Report No. CG-D-12-92

AD-A252 345

SPRING 1985 LEEWAY EXPERIMENT

Louis Nash
and
James Willcox

U.S. Coast Guard
Research and Development Center
1082 Shennecossett Road
Groton, CT 06340-6096

FINAL REPORT
OCTOBER 1991

This document is available to the U.S. public through the
National Technical Information Service, Springfield, Virginia 22161

Prepared for:

U.S. Department Of Transportation
United States Coast Guard
Office of Engineering, Logistics, and Development
Washington, DC 20593-0001

92-16733

92 6 24 079

NOTICE

SAMUEL F. POWEL, III
Technical Director
U.S. Coast Guard Research and Development Center
Avery Point, Groton, Connecticut 06340-6096

Technical Report Documentation Page

1. Report No. CG-D-12-92	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle SPRING 1985 LEEWAY EXPERIMENT		5. Report Date October 1991
		6. Performing Organization Code
7. Author(s) Louis Nash and James Willcox		8. Performing Organization Report No. R&DC 01/88
9. Performing Organization Name and Address U.S. Coast Guard Research and Development Center 1082 Shennecossett Road Groton, Connecticut 06340-6096		10. Work Unit No. (TRAIS)
		11. Contract or Grant No.
12. Sponsoring Agency Name and Address Department of Transportation U.S. Coast Guard Office of Engineering, Logistics, and Development Washington, D.C. 20593-0001		13. Type of Report and Period Covered FINAL
		14. Sponsoring Agency Code

15. Supplementary Notes

This report is the third on leeway and the 20th in a series that documents the Probability of Detection in Search and Rescue (POD/SAR) Project at the U.S. Coast Guard Research and Development Center (R&DC).

16. Abstract

The U.S. Coast Guard R&DC and Florida Atlantic University (FAU) conducted an experiment off the east coast of Florida during March and April 1985 in order to determine the leeway of various craft common in Search and Rescue (SAR) situations. Leeway, defined as the response of a survivor craft to the effect of wind alone, is an important component of the total drift calculation for a survivor craft. Other components are the sea current, tidal current, and wind-driven current. Leeway data will be utilized by search planners to predict the movement of various search targets. The search targets evaluated were three types of 4-man life rafts, one 6-man life raft, and three types of small boats (less than 21 feet in length). This report presents results of the R&DC's statistical analysis. Results of FAU's use of the data to calibrate and test a numerical model are presented separately, DOT/OST/P-34/87/058, August 1986.

Leeway was calculated as the difference between the test craft's velocity and the average current of the upper three feet of the water column. The oceanic surface current at the test craft was determined from an array of drifters surrounding the test craft. The drifters and small craft were tracked by a Microwave Tracking System (MTS). The wind was measured onboard the small craft at a height of six feet above the ocean surface. The apparent wind relative to the current at the raft was used in the analysis.

Two circular canopied rafts with deep-draft ballast systems with drogue attached had nearly zero leeway. The leeway rates without a drogue attached were 0.0099 and 0.0144. The leeway for an undrogued canopied 4-man raft with ballast bags was less than values currently used in search planning. The leeway rate for a canopied raft without ballast or drogue was 0.0490. The 14-foot outboard drifted beam to the wind, at an angle of 14 to 24 degrees off downwind and with a leeway rate of 0.0398. The 19-foot center-console sport fisherman and 20-foot cabin cruiser drifted downwind with their sterns to the wind and had leeway rates of 0.0493 and 0.0582, respectively.

During the experiment, wind speeds of 1.4 to 15.9 knots, waves of 0 to 5 feet, and swells up to 6 feet prevailed.

17. Key Words	18. Distribution Statement
llife raft drogue leeway	Document is available to the U.S. public through the National Technical Information Service, Springfield, Virginia 22161

19. Security Classif. (of this report)	20. SECURITY CLASSIF. (of this page)	21. No. of Pages	22. Price
UNCLASSIFIED	UNCLASSIFIED		

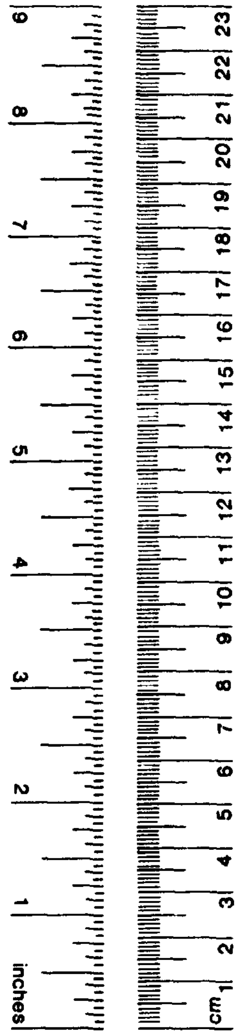
Form DOT F 1700.7 (8/72) Reproduction of form and completed page is authorized

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

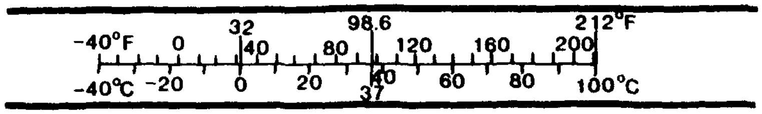
Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (WEIGHT)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (EXACT)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures. Price $2.25. SD Catalog No. C13.10.286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (WEIGHT)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	0.125	cups	c
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (EXACT)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



ACKNOWLEDGMENTS

The assistance of many individuals made this research possible, especially the team from FAU under Dr. T. C. Su and Dr. F.S. Hotchkiss, and the crew of the R/V BELLOWS under Captain W. Millender from the Florida Institute of Oceanography. The Department of Transportation (DOT) Office of University Research provided the opportunity for the cooperative effort.

Special thanks go to R&D field team members Art Allen, Mike Couturier, Rick Sager, and Tim Noble. Mike was responsible for programming the tracking system and a good portion of the analysis programs. Rick and Tim were the hands-on personnel.

