INCH-POUND

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1 July 1999

SUPERSEDING
NAVFAC DM-26.4
April 1986
NAVFAC DM-26.5
June 1985
NAVFAC DM-26.6
April 1986

DEPARTMENT OF DEFENSE
HANDBOOK

MOORING DESIGN

THIS HANDBOOK IS FOR GUIDANCE ONLY. DO NOT CITE THIS DOCUMENT AS A REQUIREMENT.

AMSC N/A **AREA FACR**

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ABSTRACT

This handbook is intended for use by facility and ship designers and contains policy and procedures for the design of moorings for Department of Defense (DOD) vessels.

For the purposes of this handbook, a mooring is defined as a compliant structure that restrains a vessel against the action of wind, wave, and current forces.

For the purposes of this handbook, the emphasis is on moorings composed of tension members (chain, line, wire rope, etc.) and compression members (fenders, camels, etc.) used to secure vessels (surface ships, submarines, floating drydocks, yard craft, etc.). The term mooring in this handbook includes anchoring of ships.

The primary emphasis of this handbook is the mooring of floating structures or 'vessels,' such as ships, yard craft, submarines, and floating drydocks in harbors. This handbook does not address systems where the environmental forcing on the mooring members themselves is important, as may be the case for towed underwater bodies, ship-to-ship at-sea mooring, and towing of one vessel by another.

FOREWORD

The DOD, through the U.S. Navy, Military Sealift Command, and U.S. Army, has a long history of mooring vessels in harbors throughout the world. This experience has shown that the ability to analyze moorings according to a set of common and well understood basic principles is critical for safe and cost-effective mooring operations.

This handbook presents procedures for the evaluation and design of mooring facilities for DOD vessels. It is intended to provide guidance to users, operators, and designers of mooring facilities for DOD vessels.

Mooring systems are designed to withstand forces and moments generated by winds, waves, and currents acting upon the vessel. Designers must appreciate the user's environmental and operational requirements that are unique at each site and to each vessel. Similarly, ship and facility operators must appreciate the design parameters that the designers have employed for their particular vessel and facility.

In the development of this handbook, particular emphasis has been placed on "lessons learned" from past DOD mooring operations as well as new technology and procedures for mooring analysis which have been developed in both the commercial and Government sectors.

This handbook uses, to the maximum extent feasible, national and institute standards in accordance with Commander, Naval Facilities Engineering Command (NAVFACENGCOM) and Commander, Naval Sea Systems Command (NAVSEASYSCOM) policy. Do not deviate from this handbook without prior approval of the NAVFACENGCOM Criteria Office.

Recommendations for improvement are encouraged from within the Navy, other Government agencies, and the private sector and should be furnished on the DD Form 1426 provided inside the back cover to Commander, Naval Facilities Engineering Command, NAVFACENGCOM Criteria Office, 1510 Gilbert Street, Norfolk, VA 23511-2699; telephone commercial (757) 322-4200, facsimile machine (757) 322-4416.

DO NOT USE THIS HANDBOOK AS A REFERENCE DOCUMENT FOR PROCUREMENT OF FACILITIES CONSTRUCTION. USE IT IN THE PURCHASE OF FACILITIES OR SHIP ENGINEERING STUDIES AND DESIGN (FINAL PLANS, SPECIFICATIONS, AND COST ESTIMATES). DO NOT REFERENCE IT IN MILITARY OR FEDERAL SPECIFICATIONS OR OTHER PROCUREMENT DOCUMENTS.

WATERFRONT FACILITIES CRITERIA MANUALS

Criteria Manual	Title	Preparing Activity
MIL-HDBK-1025/1	Piers and Wharves	LANTDIV
MIL-HDBK-1025/2	Dockside Utilities for Ship Service	NAVFAC
MIL-HDBK-1025/3	Cargo Handling Facilities (Textbook)	N/A
MIL-HDBK-1025/4	Seawalls, Bulkheads and Quaywalls	NFESC
MIL-HDBK-1025/5	Ferry Terminals and Small Craft Berthing Facilities (Textbook)	N/A
MIL-HDBK-1025/6	General Criteria for Waterfront Facilities	LANTDIV

HARBOR AND COASTAL FACILITIES DESIGN MANUALS

26.1	Harbors	NFESC
26.2	Coastal Protection (superseded **by** Army Corps of Engineering "Shore Protection Manual" 1984)	
26.3	Coastal Sedimentation and Dredging	NFESC
MIL-HDBK-1026/4	Mooring Design	NFESC
26.5	Fleet Moorings (superseded by MIL-HDBK-1026/4)	N/A
26.6	Mooring Design Physical and NFESC Report TR-6014-OCN)	NAVFAC

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MOORING DESIGN

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Section 1: INTRODUCTION

1.1 Scope. This military handbook, MIL-HDBK-1026/4, provides design policy and procedures for design of moorings for U.S. Department of Defense (DOD) vessels.

1.2 Purpose of Criteria. The purpose of this handbook is to ensure quality, consistency, and safety of DOD vessels, mooring hardware, and mooring facilities throughout the world.

1.3 Definition. A mooring, in general terms, is defined as a compliant structure that restrains a vessel against the action of wind, wave, and current forces. For the purposes of this handbook, the emphasis is on moorings composed of tension members (chain, line, wire rope, etc.) and compression members (fenders, camels, etc.) used to secure vessels (surface ships, submarines, floating drydocks, yard craft, etc.). The term mooring in this handbook includes anchoring of ships.

1.4 Cancellation. This handbook, MIL-HDBK-1026/4, dated 1 July 1999, cancels and supersedes:

a) DM 26.4, Fixed Moorings, Naval Facilities Engineering Command, April 1986.

b) DM 26.5, Fleet Moorings, Naval Facilities Engineering Command, June 1985.

c) DM 26.6, Mooring Design Physical and Empirical Data, Naval Facilities Engineering Command, April 1986.

1.5 Related Technical Documents. The following documents will have to be obtained to effectively use this military handbook.

Naval Facilities Engineering Service Center (NFESC), 1100 23rd Ave., Port Hueneme, CA 93043

CR-6108-OCN — Anchor Mooring Line Computer Program Final Report, User's Manual for Program CSAP2

TR-2039-OCN — Design Guide for Pile Driven Plate Anchors

TR-6005-OCN (Rev B) EMOOR – A Quick and Easy Method of Evaluating Ship Mooring at Piers and Wharves

TR-6014-OCN Mooring Design Physical and Empirical Data

TR-6015-OCN Foam-Filled Fender Design to Prevent Hull Damage

1.6 Organizational Roles and Responsibilities. Over the design life of a mooring facility, many organizations are involved with the various aspects of a facility. Personnel involved range from policy makers, who set the initial mission requirements for vessels and facilities, to deck personnel securing lines. Figure 1 illustrates the DOD organizations that must understand the various aspects of moorings. In addition, all these groups must maintain open communications to ensure safe and effective moorings.

Safe use of moorings is of particular importance for the end users (the ship's personnel and facility operators). They must understand the safe limits of a mooring to properly respond to significant events, such as a sudden storm, and to be able to meet mission requirements.

It is equally important for all organizations and personnel shown in Figure 1 to understand moorings. For example, if the customer setting the overall mission requirement states "We need a ship class and associated facilities to meet mission X, and specification Y will be used to obtain these assets" and there is a mismatch between X and Y, the ship and facility operators can be faced with a lifetime of problems, mishaps, and/or serious accidents.

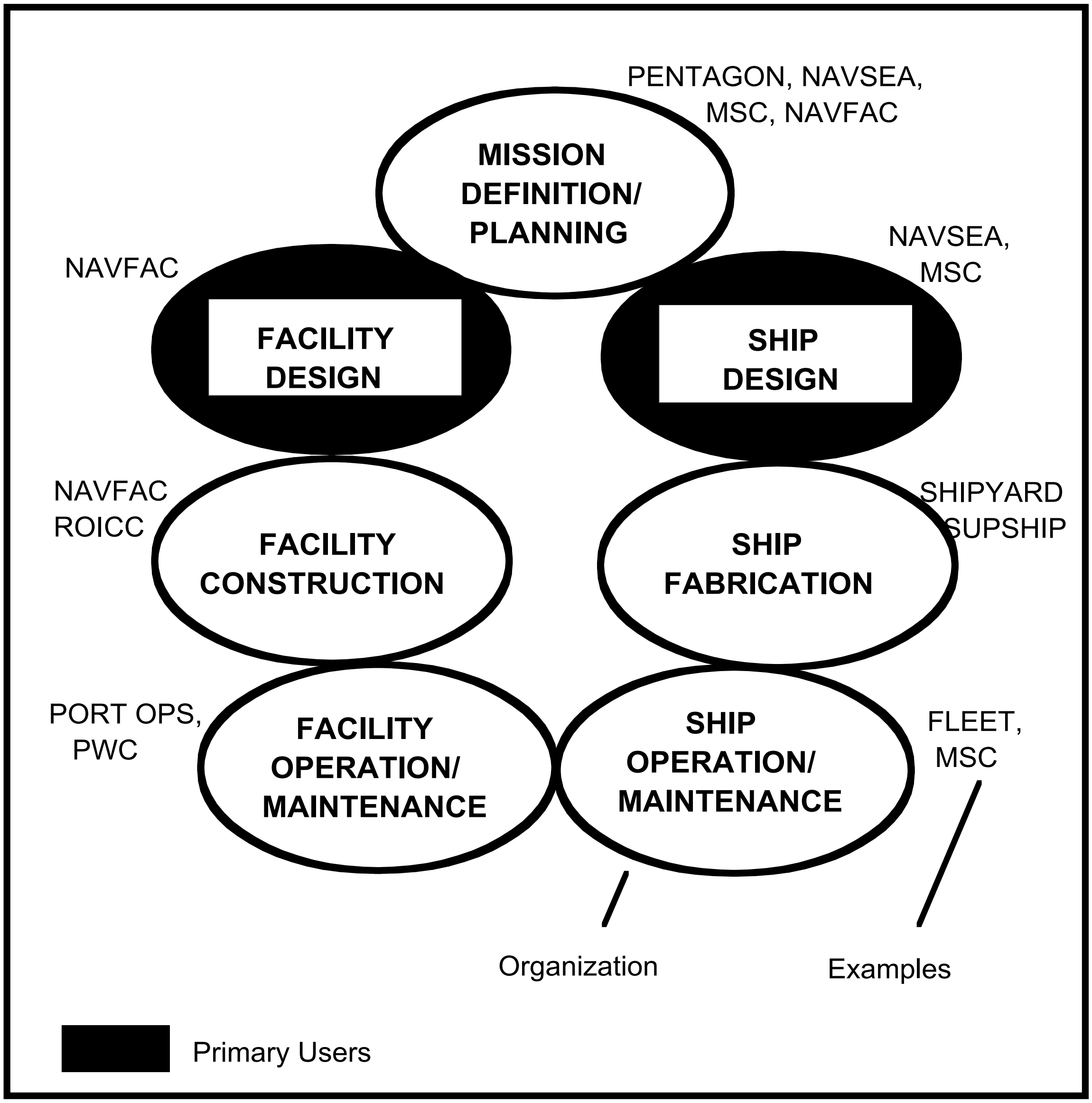


Figure 1
DOD Organizations Involved With Ship Moorings

Section 2: MOORING SYSTEMS

2.1 Introduction. The DOD uses several types of mooring systems to moor ships. These systems can be summarized into two broad categories of moorings:

a) Fixed Moorings - Fixed moorings are defined as systems that include tension and compression members. Typical fixed mooring systems include moorings at piers and wharves.

b) Fleet Moorings - Fleet moorings are defined as systems that include primarily tension members. Mooring loads are transferred into the earth via anchors. Examples of fleet moorings include fleet mooring buoys and ship’s anchor systems.

The more common types of moorings are discussed in this section.

2.1.1 Purpose of Mooring. The purpose of a mooring is to safely hold a ship in a certain position to accomplish a specific mission. A key need is to safely hold the vessel to protect the ship, life, the public interest, and to preserve the capabilities of the vessel and surrounding facilities. Ship moorings are provided for:

a) Loading/Unloading - Loading and unloading items such as stores, cargo, fuel, personnel, ammunition, etc.

b) Ship Storage - Storing the ship in a mooring reduces fuel consumption and personnel costs. Ships in an inactive or reserve status are stored at moorings.

c) Maintenance/Repairs - Making a variety of repairs or conducting maintenance on the ship is often performed with a ship moored.

d) Mission - Moorings are used to support special mission requirements, such as surveillance, tracking, training, etc.

Most DOD moorings are provided in harbors to reduce exposure to waves, reduce ship motions, and reduce dynamic mooring loads. Mooring in harbors also allows improved access to various services and other forms of transportation.

2.2 Types of Mooring Systems. Examples of typical moorings systems are given in this section.

2.2.1 Fixed Mooring Systems. Examples of typical fixed moorings are given in Table 1 and illustrated in Figures 2 through 6.

2.2.2 Fleet Mooring Systems. Examples of typical fleet moorings are given in Table 2 and illustrated in Figures 7 through 14.

Table 1
Examples of Fixed Moorings

a. Single Vessel Secured at Multiple Points

MOORING TYPE	FIGURE NUMBER	DESCRIPTION
Pier/Wharf	2 3	Multiple tension lines are used to secure a vessel next to a pier/wharf. Compliant fenders, fender piles and/or camels keep the vessel offset from the structure. A T-pier may be used to keep the ship parallel to the current, where the current speed is high.
Spud Mooring	4	Multiple vertical structural steel beams are used to secure the vessel, such as a floating drydock. This type of mooring is especially effective for construction barges temporarily working in shallow water. Spud moorings can be especially susceptible to dynamic processes, such as harbor seiches and earthquakes.

b. Multiple Vessel Moorings

MOORING TYPE	FIGURE NUMBER	DESCRIPTION
Opposite Sides of a Pier	5	Vessels can be placed adjacent to one another on opposite sides of a pier to provide some blockage of the environmental forces/moments on the downstream vessel.
Multiple Vessels Next to One Another	6	Vessels can be placed adjacent to one another to provide significant blockage of the environmental forces/ moments on the downstream vessel(s).

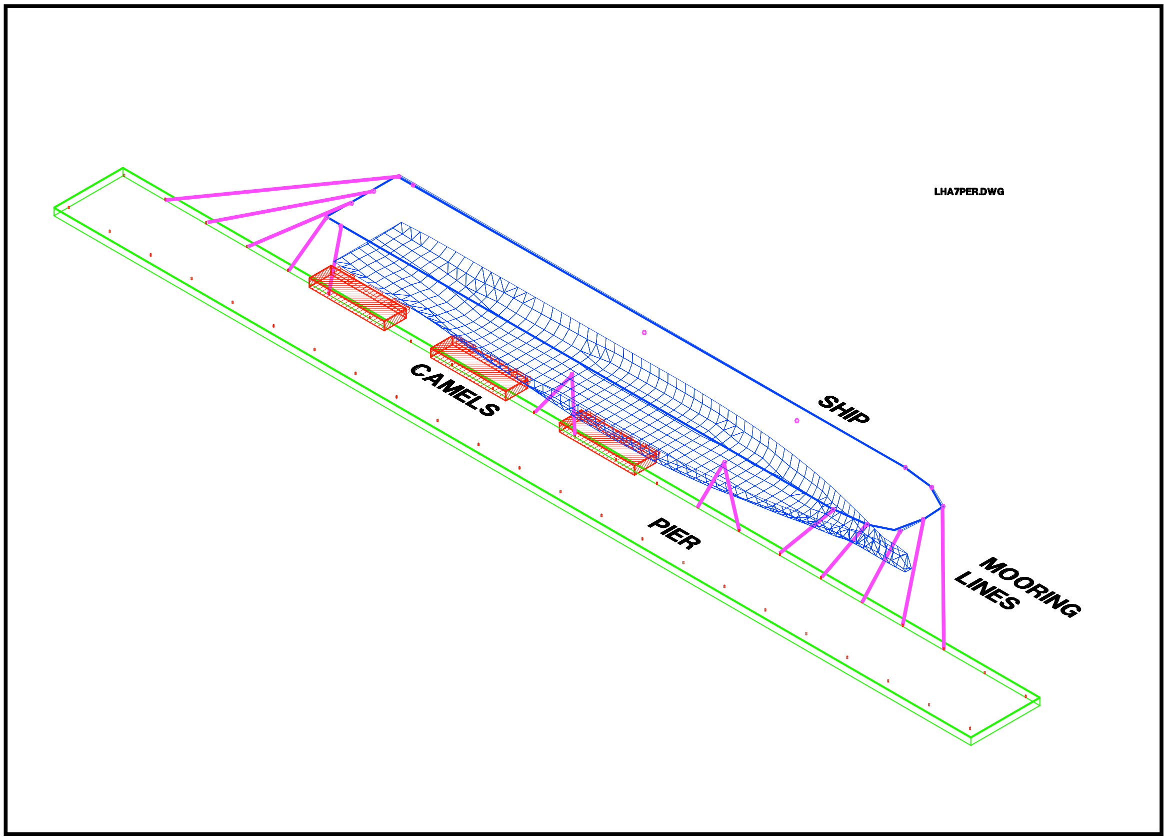


Figure 2
Single Ship, Offset From a Pier With Camels

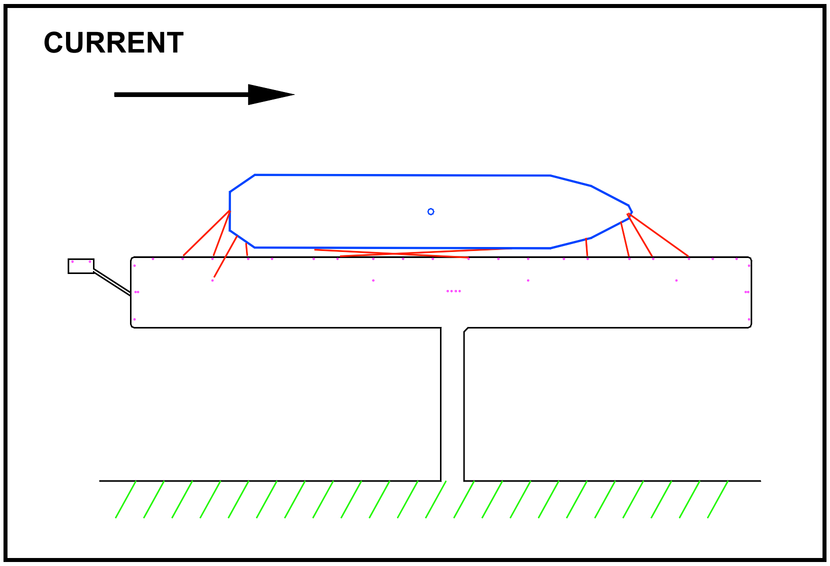


Figure 3
Ship at a T-Pier (plan view)

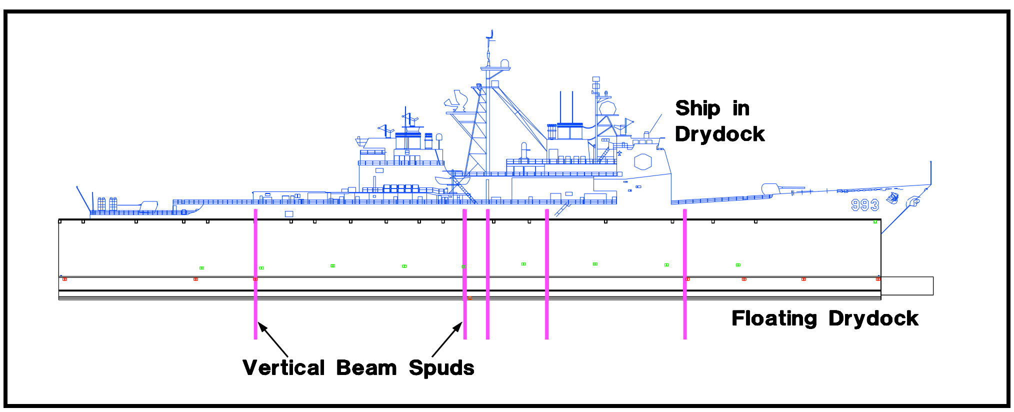


Figure 4
Floating Drydock Spud Moored
(spuds are secured to a pier, which is not shown, and the floating drydock rides up and down on the spuds; profile view is shown)

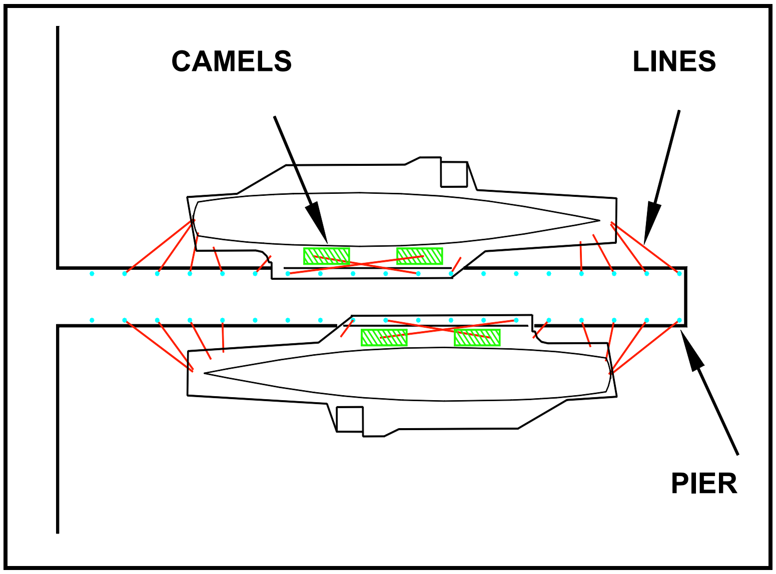


Figure 5
Ships on Both Sides of a Pier (plan view)

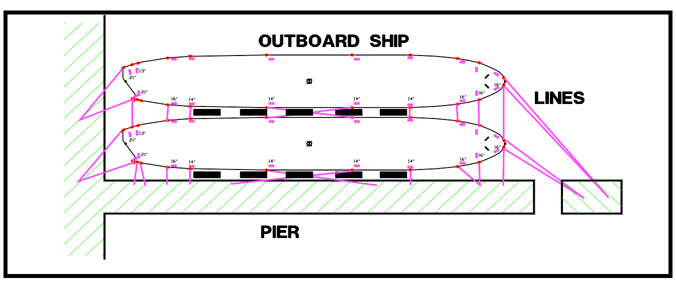


Figure 6
Two Ships on One Side of a Pier (plan view)

Table 2
Examples of Fleet Moorings

a. Vessel Secured at a Single Point

MOORING TYPE	FIGURE NUMBER	DESCRIPTION
At Anchor	7	Typical configuration includes the ship deploying a single drag anchor off the bow. This is usually a temporary mooring used as a last resort in benign conditions. A large amount of harbor room is required for the ship swing watch circle. If the wind changes direction dramatically then the anchor will have to reset. Dynamic fishtailing, even under steady winds and currents, may be a problem. Putting out a second anchor in what is known as a Hammerlock mooring may be required in storm anchoring.
Single Mooring Buoy	8 9	A single point mooring (SPM) buoy is secured to the seafloor typically with 1 to 12 ground legs and either drag or plate anchors. The ship moors to the buoy using an anchor chain or hawser. The vessel weathervanes under the action of forcing, which helps to reduce the mooring load. This type of mooring requires much less room than a ship at anchor because the pivot point is much closer to the vessel. A vessel at a mooring buoy is much less prone to fishtailing than a ship at anchor. Many of the mooring buoys at U.S. Navy facilities around the world are provided under the U.S. Navy’s Fleet Mooring Program.

Table 2
Examples of Fleet Moorings (Continued)

b. Vessel Secured at Two Points

MOORING TYPE	FIGURE NUMBER	DESCRIPTION
Bow-Stern Mooring	10	A vessel is moored with one buoy to the bow and another to the stern. This system has a much smaller watch circle than a vessel at a single mooring buoy. Also, two moorings share the load. However, the mooring tension can be much higher if the winds, currents, or waves have a large broadside component to the ship.

c. Vessel Secured at Multiple Points

MOORING TYPE	FIGURE NUMBER	DESCRIPTION
Med-Mooring	11	The vessel bow is secured to two mooring buoys and the stern is moored to the end of a pier or wharf. This type of mooring is commonly used for tenders or in cases where available harbor space is limited. Commonly used in the Mediterranean Sea. Hence, the term “Med” Mooring.
Spread Mooring	12	Multiple mooring legs are used to secure a vessel. This arrangement of moorings is especially useful for securing permanently or semi-permanently moored vessels, such as floating drydocks and inactive ships. The ship(s) are usually oriented parallel to the current.

Table 2
Examples of Fleet Moorings (Continued)

d. Multiple Vessel Moorings

MOORING TYPE	FIGURE NUMBER	DESCRIPTION
Nest	5 6 13 14	Multiple tension members are used to secure several vessels together. Camels or fenders are used to keep the vessels from contacting one another. Nests of vessels are commonly put into spread moorings. Nested vessels may be of similar size (as for inactive ships) or much different size (as a submarine alongside a tender). Advantages of nesting are: a nest takes up relatively little harbor space and forces/moments on a nest may be less than if the ships were moored individually.

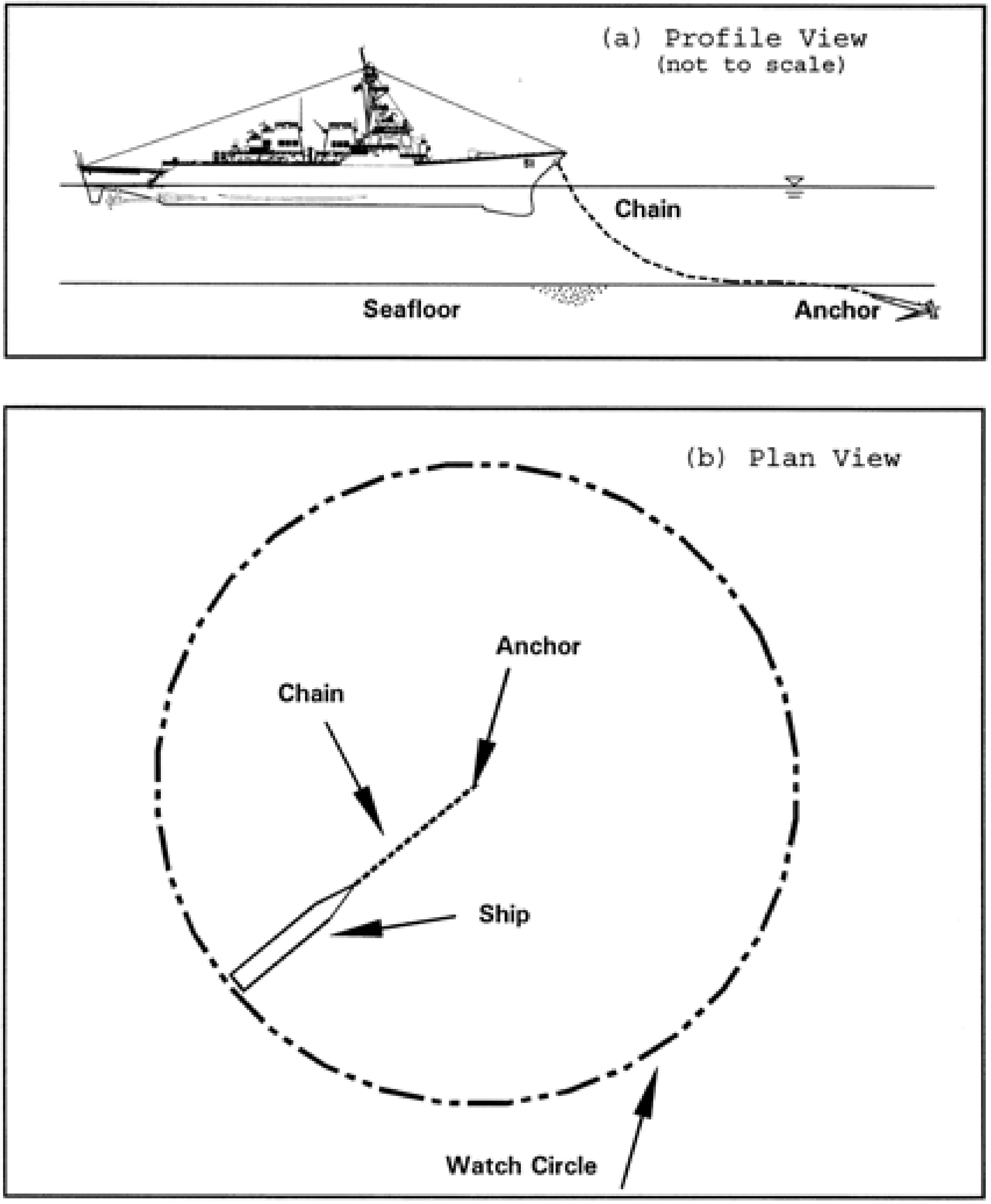


Figure 7
Ship at Anchor

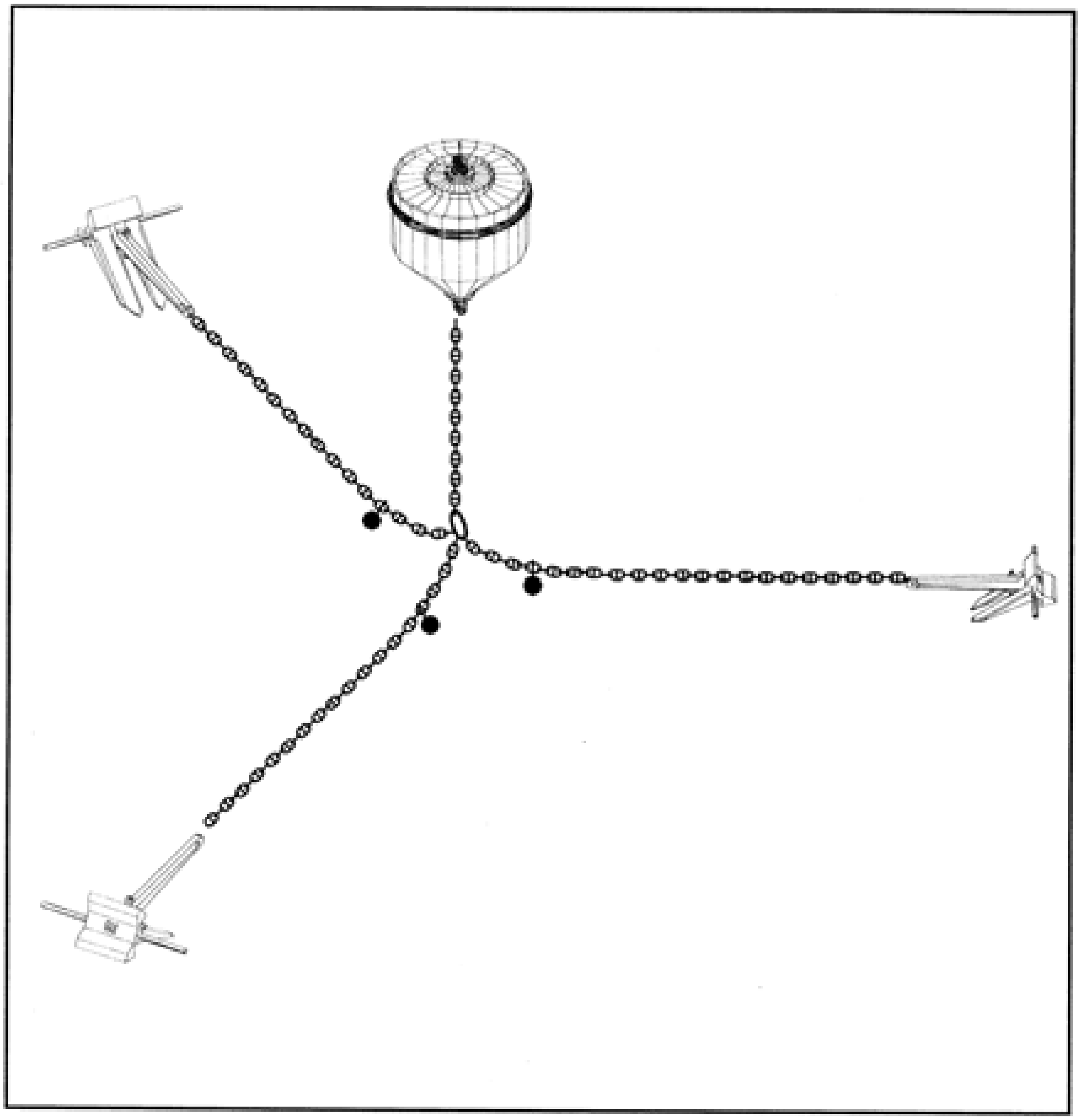


Figure 8
Single Point Mooring With Drag Anchors

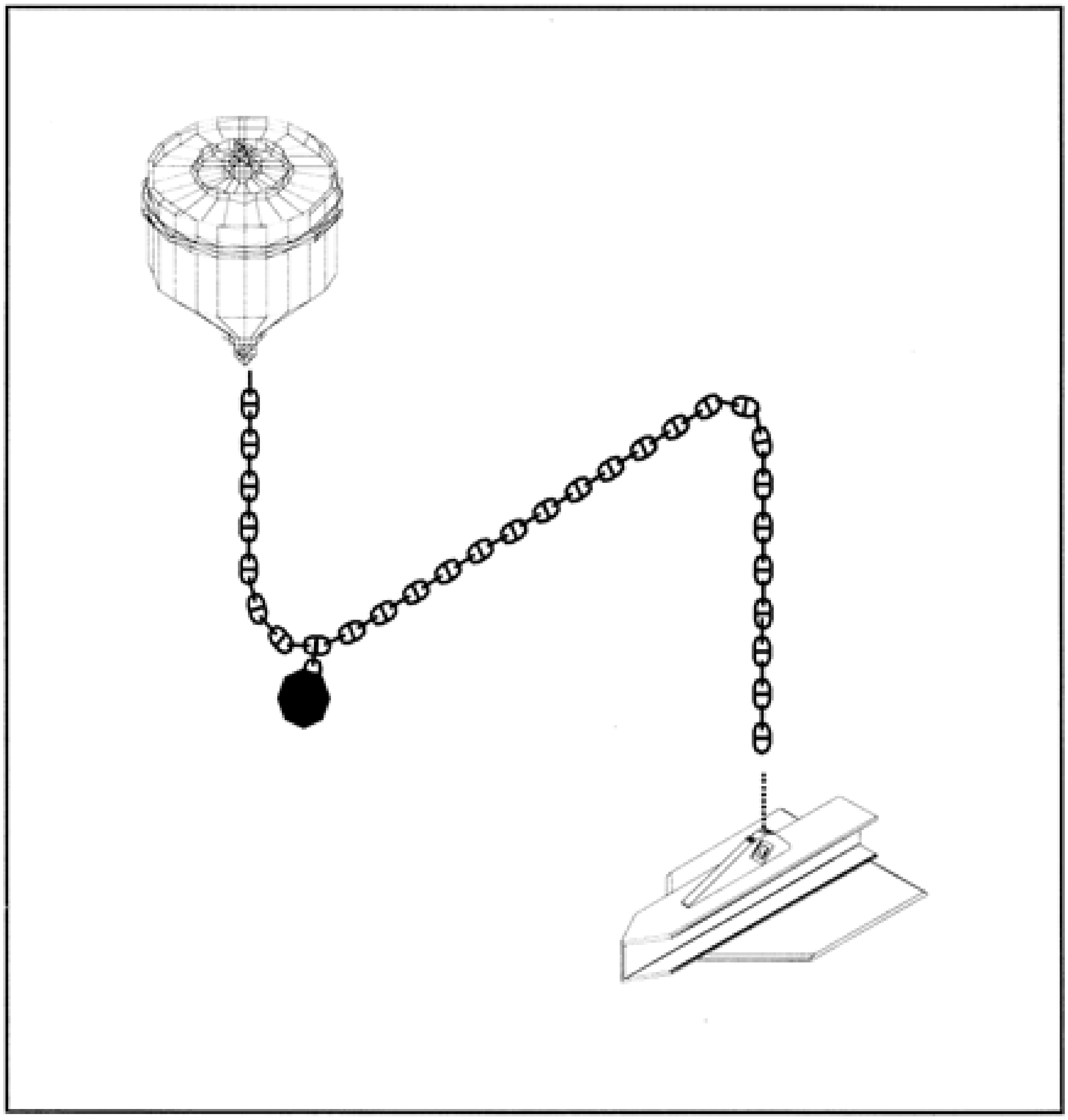


Figure 9
Single Point Mooring With a Plate Anchor and a Sinker

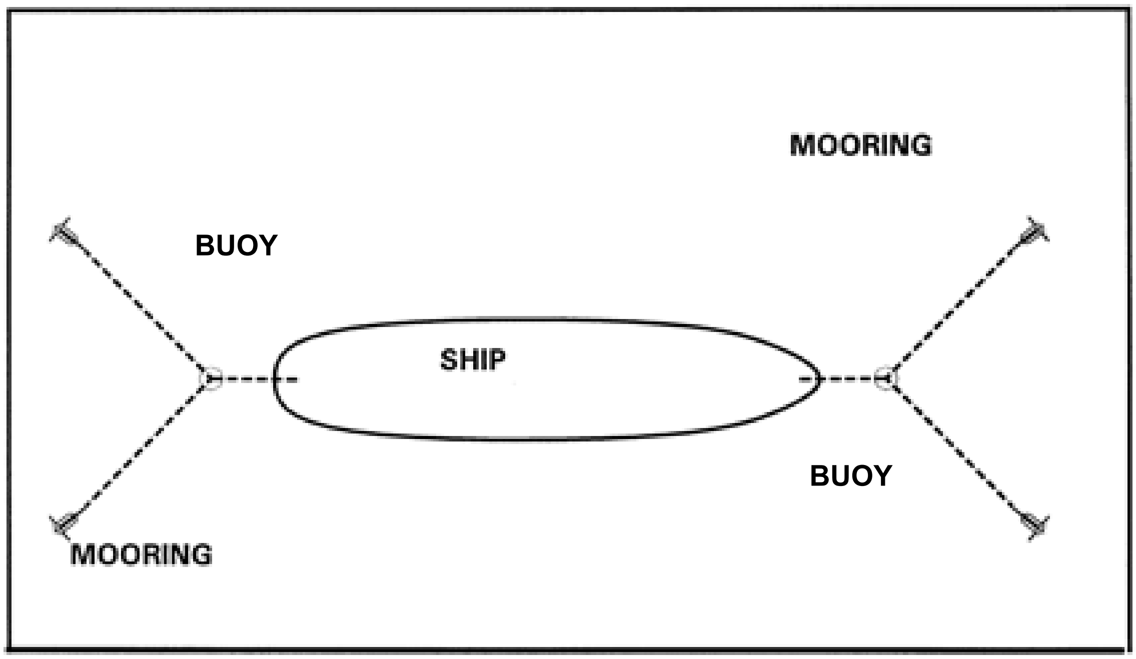


Figure 10
Bow-Stern Mooring Shown in Plan View

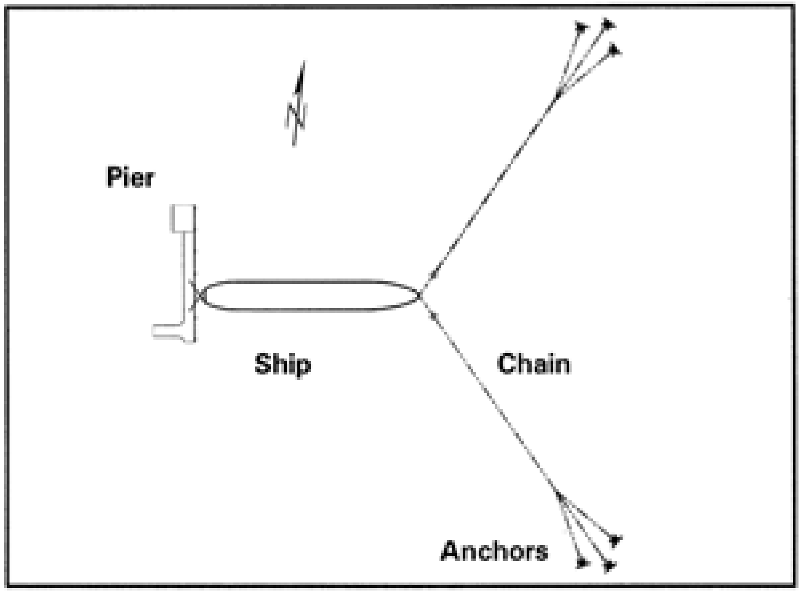


Figure 11
Med-Mooring

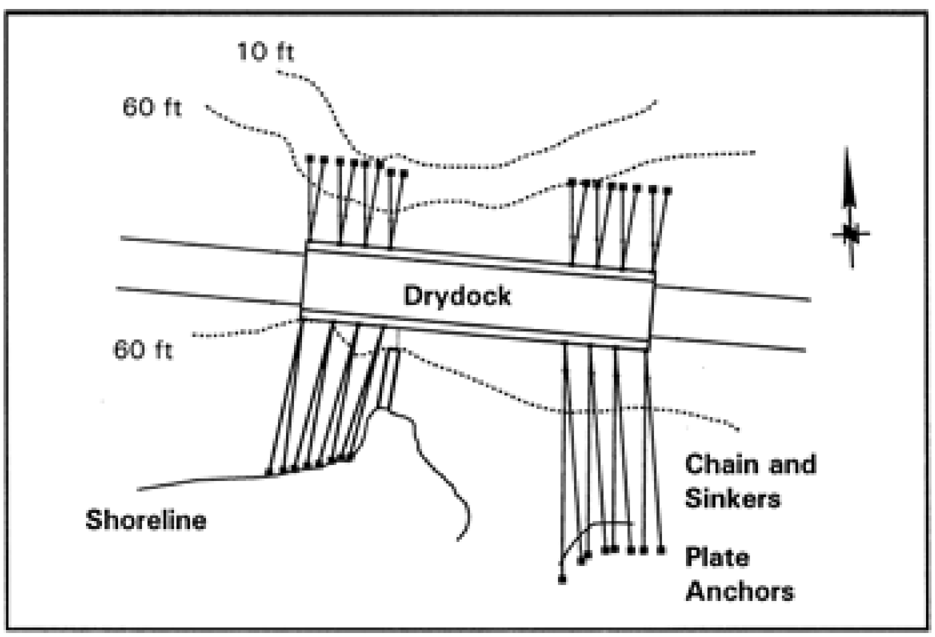


Figure 12
Spread Mooring

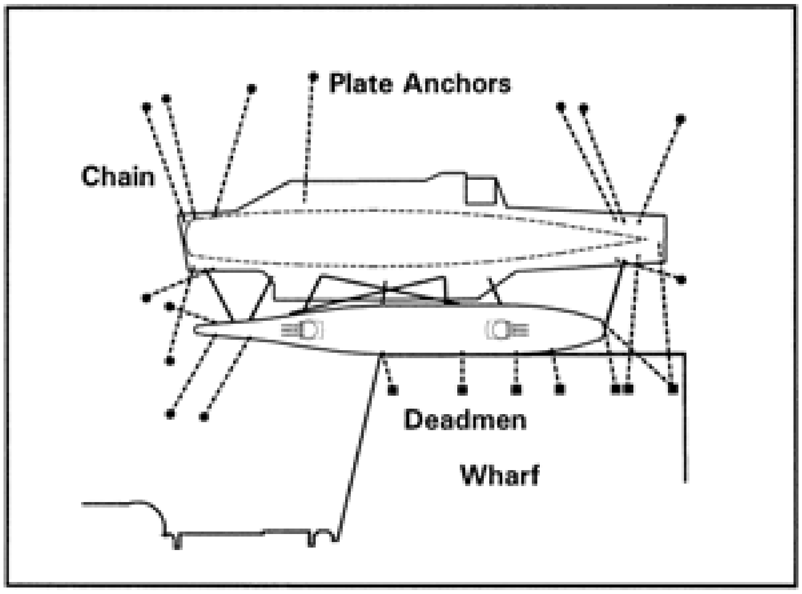


Figure 13
Two Inactive Ships Moored at a Wharf
(Camels between ships not shown)

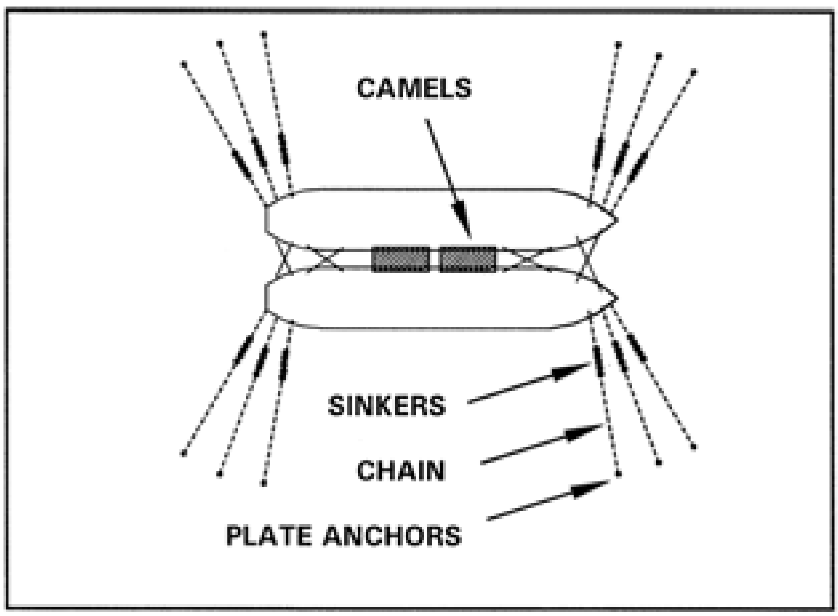


Figure 14
Spread Mooring

Section 3: BASIC DESIGN PROCEDURE

3.1 Design Approach. Begin the design with specified parameters and use engineering principles to complete the design. Types of parameters associated with mooring projects are summarized in Table 3. The basic approach to performing mooring design with the ship known is given in Table 4.

Table 3
Parameters in a Mooring Project

PARAMETER	EXAMPLES
1. Operational Parameters	Required ship position, amount of motion allowed
2. Ship Configuration	Basic ship parameters, such as length, width, draft, displacement, wind areas, mooring fitting locations, wind/current force, and moment coefficients
3. Facility Configuration	Facility location, water depth, dimensions, locations/type/capacity of mooring fittings/fenders, facility condition, facility overall capacity
4. Environmental Parameters	Wind speed, current speed and direction, water levels, wave conditions and possibility of ice
5. Mooring Configuration	Number/size/type/location of tension members, fenders, camels, etc.
6. Material Properties	Stretch/strain characteristics of the mooring tension and compression members

Table 4
Basic Mooring Design Approach With Known Facility for a Specific Site and a Specific Ship

STEP	NOTES
Define customer(s) requirements	Define the ship(s) to be moored, the type of service required, the maximum allowable ship motions, and situations under which the ship will leave.
Determine planning requirements	Define the impact/interaction with other facilities and operations, evaluate explosive arcs, determine permit requirements, establish how the mooring is to be used, review the budget and schedule.
Define site and environmental parameters	Determine the water depth(s), engineering soil parameters, design winds, design currents, design waves, design water levels, and evaluate access.
Ship characteristics	Find the engineering characteristics of the ship(s) including sail areas, drafts, displacements, ship mooring fittings, allowable hull pressures, and other parameters.
Ship forces/moments	Determine the forces, moments, and other key behaviors of the ship(s).
Evaluate mooring alternatives	Evaluate the alternatives in terms of safety, risk, cost, constructability, availability of hardware, impact on the site, watch circle, compatibility, maintenance, inspectability, and other important aspects.
Design Calculations	Perform static and/or dynamic analyses (if required) for mooring performance, anchor design, fender design, etc

Table 4 (Continued)
Basic Mooring Design Approach With Known Facility for a Specific Site and a Specific Ship

STEP	NOTE
Plans/Specs	Prepare plans, specifications, and cost estimates.
Permits	Prepare any required environmental studies and obtain required permits.
Installation planning	Prepare instructions for installation, including safety and environmental protection plans.
Installation monitoring	Perform engineering monitoring of the installation process.
Testing	Perform pull tests of all anchors in mooring facilities to ensure that they hold the required load.
Documentation	Document the design and as-built conditions with drawings and reports.
Instructions	Provide diagrams and instructions to show the customer how to use and inspect the mooring.
Inspection	Perform periodic inspection/testing of the mooring to assure it continues to meet the customer(s) requirements.
Maintenance	Perform maintenance as required and document on as-built drawings.

3.2 General Design Criteria. General design issues shown in Table 5 should be addressed during design to help ensure projects meet customers' needs.

Table 5
Design Issues

CRITERIA	NOTES
Vessel operating conditions	Under what conditions will the vessel(s) exit? What are the operating mission requirements for the ship? What is the maximum allowable hull pressure?
Allowable motions	How much ship motion in the six degrees-of-freedom will be allowable for the moored ship? This is related to brow positions and use, utilities, ship loading and unloading operations, and other requirements. Note that most ships have a very high buoyancy force and moorings should be designed to allow for water level changes at a site.
User skills	Is the user trained and experienced in using the proposed system? What is the risk that the mooring would be improperly used? Can a design be formulated for easy and reliable use?
Flexibility	How flexible is the design? Can it provide for new mission requirements not yet envisioned? Can it be used with existing facilities/ships?
Constructability	Does the design specify readily available commercial products and is it able to be installed and/or constructed using standard techniques, tolerances, etc.?
Cost	Are initial and life cycle costs minimized?
Inspection	Can the mooring system be readily inspected to ensure continued good working condition?
Maintenance	Can the system be maintained in a cost-effective manner?
Special requirements	What special requirements does the customer have? Are there any portions of the ship that cannot come in contact with mooring elements (e.g., submarine hulls)?

3.2.1 Mooring Service Types. There are several types of standard services that moorings provide for DOD vessels in harbors. Therefore, the facilities and ship’s mooring hardware should accommodate the types of services shown in Table 6.

Table 6
Mooring Service Types

MOORING SERVICE TYPE	DESCRIPTION
TYPE I	This category covers moorings that are used in winds of less than 34 knots and currents less than 2 knots. Moorings include ammunition facilities, fueling facilities, deperming facilities, and ports of call. Use of these moorings is normally selected concomitant with forecasted weather.
TYPE II	This category covers moorings that for general purpose berthing by a vessel that **will leave** prior to an approaching tropical hurricane, typhoon, or flood.
TYPE III	This category covers moorings that are used for **up to 2 years** by a vessel that **will not leave** prior to an approaching tropical hurricane or typhoon. Moorings include fitting-out, repair, drydocking, and overhaul berthing facilities. Ships experience this service approximately every 5 years. Facilities providing this service are nearly always occupied.
TYPE IV	This category covers moorings that are used for **2 years or more** by a vessel that **will not leave** in case of a hurricane, typhoon, or flood. Moorings include inactive, drydock, ship museum, and training berthing facilities.

3.2.2 Facility Design Criteria for Mooring Service Types. Mooring facilities should be designed using the site specific criteria given in Table 7. Table 7 gives design criteria in terms of environmental design return intervals, R, and in terms of probability of exceedence, P, for 1 year of service life, N = 1.

3.2.3 Ship Hardware Design Criteria for Mooring Service Types. Ship mooring hardware needs to be designed to accommodate various modes of ship operation. During Type II operation, a ship may be moored in relatively high broadside current and get caught by a sudden storm, such as a thunderstorm. Type III mooring during repair may provide the greatest potential of risk, because the ship is moored for a significant time and cannot get underway. During Type IV mooring, the ship should be aligned with the current, extra padeyes can be welded to the ship hull for mooring, etc., so special provisions can be made for long-term storage. There are several U.S. shipyards where DOD ships can undergo major repairs. The area near Norfolk/Portsmouth, Virginia has the most extreme design criteria, so use conditions derived from that site for the ship's hardware design. Bremerton, Washington, and Pearl Harbor, Hawaii have major U.S. Navy repair shipyards with lower design winds and currents at those sites. Ship mooring hardware environmental design criteria are given in Table 8.

3.2.4 Strength. Moorings should be designed and constructed to safely resist the nominal loads in load combinations defined herein without exceeding the appropriate allowable stresses for the mooring components. Normal wear of materials and inspection methods and frequency need to be considered. Due to the probable chance of simultaneous maximum occurrences of variable loads, no reduction factors should be used.

3.2.5 Serviceability. Moorings should be designed to have adequate stiffness to limit deflections, vibration, or any other deformations that adversely affect the intended use and performance of the mooring. At the same time moorings need to be flexible enough to provide for load sharing and allow for events, such as tidal changes.

Table 7
Facility Design Criteria for Mooring Service Types

MOORING SERVICE TYPE	WIND*	CURRENT**	WATER LEVEL	WAVES
TYPE I	Less than 34 knots	2 knots or less	mean lower low to mean higher high	P=1 or R=1 yr
TYPE II	P=0.02 (min.) R=50 yr (min.) V_w=64 knots (max.)	P=0.02 R=50 yr	extreme lower low to mean higher high	P=1 or R=1 yr
TYPE III	P=0.02 or R=50 yr	P=0.02 or R=50 yr	extreme lower low to high	P=0.02 or R=50 yr
TYPE IV	P=0.01 or R=100 yr	P=0.01 or R=100 yr	extreme water levels	P=0.01 or R=100 yr

*Use exposure D (American Society of Civil Engineers (ASCE) 7-95, Minimum Design Loads for Buildings and Other Structures; flat, unobstructed area exposed to wind flowing over open water for a distance of at least 1 mile or 1.61 km) for determining design wind speeds. Note that min. = minimum return interval or probability of exceedence used for design; max. = maximum wind speed used for design.

**To define the design water depth, use T/d = 0.9 for flat keeled ships; for ships with non-flat hulls, that have sonar domes or other projections, take the ship draft, T, as the mean depth of the keel and determine the water depth, d, by adding 0.61 meter (2 feet) to the maximum navigation draft of the ship.

Table 8
Ship Mooring Hardware Design Criteria

a. Ship Anchor Systems*

MAXIMUM WATER DEPTH	MINIMUM WIND SPEED	MINIMUM CURRENT SPEED	CHAIN FACTOR OF SAFETY	ANCHOR HOLDING FACTOR OF SAFETY
240 ft 73 m	70 knots 36.0 m/s	4 knots 2.06 m/s	4.0	1.0

b. Submarine Anchor Systems*

MAXIMUM WATER DEPTH	MINIMUM WIND SPEED	MINIMUM CURRENT SPEED	CHAIN FACTOR OF SAFETY	ANCHOR HOLDING FACTOR OF SAFETY
120 ft 36.6 m	70 knots 36.0 m/s	4 knots 2.06 m/s	4.0	1.0

c. Ship Mooring Systems**

CONDITION	MINIMUM WIND SPEED	MINIMUM CURRENT SPEED	MOORING LINE FACTOR OF SAFETY
Normal weather condition	25 knots 12.9 m/s	1 knot 0.51 m/s	9.0
Heavy weather condition	50 knots 25.7 m/s	3 knots 1.54 m/s	3.0

*Quasi-static design assuming wind and current are co-linear for ship and submarine anchor systems (after NAVSEA DDS-581).

**Quasi-static design assuming current is broadside and wind can approach from any direction (after NAVSEA DDS-582-1).

3.2.6 General Mooring Integrity. For multiple-member moorings, such as for a ship secured to a pier by a number of lines, the mooring system strongly relies on load sharing among several members. If one member is lost, the ship should remain moored. Therefore, design multiple member mooring to ensure that remaining members maintain a factor of safety at least 75 percent of the intact mooring factors of safety shown in Table 9 with any one member missing.

3.2.7 Quasi-Static Safety Factors. Table 9 gives recommended minimum factors of safety for "quasi-static" design based on material reliability.

3.2.8 Allowable Ship Motions. Table 10 gives recommended operational ship motion criteria for moored vessels. Table 10(a) gives maximum wave conditions for manned and moored small craft (Permanent International Association of Navigation Congresses (PIANC), Criteria for Movements of Moored Ships in Harbors; A Practical Guide, 1995). These criteria are based on comfort of personnel on board a small boat, and are given as a function of boat length and locally generated.

Table 10(b) gives recommended motion criteria for safe working conditions for various types of vessels (PIANC, 1995).

Table 10(c) gives recommended velocity criteria and Table 10(d) and (e) give special criteria.

Table 9
Minimum Quasi-Static Factors of Safety

COMPONENT	MINIMUM FACTOR OF SAFETY	NOTES
Stockless & balanced fluke anchors	1.5	For ultimate anchoring system holding capacity; use 1.0 for ship's anchoring*
High efficiency drag anchors	2.0	For ultimate anchoring system holding capacity use 1.0 for ship's anchoring*
Fixed anchors (piles & plates)	3.0	For ultimate anchoring system holding capacity*
Deadweight anchors	-	Use carefully (see Naval Civil Engineering Laboratory (NCEL) Handbook for Marine Geotechnical Engineering, 1985)
Chain	3.0 4.0	For relatively straight lengths. For chain around bends. These factors of safety are for the new chain break strength.
Wire rope	3.0	For the new wire rope break strength.
Synthetic line**	3.0	For new line break strength.
Ship bitts	***	Use American Institute of Steel Construction (AISC) code.
Pier bollards	***	Use AISC & other applicable codes.

*It is recommended that anchors be pull tested.
**Reduce effective strength of wet nylon line by 15 percent.
*** For mooring fittings take 3 parts of the largest size of line used on the fitting; apply a load of: 3.0*(minimum line break strength)*1.3 to determine actual stresses, $\sigma_{act.}$; design fittings so $(\sigma_{act.}/\ \sigma_{allow.})<1.0$, where $\sigma_{allow.}$ is the allowable stress from AISC and other applicable codes.

Table 10
Recommended Practical Motion Criteria for Moored Vessels

(a) Safe Wave Height Limits for Moored Manned Small Craft
(after PIANC, 1995)

	Beam/Quartering Seas		Head Seas	
Vessel Length (m)	Wave Period (sec)	Maximum Sign Wave Height, H_s (m)	Wave Period (sec)	Maximum Sign Wave Height, H_s (m)
4 to 10	<2.0	0.20	<2.5	0.20
"	2.0-4.0	0.10	2.5-4.0	0.15
"	>4.0	0.15	>4.0	0.20
10-16	<3.0	0.25	<3.5	0.30
"	3.0-5.0	0.15	3.5-5.5	0.20
"	>5.0	0.20	>5.5	0.30
20	<4.0	0.30	<4.5	0.30
"	4.0-6.0	0.15	4.5-7.0	0.25
"	>6.0	0.25	>7.0	0.30

Table 10 (Continued)
Recommended Practical Motion Criteria for
Moored Vessels

(b) Recommended Motion Criteria for Safe Working Conditions[1] (after PIANC, 1995)

Vessel Type	Cargo Handling Equipment	Surge (m)	Sway (m)	Heave (m)	Yaw (°)	Pitch (°)	Roll (°)
Fishing vessels 10-3000 GRT[2]	Elevator crane	0.15	0.15	-	-	-	-
	Lift-on/off	1.0	1.0	0.4	3	3	3
	Suction pump	2.0	1.0	-	-	-	-
Freighters & coasters <10000 DWT[3]	Ship's gear	1.0	1.2	0.6	1	1	2
	Quarry cranes	1.0	1.2	0.8	2	1	3
Ferries, Roll-On/ Roll-Off (RO/RO)	Side ramp[4]	0.6	0.6	0.6	1	1	2
	Dew/storm ramp	0.8	0.6	0.8	1	1	4
	Linkspan	0.4	0.6	0.8	3	2	4
	Rail ramp	0.1	0.1	0.4	-	1	1
General cargo 5000-10000 DWT	-	2.0	1.5	1.0	3	2	5
Container vessels	100% efficient	1.0	0.6	0.8	1	1	3
	50% efficient	2.0	1.2	1.2	1.5	2	6
Bulk carriers 30000-150000 DWT	Cranes	2.0	1.0	1.0	2	2	6
	Elevator/ bucket-wheel	1.0	0.5	1.0	2	2	2
	Conveyor belt	5.0	2.5	-	3	-	-
Oil tankers	Loading arms	3.0[5]	3.0	-	-	-	-
Gas tankers	Loading arms	2.0	2.0	-	2	2	2

Table 10 (Continued)
Recommended Practical Motion Criteria for
Moored Vessels

Notes for Table 10(b):

[1]Motions refer to peak-to-peak values (except for sway, which is zero-to-peak)

[2]GRT = Gross Registered Tons expressed as internal volume of ship in units of 100 ft^3 (2.83 m^3)

[3]DWT = Dead Weight Tons, which is the total weight of the vessel and cargo expressed in long tons (1016 kg) or metric tons (1000 kg)

[4]Ramps equipped with rollers.

[5]For exposed locations, loading arms usually allow for 5.0-meter motion.

(c) Recommended Velocity Criteria for Safe Mooring Conditions for Fishing Vessels, Coasters, Freighters, Ferries and Ro/Ro Vessels (after PIANC, 1995)

Ship Size(DWT)	Surge (m/s)	Sway (m/s)	Heave (m/s)	Yaw (°/s)	Pitch (°/s)	Roll (°/s)
1000	0.6	0.6	-	2.0	-	2.0
2000	0.4	0.4	-	1.5	-	1.5
8000	0.3	0.3	-	1.0	-	1.0

(d) Special Criteria for Walkways and Rail Ramps (after PIANC, 1995)

Parameter	Maximum Value
Vertical velocity	0.2 m/s
Vertical acceleration	0.5 m/s^2

Table 10 (Continued)
Recommended Practical Motion Criteria
for Moored Vessels

(e) Special Criteria

CONDITION	MAXIMUM VALUES	NOTES
Heave	-	Ships will move vertically with any long period water level change (tide, storm surge, flood, etc.). The resulting buoyancy forces may be high, so the mooring must be designed to provide for these motions due to long period water level changes.
Loading/unloading preposition ships	0.6 m (2 feet)	Maximum ramp motion during loading/unloading moving wheeled vehicles.
Weapons loading/unloading	0.6 m (2 feet)	Maximum motion between the crane and the object being loaded/unloaded.

3.3 Design Methods

3.3.1 Quasi-Static Design. Practical experience has shown that in many situations such as for Mooring Service Types I and II, static analysis tools can be used to reliably determine mooring designs in harbors. Winds are a key forcing factor in mooring harbors. Winds can be highly dynamic in heavy weather conditions. However, practical experience has shown that for typical DOD ships, a wind speed with a duration of 30 seconds can be used, together with static tools, to develop safe mooring designs. The use of the 30-second duration wind speed with static tools and the approach shown in Table 11 is called "quasi-static" design.

Table 11
Quasi-Static Design Notes

CRITERIA	NOTES
Wind speed	Determine for the selected return interval, R. For typical ships use the wind that has a duration of 30 seconds at an elevation of 10 m.
Wind direction	Assume the wind can come from any direction except in cases where wind data show extreme winds occur in a window of directions.
Current speed	Use conditions for the site (speed and direction).
Water levels	Use the range for the site.
Waves	Neglected. If waves are believed to be important, then dynamic analyses are recommended.
Factors of safety	Perform the design using quasi-static forces and moments (see Section 4), minimum factors of safety in Table 9, and design to assure that all criteria are met.

3.3.2 Dynamic Mooring Analysis. Conditions during Mooring Service Types III and IV, and during extreme events can be highly dynamic. Unfortunately, the dynamic behavior of a moored ship in shallow water can be highly complex, so dynamics cannot be fully documented in this handbook. An introduction to dynamics is provided in Section 8. Information on dynamics is found in: Dynamic Analysis of Moored Floating Drydocks, Headland et. al. (1989); Advanced Dynamics of Marine Structures, Hooft (1982); Hydrodynamic Analysis and Computer Simulation Applied to Ship Interaction During Maneuvering in Shallow Channels, Kizakkevariath (1989); David Taylor Research Center (DTRC), SPD-0936-01, User's Manual for the Standard Ship Motion Program, SMP81; Low Frequency Second Order Wave Exciting Forces on Floating Structures, Pinkster (1982); Mooring Dynamics Due to Wind Gust Fronts, Seelig and Headland (1998); and A Simulation Model for a Single Point Moored Tanker, Wichers (1988). Some conditions when mooring dynamics may be important to design or when specialized considerations need to be made are given in Table 12.

3.4 Risk. Risk is a concept that is often used to design facilities, because the probability of occurrence of extreme events (currents, waves, tides, storm surge, earthquakes, etc.) is strongly site dependent. Risk is used to ensure that systems are reliable, practical, and economical.

A common way to describe risk is the concept of 'return interval', which is the mean length of time between events. For example, if the wind speed with a return interval of R = 100 years is given for a site, this wind speed would be expected to occur, on the average, once every 100 years. However, since wind speeds are probabilistic, the specified 100-year wind speed might not occur at all in any 100-year period. Or, in any 100-year period the wind speed may be equal to or exceed the specified wind speed multiple times.

The probability or risk that an event will be equaled or exceeded one or more times during any given interval is determined from:

EQUATION: $$P = 100\% * (1 - (1 - 1/R)^{N}) \qquad (1)$$

where

P = probability, in percent, of an event being equaled or exceeded one or more times in a specified interval
R = return interval (years)
N = service life (years)

Figure 15 shows risk versus years on station for various selected values of return interval. For example, take a ship that is on station at a site for 20 years (N = 20). There is a P = 18.2 percent probability that an event with a return interval of R = 100 years or greater will occur one or more times at a site in a 20-year interval.

Table 12
Conditions Requiring Special Analysis

FACTOR	SPECIAL ANALYSIS REQUIRED
Wind	> 45 mph for small craft > 75 mph for larger vessels
Wind waves	> 1.5 ft for small craft > 4 ft for larger vessels
Wind gust fronts	Yes for SPMs
Current	> 3 knots
Ship waves and passing ship effects	Yes for special cases (see Kizakkevariath, 1989; Occasion, 1996; Weggel and Sorensen, 1984 & 1986)
Long waves (seiches and tidal waves or tsunamis)	Yes
Berthing and using mooring as a break	Yes (see MIL-HDBK-1025/1)
Parting tension member	May be static or dynamic
Ship impact or other sudden force on the ship	Yes (if directed)
Earthquakes (spud moored or stiff systems)	Yes
Explosion, landslide, impact	Yes (if directed)
Tornado (reference NUREG 1974)	Yes
Flood, sudden water level rise	Yes (if directed)
Ice forcing	Yes (if a factor)
Ship/mooring system dynamically unstable (e.g., SPM)	Yes (dynamic behavior of ships at SPMs can be especially complex)
Forcing period near a natural period of the mooring system	Yes; if the forcing period is from 80% to 120% of a system natural period

Note: SPM = single point mooring

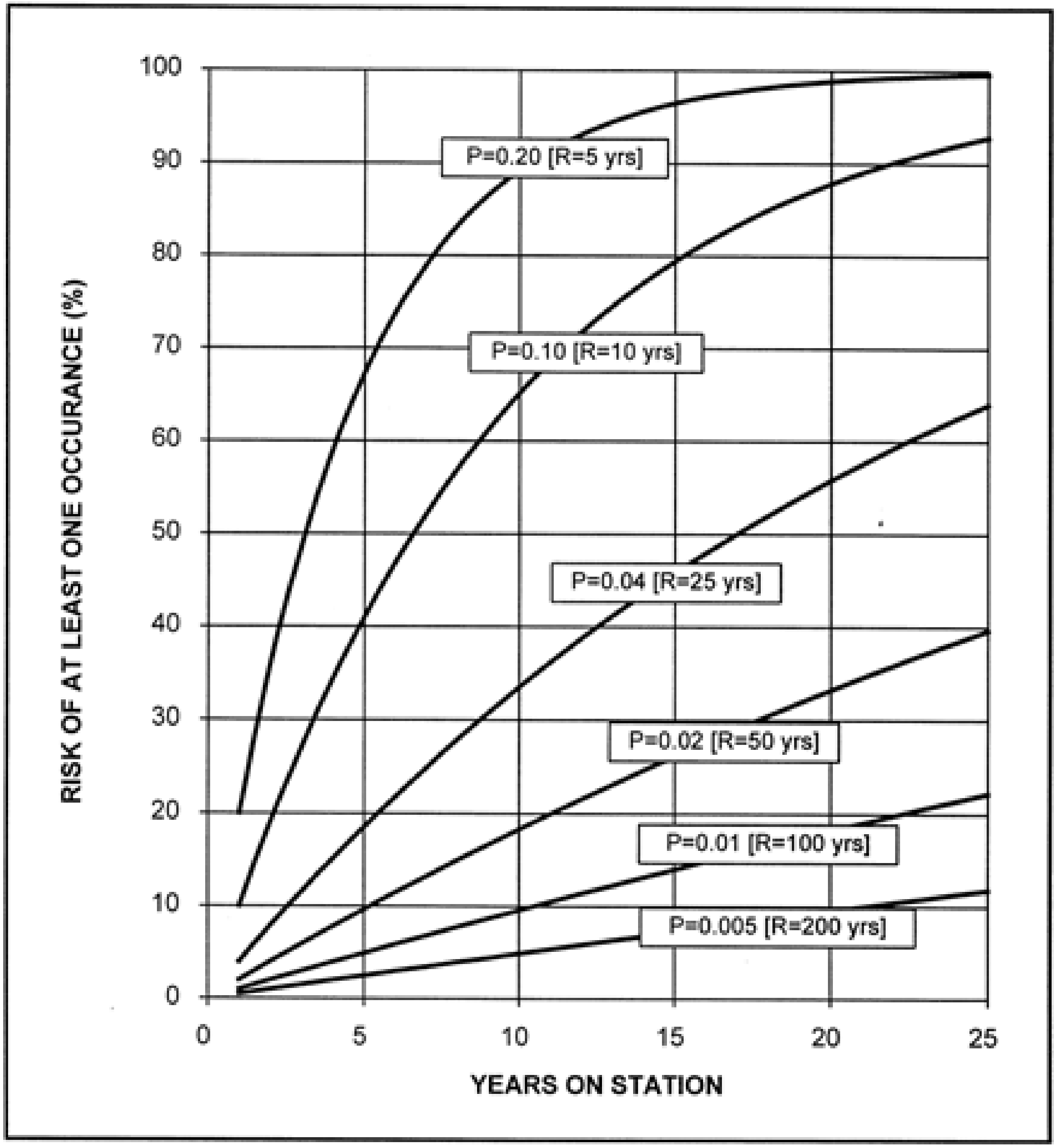


Figure 15
Risk Diagram

3.5 Coordinate Systems. The various coordinate systems used for ships and mooring design are described below.

3.5.1 Ship Design/Construction Coordinates. A forward perpendicular point (FP), aft perpendicular point (AP), and regular spaced frames along the longitudinal axes of the ship are used to define stations. The bottom of the ship keel is usually used as the reference point or “baseline” for vertical distances. Figure 16 illustrates ship design coordinates.

