, used in this report for mooring loads, the estimated number of piling (72-inch diameter, 1-inch wall thickness) required would be 16 for each 300-foot section of DeLong pier. This would be for one cargo ship at the pier. The elevated pier mooring concept shown in Table 9* depicts the PCM system as being required to maneuver and berth the cargo ship and mooring winches would be required on the pier to assist in berthing and in holding the ship to the pier. The ability to unload the ship, in this concept, will depend upon the wave

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*Table 9 summarizes the proposed mooring methods for the unloading platforms and cargo ships.

direction and fendering system, while the mooring lines will contain but not reduce the ship motion by any significant amount.

The conventional anchors and stake pile appear adequate to provide the required holding powers for the open-beach operations in most situations. However they are relatively slow to install and will not operate in hard bottoms. The explosive embedment anchor[3] is more versatile than conventional anchors in that it will function in a sand, coral or hardpan seafloor and is preset upon embedment; but it does require special handling because of the explosive propellent. Development effort is required to increase the holding-power capacity from the present 150,000 pounds up to the required 300,000 pounds. An examination of the design and operational problems associated with producing an explosive embedment anchor of this capacity indicates that a major technological advancement will be required over the current state of the art. A second mooring method for use in hard bottoms is drilled-in anchors. This is standard practice used by offshore oil rigs when conventional anchors will not hold. Special installation equipments are required but drilled-in anchors have been emplaced in 12-foot waves with 60 mile per hour winds.

Most of the mooring systems use wire rope as one component, and this material together with its connecting accessories are one of the major causes of system failures. Studies[9] of wire rope failures indicate the following causes:

1. Cable not suited to application - 35%
2. Related equipment (winches, sheaves, fittings) not suited to applications - 26%
3. Improper operating technique - 27%
4. Other causes - 12%

The major causes of failures in item 1 were improper cable construction and corrosion. Item 2 failures were equally divided between wrong size or improper material in the sheaves and fittings, and improper winch capacity and control. Item 3 failures referred to insufficient personnel training and poor equipment use and maintenance.

A test program[10] conducted by NCEL on cathodic protection of mooring buoys showed that some of the cathodic protection was being transferred to the ground tackle. A second study was made in which specially cast zinc anodes were installed on some chain links in the ground tackle, and steel cables threaded through the chain links provided complete corrosion protection to the ground tackle. It was estimated that the zinc anodes would provide this protection for 10 years before replacement would be necessary.

Wire rope of the 6 x 19, IWRC, regular lay appears to be less desirable than a torque-balanced wire rope for operations where the line may go slack after being loaded. Kinking occurs most often when a regular lay wire is heavily loaded and then allowed to go slack.

Experience[11] in the use of riser line tensions for oil drilling stems have indicated fatigue-type failures of the lines occur after about 1800 ton-days of operations. This result is based on about 15 to 20-ton of pretension on the lines which is 120 to 90 days of operation. From this experience, lines are changed after about 900 ton-days use.

CONCLUSIONS

Mooring components appear adequate to meet the mooring load requirements, but specialized systems need to be developed to meet the remaining criteria imposed by the operational environment of open coastal sites.

The dynamic positioning system has many advantages in terms of logistic burden installation requirements, operation and retrieval. However, the disadvantages of high horsepower requirements, high initial costs and high operational risk reduced its total effectiveness rating.

The cargo ships will require a positive method of berthing in the shoal area and a quick and reliable means will have to be provided for handling and passing the mooring lines to the cargo ship. The use of tugs to maneuver the cargo ships does not appear to provide the amount of positive control needed for the ELF type operations.

Developmental effort will be required to produce suitable mooring systems for the ELF operations. All proposed mooring concepts are limited in the ability of the anchoring component to be placed in hard bottoms and to restrict platform/ship motions.

The most significant technical barriers to mooring operations are:

(a) The limited control of ship motion provided by the mooring lines.

(b) The limited capability to install and operate anchors in hard bottoms.

(c) The limited amount of equipment available for vertical mooring line operations.

(d) The unavailability of equipment specifically designed for installing and handling anchors and mooring lines in open shoal water.

(e) The lack of test data in ship and mooring operations in open shoal water.

Corrosion damage to the buoys and ground tackle may be controlled by a proper maintenance program and by the fact that the ELF system is planned to be used for periods only up to one year. However, consideration should be given to apply cathodic protection to the mooring components. Tests[12] have shown positive results of cathodic protection for the ground tackle as well as the mooring buoys.

The relative ship motions, which will exist with the identified mooring systems, will require some type of fendering system. A substantial level of effort will be needed to identify and develop the most suitable system.