Finally, the assistance of Dr. D. F. Paskausky, Dr. D. L. Murphy, and Mr. Larry Nivert is gratefully acknowledged.

LIST OF ACRONYMS

CASP	Computer Assisted Search Planning
CTTO	Canadian Central Tactics and Trials Organization
DLR	Downwind Leeway Rate
DOT	Department of Transportation
FAU	Florida Atlantic University
LA	Leeway Angle
MTS	Microwave Tracking System
N/A	Not Applicable
NPL	National Physics Laboratory
POD/SAR	Probability of Detection/Search and Rescue
R&DC	Research and Development Center
rms	root mean square
RWD	Relative Wind Direction
SAR	Search and Rescue
XBT	Expendable Bathythermograph

TABLE OF CONTENTS

TABLE OF CONTENTS (Cont'd.)

TABLE OF CONTENTS (Cont'd.)

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (cont'd)

LIST OF TABLES

LIST OF TABLES (Cont'd)

[THIS PAGE INTENTIONALLY LEFT BLANK]

EXECUTIVE SUMMARY

INTRODUCTION

The Spring 1985 Leeway Experiment was a joint effort by the U.S. Coast Guard Research and Development Center (R&DC) and Florida Atlantic University (FAU). The experiment was conducted off the east coast of Florida during March and April, 1985. This report presents the results of the R&DC statistical analysis of the data. FAU used the data to calibrate and test a numerical leeway model. Their results are presented separately.

Leeway is defined as that movement of a craft through the water caused by the wind acting on the exposed surface of the craft. Leeway values of life rafts and small craft are needed in order to predict the locations of survivors at sea. There are seven classes of leeway targets in the current search planning doctrine. A rule of thumb is provided for calculating leeway of rafts with the addition of ballast buckets and a canopy; no guidance is given for calculating the leeway of the newer deep-draft ballasted type raft with drogue.

Four canopied life rafts and three small boats representing the two broadest leeway classes and canopy/ballast bucket cases were tested. A new category, the deep-draft ballasted raft with drogue, was also represented. The life rafts were a Switlik 4-man raft, a Givens 6-man raft, an Avon 4-man raft, and a Winslow 4-man raft. All but the Avon 4-man raft were deployed with and without a drogue. The Switlik 4-man and the Givens 6-man rafts were circular canopied life rafts with deep-draft ballast systems. The Avon 4-man raft was a circular canopied raft with ballast bags. The Winslow 4-man raft was an oblong canopied raft with no ballast system.

The three small boats were a 14-foot outboard, a 19-foot outboard and a 20-foot cabin cruiser. The 14-foot outboard was a flat-bottomed Boston Whaler-type outboard. The 19-foot outboard was a sport fisherman with center console and outboard motor.

The 20-foot cabin cruiser was a small, light-displacement cabin cruiser with two inboard-outboard motors.

The leeway of the small craft was determined by subtracting the current of the upper three feet of the ocean from the test craft's velocity. The current at the test craft was calculated from an array of drifters surrounding the test craft. The velocities of the drifters and the test craft were calculated from their successive positions as determined by a Microwave Tracking System (MTS). The wind was measured onboard the test craft at a height of 6 feet.

RESULTS

During these tests a new class of leeway drift objects was identified and tested. This new leeway class was canopied rafts with deep-draft ballast system and drogue. Both representatives of this class were circular rafts. When drogued, these two rafts were found to have zero or near-zero leeway for winds up to 13 knots.

Current leeway doctrine classifies the undrogued canopied raft with the deep-draft ballast system as a light-displacement vessel with drogue. The Computer Assisted Search Planning (CASP) system uses a range of leeway rates from 0.0335 to 0.0665. The leeway rates of the Switlik 4-man and Givens 6-man rafts were considerably lower than these and are presented below. This confirms the results from the Summer 1983 Experiment that these rafts drift more slowly than previously believed (Nash and Willcox, 1985).

The raft with canopy and ballast buckets tested in this experiment was the Avon 4-man raft. Present leeway doctrine has this raft drifting at the same rate as an unballasted raft without canopy, i.e., 7% of the wind (using the rules of thumb of adding 20% for the canopy and subtracting 20% for the addition of ballast buckets). CASP uses a range of leeway rates from 0.0469 to 0.0931. Leeway speeds for the Avon 4-man raft from this experiment were substantially lower than speeds calculated from the leeway rates in CASP and are presented below. During the Summer 1983 Experiment, the leeway of a 6-man raft of different design, with fewer ballast bags and a different canopy style, was found to be within present doctrine.

Data for the Winslow 4-man raft (canopy, no ballast) with drogue are too limited for any firm conclusions. The leeway of the Winslow 4-man raft without drogue was found to increase with increasing wind speed and swell height. Using the rule of thumb for adding a canopy, the leeway rates used by CASP would range from 0.056 to 0.112. Leeway rates from this experiment for the Winslow 4-man raft are lower than the rates used in CASP, they are presented below.

The three small boats tested fit into the classification of light displacement vessels. The leeway rates as used by CASP for this classification are 0.0469 through 0.0931. Of the three small craft, only the 14-foot outboard fell outside that range. The 19-foot outboard and the 20-foot cabin cruiser drifted downwind with their sterns to the wind. The 14-foot outboard drifted beam to the wind and off the downwind direction by +14° to -24°, ±10°. This deflection off downwind was well within the 35° used under the present doctrine.

RECOMMENDATION FOR OPERATIONAL LEEWAY GUIDANCE

The proposed modifications to existing search planning doctrine are presented in CASP format since CASP is used for most predictions involving any significant amount of drift time.

<u>Canopied rafts with deep-draft ballast system and drogue</u>: For wind speeds up to 13 knots, the leeway speed is negligible. There are no data for winds above 13 knots. The maximum

deflection left or right of downwind for these rafts with drogue does not exceed 10°.