3.5.2 Ship Hydrostatics/Hydrodynamics Coordinates. The forward perpendicular is taken as Station 0, the aft perpendicular is taken as Station 20, and various cross-sections of the ship hull (perpendicular to the longitudinal axis of the ship) are used to describe the shape of the ship hull. Figure 16 illustrates ship hydrostatic conventions.

3.5.3 Local Mooring Coordinate System. Environmental forces on ships are a function of angle relative to the vessel’s longitudinal centerline. Also, a ship tends to move about its center of gravity. Therefore, the local “right-hand-rule” coordinate system, shown in Figure 17, is used in this handbook. The midship’s point is shown as a convenient reference point in Figures 17 and 18.

3.5.4 Global Coordinate System. Plane state grids or other systems are often used to describe x and y coordinates. The vertical datum is most often taken as relative to some water level, such as mean lower low water (MLLW).

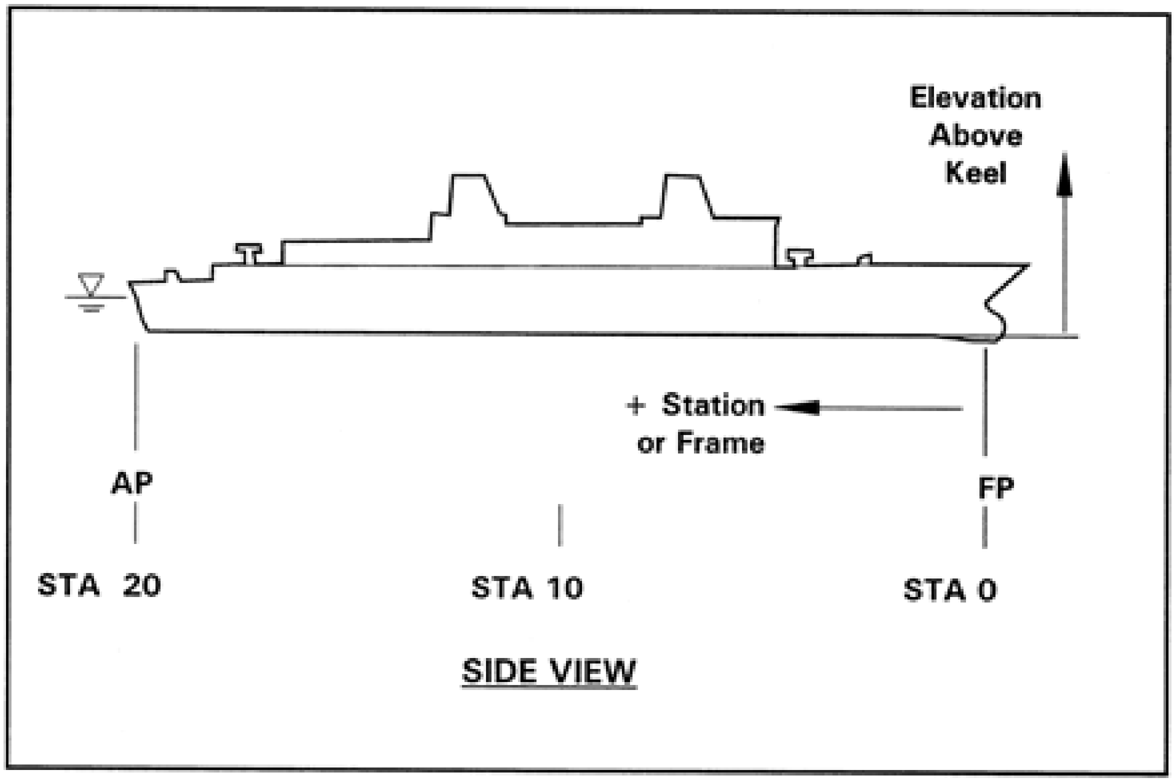


Figure 16
Ship Design and Hydrostatic Coordinates

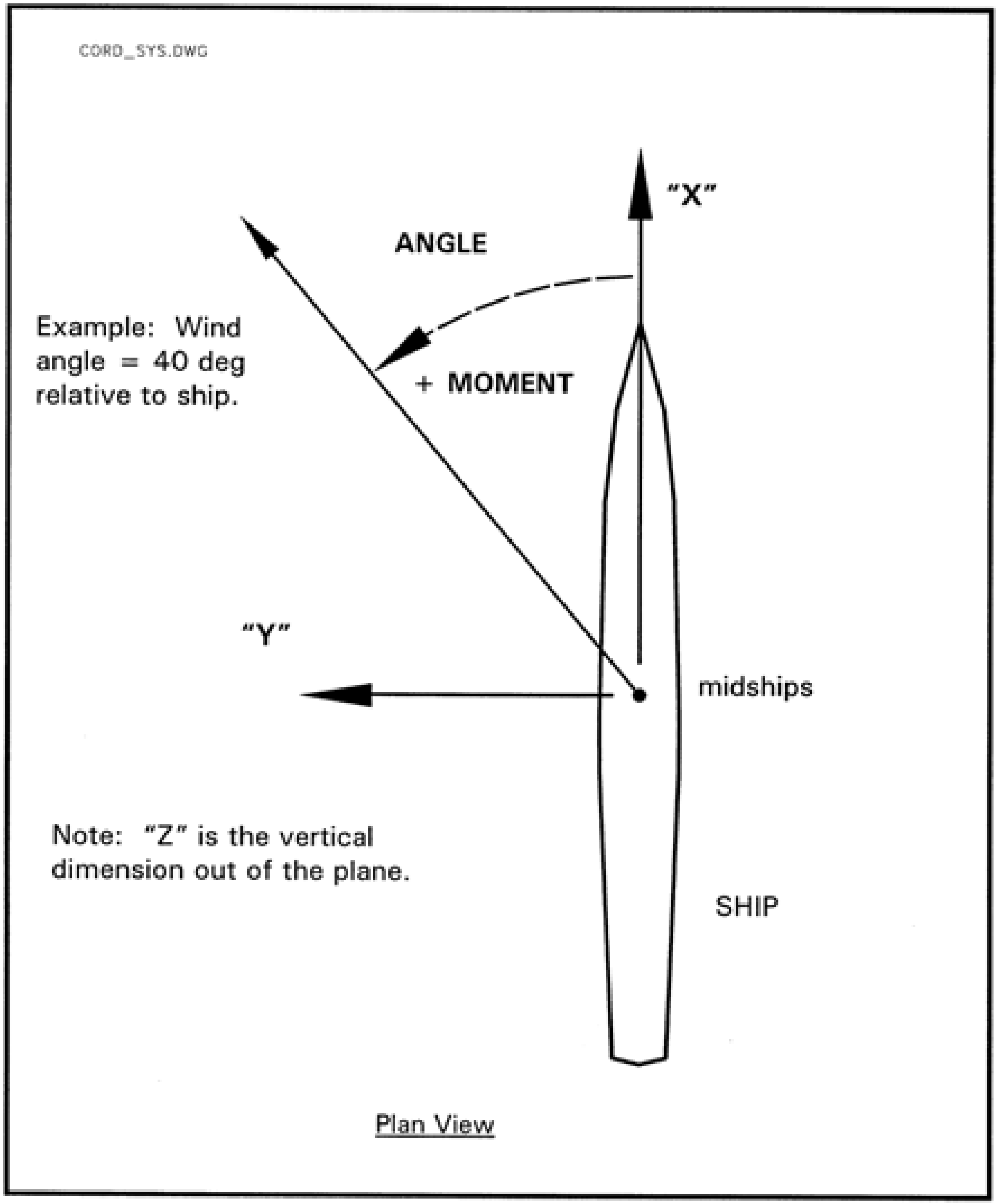


Figure 17
Local Mooring Coordinate System for a Ship

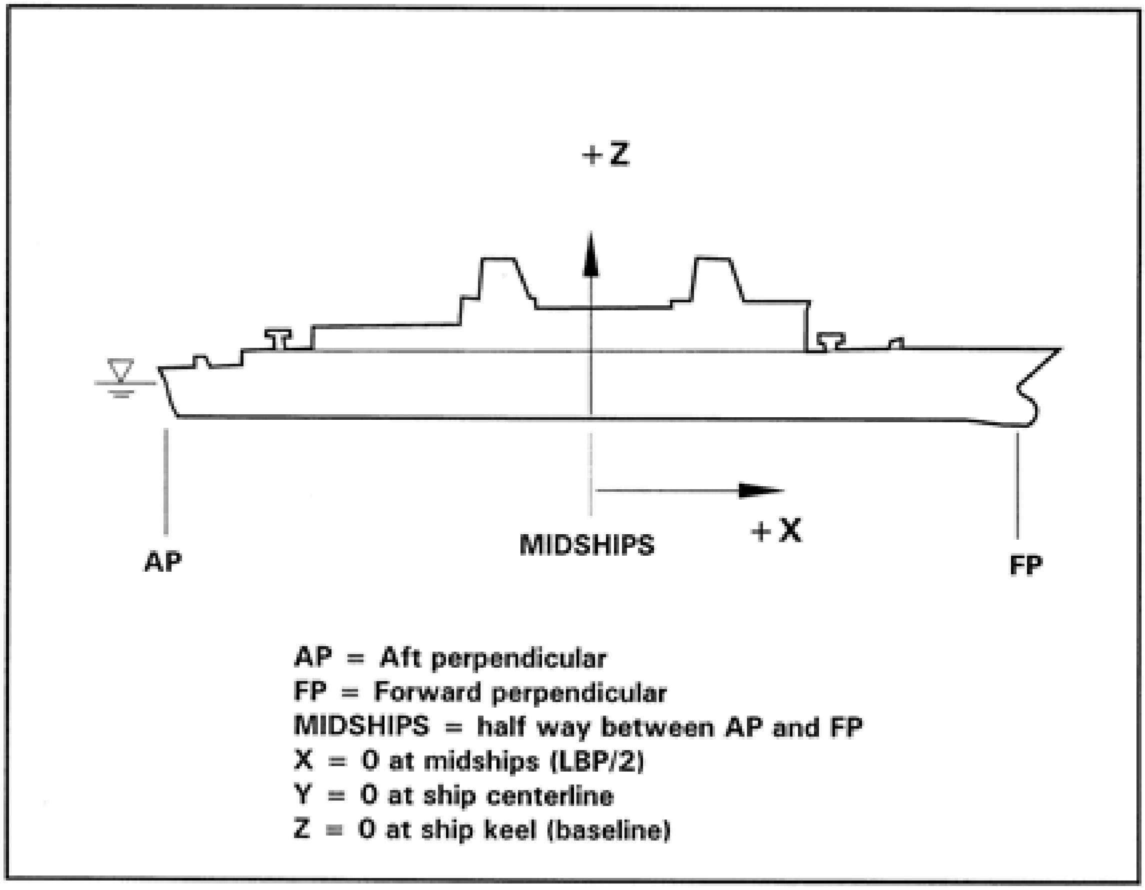


Figure 18
Local Mooring Coordinate System for a Ship

3.6 Vessel Design Considerations. Some important vessel mooring design considerations are summarized in Table 13.

Table 13
Design Considerations - Ship

PARAMETER	NOTES
Ship fittings	The type, capacity, location, and number of mooring fittings on the ship are critical in designing moorings.
Ship hardware	The type, capacity, location, and number of other mooring hardware (chain, anchors, winches, etc.) on the ship are critical.
Buoyancy	The ship's buoyancy supports the ship up in the heave, pitch, and roll directions. Therefore, it is usually undesirable to have much mooring capacity in these directions. A large ship, for example, may have over a million pounds of buoyancy for a foot of water level rise. If an unusually large water level rise occurs for a mooring with a large component of the mooring force in the vertical direction, this could result in mooring failure.
Hull pressures	Ships are designed so that only a certain allowable pressure can be safely resisted. Allowable hull pressures and fender design are discussed in NFESC TR-6015-OCN, Foam-Filled Fender Design to Prevent Hull Damage.
Personnel access	Personnel access must be provided.
Hotel services	Provision must be made for utilities and other hotel services.

3.7 Facility Design Considerations. Some important facility mooring design considerations are summarized in Table 14.

Table 14
Design Considerations - Facility

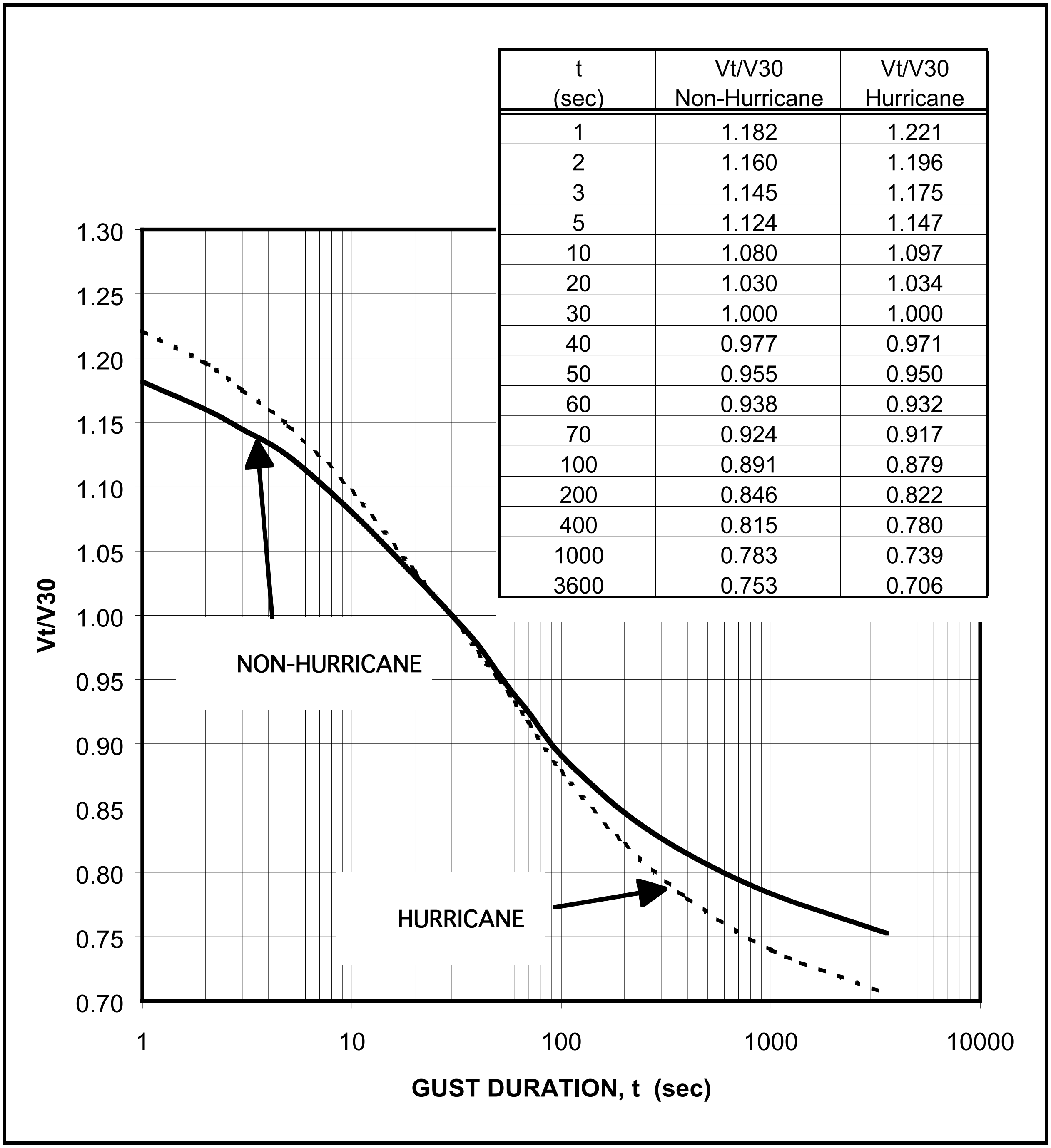
PARAMETER	NOTES
Access	Adequate ship access in terms of channels, turning basins, bridge clearance, etc. needs to be provided. Also, tugs and pilots must be available.
Mooring fittings	The number, type, location and capacity of mooring fittings or attachment point have to meet the needs of all vessels using the facility.
Fenders	The number, type, location, and properties of marine fenders must be specified to protect the ship(s) and facility.
Water depth	The water depth at the mooring site must be adequate to meet the customer’s needs.
Shoaling	Many harbor sites experience shoaling. The shoaling and possible need for dredging needs to be considered.
Permits	Permits (Federal, state, environmental, historical, etc.) are often required for facilities and they need to be considered.

3.8 Environmental Forcing Design Considerations. Environmental forces acting on a moored ship(s) can be complex. Winds, currents, water levels, and waves are especially important for many designs.

3.8.1 Winds. A change in pressure from one point on the earth to another causes the wind to blow. Turbulence is carried along with the overall wind flow to produce wind gusts. If the mean wind speed and direction do not change very rapidly with time, the winds are referred to as "stationary."

Practical experience has shown that wind gusts with a duration of approximately 30 seconds or longer have a significant influence on typical moored ships with displacements of about 1000 tons or larger. Vessels with shorter natural periods can respond to shorter duration gusts. For the purposes of this handbook, a 30-second wind duration at a 10-meter (33-foot) elevation is recommended for the design for "stationary" winds. The relationship of the 30-second wind to other wind durations is shown in Figure 19.

If wind speed and/or direction changes rapidly, such as in a wind gust front, hurricane or tornado, then winds are "non-stationary". Figure 20, for example, shows a recording from typhoon OMAR in 1992 at Guam. The eye of this storm went over the recording site. The upper portion of this figure shows the wind speed and the lower portion of the figure is the wind direction. Time on the chart recorder proceeds from right to left. This hurricane had rapid changes in wind speed and direction. As the eye passes there is also a large scale change in wind speed and direction.



t (sec)	Vt/V30 Non-Hurricane	Vt/V30 Hurricane
1	1.182	1.221
2	1.160	1.196
3	1.145	1.175
5	1.124	1.147
10	1.080	1.097
20	1.030	1.034
30	1.000	1.000
40	0.977	0.971
50	0.955	0.950
60	0.938	0.932
70	0.924	0.917
100	0.891	0.879
200	0.846	0.822
400	0.815	0.780
1000	0.783	0.739
3600	0.753	0.706

Figure 19
Ratio of Wind Speeds for Various Gusts
(after ASCE 7-95)

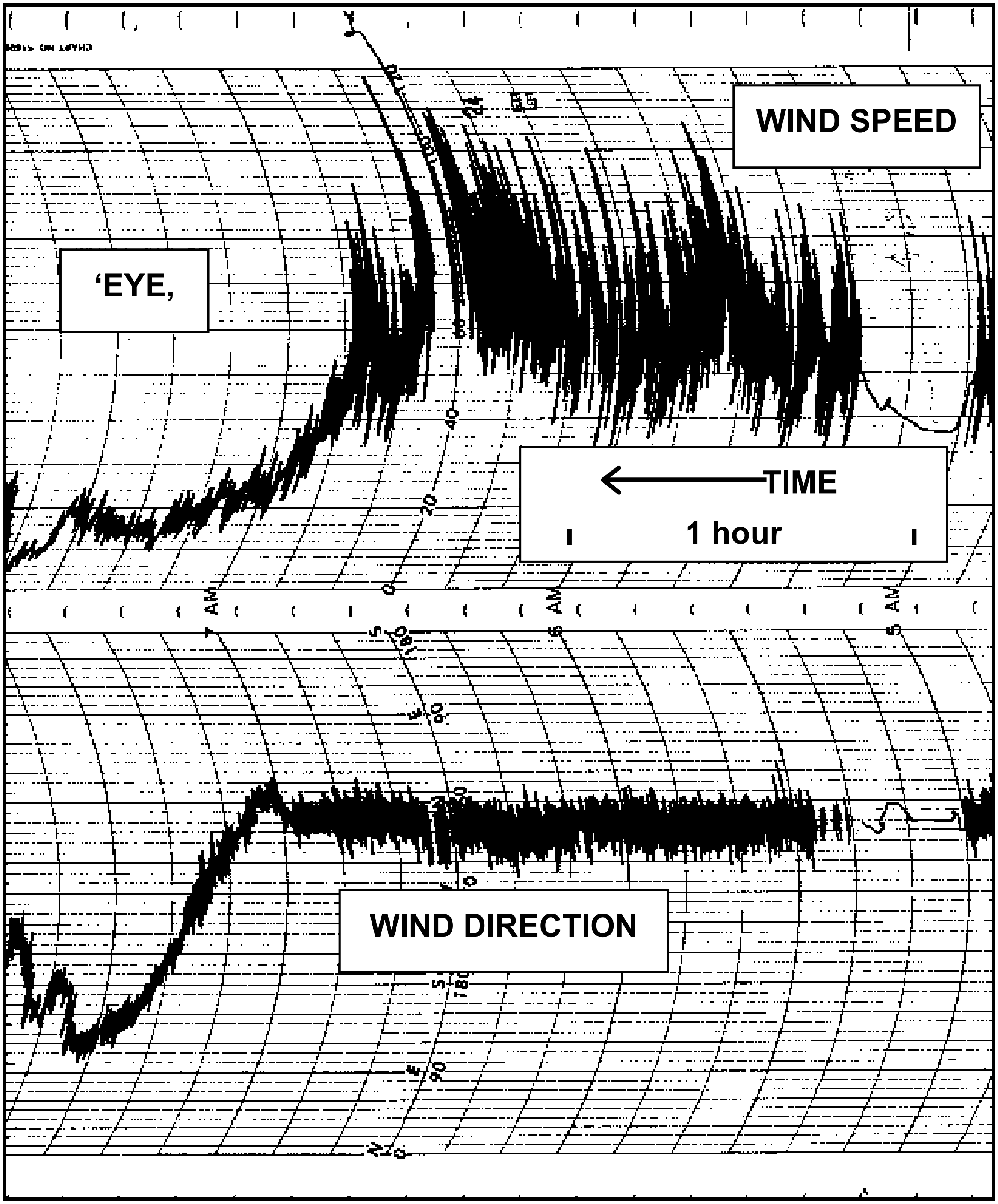


Figure 20
Typhoon *OMAR* Wind Chart Recording

3.8.2 Wind Gust Fronts. A particularly dangerous wind condition that has caused a number of mooring accidents is the wind gust front (Mooring Dynamics Due to Wind Gust Fronts, Seelig and Headland, 1998 and CHESNAVFACENGCOM, FPO-1-87(1), Failure Analysis of Hawsers on BOBO Class MSC Ships at Tinian on 7 December 1986). This is a sudden change in wind speed that is usually associated with a change in wind direction (Wind Effects on Structures, Simiu and Scanlan, 1996). The key problems with this phenomena are: (1) high mooring dynamic loads can be produced in a wind gust front, (2) there is often little warning, (3) little is known about wind gust fronts, and (4) no design criteria for these events have been established.

A study of Guam Agana National Air Station (NAS) wind records was performed to obtain some statistics of wind gust fronts (National Climatic Data Center (NCDC), Letter Report E/CC31:MJC, 1987). The 4.5 years of records analyzed from 1982 through 1986 showed approximately 500 cases of sudden wind speed change, which were associated with a shift in wind direction. These wind shifts predominately occurred in 1 minute or less and never took longer than 2 minutes to reach maximum wind speed. Figure 21 shows sudden changes in wind speed and direction that occurred over a 2-1/2 day period in October 1982. These wind gust fronts seemed to be associated with a nearby typhoon.

Table 15 gives the joint distribution of wind shifts in terms of the amount the increase in wind speed and the wind direction change. Approximately 60 percent of the wind gust fronts from 1982 through 1986 had wind direction changes in the 30-degree range, as shown in Figure 22.

Based on the Guam observations, the initial wind speed in a wind gust front ranges from 0 to 75 percent of the maximum wind speed, as shown in Figure 23. On the average, the initial wind speed was 48 percent of the maximum in the 4.5-year sample from Guam (NCDC, 1987).

Simiu and Scanlan (1996) report wind gust front increases in wind speed ranging from 3 m/sec to 30 m/sec (i.e., 6 to 60 knots). Figure 24 shows the distribution of gust front winds from the 4.5-year sample from 1982 through 1986 on Guam. This figure shows the probability of exceedence on the x-axis in a logarithmic format. The square of the wind gust front speed maximums was plotted on the y-axis, since wind force is proportional to wind speed squared. Figure 24 provides a sample of the maximum wind gust front distribution for a relatively short period at one site. Those wind gust fronts that occurred when a typhoon was nearby are identified with an "H." It can be seen that the majority of the higher gust front maximums were associated with typhoons. Also, the typhoon gust front wind speed maxima seem to follow a different distribution that the gust front maxima associated with rain and thunderstorms (see Figure 24).

Effects of winds and wind gusts are shown in the examples in Section 8 of this handbook.

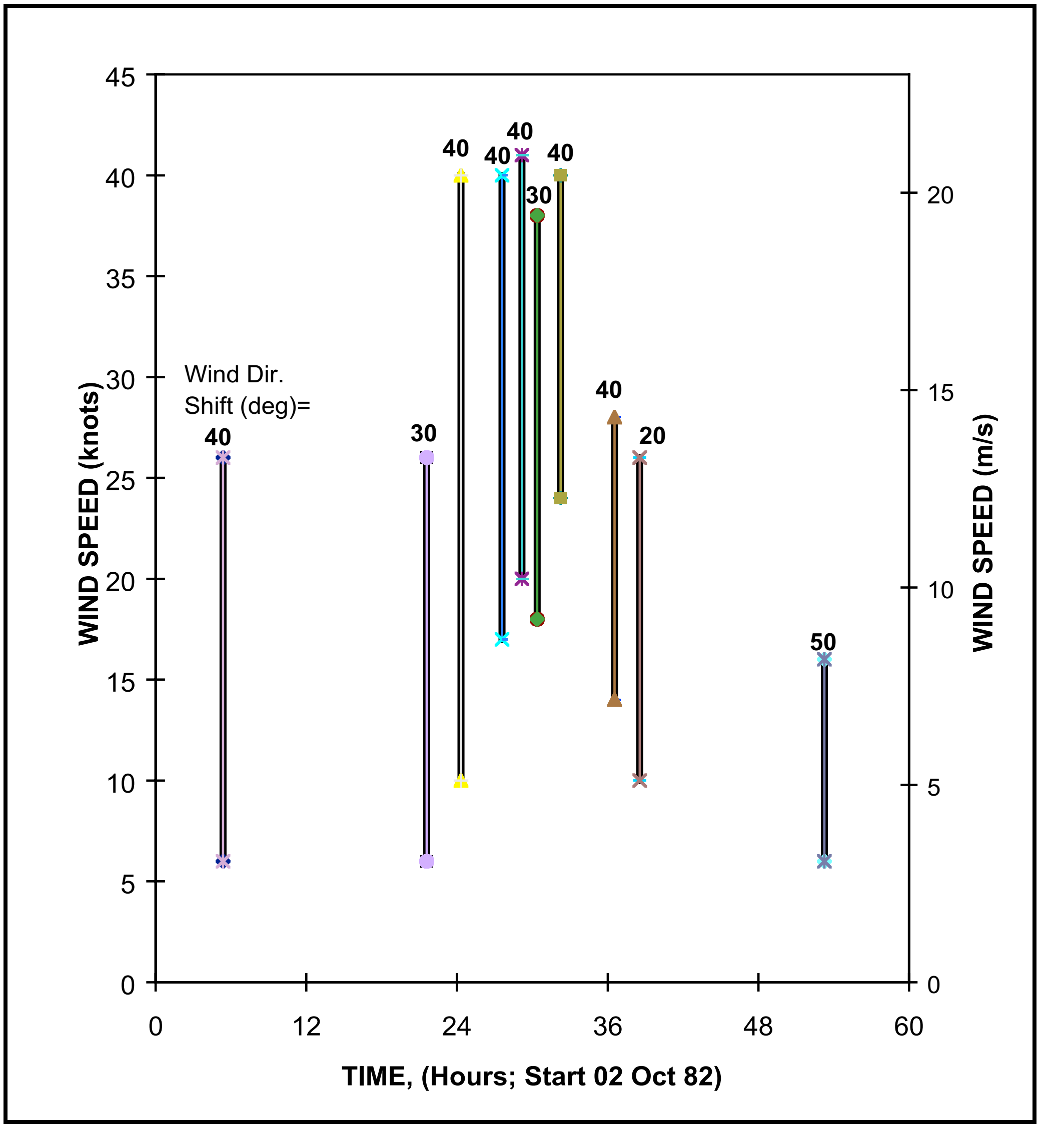


Figure 21
Sample Wind Gust Fronts on Guam, 2-4 October 1982

Table 15
Sample Distribution of Wind Gust Fronts
on Guam (Agana NAS) from 1982 to 1986

WIND SPEED CHANGE (knots)		(m/s)		**NUMBER OF OBSERVATIONS** WIND DIRECTION CHANGE							
MIN.	MAX.	MIN.	MAX.	20 deg	30 deg	40 deg	50 deg	60 deg	70 deg	80 deg	90 deg
6	10	3.1	5.1	28	241	66	30	4		2	
11	15	5.7	7.7	8	42	18	13	5	3	1	1
16	20	8.2	10.3	6	7	3	2	2			
21	25	10.8	12.9		3	2		1			
26	30	13.4	15.4			1					

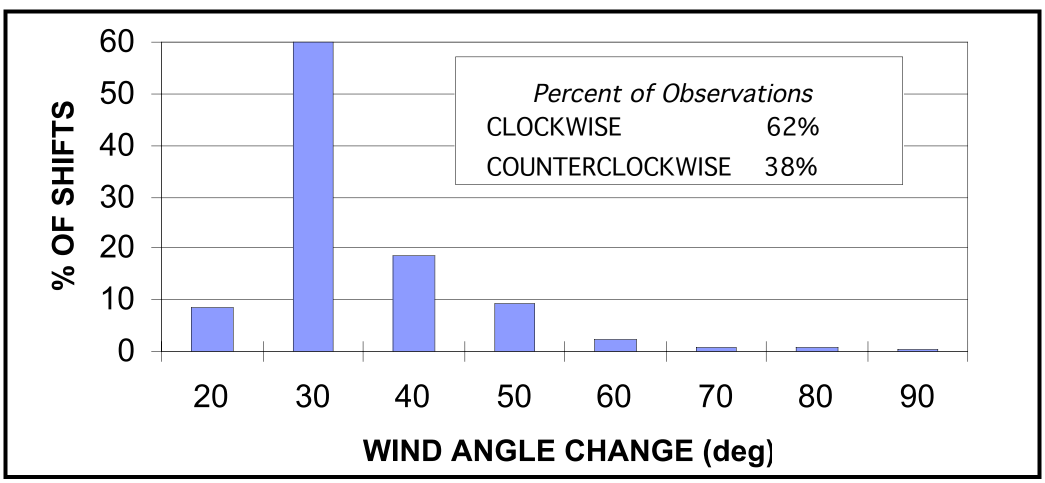
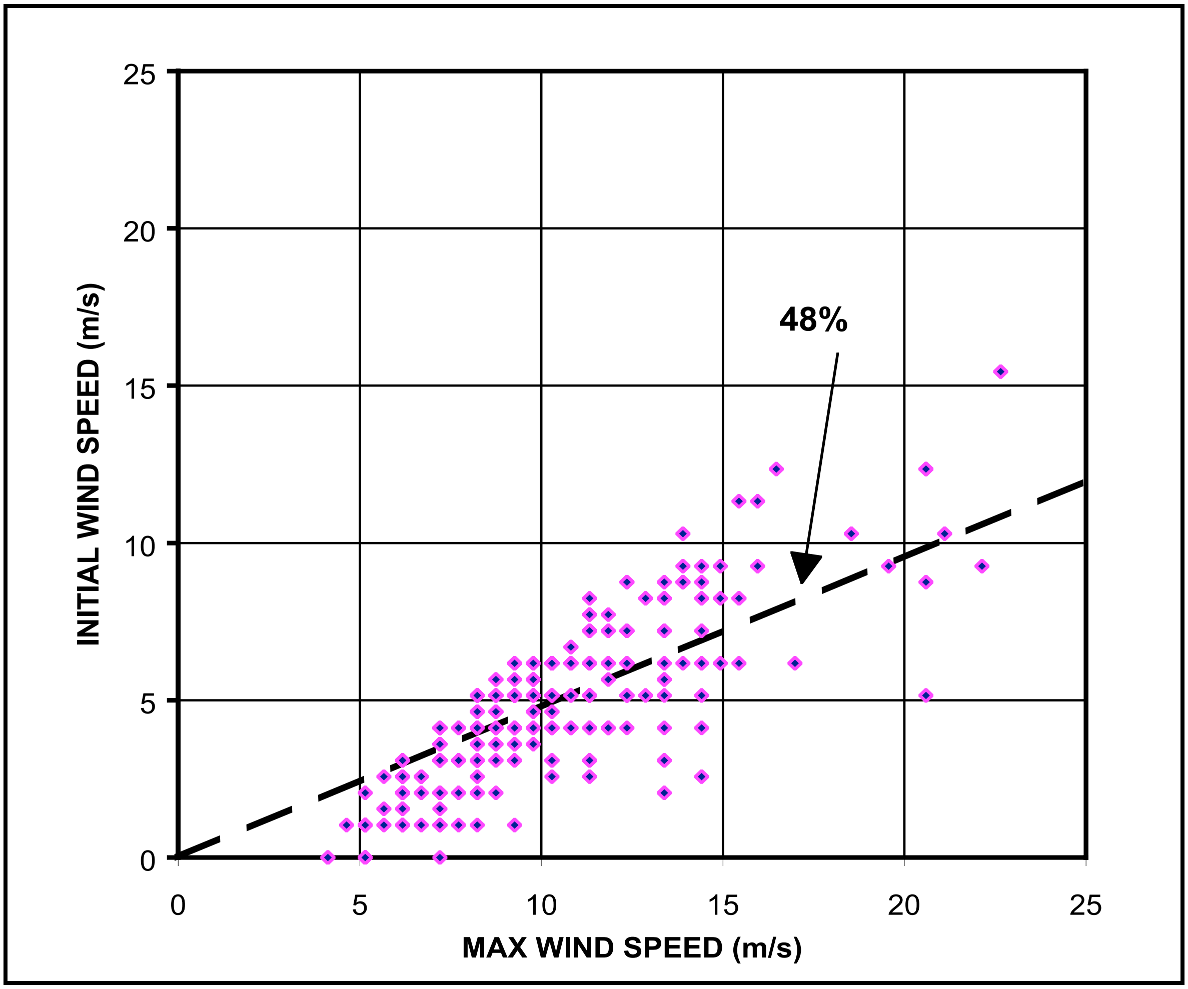


Figure 22
Distribution of Guam Wind Gust Front Wind Angle Changes

Figure 23



Initial Versus Maximum Wind Speeds for Wind Gust Fronts

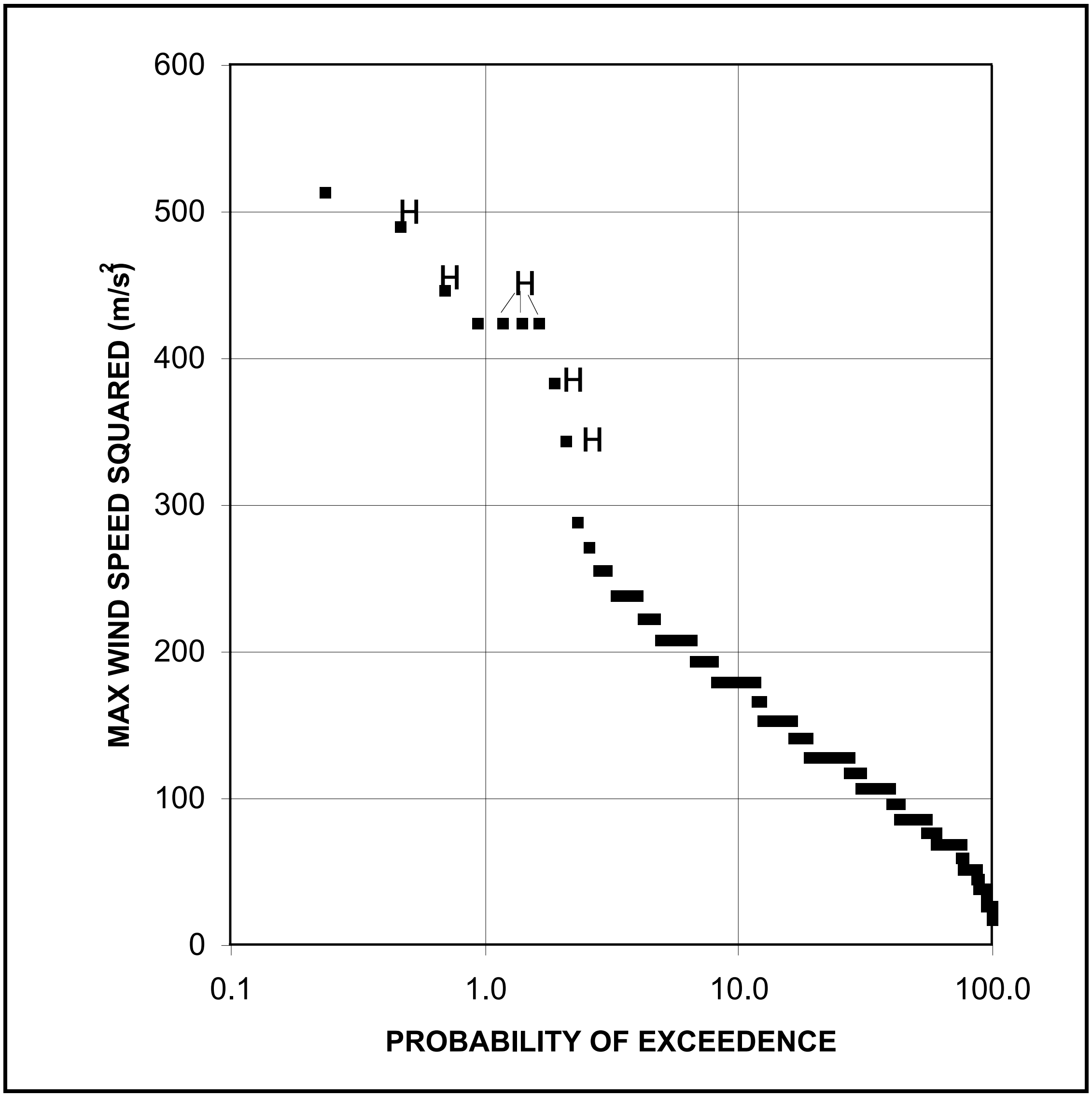


Figure 24

Wind Gust Front Maxima on Guam 1982-1986

3.8.3 Storms. Table 16 gives environmental parameters for standard storms.

Table 16
Storm Parameters

(a) Tropical Storms

STORM	LOWER WIND SPEED (m/s)	LOWER WIND SPEED (mph)	LOWER WIND SPEED (knts)	UPPER WIND SPEED (m/s)	UPPER WIND SPEED (mph)	UPPER WIND SPEED (knts)
TROPICAL DEPRESSION	10.3	23	20	17	38	33
TROPICAL STORM	18.0	40	35	32.4	74	63
HURRICANE	33.1	74	64	-	-	-

(b) Saffier-Simpson Hurricane Scale

	WIND SPEED RANGE				OPEN COAST STORM SURGE RANGE			
	LOWER		UPPER		LOWER		UPPER	
CATE-GORY	(m/s)	(mph)	(m/s)	(mph)	(m)	(ft)	(m)	(ft)
1	33.1	74	42.5	95	1.22	4	1.52	5
2	42.9	96	49.2	110	1.83	6	2.44	8
3	49.6	111	58.1	130	2.74	9	3.66	12
4	58.6	131	69.3	155	3.96	13	5.49	18
5	69.3	155	-	-	5.49	18	-	-

Table 16 (Continued)
Storm Parameters

(c) Beaufort Wind Force*

BEAUFORT WIND FORCE/ DESCRIPTION	LOWER WIND SPEED (m/s)	LOWER WIND SPEED (mph)	LOWER WIND SPEED (knts)	UPPER WIND SPEED (m/s)	UPPER WIND SPEED (mph)	UPPER WIND SPEED (knts)
0 CALM	0.0	0	0	0.5	1	1
1 LIGHT AIRS	0.5	1	1	1.5	4	3
2 LIGHT BREEZE	2.1	5	4	3.1	7	6
3 GENTLE GREEZE	3.6	8	7	5.1	12	10
4 MODERATE BREEZE	5.7	13	11	8.2	18	16
5 FRESH BREEZE	8.8	20	17	10.8	24	21
6 STRONG BREEZE	11.3	25	22	13.9	31	27
7 MODERATE GALE	14.4	32	28	17.0	38	33
8 FRESH GALE	17.5	39	34	20.6	46	40
9 STRONG GALE	21.1	47	41	24.2	54	47
10 WHOLE GALE	24.7	55	48	28.3	63	55
11 STORM	28.8	65	56	32.4	73	63
12 HURRICANE	32.9	74	64	36.6	82	71

*After <u>Handbook of Ocean and Underwater Engineers</u>, Myers et al. (1969).

Table 16 (Continued)
Storm Parameters

(d) World Meteorological Organization Sea State Scale

SEA STATE	Sign. Wave Height (ft) [m]	Sustained Wind Speed (knts) [m/s]	Modal Wave Period Range (sec)
0 CALM/GLASSY	NONE	NONE	-
1 RIPPLED	0-0.3 [0-0.1]	0-6 [0-3]	-
2 SMOOTH	0.3-1.6 [0.1-0.5]	7-10 [3.6-5.1]	3-15
3 SLIGHT	1.6-4.1 [0.5-1.2]	11-16 [5.7-8.2]	3-15.5
4 MODERATE	4.1-8.2 [1.2-2.5]	17-21 [8.7-10.8]	6-16
5 ROUGH	8.2-13.1 [2.5-4.0]	22-27 [11.3-13.9]	7-16.5
6 VERY ROUGH	13.1-19.7 [4.0-6.0]	28-47 [14.4-24.2]	9-17
7 HIGH	19.7-29.5 [6.0-9.0]	48-55 [24.7-28.3]	10-18
8 VERY HIGH	29.5-45.5[9.0-13.9]	56-63 [28.8-32.4]	13-19
9 PHENOMENAL	>45.5 [>13.9]	>63 [>32.4]	18-24

3.8.4 Currents. The magnitude and direction of currents in harbors and nearshore areas are in most cases a function of location and time. Astronomical tides, river discharges, wind-driven currents, and other factors can influence currents. For example, wind-driven currents are surface currents that result from the stress exerted by the wind on the sea surface. Wind-driven currents generally attain a mean velocity of about 3 to 5 percent of the mean wind speed at 10 meters (33 feet) above the sea surface. The magnitude of this current strongly decreases with depth.

Currents can be very site specific, so it is recommended that currents be measured at the design site and combined with other information available to define the design current conditions.

3.8.5 Water Levels. At most sites some standard datum, such as mean low water (MLW) or mean lower low water (MLLW), is established by formal methods. Water levels are then referenced to this datum. The water level in most harbors is then a function of time. Factors influencing water levels include astronomical tides, storm surges, river discharges, winds, seiches, and other factors.

The design range in water levels at the site must be considered in the design process.

3.8.6 Waves. Most DOD moorings are wisely located in harbors to help minimize wave effects. However, waves can be important to mooring designs in some cases. The two primary wave categories of interest are:

a) Wind waves. Wind waves can be locally generated or can be wind waves or swell entering the harbor entrance(s). Small vessels are especially susceptible to wind waves.

b) Long waves. These can be due to surf beat, harbor seiching, or other effects.

Ship waves may be important in some cases. The response of a moored vessel to wave forcing includes:

a) A steady mean force.

b) First order response, where the vessel responds to each wave, and

c) Second order response, where some natural long period mode of ship/mooring motion, which usually has little damping, is forced by the group or other nature of the waves.

If any of these effects are important to a given mooring design, then a six-degree-of-freedom dynamic of the system generally needs to be considered in design. Some guidance on safe wave limits is given in Table 10.

3.8.7 Water Depths. The bathymetry of a site may be complex, depending on the geology and history of dredging. Water depth may also be a function of time, if there is shoaling or scouring. Water depths are highly site specific, so hydrographic surveys of the project site are recommended.

3.8.8 Environmental Design Information. Some sources of environmental design information of interest to mooring designers are summarized in Table 17.

Table 17
Some Sources of Environmental Design Information

a. Winds

NAVFAC Climate Database, 1998
ANSI/ASCE 7-95 (1996)
National Bureau of Standards (NBS), Series 124, Hurricane Wind Speeds in the United States, 1980
Nuclear Regulatory Commission (NUREG), NUREG/CR-2639, Historical Extreme Winds for the United States - Atlantic and Gulf of Mexico Coastlines, 1982
Hurricane and Typhoon Havens Handbooks, NRL (1996) and NEPRF (1982)
NUREG/CR-4801, Climatology of Extreme Winds in Southern California, 1987
NBS Series 118, Extreme Wind Speeds at 129 Stations in the Contiguous United States, 1979

b. Currents

NAVFAC Climate Database, 1998
National Ocean Survey records
Nautical Software, Tides and Currents for Windows, 1995
U.S. Army Corps of Engineers records

Table 17 (Continued)
Some Sources of Environmental Design Information

c. Water Levels

NAVFAC Climate Database, 1998
Federal Emergency Management Agency records
U.S. Army Corps of Engineers, Special Report No. 7, Tides and Tidal Datums in the United States, 1981
National Ocean Survey records
Hurricane and Typhoon Havens Handbooks, NRL (1996) and NEPRF (1982)
Nautical Software (1995)
U.S. Army Corps of Engineers records

d. Waves

Hurricane and Typhoon Havens Handbooks, NRL (1996) and NEPRF (1982)
U.S. Army Corps of Engineers, Shore Protection Manual (1984) gives prediction methods

e. Bathymetry

From other projects in the area
National Ocean Survey charts and surveys
U.S. Army Corps of Engineers dredging records

3.9 Operational Considerations. Some important operational design considerations are summarized in Table 18.

Table 18
Mooring Operational Design Considerations

PARAMETER	NOTES
Personnel experience/ training	What is the skill of the people using the mooring?
Failure	What are the consequences of failure? Are there any design features that can be incorporated that can reduce the impact?
Ease of use	How easy is the mooring to use and are there factors that can make it easier to use?
Safety	Can features be incorporated to make the mooring safer for the ship and personnel?
Act-of-God events	Extreme events can occur unexpectedly. Can features be incorporated to accommodate them?
Future use	Future customer requirements may vary from present needs. Are there things that can be done to make a mooring facility more universal?

3.10 Inspection. Mooring systems and components should be inspected periodically to ensure they are in good working order and are safe. Table 19 gives inspection guidelines.

Table 19
Inspection Guidelines

MOORING SYSTEM OR COMPONENT	MAXIMUM INSPECTION INTERVAL	NOTES
Piers and wharves	1 year 3 years 6 years	Surface inspection Complete inspection - wood structures Complete inspection - concrete and steel structures See NAVFAC MO-104.2, Specialized Underwater Waterfront Facilities Inspections; If the actual capacity/condition of mooring fittings on a pier/wharf is unknown, then pull tests are recommended to proof the fittings.
Fleet Moorings	3 years	See CHESNAVFACENGCOM, FPO-1-84(6), Fleet Mooring Underwater Inspection Guidelines. Also inspect and replace anodes, if required. More frequent inspection may be required for moorings at exposed sites or for critical facilities.
Synthetic line	6 months	Per manufacturer's recommendations

Table 19 (Continued)
Inspection Guidelines

MOORING SYSTEM OR COMPONENT	MAXIMUM INSPECTION INTERVAL	NOTES
Ship's chain	36 months	0-3 years of service
	24 months	4-10 years of service
	18 months	>10 years of service
		(American Petroleum Institute (API) RP 2T, Recommended Practice for Planning, Designing, and Constructing Tension Leg Platforms)
Wire rope	18 months	0-2 years of service
	12 months	3-5 years of service
	9 months	>5 years of service
		(API RP 2T)

3.11 Maintenance. If excessive wear or damage occurs to a mooring system, then it must be maintained. Fleet mooring chain, for example, is allowed to wear to a diameter of 90 percent of the original steel bar diameter. As measured diameters approach 90 percent, then maintenance is scheduled. Moorings with 80 to 90 percent of the original chain diameter are restricted to limited use. If a chain diameter reaches a bar diameter of 80 percent of the original diameter, then the mooring is condemned. Figure 25 illustrates some idealized models of chain wear

3.12 General Mooring Guidelines. Experience and practical considerations show that the recommendations given in Table 20 will help ensure safe mooring. These ideas apply to both ship mooring hardware and mooring facilities.

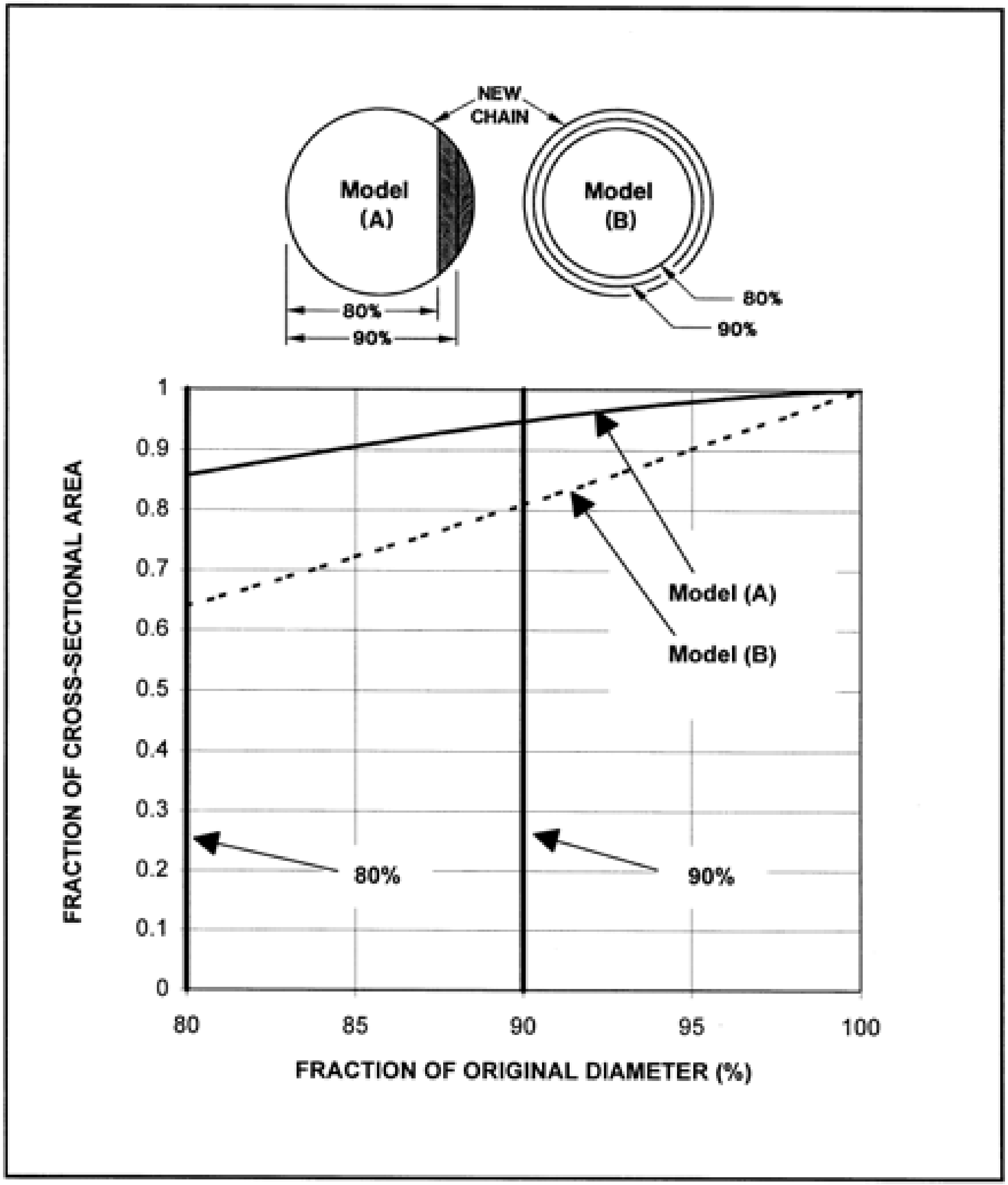


Figure 25
Idealized Models of Chain Wear

Table 20
Design Recommendations

IDEA	NOTES
Allow ship to move with rising and falling water levels	The weight and buoyancy forces of ships can be very high, so it is most practical to design moorings to allow ships to move in the vertical direction with changing water levels. The design range of water levels for a specific site should be determined in the design process.
Ensure mooring system components have similar strength	A system is only as strong as its weakest segment; a system with components of similar strength can be the most economical. Mooring lines should not have a break strength greater than the capacity of the fittings they use.
Ensure load sharing	In some moorings, such as at a pier, many lines are involved. Ensuring that members will share the load results in the most economical system.
Bridle design	In cases where a ship is moored to a single point mooring buoy with a bridle, ensure that each leg of the bridle can withstand the full mooring load, because one member may take the full load as the vessel swings.
Provide shock absorbing in mooring systems	Wind gusts, waves, passing ships, etc., will produce transient forces on a moored ship. Allowing some motion of the ship will reduce the dynamic loads. 'Shock absorbers' including marine fenders, timber piles, synthetic lines with stretch, chain catenaries, sinkers, and similar systems are recommended to allow a moored ship to move in a controlled manner.

Table 20 (Continued)
Design Recommendations

IDEA	NOTES
Limit the vertical angles of lines from ship to pier	Designing ships and piers to keep small vertical line angles has the advantages of improving line efficiency and reducing the possibility of lines pulling off pier fittings.
Select drag anchors to have a lower ultimate holding capacity than the breaking strength of chain and fittings	Design mooring system that uses drag anchor, so that the anchor will drag before the chain breaks.
Limit the loading on drag anchors to horizontal tension	Drag anchors work on the principle of 'plowing' into the soils. Keeping the mooring catenary angle small at the seafloor will aid in anchor holding. Have at least one shot of chain on the seafloor to help ensure the anchor will hold.
Pull test anchors whenever possible to the full design load	Pull testing anchors is recommended to ensure that all facilities with anchors provide the required holding capacity.

Section 4: STATIC ENVIRONMENTAL FORCES AND MOMENTS ON VESSELS

4.1 Scope. In this section design methods are presented for calculating static forces and moments on single and multiple moored vessels. Examples show calculation methods.

4.2 Engineering Properties of Water and Air. The effects of water and air at the surface of the earth are of primary interest in this section. The engineering properties of both are given in Table 21.

Table 21
Engineering Properties of Air and Water

(a) Standard Salt Water at Sea Level at 15°C (59°F)

PROPERTY	SI SYSTEM	ENGLISH SYSTEM
Mass density, ρ_w	1026 kg/m^3	1.9905 slug/ft^3
Weight density, γ_w	10060 newton/m^3	64.043 lbf/ft^3
Volume per long ton (LT)	0.9904 m^3/LT	34.977 ft^3/LT
Kinematic viscosity, ν	1.191E-6 m^2/sec	1.2817E-5 ft^2/sec

(b) Standard Fresh Water at Sea Level at 15°C (59°F)

PROPERTY	SI SYSTEM	ENGLISH OR INCH-POUND SYSTEM
Mass density, ρ_w	999.0 kg/m^3	1.9384 slug/ft^3
Weight density, γ_w	9797 newton/m^3	62.366 lbf/ft^3
Volume per long ton (LT)	1.0171 m^3/LT	35.917 ft^3/LT
Volume per metric ton (ton or 1000 kg or 1 Mg)	1.001 m^3/ton	35.3497 ft^3/ton
Kinematic viscosity, ν	1.141E-6 m^2/sec	1.2285E-5 ft^2/sec

Table 21 (Continued)
Engineering Properties of Air and Water

(c) Air at Sea Level at 20°C (68°F)*

PROPERTY	SI SYSTEM	ENGLISH OR INCH-POUND SYSTEM
Mass density, ρ_a	1.221 kg/m^3	0.00237 slug/ft^3
Weight density, γ_a	11.978 newton/m^3	0.07625 lbf/ft^3
Kinematic viscosity, ν	1.50E-5 m^2/sec	1.615E-4 ft^2/sec

* Note that humidity and even heavy rain has relatively little effect on the engineering properties of air (personal communication with the National Weather Service, 1996)

4.3 Principal Coordinate Directions. There are three primary axes for a ship:

X - Direction parallel with the ship's Longitudinal axis
Y - Direction perpendicular to a vertical plane through the ship's longitudinal axis
Z - Direction perpendicular to a plane formed by the "X" and "Y" axes

There are six principal coordinate directions for a ship:

Surge - In the "X"-direction
Sway - In the "Y"-direction
Heave - In the "Z"-direction
Roll - Angular about the "X"-axis
Pitch - Angular about the "Y"-axis
Yaw - Angular about the "Z"-axis

Of primary interest are: (1) forces in the surge and sway directions in the "X-Y" plane, and (2) moment in the yaw direction about the "Z"-axis. Ship motions occur about the center of gravity of the ship.

4.4 Static Wind Forces/Moments. Static wind forces and moments on stationary moored vessels are computed in this section. Figure 26 shows the definition of some of the terms used in this section. Figure 27 shows the local coordinate system.

4.4.1 Static Transverse Wind Force. The static transverse wind force is defined as that component of force perpendicular to the vessel centerline. In the local ship coordinate system, this is the force in the "Y" or sway direction. Transverse wind force is determined from the equation:

EQUATION: $$F_{yw} = 0.5\,\rho_a\,V_w^2\,A_y\,C_{yw}\,f_{yw}\{\theta_w\} \tag{2}$$

where

F_{yw} = transverse wind force (newtons)
ρ_a = mass density of air (from Table 20)
V_w = wind speed (m/s)
A_y = longitudinal projected area of the ship (m^2)
C_{yw} = transverse wind force drag coefficient
$f_{yw}\{\theta_w\}$ = shape function for transverse force
θ_w = wind angle (degrees)

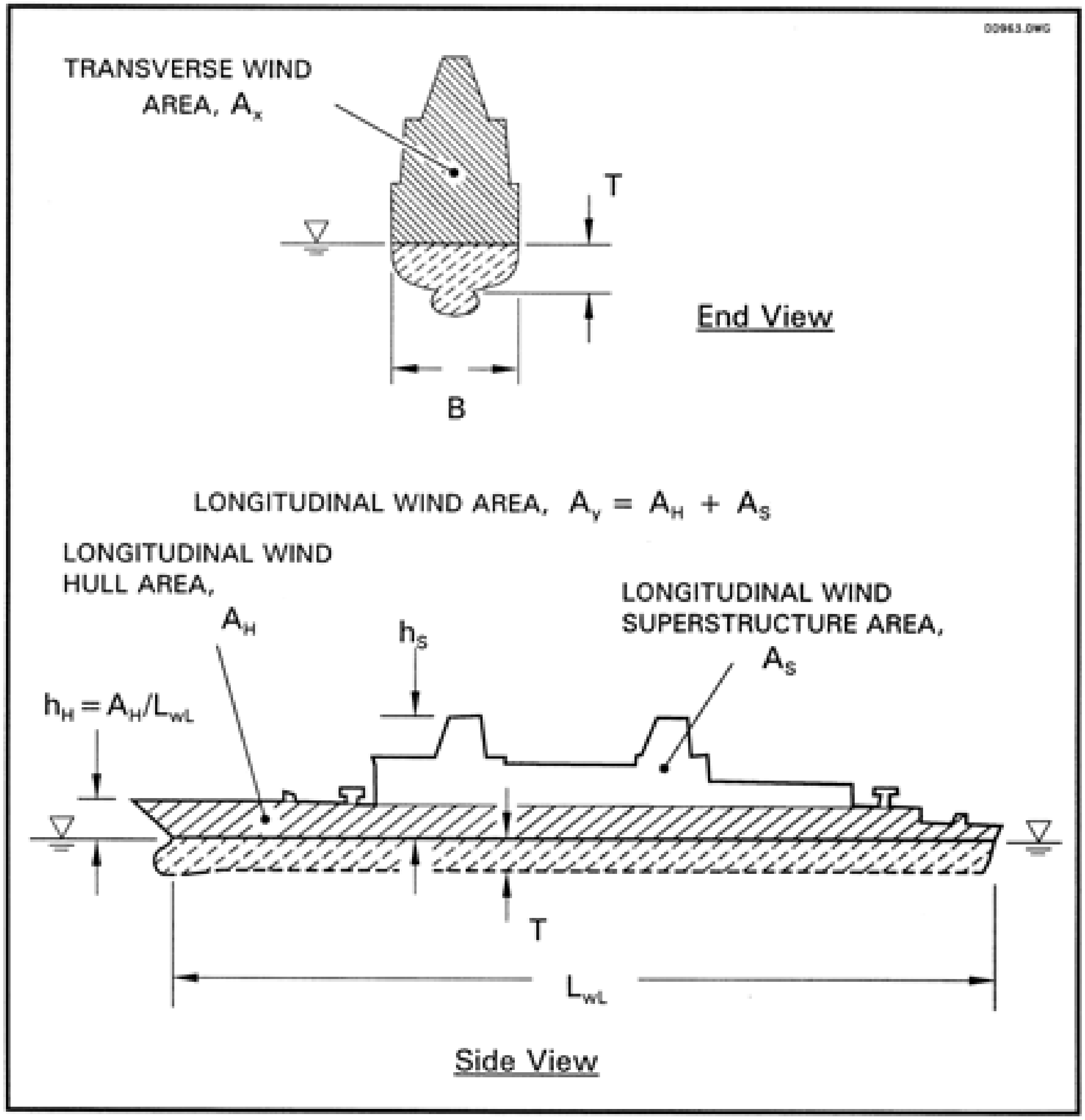


Figure 26
Definition of Terms

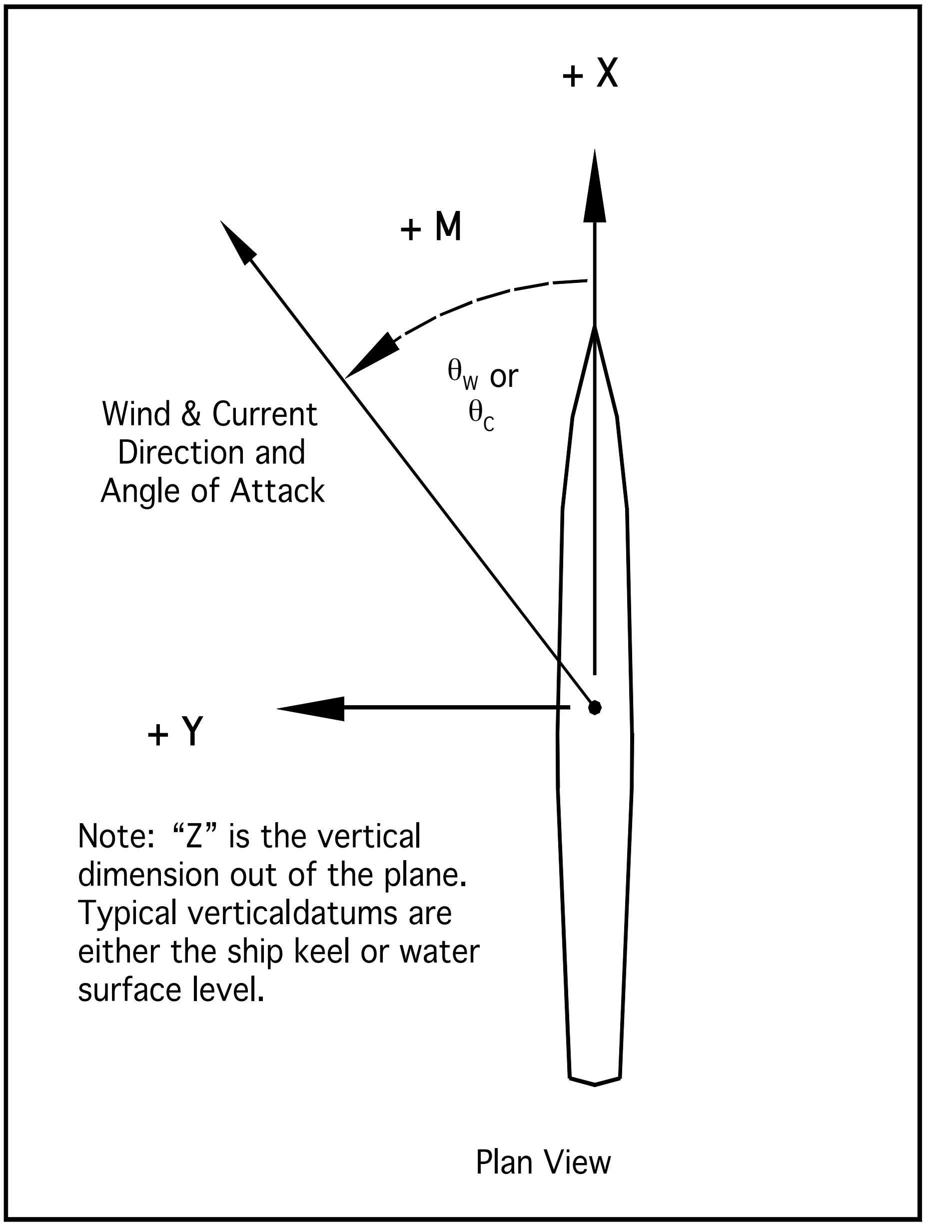


Figure 27
Local Coordinate System for a Ship

The transverse wind force drag coefficient depends upon the hull and superstructure of the vessel and is calculated using the following equation, adapted from Naval Civil Engineering Laboratory (NCEL), TN-1628, Wind-Induced Steady Loads on Ships.

EQUATION: $$C_{yw} = C*\left[((0.5(h_S + h_H))/h_R)^{2/7} A_S + (0.5*h_H/h_R)^{2/7} A_H\right]/A_Y \qquad (3)$$

where

C_{yw} = transverse wind force drag coefficient

C = empirical coefficient, see Table 22

h_R = 10 m = reference height (32.8 ft)

$h_H = A_H / L_{wL}$ = average height of the hull, defined as the longitudinal wind hull area divided by the ship length at the waterline (m)

A_H = longitudinal wind area of the hull (m^2)

L_{wL} = ship length at the waterline (m)

h_S = height of the superstructure above the waterline(m)

A_S = longitudinal wind area of the superstructure (m^2)

A recommended value for the empirical coefficient is C = 0.92 +/-0.1 based on scale model wind tunnel tests (NCEL, TN-1628). Table 22 gives typical values of C for ships and Figure 28 illustrates some ship types.

Table 22
Sample Wind Coefficients for Ships

SHIP	C	NOTES
Hull dominated	0.82	Aircraft carriers, drydocks
Typical	0.92	ships with moderate superstructure
Extensive superstructure	1.02	Destroyers, cruisers

The shape function for the transverse wind force (NCEL, TN-1628) is given by:

EQUATION: $$f_{yw}\{\theta_w\} = +(\sin\theta_w - 0.05 * \sin\{5\theta_w\}) / 0.95 \qquad (4)$$

where

$f_{yw}\{\theta_w\}$ = transverse wind coefficient shape function
θ_w = wind angle (degrees)

Equation 4 is positive for wind angles $0 < \theta w < 180$ degrees and negative for wind angles $180 < \theta w < 360$ degrees. Figure 29 shows the shape and typical values for Equation 4.

These two components were derived by integrating wind over the hull and superstructure areas to obtain effective wind speeds (NCEL, TN-1628). The following example illustrates calculations of the transverse wind force drag coefficient.