RECOMMENDATIONS

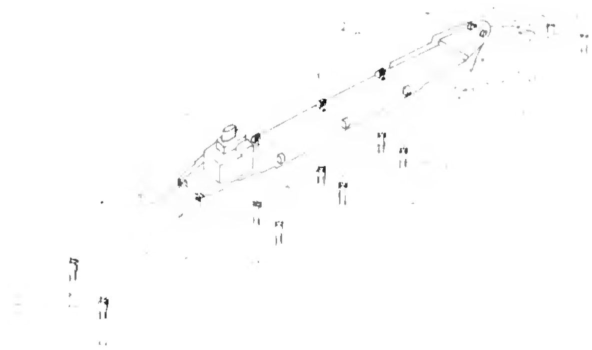
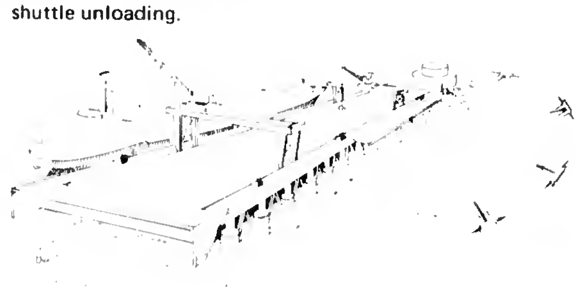
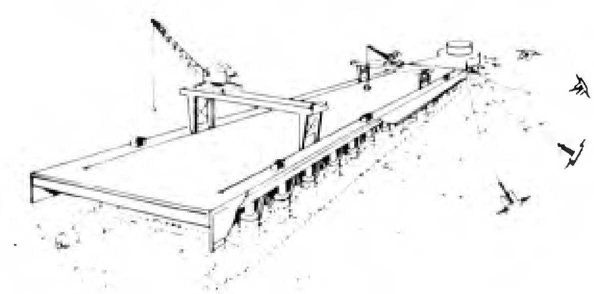
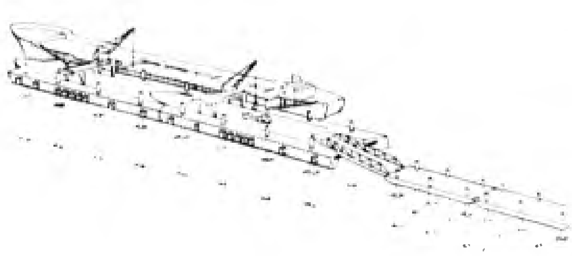
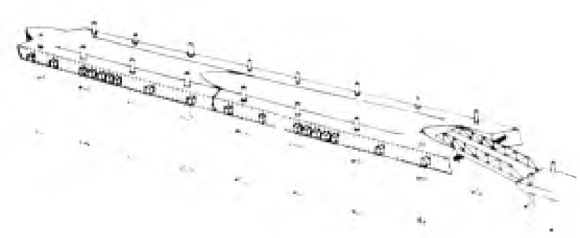
The following items are recommended:

1. Develop a positive control mooring/maneuvering system for the cargo ships, and that critical experiments (specified in the developmental program)[13] be conducted to verify technical and practical aspects of individual components/methods for use in mooring systems or for use as alternates to some mooring system components.

2. Develop the handling equipment required to install and to operate the positive control mooring system.

3. Develop fendering system (experimental design and/or model tests/critical experiments) to perform with the specified unloading platforms/cargo ships in the ELF operation.

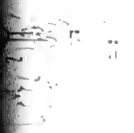
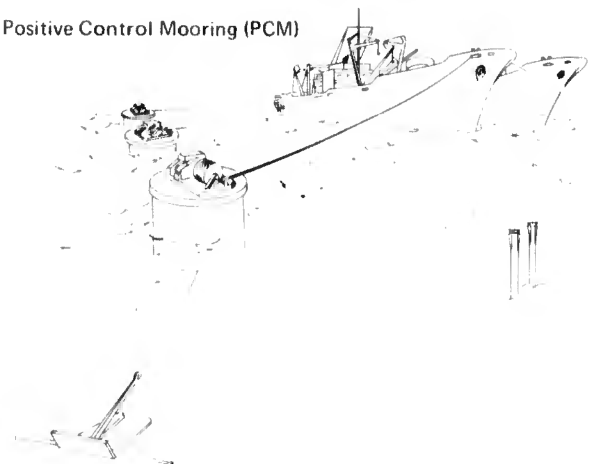
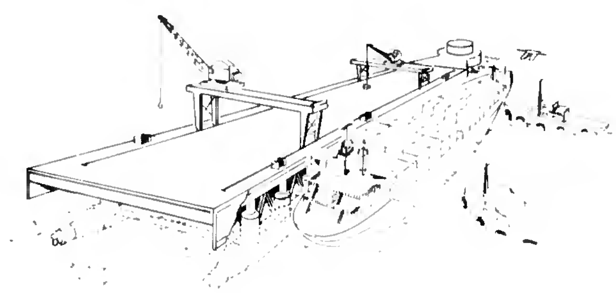
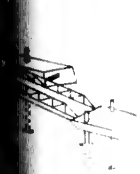
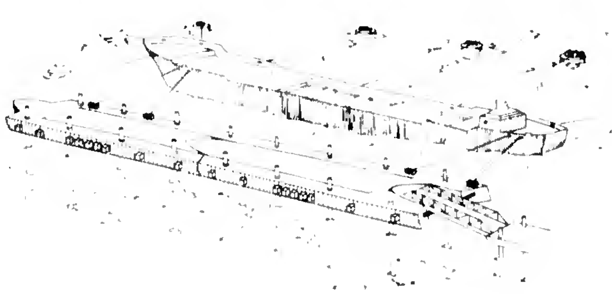
4. Continue the development of mooring components required for the other equipments in the ELF system.

Unloading Platform	Platform Mooring System	
	Type	Cost $K
Adapter Ship—single hull, attached to causeway/pier to shore. 	Mooring 'B' 	1,822
Semi-Submersible Catamaran—with shuttle unloading. 	Swing Moor 	362
DeLong Pier—with elevated causeway to beach. 	Piling 	1,140

1. Technical risk pertains only to the ability of the mooring system to meet the mooring criteria. The larger the value, the better chance of success.