Canopied rafts with deep-draft ballast systems (no drogue): Leeway rates for the two types of undrogued, canopied rafts with deep-draft ballast systems tested in this experiment were 0.0099 and 0.0144. The average of the two (base rate) is 0.0122 with a rate uncertainty of 0.25, well below values used in CASP. The rafts were found to have a deflection off the downwind direction of 0° ± 10°. Assuming that these two rafts are representative of the whole class, the leeway angle is 10° to either side of downwind.

Canopied rafts with ballast buckets: Data from the Summer 1983 Experiment for a raft in this category were within the present SAR guidelines. However, the Avon 4-man raft data described in this report did not fall within these guidelines. The authors recommend expanding the range of leeway values to cover both data sets. The recommended base rate is 0.05, with rate uncertainty of 0.96. No change is recommended for the leeway angles.

Canopied rafts without ballast or drogue: The leeway rate for the Winslow 4-man raft from this experiment is slightly below the minimum rate used under the present CASP doctrine. The proposed base rate is 0.08 (based on a leeway rate of 0.0667 plus 20% for the addition of a canopy), with a rate uncertainty of 0.40. No changes to leeway angles are recommended.

Light-displacement small craft and outboards: Because one of the three small craft used in this experiment had leeway rates lower than the present doctrine, the authors recommend expanding the rate limits. The proposed base rate is 0.062, with a rate uncertainty of 0.50. No change in leeway angles is recommended.

RECOMMENDATIONS FOR FUTURE RESEARCH

During this experiment, leeway was determined indirectly from other parameters. New technology may provide a method of measuring leeway directly without using a tracking system and the number of personnel currently required. This new technology is the electromagnetic current meter, which is capable of measuring very low velocities and working in the wave zone. The new method consists of equipping the test craft with both a wind instrument and a current meter suspended under the craft. The current meter would measure the motion of the craft through the water, i.e.; leeway, directly.

The proposed method would require development of a suitable instrument package to support a current meter and wind instrument. If successful, the method would permit the collection of leeway data without the constant maintenance of a drifter array and tracking system. Leeway data for high wind conditions could be collected by deploying a test craft before the experiment begins and leaving it unattended. Tracking could be accomplished either by satellite (Murphy and Allen, 1985) or by a LORAN-C receiver and relay. (Allen, Eynon, Robe, 1987).

The collection of leeway data for higher winds and rougher seas is needed to gain a better understanding of leeway. Variations in leeway caused by the loading of a craft should be determined. The maximum and minimum leeway values can be determined by testing the craft fully loaded and empty.

The leeway of craft greater than twenty-five (25) feet in length should be checked. The authors know of no successful work in this area since 1960 (Chapline 1960).

The rafts referred to as canopied rafts with ballast buckets need to be researched as a group. Regulations have required the addition of more ballast to this type of raft since the early 1970's. Variations in ballast configurations for this group could affect leeway. This class of rafts may constitute the majority of the Coast Guard-approved rafts in use.

CHAPTER 1
INTRODUCTION

1.1 SCOPE

The Spring 1985 Leeway Experiment was a joint experiment by the U.S. Coast Guard Research and Development Center (R&DC) and Florida Atlantic University (FAU). The experiment was conducted in the Atlantic Ocean off Fort Pierce, Florida from 18 March to 16 April, 1985. The objective of the experiment was to increase the accuracy of leeway rates used in drift predictions in search and rescue. Leeway is defined as that movement, of a craft through the water, caused by the wind acting on the exposed surface of the craft.

The small craft used in this experiment (Table 1) were four 4- to 6-man canopied life rafts and three small craft from 14 to 20 feet in length. The rafts tested with and without drogues were a 6-man circular life raft with a hemispheric ballast system, a 4-man circular life raft with a toriodal ballast system, and a 4-man oblong life raft with no ballast system. A 4-man circular life raft with ballast bags was tested without drogue. The rafts were loaded to their rated capacity. The small craft were tested without drogues.

This report presents the results of the R&DC's analysis of the data. FAU has used the data to calibrate and test a numerical leeway model and have presented their results separately. R&DC participated in the experiment under element 1010.2.4, Improved Target Prediction, of the project "Improvement of Probability of Detection in Search and Rescue," project number 1010.2. FAU's participation was funded under Grant DTRS 5683-C00033, "On Drift Prediction", by the Office of University Research, U.S. Department of Transportation.

TABLE 1

TEST CRAFT FOR SPRING 1985 LEEWAY EXPERIMENT

TEST CRAFT deployed	DESCRIPTION	DEPLOYED WITH DROGUE	DEPLOYED WITHOUT DROGUE
Switlik 4-man life raft	circular canopied raft with toroidal (deep-draft) ballast system	yes	yes
Givens Buoy 6-man life raft	circular canopied raft with hemispheric (deep-draft) ballast system	yes	yes
Avon 4-man life raft	circular canopied raft with ballast bags	no	yes
Winslow 4-man life raft	oblong canopied raft with no ballast system	yes	yes
14-Foot Outboard	Boston Whaler-type boat with outboard motor	no	yes
19-Foot Outboard	sport fisherman with center console and outboard motor	no	yes
20-Foot Cabin Cruiser	small cabin cruiser with two inboard-outboard motors	no	yes

1.2 BACKGROUND

1.2.1 Leeway in Search and Rescue

A key element of a successful search is the correct prediction of the target location. For a search object located on the surface of the water, the search planner must consider some of the following sources of drift:

- o Sea current,
- o Wind-driven currents,
- o Tidal currents,
- o Miscellaneous currents from river runoff, longshore currents, etc.,
- o Wave- and swell-induced drift, and
- o Leeway.

For the search planner, the components of leeway are leeway speed and leeway angle. Leeway speed is the speed at which the wind will push an object through the water. Leeway angle is the angle off the downwind direction to which the object will sail.

The leeway information in the National Search and Rescue Manual (SAR Manual) is presented in Table 2. The listed references are believed to be the original studies on which the equations are based. The SAR Manual does not list references. Separate equations for winds above and below 5 knots are used. For winds above 5 knots, the equations are an empirical fit of data. For winds below 5 knots, there were insufficient data. However, since there can be no leeway without wind, a straight line was drawn from the origin to the leeway for 5 knots of wind.