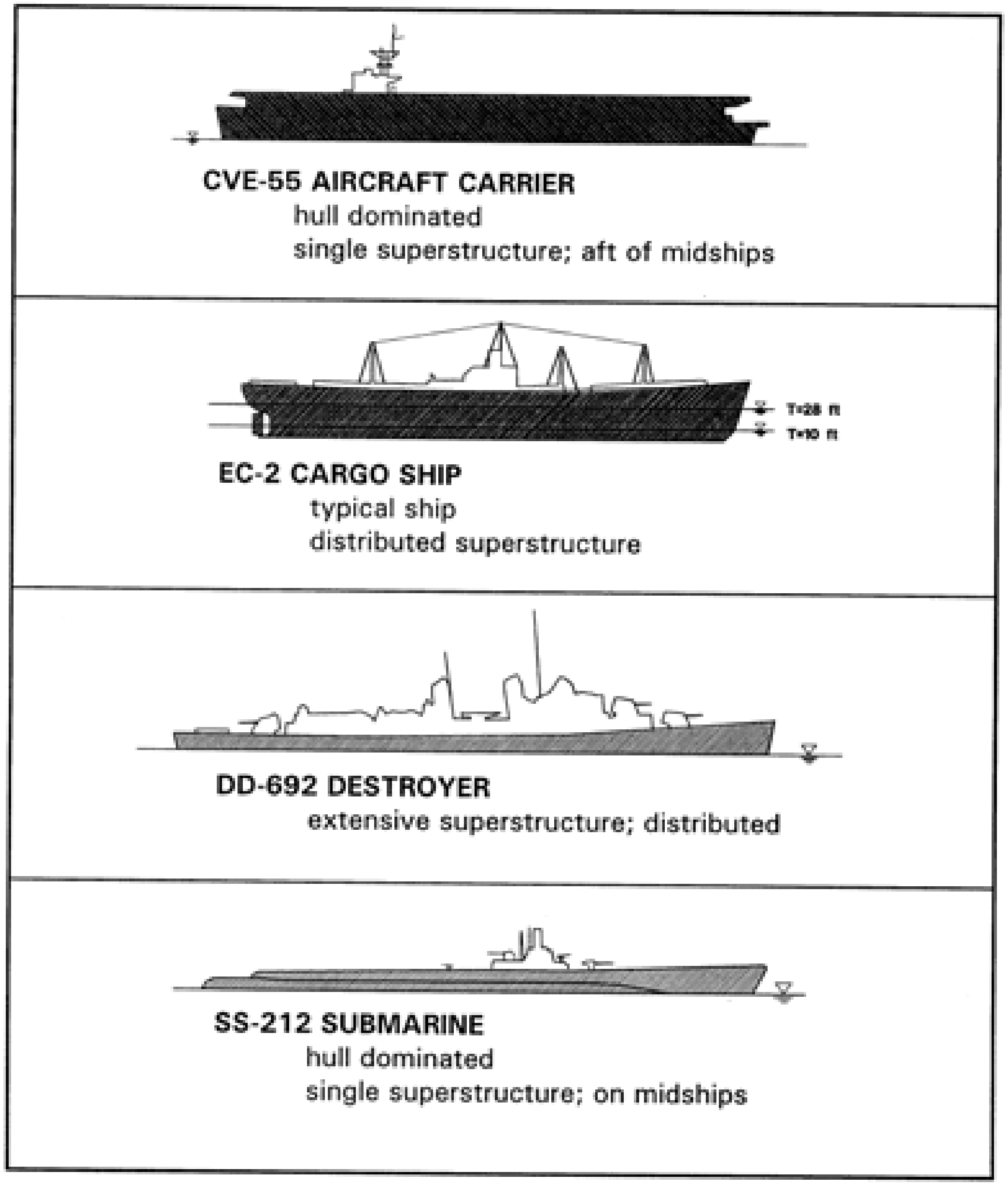


Figure 28
Sample Ship Profiles

θ_w (deg)	$f_{wy}\{\theta_w\}$		θ_w (deg)	$f_{wy}\{\theta_w\}$
0	0.000		45	0.782
5	0.069		50	0.856
10	0.142		55	0.915
15	0.222		60	0.957
20	0.308		65	0.984
25	0.402		70	0.998
30	0.500		75	1.003
35	0.599		80	1.003
40	0.695		85	1.001
45	0.782		90	1.000

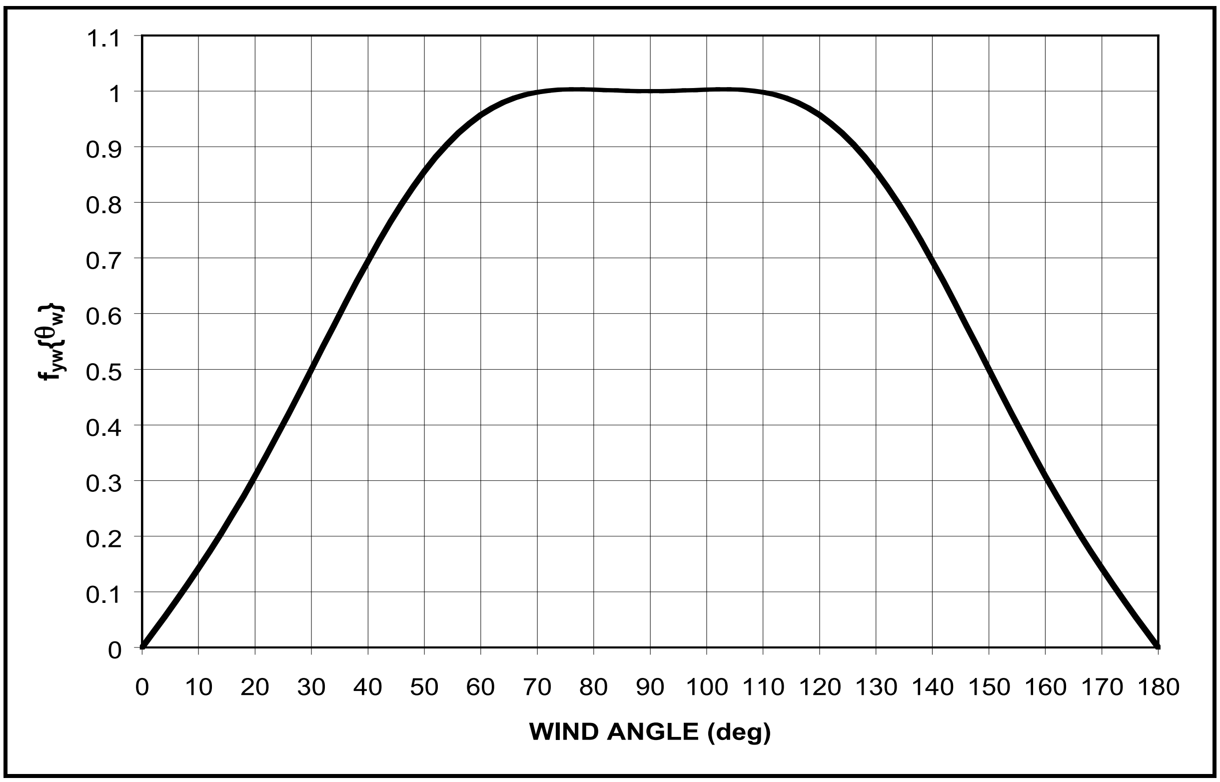


Figure 29
Shape Function for Transverse Wind Force

EXAMPLE: Find the transverse wind force drag coefficient on the destroyer shown in Figure 30.

SOLUTION: For this example the transverse wind force drag coefficient from Equation 3 is:

$$C_{yw} = C * \lfloor ((0.5(23.9m + 6.43m))/10m)^{2/7} 1203m^2 + (0.5 * 6.43m/10m)^{2/7} 1036.1m^2 \rfloor / 2239m^2$$

$$C_{yw} = 0.940 * C .$$

Destroyers have extensive superstructure, so a recommended value of C = 1.02 is used to give a transverse wind force drag coefficient of C_{yw} = 0.940*1.02 = 0.958.

Note that for cases where an impermeable structure, such as a wharf, is immediately next to the moored ship, the exposed longitudinal wind area and resulting transverse wind force can be reduced. Figure 31 shows an example of a ship next to a wharf. For Case (A), wind from the water, there is no blockage in the transverse wind force and elevations of the hull and superstructure are measured from the water surface. For Case (B), wind from land, the longitudinal wind area of the hull can be reduced by the blocked amount and elevations of hull and superstructure can be measured from the wharf elevation.

Cases of multiple ships are covered in par. 4.6.

PARAMETER	VALUE (SI UNITS)	VALUE (ENGLISH)
L_{wL}	161.23 m	529 ft
A_Y	2239 m^2	24100 ft^2
A_H	1036 m^2	11152 ft^2
A_S	1203 m^2	12948 ft^2
$h_H = A_H/L_{wL}$	6.43 m	21.1 ft
h_S	23.9 m	78.4 ft

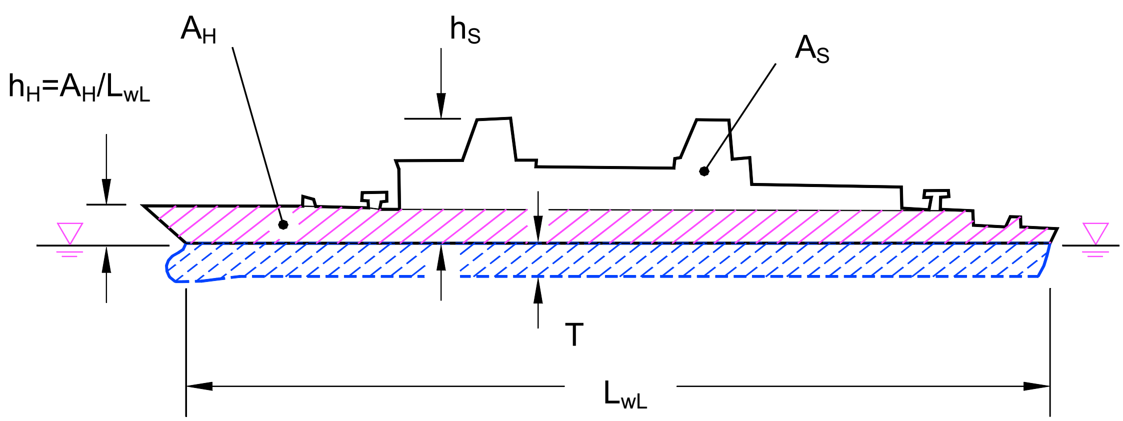
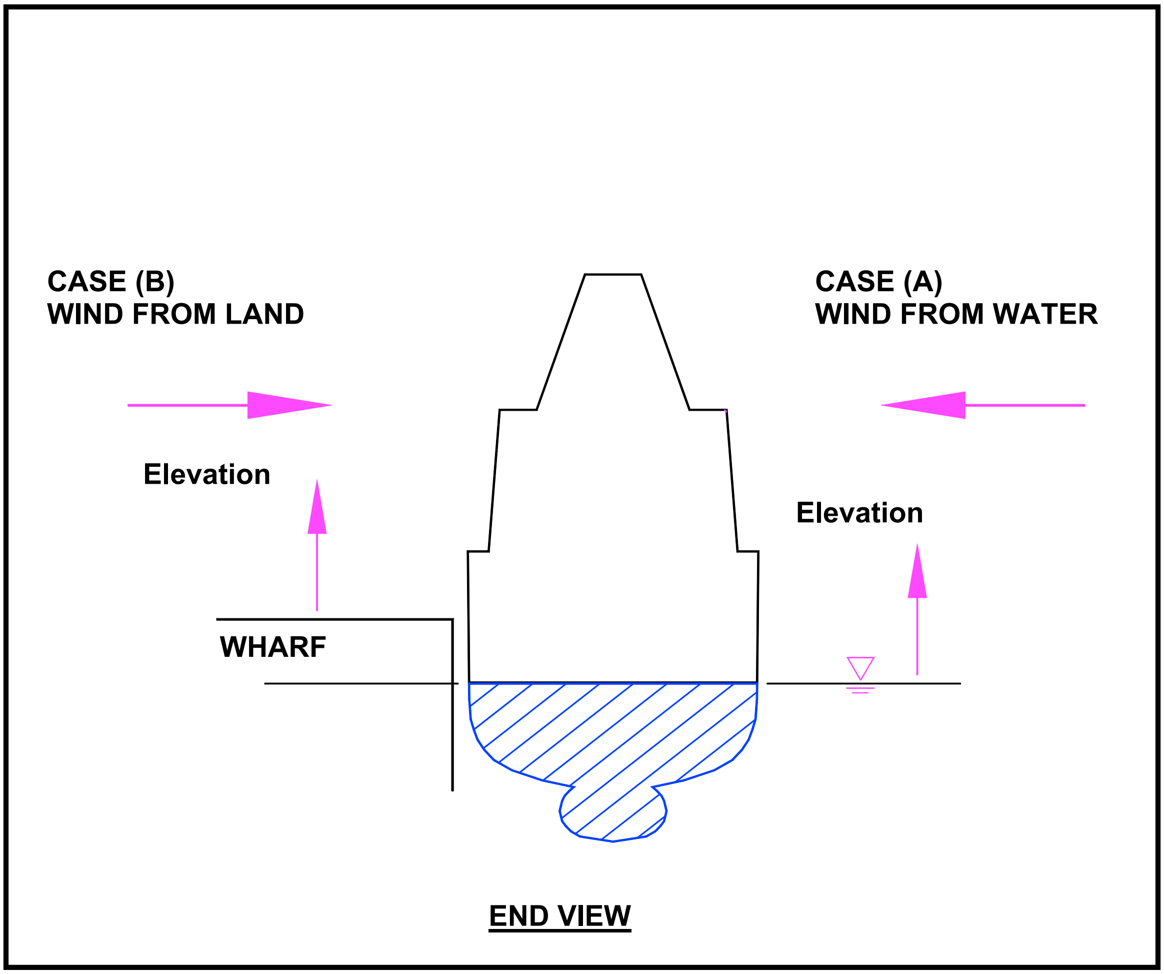


Figure 30
Example


CASE (B)
WIND FROM LAND
CASE (A)
WIND FROM WATER
Elevation
Elevation
WHARF
END VIEW

4.4.2 <u>Static Longitudinal Wind Force</u>. The static longitudinal wind force on a vessel is defined as that component of wind force parallel to the centerline of the vessel. This is the force in the "X" or surge direction in Figure 27. Figure 26 shows the definition of winds areas.

The longitudinal force is determined from NCEL, TN-1628 using the equation:

EQUATION: $$F_{xw} = 0.5\,\rho_a\,V_w^2 A_x\,C_{xw}\,f_{xw}(\theta_w) \qquad (5)$$

where

F_{xw} = longitudinal wind force (newtons)
ρ_a = mass density of air (from Table 21)
V_w = wind speed (m/s)
A_x = transverse wind area of the ship (m^2)
C_{xw} = longitudinal wind force drag coefficient
$f_{xw}(\theta_w)$ = shape function for longitudinal force
θ_w = wind angle (degrees)

The longitudinal wind force drag coefficient, C_{xw}, depends on specific characteristics of the vessel. Additionally, the wind force drag coefficient varies depending on bow (C_{xwB}) or stern (C_{xwS}) wind loading. Types of vessels are given in three classes: hull dominated, normal, and excessive superstructure. Recommended values of longitudinal wind force drag coefficients are given in Table 23.

Table 23
Recommended Ship Longitudinal Wind Force Drag Coefficients

VESSEL TYPE	C_{xwB}	C_{xwS}
Hull Dominated (aircraft carriers, submarines, passenger liners)	0.40	0.40
Normal*	0.70	0.60
Center-Island Tankers*	0.80	0.60
Significant Superstructure (destroyers, cruisers)	0.70	0.80

*An adjustment of up to +0.10 to C_{xwB} and C_{xwS} should be made to account for significant cargo or cluttered decks.

The longitudinal shape function also varies over bow and stern wind loading regions. As the wind direction varies from headwind to tailwind, there is an angle at which the force changes sign. This is defined as θ_x and is dependent on the location of the superstructure relative to midships. Recommended values of this angle are given in Table 24.

Table 24
Recommended Values of θ_x

LOCATION OF SUPERSTRUCTURE	θ_x (deg)
Just forward of midships	100
On midships	90
Aft of midships (tankers)	80
Warships	70
Hull dominated	60

Shape functions are given for general vessel categories below:

CASE I SINGLE DISTINCT SUPERSTRUCTURE

The shape function for longitudinal wind load for ships with single, distinct superstructures and hull-dominated ships is given below (examples include aircraft carriers, EC-2, and cargo vessels):

EQUATION: $$f_{xw}(\theta_w) = \cos(\phi) \quad (6)$$

where $$\phi_- = \left(\frac{90°}{\theta_x}\right)\theta_w \text{ for } \theta_w < \theta_x \quad (6a)$$

$$\phi_+ = \left(\frac{90°}{180°-\theta_x}\right)(\theta_w - \theta_x) + 90° \text{ for } \theta_w > \theta_x \quad (6b)$$

θ_x = incident wind angle that produces no net longitudinal force (Table 24)

θ_w = wind angle

Values of $f_{xw}(\theta_w)$ are symmetrical about the longitudinal axis of the vessel. So when $\theta_w > 180°$, use $360° - \theta_w$ as θ_w in determining the shape function.

CASE II DISTRIBUTED SUPERSTRUCTURE

EQUATION: $$f_{xw}(\theta_w) = \frac{\left(\sin(\gamma) - \frac{\sin(5\gamma)}{10}\right)}{0.9} \quad (7)$$

where $$\gamma_- = \left(\frac{90°}{\theta_x}\right)\theta_w + 90° \text{ for } \theta_w < \theta_x \quad (7a)$$

$$\gamma_+ = \left(\frac{90°}{180°-\theta_x}\right)(\theta_W) + \left(180° - \left(\frac{90°\theta_x}{180°-\theta_x}\right)\right) \text{ for } \theta_w > \theta_x \quad (7b)$$

Values of $f_{xw}(\theta_w)$ are symmetrical about the longitudinal axis of the vessel. So when $\theta_w > 180°$, use $360° - \theta_w$ as θ_w in determining the shape function. Note that the maximum longitudinal wind force for these vessels occurs for wind directions slightly off the ship's longitudinal axis.

EXAMPLE: Find the longitudinal wind drag coefficient for a wind angle of 40 degrees for the destroyer shown in Figure 30.

SOLUTION: For this destroyer, the following values are selected:

$\theta_x = 70°$ from Table 24

$C_{xwB} = 0.70$ from Table 23

$C_{xwS} = 0.80$ from Table 23

This ship has a distributed superstructure and the wind angle is less than the crossing value, so Equation 7a is used to determine the shape function:

$$\gamma\_ = \left(90° / (70°)\right) 40° + 90° = 141.4°$$

$$f_{xw}(\theta_w) = \frac{\left(\sin\left(141.4°\right) - \frac{\sin(5 * 141.4°)}{10}\right)}{0.9} = 0.72$$

At the wind angle of 40 degrees, the wind has a longitudinal component on the stern. Therefore, the wind longitudinal drag coefficient for this example is:

$$C_{xw}\, f_{xw}(\theta_w) = 0.8 * 0.72 = 0.57$$

4.4.3 Static Wind Yaw Moment. The static wind yaw moment is defined as the product of the associated transverse wind force and its distance from the vessel's center of gravity. In the local ship coordinate system, this is the moment about the "Z" axis. Wind yaw moment is determined from the equation:

EQUATION: $$M_{xyw} = 0.5\,\rho_a\ V_w^{\,2}\ A_y\ L C_{xyw}\{\theta_w\}$$ (8)

where

M_{xyw} = wind yaw moment (newton*m)
ρ_a = mass density of air (from Table 21)
V_w = wind speed (m/s)
A_y = longitudinal projected area of the ship (m^2)
L = length of ship (m)
$C_{xyw}\{\theta_w\}$ = normalized yaw moment coefficient
= moment arm divided by ship length
θ_w = wind angle (degrees)

The normalized yaw moment coefficient depends upon the vessel type. Equation 9 gives equations for computing the value of the yaw moment coefficient and Table 25 gives empirical parameter values for selected vessel types. The normalized yaw moment variables is found from:

EQUATION: $$C_{xyw}\{\theta_w\} = -a1 * \sin\left(\frac{\theta_w * 180}{\theta_z}\right) \qquad 0<\theta_w<\theta_z$$ (9)

$$C_{xyw}\{\theta_w\} = a2 * \sin\left[(\theta_w - \theta_z) * \lambda\right] \qquad \theta_z \le \theta_w < 180 \text{ deg}$$ (9a)

and symmetrical about the longitudinal axis of the vessel, where

$C_{xyw}\{\theta_w\}$ = normalized wind yaw moment coefficient
$a1$ = negative peak value (from Table 25)
$a2$ = positive peak value (from Table 25)
θ_w = wind angle (degrees)
θ_z = zero moment angle (degrees) (from Table 25)

$$\lambda = \frac{180 * \deg}{\left[(180 * \deg - \theta_z)\right]} \quad \text{(dimensionless)} \qquad (9b)$$

Table 25
Normalized Wind Yaw Moment Variables

SHIP TYPE	Zero Moment Angle (θ_z)	Negative Peak (a1)	Positive Peak (a2)	NOTES
Liner	80	0.075	0.14	
Carrier	90	0.068	0.072	
Tanker	95	0.077	0.07	Center island w/ cluttered deck
Tanker	100	0.085	0.04	Center island w/ trim deck
Cruiser	90	0.064	0.05	
Destroyer	68	0.02	0.12	
Others:	130	0.13	0.025	stern superstructure
	102	0.096	0.029	aft midships superstructure
	90	0.1	0.1	midships superstructure
	75	0.03	0.05	forward midships superstructure
	105	0.18	0.12	bow superstructure

A plot of the yaw normalized moment coefficient for the example shown in Figure 30 is given as Figure 32.

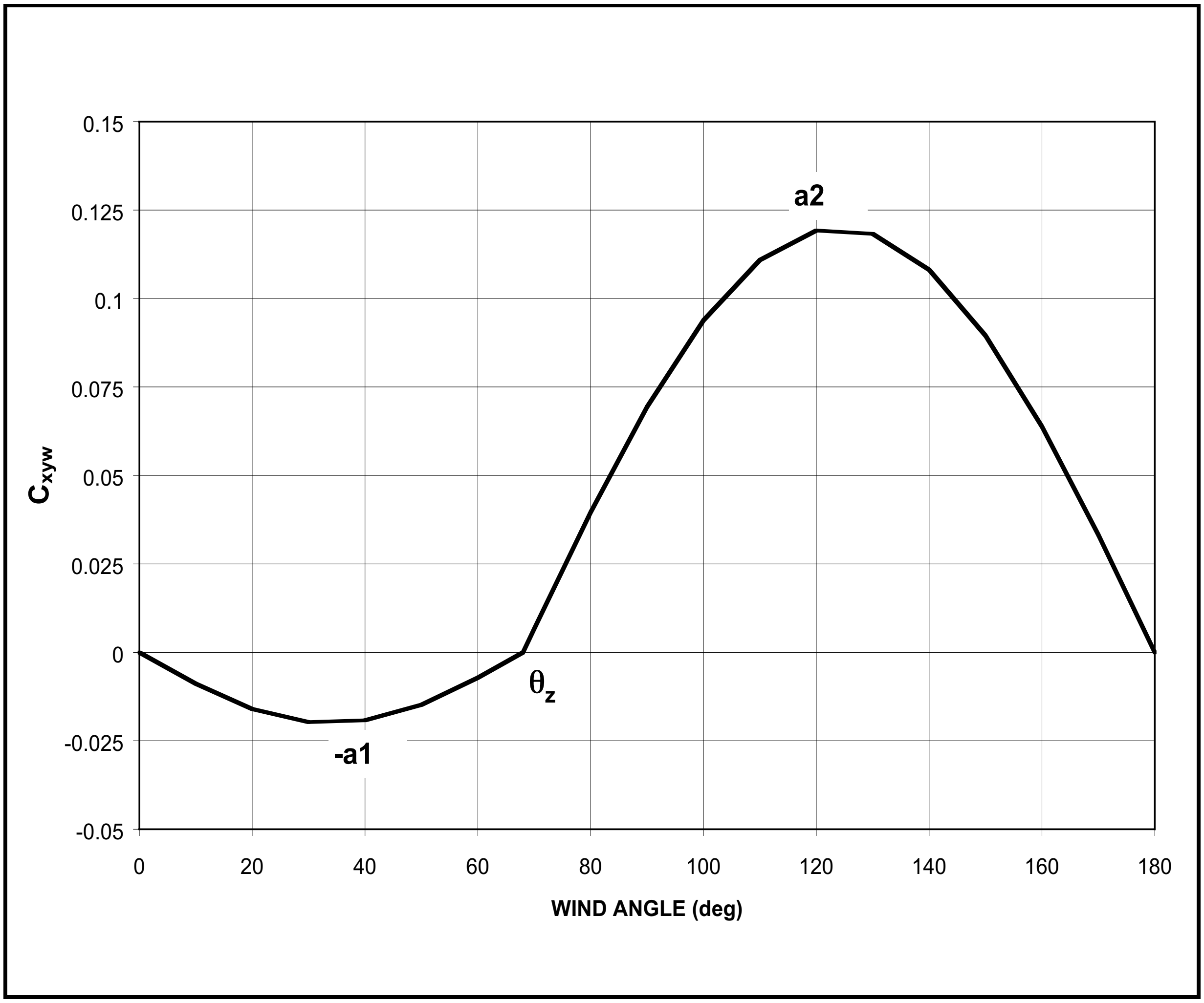


Figure 32
Sample Yaw Normalized Moment Coefficient

4.5 Static Current Forces/Moments. Methods to determine static current forces and moments on stationary moored vessels in the surge and sway directions and yaw moment are presented in this section. These planar directions are of primary importance in many mooring designs.

4.5.1 Static Transverse Current Force. The transverse current force is defined as that component of force perpendicular to the vessel centerline. If a ship has a large underkeel clearance, then water can freely flow under the keel, as shown in Figure 33(a). If the underkeel clearance is small, as shown in Figure 33(b), then the ship more effectively blocks current flow, and the transverse current force on the ship increases. These effects are considered and the transverse current force is determined from the equation:

EQUATION: $$F_{yc} = 0.5\,\rho_w\, V_c^2\, L_{wL}\, T\, C_{yc} \sin\theta_c \qquad (10)$$

where

F_{yc} = transverse current force (newtons)
ρ_w = mass density of water (from Table 20)
V_c = current velocity (m/s)
L_{wL} = vessel waterline length (m)
T = average vessel draft (m)
C_{yc} = transverse current force drag coefficient
θ_c = current angle (degrees)

The transverse current force drag coefficient as formulated in Broadside Current Forces on Moored Ships, Seelig et al. (1992) is shown in Figure 34. This drag coefficient can be determined from:

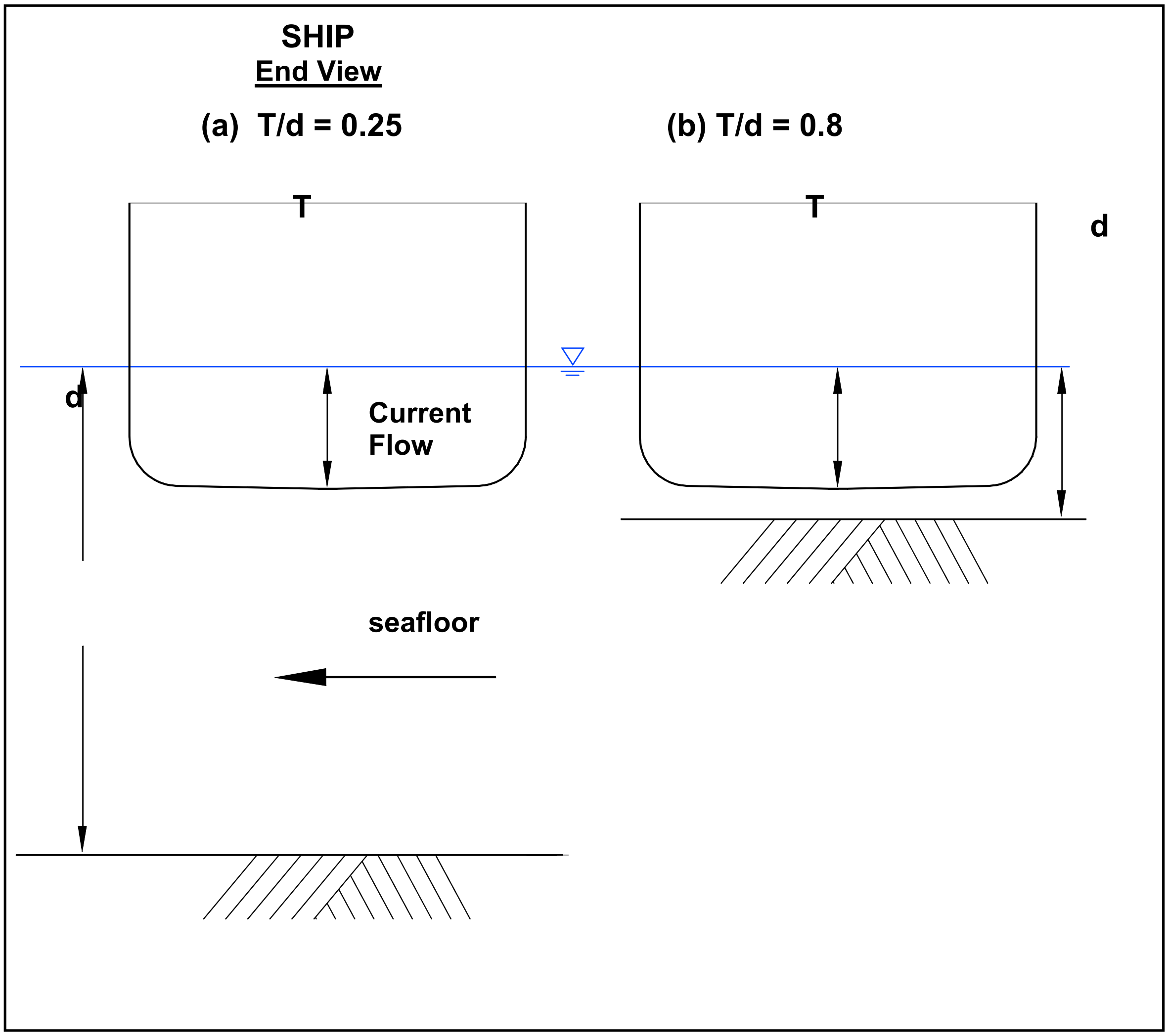


Figure 33
Examples of Ratios of Ship Draft (T) to Water Depth (d)

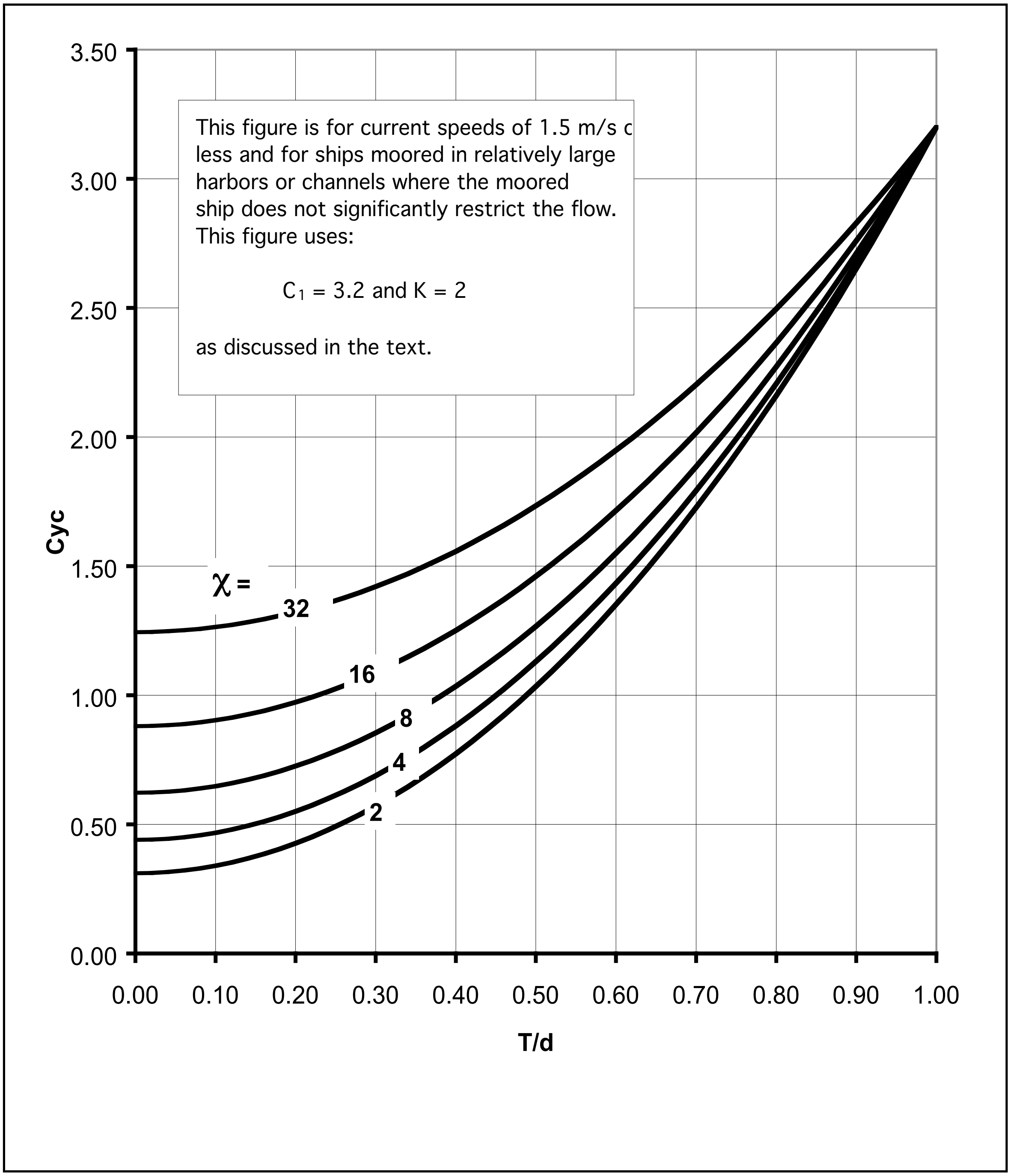


Figure 34
Broadside Current Drag Coefficient

EQUATION: $$C_{yc} = C_0 + (C_1 - C_0) * (T/d)^K \qquad (11)$$

where C_O = deepwater current force drag coefficient for T/d ≈ 0.0; this deepwater drag coefficient is estimated from:

EQUATION: $$C_0 = 0.22 * \sqrt{\chi} \qquad (12)$$

where χ is a dimensionless ship parameter calculated as:

EQUATION: $$\chi = L_{wL}{}^2 * A_m / (B * V) \qquad (13)$$

where

L_{wL} is the vessel length at waterline(m)

A_m is the immersed cross-sectional area of the ship at midsection (m^2)

B is the beam (maximum ship width at the waterline) (m), and

V is the submerged volume of the ship (which can be found by taking the displacement of the vessel divided by the unit weight of water, given in Table 20 (m^3)).

C_1 = shallow water current force drag coefficient where T/d = 1.0; for currents of 1.5 m/s (3 knots or 5 ft/sec) or less

T = average vessel draft (m)

d = water depth (m)

K = dimensionless exponent; laboratory data from ship models shows:

K = 2 Wide range of ship and barge tests; most all of the physical model data available can be fit with this coefficient

K = 3 From a small number of tests on a fixed cargo ship and for a small number of tests on an old aircraft carrier, CVE-55

K = 5 From a small number of tests on an old submarine hull, SS-212

The immersed cross-sectional area of the ship at midships, A_m, can be determined from:

EQUATION: $$A_m = C_m * B * T \qquad (14)$$

Values of the midship coefficient, C_m, are provided in the NAVFAC Ship's Database for DOD ships.

The above methods for determining the transverse current force are recommended for normal design conditions with moderate current speeds of 1.5 m/s (3 knots or 5 ft/sec) or less and in relatively wide channels and harbors (see Seelig et al., 1992).

If the vessel is moored broadside in currents greater than 1.5 m/s (3 knots or 5 ft/sec), then scale model laboratory data show that there can be significant vessel heel/roll, which effectively increases the drag force on the vessel. In some model tests in shallow water and at high current speeds this effect was so pronounced that the model ship capsized. Mooring a vessel broadside in a high current should be avoided, if possible.

Scale physical model tests show that a vessel moored broadside in a restricted channel has increased current forces. This is because the vessel decreases the effective flow area of a restricted channel, which causes the current speed and current force to increase.

For specialized cases where:

(1) vessels are moored in current of 1.5 m/s (3 knots or 5 ft/sec) or more, and/or

(2) for vessels moored in restricted channels

then the designer should contact the Moorings Center of Expertise, NFESC ECDET, Washington Navy Yard Bldg. 218, 901 M St. SE, Washington DC 20374-5063.

EXAMPLE: Find the current force on an FFG-7 vessel produced by a current of θ_C=90 degrees to the ship centerline with a speed of 1.5 m/s (2.9 knots or 4.9 ft/sec) in salt water for a given ship draft. At the mooring location, the harbor has a cross-sectional area much larger than the submerged ship longitudinal area, $L_{wL} * T$.

SOLUTION: Dimensions and characteristics of this vessel are summarized in the lower right portion of Figure 35. Transverse current drag coefficients predicted using Equation 11 are shown on this figure as a solid bold line. Physical scale model data (U.S. Naval Academy (USNA), EW-9-90, Evaluation of Viscous Damping Models for Single Point Mooring Simulation) are shown as symbols in the drawing, showing that Equation 11 provides a reasonable estimate of drag coefficients. Predicted current forces for this example are given in Table 26.

Table 26
Predicted Transverse Current Forces on FFG-7
for a Current Speed of 1.5 m/s (2.9 knots)

T/d	d (m)	D (ft)	Fyc (MN)*	Fyc (kips)**
0.096	45.7	150	0.55	123
0.288	15.2	50	0.66	148
0.576	7.62	25	1.03	231
0.72	6.096	20	1.30	293
0.96	4.572	15	1.90	427

* MN = one million newtons
**kip = one thousand pounds force

This example shows that in shallow water the transverse current force can be three times or larger than in deep water for an FFG-7.

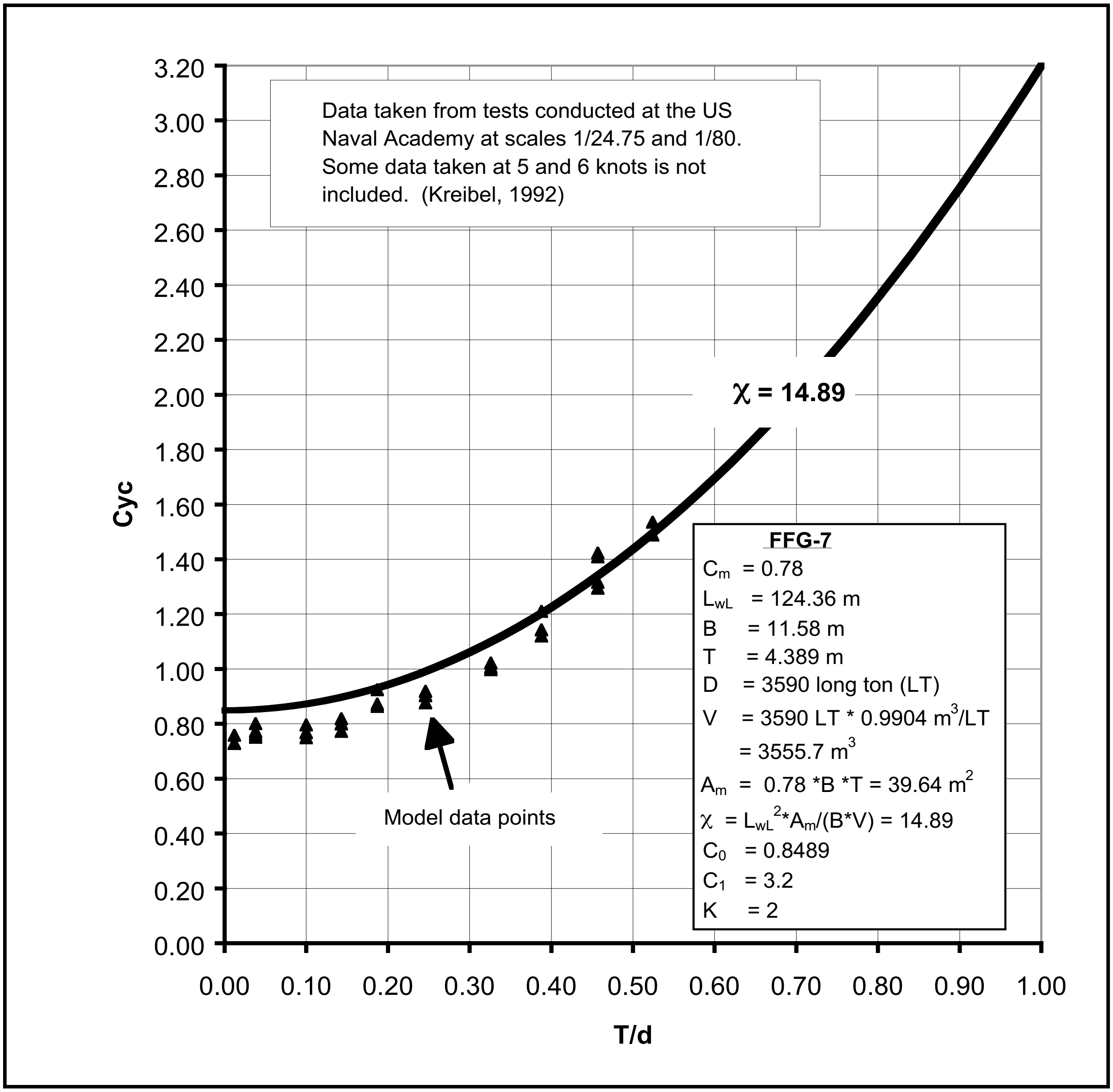


Figure 35
Example of Transverse Current Drag Coefficients

4.5.2 Static Longitudinal Current Force. The longitudinal current force is defined as that component of force parallel to the centerline of the vessel. This force is determined from the following equation (Naval Civil Engineering Laboratory (NCEL), TN-1634, STATMOOR - A Single-Point Mooring Static Analysis Program):

EQUATION: $$F_{xc} = F_{x\,FORM} + F_{x\,FRICTION} + F_{x\,PROP} \qquad (15)$$

where

F_{xc} = total longitudinal current load (newtons)
F_{xFORM} = longitudinal current load due to form drag (newtons)
$F_{xFRICTION}$ = longitudinal current load due to skin friction (newtons)
F_{xPROP} = longitudinal current load due to propeller drag (newtons)

The three elements of the general longitudinal current load equation, F_{xFORM}, $F_{xFRICTION}$, and F_{xPROP} are described below:

F_{xFORM} = longitudinal current load due to form drag

EQUATION: $$F_{xFORM} = \frac{1}{2}\rho_w V_c^2 B\, T\, C_{xcb} \cos(\theta_c) \qquad (16)$$

where

ρ_w = mass density of water, from Table 20
V_c = current speed (m/s)
B = maximum vessel width at the waterline(m)
T = average vessel draft (m)
C_{xcb} = longitudinal current form drag coefficient = 0.1
θ_c = current angle (degrees)

$F_{xFRICTION}$ = longitudinal current load due to skin friction

EQUATION: $$F_{xFRICTION} = \frac{1}{2}\rho_w V_c^2 S C_{xca} \cos(\theta_c) \qquad (17)$$

where

ρ_w = mass density of water, from Table 20
V_c = current speed (m/s)
S = wetted surface area (m^2); estimated using

$$S = 1.7 T L_{wL} + \left(\frac{D}{T\gamma_w}\right) \qquad (18)$$

T = average vessel draft (m)
L_{wL} = waterline length of vessel (m)
D = ship displacement (newtons)
γ_w = weight density of water, from Table 21
C_{xca} = longitudinal skin friction coefficient, estimated using:

$$C_{xca} = 0.075 / \left(\left(\log_{10} R_N\right) - 2\right)^2 \qquad (19)$$

R_N = Reynolds Number

$$R_N = \left|\frac{V_c L_{wL} \cos(\theta_c)}{\nu}\right| \qquad (20)$$

ν = kinematic viscosity of water, from Table
θ_c = current angle (degrees)

F_{xPROP} = longitudinal current load due to fixed propeller drag

EQUATION: $$F_{xPROP} = \frac{1}{2}\rho_w V_c^2 A_p C_{PROP} \cos(\theta_C) \qquad (21)$$

where

ρ_w = mass density of water, from Table 21
V_c = current speed (m/s)
A_p = propeller expanded blade area (m^2)
C_{PROP} = propeller drag coefficient = 1.0
θ_C = current angle (degrees)

$$A_p = \frac{A_{Tpp}}{1.067 - 0.229\,(p / d)} = \frac{A_{Tpp}}{0.838} \quad (22)$$

A_{Tpp} = total projected propeller area (m^2) for an assumed propeller pitch ratio of p/d =1.0

$$A_{Tpp} = \frac{L_{wL}\,B}{A_R} \quad (23)$$

A_R is a dimensionless area ratio for propellers. Typical values of this parameter for major vessel groups are given in Table 27.

Table 27
A_R for Major Vessel Groups

SHIP	AREA RATIO, A_R
Destroyer	100
Cruiser	160
Carrier	125
Cargo	240
Tanker	270
Submarine	125

Note that in these and all other engineering calculations discussed in this handbook, the user must be careful to keep units consistent.

EXAMPLE: Find the longitudinal current force with a bow-on current of θ_c=180 degrees with a current speed of 1.544 m/sec (3 knots) on a destroyer in salt water with the characteristics shown in Table 28.

SOLUTION: Table 29 shows the predicted current forces. Note that these forces are negative, since the bow-on current is in a negative "X" direction. For this destroyer, the force on the propeller is approximately two-thirds of the total longitudinal current force. For commercial ships, with relatively smaller propellers, form and friction drag produce a larger percentage of the current force.

Table 28
Example Destroyer

PARAMETER	SI SYSTEM	ENGLISH OR INCH-POUND SYSTEM
L_{wL}	161.2 m	529 ft
T	6.4 m	21 ft
B	16.76 m	55 ft
D, ship displacement	7.93E6 kg	7810 long tons
$C_{m;}$ estimated	0.83	0.83
S; est. from Eq 18	2963 m^2	31897 ft^2
A_R; from Table 27	100	100
R_N; from Eq 20	2.09E8	2.09E8
C_{xca}; est. from Eq 19	0.00188	0.00188
Ap; est. from Eq 22	32.256 m^2	347.2 ft^2

Table 29
Example Longitudinal Current Forces on a Destroyer

FORCE	SI SYSTEM	ENGLISH OR INCH-POUND SYSTEM	PERCENT OF TOTAL FORCE
F_{xFORM}; Eq 15	-13.1 kN*	-2.95 kip**	22%
$F_{xFRICTION}$; Eq 16	-6.8 kN	-1.53 kip	12%
F_{xPROP}; Eq 17	-39.4 kN	-8.87 kip	66%
Total F_{xc} =	-59.4 kN	-13.4 kip	100%

* kN = one thousand newtons
**kip = one thousand pounds force

4.5.3 Static Current Yaw Moment. The current yaw moment is defined as that component of moment acting about the vessel's vertical "Z"-axis. This moment is determined from the equation:

EQUATION: $$M_{xyc} = F_{yc}\left(\frac{e_c}{L_{wL}}\right)L_{wL} \qquad (24)$$

where

M_{xyc} = current yaw moment (newton*m)
F_{yc} = transverse current force (newton)
$\frac{e_c}{L_{wL}}$ = ratio of eccentricity to vessel waterline length
e_c = eccentricity of F_{yc} (m)
L_{wL} = vessel waterline length (m)

The dimensionless moment arm $\frac{e_c}{L_{wL}}$ is calculated by choosing the slope and y-intercept variables from Table 30 which are a function of the vessel hull. The dimensionless moment arm is dependent upon the current angle to the vessel, as shown in Equation 25:

EQUATION: $$\frac{e}{L_{wL}} = a + b*\theta_c \qquad \theta_c = 0° \text{ to } 180° \qquad (25)$$

$$\frac{e}{L_{wL}} = -a - (b*(360\deg - \theta_c)) \qquad \theta_c = 180° \text{ to } 360° \qquad (25a)$$

where

$\frac{e_c}{L_{wL}}$ = ratio of eccentricity to vessel waterline length
a = y-intercept (refer to Table 30) (dimensionless)
b = slope per degree (refer to Table 29)
θ_c = current angle (degrees)

The above methods for determining the eccentricity ratio are recommended for normal design conditions with moderate current speeds of less than 1.5 m/s (3 knots or 5 ft/sec). Values provided in Table 30 are based upon least squares fit of scale model data taken for the case of ships with level keels. Data are not adequately available for evaluating the effect of trim on the current moment.

Table 30
Current Moment Eccentricity Ratio Variables

SHIP	a Y-INTERCEPT	b SLOPE PER DEGREE	NOTES
SERIES 60	-0.291	0.00353	Full hull form typical of cargo ships
FFG	-0.201	0.00221	“Rounded” hull typical of surface warships
CVE-55	-0.168	0.00189	Old attack aircraft carrier
SS-212	-0.244	0.00255	Old submarine

4.6 Wind and Current Forces and Moments on Multiple Ships. If ships are moored in close proximity to one another then the nearby ship(s) can influence the forces/moments on a given ship. The best information available on the effects of nearby ships are results from physical model tests, because the physical processes involved are highly complex. Appendix A provides scale model test results of wind and current forces and moments for multiple identical ships. From two to six identical ships were tested and the test results were compared with test results from a single ship. Data are provided for aircraft carriers, destroyers, cargo ships, and submarines.

Cases included in Appendix A include: individual ships, ships in nests and ships moored on either sides of piers. Results are provided for the effects of winds and currents in both tabular and graphical form.

Section 5: ANCHOR SYSTEM DESIGN PROCEDURES

5.1 General Anchor Design Procedure. Anchor systems ultimately hold the mooring loads in fleet mooring systems. Anchors are used on both ships and in mooring facilities, so selection and design of anchors are included in this section.

The type and size of anchor specified depends upon certain parameters, such as those shown in Table 31.

The most commonly used anchors in DOD moorings are drag-embedment anchors and driven-plate anchors, so they will be discussed here. Other types of specialized anchors (shallow foundations, pile anchors, propellant-embedment anchors, rock bolts, etc.) are discussed in the NCEL Handbook for Marine Geotechnical Engineering.

Figures 36 and 37 illustrate typical drag-embedment anchors. Figure 38 illustrates a driven-plate anchor. Some characteristics of these two categories of anchors are given in Table 32.

Table 31
Anchor Specification Considerations

PARAMETER	DESCRIPTION
Holding capacity	The size/type of anchor will depend on the amount of anchor holding required.
Soils	Engineering properties and sediment layer thickness influence anchor design.
Use	If anchors will be relocated, then drag anchors are most commonly used.
Weight	The amount of weight that can be handled or carried may control anchor specification.
Equipment	The size and characteristics of installation equipment are important in anchor specification.
Directionality	Drag anchors may provide little uplift capacity and primarily hold in one direction; driven plate anchors provide high omnidirectional capacity.
Performance	Whether anchor will be allowed to drag or not, as well as the amount of room available for anchors systems, will influence anchor specification.

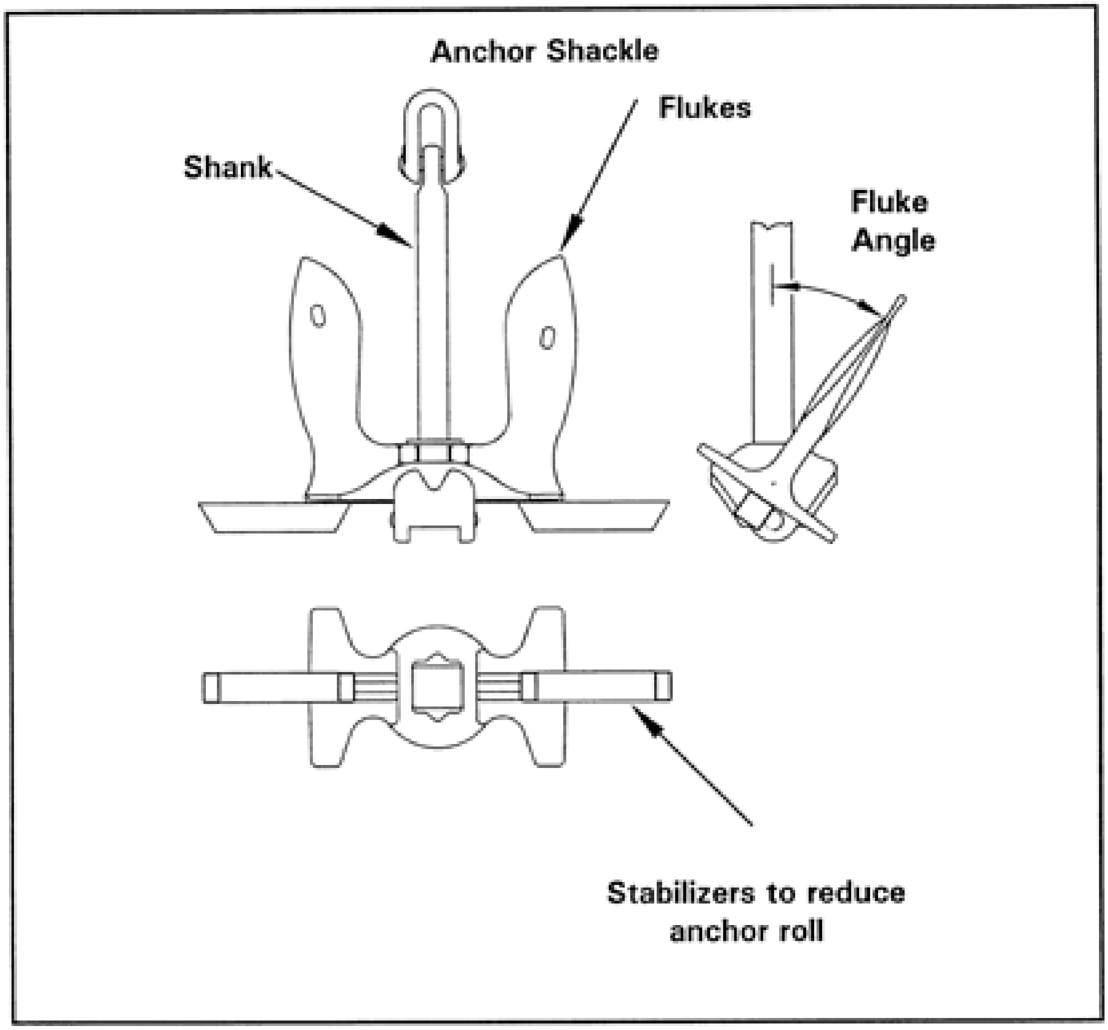


Figure 36
Example of a Drag-Embedment Anchor
(Stabilized Stockless Anchor)

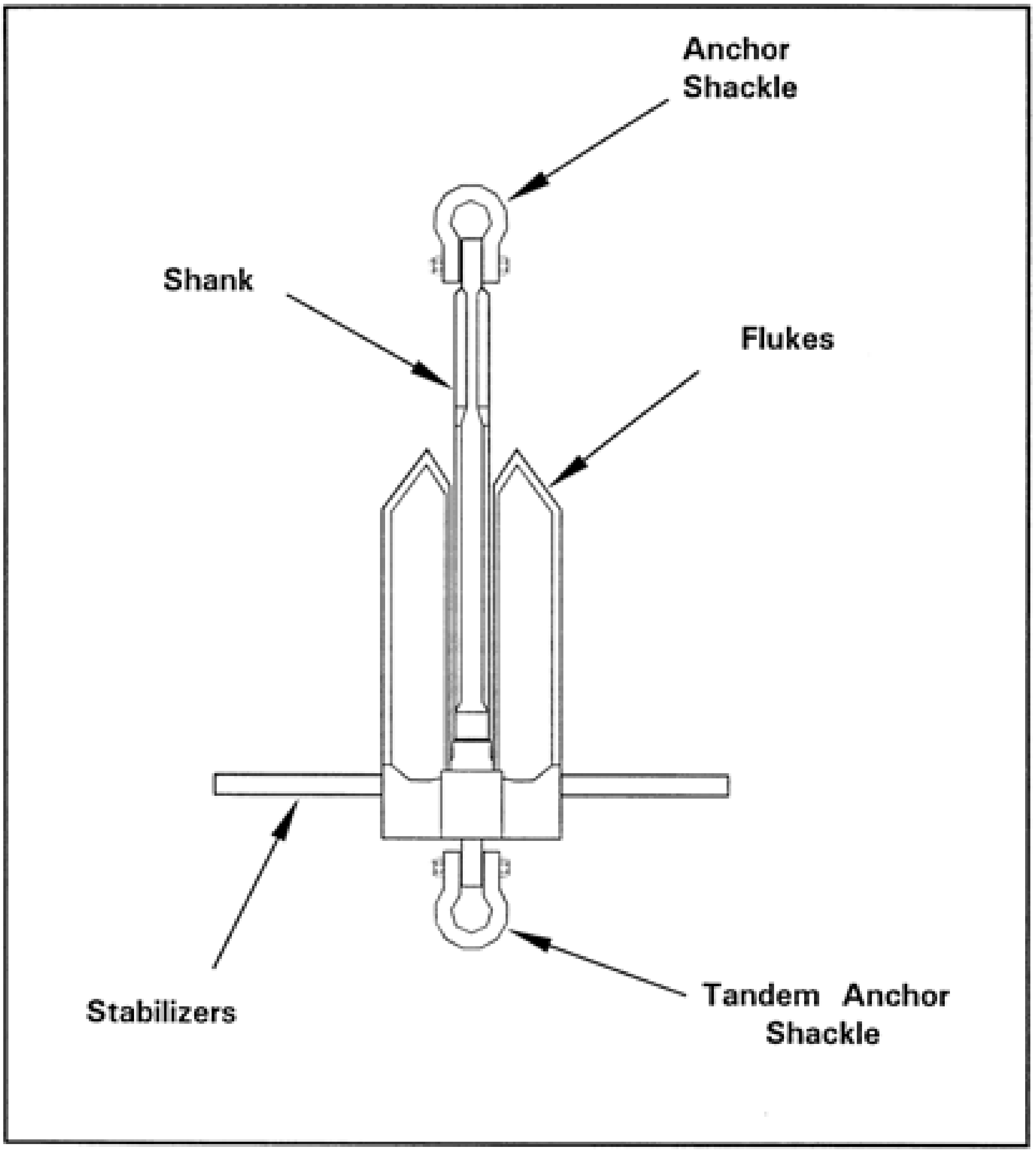
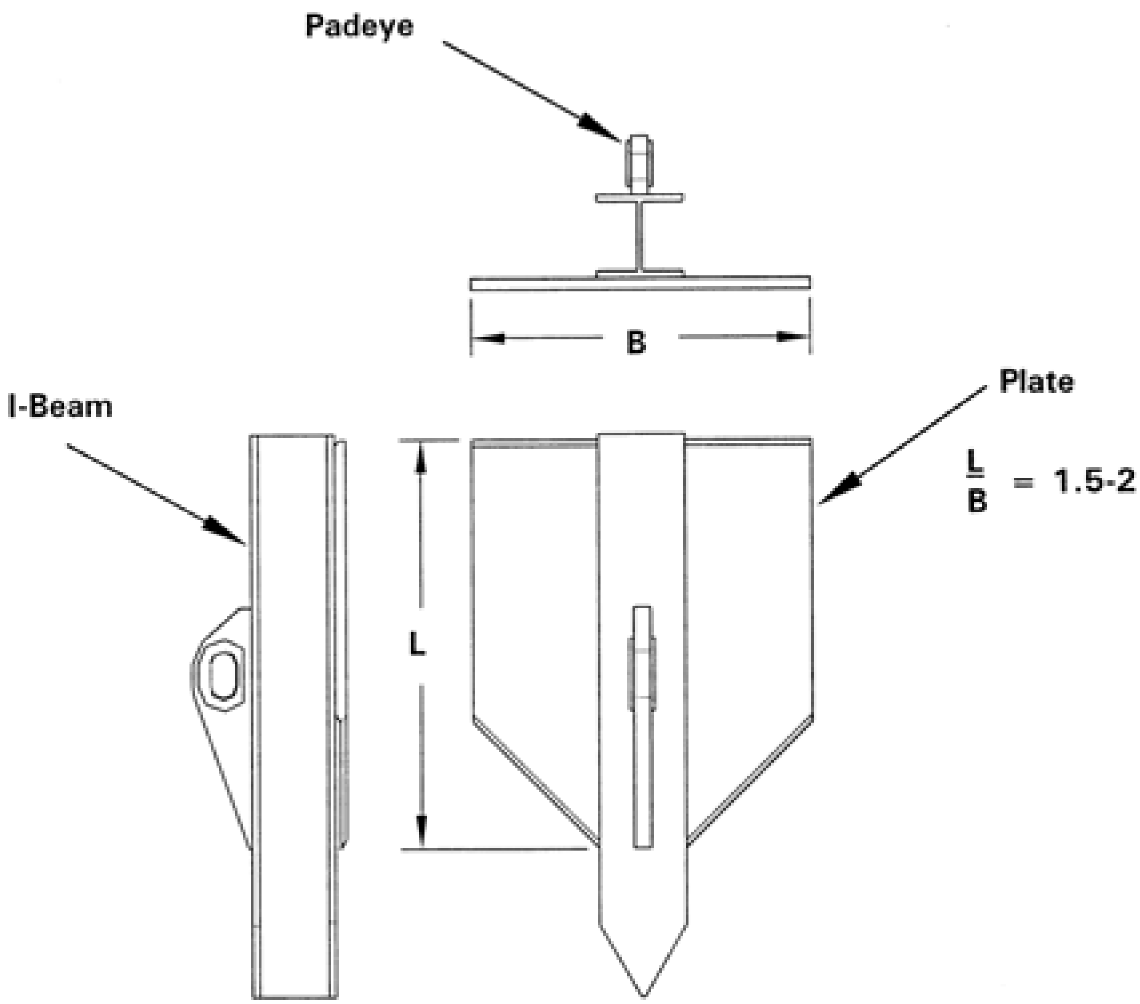


Figure 37
Example of a Drag-Embedment Anchor
(NAVMOOR Anchor)



Keying flaps (not shown) can be added to the back of the anchor, opposite the padeye, to decrease the keying distance in cohesive soils (mud).

Figure 38
Driven-Plate Anchor

Table 32
Anchor Characteristics

(a) Drag-Embedment Anchors

CHARACTERISTICS	NOTES
Many basic designs and sizes are available from manufacturers.	NAVMOOR-10 & -15 and stockless of 20 to 30 kips are stocked by NFESC.
Works primarily in one horizontal direction.	Enough scope of chain and/or wire rope needs to be provided to minimize uplift forces, which can pull the anchor out. If a load is applied to a drag anchor at a horizontal axis off the centerline of the anchor, then the anchor may drag and reset.
Flukes should be set for the soil type.	Anchor performance depends strongly on the soil type. Fixing the maximum angle of the fluke will help ensure optimum performance. For mooring installations the flukes should be fixed open and stabilizers added for stockless anchors to help prevent overturning.
Adequate sediment required.	Sand layer thickness needs to be approximately one fluke length and mud needs to be 3 to 5 fluke lengths thick.
May not work in all seafloor types.	May be unreliable in very hard clay, gravel, coral, or rock seafloors; and in highly layered seafloors.
May not work well for sloping seafloors.	If the seafloor has a slope of more than several degrees, then the anchor may not hold reliably in the down-slope direction.

Table 32 (Continued)
Anchor Characteristics

(a) Drag-Embedment Anchors (Continued)

Anchor can drag.	If the anchor is overloaded at a slow enough rate, then the anchor can drag, which reduces the peak load. Anchor dragging can be a problem if the room for mooring is restricted. If adequate room is available then anchor drag can help prevent failure of other mooring components.
Anchors can be reused.	Drag-embedment anchors can be recovered and reused.
Proof loading recommended.	Pulling the anchor at the design load in the design direction will help set the anchor and assure that the soil/anchor interaction provides adequate holding.

Table 32 (Continued)
Anchor Characteristics

(b) Driven-Plate Anchors

CHARACTERISTICS	NOTES
Size and design of anchor are selected to provide adequate holding, to allow driving, and to provide adequate structural capacity.	These anchors have been used in a variety of soils from soft mud to hard coral. A driving analysis is recommended for hard soil, because the anchor must be able to be driven in order to work.
Multi-directional.	Can be used on short scope, since the anchor resists uplift forces. One plate anchor may be used to replace several drag anchor legs, since the anchors are multi-directional.
Anchors designed for the soil type.	Anchors designed for the soil engineering characteristics at the site.
Adequate sediment required.	A minimum of several fluke lengths of sediment is required to provide for keying and allow the anchor to hold (NFESC TR-2039-OCN, Design Guide for Pile-Driven Plate Anchors).
Anchor is fixed.	The anchor will not drag, so this type of anchor is well suited to locations with limited mooring area available. The anchors cannot be recovered or inspected.
Proof loading recommended.	Pulling the anchor at the design load in the design direction will help key the anchor and assure that the soil/anchor interaction provides adequate holding.
Installation equipment.	Mobilization can be expensive, so installing a number of anchors at a time reduces the unit installation cost.

5.2 Drag-Embedment Anchor Specification. Drag-embedment anchors are carried on ships and used in many fleet mooring facilities. Key considerations in selecting an anchor are: soil type, anchoring holding capacity, anchor weight, anchor stowage, cost, availability, and installation assets. Note that in SI units the anchor mass is used to characterize anchor size, while in U.S. customary units the anchor weight as a force is used.

Drag-embedment anchor holding capacities have been measured in full-scale tests, modeled in the laboratory, and derived from soil analyses. Empirical anchor holding curves were developed from this information (Naval Civil Engineering Laboratory (NCEL), TDS 83-08R, Drag Embedment Anchors for Navy Moorings). Predicted static ultimate anchor holding is given by:

EQUATION: $$H_M = H_R (W_A / W_R)^b \qquad (26)$$

where

H_M = ultimate anchor system static holding capacity (kips or kN)
H_R = reference static holding capacity
W_A = weight of the anchor in air (for SI units use anchor weight in kilograms; for U.S. units use anchor weight in pounds force)
W_R = reference anchor weight in air (for SI units use 4536 kg; for U.S. units use 10000 lbf)
b = exponent

Values of H_R and b depend on the anchor and soil types. Values of these parameters are given in U.S. customary units in Table 33 and for SI units in Table 34.

Figures 39 and 40 give holding capacities of selected anchors for mud and sand seafloors.

Table 33
Drag Anchor Holding Parameters
U.S. Customary

Anchor Type (a)	SOFT SOILS (Soft clays and silts)		HARD SOILS (Sands and stiff clays)	
	H_R (kips)	b	H_R (kips)	b
Boss	210	0.94	270	0.94
BRUCE Cast	32	0.92	250	0.8
BRUCE Flat Fluke Twin Shank	250	0.92	*(c)*	*(c)*
BRUCE Twin Shank	189	0.92	210	0.94
Danforth	87	0.92	126	0.8
Flipper Delta	139	0.92	*(c)*	*(c)*
G.S. AC-14	87	0.92	126	0.8
Hook	189	0.92	100	0.8
LWT (Lightweight)	87	0.92	126	0.8
Moorfast	117	0.92 *(i)*	60 100 *(d)*	0.8 0.8
NAVMOOR	210	0.94	270	0.94
Offdrill II	117	0.92 *(i)*	60 100 *(d)*	0.8 0.8
STATO	210	0.94	250 *(e)* 190 *(f)*	0.94 0.94
STEVDIG	139	0.92	290	0.8
STEVFIX	189	0.92	290	0.8
STEVIN	139	0.92	165	0.8
STEVMUD	250	0.92	*(g)*	*(g)*
STEVPRIS (straight shank)	189	0.92	210	0.94
Stockless (fixed fluke)	46	0.92	70 44 *(h)*	0.8 0.8
Stockless (movable fluke)	24	0.92	70 44 *(h)*	0.8 0.8

(a) Fluke angles set for 50 deg in soft soils and according to manufacturer's specifications in hard soils, except when otherwise noted.
(b) "b" is an exponent constant.
(c) No data available.
(d) For 28-deg fluke angle.
(e) For 30-deg fluke angle.
(f) For dense sand conditions (near shore).
(g) Anchor not used in this seafloor condition.
(h) For 48-deg fluke angle.
(i) For 20-deg fluke angle (from API 2SK effective March 1, 1997).