2. Fender systems development are required for all systems.

Table 9. Summary of Mooring Systems

...g System	Cost $K	Technical Risk (%)[1]	Cargo Ship Mooring System: Type	Cost $K	Technical Risk (%)[1]	Total Initial Cost $K	Technical Limitation...
	1,822	40	Positive Control Mooring (PCM) 	2,109	35	3,931	1. Anchor/stake pile cannot ... hard bottom such as cora... hardpan. 2. Stake pile installation in ... wave motion. 3. Corrosion and wear of wi... fittings. 4. Continuous operation of ... mooring winches. 5. Limited control of platfo... provided by mooring syst...
	362	40	Constant-Tension Winches and Tugs 	1,100	40	1,462	1. Anchors cannot penetrat... such as coral, shale, or ha... 2. Operation of large special... open sea.
	1,140	90	Positive Control Mooring (PCM) 	2,109	35	3,249	1. Installation of piling limi... state. 2. Anchors/piling cannot pe... bottoms such as coral, sh... 3. Structural capacity of pil... water depth/soil compos...

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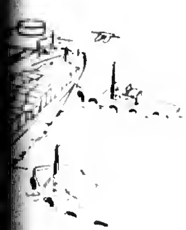
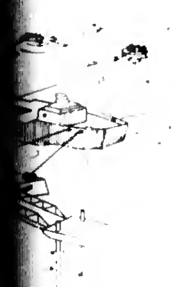
ems

ring System			Total Initial Cost $K	Technical Limitations[2]	Developmental Efforts
	Cost $K	Technical[1] Risk (%)			
	2,109	35	3,931	1. Anchor/stake pile cannot penetrate hard bottom such as coral, shale, or hardpan. 2. Stake pile installation in open sea, wave motion. 3. Corrosion and wear of wire rope and fittings. 4. Continuous operation of platform mooring winches. 5. Limited control of platform motion provided by mooring system.	1. Development and prototype test of anchor for hard bottom—(300,000-pound capacity explosive anchor/drilled-in anchor) 2. Prototype test of stake pile for repetitive vertical loads. 3. Installation equipment development. 4. Prototype test of winch/buoy to establish operational procedures and environmental limitations.
	1,100	40	1,462	1. Anchors cannot penetrate hard bottom such as coral, shale, or hardpan. 2. Operation of large special buoy in open sea.	1. Buoy design. 2. Installation equipment development. 3. Development and prototype test of anchor for hard bottom (300,000-pound capacity explosive anchor/drilled-in anchor) 4. Prototype tests for development of mooring operations and procedures.
	2,109	35	3,249	1. Installation of piling limited by sea state. 2. Anchors/piling cannot penetrate hard bottoms such as coral, shale or hardpan. 3. Structural capacity of piling limited by water depth/soil composition.	1. Installation equipment development. 2. Development and prototype test of anchor/pile for hard bottom. 3. Prototype test of winch/buoy to establish operational procedures and environmental limitations.

Appendix A

OPERATIONAL/ENGINEERING METHODOLOGY

OPERATIONAL METHODOLOGY

The purpose of the operational model is to assess the feasibility of the mooring systems in terms of logistic burden, installation and operational modes. In the process of describing and analyzing the system operation, it should be possible to identify uncertainties and required developmental efforts to realize concepts. Also choices available between state of the art components and advanced solution may become apparent.

Step 1. Mooring Components Logistic Burden

a. Transport ship (square feet/special storage required such as deck or interior space).
b. Unload components at objective area.

Item to be considered: Material handling facilities required; temporary mooring/storage required for components and equipments; relative motion problems, regarding, unloading mooring components; installation equipment shipping space required.

Step 2. Mooring Installation

a. Install mooring components for unloading platform/cargo ship.
b. Position unloading platform and install mooring lines.

Items to be considered: Equipment required to install mooring components (for cargo ship, or platform); equipment required to maneuver or handle unloading platform; installation time required; relative motion problems, regarding installation of components.

Step 3. Operational Mode

a. Position cargo ship for unloading.

Items to be considered: Handling/maneuvering equipment required for cargo ship; problems relative to mooring system clearance; mooring control, versitility, regarding line tensions, maneuverability to position platforms in favorable position relative to waves, current, wind; cargo ship/unloading platform restraint/control provided by mooring systems, regarding cargo handling, small craft, large ships; mooring reliability; winch operation for cargo ship/unloading platform mooring operation; mooring line tension control provided by system.

Step 4. Remove Cargo Ship

a. Maneuver/handle cargo ship away from unloading platform.

Items to be considered: Equipment required.

Step 5. Retrieve Mooring Components

a. Retrieve mooring components.
b. Load on transport ship.
c. Clear area of components not retrieved.

Items to be considered: Equipment required to retrieve, reload, and clear area.

ENGINEERING METHODOLOGY

The engineering methodology identified the hardware (and alternatives) available for the mooring components. State of the art equipments are listed while items requiring technical development can be identified.

1. Mooring Components

    a. Anchors/piles
    b. Handling equipment
    c. Accessories

2. Mooring Installation Equipment

    a. Handling equipment
    b. Floating/transport equipment
    c. Installation equipment

3. Line Handling Equipment

    a. Line transfer equipment

4. Retrieval/Reload Equipment

    a. Equipment to retrieve mooring components
    b. Equipment to reload mooring components on to ship

5. Area Clearance/Cleanup

    a. Equipment to demolish fixed components
    b. Cleanup equipment

EXAMPLE

In the following example, the PCM system is provided for maneuvering and mooring the cargo ship while System "B" is used to moor the adapter ship. The 2,500 shp tugs required with the System "B" were assumed to be part of the adapter ship system and not part of its mooring system, although it has been indicated that the tugs would be required to position the adapter ship for mooring. It is possible for the PCM system to be used in positioning the adapter ship over its mooring location.