The SAR Manual advises that the leeway speed for rafts in Table 2 should be increased by 20% for the addition of a canopy and decreased by 20% for the addition of ballast buckets.

TABLE 2. LEEWAY INFORMATION AVAILABLE IN SAR MANUAL

TYPE OF CRAFT	WIND SPEED*	LEEWAY SPEED*,**	LEEWAY ANGLE (deg)	REFERENCE
Light-displacement cabin cruisers (no drogue) Outboards (no drogue)	0 to 5	0.078U	±35	Hufford and Broida (1974)
Rafts without canopies/ballast system (no drogue) Rafts with canopies and ballast buckets	5 to 40	0.07U + 0.04		
Light-displacement cabin cruisers (with drogue) Outboards (with drogue)	0 to 5	0.026U	±35	Hufford and Broida (1974) [Confirmed by Scobie and Thompson (1979) for deep-draft raft]
Rafts without canopies or ballast system (with drogue) Canopied raft with deep-draft ballast system	5 to 40	0.05U - 0.12		
Large cabin cruisers	0 to 40	0.05U	±60	Chapline (1960)
Medium-displacements sailboats Fishing boats (e.g., trawlers, trollers, tuna boats)	0 to 40	0.04U	±60	Chapline (1960)
Heavy-displacement, deep-draft sailing vessels	0 to 40	0.03U	±45	Chapline (1960)
Surfboards	0 to 40	0.02U	±35	Chapline (1960)

NOTE: Leeway speed and angle information available in the National Search and Rescue Manual is listed with the most likely original source of the equations.

* Values and equations are in knots.
** U is wind speed.

The leeway information used by the Computer Assisted Search Planning (CASP) system as of December 1985 is presented in Table 3. Leeway rate is the ratio of leeway speed to wind speed. The base leeway rate is the estimated rate for a particular craft. Rate uncertainty is a measure of the scatter in the leeway rate data. A rate uncertainty of 0.33 means that the true leeway rate is within ± 33% of the base leeway rate.

TABLE 3

LEEWAY INFORMATION AVAILABLE IN CASP

Target Description	Base Leeway Rate	Rate Uncertainty	Leeway Angle (degrees)
Anchored on land (no drift)	0.00	0.00	00.0
Person in the water (zero leeway)	0.00	0.00	00.0
Light-displacement vessel without drogue.	0.07	0.33	35.0
Large cabin cruiser	0.05	0.33	60.0
Light-displacement vessel with drogue	0.05	0.33	35.0
Medium-displacement sailboat/fishing vessel	0.04	0.33	60.0
Heavy-displacement deep-draft sailing vessel	0.03	0.33	45.0
Surfboard	0.02	0.33	35.0

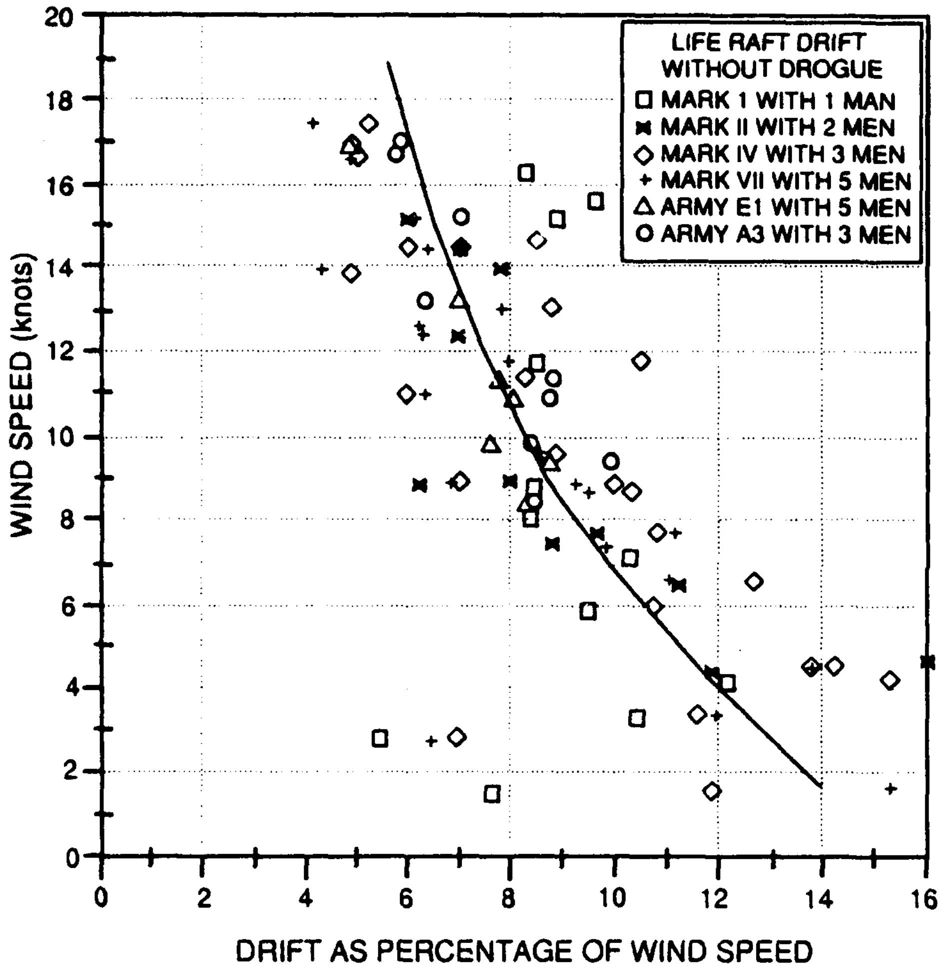
Using a Monte-Carlo simulation, CASP computes many replications of a given target's drift using the base parameters (time, position, current, wind and leeway characteristics) and the uncertainty for each parameter. CASP permits the operator to define leeway characteristics (base leeway rate, rate uncertainty, and leeway angle). For any given replication, a leeway angle is randomly selected from a uniform distribution of leeway angles ranging from the maximum leeway angle to the left of downwind to the maximum leeway angle to the right of downwind. The replication's leeway rate is randomly selected from a uniform distribution of leeway rates ranging from the base leeway rate multiplied by (1.0 - rate uncertainty) to the base leeway rate multiplied by (1.0 + rate uncertainty).