Table 34
Drag Anchor Holding Parameters
SI Units

Anchor Type (a)	SOFT SOILS (Soft clays and silts)		HARD SOILS (Sands and stiff clays)	
	H_R (kN)	b	H_R (kN)	b
Boss	934	0.94	1201	0.94
BRUCE Cast	142	0.92	1112	0.8
BRUCE Flat Fluke Twin Shank	1112	0.92	*(c)*	*(c)*
BRUCE Twin Shank	841	0.92	934	0.94
Danforth	387	0.92	560	0.8
Flipper Delta	618	0.92	*(c)*	*(c)*
G.S. AC-14	387	0.92	560	0.8
Hook	841	0.92	445	0.8
LWT (Lightweight)	387	0.92	560	0.8
Moorfast	520	0.92 *(i)*	267 445 *(d)*	0.8 0.8
NAVMOOR	934	0.94	1201	0.94
Offdrill II	520	0.92 *(i)*	267 445 *(d)*	0.8 0.8
STATO	934	0.94	1112 *(e)* 845 *(f)*	0.94 0.94
STEVDIG	618	0.92	1290	0.8
STEVFIX	841	0.92	1290	0.8
STEVIN	618	0.92	734	0.8
STEVMUD	1112	0.92	*(g)*	*(g)*
STEVPRIS (straight shank)	841	0.92	934	0.94
Stockless (fixed fluke)	205	0.92	311 196 *(h)*	0.8 0.8
Stockless (movable fluke)	107	0.92	311 196 *(h)*	0.8 0.8

(a) Fluke angles set for 50 deg in soft soils and according to manufacturer's specifications in hard soils, except when otherwise noted.
(b) "b" is an exponent constant.
(c) No data available.
(d) For 28-deg fluke angle.
(e) For 30-deg fluke angle.
(f) For dense sand conditions (near shore).
(g) Anchor not used in this seafloor condition.
(h) For 48-deg fluke angle.
(i) For 20-deg fluke angle (from API 2SK effective March 1, 1997).

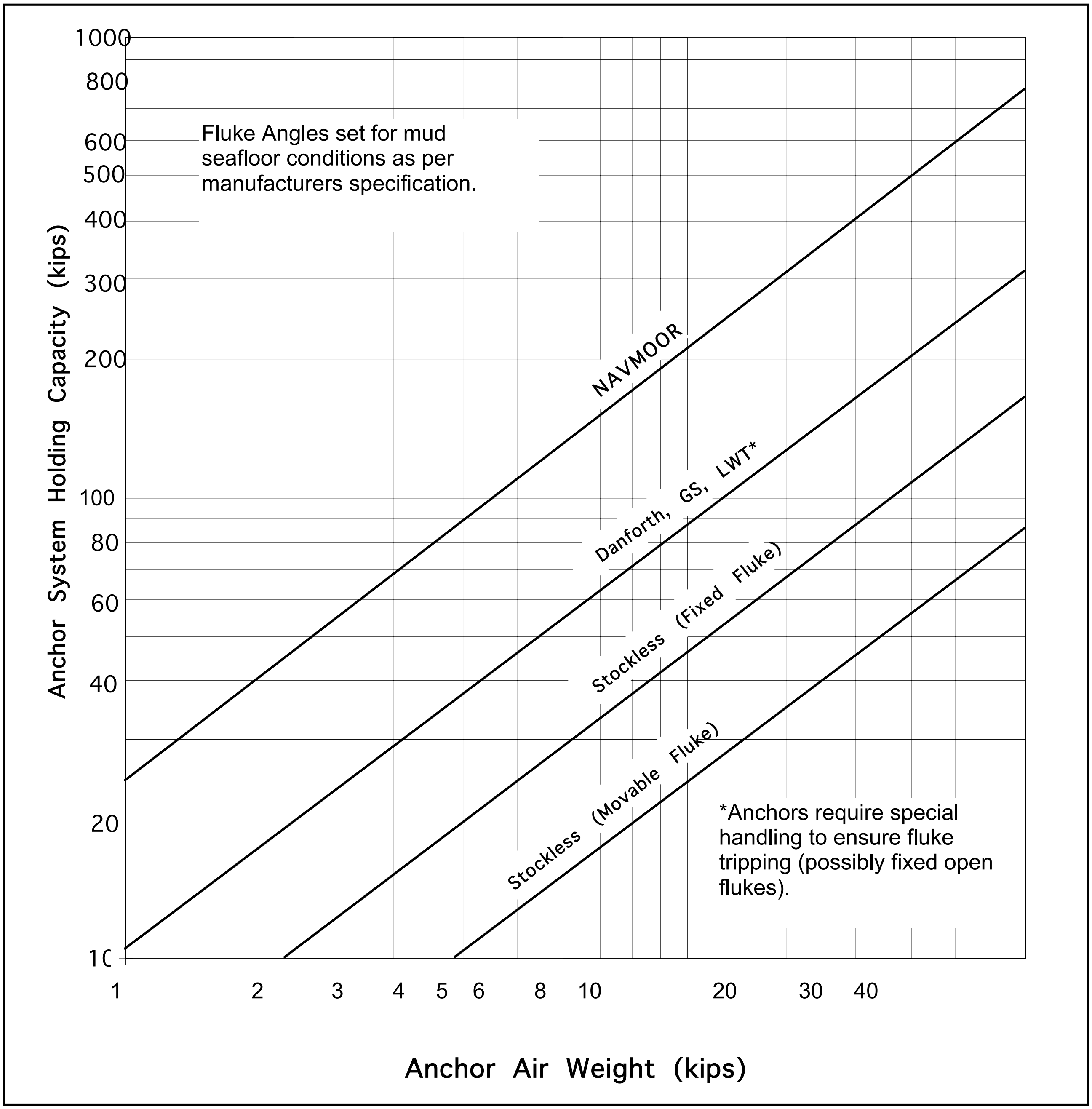


Figure 39
Anchor System Holding Capacity in Cohesive Soil (Mud)

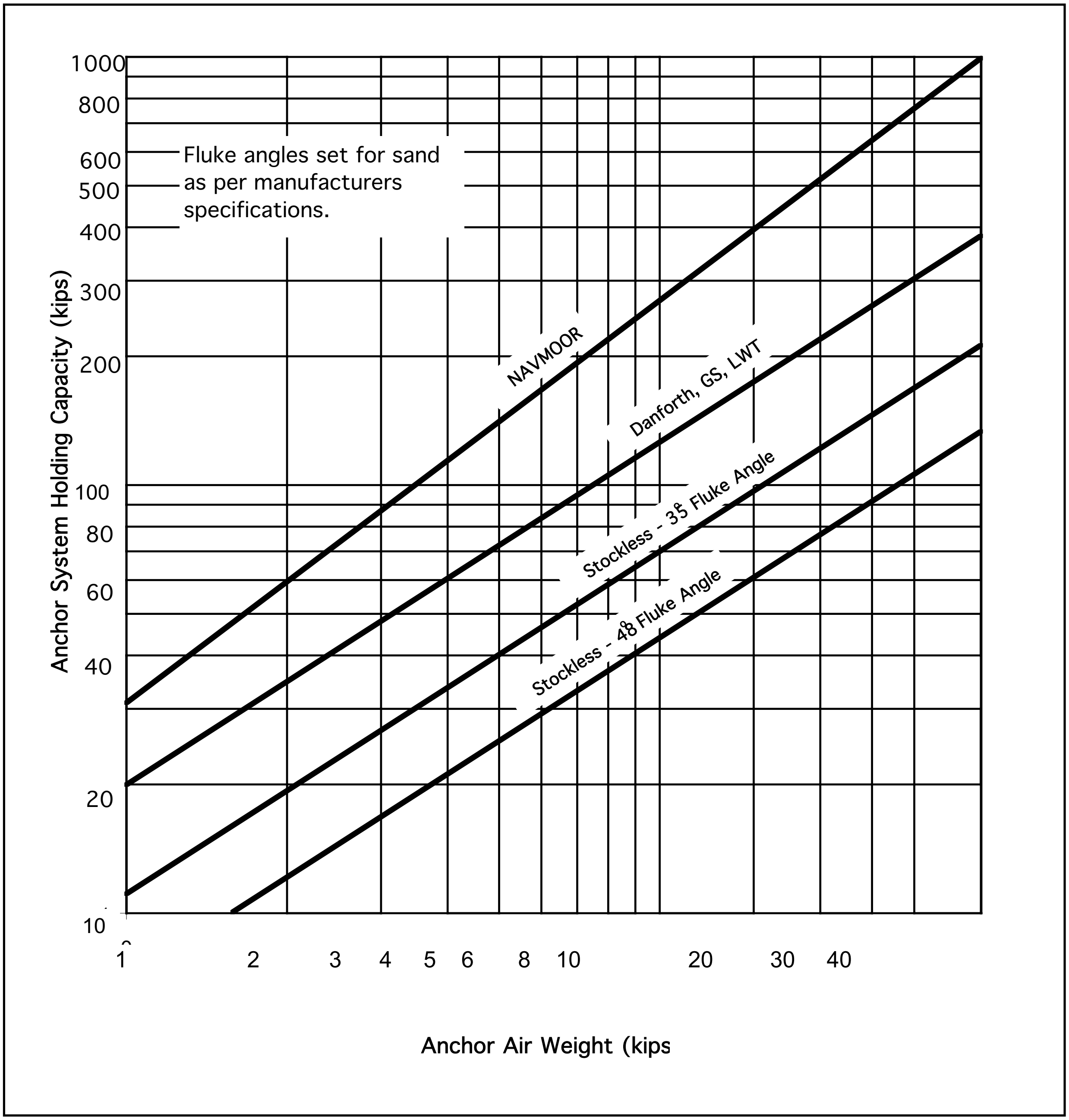


Figure 40
Anchor System Holding Capacity in Cohesionless Soil (Sand)

5.3 Driven-Plate Anchor Design. The U.S. Naval Facilities Engineering Service Center has found that various types of plate anchors are an efficient and cost effective method of providing permanent moorings. Detailed design procedures for these anchors are given in NFESC TR-2039-OCN, Design Guide for Pile-Driven Plate Anchors. Additional information is given in NCEL Handbook for Marine Geotechnical Engineering. An overview of plate anchor design is given here.

A driven-plate anchor consists of the components shown in Figure 38 and discussed in Table 35.

Table 35
Driven-Plate Anchor Components

COMPONENT	NOTES
Plate	Size the area and thickness of the plate to hold the required working load in the given soils. A plate length-to-width ratio of L/B = 1.5 to 2 is shown by practical experience to give optimum performance.
I-Beam	Size the beam to provide: a driving member; stiffness and strength to the anchor; and to separate the padeye from the plate to provide a moment that helps the anchor key during proof testing.
Padeye	Size this structure as the point where the chain or wire rope is shackled onto the anchor prior to driving.
Follower	Length and size specified so assembly can safely be picked up, driven, and removed.
Hammer	Sized to drive the anchor safely. In most cases it is preferable to use an impact hammer. A vibratory hammer may be used in cohesionless soils or very soft mud. A vibratory hammer may also be useful during follower extraction.
Template	A structure is added to the side of the driving platform to keep the follower in position during setup and driving.

Installation of a plate anchor is illustrated in Figure 41. Installation consists of three key steps, as outlined in Table 36.

Table 36
Major Steps in Driven-Plate Anchor Installation

STEP	DESCRIPTION
1	Moor installation platform, place anchor in follower, shackle anchor to chain, place the follower/anchor assembly at the specified anchor location and drive the anchor to the required depth in the sediment (record driving blow count).
2	Remove follower with a crane and/or extractor.
3	Proof load the anchor. This keys the anchor, proves that the anchor holds the design load, and removes slack from the chain.

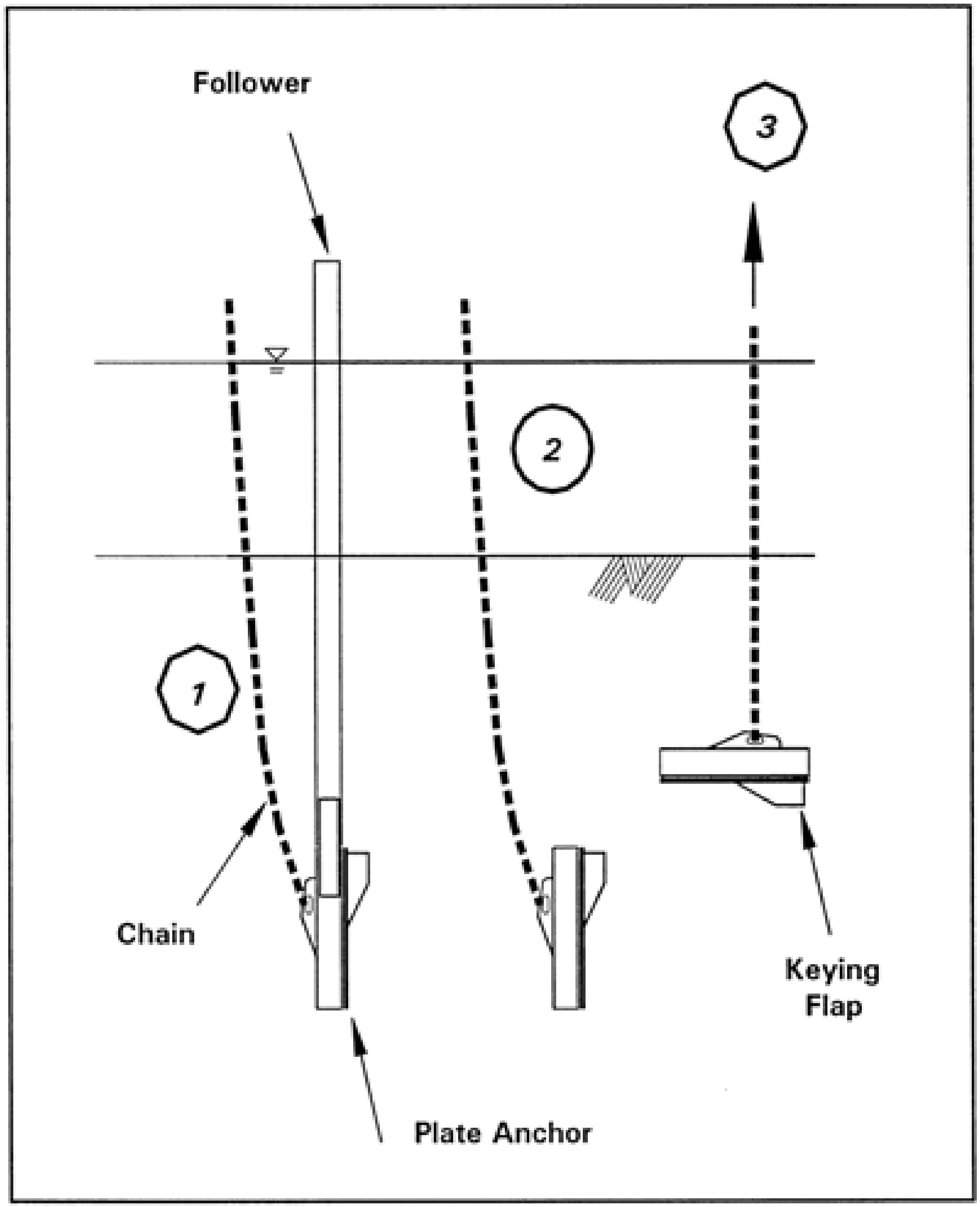


Figure 41
Major Steps of Driven-Plate Anchor Installation

Examples of plate anchors that have been used at various sites are summarized in Table 37.

Table 37
Typical Driven-Plate Anchors

SIZE/LOCATION	SEAFLOOR TYPE	DRIVING DISTANCE INTO COMPOTENT SEDIMENT	PROOF LOAD
0.91 m x 1.22 m (3 ft x 4 ft) Philadelphia, PA	Hard Clay	9 m (30 ft)	670 kN (150 kips) Vertical
0.61 m x 1.22 m (2 ft x 4 ft) San Diego, CA	Sand (Medium)	8 m (27 ft)	890 kN (200 kips) Vertical
1.52 m x 1.83 m (5 ft x 6 ft) Guam	Coral Limestone	12 m (40 ft)	1000 kN (225 kips) Vertical
1.83 m x 3.35 m (6 ft x 11 ft) Pearl Harbor, HI	Mud	21 m (70 ft)	890 kN (200 kips) Horizontal

The recommended minimum plate anchor spacing is five times the anchor width for mud or clay and 10 times the anchor width for sand.

Section 6: FACILITY MOORING EQUIPMENT GUIDELINES

6.1 Introduction. Equipment most often used in mooring facilities is discussed in this section.

6.2 Key Mooring Components. A mooring is a structure that holds a ship in a position using tension and compression members. The resulting mooring loads are transferred to the earth via anchors or some other members, such as pier piles or a wharf structure.

6.2.1 Tension Members. The most commonly used tension members in moorings are:

Chain
Synthetic line
Wire rope
Tension bar buoys

6.2.2 Compression Members. The most commonly used compression members in moorings are:

Marine fenders
Fenders
Camels
Mooring dolphins
Piers
Wharves

6.3 Anchors. Anchors are structures used to transmit mooring loads to the earth. Anchors operate on the basis of soil structure interaction, so their behavior can be complex. Fortunately, the U.S. Navy has extensive experience with full-scale testing of a number of different anchor types in a wide variety of soils and conditions (NCEL Handbook for Marine Geotechnical Engineering). This experience provides a strong basis for design. However, due to the complex nature of structure/soil interaction, it is strongly recommended that anchors always be pull tested to their design load during installation. Design and illustration of some of the common anchor types routinely used are discussed in Chapter 5 of this handbook, and in NCEL Handbook for Marine Geotechnical Engineering.

A brief summary of some anchor experience is given in Table 38.

Table 38
Practical Experience With Anchors

ANCHOR TYPE	DESCRIPTION
Low Efficiency Drag Embedment Anchors (i.e., Stockless)	Reliable if stabilizers are added (see Figure 36). Not very efficient, but reliable through 'brute force'. Extensive experience. A large number available in the U.S. Navy Fleet Mooring inventory. Efficiency increased by fixing the flukes for the type of soil at the site. Should be set and proof tested during installation. Can be used in tandem in various configurations (NCEL TDS 83-05, Multiple STOCKLESS Anchors for Navy Fleet Moorings). Vertical angle of tension member should be approximately zero at the seafloor.
High Efficiency Drag Embedment Anchors (i.e., NAVMOOR)	Very efficient, highly reliable and especially designed so it can easily be used in tandem (NCEL TN-1774, Single and Tandem Anchor Performance of the New Navy Mooring Anchor). Excellent in a wide variety of soil conditions. These are available in the U.S. Navy Fleet Mooring inventory. Should be set and proof tested during installation. Vertical angle of tension member should be approximately zero at the seafloor in most cases.

Table 38 (Continued)
Practical Experience With Anchors

ANCHOR TYPE	DESCRIPTION
Driven-Plate Anchors	Extremely efficient, can be designed to hold extremely high loads and will work in a wide variety of soils from mud to limestone (NFESC TR-2039, Design Guide for Pile-Driven Plate Anchors). Can take loads at any angle, so short scope moorings can be used. Extensive experience. Requires a follower and driving equipment. Most cost effective if a number are to be installed at one site at one time. Should be keyed and proof tested during installation.
Deadweight Anchors	Very low efficiency. Full scale tests (NCEL, Fleet Mooring Test Program – Pearl Harbor) show anchor holding capacity dramatically decreases after anchor starts dragging, just when the anchor capacity required may be most needed. As a result, use of this type of anchor can be dangerous. Deadweight anchors should be used with caution.
Other anchor types	NCEL Handbook for Marine Geotechnical Engineering gives extensive technical and practical information on a wide variety of anchors and soil/structure interaction.

A summary sheet describing the stockless anchors in the U.S. Navy Fleet Mooring inventory is given in Table 39. NAVMOOR anchors in inventory are described in Table 40.

Table 39
Stockless Anchors in the U.S. Navy Fleet Mooring Inventory

ANCHOR IN AIR WEIGHT (1000 lbf)	20	25	30
LENGTH *(inches)*	127.25	137	145.63
STABILIZER EXTENSION *(inches)*	45	48	50
FLUKE LENGTH *(ft)*	7.65	8.24	8.94
FLUKE AREA *(sq. ft)*	35.1	40.7	46.9
SAFE HOLDING CAPACITIES WITH FS = 1.5*			
MUD SEAFLOOR Fluke Angle = 48 deg			
Minimum MUD Thickness (ft)**	22 ft	24 ft	25 ft
Typical Anchor Drag (ft)***	31 ft	33 ft	36 ft
Single Holding (x1000 lbf)	58	71	84
Tandem Holding (x1000 lbf)	116	142	169
SAND SEAFLOOR Fluke Angle = 35 deg			
Minimum SAND Thickness (ft)**	8 ft	8 ft	9 ft
Typical Anchor Drag (ft)***	33 ft	36 ft	39 ft
Single Holding (x1000 lbf)	81	97	112
Tandem Holding (x1000 lbf)	163	194	225

* design mooring properly ** for ultimate holding*** fix flukes open

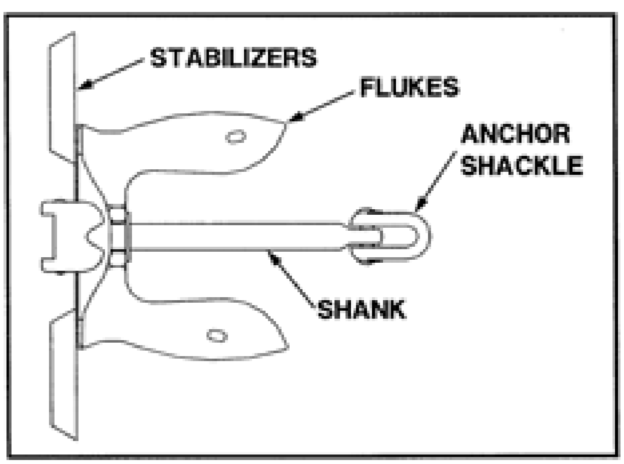
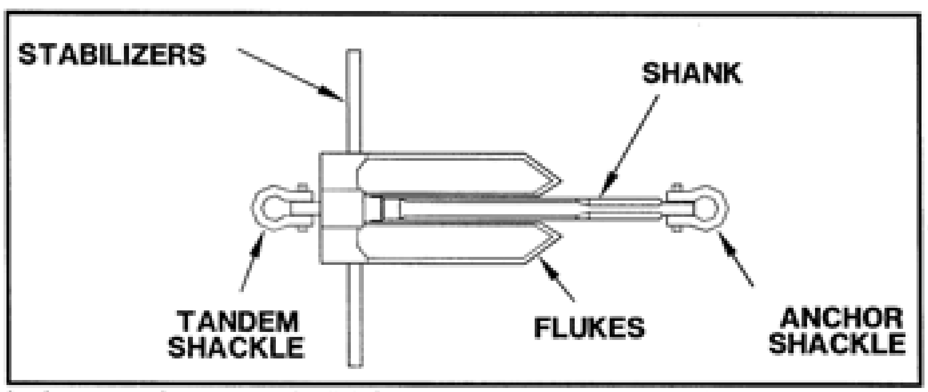


Table 40
NAVMOOR Anchors in the U.S. Navy Fleet Mooring Inventory

ANCHOR SIZE =	NAVMOOR-12	NAVMOOR-15
IN AIR WEIGHT *(pounds)*	12400	19200
LENGTH OVERALL *(inches)*	192	219
STABILIZER WIDTH *(inches)*	192	219
FLUKE LENGTH *(ft)*	8.54	9.73
FLUKE AREA *(sq. ft)*	38.54	50.07
SAFE HOLDING CAPACITIES FS = 2*		
MUD SEAFLOOR Fluke Angle = 50 deg		
Minimum MUD Thickness (ft)**	38 ft	44 ft
Typical Anchor Drag (ft)***	30-35 ft	35-40 ft
Single Holding (x1000 lbf)	125	168
Tandem Holding (x1000 lbf)	310	420
SAND SEAFLOOR Fluke Angle = 32 deg		
Minimum SAND Thickness (ft)**	9 ft	10 ft
Typical Anchor Drag (ft)***	25 ft	30 ft
Single Holding (x1000 lbf)	160	215
Tandem Holding (x1000 lbf)	400	535



* design mooring properly ** for ultimate holding *** fix flukes open

6.4 Chain and Fittings. Chain is often used in fleet moorings because chain:

Is easy to terminate
Can easily be lengthened or shortened
Is durable
Is easy to inspect
Is easy to provide cathodic protection
Has extensive experience
Is available
Is cost effective
Provides catenary effects

DOD commonly uses stud link chain, with each chain link formed by bending and butt welding a single bar of steel. Chain used in fleet moorings is Grade 3 stud link chain specifically designed for long term in-water use (Naval Facilities Engineering Service Center (NFESC), FPO-1-89(PD1), Purchase Description for Fleet Mooring Chain and Accessories). This chain is designated as FM3. Properties of FM3 carried in stock are shown in Table 41. Anodes for use on each link of FM3 chain, designed for diver replacement, are described in Table 42. Note that oversized anodes may be used to extend the anode life and increase the time interval required for anode replacement.

Older ships may use Di-Loc chain (not shown), which was made by pressing together male and female parts to form each link. Di-Loc is not recommended for long-term in-water use, because water may seep in between the male and female parts. The resulting corrosion is difficult to inspect.

Chain routinely comes in 90-foot (27.4-meter) lengths called 'shots'. A number of other accessories are used with chain, as shown in Figure 42. For example, shots of chain are connected together with chain joining links. Anchor joining links are used to connect chain to anchors. Ground rings provide an attachment point for multiple chains. Buoy swivels are used to connect chain to buoys. Refer to NFESC TR-6014-OCN, Mooring Design Physical and Empirical Data and NFESC FPO-1-89(PD1) for additional information on chain and fittings.

Table 41
FM3 Mooring Chain Characteristics

NOMINAL SIZE *(inches)*	1.75	2	2.25	2.5	2.75	3.5	4
NUMBER OF LINKS PER SHOT	153	133	119	107	97	77	67
LINK LENGTH *(inches)*	10.6	12.2	13.7	15.2	16.7	21.3	24.3
WEIGHT PER SHOT IN AIR *(lbf)*	2525	3276	4143	5138	6250	10258	13358
WEIGHT PER LINK IN AIR *(lbf)*	16.5	24.6	34.8	48	64.4	133.2	199.4
WEIGHT PER FOOT SUB. *(lbs/ft)*	26.2	33.9	42.6	52.7	63.8	104.1	135.2
BREAKING STRENGTH *(thousands lbf)*	352	454	570	692	826	1285	1632
WORKING STRENGTH (FS=3) *(thousands lbf)*	117.2	151.2	189.8	230.4	275.1	427.9	543.5

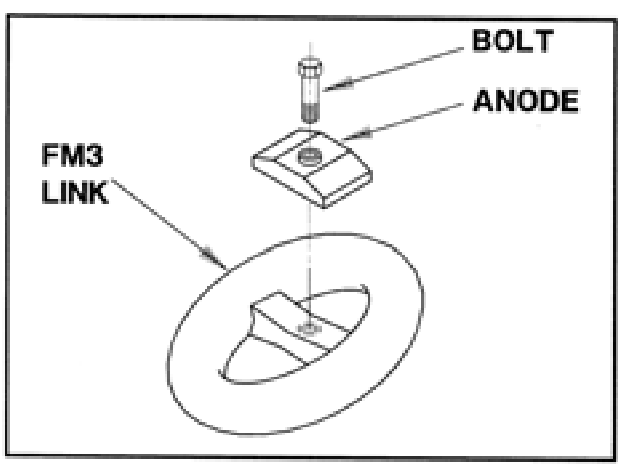
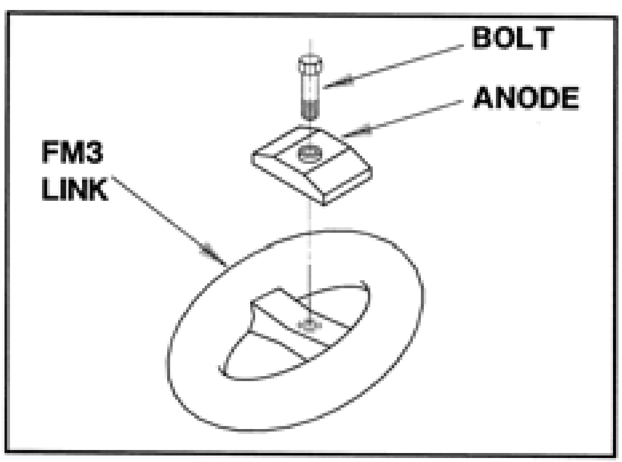


Table 42
Properties of FM3 Chain Anodes

NOMINAL SIZE *(inches)*	1.75	2	2.25	2.5	2.75	3.5	4
ANODE WEIGHT *(lbs)*	0.80	1.10	1.38	1.70	2.04	3.58	4.41
SCREW LENGTH *(inches)*	1.25	1.50	1.75	1.75	2.00	2.25	2.25
ANODE WIDTH *(inches)*	1.50	1.62	1.75	1.94	2.06	2.38	2.69
LINK GAP *(lbf)*	3.74	4.24	4.74	5.24	5.74	7.48	8.48
ANODES PER FULL DRUM	1106	822	615	550	400	158	122
WEIGHT PER FULL DRUM *(approx. lbf)*	976	979	917	993	869	602	550

NOTE: 1. ALL SCREWS ARE .375-16UNC-2A, GRADE 5, HEX CAP
2. 4.00 INCH ANODES FIT ALL CHAIN SIZES
3. ALL SCREW HEADS ARE 9/16 INCH



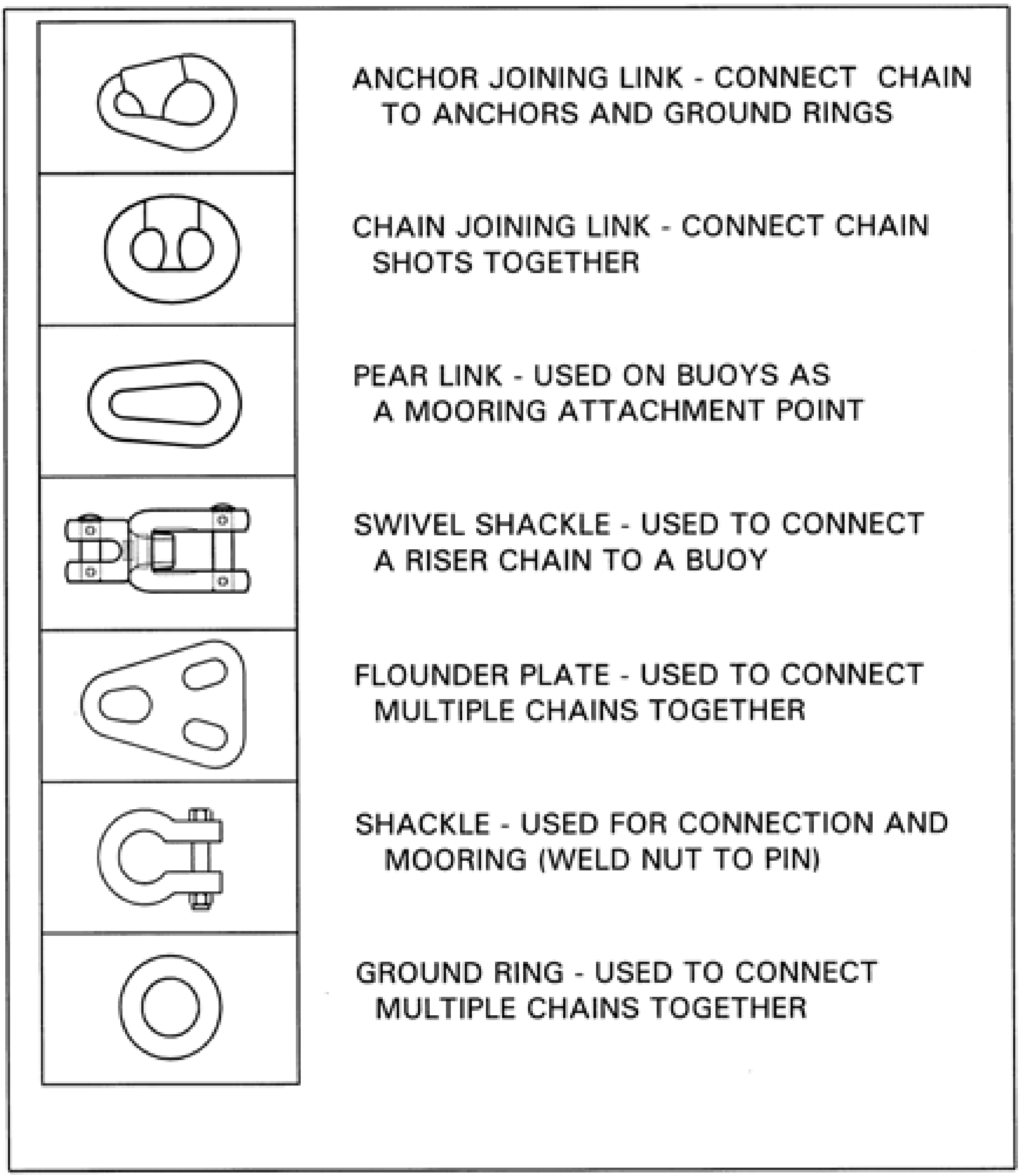


Figure 42
Chain Fittings

6.5 Buoys. There are two buoys commonly used on U.S. Navy Fleet moorings: an 8-foot diameter buoy and a 12-foot diameter buoy. These buoys have a polyurethane shell, are filled with foam, and have a tension bar to transmit mooring loads to the chain. Properties of these buoys are given in Table 43. Some of the key features of these buoys are that they require little maintenance and they are self-fendering. A variety of older steel buoys in use are being phased out, due to their relatively high maintenance cost.

6.6 Sinkers. Sinkers are placed on fleet moorings to tune the static and dynamic behavior of a mooring. Sinkers are usually made of concrete or low cost metal. Key sinker parameters that can be specified in design include:

Mass
Weight
Location
Number
Size
Design

6.7 Mooring Lines. The most common tension member lines used are synthetic fiber ropes and wire rope. Synthetic lines have the advantage of easy handling and some types have stretch, which can be used to fine tune static and dynamic mooring behavior and aid in load sharing between tension members. Wire rope has the advantage of durability.

6.7.1 Synthetic Fiber Ropes. Mooring lines are formed by weaving a number of strands together to form a composite tension member. Lines are made of different types of fiber and various constructions. Stretch/strain properties of selected lines are shown in Table 44 and Figure 43. Engineering characteristics of some double braided nylon and polyester lines are given in Tables 45 and 46. Additional information is provided in NFESC TR-6014-OCN, Mooring Design Physical and Empirical Data. The size and type of synthetic line specified in a given design will depend upon parameters such as those shown in Table 47.

Table 43
Foam-Filled Polyurethane Coated Buoys

PARAMETERS	8-FOOT BUOY	12-FOOT BUOY
Weight in Air	4,500 lbs	10,400 lbs
Net Buoyancy	15,000 lbs	39,000 lbs
Working Buoyancy (24" FB)	6,150 lbs	20,320 lbs
Proof Load on Bar (0.6 Fy)	300 kips	600 kips
Working Load of Bar (0.3Fy)	150 kips	300 kips
Diameter Overall (w/fenders)	8 ft 6 in	12 ft
Diameter of Hull	8 ft	11 ft 6 in
Length of Hull Overall	7 ft 9 in	8 ft 9 in
Length of Tension Bar	11 ft 4 In	13 ft I in
Height of Cylindrical Portion	4 ft 4 in	5 ft 7 in
Height of Conical Portion	3 ft 5 in	3 ft 2 in
Bar Thickness (top/bottom)	4.5/3 in	5/3.5 in
Top Padeye ID (top/bottom)	3.5/3.5 in	4.5/5 in
Shackle on Top	3 inch	4 inch
Maximum Chain Size	2.75 inch	4 inch
Min. Recommended Riser Wt	1,068 lbs	7,500 lbs
Riser Wt for 24" freeboard	8,850 lbs	18,680 lbs
Max. Recommended Riser Wt	7,500 lbs	21,264 lbs
Moment to Heel 1 deg:		
Min Riser Wt	108 ft-lbs	1,183 ft-lbs
Max Riser Wt	648 ft-lbs	2,910 ft-lbs

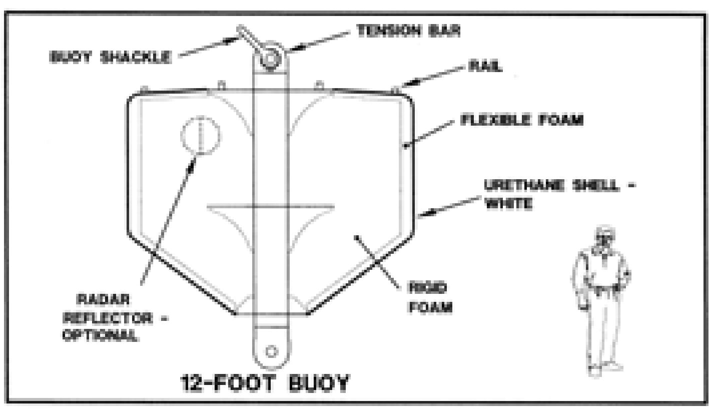


Table 44
Stretch of Synthetic Lines

% Break Strength (T/Tb)	SPECTRA BRAID % Stretch (1)	DOUBLE BRAIDED POLYTESTER % Stretch (2)	DOUBLE BRAIDED NYLON % Stretch (3)	DOUBLE BRAIDED NYLON % Stretch (4)	ULTRA-STRONG % Stretch (5)
0	0	0	0	0	0
5	0.38	0.8	5.8	2.04	
10	0.58	1.5	9.1	3.89	1.68
15	0.72	2.1	11.5	5.46	
20	0.87	2.6	13.2	6.85	3.23
25	0.92	3.1	14.6	8.13	
30	0.98	3.6	15.7	9.26	4.7
35	1.07	4	16.6	10.28	
40	1.135	4.7	17.6	11.3	6.02
45	1.196	5.2	18.5	12.1	
50	1.25	5.7	19.3	12.8	7.58
55	1.305	6.2	20.1	(no data)	
60	1.354	6.8	20.9		9.05
65	1.412	7.3	21.7		
70	1.448	7.8	22.5		10.51
75	1.492	8.3	23.3		
80	1.535	8.8	24.1		12.08
85	1.578	9.3	24.9		
90	1.617	9.8	25.7		13.73
95	1.655	10.3	26.6		
100	1.693	10.9	27.4		15.35

(1) SPECTRON 12; Sampson
(2) 2-IN-1 STABLE BRAID; Sampson (engineering data sheet); cyclic loading
(3) DOUBLE BRAIDED; Sampson (engineering data sheet); cyclic loading; WET
(4) DOUBLE BRAIDED; Sampson (engineering data sheet); cyclic loading; DRY
(5) BLENDED ROPE; Sampson (engineering data sheet); cycled 50 times

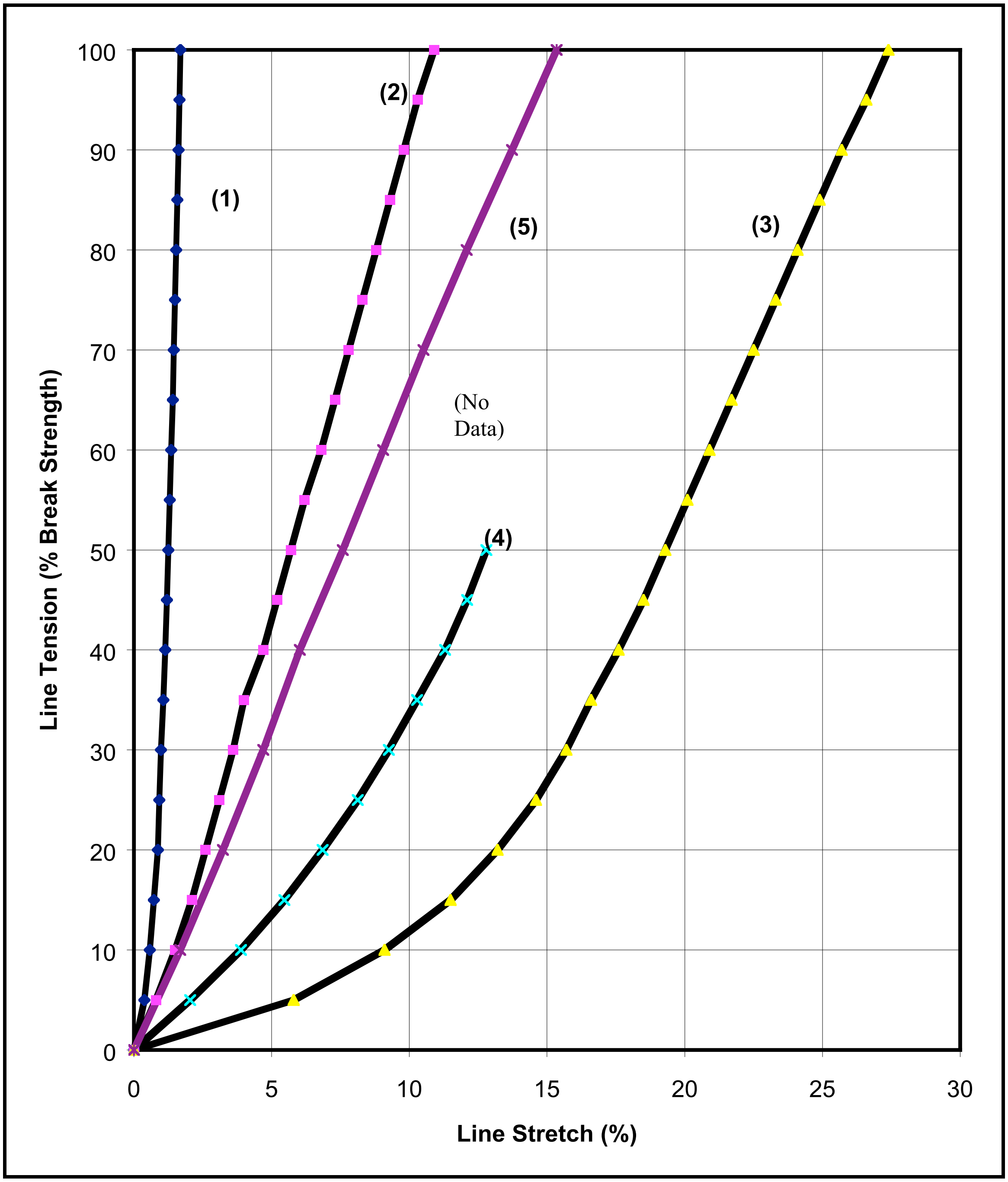


Figure 43
Synthetic Line Stretch

Table 45
Double Braided Nylon Line*

		SINGLE LINE				THREE PARTS LINE			
DIA. (in)	CIR. (in)	Av Fb (kips)	Av Fb (E5 N)	AE (kips)	AE (E5 N)	Av Fb (kips)	Av Fb (E5 N)	AE (kips)	AE (E5 N)
1.0	3	33.6	1.495	118.9	5.29	100.8	4.48	356.8	15.87
1.1	3.5	45	2.002	159.3	7.09	135	6.01	477.9	21.26
1.2	3.75	52	2.313	184.1	8.19	156	6.94	552.2	24.56
1.3	4	59	2.624	208.8	9.29	177	7.87	626.5	27.87
1.4	4.5	74	3.292	261.9	11.65	222	9.88	785.8	34.96
1.6	5	91	4.048	322.1	14.33	273	12.14	966.4	42.99
1.8	5.5	110	4.893	389.4	17.32	330	14.68	1168.1	51.96
1.9	6	131	5.827	463.7	20.63	393	17.48	1391.2	61.88
2.1	6.5	153	6.806	541.6	24.09	459	20.42	1624.8	72.27
2.2	7	177	7.873	626.5	27.87	531	23.62	1879.6	83.61
2.4	7.5	202	8.985	715.0	31.81	606	26.96	2145.1	95.42
2.5	8	230	10.231	814.2	36.22	690	30.69	2442.5	108.65
2.7	8.5	257	11.432	909.7	40.47	771	34.30	2729.2	121.40
2.9	9	285	12.677	1008.8	44.88	855	38.03	3026.5	134.63
3.2	10	322	14.323	1139.8	50.70	966	42.97	3419.5	152.11
3.5	11	384	17.081	1359.3	60.46	1152	51.24	4077.9	181.39
3.8	12	451	20.061	1596.5	71.01	1353	60.18	4789.4	213.04
4.1	13	523	23.264	1851.3	82.35	1569	69.79	5554.0	247.05
4.5	14	599	26.645	2120.4	94.32	1797	79.93	6361.1	282.95
4.8	15	680	30.248	2407.1	107.07	2040	90.74	7221.2	321.22

*After Sampson, dry, cyclic loading; reduce nylon lines by 15% for wet conditions

Note: Dia. = diameter, Cir. = circumference, Av Fb = average break strength,
AE = cross-sectional area times modulus of elasticity (this does not include the highly nonlinear properties of nylon, shown in Figure 43)

Table 46
Double Braided Polyester Lines*

		SINGLE LINE				THREE PARTS LINE			
DIA. (in)	CIR. (in)	Av Fb (kips)	Av Fb (E5 N)	AE (kips)	AE (E5 N)	Av Fb (kips)	Av Fb (E5 N)	AE (kips)	AE (E5 N)
1.0	3	37.2	1.655	316.6	14.08	111.6	4.96	949.8	42.25
1.1	3.5	45.8	2.037	389.8	17.34	137.4	6.11	1169.4	52.02
1.2	3.75	54.4	2.420	463.0	20.59	163.2	7.26	1388.9	61.78
1.3	4	61.5	2.736	523.4	23.28	184.5	8.21	1570.2	69.85
1.4	4.5	71.3	3.172	606.8	26.99	213.9	9.51	1820.4	80.98
1.6	5	87.2	3.879	742.1	33.01	261.6	11.64	2226.4	99.03
1.8	5.5	104	4.626	885.1	39.37	312	13.88	2655.3	118.11
1.9	6	124	5.516	1055.3	46.94	372	16.55	3166.0	140.83
2.1	6.5	145	6.450	1234.0	54.89	435	19.35	3702.1	164.68
2.2	7	166	7.384	1412.8	62.84	498	22.15	4238.3	188.53
2.4	7.5	190	8.452	1617.0	71.93	570	25.35	4851.1	215.79
2.5	8	212	9.430	1804.3	80.26	636	28.29	5412.8	240.77
2.7	8.5	234	10.409	1991.5	88.59	702	31.23	5974.5	265.76
2.9	9	278	12.366	2366.0	105.24	834	37.10	7097.9	315.73
3.2	10	343	15.257	2919.1	129.85	1029	45.77	8757.4	389.55
3.5	11	407	18.104	3463.8	154.08	1221	54.31	10391.5	462.24
3.8	12	470	20.907	4000.0	177.93	1410	62.72	12000.0	533.79
4.1	13	533	23.709	4536.2	201.78	1599	71.13	13608.5	605.34
4.5	14	616	27.401	5242.6	233.20	1848	82.20	15727.7	699.60
4.8	15	698	31.049	5940.4	264.24	2094	93.15	17821.3	792.73

*After Sampson, dry, cyclic loading

Note: Dia. = diameter, Cir. = circumference, Av Fb = average break strength, AE = cross-sectional area times modulus of elasticity

Table 47
Some Factors to Consider When
Specifying Synthetic Line or Wire Rope

PARAMETER
Safety
Break strength
Diameter
Weight
Buoyancy and hydrodynamic properties
Ease of handling
Equipment to be used
Stretch/strain properties
Load sharing between lines
Dynamic behavior
Reliability
Durability
Fatigue
Exposure
Chaffing/abrasion
Wet vs. dry condition
Experience
Ability to splice
Ability to provide terminations
Inspection
Cost
Availability

6.7.2 Wire Ropes. Wire rope is composed of three parts: wires, strands, and a core. The basic unit is the wire. A predetermined number of wires of the proper size are fabricated in a uniform geometric arrangement of definite pitch or lay to form a strand of the required diameter. The required number of strands are then laid together symmetrically around a core to form the rope. Refer to Naval Ship's Technical Manual Chapter 613 (NAVSEASYSCOM) for additional information. Some of the features to consider when specifying wire rope are listed in Table 47.

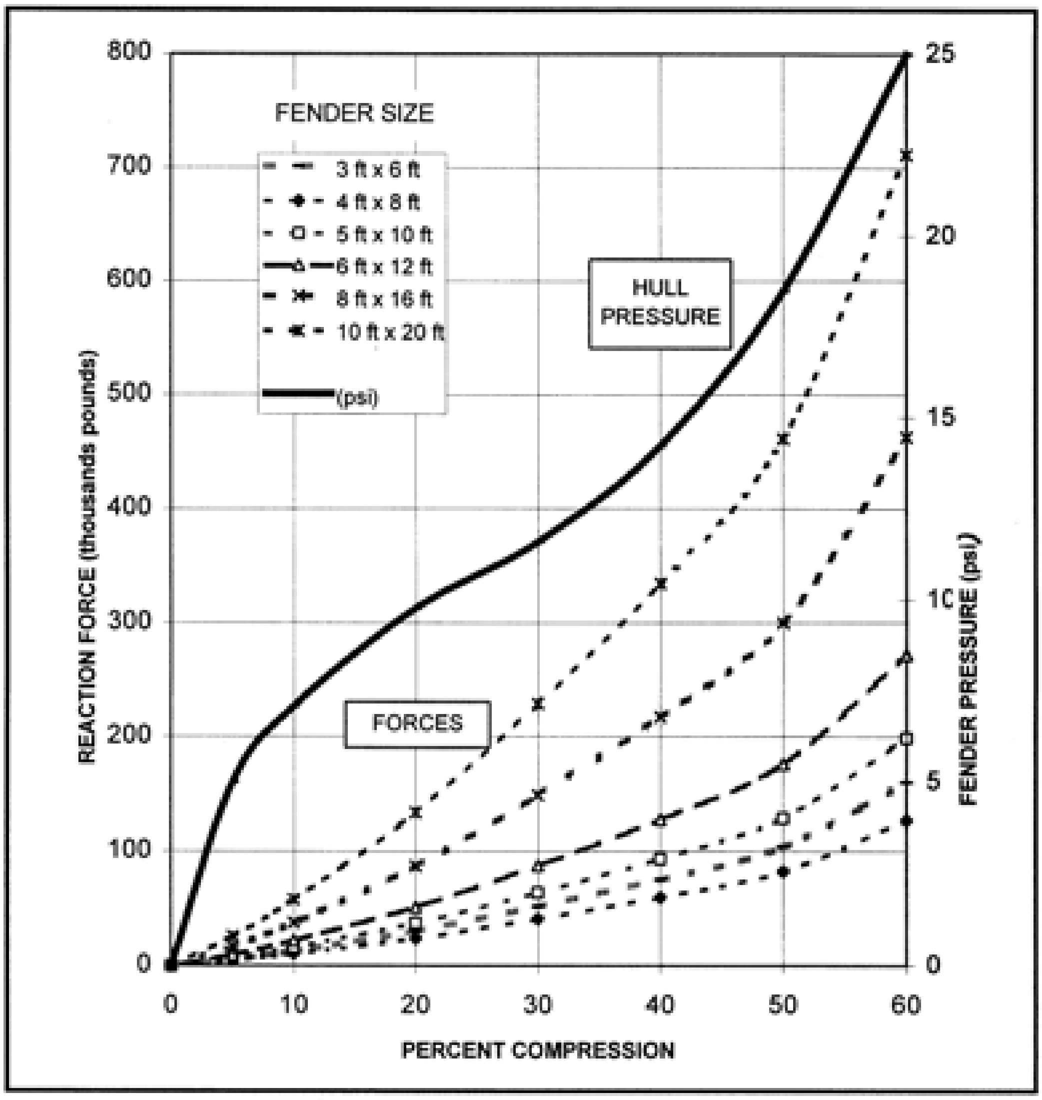
6.8 Fenders. Fendering is used between ships and compression structures, such as piers and wharves, in fixed moorings. Fenders act to distribute forces on ship hull(s) and minimize the potential for damage. Fendering is also used between moored ships. A wide variety of types of fenders are used including:

- Wooden piles
- Cylindrical marine fenders
- Hard rubber fenders
- Mooring dolphins
- Specially designed structures

The pressure exerted on ships hulls is a key factor to consider when specifying fenders. Allowable hull pressures on ships are discussed in NFESC TR-6015-OCN, Foam-Filled Fender Design to Prevent Hull Damage.

Behaviors of some common types of cylindrical marine fenders are shown in Figures 44 and 45.

Refer to MIL-HDBK-1025/1 and Naval Ship's Technical Manual Chapter 611(NAVSEASYSCOM) for detailed information on fenders.



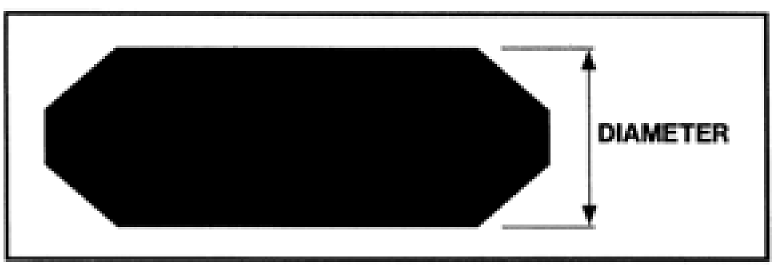


Figure 44
SEA-GUARD Fender Information

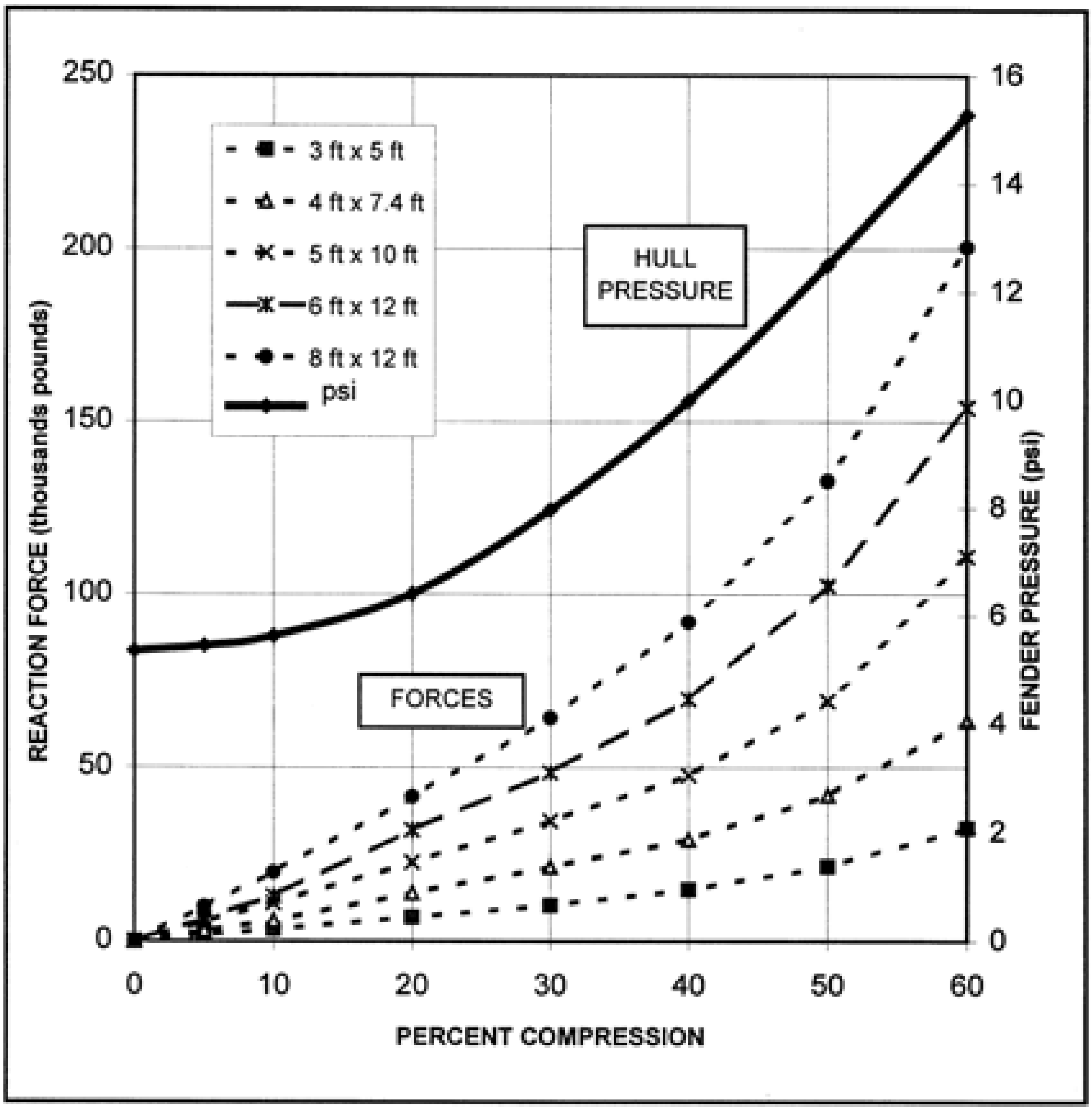


Figure 45
SEA-CUSHON Fender Performance

6.9 Pier Fittings. Standard pier and wharf mooring fittings, as shown in Figure 46, include:

Bollards
Bitts
Cleats

Cleats are not recommended for ships, unless absolutely necessary, because they are low capacity.

Some of the fittings commonly used on U.S. Navy piers are summarized in Table 48. Guidance for placing pier fittings in pier/wharf design is given in MIL-HDBK-1025/1.

Table 48
Commonly Used U.S. Navy Pier Mooring Fittings

DESCRIPTION	SIZE	BOLTS	WORKING CAPACITY (kips)
SPECIAL MOORING BOLLARD “A”	Height=48 in. Base 48x48 in.	12 x 2.75-in. dia.	Horz. = 660 @45 deg = 430 Nom. = 450
SPECIAL MOORING BOLLARD “B”	Height=44.5 in. Base 39x39 in.	8 x 2.25-in. dia.	Horz. = 270 @45 deg = 216 Nom. = 200
LARGE BOLLARD WITH HORN	Height=44.5 Base 39x39 in.	4 x 1.75-in. dia.	Horz. = 104 @45 deg = 66 Nom. = 70
LARGE DOUBLE BITT WITH LIP	Height=26 in. Base 73.5x28 in.	10 x 1.75-in. dia.	Nom. = 75*
LOW DOUBLE BITT WITH LIP	Height=18 in. Base 57.5x21.5 in.	10 x 1.625-in. dia.	Nom. = 60*
42-INCH CLEAT	Height=13 in. Base 26x14.25 in.	6 x 1.125-in. dia.	Nom. = 40
30-INCH CLEAT	Height=13 in. Base 16x16 in.	4 x 1.125-in. dia.	Nom. = 20

*Working capacity per barrel; after NAVFAC Drawing No. 1404464

Additional information concerning the sizes and working capacities of pier and wharf mooring fittings is found in NFESC TR-6014-OCN, Mooring Design Physical and Empirical Data and in MIL-HDBK-1025/1.

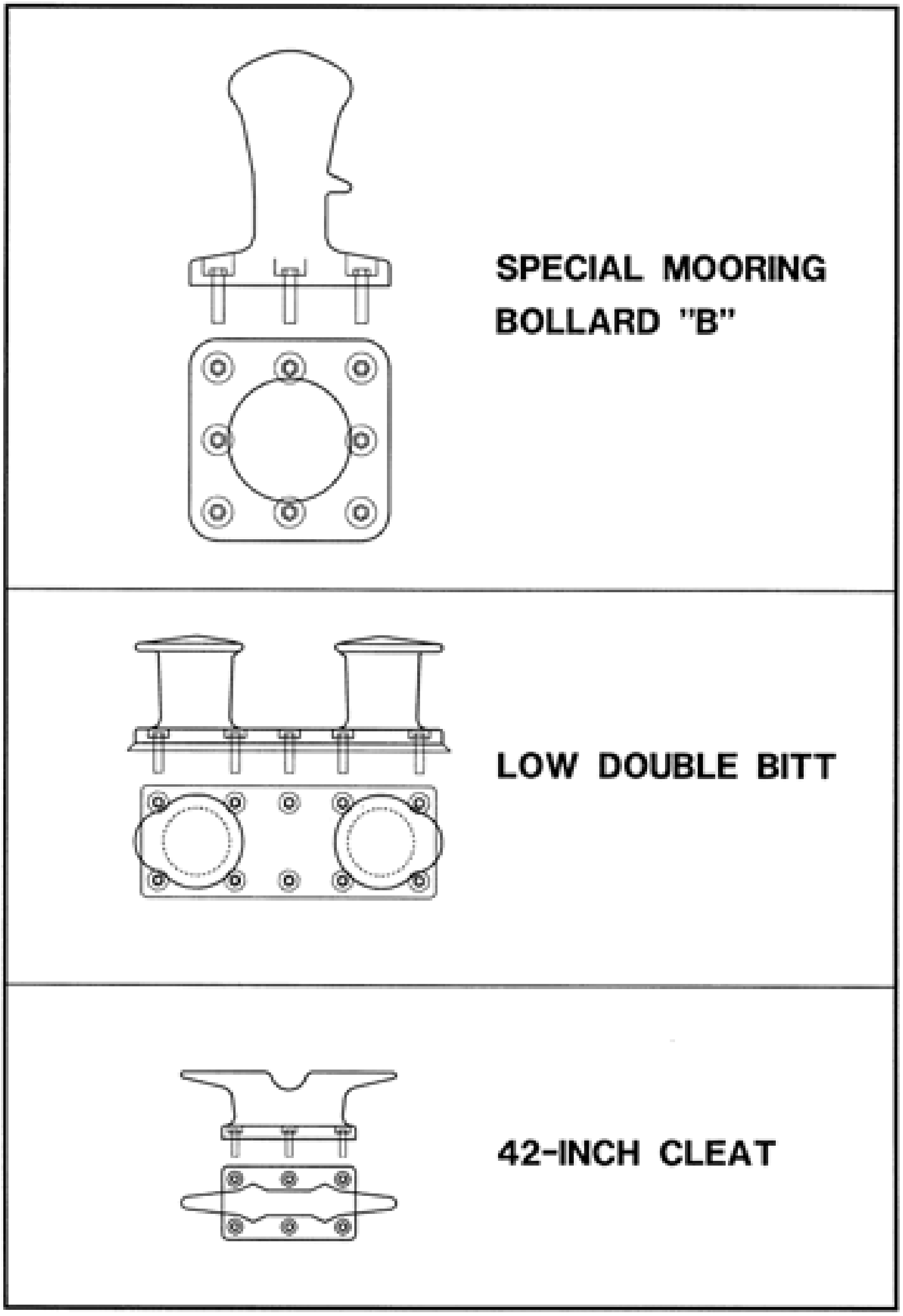


Figure 46
Pier and Wharf Mooring Fittings Shown in Profile and Plan Views

6.10 Catenary Behavior. It is not desirable or practical to moor a ship rigidly. For example, a ship can have a large amount of buoyancy, so it usually must be allowed to move with changing water levels. Another problem with holding a ship too rigidly is that some of the natural periods of the ship/mooring system can become short, which may cause dynamic problems.

A ship can be considered a mass and the mooring system as springs. During mooring design, the behavior of the mooring 'springs' can be controlled to fine tune the ship/mooring system behavior to achieve a specified performance. This can be controlled by the weight of chain or other tension member, scope of chain, placement of sinkers, amount the anchor penetrates the soil, and other parameters. The static behavior of catenaries can be modeled using the computer program CSAP2 (NFESC CR-6108-OCN, Anchor Mooring Line Computer Program Final Report, User's Manual for Program CSAP2). This program includes the effects of chain and wire rope interaction with soils, as well as the behavior of the catenary in the water column and above the water surface.

As an example, take the catenary shown in Figure 47. This mooring leg consists of four sections. The segment next to the anchor, Segment 1, consists of wire rope, followed by three segments of chain. Sinkers with the shown in-water weight are located at the ends of Segments 2 and 3. In this example, a plate anchor is driven 55 feet (16.8 meters) into mud below the seafloor. The chain attachment point to the ship is 64 feet (19.5 meters) above the seafloor. The mooring leg is loaded to its design horizontal load of H = 195 kips (8.7 E5 newtons) to key and proof load the anchor soon after the anchor is installed. The keying and proofing corresponds to a tension in the top of the chain of approximately 210 kips. Figure 47 shows the shape of the chain catenary predicted by CSAP2 for the design load.

The computed load/deflection curve for the design water level for this mooring leg, after proofing, is shown in Figure 48. The shape of this and the other mooring legs in this mooring, which are not shown, will strongly influence the static and dynamic behavior of the ship/mooring system during forcing.

SEGMENT	TYPE	DIA	WEIGHT	LENGTH	SINKER
		(inches)	(lbf/ft)	(ft)	(kips)
1	W	3.00	13.15	30	0
2	C	2.75	62.25	156	13.35
3	C	2.75	62.25	15	17.8
4	C	2.75	62.25	113	0

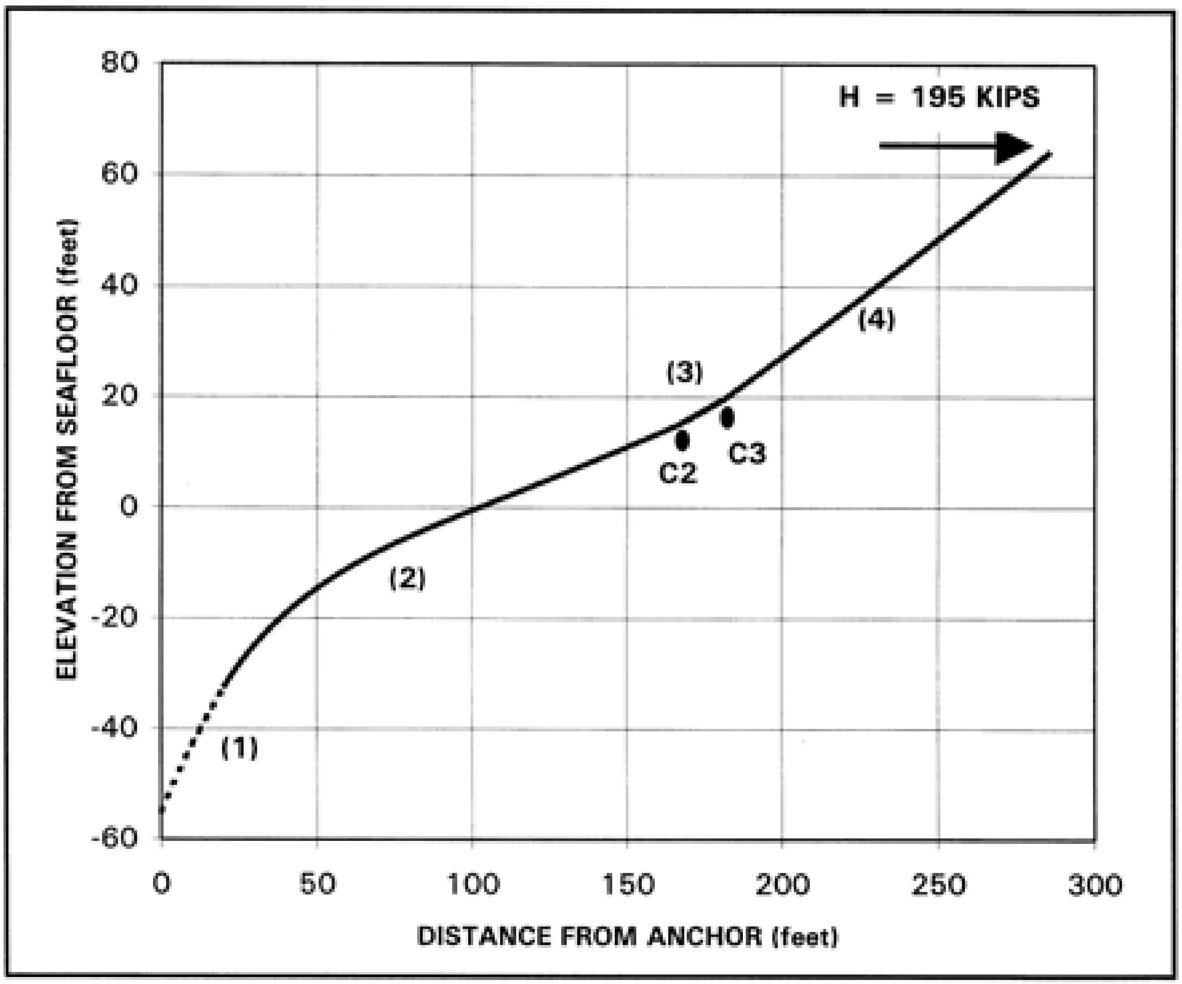


Figure 47
Sample Catenary

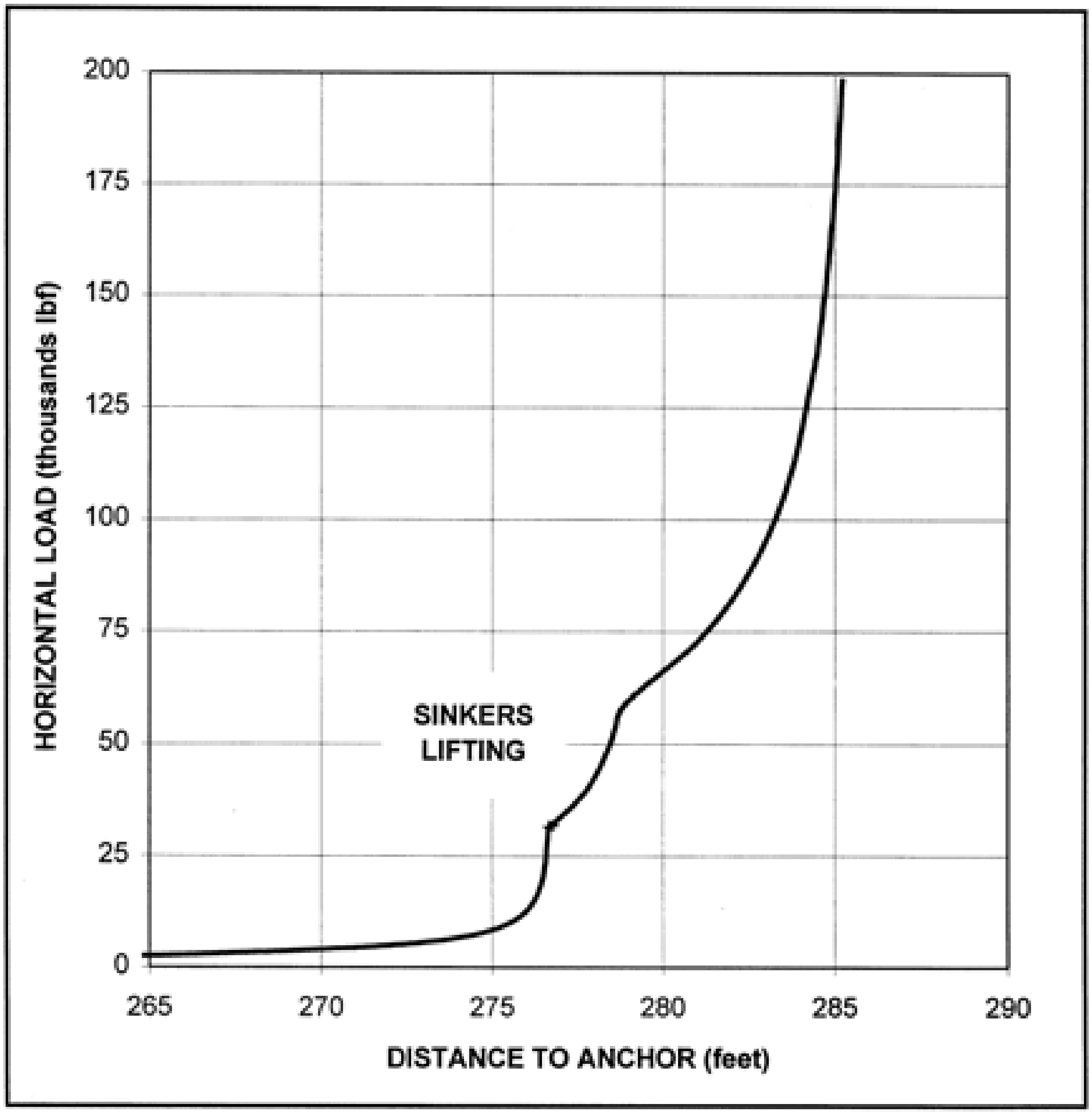


Figure 48
Load/Deflection Curve for the Example Mooring Leg

6.11 Sources Of Information. Detailed NAVFAC information, including drawings, specifications, and manuals, is available in the National Institute of Building Sciences, "Construction Criteria Base." Further information can be obtained from the Naval Facilities Engineering Command Criteria Office (Code 15C) and the Naval Facilities Engineering Service Center, Moorings Center of Expertise (Code 551). A list of sources for information on facility mooring equipment is provided in Table 49.