OPERATIONAL METHODOLOGY

Example

Positive-Control Mooring System (PCM) for Cargo Ship
System "B" Mooring for Adapter Ship

Step 1. Mooring Components Logistic Burden

a. Transport ship

The PCM system requires an estimated 11,000 square feet (1,568 tons) of ship storage area. Of this space, 9,000 square feet of deck space will be required to handle the buoys and winches. This shipping space may be provided by the adapter ship or a cargo ship such as an LKA. The System "B" mooring components require 3,941 square feet (629,000 pounds) of ship storage area and this space may be provided by the adapter ship or LKA. The PCM system requires transport for a warping tug and storage barge while the System "B" requires transport for pile drivers, crane and leads, and a work barge.

Unloading of the mooring components for both systems can be handled by the ship's gear. The heaviest lift will be about 25 tons. Temporary storage/transport of the mooring components will be accomplished by use of the barges and by installation of auxiliary mooring buoys.

Major problems appear to be relative motions between ship and barges while unloading mooring components. Required transport/handling facilities appear to be state of the art with only design development necessary.

Step 2. Mooring Installation

a. Install mooring components

Stake pile for mooring System "B" are installed by the work barge, using the crane and leads and pile drivers. Time to install the stake piles is estimated to be 10 days. The warping tug and barge are used to preset the 20,000-pound STATO anchors to 300,000 pounds holding power for each buoy/winch B_1, B_2, B_3, B_4 and B_5 as shown in Figure A-1. Buoys are attached to the mooring chains. Estimated installation time for the PCM system is 7 days. All equipment items for these installation operations are state-of-the-art technology.

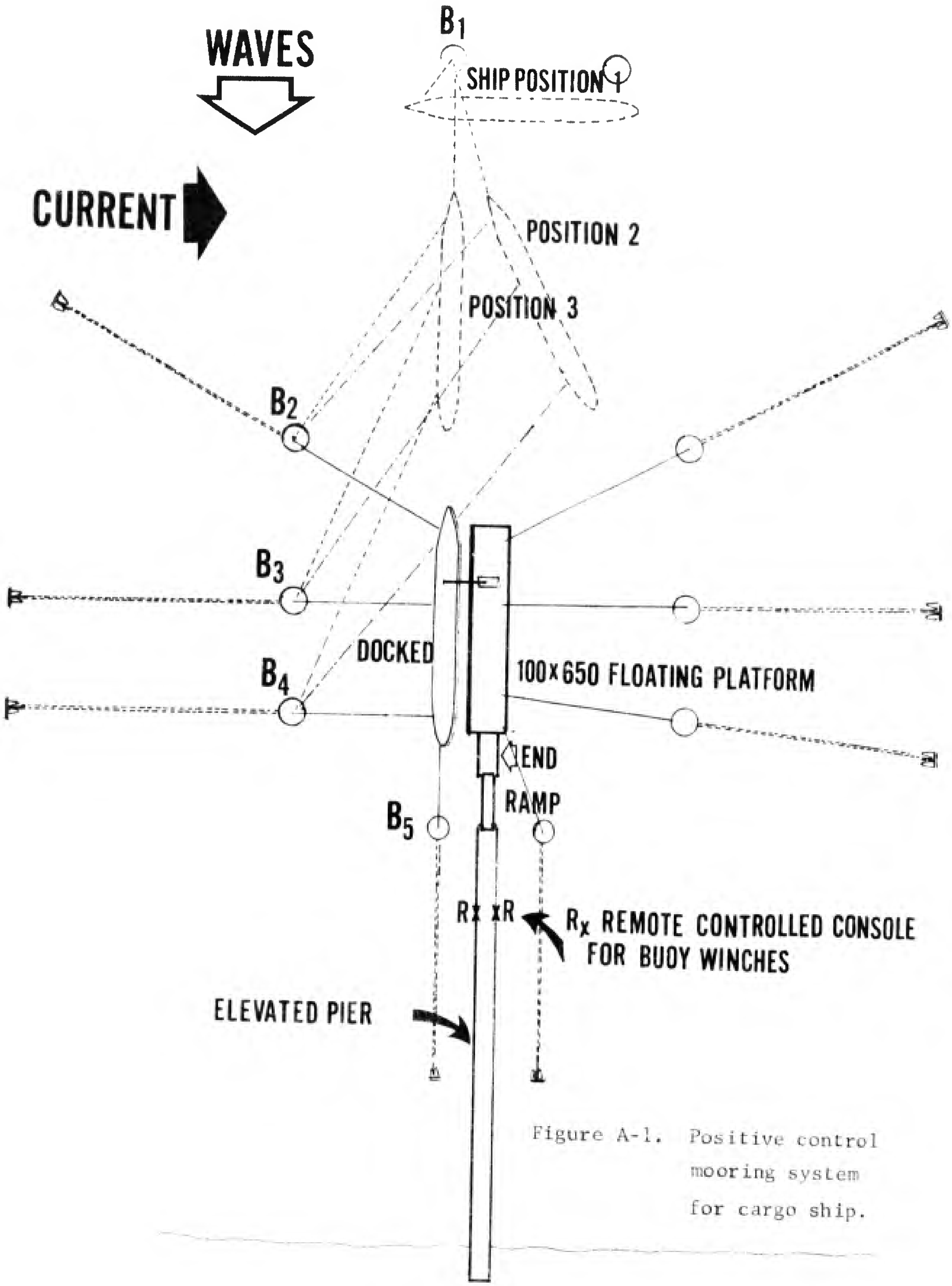


Figure A-1. Positive control mooring system for cargo ship.