1.2.2 Previous Leeway Investigations

1. The Woods Hole Oceanographic Institution conducted a series of leeway drift studies from November 1943 through April 1944 using the Navy Mark I, II, IV, and VII and the Army A-3 and E-1 rafts (Pingree, 1944). These small 1- to 5-man rafts were tested loaded, with and without drogues. The tests were conducted in three marine environments: Buzzards Bay, Massachusetts; off of Boca Grande Island, Florida; and in the open ocean northeast of the Bahama Islands. Pingree's (1944) drift results were calculated using currents in the upper 15 feet of the ocean (Figures 1 and 2). Note the considerable scatter at wind speeds of 4 knots and less.

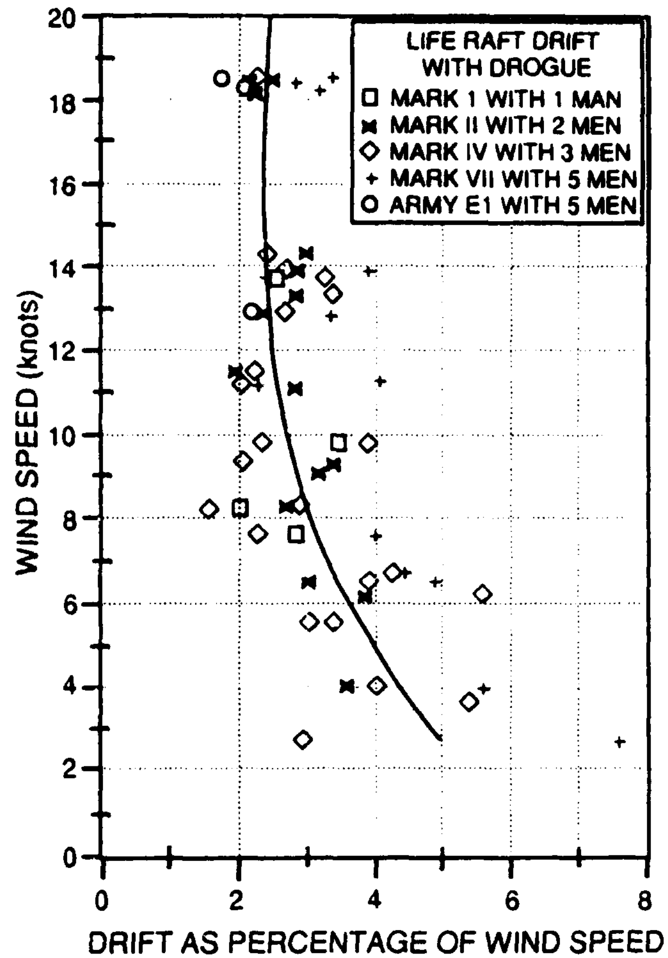
2. In 1959, a leeway study called "Operation Spindrift" was conducted offshore of Hawaii using vessels and small craft from the Coast Guard Auxiliary, local commercial fishermen, and other willing boaters (Chapline, 1960). The drift due to currents was removed by recording all positions relative to a 300-foot-long by 15-foot-wide fine mesh drift net. The observation vessel took positions by radar ranges and visual bearing every half hour. No mention was made of the use of drogues. Chapline (1960) used a linear model passing through the origin for the analysis (Table 4). This model assumes that leeway is a constant percentage of wind speed for a particular craft.

3. The Canadian Central Tactics and Trials Organization (CTTO),



Results based on tests conducted by
Woods Hole Oceanographic Institution June 15, 1944

FIGURE 1. LIFE RAFT DRIFT WITHOUT DROGUE
(PINGREE, 1944)



Results based on tests conducted by
Woods Hole Oceanographic Institution June 15, 1944

FIGURE 2. LIFE RAFT DRIFT WITH DROGUE
(PINGREE, 1944)

TABLE 4
LEEWAY RATES FOR MODERATE-TO-FRESH WINDS
(Chapline, 1960)

Group	Craft	Leeway Rate
I	Surfboards	0.02
II	Heavy-displacement, deep-draft sailing vessels	0.03
III	Moderate-displacement, moderate-draft sailing vessels and fishing vessels such as trawlers, trollers, sampans, draggers, seiners, tuna boats, halibut boats, etc.	0.04
IV	Moderate-displacement cruisers	0.05
V	Light-displacement cruisers, outboards, planing hull types, skiffs, etc.	0.06

working with the Canadian National Physics Laboratory (NPL), conducted laboratory tests in late 1972 and early 1973 to determine the leeway drift rates for several life rafts. Wind drag was determined in wind tunnel testing, water drag was determined in a tow tank, and wave-induced drift was measured in a tank equipped with a wavemaker. The life rafts were 1-, 5-, 9-, and 26-man canopied life rafts with inflatable floors. Personnel were simulated at 180 pounds per person. The report made no mention of any type of ballast system on the rafts. The rafts were tested with different degrees of loading, closed and open doors, inflated and deflated floors, and undrogued and drogued with two different types of drogues. Based on the wave tank test, CTTO gave a wave-induced drift velocity of 0.6 to 1.0 knots for fully developed seas due to winds in excess of 15 knots.