Table 49
Sources of Information for Facility Mooring Equipment

ITEM	SOURCE
Standard fittings for waterfront structures	NAVFAC Drawing No. 1404464
Marine fenders	NAVFAC Spec. 02396A "Resilient Foam-Filled Marine Fenders" NAVFAC Spec. 02397B "Arch-Type Rubber Marine Fenders" NAVFAC Spec. 02395 "Prestressed Concrete Fender Piling" NAVFAC Spec. Y02882D "Fenders (Yokosuka, JA)"
Camels	MIL-C-28628C(YD) "Camel, Wood, Marine; Single Log Configuration, Untreated" "Standard Aircraft Carrier Mooring Camel" NAVFAC Drawings SD-1404045A to 52 and NAVFAC Spec. C39 "Standard Submarine Mooring Camel" NAVFAC Drawings SD-1404943 to 47 and NAVFAC Spec. C46 "Standard Attack Submarine Mooring Camel" NAVFAC Drawings SD-1404667 to 70 and NAVFAC Spec. C49
Mooring lines	Cordage Institute Technical Manual

Table 49 (Continued)
Sources of Information for Facility Mooring Equipment

ITEM	SOURCE
Foam buoys	NFESC purchase descriptions of Mar. 1988, Dec. 1989 and May 1990.
Stud link chain and fittings	NFESC purchase description of Mar. 1995.
NAVMOOR anchors	NFESC purchase description of Nov. 1985 and drawing package of July 1990.
Stud link chain anodes	NFESC purchase description of June 1990.

Section 7: VESSEL MOORING EQUIPMENT GUIDELINES

7.1 Introduction. A vessel must be provided with adequate mooring equipment to serve its missions. This equipment enables the ship to anchor in a typical soil under design environmental conditions. In addition, the ship can moor to various piers, wharfs, fleet moorings, and other facilities. Equipment on board the ship must be designed for Mooring Service Types I, II and III, as discussed in Section 3.1. Additional mooring hardware, such as specialized padeyes, mooring chains, wire ropes, and lines, can be added for Mooring Service Type IV situations.

7.2 Types of Mooring Equipment. Basic shipboard mooring equipment is summarized in Table 50. Additional information is provided in NAVSEA NSTM Chapters 581, 582, 611 and 613; from Naval Sea Systems Command drawings and publications; Cordage Institute, Cordage Institute Technical Manual; Guidelines for Deepwater Port Single Point Mooring Design, Flory et al. (1977); The Choice Between Nylon and Polyester for Large Marine Ropes, Flory et al. (1988); A Method of Predicting Rope Life and Residual Strength, Flory et al. (1989); Fiber Ropes for Ocean Engineering in the 21st Century, Flory et al, (1992a); Failure Probability Analysis Techniques for Long Mooring Lines, Flory et al. (1992b); Modeling the Long-Term Fatigue Performance of Fibre Ropes, Hearle et al. (1993); Oil Companies International Marine Forum (OCIMF), Mooring Equipment Guidelines (1992); OCIMF Recommendations for Equipment Employed in the Mooring of Ships at Single Point Moorings (1993); OCIMF Prediction of Wind and Current Loads on VLCCs (1994); OCIMF Single Point Mooring Maintenance and Operations Guide (1995); and Fatigue of SPM Mooring Hawsers, Parsey (1982).

7.3 Equipment Specification. Whenever possible, standard equipment is used on board ships as mooring equipment. The specification, size, number, and location of the equipment is selected to safely moor the ship. Some of the many factors that need to be considered in equipment specification are weight, room required, interaction with other systems, power requirements, reliability, maintenance, inspection, and cost.

7.4 Fixed Bitts. Bitts provide a termination for tension members. Fixed bitts, Figure 49, are typically placed in pairs within a short distance forward or aft of a chock location. They are often placed symmetrically on both the port and starboard sides, so that the ship can moor to port or starboard. Capacities of the bitts are based on their nominal diameter. Table 51 provides fixed bitt sizes with their associated capacities.

7.5 Recessed Shell Bitts. Recessed shell bitts, Figure 50, are inset into ships' hulls well above the waterline. These bitts are used to moor lighterage or harbor craft alongside. They also assist in mooring at facilities. The NAVSEA shell bitt has a total working capacity of 92 kips (4.27 E5 newtons) with two lines of 46 kips maximum tension each.

7.6 Exterior Shell Bitts. Aircraft carriers have exterior shell bitts, Drawing No. 600-6601101, that are statically proof loaded to 184 kips (8.2 E5 newtons). This proof load is applied 11 inches (280 mm) above the base. This testing is described in the Newport News Shipbuilding testing report for USS HARRY S TRUMAN Bitts, Chocks and Mooring Rings.

7.7 Chocks. There are many types of chocks, such as closed chocks, Panama chocks, roller chocks, and mooring rings. Closed clocks are often used and characteristics of these fittings are shown in Table 52.

7.8 Allowable Hull Pressures. As a ship berths or when it is moored, forces may be exerted by structures, such as fenders, camels, and dolphins, on the ship hull. NFESC TR-6015-OCN, Foam-Filled Fender Design to Prevent Hull Damage provides a rational design criteria to prevent yielding of vessel hull plating.

7.9 Sources of Information for Ships' Mooring Equipment. Additional information is available from the Naval Sea Systems Command (NAVSEA 03P), Military Sealift Command (MSC), and the U.S. Coast Guard (USCG). Table 53 provides a list of selected referenced materials.

Table 50
Types of Ship Based Mooring Equipment*

EQUIPMENT	DESCRIPTION
Drag embedment anchors	One or more anchors required. See Section 7 for anchor information.
Anchor chain	Stud link grade 3 chain (see Section 6.4) is used.
Anchor windlass/wildcat and associated equipment	Equipment for deploying and recovering the anchor(s), including the windlass(s), hawse pipe(s), chain stoppers, chain locker, and other equipment.
Bitts	Bitts for securing mooring lines.
Chocks, mooring rings and fairleads	Fittings through which mooring lines are passed.
Padeyes	Padeyes are provided for specialized mooring requirements and towing.
Mooring lines	Synthetic lines for mooring at piers, wharfs, and other structures. See Section 6.7 for information.
Capstans	Mechanical winches used to aid in handling mooring lines.
Wire ropes	Wire rope is sometimes used for mooring tension members.
Fenders	Marine fenders, as discussed in Section 6.8, are sometimes carried on board.
Winches	Winches of various types can support mooring operations. Some ships use constant tension winches with wire rope automatically paid out/pulled in to adjust to water level changes and varying environmental conditions. Fixed-length synthetic spring lines are used in pier/wharf moorings that employ constant tension winches to keep the ship from ‘walking’ down the pier.
Other	Various specialized equipment is carried to meet needs (such as submarines).

*See NAVSEASYSCOM Naval Ships’ Technical Manual for additional information and Section 3.1 for design criteria.

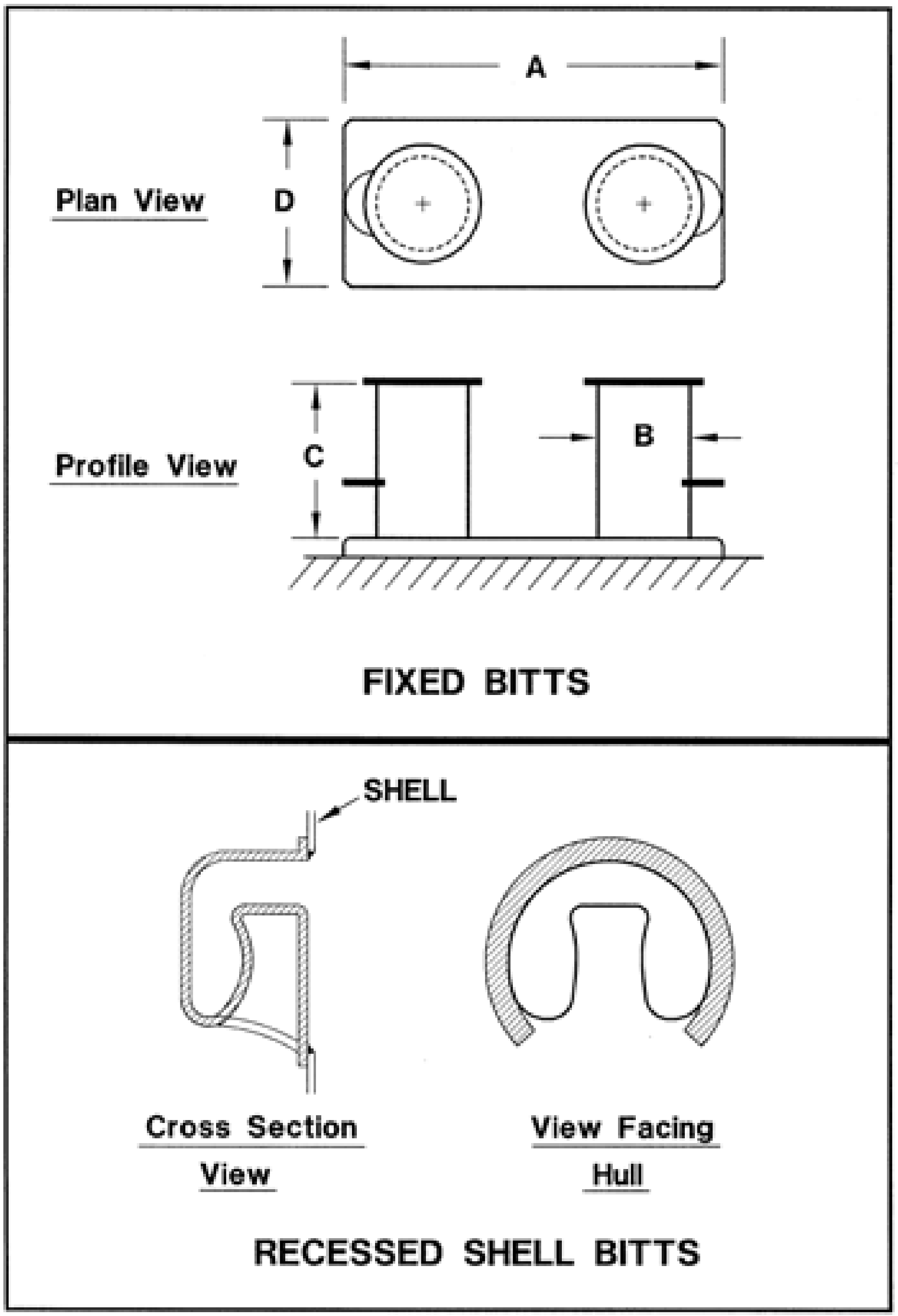


Figure 49
Fixed and Recessed Shell Bitts

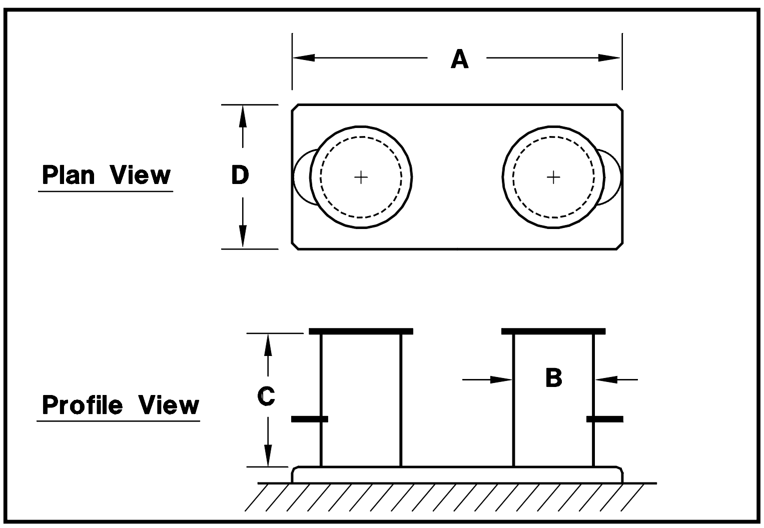
Table 51
Fixed Ships' Bitts (minimum strength requirements)

NAVSEA FIXED BITTS (after 804-1843362 REV B OF 1987)

NOMINAL SIZE (inches)	4	8	10	12	14	18
MAX. LINE CIR. (inches)	3	5	6.5	8	10	12
MAX. LINE DIA. (inches)	1.0	1.6	2.1	2.5	3.2	3.8
MAX. MOMENT (lbf-in x 1000)	134	475	1046	1901	3601	6672
MAX. CAPACITY (lbf x 1000)*	26.8	73.08	123.1	181	277	417
A - BASE LENGTH (inches)	16.5	28.63	36.75	44.25	52.5	64
B - BARREL DIA. (inches)	4.5	8.625	10.75	12.75	14	18
C - BARREL HT. (inches)	10	13	17	21	26	32
D - BASE WIDTH (inches)	7.5	13.63	17.25	20.25	22.5	28

MAX. LINE CIR. (mm)	76	127	165	203	254	305
MAX. CAPACITY (newton x 100000)*	1.19	3.25	5.47	8.05	12.32	18.55
A - BASE LENGTH (inches)	419	727	933	1124	1334	1626
B - BARREL DIA. (inches)	114	219	273	324	356	457
C - BARREL HT. (inches)	254	330	432	533	660	813
D - BASE WIDTH (inches)	191	346	438	514	572	711

* force applied at half the barrel height



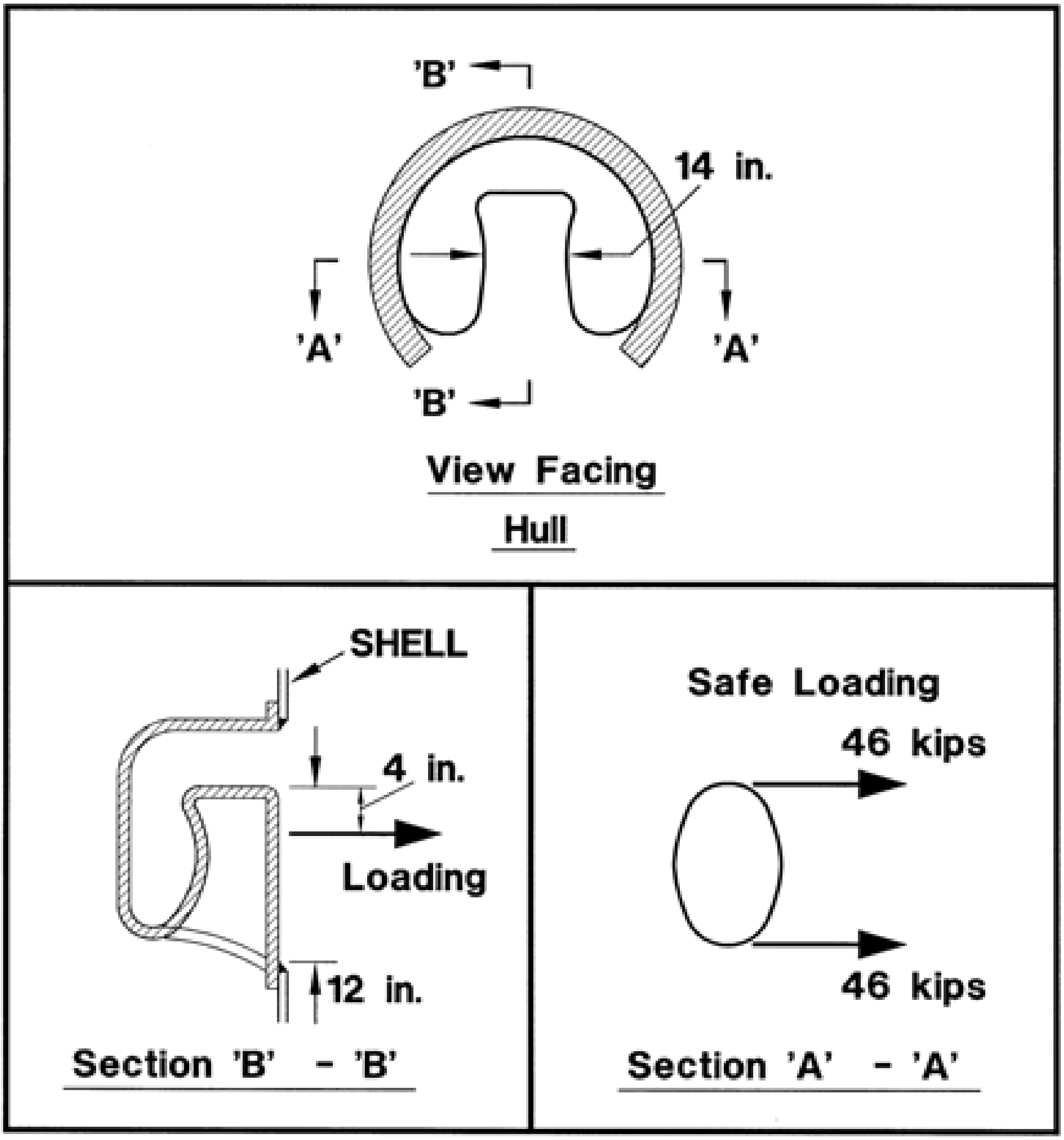
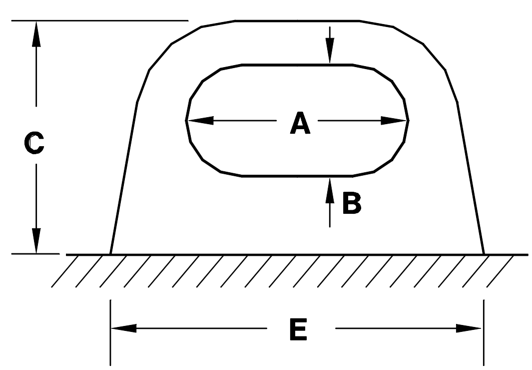


Figure 50
Recessed Shell Bitt
(minimum strength requirements)

Table 52
Closed Chocks (minimum strength requirements)

NAVSEA CLOSED CHOCKS (from Drawing 804-1843363)

CHOCK SIZE (inches)	6	10	13	16	20	24
MAX. LINE CIR. (inches)	3	5	6.5	8	10	12
LINE BREAK (lbf x 1000)	26.8	73	123	181	277	417
A - HOLE WIDTH (inches)	6	10	13	16	20	24
B - HOLE HEIGHT (inches)	3	5	6.5	8	10	12
C - HEIGHT (inches)	8.5	11.25	13.88	16.75	25.75	25.25
D - BASE THICKNESS (inches)	5.25	6.5	7.5	9	16	13.5
E - LENGTH (inches)	13	19	23	28	38.75	40
MAX. LINE CIR. (mm)	76	127	165	203	254	305
LINE BREAK (newton x 100000)	1.19	3.25	5.47	8.05	12.32	18.55
A - HOLE WIDTH (mm)	152	254	330	406	508	610
B - HOLE HEIGHT (mm)	76	127	165	203	254	305
C - HEIGHT (mm)	216	286	352	425	654	641
D - BASE THICKNESS (mm)	133	165	191	229	406	343
E - LENGTH (mm)	330	483	584	711	984	1016



Note: D = thickness at the base

Table 53
Sources of Information for Ships' Mooring Equipment

ITEM	SOURCE
Information on existing U.S. Navy ships, drawings, and mooring hardware	NAVFAC Ships Database
Chocks	NAVSEA Drawing No. 804-1843363 & S1201-921623 (Roller Chock)
Panama chocks	NAVSEA Drawing No. 804-1843363
Fixed bitts	NAVSEA Drawing No. 804-1843362
Recessed shell bitts	NAVSEA Drawing No. 805-1841948
Exterior shell bitts	Newport News Shipbuilding Drawing No. 600-6601101
Cleats	NAVSEA Drawing No. 804-2276338
Capstans/gypsy heads	NAVSEA Drawing No. S260-860303 & MIL-C-17944
Hawser reels	NAVSEA Drawing No. S2604-921841 & 42
Mooring lines	Cordage Institute Technical Manual

Section 8: EXAMPLE PROBLEMS

8.1 Introduction. The design of mooring systems is illustrated through the use of several examples in this section. The emphasis of this handbook is on statics, so static results are shown. However, the marine environment can be dynamic, so dynamic effects are illustrated in the examples.

8.2 Single Point Mooring - Basic Approach. Design of single point fleet moorings (SPMs) is illustrated here.

Let us first assume that the wind is coming from a specified direction and has stationary statistical properties. The current speed and direction are constant. In this case there are three common types of ship behavior, shown in Figure 51, that a vessel at a single point mooring can have:

a) Quasi-static. In this case the ship remains in approximately a fixed position with the forces and moments acting on the ship in balance. For quasi-static behavior, the tension in the attachment from the ship to mooring will remain approximately constant. Quasi-static analyses can be used for design in this case.

b) Fishtailing. In this case the ship undergoes significant surge, sway, and yaw with the ship center of gravity following a butterfly-shaped pattern. The mooring can experience high dynamic loads, even though the wind and current are constant.

c) Horsing. In this case the ship undergoes significant surge and sway with the ship center of gravity following a U-shaped pattern. The mooring can experience high dynamic loads.

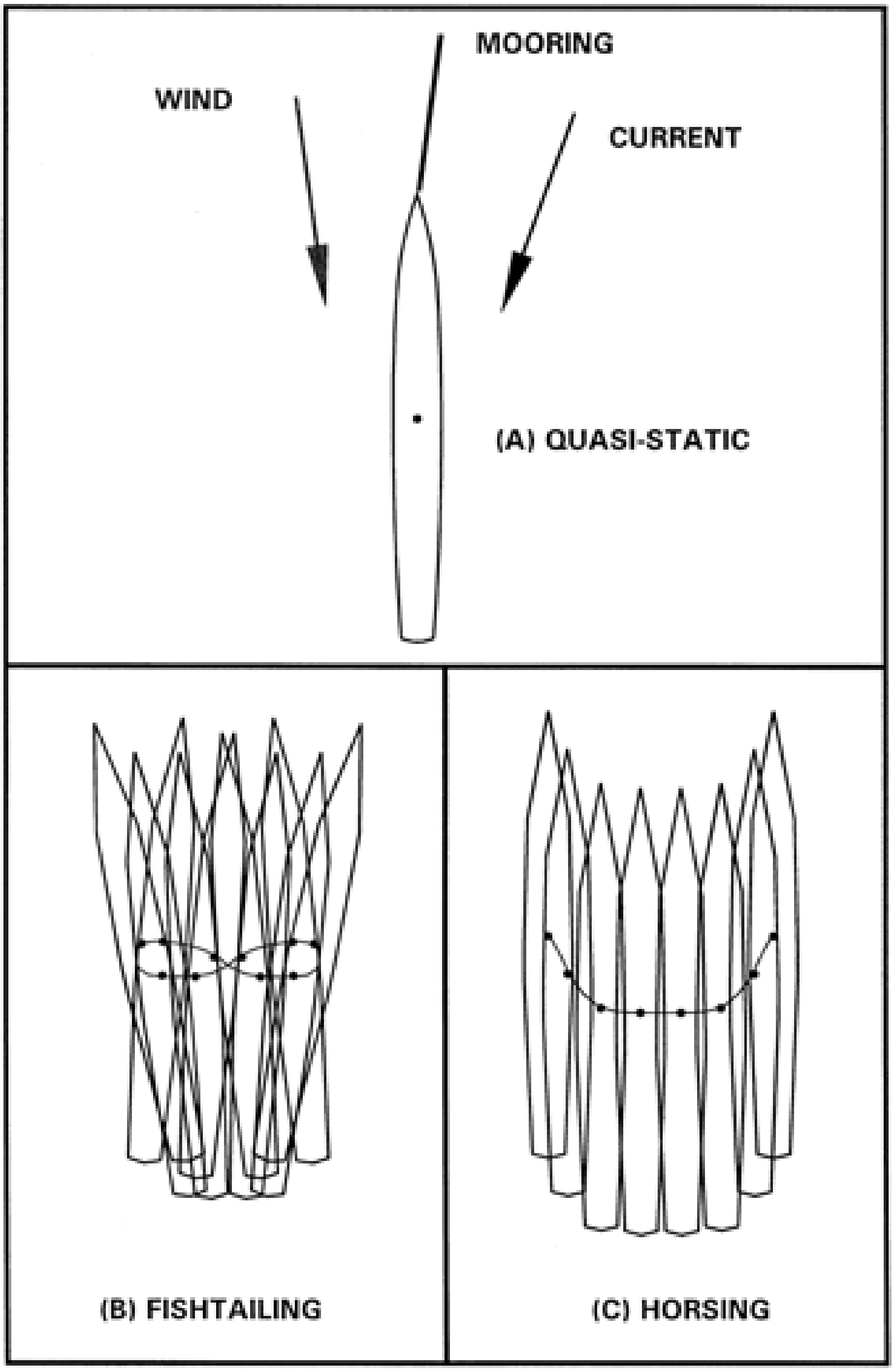


Figure 51
Some Types of Behavior of Ships at Single Point Moorings

These cases show that the type of behavior of a given ship at a given single point mooring in a given environment can be very complex (Wichers, 1988), even though the wind and current are steady. It is recommended that a dynamic stability analysis first be conducted (Wichers, 1988) at the early stages of single point mooring design. Then the type of analysis required can be determined. The results from this analysis will suggest what type of method should be used to design a single point mooring. These methods are complex and beyond the scope of this handbook. Behavior of single point moorings is illustrated by example.

8.2.1 Background for Example. In this example two moorings were designed and installed. The original designs were based on quasi-static methods. Ships moored to these buoys broke their mooring hawsers when a wind gust front struck the ships. In this example, the design and hawser failures are reviewed. The effects of wind dynamics on a single point mooring are illustrated.

8.2.2 Ship. A single 2nd LT JOHN P. BOBO (T-AK 3008) class ship was moored at each of two fleet mooring buoys. Table 54 gives basic characteristics of the ships.

Table 54
2nd LT JOHN P BOBO Parameters (Fully Loaded)

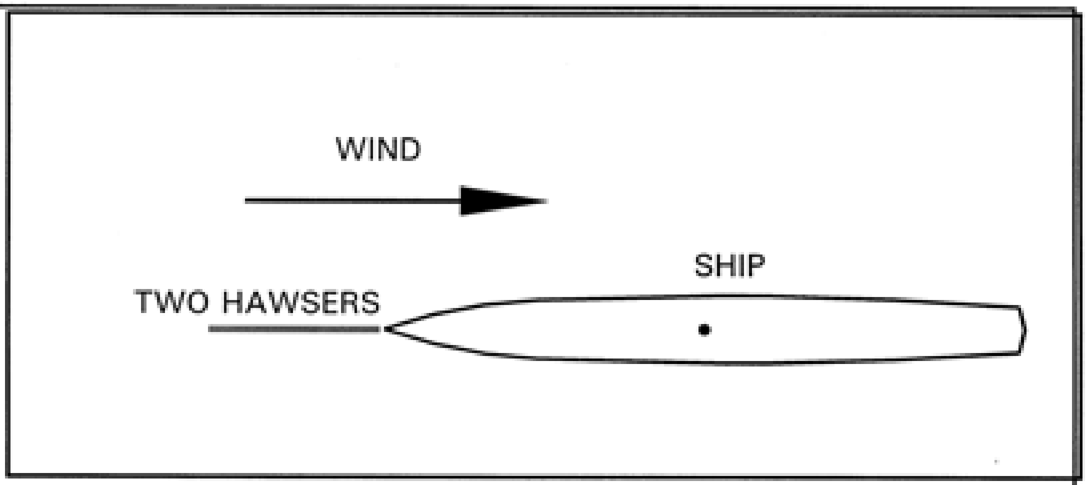
PARAMETER	DESIGN BASIS (SI units)	DESIGN BASIS (English units)
Length		
Overall	193.2 m	633.76 ft
At Waterline	187.3 m	614.58 ft
Between Perpendiculars	187.3 m	614.58 ft
Beam @ Waterline	9.80	32.15 ft
Draft	9.75 m	32 ft
Displacement	4.69E7 kg	46111 long tons
Line Size (2 nylon hawsers)	-	12 inches

8.2.3 Forces/Moments. In this case the design wind speed is 45 knots (23 m/s). Currents, waves, and tidal effects are neglected for these 'fair weather' moorings. The bow-on ship wind drag coefficient is taken as the value given for normal ships of 0.7, plus 0.1 is added for a clutter deck to give a drag coefficient of 0.8. Methods in Section 4 are used to compute the forces and moments on the ship. The computed bow-on wind force is 68.6 kips (3.0 E5 newtons) for 45-knot (23-m/s) winds, as shown in Figure 52.

8.2.4 Quasi-Static Design. Quasi-static design procedures place the ship parallel to the wind for this example, because in this position the forces and moments on the ship are balanced out. Two mooring hawsers were specified for this design. Extra factor of safety was specified for the two 12-inch nylon mooring hawsers, which had a new wet breaking strength of 406 kips (1.8 E6 newtons), to account for poor load sharing between the two hawsers.

8.2.5 Mooring Hawser Break. The ships were moored and faced into 15-knot winds. The weather was unsettled, due to two nearby typhoons, so the ships had their engines in idle. A wind gust front struck very quickly with a wind speed increase from 15 to 50 knots. As the wind speed increased, the wind direction changed 90 degrees, so the higher wind speed hit the ships broadside. The predicted peak dynamic tension on the mooring hawsers was 1140 kips (5.07 E6 newtons), (Seelig and Headland, 1998). Figure 53 is a simulation predicting the dynamic behavior of the moored ship and hawser tension. In this case, the mooring hawsers broke and the predicted factor of safety dropped to less than 1. In this event, the peak dynamic tension on the mooring hawser is predicted to be 13.5 times the bow-on wind force for 50-knot (25.7-m/s) winds.

This example shows that single point moorings can be susceptible to dynamics effects, such as those caused by wind gust fronts or other effects.



CONDITION	BOW-ON SHIP WIND LOAD	F.S. FOR 1 HAWSER	F.S. FOR 2 HAWSERS
45-KNOT WIND	68.5 KIPS	5.9	11.9
50-KNOT WIND	84.5 KIPS	4.8	9.6

Figure 52
Example Single Point Mooring

Figure 53
Example Mooring Failure Due to a Wind Gust Front

8.3 Fixed Mooring - Basic Approach. Development of a design concept for a fixed mooring, a mooring that includes both tension and compression members, is illustrated here.

8.3.1 Background. Several new aircraft carrier berthing wharf facilities are being programmed. Users expressed concerns regarding the possibility of excessive ship movement. Wind is the major environmental parameter of concern. Assume the proposed sites have small tidal ranges and tidal currents.

8.3.2 Goal. Develop a concept to moor USS NIMITZ (CVN-68) class ships at newly constructed wharves. Assume the Mooring Service Type is II and the design wind speed is 75 mph (33.5 m/s).

8.3.3 Ship. Fully loaded USS NIMITZ (CVN-68) class ships are used in this example. Table 55 gives some ship parameters. Additional information is found in the Naval Facilities Engineering Command (NAVFAC) Ships Characteristics Database.

Table 55
CVN-68 Criteria (Fully Loaded)

PARAMETER	DESIGN BASIS (SI units)	DESIGN BASIS (English units)
Length		
Overall	249.9 m	115 ft
At Waterline	233.2 m	1056 ft
Between Perpendiculars	237.1 m	1040 ft
Beam @ Waterline	32.3	134 ft
Draft	11.55 m	37.91 ft
Displacement	9.644E7 kg	94917 long tons
Bitt Size	-	12 inches
Line Size (nylon)	-	8 and 9 inches

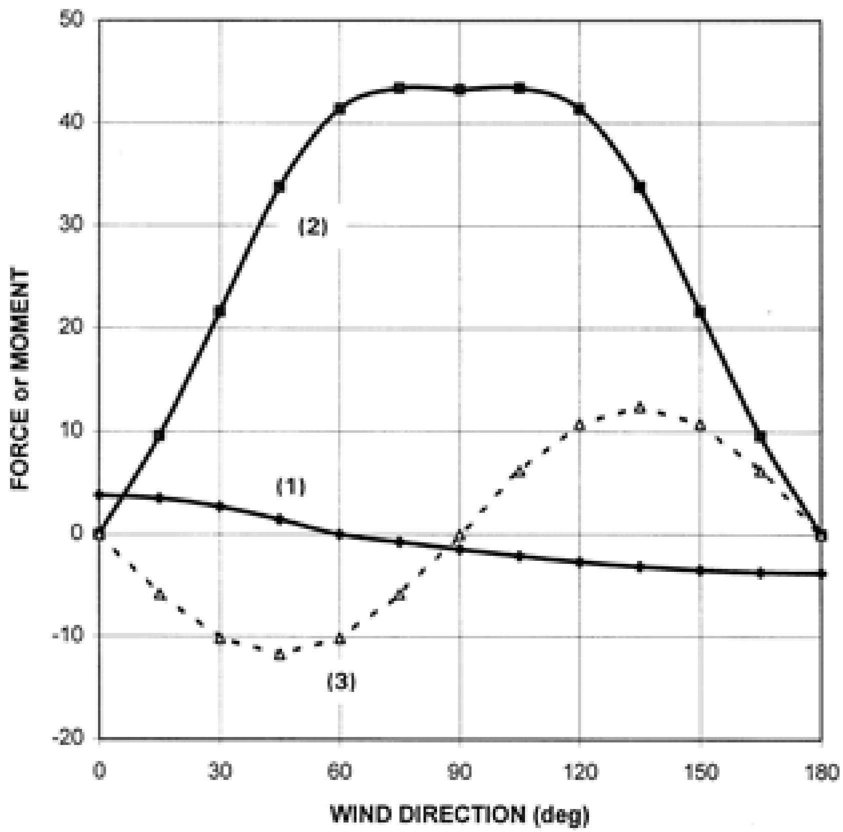
8.3.4 Forces/Moments. Methods in Section 4 are used to compute the forces and moments on the ship. These values are summarized in Figure 54.

8.3.5 Definitions. In this example we define a global coordinate system with "X" parallel to the wharf, as shown in Figure 55. Then "Y" is a distance perpendicular to the wharf in a seaward direction and "Z" is a vertical distance. Let "Pt 2" be the ship chock coordinate and "Pt 1" be the pier fitting. A spring line is defined as a line whose angle in the horizontal plane is less than 45 degrees and a breasting line whose angle in the horizontal plane is greater than or equal to 45 degrees, as shown in Figure 55.

8.3.6 Preliminary Analysis. The first step for fixed mooring design is to analyze the mooring requirements for the optimum ideal mooring shown in Figure 56. Analyzing the optimum ideal arrangement is recommended because: (1) calculations can be performed by hand and; (2) this simple arrangement can be used as a standard to evaluate other fixed mooring configurations (NFESC TR-6005-OCN, EMOOR - A Quick and Easy Method for Evaluating Ship Mooring at Piers and Wharves.

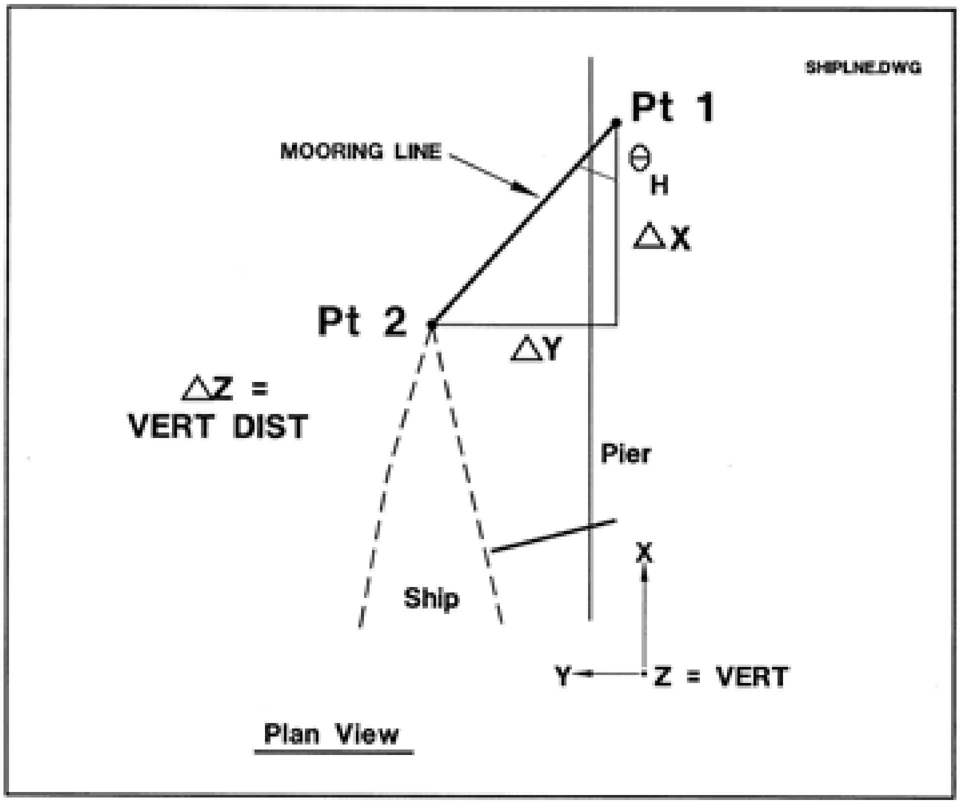
The optimum ideal mooring shown in Figure 55 consists of two spring lines, Lines 1 and 4, which are assumed to resist longitudinal forces. There are two breast lines, Lines 2 and 3, which are assumed to resist lateral forces and moments for winds with directions from 0 to 180 degrees. Fenders are not shown. All lines are assumed to be parallel to the water surface in the ideal mooring.

A free body diagram is made of the optimum ideal mooring for a loaded CVN-68 in 75-mph (33.5-m/s) winds. It is found that the sum of the working mooring capacity required for Lines 1 and 4 is 174 kips (7.7 E5 newtons) and the sum of the working mooring capacity required for Lines 2 and 3 is 1069 kips (4.76 E5 newtons), as shown in Figure 57. Note that no working line capacity is required in the 'Z' direction, because the ship's buoyancy supports the ship. The sum of all the mooring line working capacities for the optimum ideal mooring is 1243 kips (5.53 E6 newtons).



PARAMETER	CURVE	GRAPH UNITS	MAX. VALUE
F_{xw}	(1)	E5 N	84.6 kips
F_{yw}	(2)	E5 N	975.5 kips
M_{xyw}	(3)	E7 N-m	91421 kip-ft

Figure 54
Wind Forces and Moments on a Single Loaded
CVN-68 for a 75-mph (33.5-m/s) Wind



DEFINITIONS:

$$\theta_H = \tan^{-1} \left| \frac{\Delta Y}{\Delta X} \right|$$

$$\theta_V = \tan^{-1} \left| \frac{\Delta Z}{\Delta Y} \right|$$

IF $|\theta_H| < 45$ deg → SPRING LINE

IF $|\theta_H| \geq 45$ deg → BREASTING LINE

Figure 55
Definitions

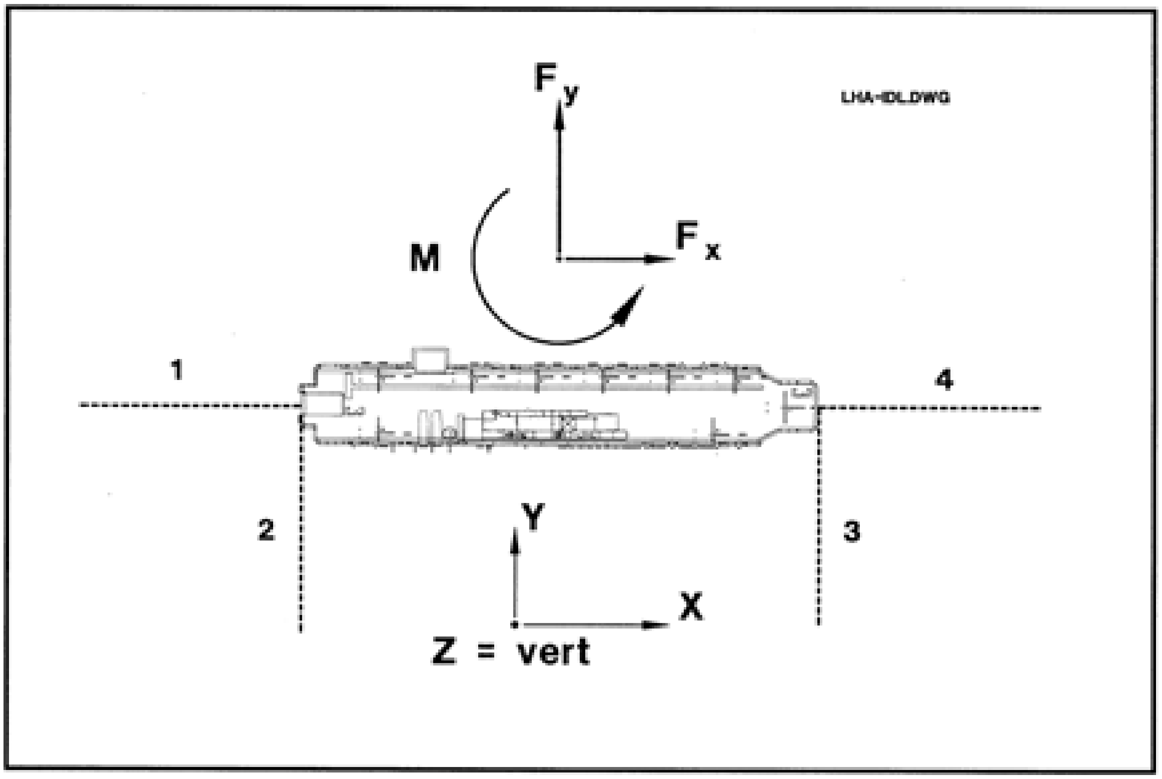


Figure 56
Optimum Ideal Mooring
(Lines are parallel to the water surface and breasting lines are spaced one-half ship's length from midships)

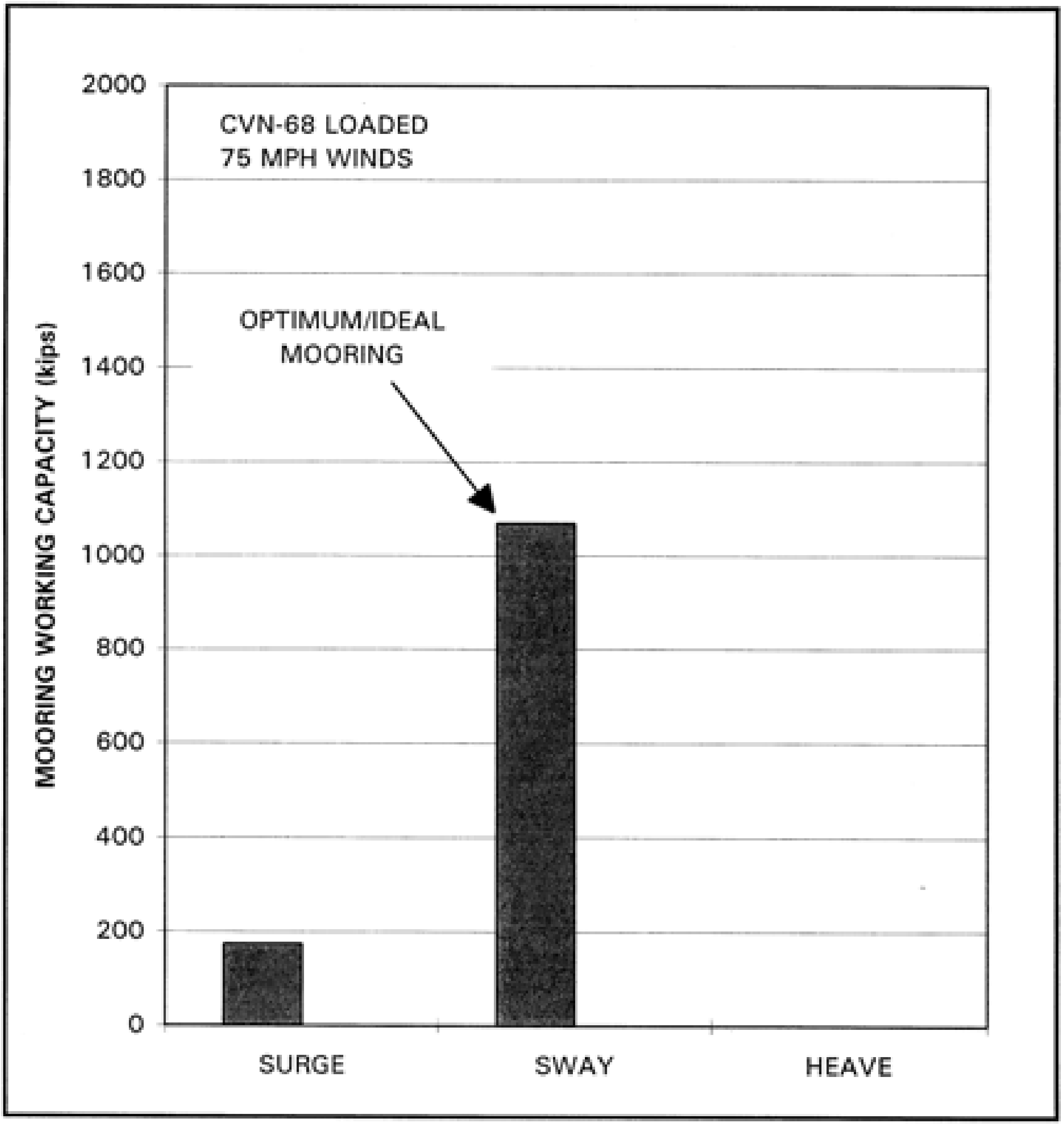


Figure 57
Required Mooring Capacity Using the
Optimum Ideal Mooring

8.3.7 Wharf Mooring Concept. Camels and fenders are located between the wharf and ship to offset the ship in this design. Also, the wharf breasting line bollards are set back from the face of the wharf, so that the vertical angles of the breasting lines are approximately 10 degrees. Figure 58, from a study of a number of ship moorings at piers and wharves (NFESC TR-6005-OCN) is used to estimate that a mooring system using synthetic lines will have an efficiency of approximately 0.67 for the case of breasting lines with a 10-degree vertical angle. The estimated total required working mooring line capacity is the working line capacity of the optimum ideal mooring divided by the efficiency. In this case, the estimated working line capacity required is 1243 kips/0.67 or approximately 1855 kips.

For extra safety, the selected concept 'Model 2' is given 11 mooring lines of three parts each of aramid mooring line, as shown in Figure 59. A single part of line is taken as having a break strength of 215 kips (9.2 E5 newtons). These lines have a combined working strength of 11*3*215/3 = 2365 kips with a factor of safety of 3. These lines are selected to provide extra safety. A component analysis, Figure 60, suggests that this mooring concept has adequate mooring line capacity in the surge and sway directions.

Quasi-static analyses are performed by computer using a fixed mooring software program (W.S. Atkins Engineering Sciences, AQWA Reference Manual). Analyses are performed for various wind directions around the wind rose. Results show that the mooring line factors of safety are larger than the required minimum of 3 (i.e., line tensions divided by the new line break strength is less than 0.33), as shown in Figure 61. This extra safety is justified, because the ship is nuclear powered. In this concept the spring lines are especially safe with a factor of safety of about 10. These analyses show ship motions of approximately 1 foot (0.3 meter) under the action of the 75-mph (33.5-m/s) design winds.

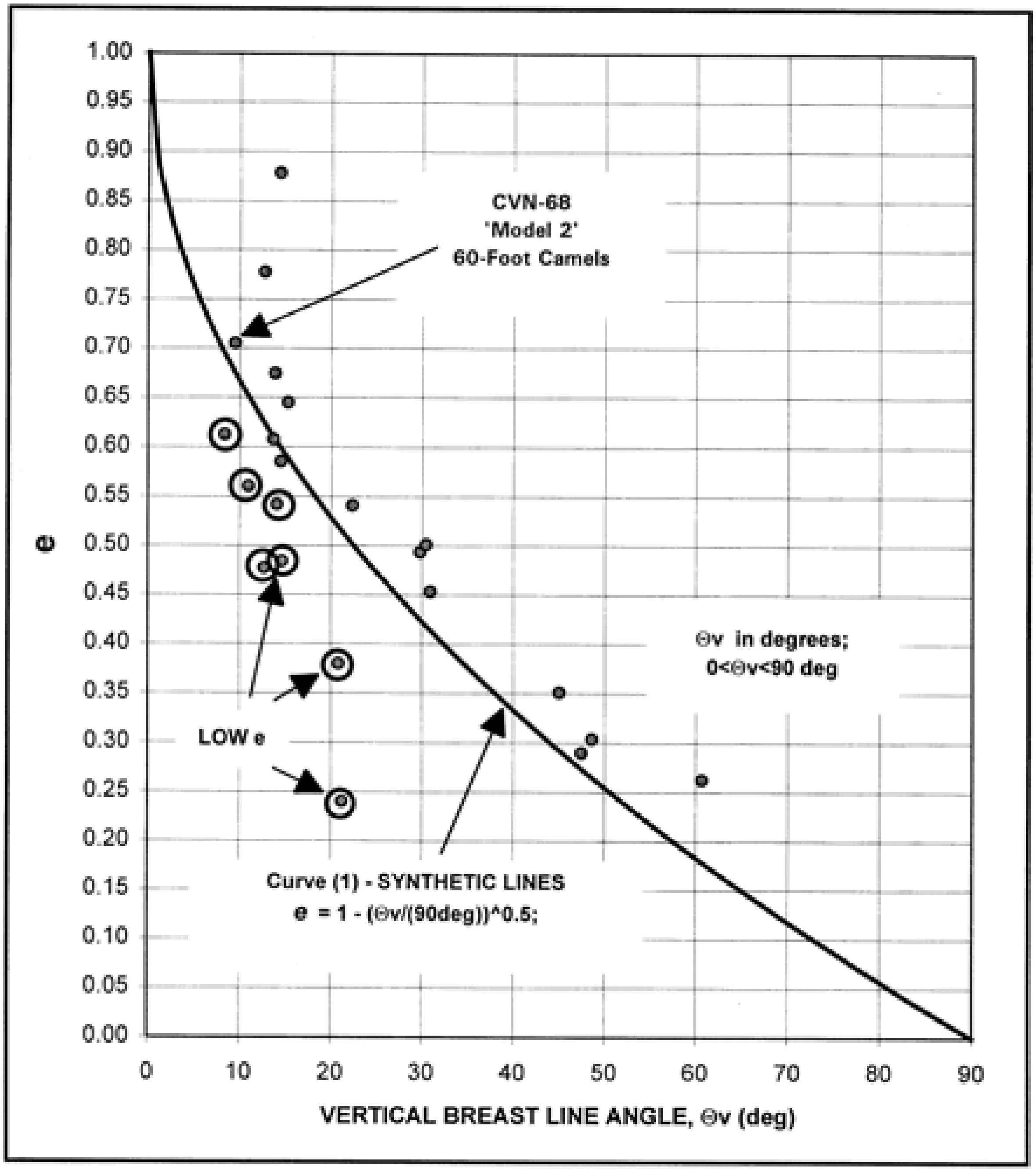


Figure 58
Efficiency of Ship Moorings Using Synthetic
Lines at Piers and Wharves (after NFESC TR-6005-OCN)

Figure 59
CVN-68 Wharf Mooring Concept
('Model 2')

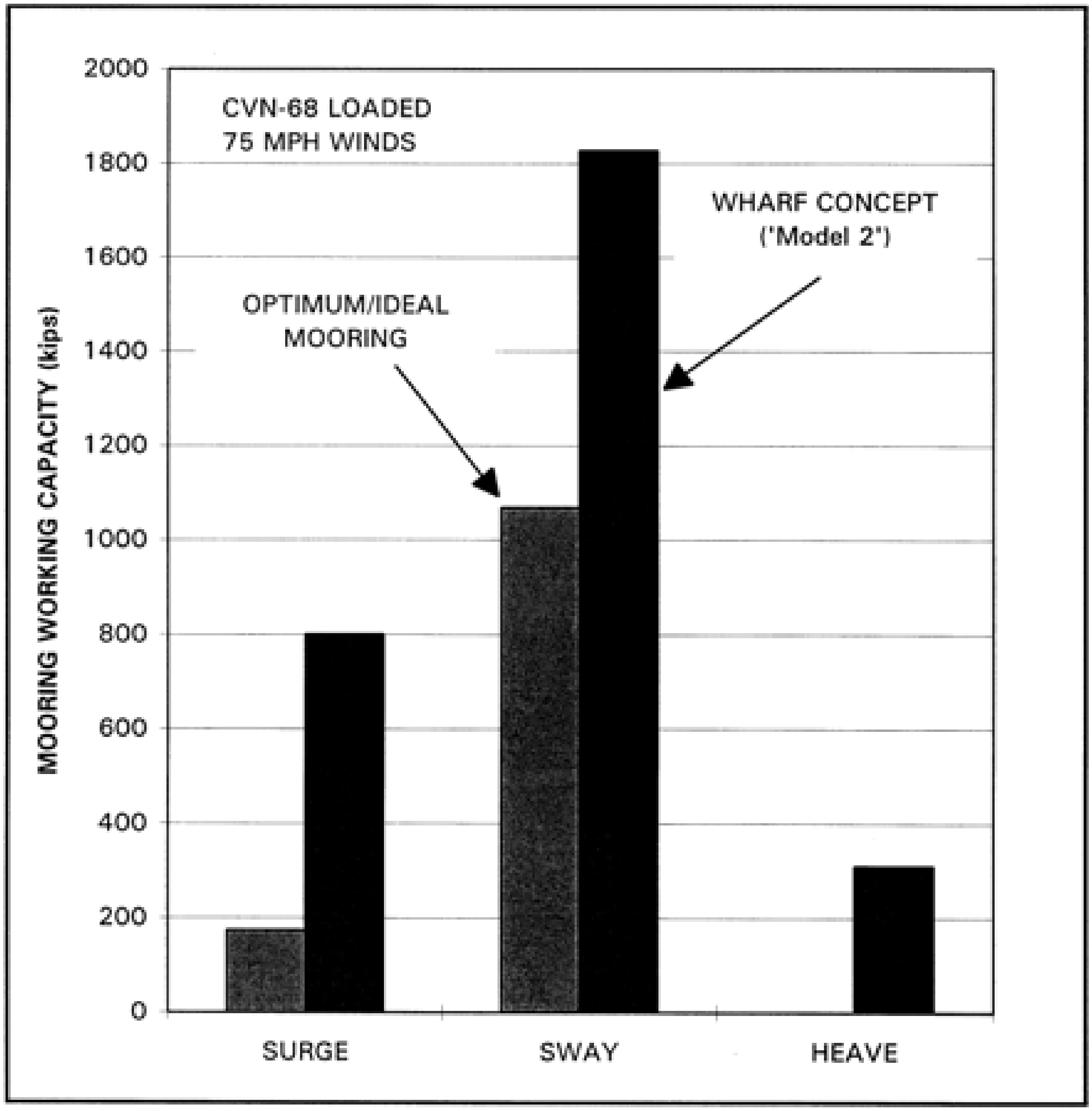


Figure 60
Component Analysis of Mooring Working Capacity

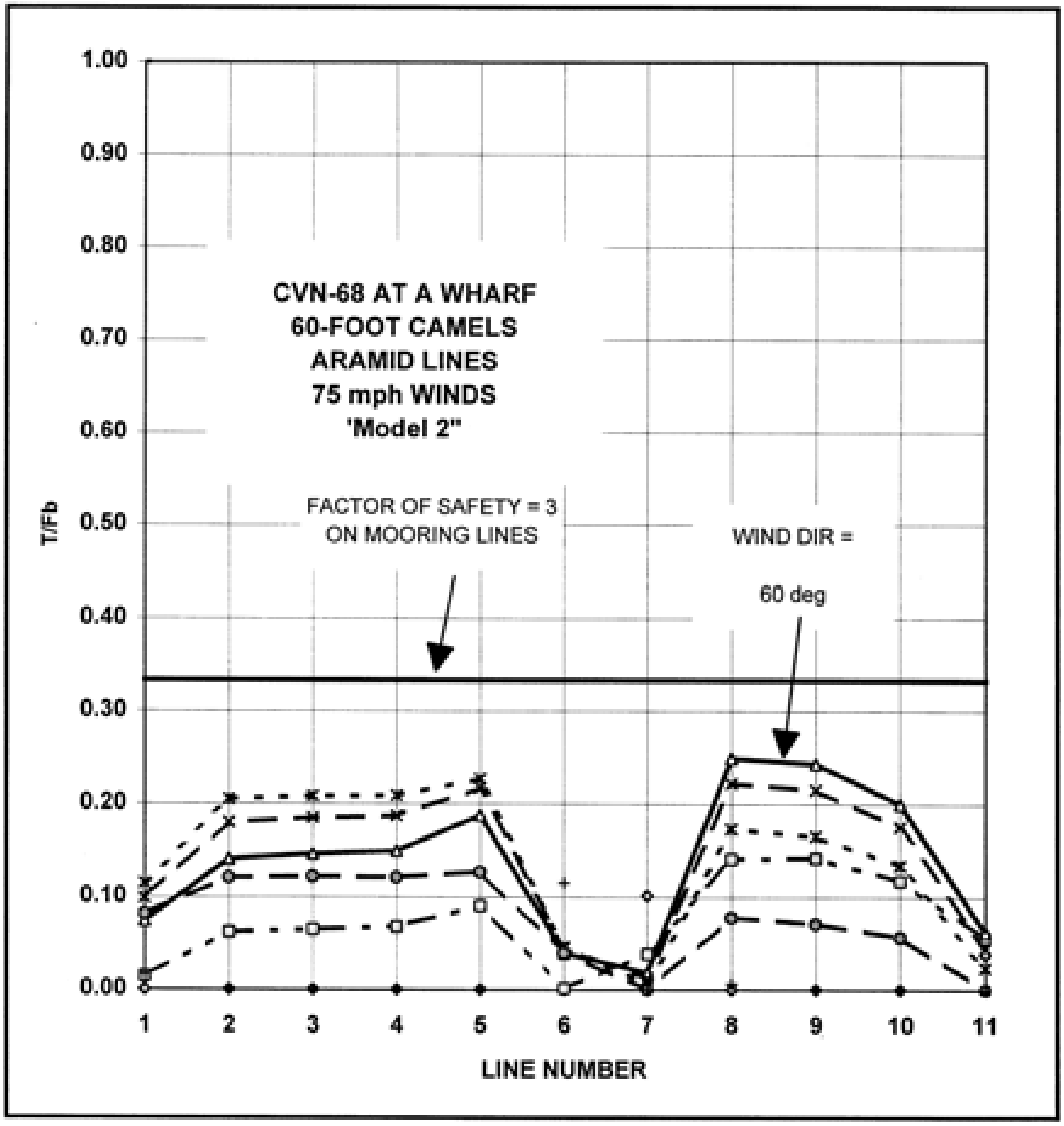


Figure 61
Mooring Line Tensions for a CVN-68 Moored at a Wharf
With 75 mph (33.5 m/s) Winds ('Model 2')

Further quasi-static analyses show this concept is safe in up to 87-mph (38.9-m/s) winds with a factor of safety of 3 or more on all the mooring lines. The computed mooring efficiency for 'Model 2' at this limiting safe wind speed is 0.705, which is slightly higher than the estimated value of 0.67, as shown in Figure 58.

These preliminary calculations show that this fixed mooring concept could safely secure the ship. Figure 62 illustrates the mooring concept in perspective view. Further information on this example is provided in NFESC TR-6004-OCN, Wind Effects on Moored Aircraft Carriers.

8.4 Spread Mooring - Basic Approach. Design of a spread mooring for a nest of ships is illustrated in this section.

8.4.1 Background for Example. SPRUANCE class (DD 963) destroyers are scheduled for inactivation and a mooring is required to secure four of these vessels (NFESC SSR-6119-OCN, D-8 Mooring Upgrade Design Report). These ships are inactive and cannot go out to sea, so the mooring must safely secure the vessels in a hurricane using Mooring Service Type IV design criteria. At this location, wind is the predominant environmental factor of concern. At this site the tidal range and tidal current are small. Soil conditions at the site consist of an upper soft silty layer between 50 to 80 feet in depth (15 to 24 meters) over a stiff clay underneath. Water depth at the site ranges between 31 to 35 feet (9.4 to 10.7 meters) MLLW.

8.4.2 Goal. Develop a concept to moor four DD 963 class destroyers in a spread mooring. Use Mooring Service Type IV criteria and a design wind speed of 78.3 mph (68 knots or 35 m/s).

8.4.3 Ship. The ships are assumed to be at one-third stores/cargo/ballast condition, since DD-963 vessels are unstable in the light condition. Table 56 gives some ship parameters. Additional information is found in the NAVFAC Ships Characteristics Database.

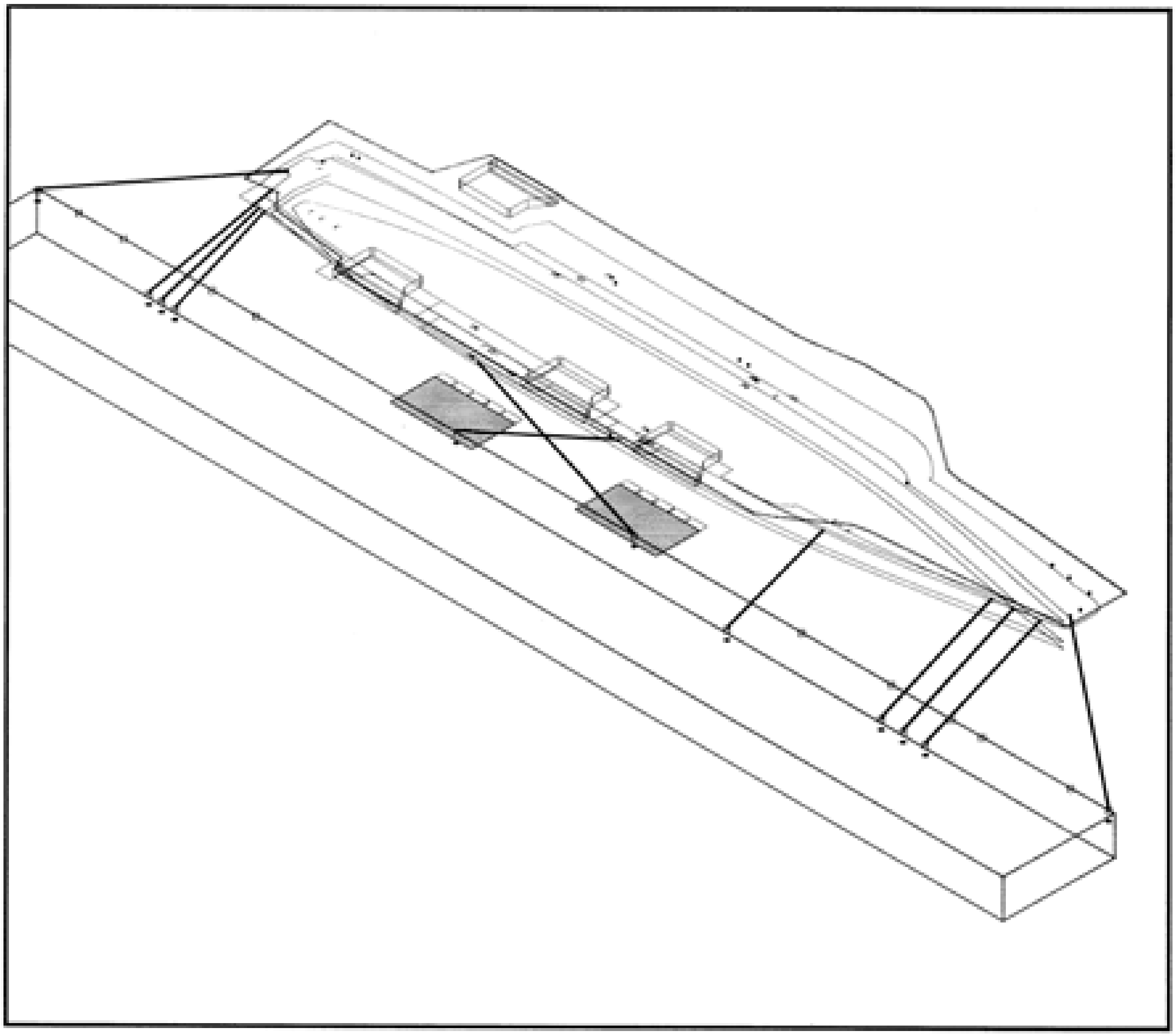


Figure 62
Aircraft Carrier Mooring Concept
(perspective view)

Table 56
DD 963 Criteria (1/3 Stores)

PARAMETER	DESIGN BASIS (SI units)	DESIGN BASIS (English units)
Length Overall At Waterline	171.9 m 161.2 m	564 ft 529 ft
Beam @ Waterline	16.8 m	55 ft
Average Draft Draft at Sonar Dome	6.5 m 8.8 m	21.2 ft 29 ft
Displacement	9.07E6 kg	8928 long tons
Chock Height From Baseline	10.7m stern 15.9m bow	35 ft 52 ft

8.4.4 Forces/Moments. Methods in Section 4, as well as data in Appendix A, are used to compute the forces and moments on the ships. These values are summarized in Figure 63. Wind angles are based on the local coordinate system for a ship shown in Figure 27.

Note that wind tunnel model tests show that there is significant sheltering in the transverse direction of downwind ships in this nest of identical ships, as shown in Appendix A. However, there is little wind sheltering in the longitudinal direction. Table 57 summarizes the environmental force calculations used for this example.

Table 57
Environmental Forces

Condition	Load (Metric)	Load (US)	Comments
Single DD 963	1663.8 kN 257 kN 35972 m-kN 104.2 kN 2.5 kN 1216 m-kN	374 kips 57.82 kips 26531 ft-kips 23.4 kips 0.56 kips 863.1 ft-kips	Transverse Wind Longitudinal Wind Wind-Yaw Moment Transverse Current Longitudinal Current Current Yaw Moment
4 ea DD 963	1989.9 kN 1028.7 kN 64595 m-kN 190.6 kN 9.8 kN 3342 m-kN	447.4 kips 231.3 kips 47643 ft-kips 42.8 kips 2.2 kips 2372.7 ft-kips	Transverse Wind Longitudinal Wind Wind-Yaw Moment Transverse Current Longitudinal Current Current Yaw Moment

8.4.5 Anchor Locations. Driven-plate anchors are selected as a cost-effective method to safely moor the nest of ships. The soils at the site are soft harbor mud of depths between 50 to 80 feet (15 to 24 meters), so a chain catenary will form below the seafloor (in the mud) as well as it the water column, as illustrated in Figure 47 (Section 6.10). A horizontal distance of 100 feet (30 meters) between the anchor location and the chain daylight location (point where the anchor leg chain exits the seafloor) is estimated based on Chain Soil Analysis Program (CSAP) modeling of the chain catenary in the soil and in the water column.