Operational problems for the PCM system will be the handling and layout of the mooring chains, maneuvering and attachment of the buoy/winch in the open sea and placement of the remote control lines for the winch operation to prevent fouling. The mooring system "B" will encounter problems in handling and driving the stake piles in the deep water in the open sea and reeving of the mooring lines.

b. Position unloading platform (adapter ship) and install mooring lines

The adapter ship will require tug assistance, or other means such as the PCM system, to move into position over the stake pile. Divers, together with a crane barge will be needed to install the mooring lines from the constant-tension winches on the adapter ship.

Major operational problem will be the handling of the adapter ship prior to connecting the mooring lines.

Step 3. Operational Mode

a. Position cargo ship alongside unloading platform

Typical cargo ship, e. g., Master Mariner, 12,700 dwt, 564 feet long, 76-foot beam, and 32-foot draft, approaches the anchorage area headed into the prevailing current (0 to 4 knots) on the beach side of the offshore mooring buoy, B_1, Figure A-1 (ship position 1).

The line handling equipment will pass the wire rope mooring line from the winch directly to the ship's bow. The cargo ship will begin backing down on this bow line, swinging the stern into the shore direction, (positions 1 and 2 of Figure A-1). Mooring lines from B_2, B_3, B_4, and B_5 are passed to the ship by the mooring line handling equipment at position 3 of Figure A-1. All of the buoy mooring winches are remote-controlled, constant-tension type.

A constant tension is applied to the bow and stern buoy winches, with the stern line tension exceeding the bow tension. This will turn the ship into a heading with the stern to the beach and cause the ship to be pulled towards the shore and the unloading platform. An appropriate tension is applied to the side lines, B_2 and B_4, to hold the ship in alignment away from the unloading platform.

The cargo ship is maneuvered alongside the unloading platform, position Docked, Figure A-1, and suitable line tensions are set by the mooring winches before the lines are locked off by the winch brakes. Ship approach speeds to the platform are monitored by an approach-velocity meter and the tension in the mooring lines are adjusted accordingly.

Problem areas to be investigated to ascertain technlogoical/operational limitations include:

(a) The handling/passing of the heavy mooring line directly to the cargo ship. This will require some mechanical system such as a crane.

(b) The docking operation is limited to the upstream side of the adapter platform when maximum current forces exist.

(c) Kinking of the wire rope in handling and during operation with tension in the rope being varied causing an unlaying or kinking of the strands.

(d) Mooring winch control/spooling/cleaning of the mooring wire rope.

(e) Maintenance/operation of the winches in the marine environment; clearance of cargo ship and mooring lines for unloading platforms.

(f) Relative motions between cargo ship/barge/buoys/line handling equipment.

Step 4. Remove cargo ship from unloading platform

The constant-tension winches are used to pull the cargo ship away from the unloading platform and out to buoy B_1, ship position 1, Figure A-1. Bascially this operation will be the reverse of Step 3.

Step 5. Retrieve mooring components

All mooring components for the cargo ship may be retrieved by the warping tug and back-loaded onto the transport ship. All components for the unloading platform may be retrieved including the stake piles, if a water jet system is provided for jetting the piles loose from the bottom. If drilled-in anchors are used for both systems, the piles will be abandoned. The installation equipment used for each system will be used to retrieve the mooring components.

Major problems will be the relative motions present during retrieval of the components and back-loading.

ENGINEERING METHODOLOGY

Example

	Technical Limitations
1. Mooring Components	
Anchors, 20,000-lb STATO, 16 ea.	(SOA)
Chain, anchor, 3-inch dia., 7,200 ft	(SOA)
Buoy, mooring, 30-foot dia., 10 ea.	(XD)
Winch, mooring, 300,000-lb capacity, remote control, constant tension, 10 ea.	(AD)
Wire rope, 2 1/2-inch dia., 12,000 ft	(SOA)
Fittings, chain	(SOA)
2. Installation Equipment	
Wapring tug with 30-ton capacity crane, 1 ea.	(SOA)

	Technical Limitations
2. Installation Equipment (Cont)	
Barge for equipment stowage/handling 2 ea.	(SOA)
Temporary anchorage	(SOA)
3. Line Handling Equipment	
Warping tug with 30-ton capacity crane	(XD)
4. Retrieval Equipment	
Warping tug with 30-ton capacity crane	(SOA)

ENGINEERING

Example

System"B" Mooring

	Technical Limitations
1. Mooring Components	
Stake pile, 16-inch dia., 15 ft long, 12 ea.	(SOA)
Wire rope, 1 1/2-inch dia., 3,600 feet	(SOA)
Fittings	(SOA)
Winch, 150,000-lb constant tension capacity, 12 ea.	(AD)
2. Installation Equipment	
Crane barge with leads	(SOA)
Pile driver, diesel DE 20, 16,000 ft-lb	(SOA)
Barge for equipment stowage/handling, 2 ea.	(SOA)
Divers	(SOA)
Tugs, 2,50 shp, 4 ea.	(SOA)
3. Line Handling Equipment	
None	
4. Retrieval Equipment	
Crane barge	(SOA)
Water jet equipment	(SOA)

SOA - State of the art
XD - Experimental development
AD - Advanced development

APPENDIX B

SYSTEM EFFECTIVENESS ANALYSIS

SYSTEM EFFECTIVENESS PARAMETERS

The mission effectiveness parameters used in this analysis are:

Operational Readiness - The condition that the system is available for use at the required place when needed. Operational Readiness covers the period through installation. A candidate system which did not possess the required qualifications and/or capabilities for a particular mission was not considered for that mission.