In the CTTO report, leeway speed to wind speed was presented for the different rafts in back-to-back logarithmic plots (not reproduced here). This information has been generalized into leeway rates by the raft's capacity and drogue employment (see Table 5). The range of leeway rates results from variations in

TABLE 5
LEEWAY RATES FOR FULLY LOADED CANOPIED LIFE RAFTS (CTTO)

Raft	Drogued	Undrogued
1-man	0.020 to 0.030	0.031 to 0.052
5-man	0.025 to 0.031	0.047 to 0.062
9-man	0.034 to 0.043	0.061 to 0.074
26-man	0.042 to 0.049	0.058 to 0.072

the configurations and wind speed. There was approximately 19% difference in leeway speed between the two types of drogues. The 5-man raft was tested with a 5-man and a 2-man load. When undrogued it had the same leeway with the 2-man load as with the 5-man load. When drogued, it was 10% faster with a 2-man load than with the 5-man load. The report claimed that inflating or deflating the floor made a difference in the leeway of life rafts. The leeway difference attributed to floor inflation was not inconsistent from one raft to another.

4. From November 1972 through 1974, the United States Coast Guard R&DC conducted a series of leeway experiments in Fishers Island Sound and Block Island Sound (Hufford and Broida, 1974). The experiments used drogued and undrogued small craft ranging from 9 to 24 feet in length. A 12-foot 7-man raft without canopy or ballast system was included as one of the small craft. The current was measured using a dye patch to mark a parcel of water. All positions were recorded relative to the dye patch using aerial photography.

Results were presented for 12- to 22-foot small craft with winds ranging from 5 to 20 knots. The leeway angle varied from 5° to 60° for craft with small keel plane area. Use of a drogue reduced leeway angle by approximately one half.

Leeway speed was not significantly different for the different craft, so all were combined into drogued and undrogued categories. For undrogued craft, the leeway speed (L) was found to be:

$$L = 0.04 + 0.07\ W,$$

where W is the wind speed and both L and W are in knots. For small craft with drogues, the relationship is

$$L = -0.12 + 0.05\ W,$$

where L and W are in knots.

Hufford and Broida (1974) reported that an increase in seas from 2 feet to 4 feet resulted in an increase in leeway of approximately 15%.

5. The U.S. Coast Guard Oceanographic Unit conducted a series of leeway experiments from January 1968 through March 1971 (Morgan, et al., 1977). The test craft were the MK7 life raft without canopy, a 16-foot outboard motor boat, an 18-foot motor launch, and a 30-foot utility boat with cabin. The MK7 life raft, a 7-man oblong raft without any ballast system, is approximately 12 feet long. The current was measured by means of a buoy with a 28-foot diameter parachute drogue. All positions were determined by visual bearings and radar ranges from the research vessel. The results in Figure 3 were determined by using a linear regression on 5-knot intervals of wind speed data.

Morgan (1978) presented the results for the MK7 life raft with drogue (sea anchor). The leeway rate for winds above 5 knots was found to be "essentially constant at 0.04" with a range of ± 0.03. The leeway angle was found to be 35° to the right for a 5-knot wind and approximately 0° for wind speeds above 10 knots.

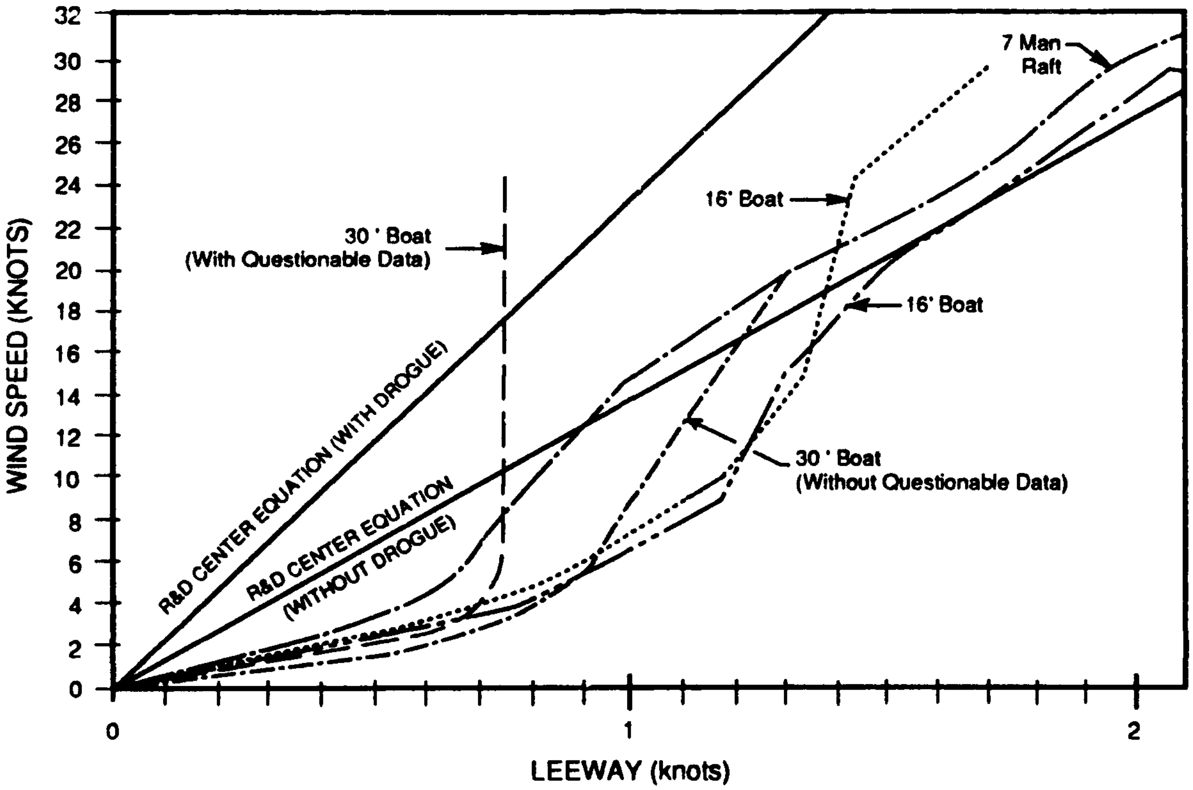


FIGURE 3. LEEWAY VERSUS WIND SPEED (Adapted From Morgan, 1977. The lines denoted as "R&D Center Equation" are from Hufford and Broida, 1974.)