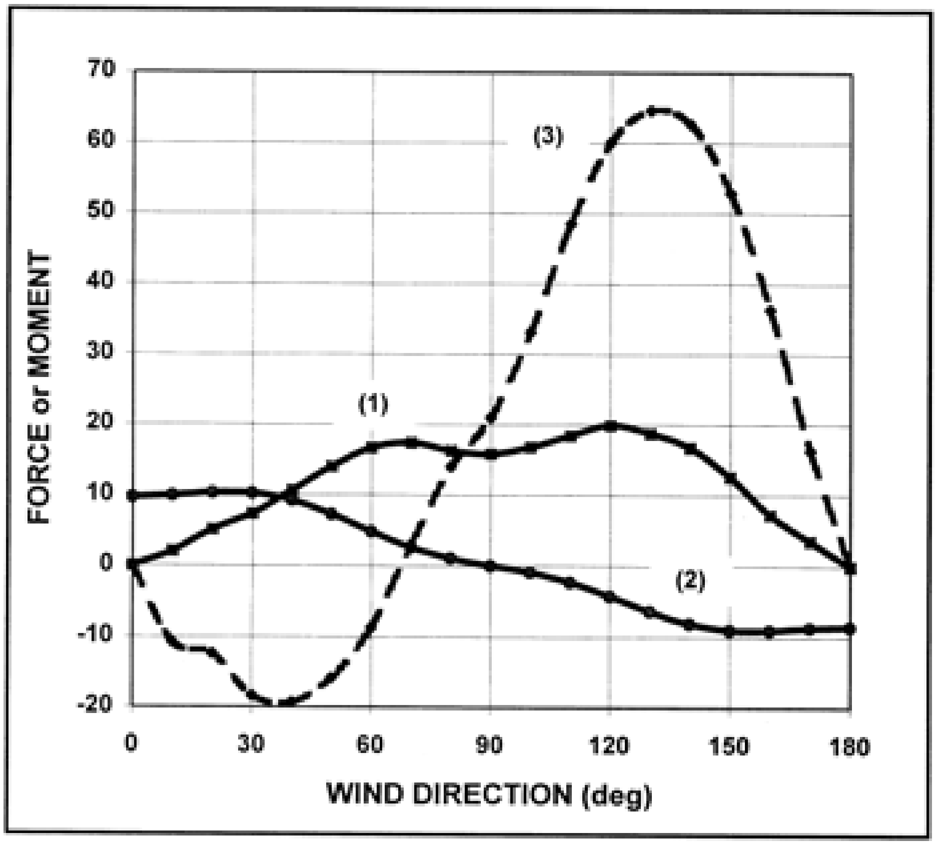


Figure 63
Wind Forces and Moments on a Nest of Four DD 963 Class Vessels for a Wind Speed of 78 mph (35 m/s)

CURVE		GRAPH LIMITS	MAX. VALUE
(1)	Transverse Wind Force	E5 N	447.4 kips
(2)	Longitudinal Wind Force	E5 N	231.3 kips
(3)	Yaw Moment	E6 N	47643 kip-ft

To ensure the mooring legs are efficient in resisting the imposed environmental horizontal forces, a target horizontal distance of 170 feet (52 meters) is chosen between the predicted daylight location (where the chain exits the soil) and the attachment point on the ship for each of the mooring legs. Therefore, anchor locations are established at a horizontal distance of 270 feet (82 meters) away from the vessel.

8.4.6 Definitions. In this example, a local ship and a global coordinate system are defined. The local ship coordinate system is used to determine environmental loads at the various wind and current attack angles, as shown in Figure 27, with the origin of the "Z" direction at the vessel keel. A global coordinate system for the entire spread mooring design is selected with the point (0,0,0) defined to be at a specific location. For this example, the origin is selected to be in the middle of the vessel nest and 164 feet (50 meters) aft of the stern of the vessels. The origin for the "Z" direction in the global coordinate system is at the waterline. This global coordinate system is used by the various analysis programs to define the "chain daylight" locations and the location of the vessel center of gravity within the spread mooring footprint.

8.4.7 Number of Mooring Legs. It is estimated that eight 2.75-inch chain mooring legs are required, based on the safe working load the chain (289 kips or 1.29 E6 newtons) and the applied environmental forces and moments on the nest of ships. Four legs are situated on both sides of the nest and each mooring leg is angled to be effective in resisting the longitudinal wind forces, as well as lateral wind forces and moments, from winds approaching at angles other than broadside. Legs are also placed toward the ends of the nest to be effective in resisting the yaw moment. To help control ship motions, two 20-kip (9000-kg) sinkers are placed on each mooring leg approximately midway between the vessel attachment point and the predicted chain daylight location. A schematic of the planned spread mooring arrangement is shown in Figure 64.

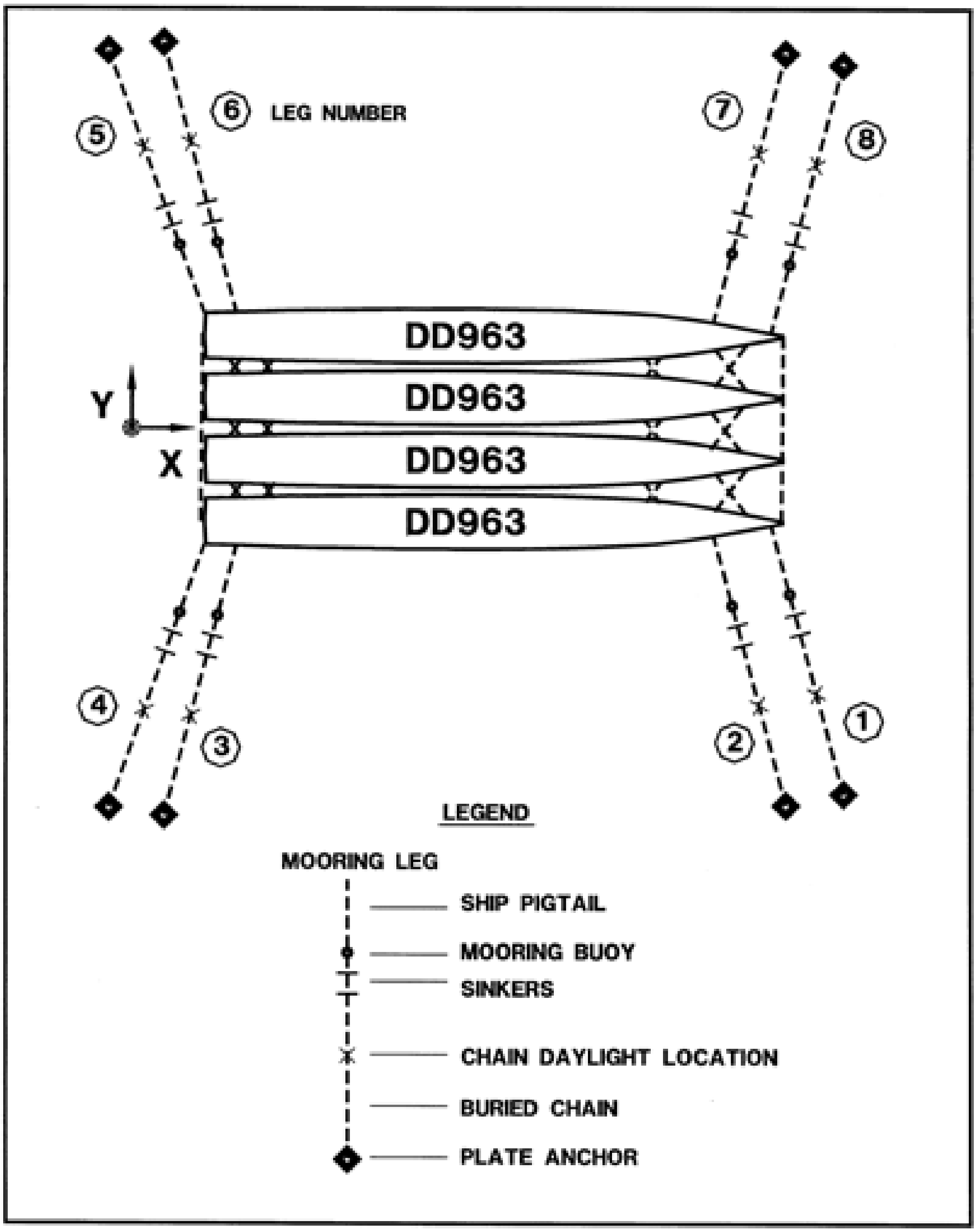


Figure 64
Spread Mooring Arrangement for a Nest of Four Destroyers

8.4.8 Static Analysis. A quasi-static analysis is performed on the mooring system using a mooring analysis program (W.S. Atkins Engineering Sciences, AQWA Reference Manual). Each mooring leg is initially pretensioned to a tension of 3.6 knots (10 kips). Quasi-static analysis is performed for various combinations of wind and current directions. Quasi-static results for various wind directions in conjunction with a 60-degree flood tidal current of 0.6 knots (0.31 m/s) are shown in Table 58.

Table 58
Quasi-Static Leg Tensions for the Spread Mooring at Various Wind Directions With a Flood Tidal Current

Wind Direction							
LEG	**0**	**30^0**	**60^0**	**90^0**	**120^0**	**150^0**	**180^0**
kN							
1	52.49	214.99	447.01	609.02	**945.05**	866.04	541.00
2	-	62.50	347.99	486.02	769.03	927.03	571.03
3	693.00	941.04	844.02	588.02	560.00	343.99	93.50
4	668.00	808.04	611.02	387.00	255.02	45.60	-
5	622.01	490.03	84.52	-	-	-	-
6	563.02	454.00	64.72	-	-	-	-
7	-	-	-	-	-	220.99	449.01
8	-	-	-	-	-	309.02	564.00
Kips							
1	11.8	48.33	100.49	136.91	**212.45**	194.69	121.62
2	-	14.05	78.23	109.26	172.88	208.4	128.37
3	155.79	211.55	189.74	132.19	125.89	77.33	21.02
4	150.17	181.65	137.36	87	57.33	10.25	-
5	139.83	110.16	19	-	-	-	-
6	126.57	102.06	14.55	-	-	-	-
7	-	-	-	-	-	49.68	100.94
8	-	-	-	-	-	69.47	126.79

- Indicates that the leg does not get loaded

A maximum load of 945 knots (212 kips) occurs on Leg 1 at a wind direction of 120 degrees. This provides a quasi-static factor of safety of approximately 4 to the breaking strength of 2.75-inch FM3 chain.

8.4.9 Dynamic Analysis. A dynamic analysis is performed on the mooring system to evaluate peak mooring loads and vessel motions using a mooring analysis program (W.S. Atkins Engineering Sciences, AQWA Reference Manual). The initial location of the vessel nest is based on the equilibrium location of the vessel nest determined in the quasi-static analysis. An Ochi-Shin wind spectrum is used to simulate the design storm (Wind Turbulent Spectra for Design Consideration of Offshore Structures, Ochi-Shin, 1988). This simulation is performed for a 60-minute duration at the peak of the design storm.

Figure 64 shows that the four vessels in the nest are close together and Figure 65 shows that the ships have a large ratio of ship draft to water depth. In this case it is estimated that the ships will capture the water between them as the ships move. Therefore, the nest of moored ships was modeled as a rectangular box having a single mass with the dimensions of 161.2 meters (length of each ship at the waterline), 71.62 meters wide (four ship beams + 5 feet spacing between ships), and 6.5 meters deep (average vessel draft). Added mass for sway and surge was computed as if the nest was cylindrical in shape with a diameter equal to the average draft. Damping as a function of frequency was estimated from a diffraction analysis (W.S. Atkins Engineering Sciences, AQWA Reference Manual).

Dynamic analyses were performed for various combinations of wind and current directions using a wind speed time history that simulated the design storm. Results showing the instantaneous peak tensions for various wind directions in conjunction with a flood tidal current of 0.6 knots (0.31 m/s) are shown on Table 59.

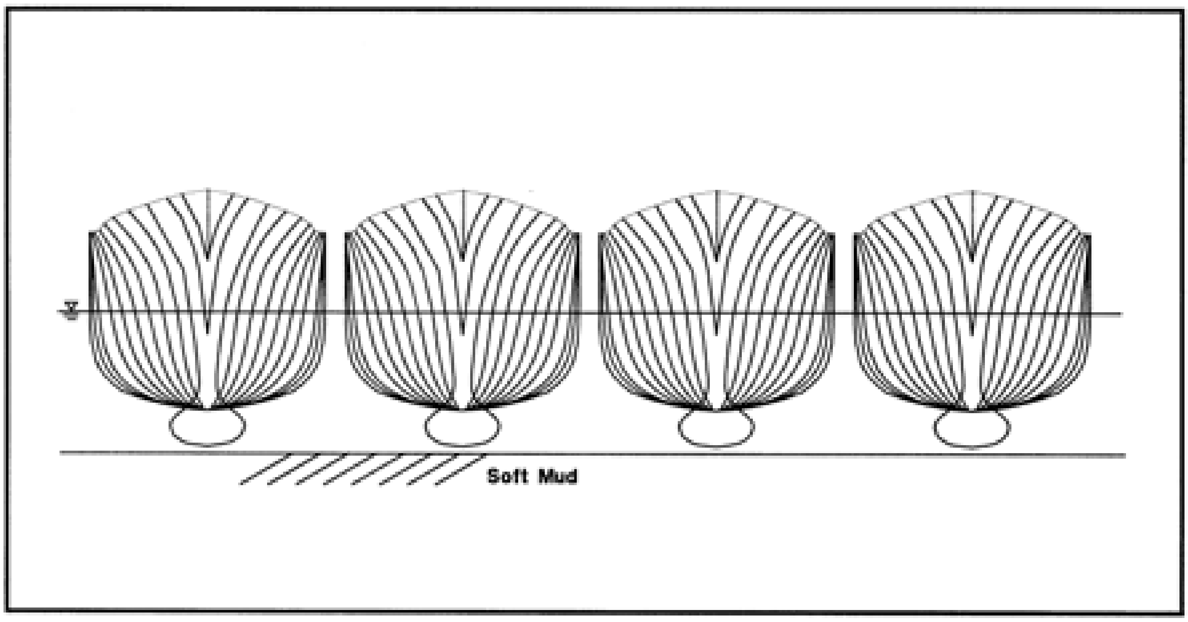


Figure 65
End View of DD 963 Mooring Nest

Table 59
Peak Dynamic Chain Tensions for DD 963 Nest for Various Wind Directions and a Flood Tidal Current

Wind Direction							
LEG	**0**	**30^0**	**60^0**	**90^0**	**120^0**	**150^0**	**180^0**
KN							
1	167.05	288.9	634.03	828.68	**2246.2**	1848.5	731.73
2	55.089	174.58	430.31	545.27	1067.2	1152.1	720.54
3	1202.5	1625	995.98	818.81	1370	647.78	210.62
4	1362.2	1651.7	653.82	480.82	486.77	240.56	-
5	1284.2	1356.4	219.12	-	-	-	-
6	938.06	901.87	217.04	-	-	-	-
7	-	-	-	-	55.019	374.91	514.26
8	-	-	-	-	170.54	485.43	834.54
Kips							
1	37.55	64.95	142.53	186.29	**504.95**	415.55	164.50
2	12.38	39.25	96.74	122.58	239.91	259.00	161.98
3	270.33	365.31	223.90	184.07	307.98	145.62	47.35
4	306.23	371.31	146.98	108.09	109.43	54.08	-
5	288.69	304.92	49.26	-	-	-	-
6	210.88	202.74	48.79	-	-	-	-
7	-	-	-	-	12.37	84.28	115.61
8	-	-	-	-	38.34	109.13	187.61

Modeling shows that the instantaneous peak chain tension of 2246 knots (505 kips) is predicted on Leg 1 as the moored vessel nest responds to wind gusts. This provides a peak instantaneous factor of safety of 1.5 on the breaking strength of the selected chain size. For this example, the peak dynamic chain tension during the 1 hour at the peak of the design storm is 2.4 times the quasi-static tension in the mooring leg with the highest tension, Leg 1.

Nest motions for surge, sway, and yaw are provided in Table 60. This table shows that the maximum surge of the vessel nest is approximately 7.4 meters (24.3 feet) from its equilibrium condition at no loading. Maximum sway and yaw of the vessel nest is 3.2 meters (10.5 feet) and 1.59 degrees clockwise, respectively. During a dynamic analysis simulation, nest motions oscillated up to 5.4 meters (17.7 feet) in surge (for a wind direction coming from the stern), 1.9 meters (6.2 feet) in sway (for a wind direction 30 degrees aft of broadside), and 2.1 degrees in yaw (for a wind direction 30 degrees off the stern).

8.4.10 Anchor Design. Using the quasi-static design mooring leg tension, anchor capacity and loads on the embedded plate anchor are calculated using procedures outlined in NFESC TR-2039-OCN, Design Guide for Pile-Driven Plate Anchors and NFESC CR-6108-OCN, Anchor Mooring Line Computer Program Final Report, User's Manual for Program CSAP2. Due to the lower shear strengths of the soft silty upper layers at the site, a 6-foot by 11-foot mud plate anchor, as described in Table 36 (par. 5.3) is specified. A design keyed depth of 55 feet is selected for the plate anchor. This will provide an estimated static holding capacity of 1913 kN (430 kips).

CSAP is used to predict the mooring leg tension at the anchor. Input requirements of CSAP include: (1) mooring leg configuration between the anchor and the buoy or chock; (2) water depth or height of chock above the seafloor; (3) soil profiles and strength parameters; (4) location and size of sinkers; (5) horizontal tension component of the mooring leg at the buoy or chock; (6) horizontal distance or total length of the mooring leg between anchor and buoy or chock; and (7) anchor depth. Output provided by CSAP includes: (1) chain catenary profile from the anchor to the buoy or chock attachment point; (2) angle of the mooring leg from the horizontal at the anchor, the seafloor, and the buoy or chock; (3) tension of the mooring leg at the anchor, seafloor, and at the buoy or chock; (4) predicted daylight location for the mooring leg; and (5) length of mooring leg required or horizontal distance between anchor and buoy or chock.

Table 60
DD 963 Nest Motions for Surge, Sway, and Yaw at Various Wind Directions with a Flood Tidal Current

	Wind Direction						
Motion	**0^0**	**30^0**	**60^0**	**90^0**	**120^0**	**150^0**	**180^0**
Surge (meters)							
Origin	98.17	98.17	98.17	98.17	98.17	98.17	98.17
Start	105.6	105.4	103.6	98.1	93.7	89.2	88.1
Max	106.9	106.8	103.9	98.8	95.1	93.4	93.5
Min	102.3	102.3	102.4	98.1	93.7	89.2	88.1
Diff	4.6	4.5	1.5	0.7	1.4	4.2	5.4
Sway (meters)							
Origin	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Start	0.84	1.49	2.39	2.97	1.27	2.02	1.14
Max	0.84	1.49	2.65	3.13	3.22	2.50	1.45
Min	0.52	0.83	0.93	1.35	1.27	1.43	1.11
Diff	0.32	0.66	1.72	1.78	1.93	1.07	0.34
Yaw (degrees)							
Origin	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Start	0.76	1.09	1.43	0.64	-0.08	-0.74	-0.89
Max	0.76	1.18	1.59	0.80	-1.22	-1.49	-1.12
Min	0.38	0.27	0.43	-0.25	0.76	0.54	-0.83
Diff	0.38	0.91	1.16	1.05	1.96	2.03	0.29

For this example, a keyed anchor depth of 55 feet was selected. Input data included: (1) configuration of the mooring leg (30 feet of 3-inch wire attached to 2+ shots of 2.75-inch chain); (2) height of seafloor to vessel chock (46 feet stern and 64 feet bow); (3) soil profile and strength for the site (shear strength increases linearly at 10 pounds per ft^2 per foot of depth); (4) information on the sinkers (2 each 20-kip sinkers placed a horizontal distance of 170 feet away from the anchor; (5) horizontal tension component of the mooring leg from the quasi-static results (195 kips); (6) horizontal distance between anchor and chock (280 feet) from the quasi-static results; and (7) depth of anchor (55 feet).

CSAP results for this design leg at this anchor depth indicate that the predicted daylight location of the mooring leg is approximately 99 feet (30 meters) from the anchor location and the leg tension at the anchor is 166 kips. A profile of this leg is shown in Figure 47, Section 6.10. Note that the interaction between the chain and the soil accounts for a 25 percent reduction in tension on the mooring leg at the anchor. This gives a predicted quasi-static anchor holding factor of safety of 2.6.

Based on the CSAP results, 6-foot by 11-foot plate anchors are specified. Based on predicted keying distances required for this anchor, as outlined in NFESC TR-2039-OCN, Design Guide for Pile-Driven Plate Anchors, the anchors should be installed to a tip depth of 70 feet (21 meters) below the mudline to ensure that the anchor is keyed at a minimum depth of 55 feet (16.8 meters). Figure 66 provides a comparison between tip depth, keyed depth and ultimate capacity for this size anchor.

Further information concerning this design is provided in NFESC SSR-6119-OCN.

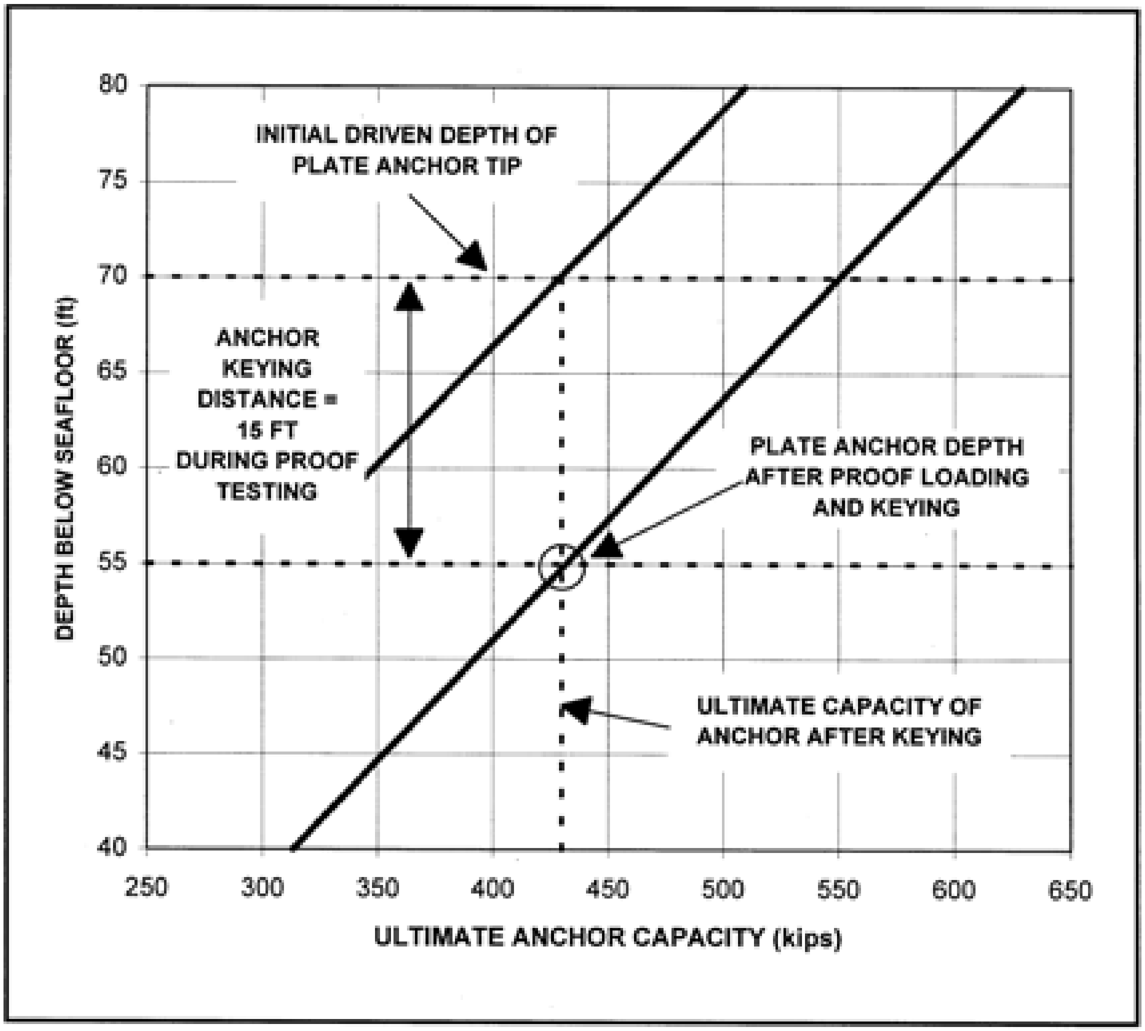


Figure 66
Plate Anchor Holding Capacity
(6-foot x 11-foot anchor with keying flaps in soft mud)

APPENDIX A
WIND AND CURRENT FORCES/MOMENTS
ON MULTIPLE VESSELS

A.1 INTRODUCTION

Ships are often moored close to one another to make optimum use of valuable harbor space. Another benefit of nearby ships is to take advantage of "sheltering" effects of one ship on another. For example, the transverse wind force for two identical ships across a pier will be less than for the two ships moored at separate piers.

Examination of laboratory scale-model wind tunnel and flume tests taken at the U.S. Navy David Taylor Model Basin for from 1 to 6 aircraft carriers, destroyers, cargo ships and submarines shows that this data provides much valuable design information. However, the effects of some of the parameters on the transverse force and moments are sometimes complex.

The results are therefore provided in graphical forms for design engineer use. The intent is for these materials to be reviewed and applied with sound engineering judgment. Additional information, background discussion, tabular and graphical data are provided in NFESC TR-6003-OCN, Wind and Current Forces/Moments on Multiple Ships, Seelig 1997.

Figure A-1 shows the ships tested, Figure A-2 illustrates the coordinate system used and Figure A-3 shows definition of some terms. Figure A-4, A-5 and A-6 illustrate some of the many ship arrangements tested.

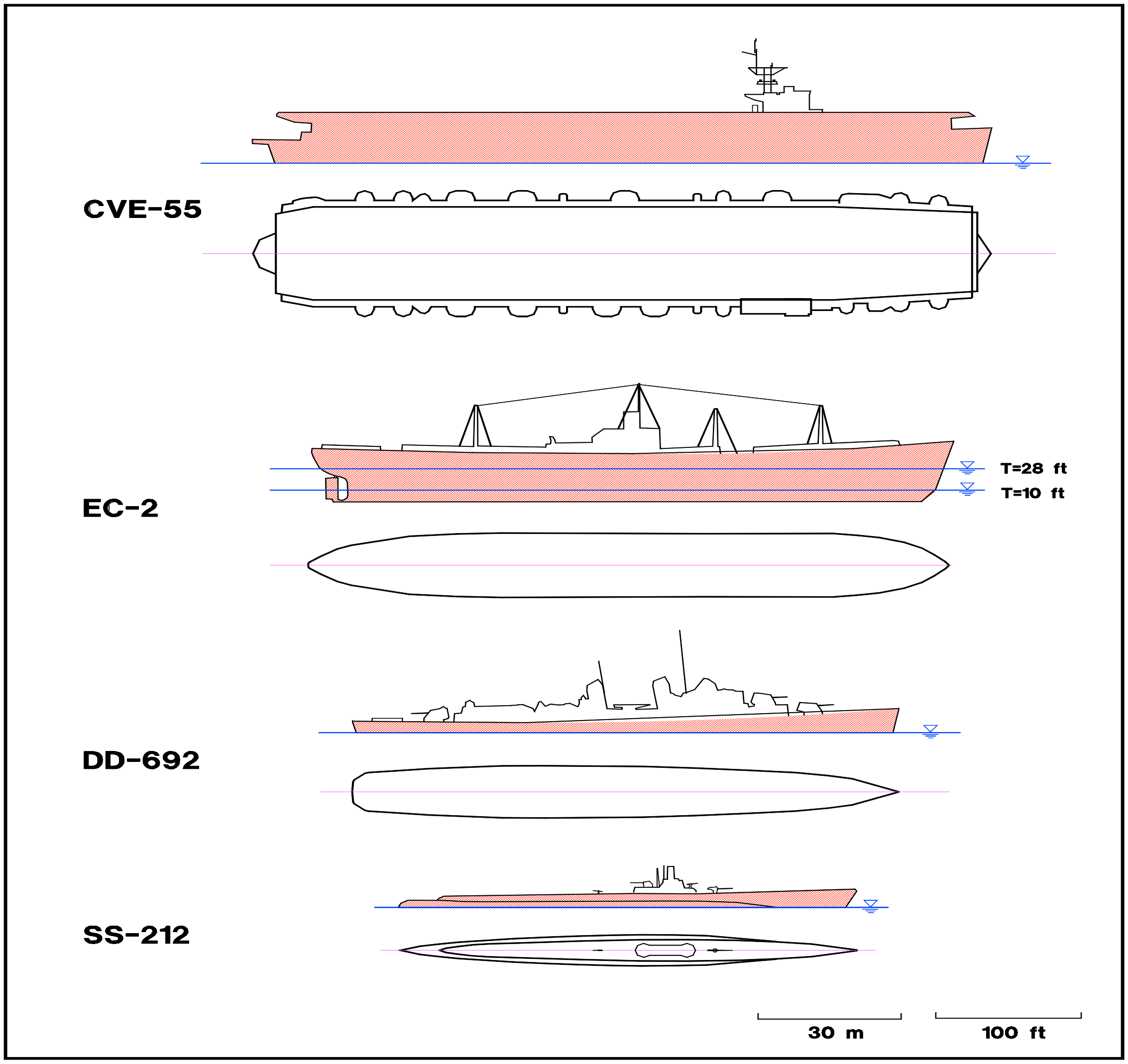


Figure A-1
Plan and Profile Views of Ships Tested

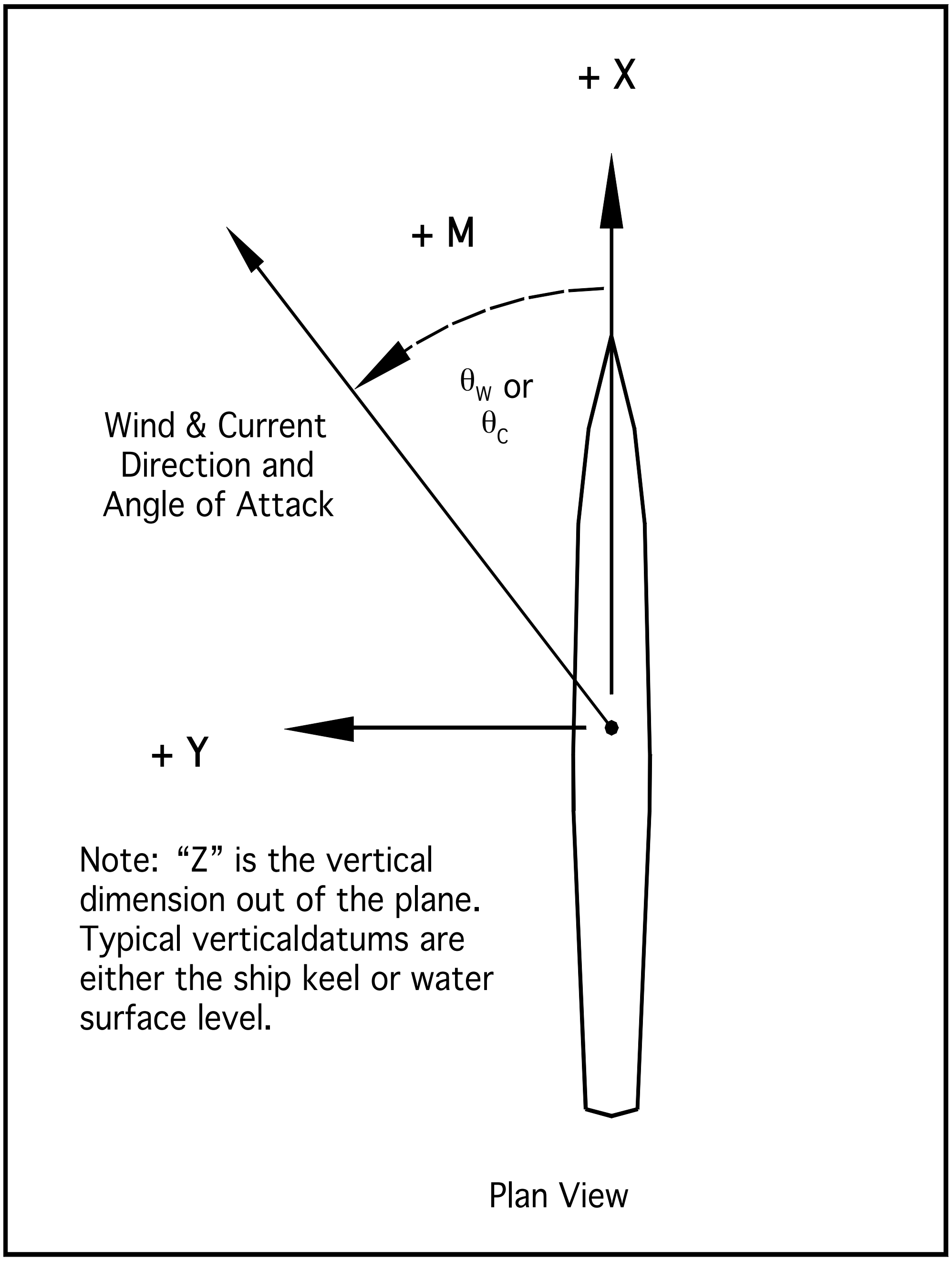


Figure A-2
Coordinate System

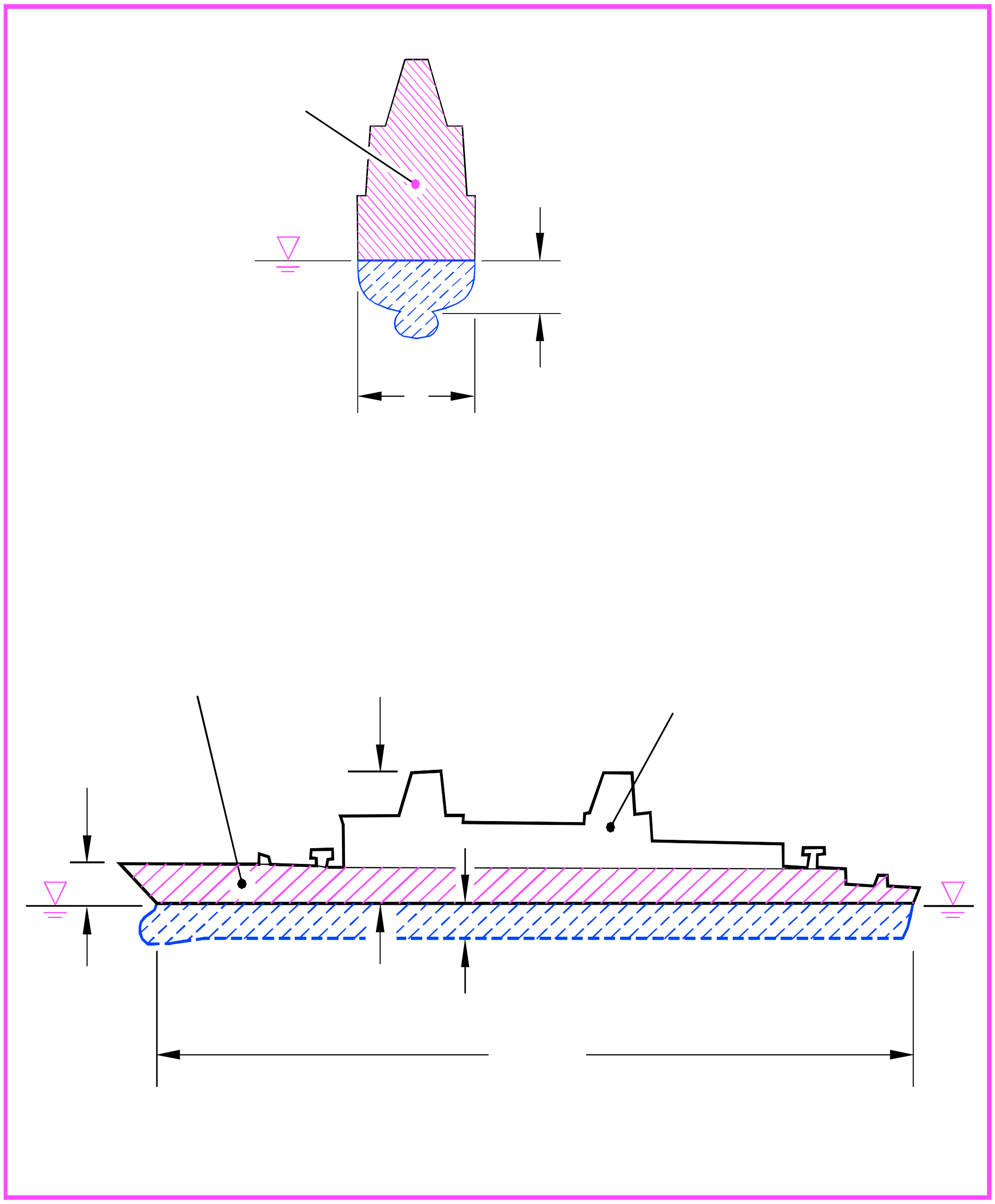


Figure A-3
Definition of Some Terms

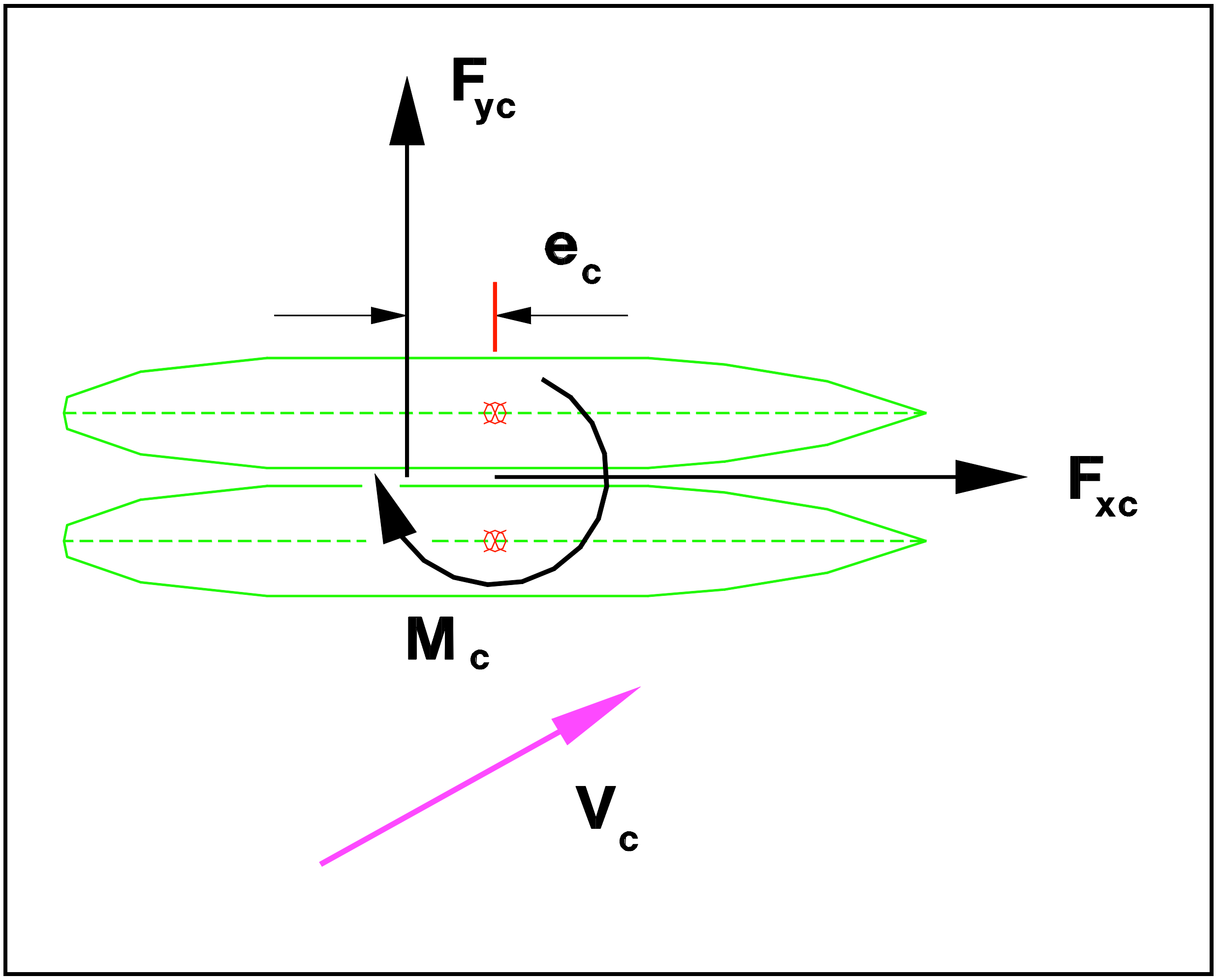


Figure A-4
Sample Condition

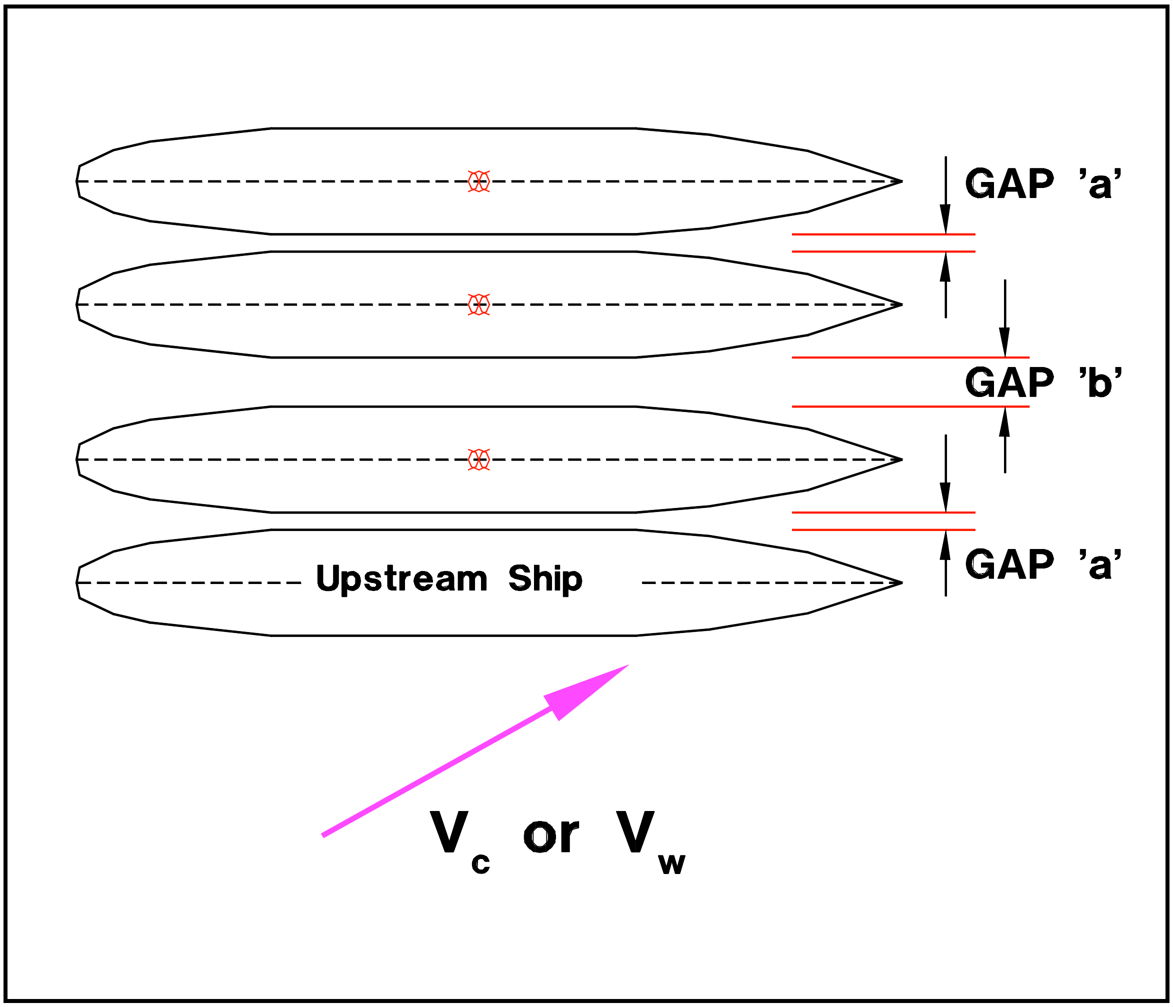


Figure A-5
Example of Four Ships
Moored Adjacent to One Another

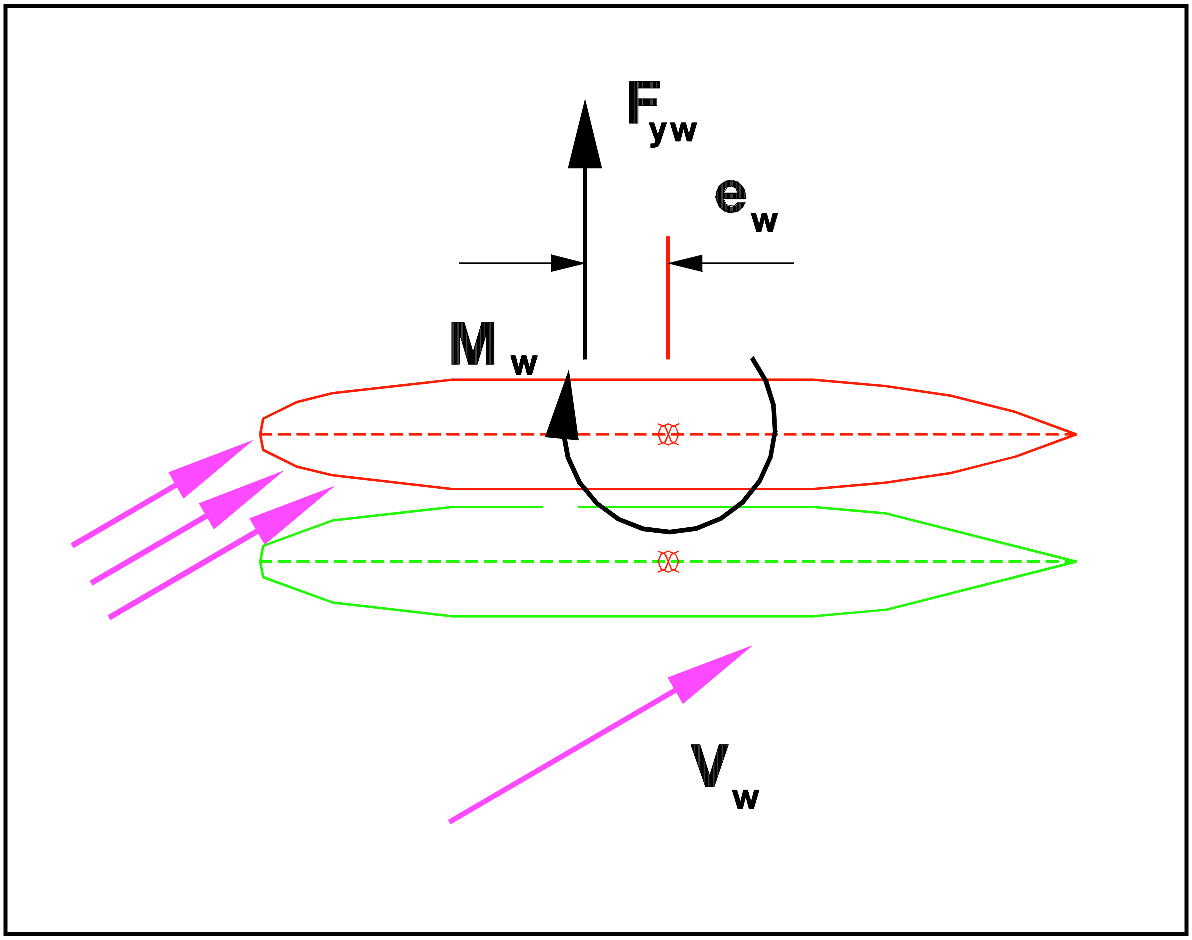


Figure A-6
Example of Two Ships Moored Next to One Another

A-2. GRAPHICAL DATA OF RESULTS

Table A-1 shows the ship classes tested and location of results.

Table A-1
Multiple Ship Testing

SHIP CLASS*	FIGURES	NOTES
CVE-55	A-7	Test arrangement
CVE-55 Wind	A-8 to -11	Results
CVE-55 Current	A-12 to -15	Results for T/d = 0.55
DD-692	A-16	Test arrangement
DD-692 Wind	A-17 to -20	Results
DD-692 Current	A-21 to -24	Results for T/d = 0.425
EC-2	A-25	Test Arrangement
EC-2 Wind	A-26 to -32	Results
EC-2 Current	A-33 to -38	Results for T/d = 0.4
SS-212	A-39	Test arrangement
SS-212 Current	A-40 to -44	Results for T/d = 0.648
SS-212 Wind	A-45 to -48	Results

* CVE-55 is an attack aircraft carrier
DD-692 is a destroyer
EC-2 is a cargo liberty ship
SS-212 is a submarine