Mission Performance - A measure of the ability of the system to achieve mission criteria, given the operational conditions during the mission. Performance measurement begins after the system has been installed.

Survivability - A measure of the system's ability to survive in an extreme natural environment or in a military attack. System would survive but not be required to perform its normal mission functions during the critical period. Survivability measure beings after installation.

System Parameter Characteristics

Operational Readiness - The characteristics used to define this parameter include, or are influenced by the factors listed under each of the following characteristics:

1. Availability/Transportability - The off-the-shelf general availability of the equipments as versus requirement for special ship or shipping requirement, (special need for interior or exterior shipping space).
2. Unloading - The requirement for general or special unloading platform, or area.
3. Manhours Assembly - The time/manpower required to assemble the gear and installing equipment.
4. Equipment Availability Assembly - The availability of the equipment required for the installation of a mooring assembly.
5. Manhours Mooring Assembly - The time/manpower required to install a mooring assembly.
6. Operation Manhours - Time/manpower required to place a mooring assembly into operation.
7. Wind/Current - The effect of wind, current, and sea state on the installation of the mooring assembly.
8. Storage - Components' characteristics which permit the mooring materials to be stored without detrimental deterioration or endangering personnel or requiring special storage facilities.

9. Retrievability/Reload - The capability of the system for recovery and back loading onto a ship or preparation for tow, (is a special ship or retrieval equipment required?)

10. Capability/Failure - The capability of the mooring system to perform assuming partial failure/unavailability of the system.

Mission Performance - The influences considered when assigning system values for each performance characteristic are defined as:

1. Holding Power Capacity or Station Keeping Capability - The effect of specific mission loadings on the capability of a system to perform a mission. Ability to maintain station.

2. Operating Clearance - The ability of a system to perform but not hinder performance of other operations in the mooring area.

3. Surf/Waves - The effect of surf/wave conditions on the performance of a system.

4. Time - The time required to moor (or put the station keeping capability into operation) the unloading platform (or cargo ship).

5. Reliability - The capability of a system to resist failure in the performance of a mission and the capability of the system being repaired, (weather effects on equipment).

6. Control - Degree of control provided by mooring system and operational versitility (cargo unload control, cargo ship maneuverability) or other trade offs inherent in the system.

Survivability - The characteristics used to define this parameter include:

1. Natural Environment - The values given for environment represent the relative capability of systems to survive natural environmental elements. Considerations include the system capability to survive the following conditions:

With unloading platform and cargo ship:

Significant wave height - 5 feet
current - 4 knots
wind - 30 knots
tidal range - 8 feet

With unloading platform:

Significant wave height - 20 feet
current - 4 knots
wind - 75 knots

System characteristics include:

Position maintenance
Component failure or wear
System response (time to replace in service assuming component failure)

2. Military Environment - The values given for military environment represent the relative capability of systems to survive military environmental elements while performing each mission. Considerations included the system capability to survive the following:

Swimmer mines (or resistance to mines)
Catastrophic damage to components due to gunfire

Characteristics of systems considered while performing mission:

Effect on operation
Vulnerability
Desirability of system as a target

Weighting Values

A numerical value is assigned to a system characteristic which is representative of the relative capability of the system to perform that specific function. If a system does not possess the required qualifications and/or capabilities for a mission, it is not considered for that mission. Table B-1, B-3, and B-5 indicate the relative weighting of the candidate systems for each characteristic for each mission. The importance of the mission effectiveness parameters relative to the existing sea state is assumed to vary and, therefore, an Environment Weight Value was assigned to each sea state in Table B-7.

The relative sensitivity of a system's effectiveness to its characteristics also was investigated, Table B-14. Sensitivity is a measure of the amount of improvement in a system's effectiveness which could be realized by either improving a particular characteristic or by developing a capability which the system presently lacks.

The larger numerical value represents the better system or capability.

Total Effectiveness

Table B-13 summarizes the estimated costs, risks, and system effectiveness and presents a total comparitive ranking of the systems. The development costs are based on the effort necessary to develop the system components to meet the mission requirements and do not include the costs necessary to buy and test a complete system. The initial costs are for the system components required to meet the ELF requirements. Life cycle costs were estimated using a baseline life of 10 years with two operations during this period. The conventional mooring components were assumed to have an overhaul cycle of 3 years. Other components such as winches, special buoys, and special mooring wire ropes were overhauled on a 2-year basis.

The costs and risks were evaluated on a scale of 0 to 10 with the larger number representing the lesser cost/risk and weighting values from 0 to 1 were assigned to the cost/risk factors. (Table B-13) The degree of risk associated with each system includes the technical problems which must be overcome to develop the system and the acceptability of the system and its costs by the operating forces.

The total effectiveness ranking represents all system effectiveness parameters and the selected cost factors on a comparitive numberical basis. Again the larger numerical value represent the better system or lower cost/risk.