6. The U.S. Coast Guard Oceanographic Unit, on a cruise aboard the USCGC EVERGREEN (WAGO 295) from 15 February through 7 March 1978, conducted a leeway study for undrogued, canopied life rafts (Scobie and Thompson, 1979). The current was measured by a buoy equipped with a 10-foot square window-shade drogue. Results were calculated for one 6-man, one 20-man, and one 25-man life raft. All of these rafts had ballast systems. The rafts were weighted with sand bags to represent passenger loading. For winds of 10 to 35 knots and seas of 5 to 15 feet the leeway speed was found to be:

$$L = 0.060 + 0.042\ W$$

where L is leeway in knots and W is wind speed in knots. The leeway angle was less than 30° for 78% of all drifts.

7. The U.S. Coast Guard R&DC combined leeway experiments with other experiments in January 1979, February 1980, and February 1981 (Osmer, et al., 1982). The first two experiments were conducted at sea with USCGC EVERGREEN. The current was measured using a buoy with a window-shade drogue at a depth of 98 feet. Positions were determined from EVERGREEN using radar ranges and a microwave ranging system or radar and visual bearings. The third experiment was conducted near shore using a Microwave Tracking System (MTS) for positioning. The current was determined using expendable surface current probes. The experiments used a variety of 4- to 6-man life rafts with and without canopies and drogues. Due to the considerable scatter in the data, no conclusions were reached. Osmer, et al. (1982), recommended that the MTS be used in the shore-based mode for future leeway experiments.

8. In July 1982, the R&DC conducted a trial using the MTS to track both the rafts and specially constructed drifters. The drifters, designed to be tracked by the MTS, were used to determine the current near the raft. In July and August

1983, a preliminary leeway experiment was conducted in Block Island Sound using three circular, nearly empty, canopied rafts without drogues (Nash and Willcox, 1985). The rafts were a 6-man raft with two half-cylinder ballast bags (6-inch draft, RFD 6-man), a 4-man raft with a toroidal ballast system (14-inch draft, Switlik 4-man), and a 6-man raft with a hemispheric ballast system (28-inch draft, Givens 6-man). The last two rafts were deep-draft ballasted life rafts. Wind was measured at a small boat anchored in the test area. Wind speed ranged from 2 to 11 knots, with waves of 0 to 2 feet and swells up to 4 feet.

The experiment was successful in differentiating the leeway between the lightly and more heavily ballasted rafts (see Table 6). The leeway of the canopied raft with ballast bags was found to be similar to the SAR Manual's recommendation for canopied life rafts with ballast buckets. The leeway of the deep-draft ballasted life rafts was much slower than the Scobie and Thompson results.

TABLE 6
LEEWAY SPEED FROM THE SUMMER 1983
R&DC EXPERIMENT

Life Raft Capacity	Ballast System	Leeway Speed (Knots)
6-man	Ballast bags	0.145 + 0.0568 W
4-man	Toroidal	0.100 + 0.0083 W
6-man	Hemispheric	0.100 + 0.0064 W

The leeway angle for the raft with ballast bags was found to be highly dependent on the raft's orientation to the wind. The circular deep-draft life rafts drifted downwind or very close to downwind with no correlation between the leeway angle and the raft's orientation to the wind. Nash and Willcox (1985) recommended that all test craft be instrumented to measure wind speed, wind direction, and the craft's heading so that leeway angles could be determined correctly. They concluded that much of the reported variability in leeway angles was due to errors in determining the wind and current.

CHAPTER 2
THE EXPERIMENT

2.1 DESIGN AND CONDUCT

Determination of leeway requires very accurate measurement of the forces involved. The parameters that must be measured accurately are the velocity of the test craft, the speed and direction of the current, the wind at the test craft location, and the height and direction of the waves. The craft's velocity was determined using positions obtained by the MTS. The current at the test craft was calculated from the position records of an array of drifters (Figure 4) deployed around the test craft and tracked by the MTS. The wind and the craft's orientation to the wind were measured onboard the test craft. Wave height and direction were recorded by the research vessels and by an environmental buoy.

The monitor vessel (R/V OCEANEER IV) deployed two test craft and surrounded them with the drifter array. As the test craft drifted through the array, the R/V OCEANEER IV deployed additional drifters to keep the test craft surrounded and also recovered drifters no longer required for the array. The R/V OCEANEER IV collected general environmental information every 20 minutes, operations permitting. An environmental buoy, moored in the test area, collected wind, wave, and temperature data. When FAU was on scene, the R/V BELLOWS took stations to collect any additional environmental information required.

Test craft were paired according to their expected leeway characteristics to isolate differences between craft types and the effect of using drogues (see Table 7). This also minimized the dispersion of the test craft so that the drifter array could be maintained without either redeploying one of the test craft or deploying a second drifter array.