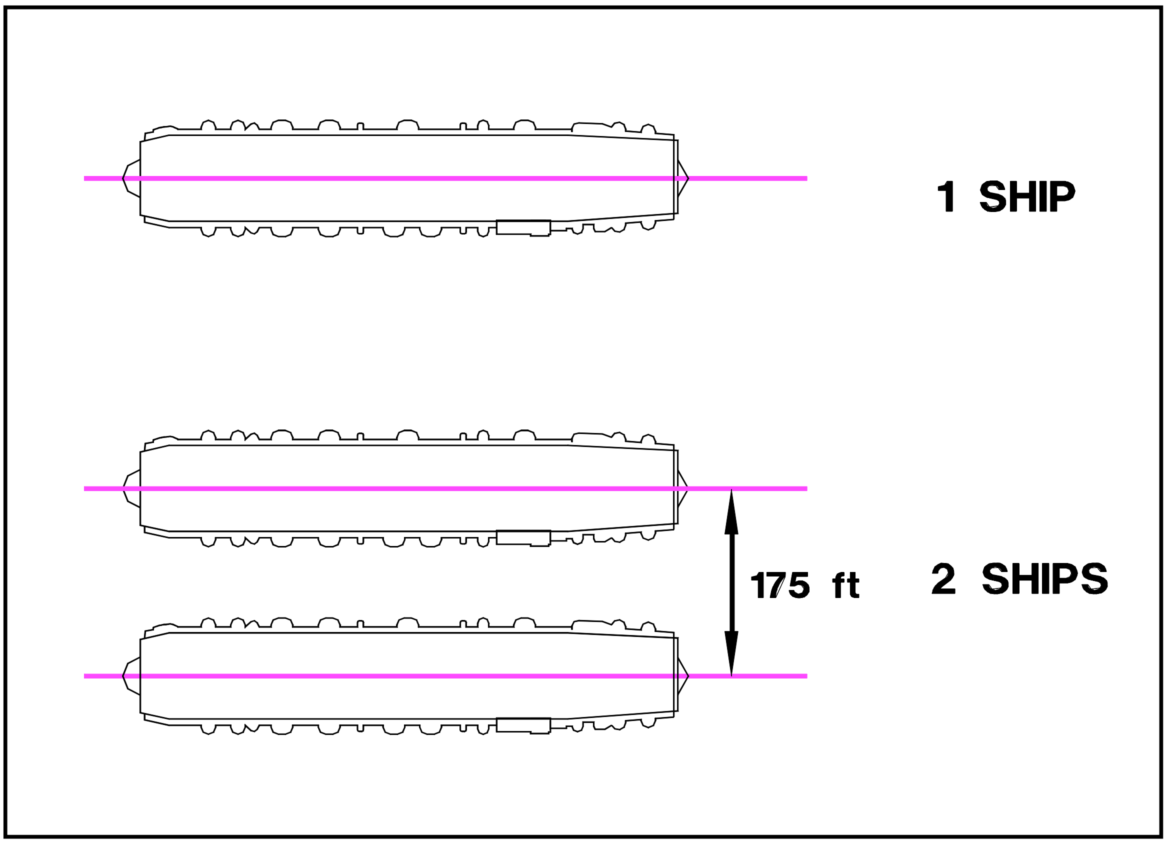


Figure A-7
CVE-55 Ship Nests Tested

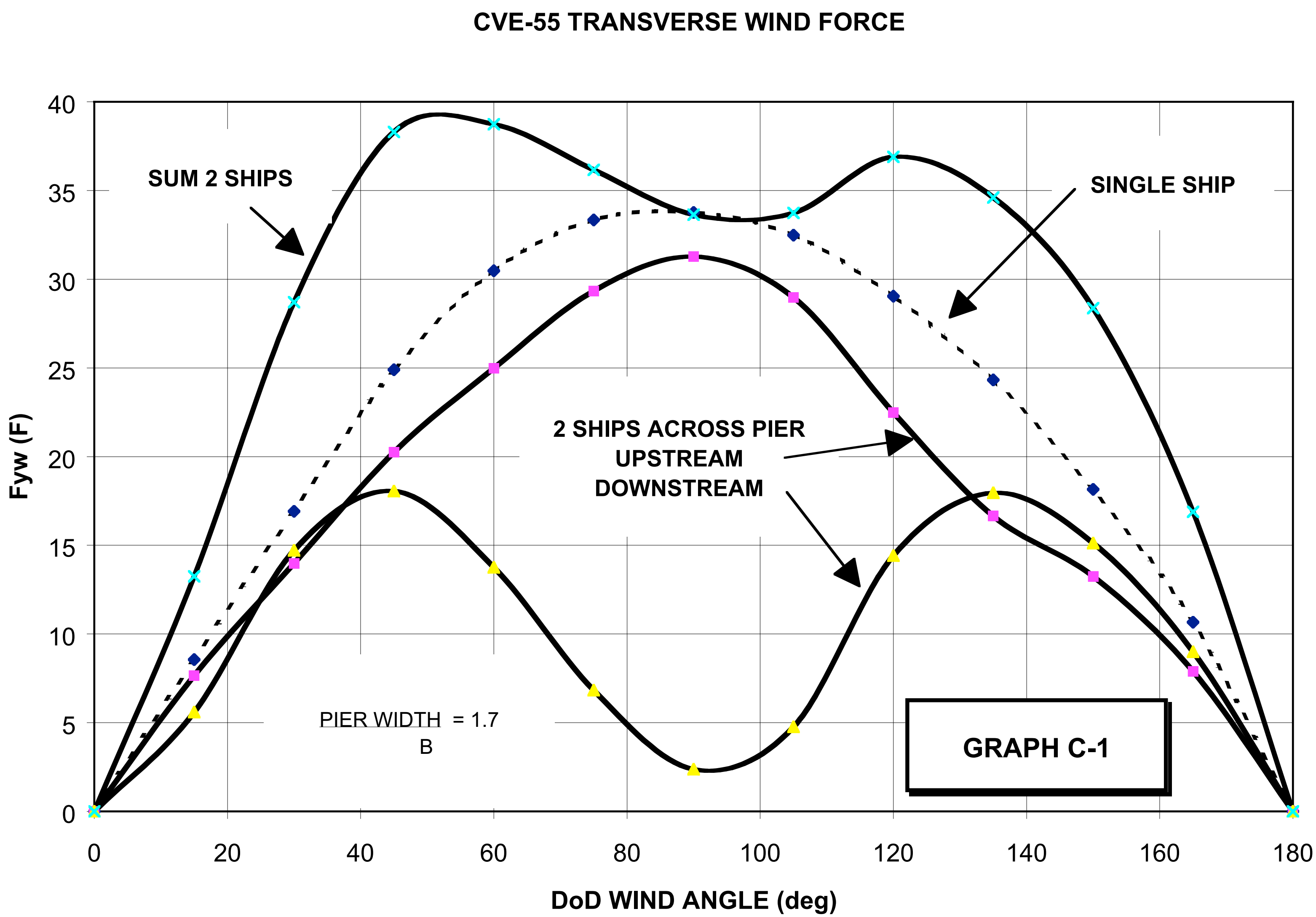


Figure A-8
CVE-55 Lateral Wind Forces

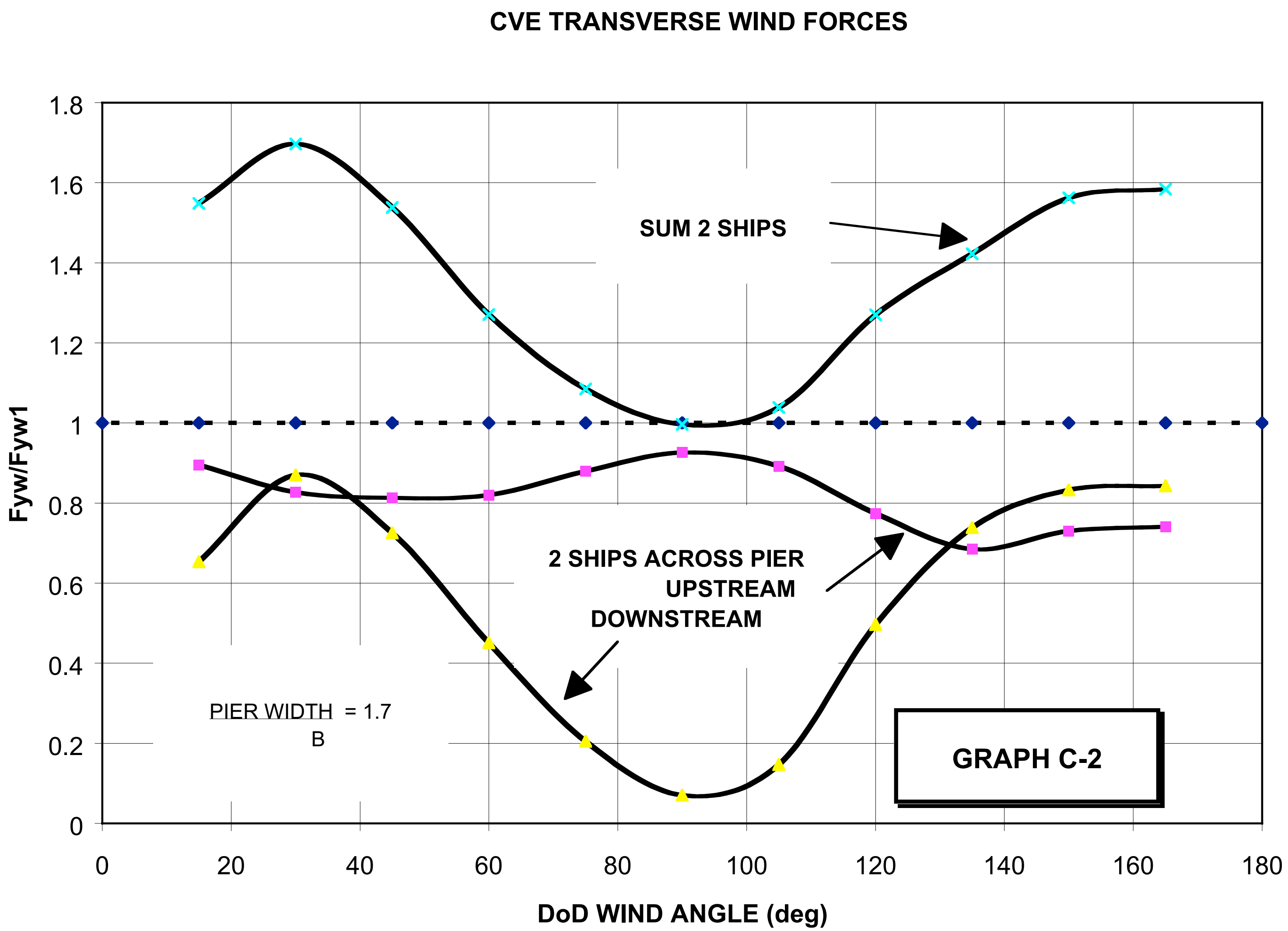


Figure A-9
CVE-55 Lateral Wind Forces Divided by the Force on One Ship

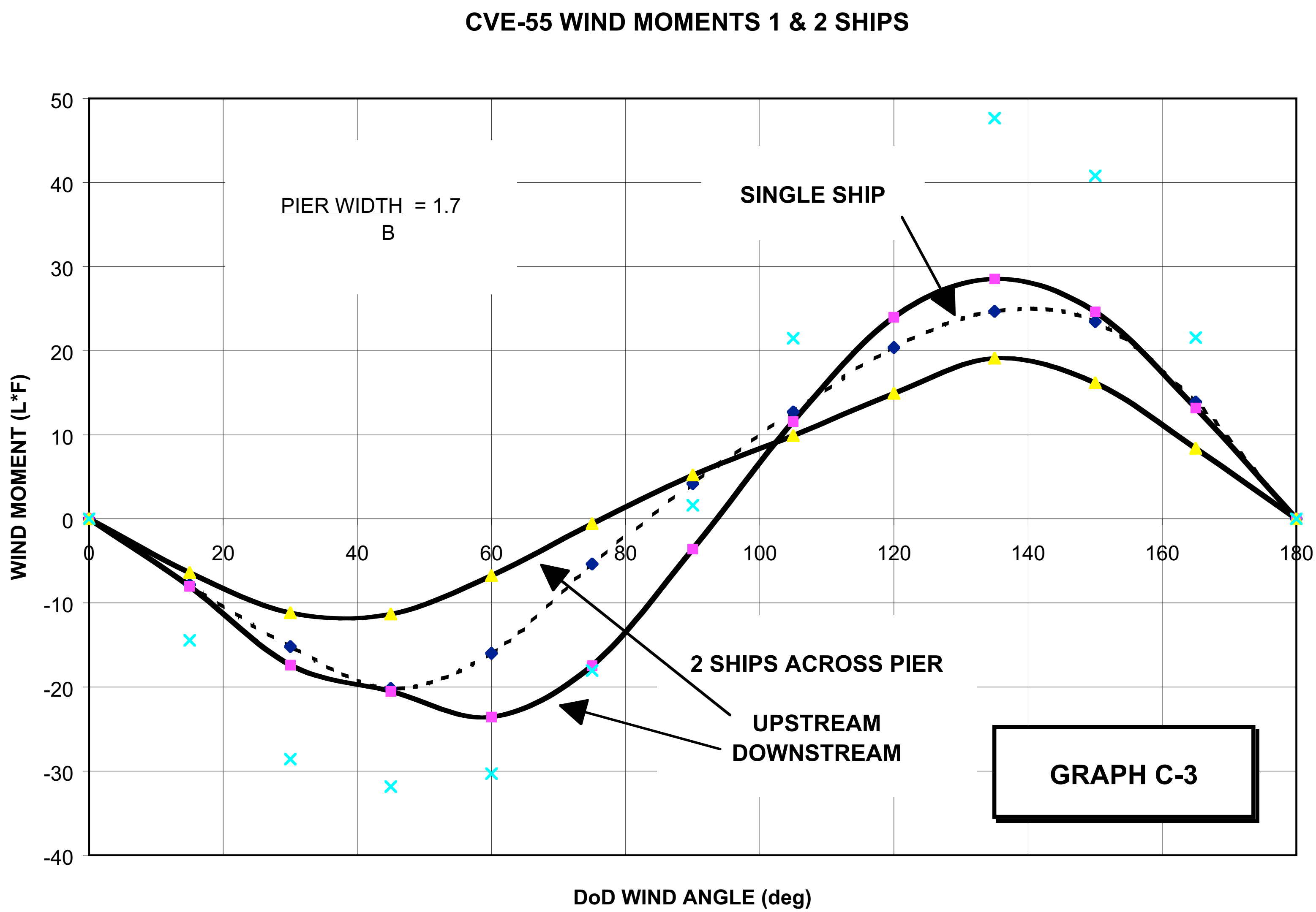


Figure A-10
CVE-55 Wind Moments on One and Two Ships

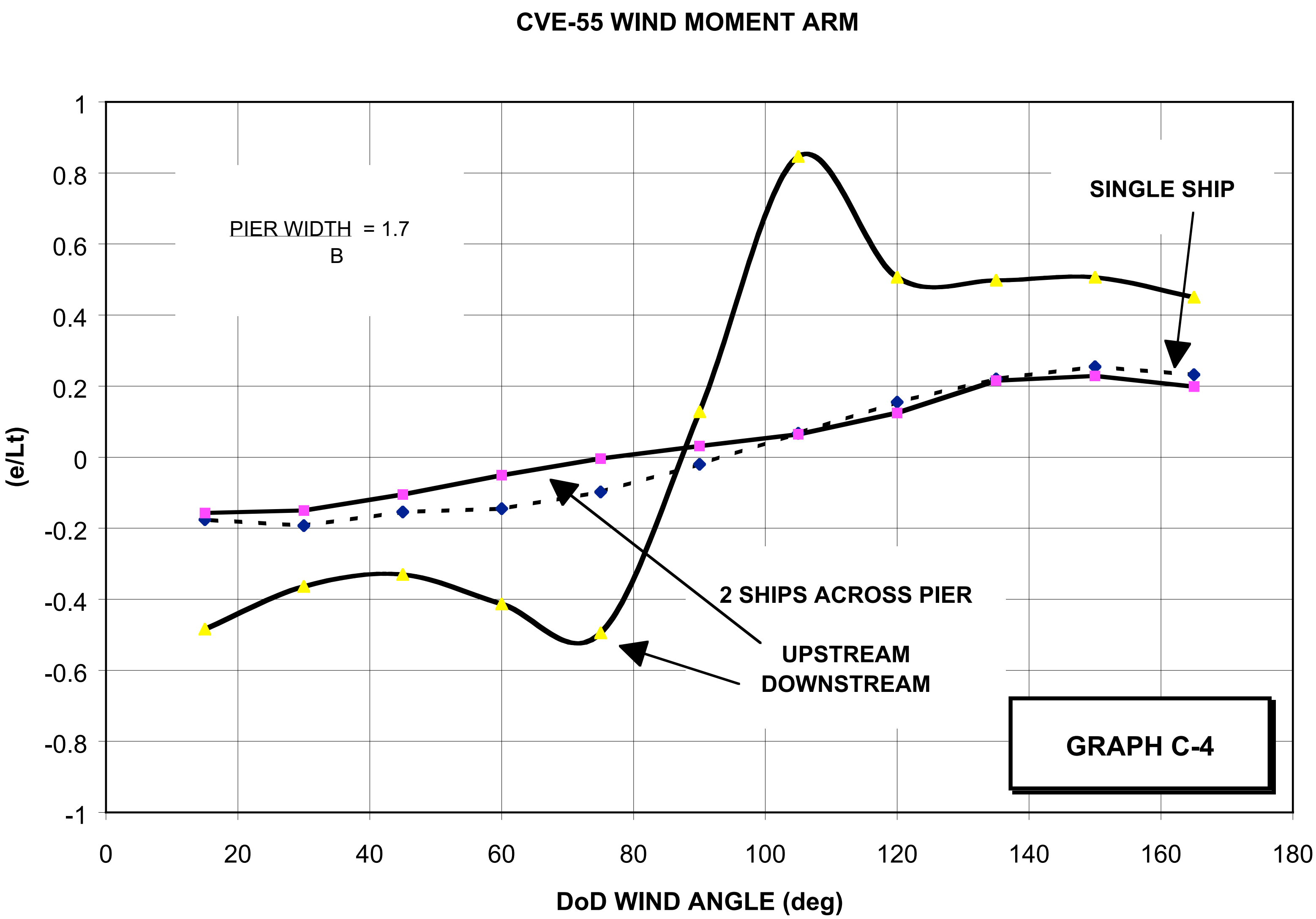


Figure A-11
CVE-55 Wind Moment Arm for One and Two Ships

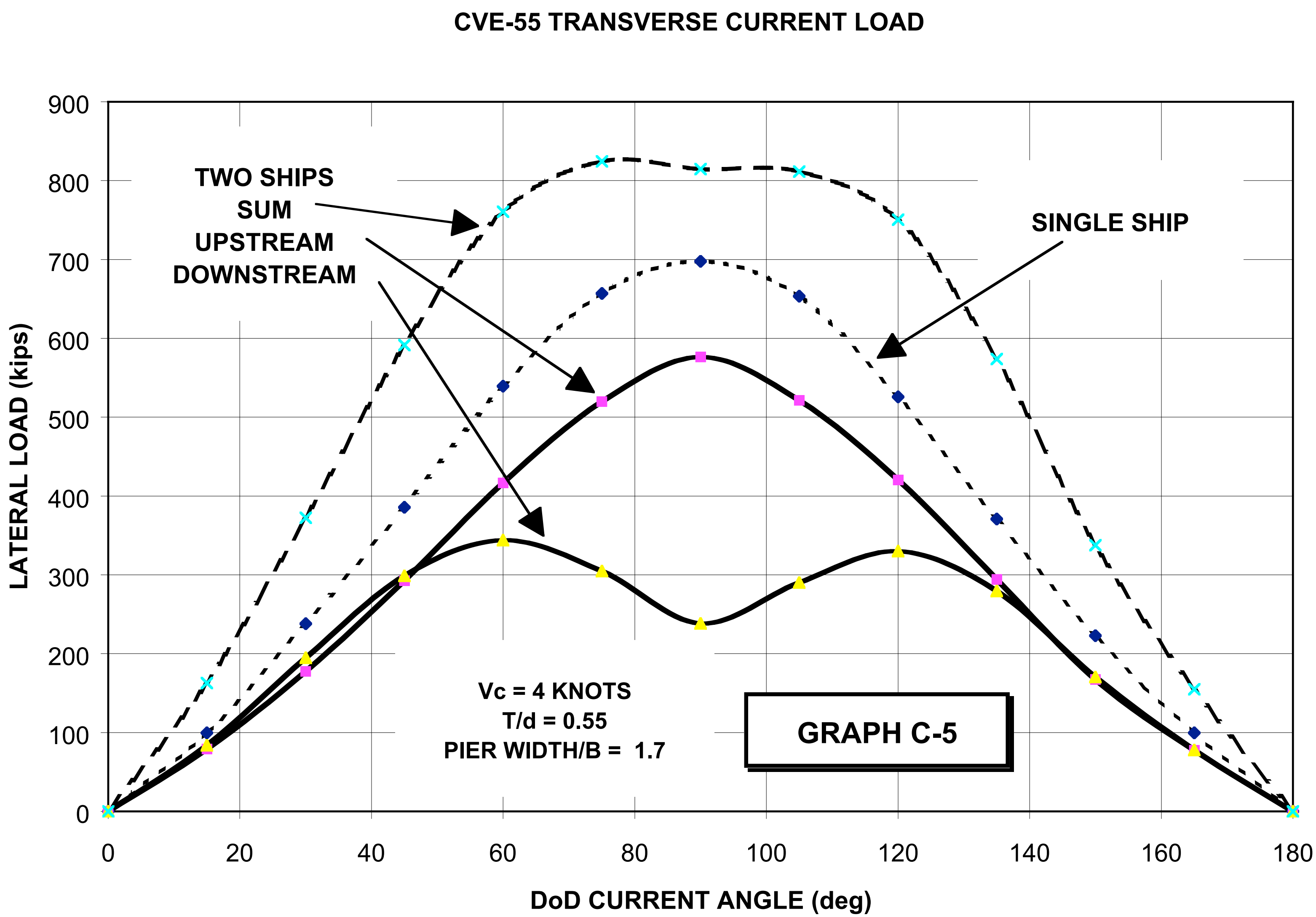


Figure A-12
CVE-55 Lateral Current Force

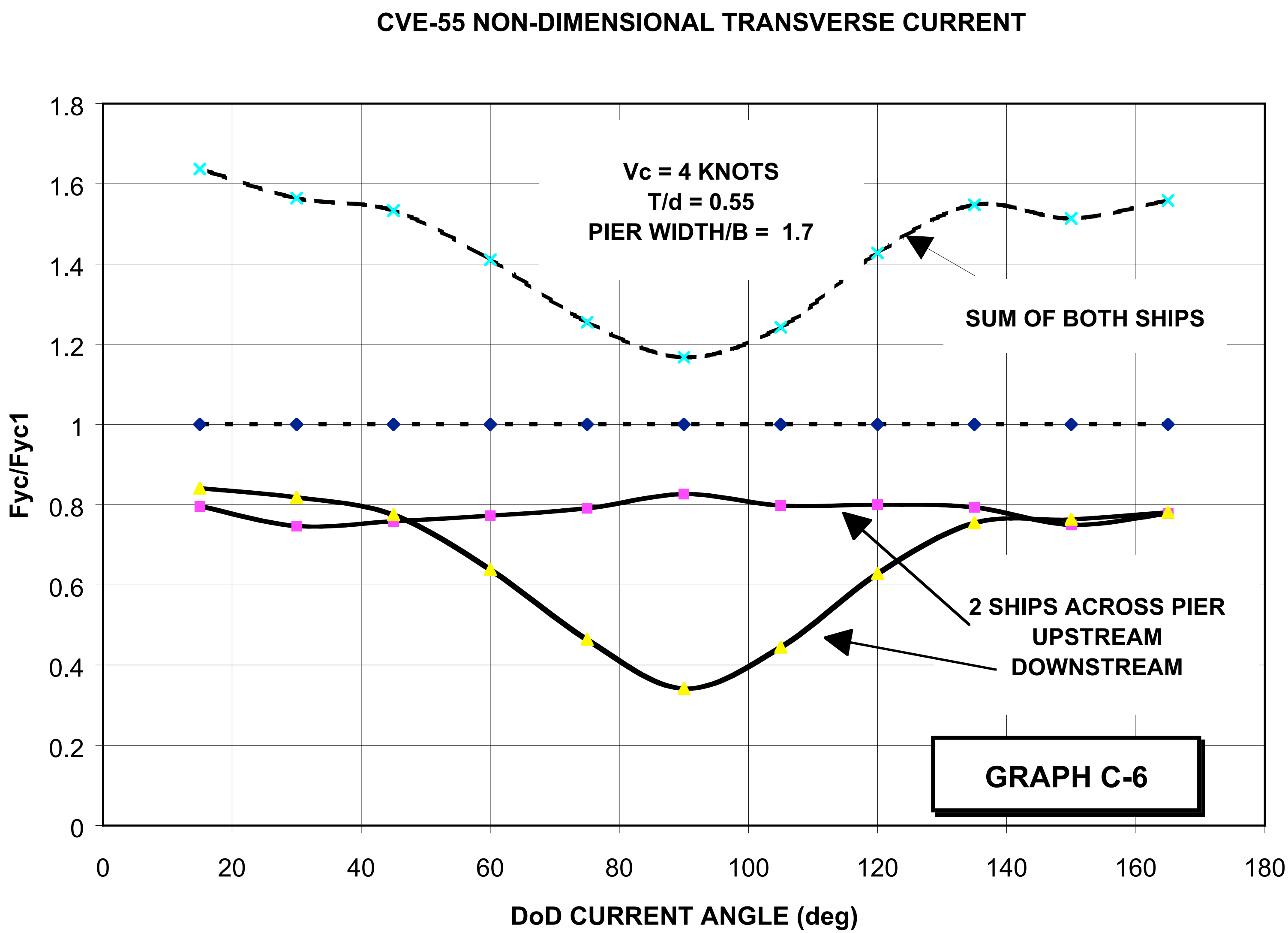


Figure A-13
CVE-55 Current Force Divided by Force for One Ship

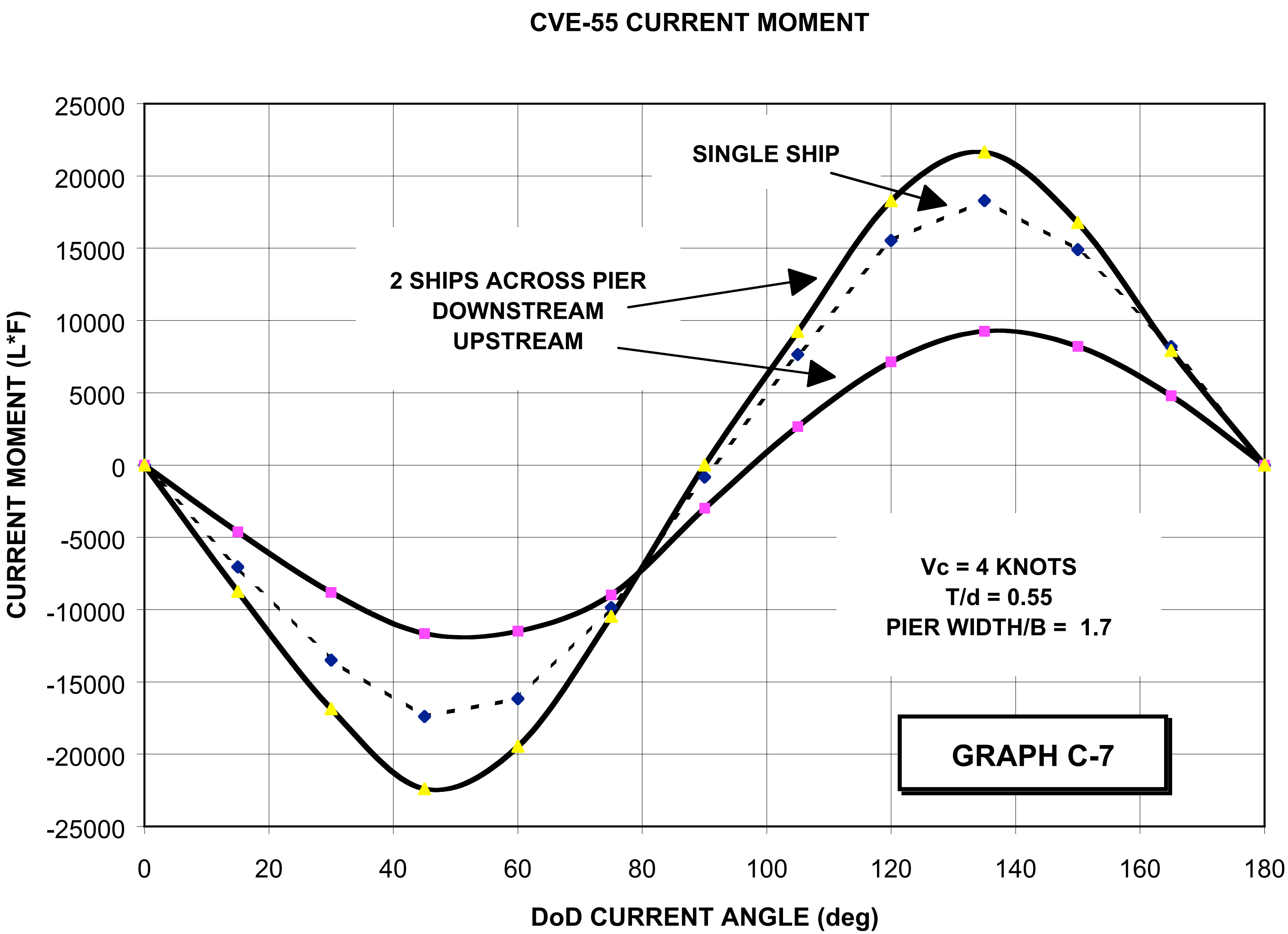


Figure A-14
CVE-55 Current Moment

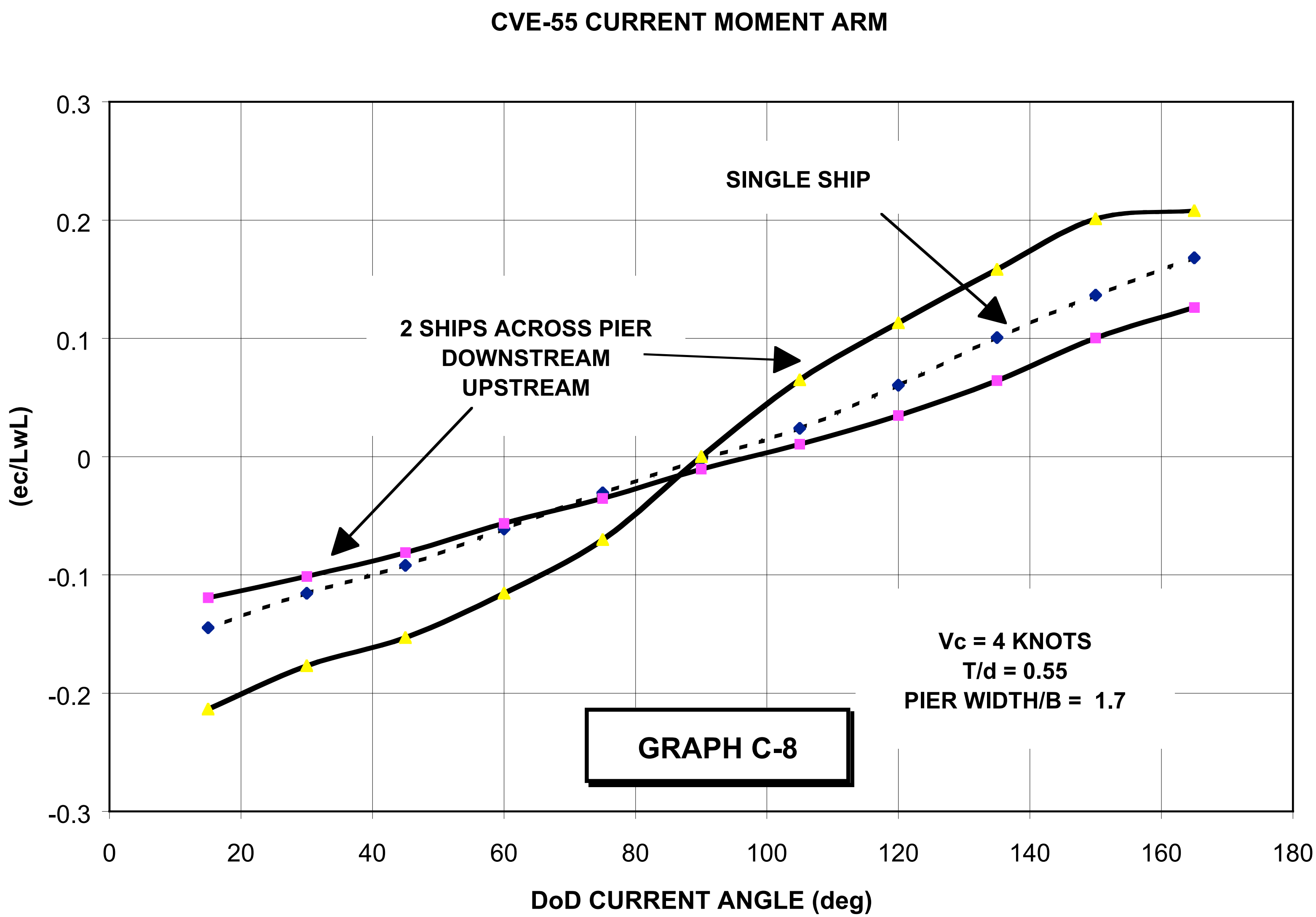


Figure A-15
CVE-55 Current Moment Arm for One and Two Ships

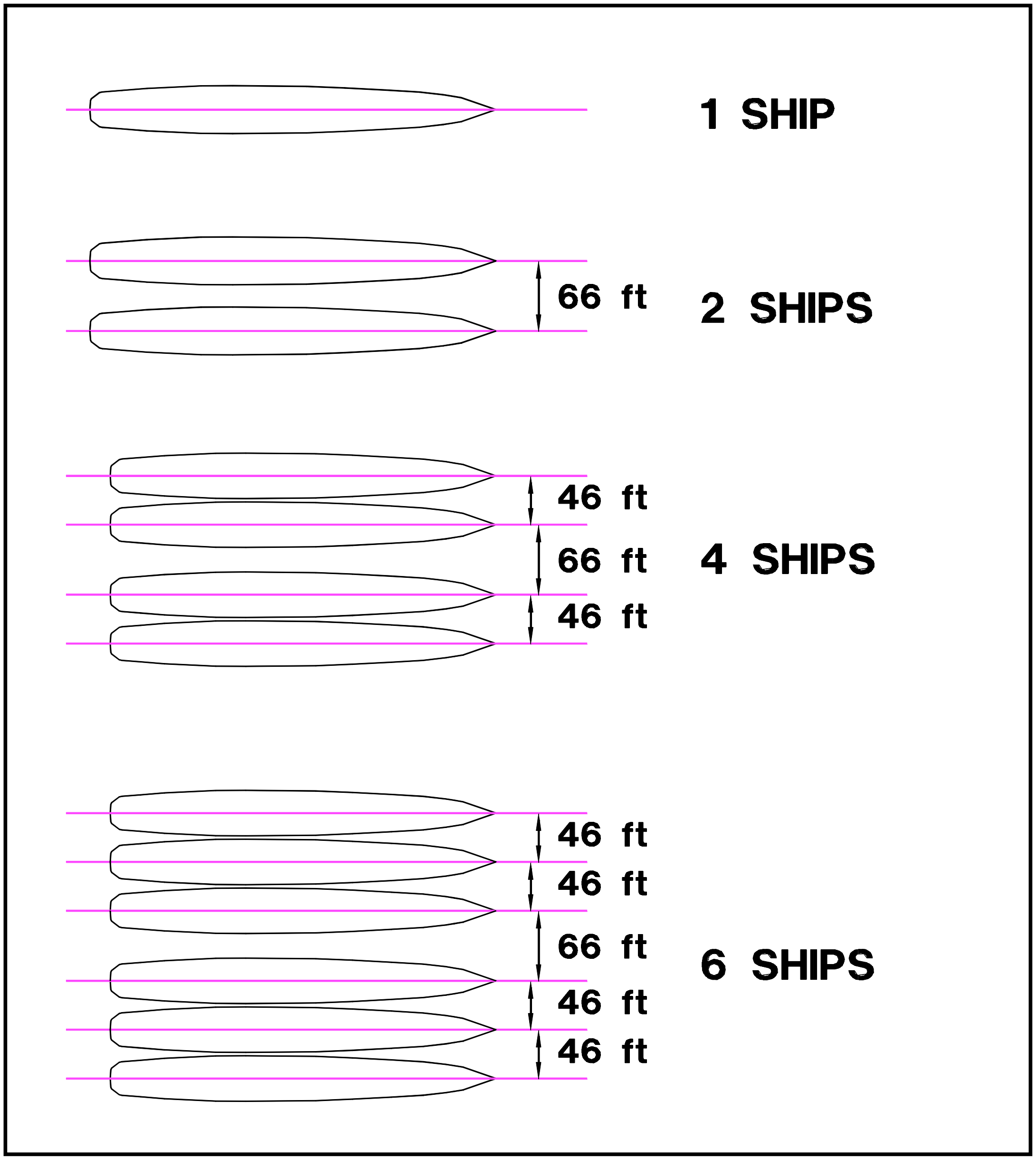


Figure A-16
DD-692 Ship Nests Tested

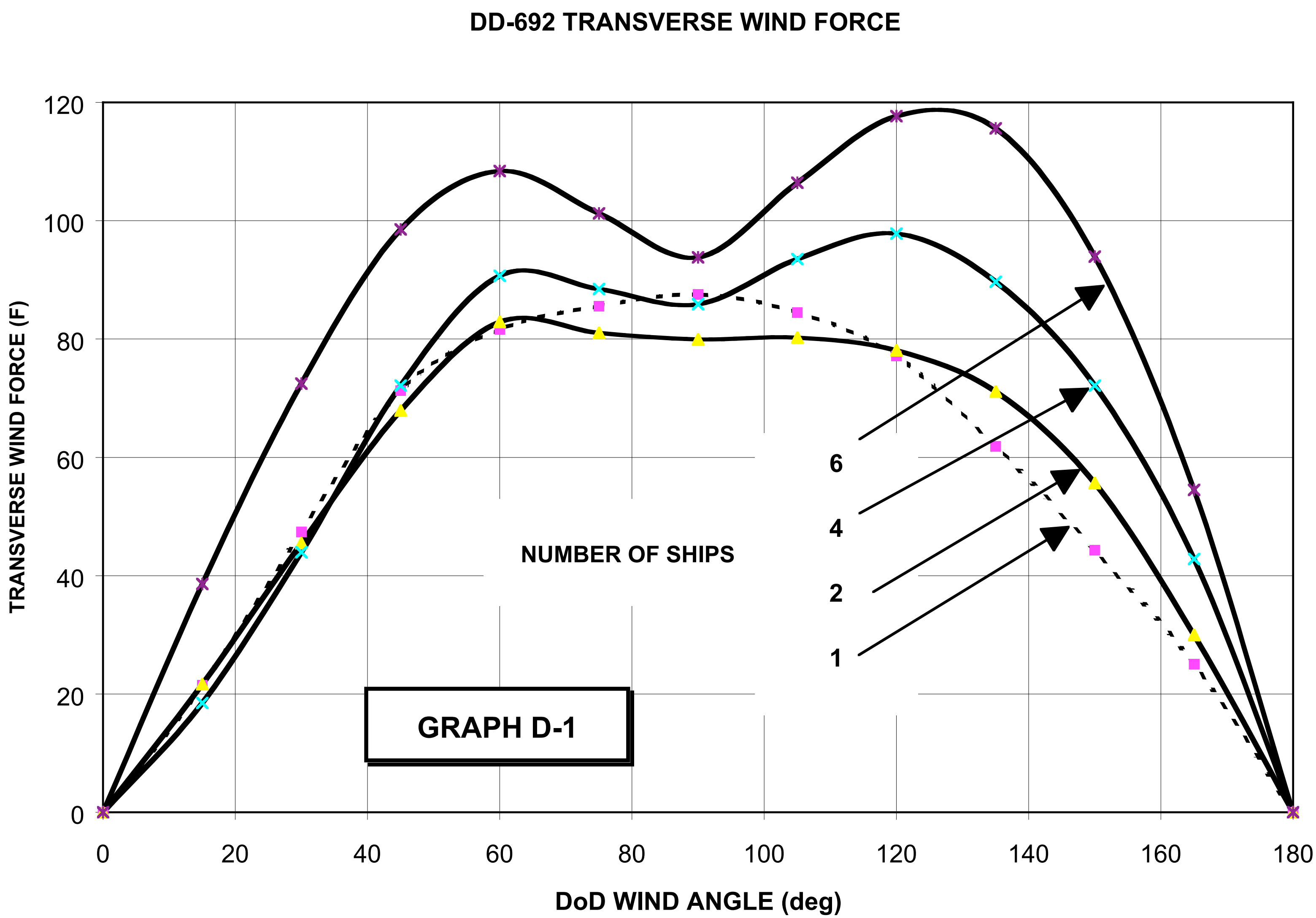


Figure A-17
DD-692 Lateral Wind Forces

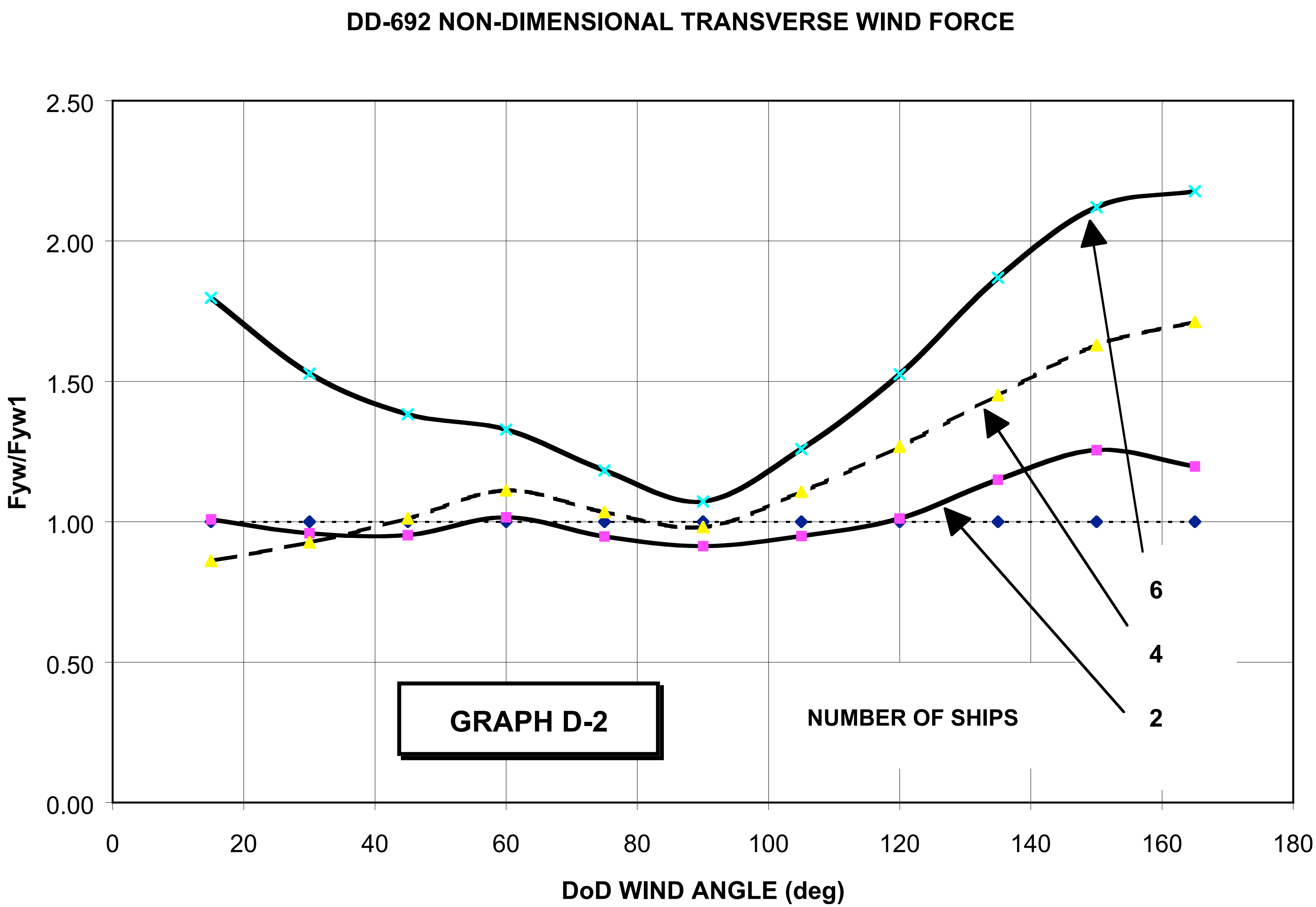


Figure A-18
DD-692 Lateral Wind Force Divided by Force on One Ship

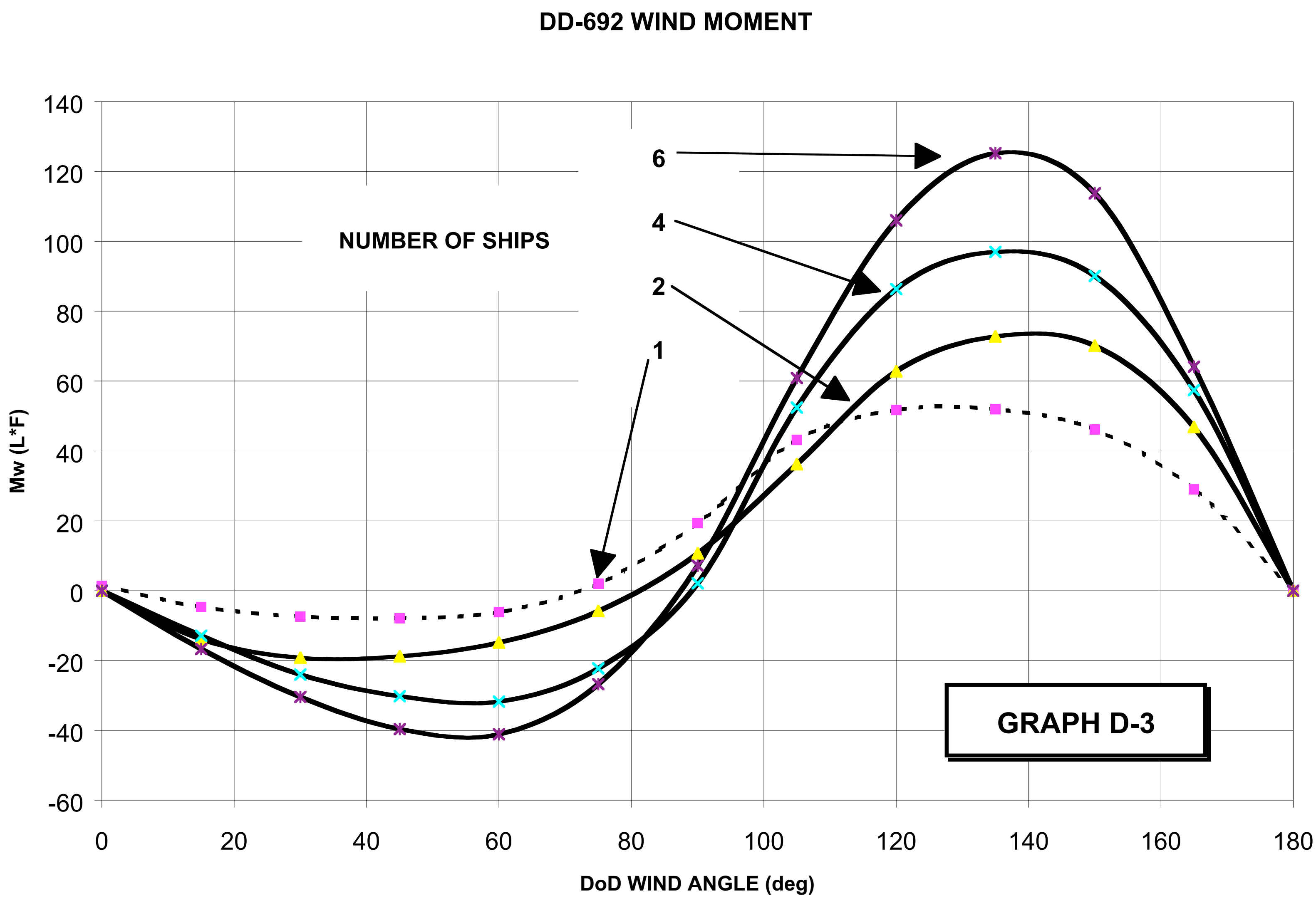


Figure A-19
DD-692 Lateral Wind Moments

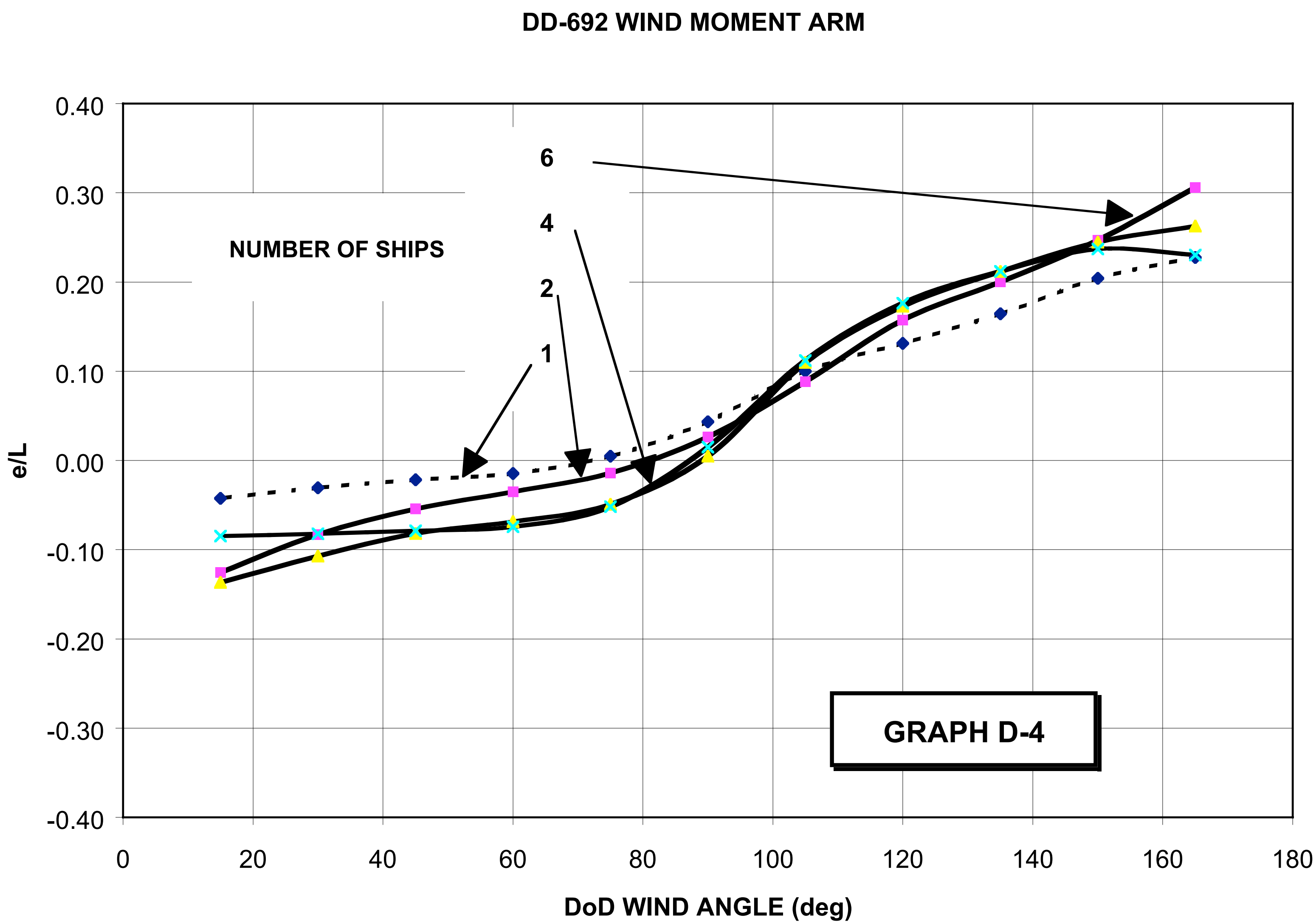


Figure A-20
DD-692 Wind Moment Arm

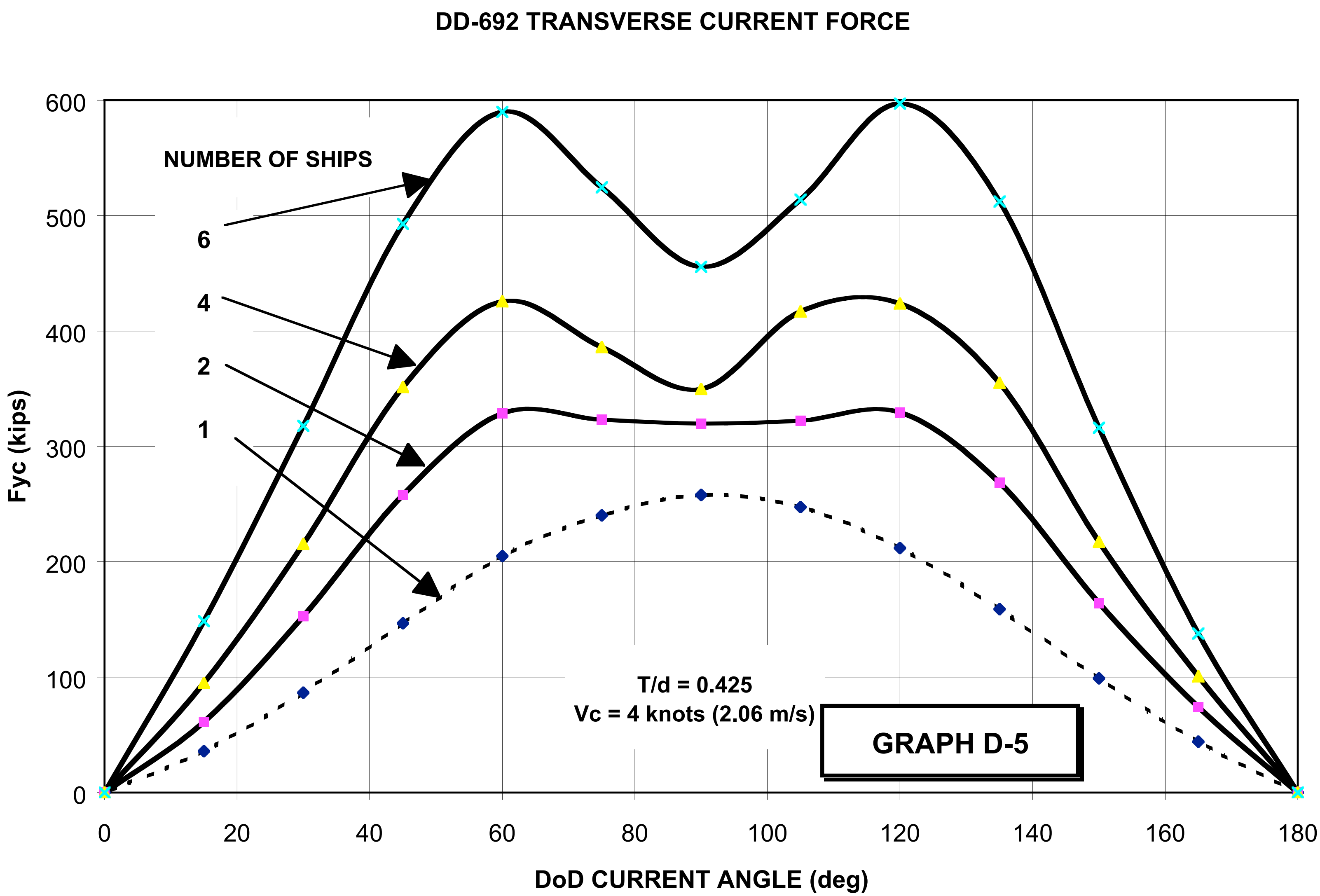


Figure A-21
DD-692 Lateral Current Force

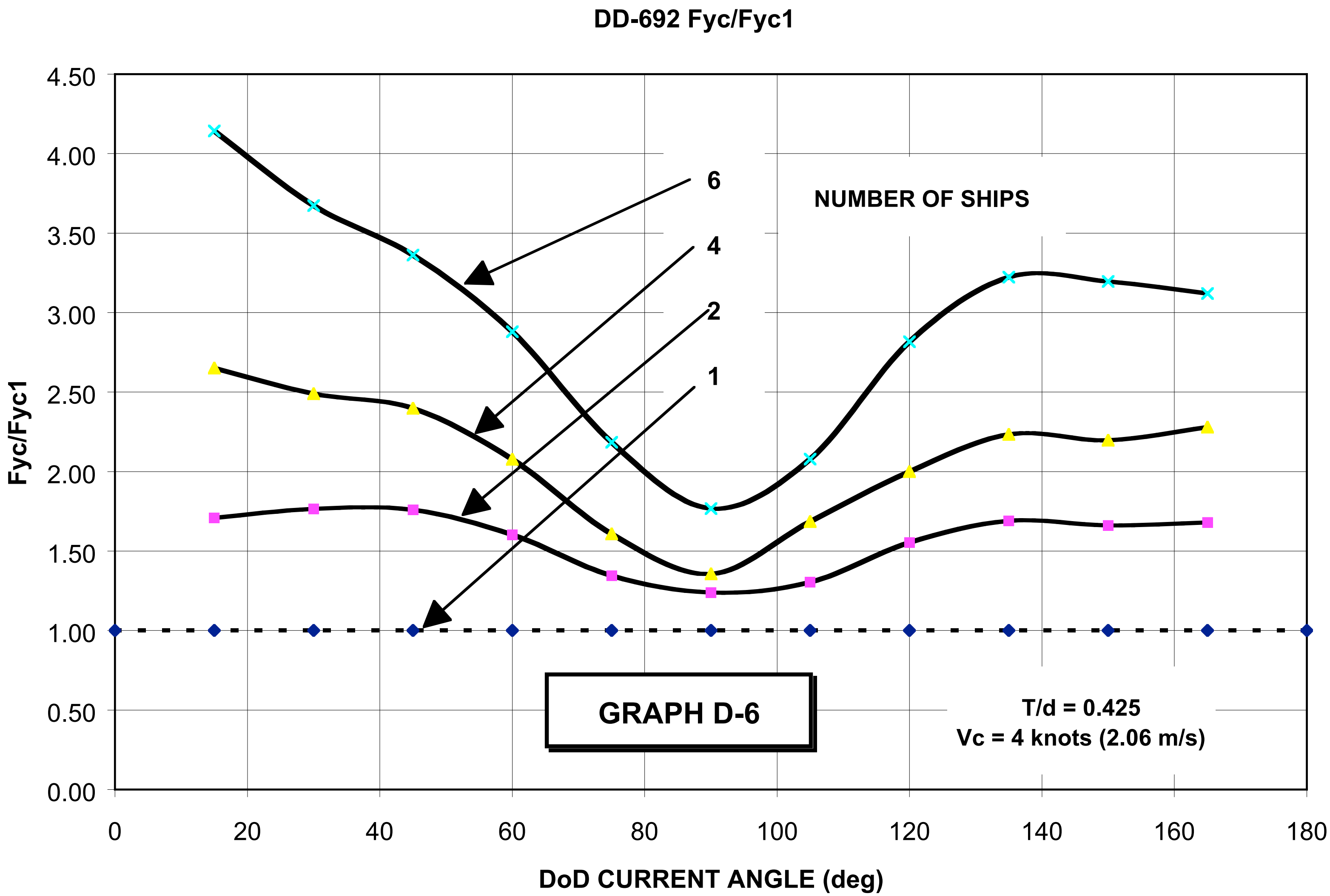


Figure A-22
DD-692 Lateral Current Force Divided by Force on One Ship

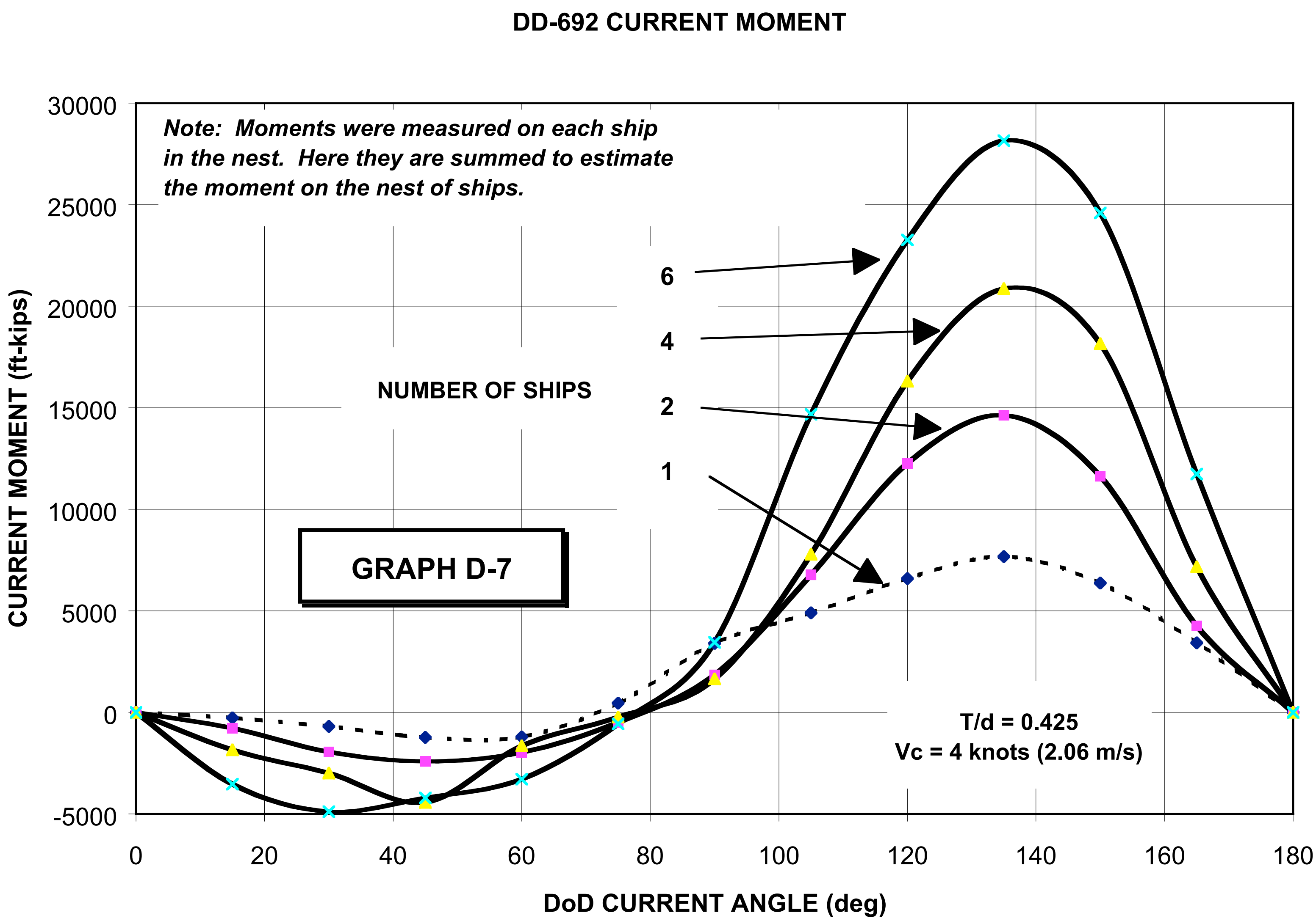


Figure A-23
DD-692 Current Moment

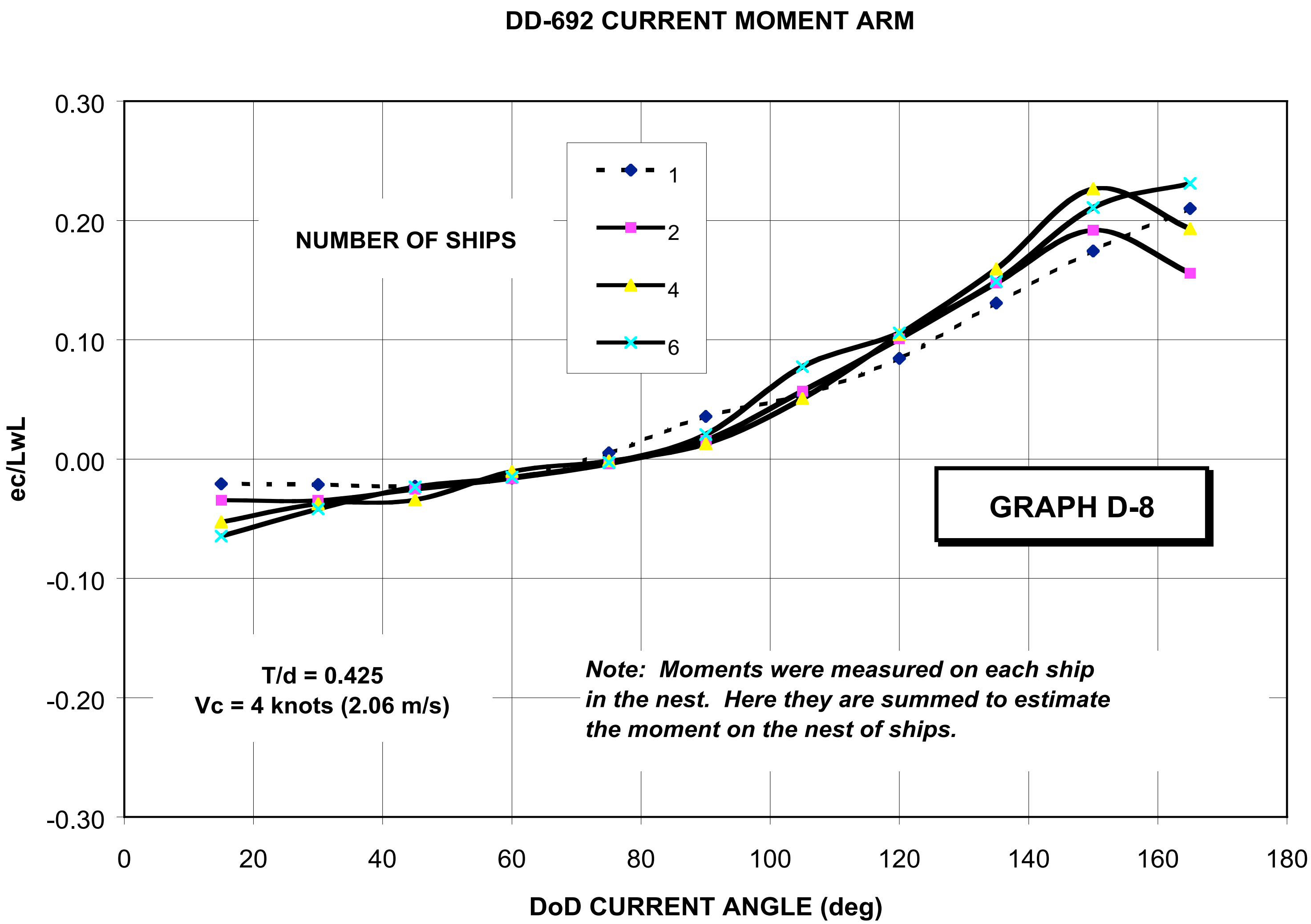


Figure A-24
DD-692 Current Moment Arm

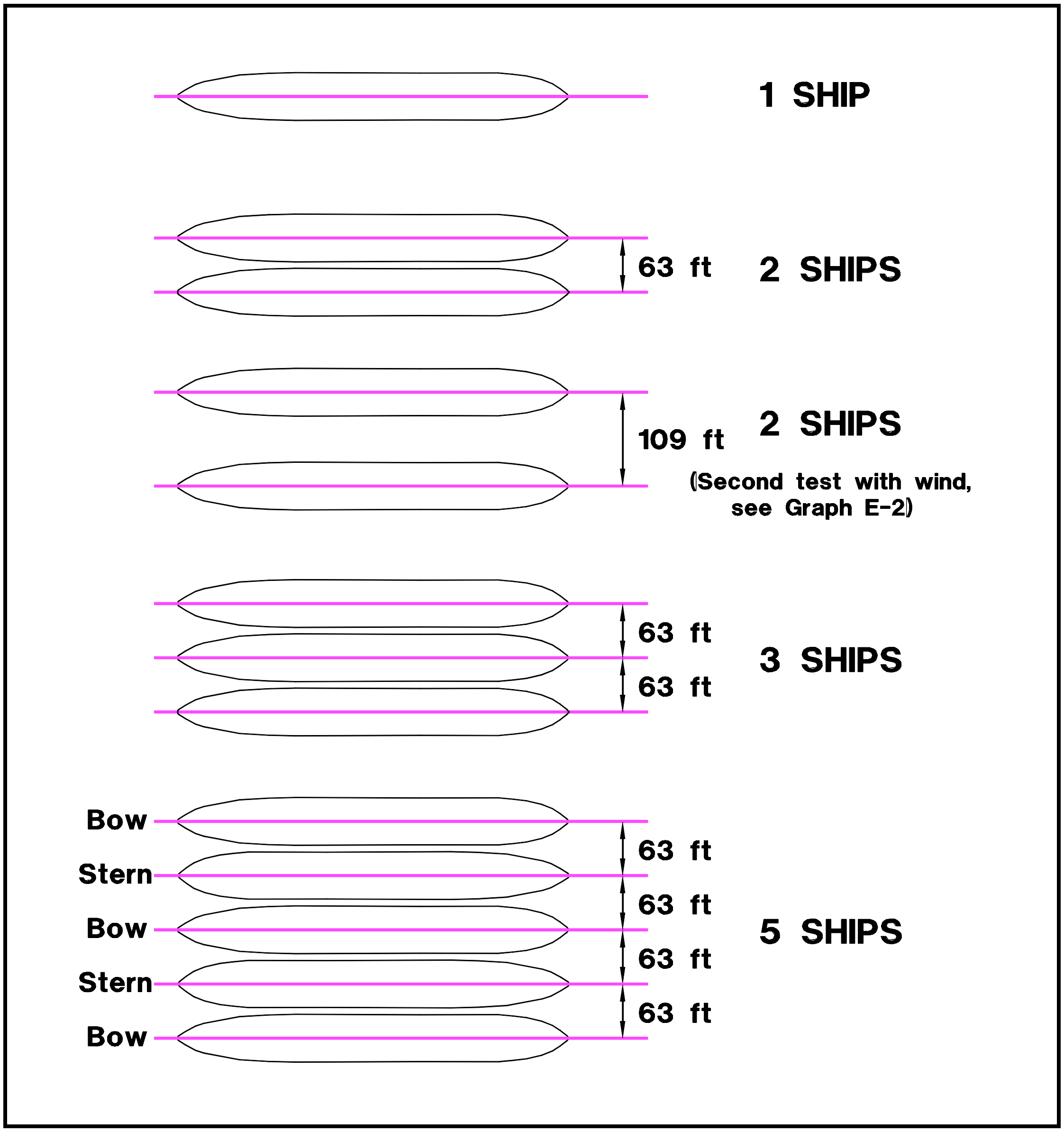


Figure A-25
EC-2 Ship Nests Tested

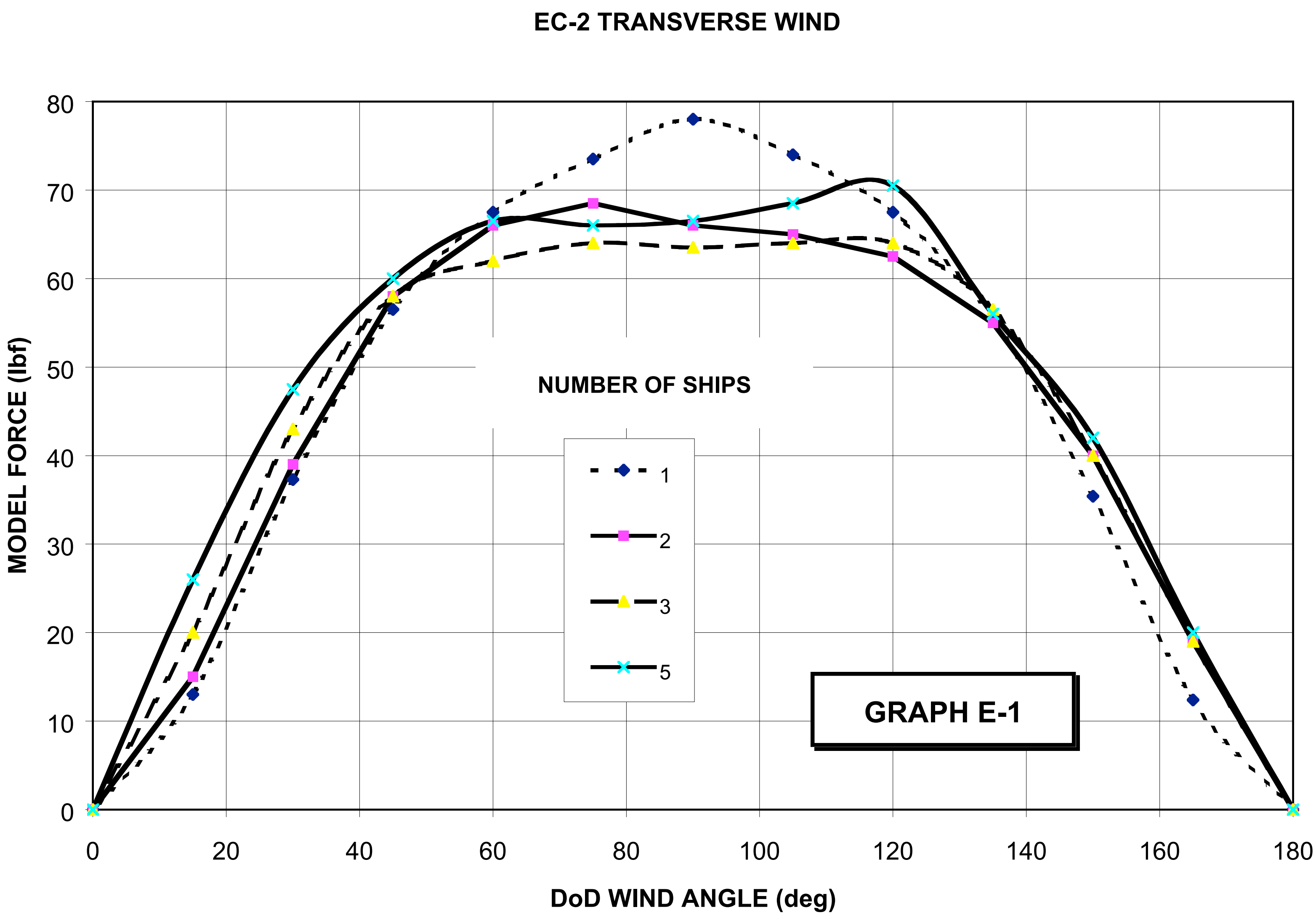


Figure A-26
EC-2 Lateral Wind Force

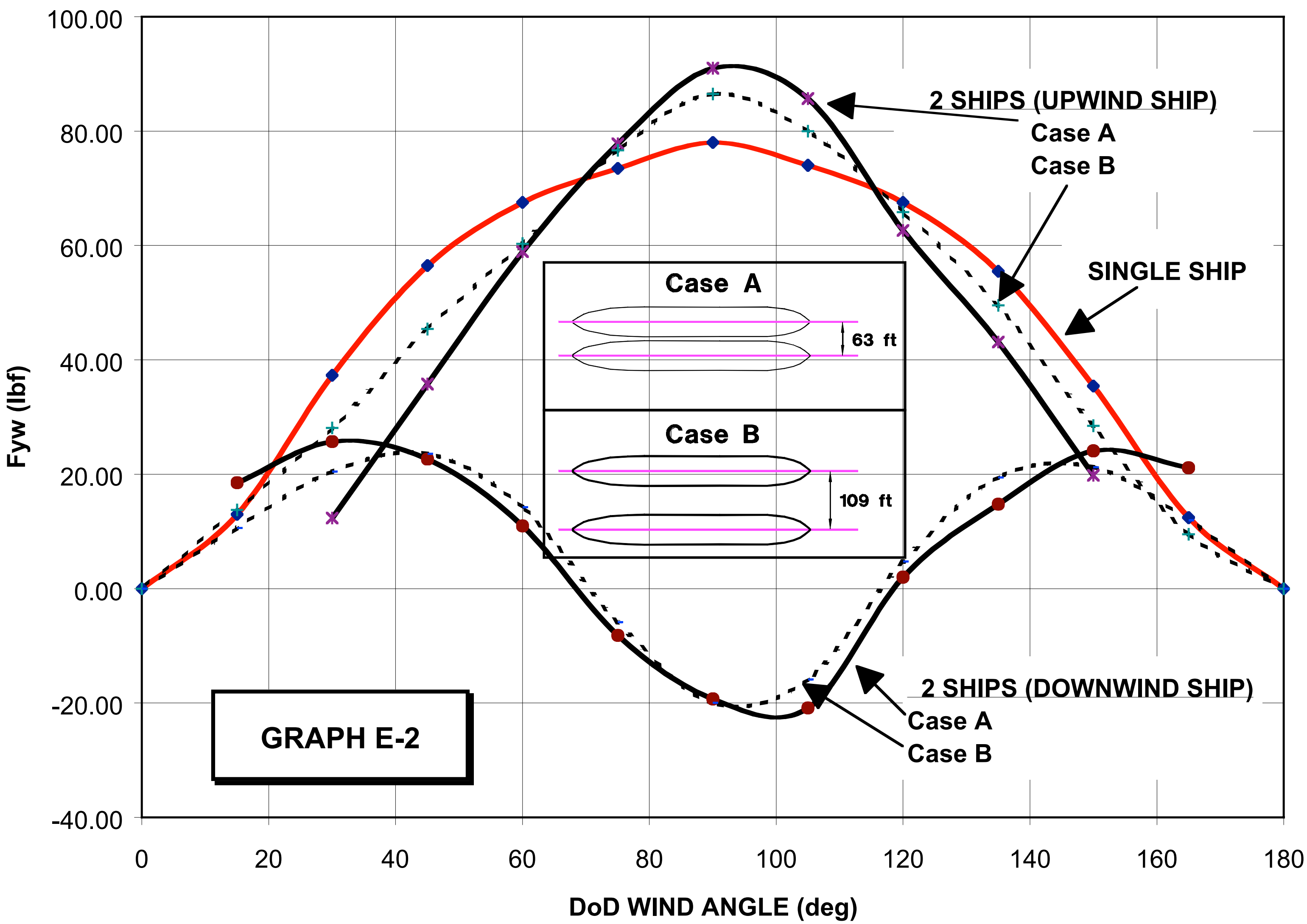


Figure A-27
EC-2 Lateral Wind Force

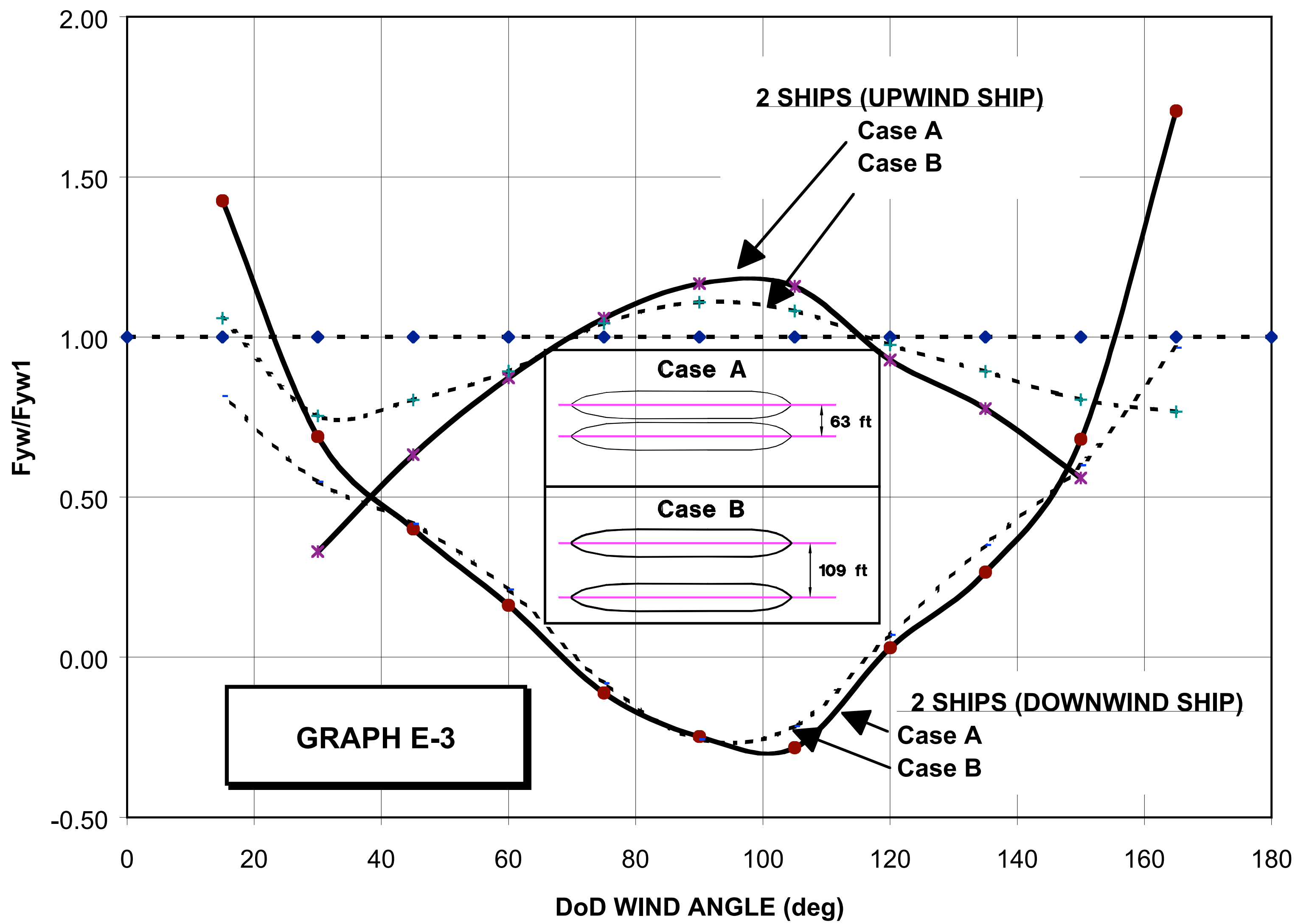


Figure A-28
EC-2 Lateral Wind Force Divided by Force on One Ship

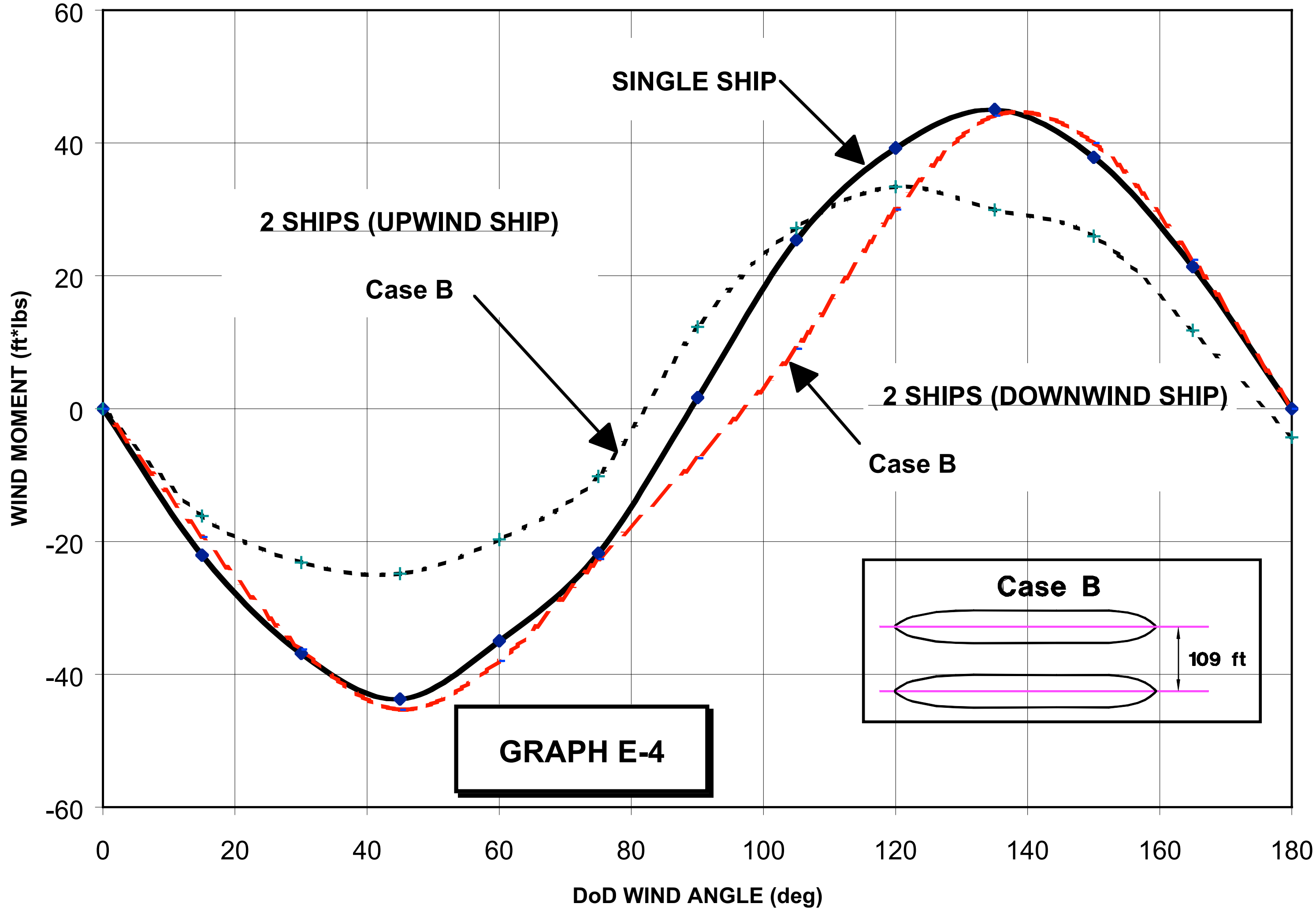


Figure A-29
EC-2 Wind Moment

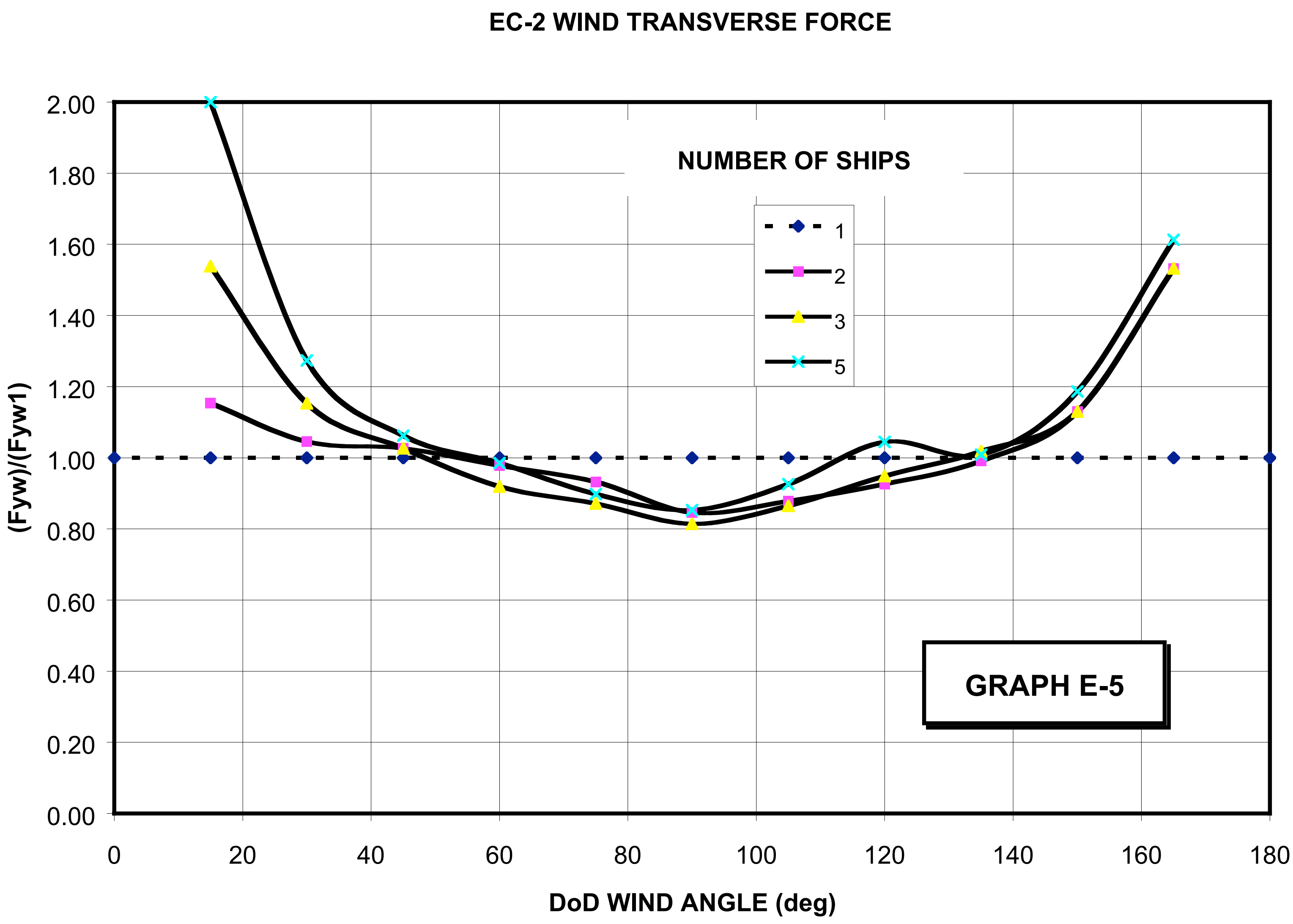


Figure A-30
EC-2 Lateral Wind Force Divided by Force on One Ship

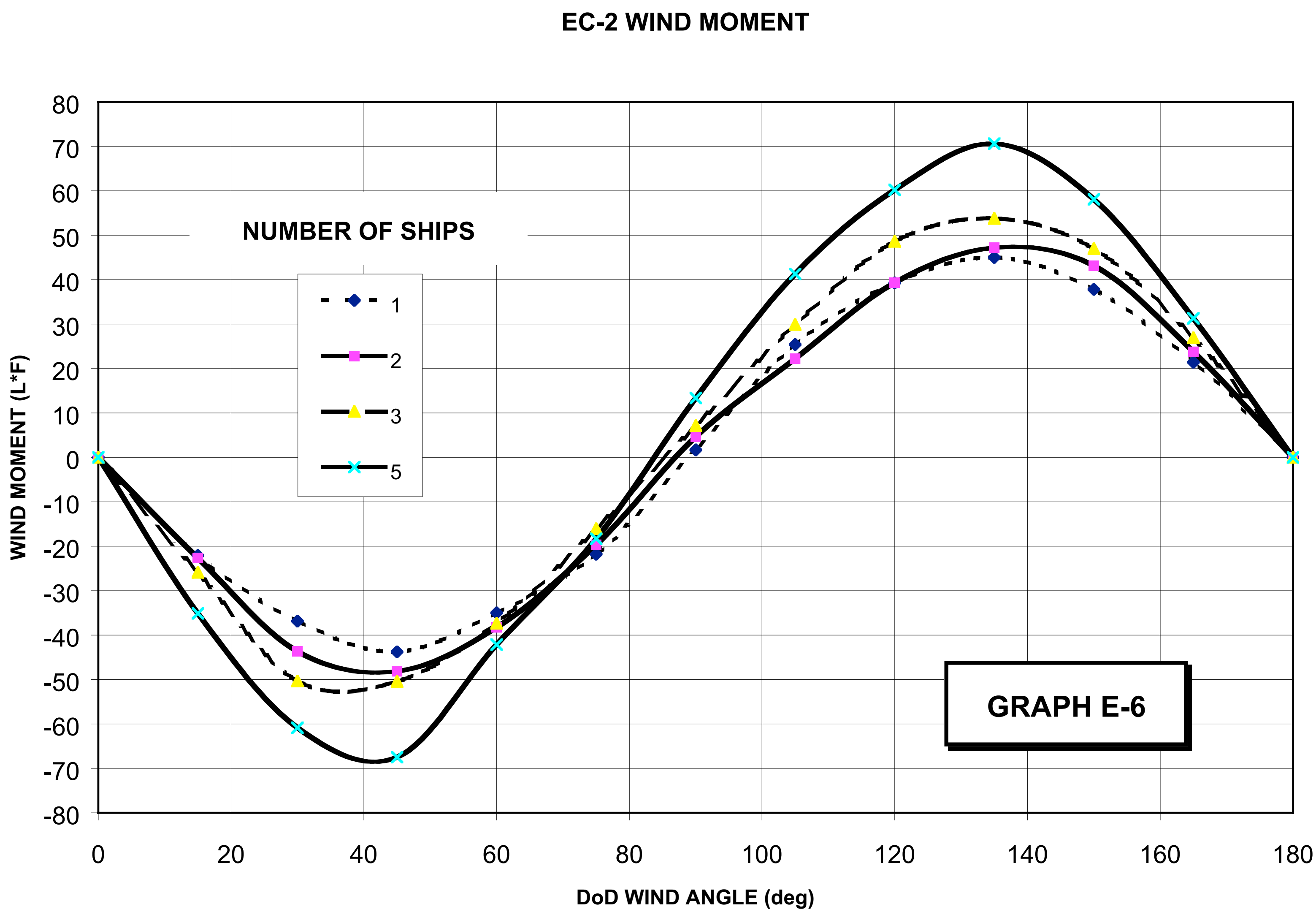


Figure A-31
EC-2 Wind Moment

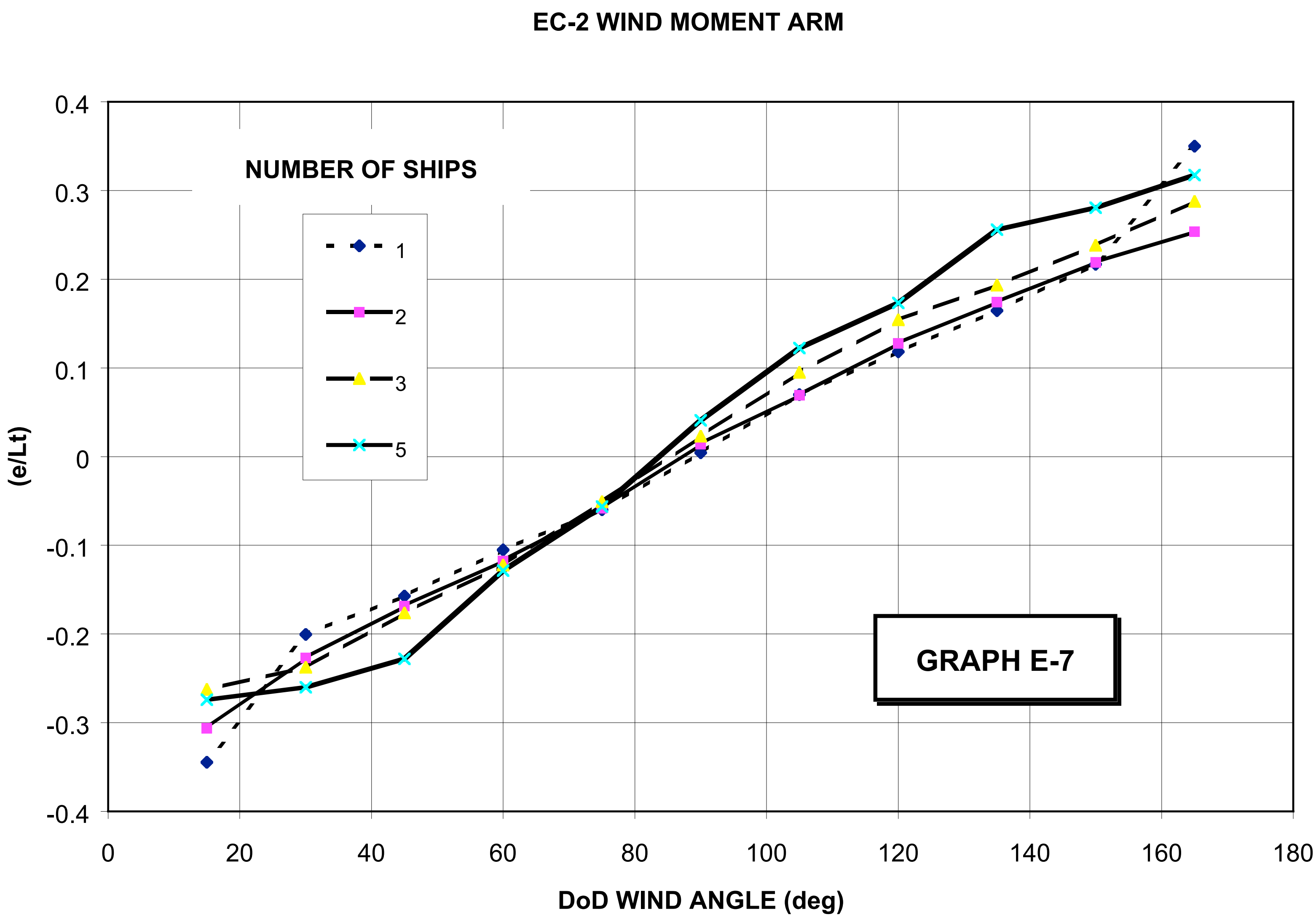


Figure A-32
EC-2 Wind Moment Arm

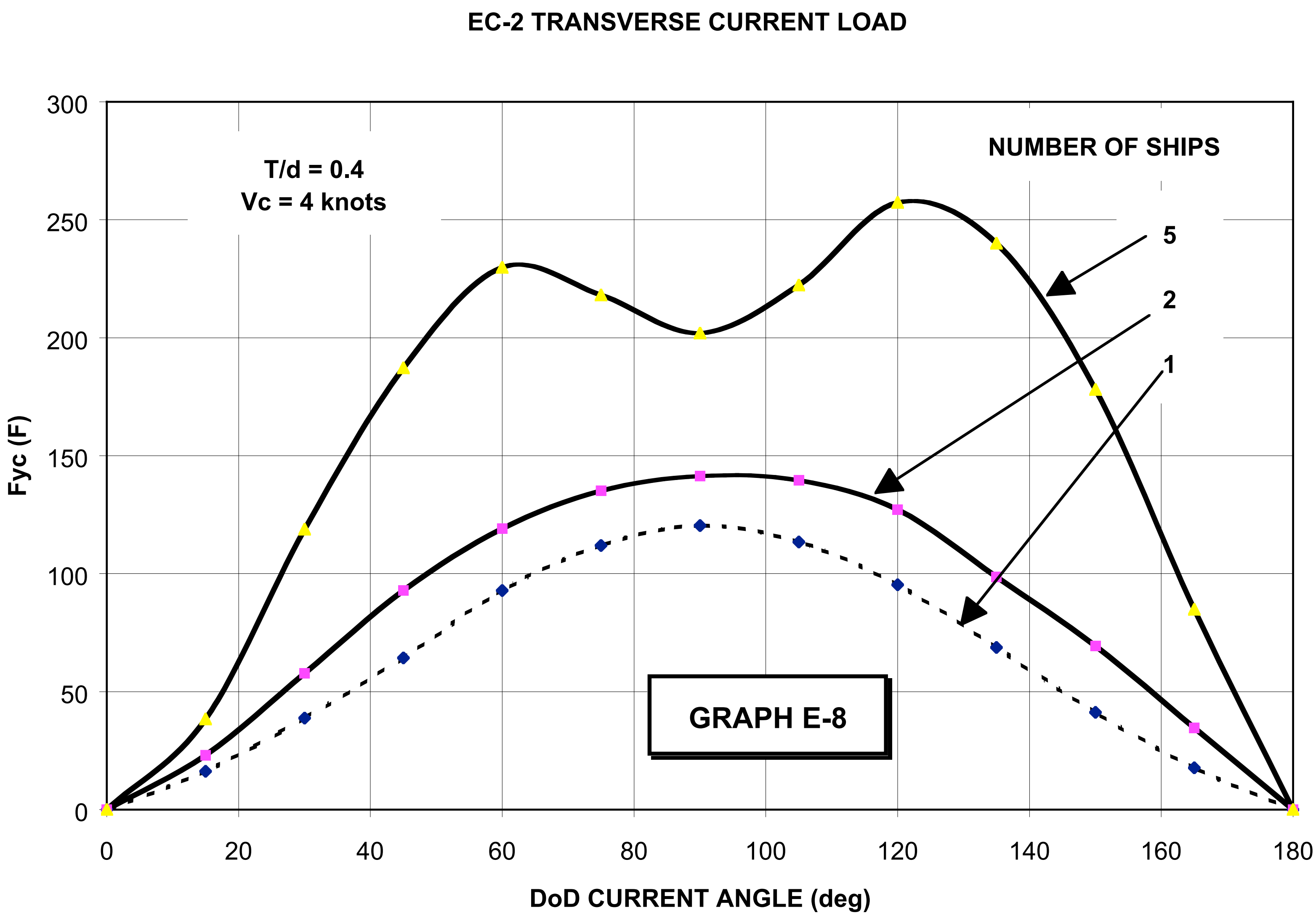


Figure A-33
EC-2 Lateral Current Forces

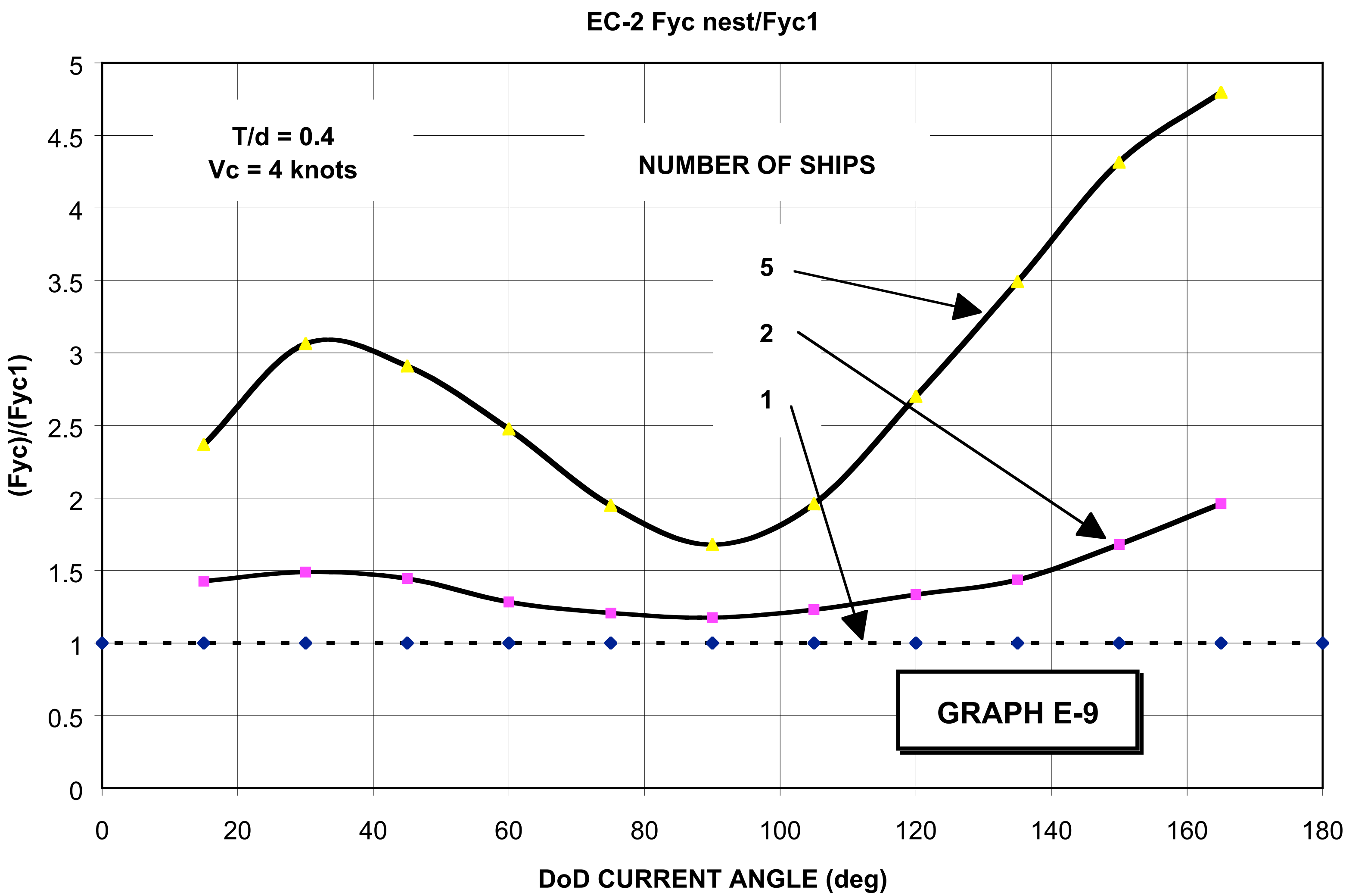