Mooring System Evaluation

The information presented in Tables B-1 through B-14 of this section is limited to a comparison of the mooring systems relative to the adapter ship - single hull-type unloading platforms, and does not include catamarans, semi-submersibles, causeways, or elevated piers, for which the data is lacking.

Step 1 - Using definitions established for the system parameters and characteristics, a numerical value, 1-10, is assigned to each mooring system characteristic. This value is entered in Table B-1, "Operational Readiness Factors," in the upper left hand corner of each mooring system/characteristic coordinate.

Step 2 - Multiply these assigned values by their characteristic parametric weight, and place the result in the lower right hand corner of the mooring system/characteristic coordinate.

Step 3 - Add the weighted values across for each system and enter in Table B-2, "Operational Readiness Values," placing the sum in the appropriate mooring system/mission coordinate.

Step 4 - Table B-3, "Performance Factors" and Table B-5 "Survivability Factors" are calculated, using Steps 1, 2, and 3 with the sums of the weighted values being entered in their respective values tables B-4 and B-6.

Step 5 - Multiply "Operational Readiness," "Performance," and "Survivability" values from Tables B-2, B-4, and B-6 by the "Operation Effectiveness Weights," Table B-7, for each sea state. The resultant values should then be placed in the "Effectiveness" Tables B-8 - B-11. Sea state 1 data is entered in Table B-8, sea state 3 data in B-9, sea state 5 data in B-10, and sea state 6 data in B-11.

Step 6 - The data is transferred from "Effectiveness" tables B-8 - B-11 to Table B-12 "Mooring System Effectiveness/Ranking." The values are entered in the appropriate Mooring System/Sea State coordinate, and the values for each system are combined additively. The system with the highest numerical rating is the system with the highest effectiveness, and is considered to be superior to the alternate systems.

Table B-13 "Total Effectiveness" is a compilation of Cost Effectiveness, Risk and Ranking Data which shows each system's relative merits. The Cost data (Development, Initial and 10 year) is calculated in the same manner as Tables B-1, B-3, and B-5; a relative cost value is entered in the upper left hand corner of each System/Cost coordinate. These values range from 0-10 with the less expensive having a higher relative value. These values are multiplied by the cost parameteric weights and the resultant weighted values are placed in the lower right hand corner.

"System Effectiveness" column is taken directly from Table B-12.

"Technical Risk" is determined as the preceding cost figures; a relative value (0-10) is assigned to each system, multiplied by the "Risk" parametric weight, and the weighted value recorded adjacent to the relative value.

The "Total Effectiveness" column is the summation of the weighted values for each system. These sums are then compared and the system with the higher numerical figure is considered superior to the alternative systems.

Table B-1. Operational Readiness Factors - Adapter Ship, Single Hull

Characteristic	Avail/ Transp.	Unload	M/Hrs Assem.	Equip. Avail. Assem.	M/Hr Mooring	Oper. M/Hr	Wind, Current, Wave	Storage	Reload	Capabil. Failure
Mooring System \ Parametric Weight	.16	.05	.16	.16	.12	.05	.04	.05	.12	.09
A	3 / .48	3 / .15	4 / .64	6 / .96	4 / .48	4 / .20	2 / .08	4 / .20	5 / .60	5 / .45
B	4 / .64	4 / .20	5 / .80	6 / .96	3 / .36	4 / .20	2 / .08	4 / .20	5 / .60	5 / .45
C-Pile Beam	4 / .64	4 / .20	1 / .16	5 / .80	2 / .24	5 / .25	1 / .04	3 / .15	2 / .24	4 / .36
Swing Moor	3 / .48	3 / .15	6 / .96	6 / .96	5 / .60	5 / .25	4 / .16	4 / .20	7 / .84	6 / .54
Dynamic Positioning	10 / 1.6	10 / .5	10 / 1.6	10 / 1.2	10 / .5	10 / .5	10 / .4	10 / .5	10 / 1.2	2 / .18

Table B-2. Operational Readiness Values

System / Mission	A	B	C-Pile Beam	Swing Moor	Dynamic Positioning
Cargo Ship					
Adapter Ship Singel Hull	4.24	449	3.08	5.14	9.28
Catamaran Ship Hull					
Catamaran Open Truss					
Elevating Barge					
Floating Barge					
Causeway					

Table B-3. Performance Factors - Adapter Ship, Single Hull

Characteristics	Holding Power	Operating Clearance	Surf/Waves	Reliability	Control
Mooring System \ Parametric Weight	.30	.15	.10	.15	.30
A	5 / 1.50	4 / .60	3 / .30	4 / .60	5 / 1.50
B	6 / 1.80	5 / .75	4 / .40	4 / .60	3 / .90
C-Pile Beam	4 / 1.20	6 / .90	2 / .20	3 / .45	1 / .30
Swing Moor	6 / 1.80	6 / .90	5 / .50	5 / .75	3 / 0.90
Dynamic Positioning	3 / .90	10 / 1.5	6 / .60	1 / .15	2 / .60

Table B-4. Performance Values

Mission \ System	A	B	C-Pile Beam	Swing Moor	Dynamic Positioning
Cargo Ship					
Adapter Ship Single Hull	4.50	4.45	3.05	4.85	3.75
Catamaran Ship Hull					
Catamaran Open Truss					
Elevating Barge					
Floating Barge					
Causeway					