Figure A-34
EC-2 Lateral Current Force Divided by Force on One Ship

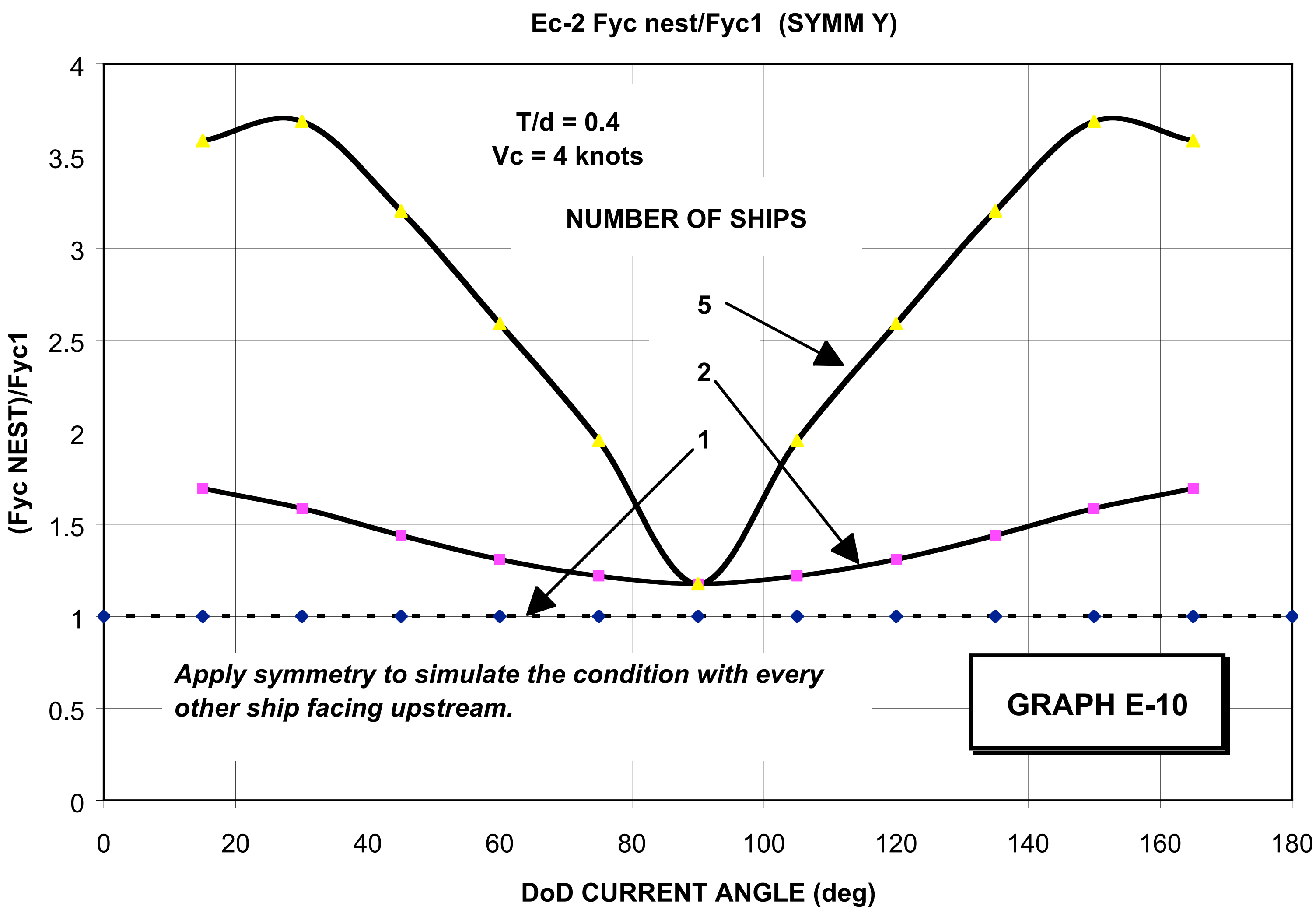


Figure A-35
EC-2 Lateral Current Force Divided by Force on One Ship

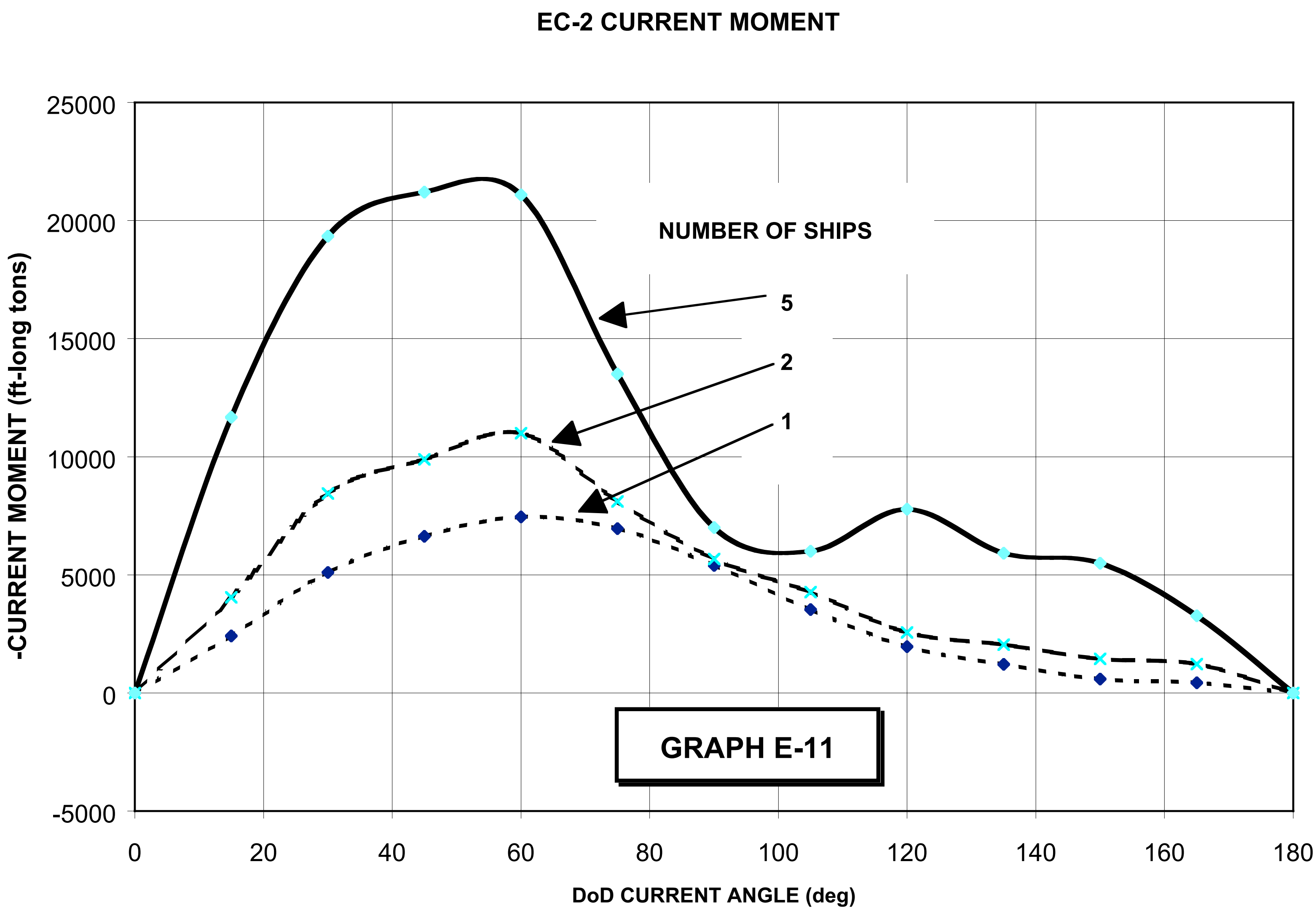


Figure A-36
EC-2 Current Moment

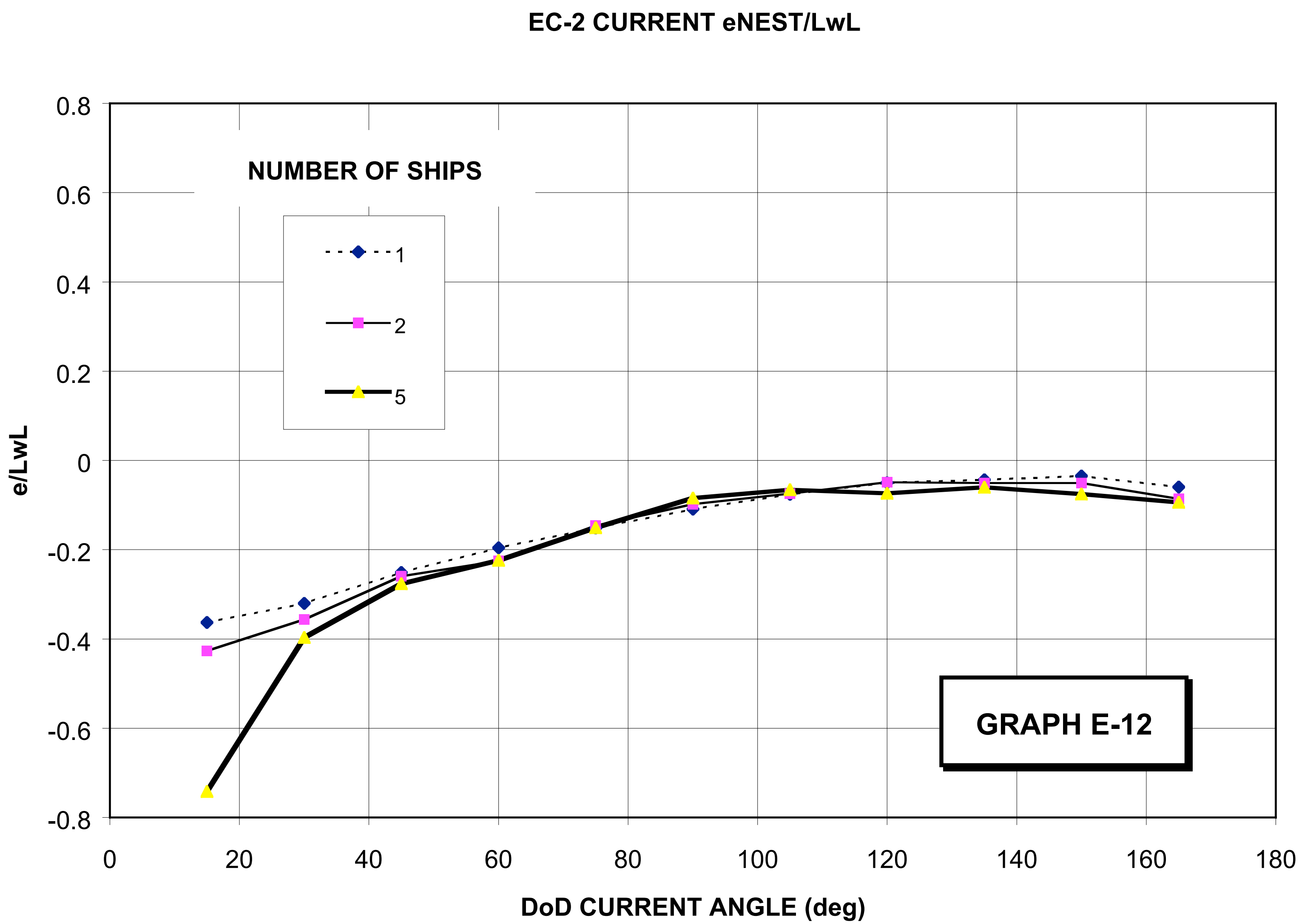


Figure A-37
EC-2 Current Moment Arm

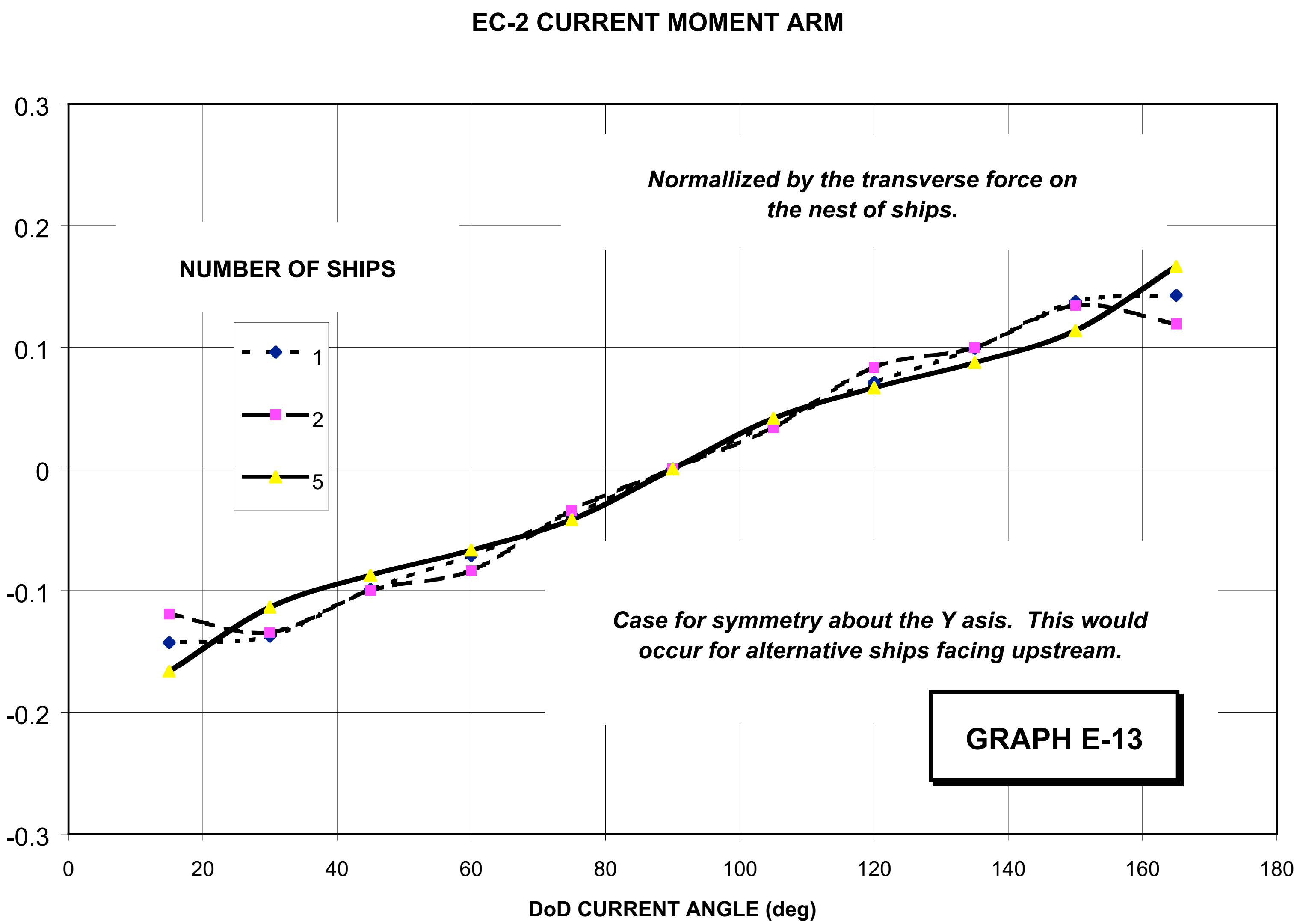


Figure A-38
EC-2 Current Moment Arm

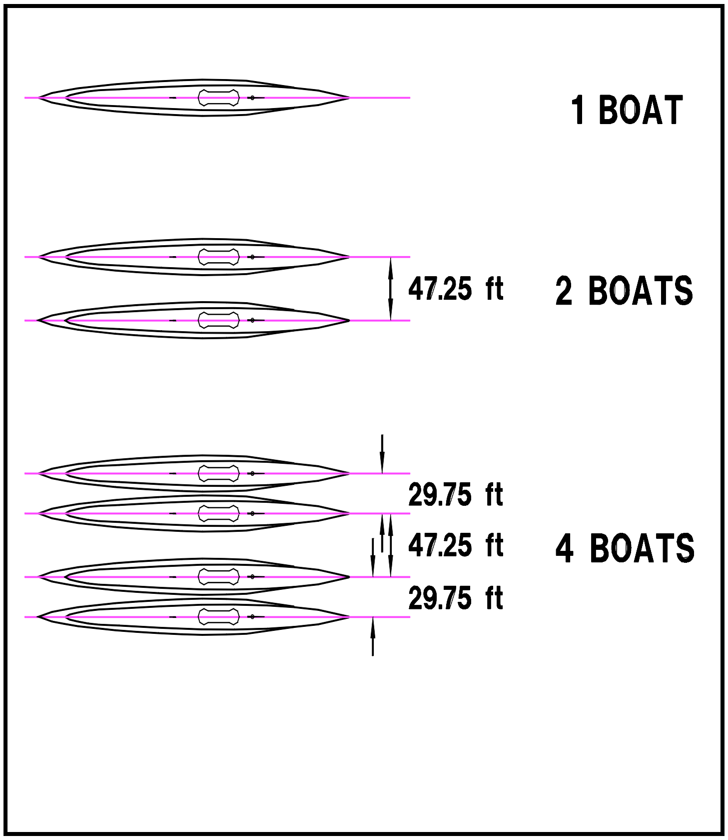


Figure A-39
SS-212 Nests Tested

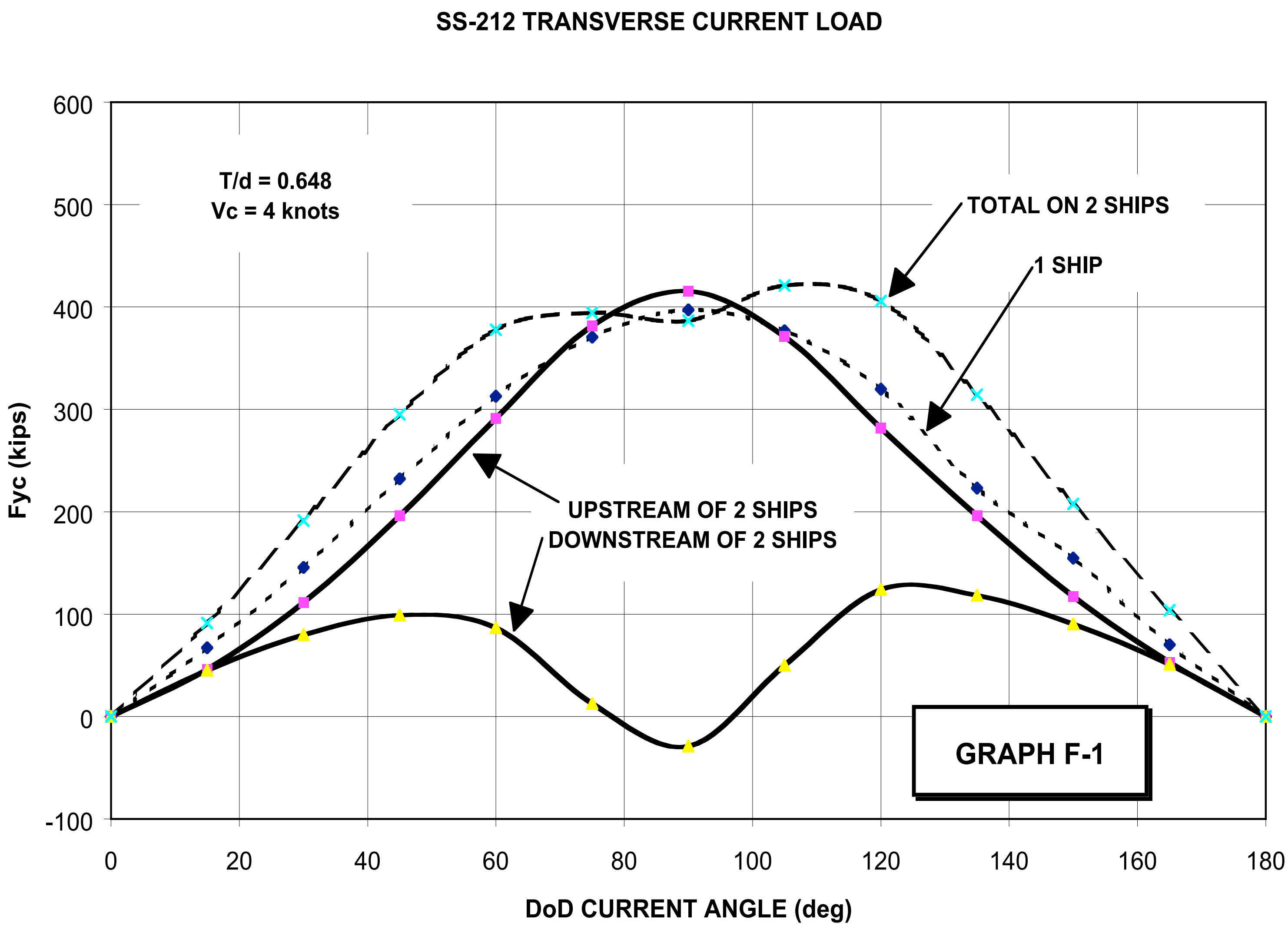


Figure A-40
SS-212 Lateral Current Forces

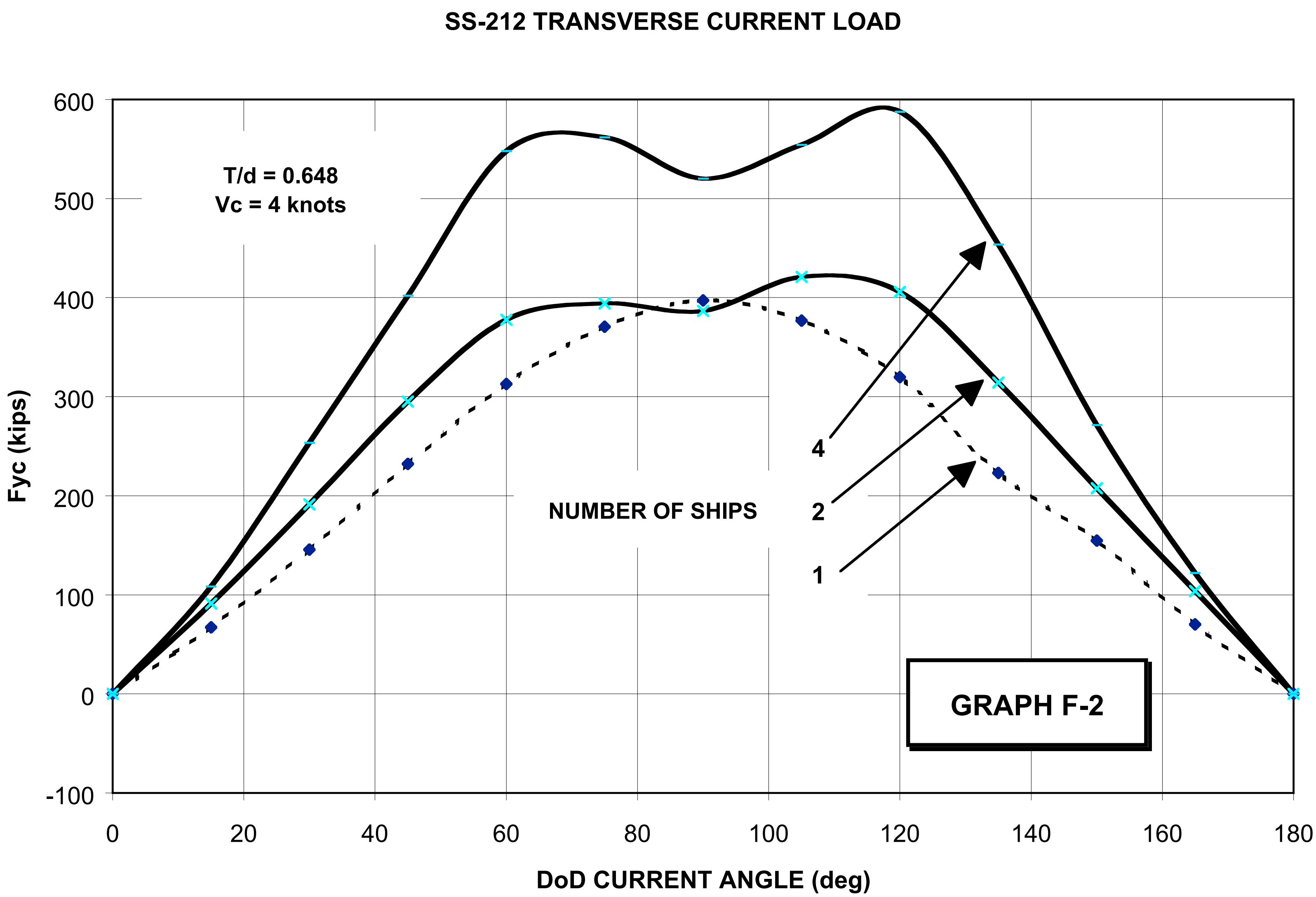


Figure A-41
SS-212 Lateral Current Forces

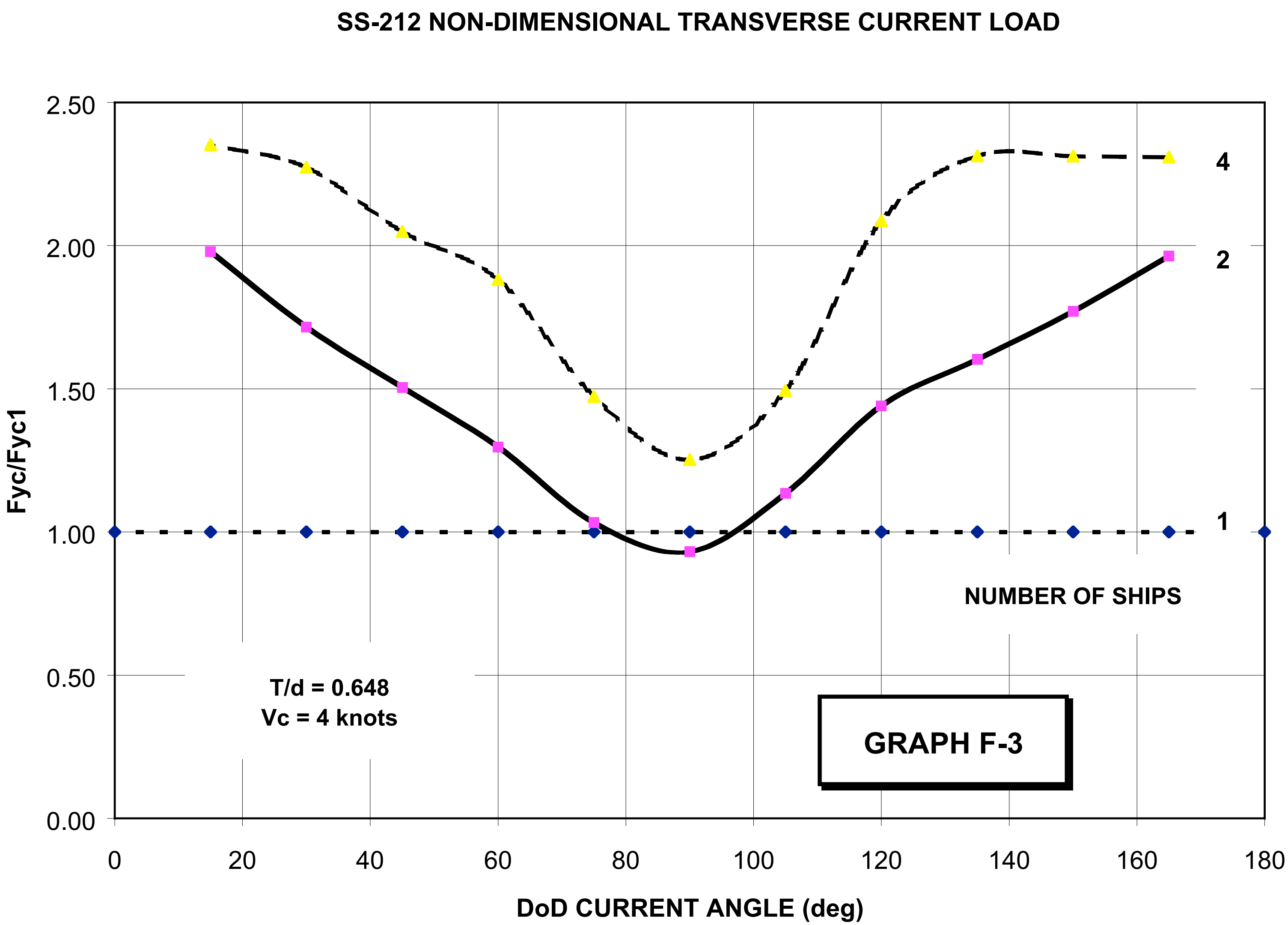


Figure A-42
SS-212 Lateral Current Force Divided by Force on One Boat
Force on One Boat

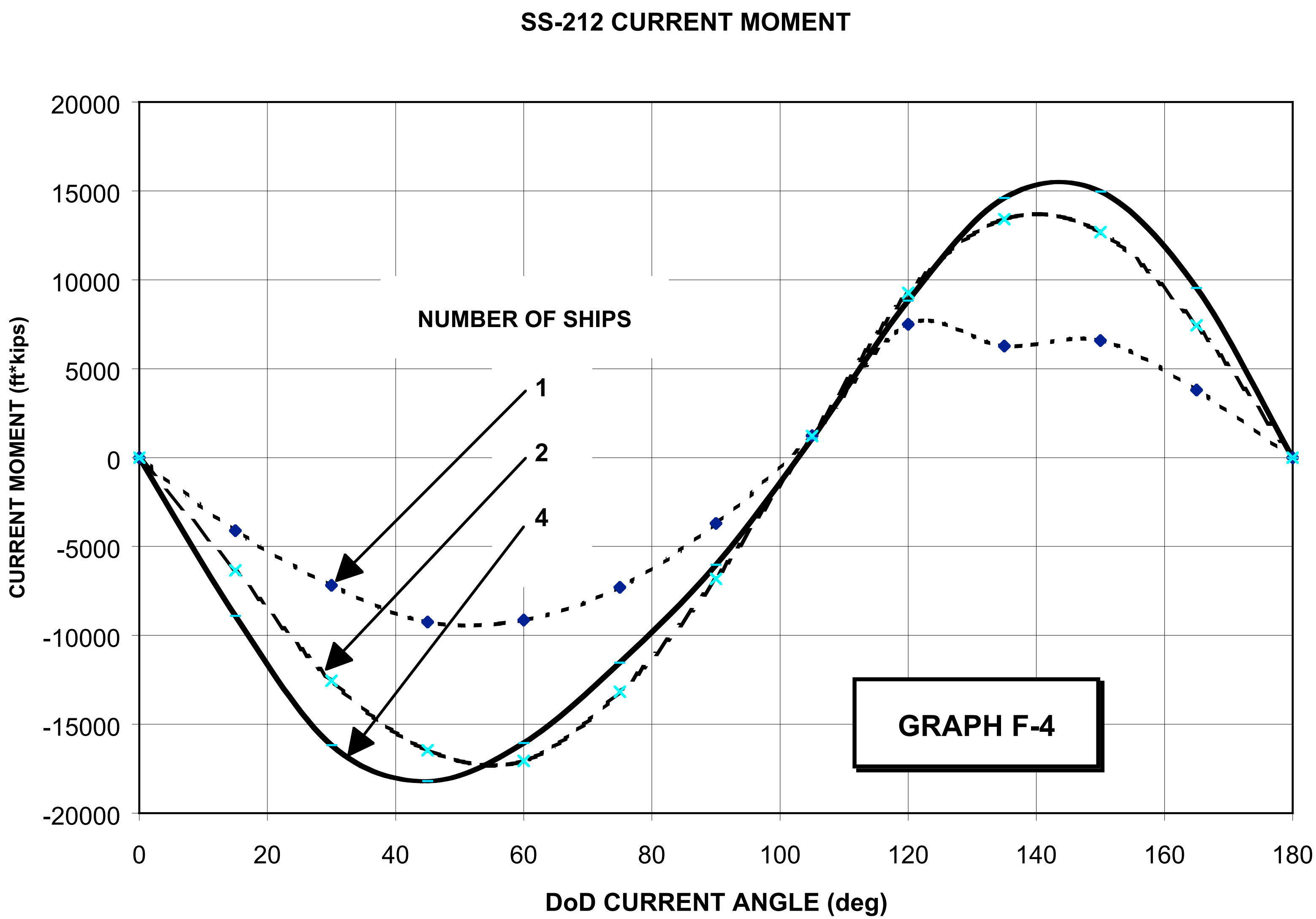


Figure A-43
SS-212 Current Moment

SS-212 CURRENT MOMENT ARM-0.30-0.20-0.100.000.100.200.300204060801001201401601800DoD CURRENT ANGLE (deg)e/LT/d :

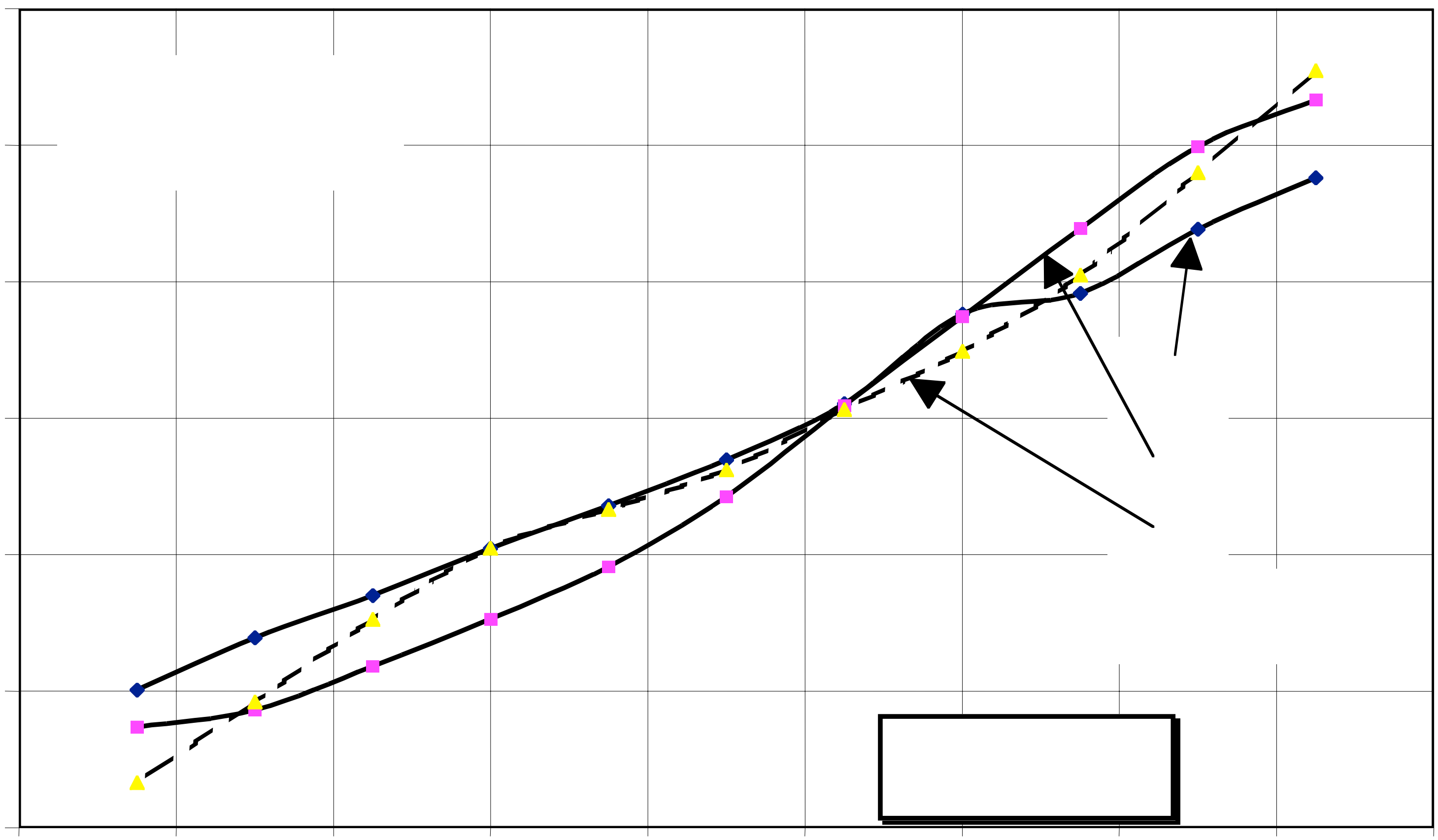


Figure A-44
SS-212 Current Moment Arm

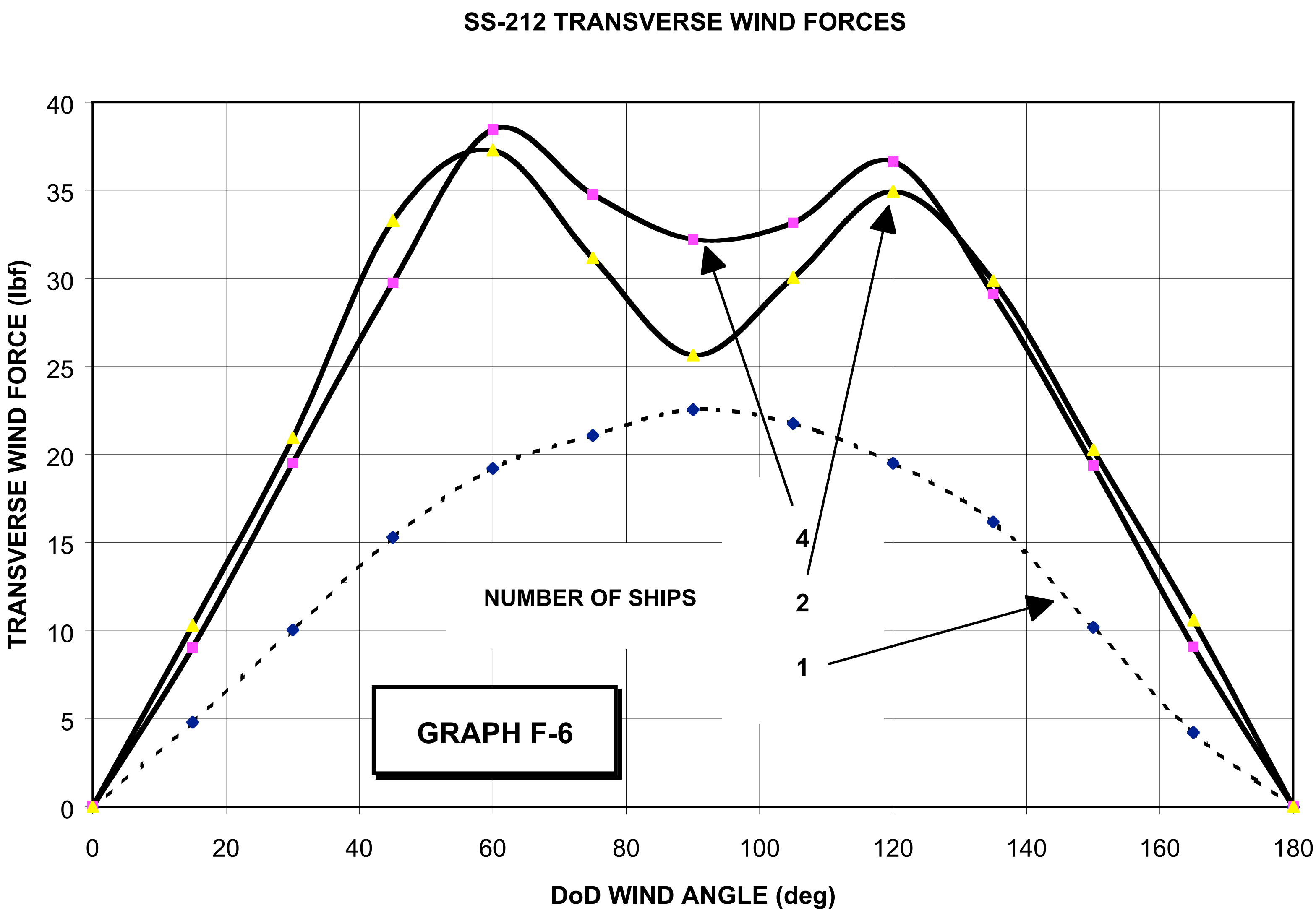


Figure A-45
SS-212 Lateral Wind Force

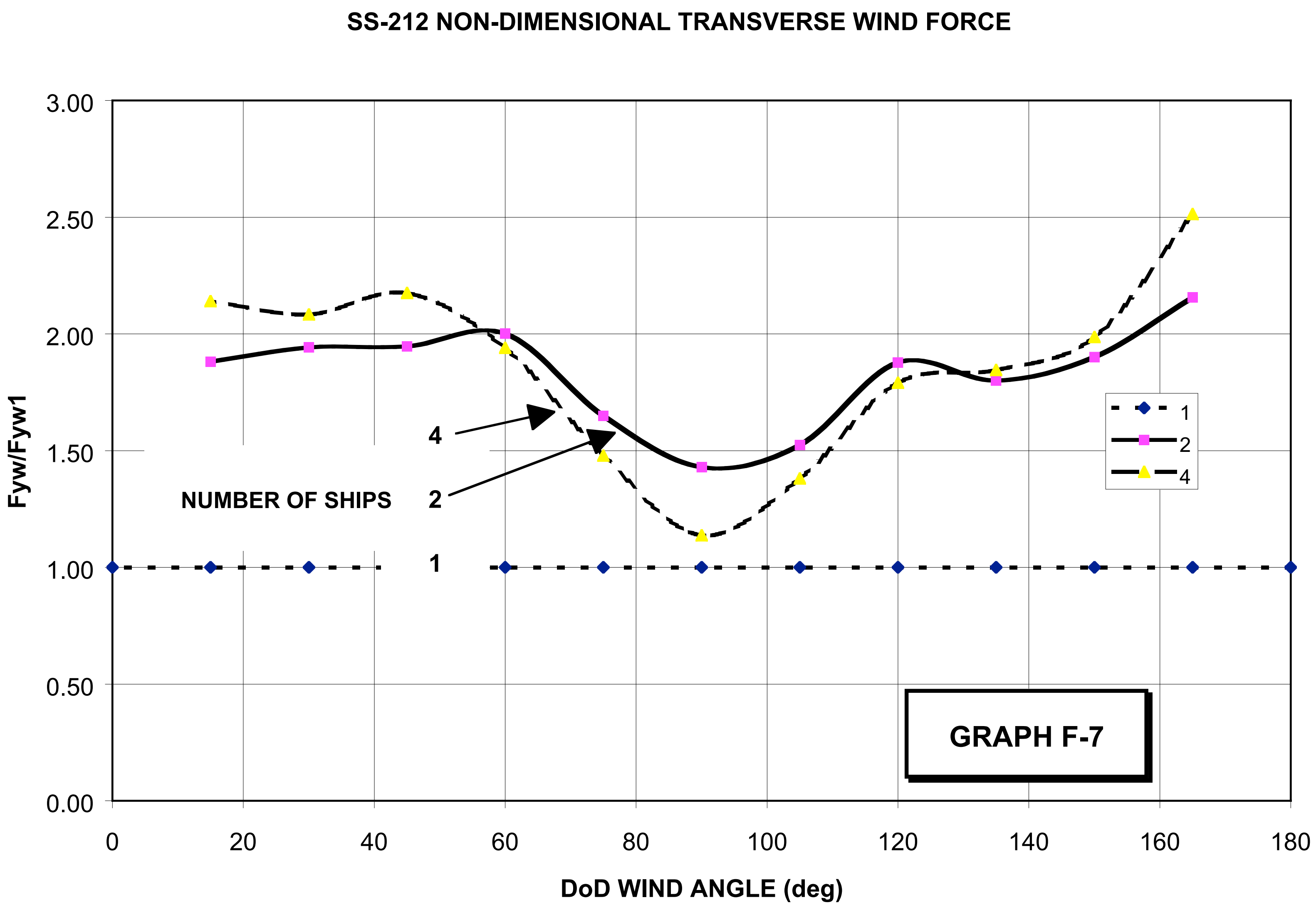


Figure A-46
SS-212 Lateral Wind Force Divided

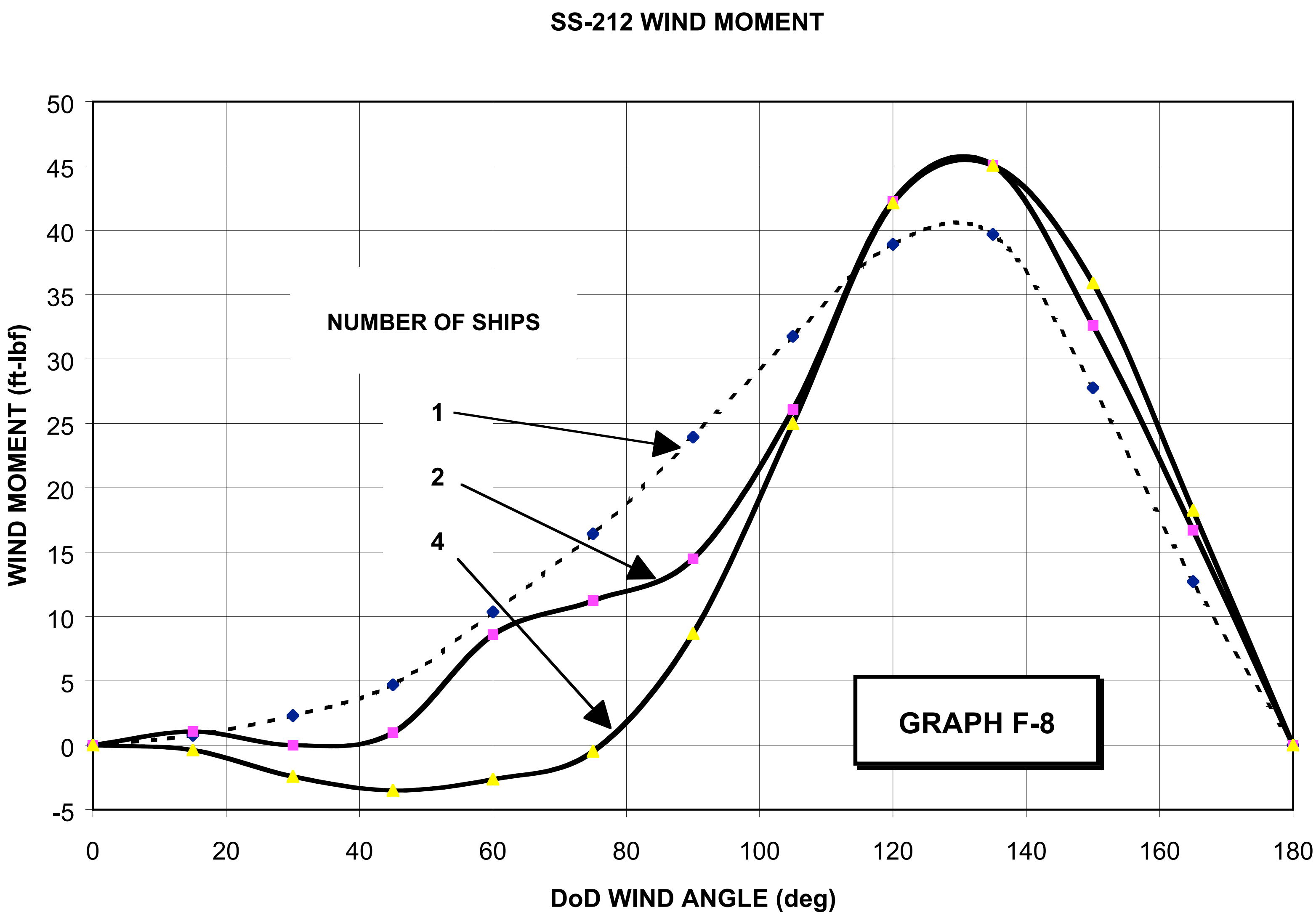


Figure A-47
SS-212 Wind Moment

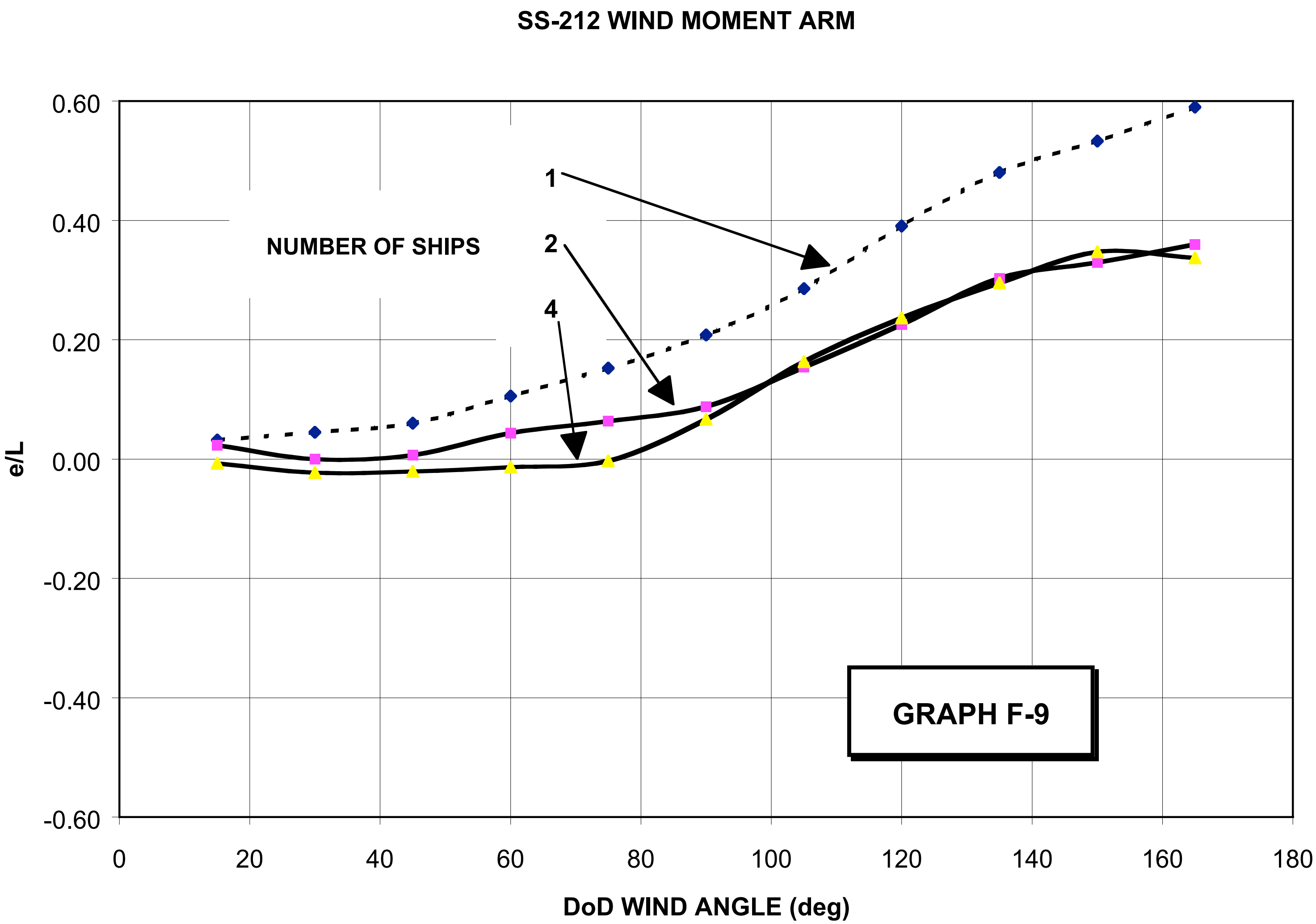


Figure A-48
SS-212 Wind Moment Arm

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GLOSSARY

AISC. American Institute of Steel Construction.

API. American Petroleum Institute.

DOD. Department of Defense.

DM. Design manual.

MLW. Mean low water.

MLLW. Mean lower low water.

MSC. Military Sealift Command.

NAVFACENGCOM. Naval Facilities Engineering Command.

NAVSEASYSCOM. Naval Sea Systems Command.

NBS. National Bureau of Standards.

NCDC. National Climatic Data Center.

NFESC. Naval Facilities Engineering Services Center.

NUREG. Nuclear Regulatory Commission.

OCIMF. Oil Companies International Marine Forum.

PIANC. Permanent International Association of Navigation Congresses.

CUSTODIAN
NAVY - YD2

PREPARING ACTIVITY
NAVY - YD2

PROJECT NO.
FACR-5005

STANDARDIZATION DOCUMENT IMPROVEMENT PROPOSAL

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4. NATURE OF CHANGE (identify paragraph number and include proposed rewrite, if possible. Attach extra sheets as needed.)

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