Table B-5. Survivability Factors - Adapter Ship, Single Hull

Characteristics	Natural Environment	Military Environment	Position Maintenance	Component Wear/Failure	System Response
Mooring System \ Parametric Weight	.40	.15	.20	.10	.15
A	4 / 1.60	3 / .45	3 / .60	2 / .20	3 / .45
B	4 / 1.60	5 / .75	4 / .80	2 / .20	3 / .45
C-Pile Beam	3 / 1.20	5 / .75	6 / 1.20	1 / .10	1 / .15
Swing Moor	5 / 2.00	5 / .75	5 / 1.00	4 / .40	5 / .75
Dynamic Positioning	3 / 1.2	2 / .30	2 / .40	1 / .10	2 / .30

Table B-6. Survivability Values

Mission \ System	A	B	C-Pile Beam	Swing Moor	Dynamic Positioning
Cargo Ship					
Adapter Ship Single Hull	3.30	3.80	3.40	4.90	2.30
Catamaran Ship Hull					
Catamaran Open Truss					
Elevating Barge					
Floating Barge					
Causeway					

Table B-7. Operation Effectiveness Weights

Environment / Weight	Sea State 1	Sea State 3	Sea State 5	Sea State 6
Operational Capability	.05	.55	.25	.15
Operational Readiness	.33	.30	.25	.20
Performance	.34	.40	.30	.30
Survivability	.33	.30	.45	.50

Table B-8. Effectiveness Sea State 1

System / Mission	A	B	C-Pile Beam	Swing Moor	Dynamic Positioning
Cargo Ship					
Adapter Ship Single Hull	0.20	0.21	0.16	0.25	0.25
Catamaran Ship Hull					
Catamaran Open Truss					
Elevating Barge					
Floating Barge					
Causeway					

Table B-9. Effectiveness Sea State 3

System / Mission	A	B	C-Pile Beam	Swing Moor	Dynamic Positioning
Cargo Ship					
Adapter Ship Single Hull	2.23	2.35	1.74	2.72	2.74
Catamaran Ship Hull					
Catamaran Open Truss					
Elevating Barge					
Floating Barge					
Causeway					

Table B-10. Effectiveness Sea State 5

System / Mission	A	B	C-Pile Beam	Swing Moor	Dynamic Positioning
Cargo Ship					
Adapter Ship Single Hull	0.97	1.04	0.80	1.24	1.12
Catamaran Ship Hull					
Catamaran Open Truss					
Elevating Barge					
Floating Barge					
Causeway					

Table B-11. Effectiveness Sea State 6

System / Mission	A	B	C-Pile Beam	Swing Moor	Dynamic Positioning
Cargo Ship					
Adapter Ship Single Hull	0.45	0.62	0.25	0.74	0.62
Catamaran Ship Hull					
Catamaran Open Truss					
Elevating Barge					
Floating Barge					
Causeway					

Table B-12. Mooring System Effectiveness/Ranking

Sea State \ System	A	B	C-Pile Beam	Swing Moor	Dynamic Positioning
1	0.20	0.21	0.16	0.25	0.25
3	2.23	2.35	1.74	2.72	2.74
5	0.97	1.04	0.80	1.24	1.12
6	0.45	0.62	0.25	0.74	0.62
Summation / Ranking	3.85 / 4	4.22 / 3	2.95 / 5	4.95 / 1	4.73 / 2
3 + 6	2.68	2.97	1.99	3.46	3.36

Table B-13. Total Effectiveness

Mooring System	Development Cost .2	Initial Cost .4	10 Year Cost .1	Technical Risk .3	System Effectiveness	Total Effectiveness	Total Effectiveness Ranking
A	60.0 9 1.8	245.0 10 4.0	93.0 10 1.0	6 1.8	2.68	11.28	1
B	113.0 8 1.6	1,822.0 3 1.2	532.0 5 0.5	4 1.2	2.97	7.47	3
C-Pile Beam	10 2.0	768.0 7 2.8	1,520.0 0 0	2 0.6	1.99	7.39	4
Swing Moor	230.0 6 1.2	362.0 9 3.6	50.0 10 1.0	4 1.2	3.46	10.62	2
Dynamic Positioning	320.0 5 1.0	2,250.0 1 0.5	337.5 7 0.7	2 0.6	3.36	6.06	5

Table B-14. Sensitivity Analysis

System \ Characteristic	Holding Power	System Response	Reliability	M/Hrs Mooring Assembly	Surf/Wave Current	Control	Improvement
A			.03 / 1%	.05 / 2%	.01 / .6%		3.6%
B						.13 / 5.5%	5.5%
C-Pile Beam		.10 / 6%	.07 / 4%	.13 / 7.5%	.02 / 1%	.26 / 15%	33.5%
Swing Moor						.13 / 5%	5%
Dynamic Positioning	.20 / 7%	.07 / 2.5%	.13 / 5%			.20 / 7%	17%

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13. ABSTRACT

The objective of this study was to develop an engineering/operational methodology to assess the feasibility of, and to design as a preliminary concept, the total mooring systems for cargo ships and associated unloading platforms operating in open and sheltered coastal waters. The methodology was to be capable of examining the mooring systems in terms of performance, logistic burden, installation, and operational modes in the context of the Expeditionary Logistics Facility. Mooring concepts are proposed and alternatives identified in terms of the state of the art and advanced technical solutions. Cost effectiveness comparisons are made of the proposed mooring concepts using the methodoloty developed in the study. Technical barriers and trade-offs are identified; RDT&E developments are recommended.

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