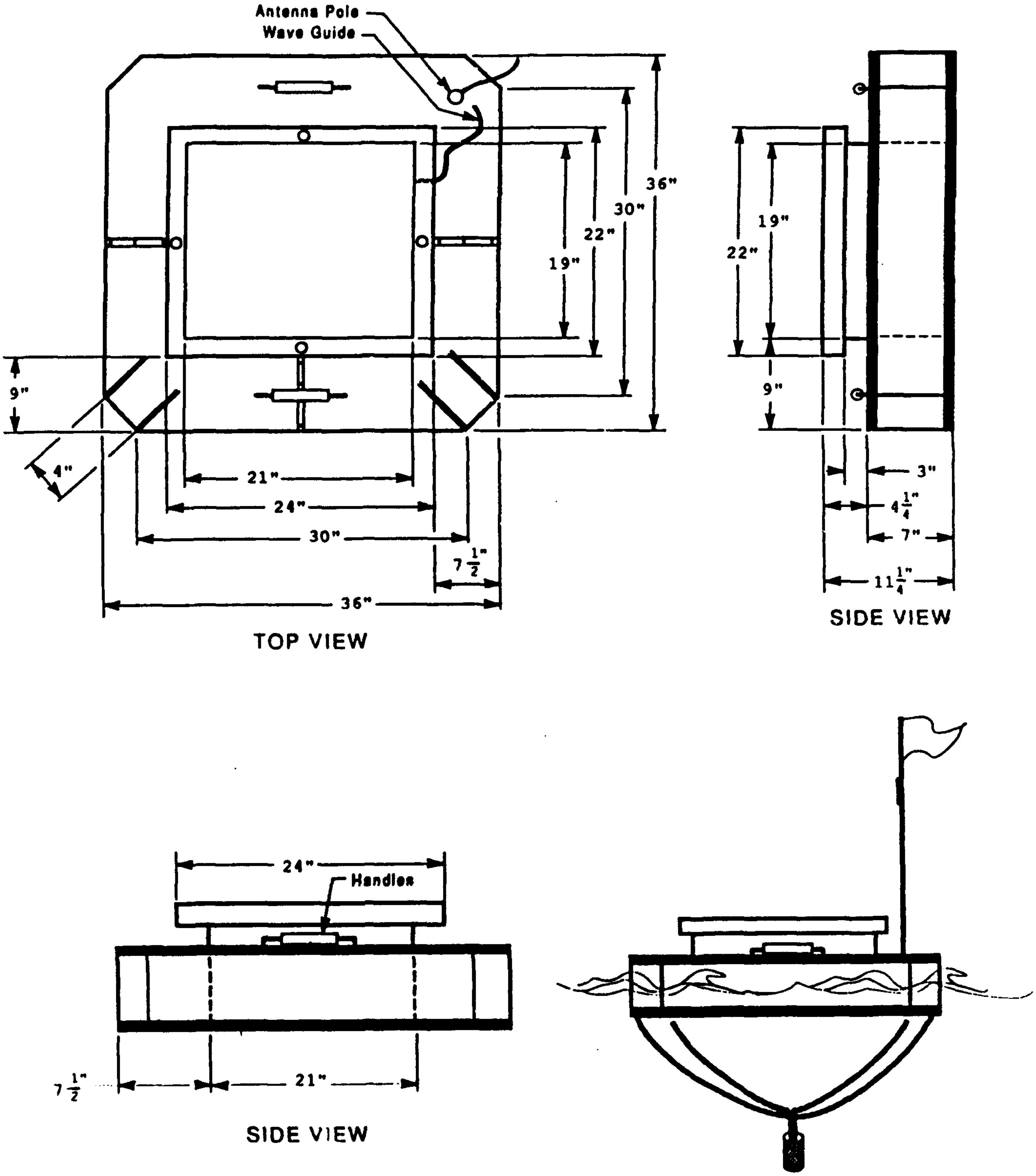


FIGURE 4. MTS DRIFTER

TABLE 7
SUMMARY OF TEST CRAFT ENVIRONMENTAL CONDITIONS

Craft Tested	Days	Wind Speed (knots)	Wave Height (feet)	Swell Height (feet)
Switlik 4-man raft with drogue, Givens 6-man raft without drogue	4	1.4 - 13.6	0 - 2.5	0 - 3
Switlik 4-man raft with drogue, Givens 6-man raft with drogue	0.5	2.5 - 6.8	0.5 - 1	0 - 1
Switlik 4-man raft without drogue, Givens 6-man raft without drogue	0.5	4.7 - 8.0	0.5 - 1	1 - 2
Switlik 4-man raft without drogue	2	8.7 - 13.6	2 - 3	2 - 6
Givens 6-man raft with drogue	1	2.3 - 13.5	0 - 0.5	1
Cabin Cruiser (20 ft) Outboard (19 ft) Outboard (14 ft)	2	2.7 - 12.2	0.5 - 3	1 - 5
Cabin Cruiser (20 ft) Outboard (19 ft)	1	1.4 - 12.2	0 - 2	1
Avon 4-man raft without drogue, Winslow 4-man raft without drogue	2	3.9 - 14.2	0.5 - 2	0 - 5
Avon 4-man raft without drogue, Winslow 4-man raft with drogue	1	3.9 - 6.6	1	2 - 3

The experiment was divided into three phases. Phase One (18 through 29 March 1985) consisted of the R&DC set up and conducting drifts of the deep-draft life rafts with and without drogues. Phase Two (30 March through 7 April 1985) was the joint part of the experiment. R&DC and FAU conducted drifts of small boats and of deep-draft life rafts with and without drogues. The environmental buoy was deployed in the middle of Phase Two. During Phase Three (8 through 16 April 1985), the R&DC conducted drifts of the lightly ballasted and unballasted rafts, and secured the experiment.

Details of data collection are discussed in the following sections.

2.1.1 Position

Positions of the deployed drifters, test craft, and research vessels were determined every two minutes by an MTS. The MTS consisted of a Motorola Falcon 492 tracking system controlled by a Hewlett-Packard HP 9920 microcomputer. The MTS is made up of three types of units: a master station whose position is known, reference stations whose positions are known, and mobile units whose positions are to be determined. An example of the operating principle of the MTS is:

a. The master station transmits a coded signal containing the identification codes of a particular mobile unit on frequency A and to a reference station on frequency B.

b. A mobile unit, upon receipt of its identification code on frequency A, retransmits the signal back to the master station on frequency C.

c. A reference station, upon receipt of its identification code on frequency B, retransmits the coded signal on frequency A which is received by the mobile unit. The mobile unit then retransmits a coded signal to the master station on frequency C for the second time. This provides the master station with a direct range to the mobile unit and a loop range from the master station to the reference station to the mobile unit and back to the master station.

d. The master station measures the time from the original transmission to receipt of the signals on frequency C, calculates the distance of the mobile unit from the master and reference stations based on the two returned signals, the speed of the transmitted signal, and the distance between the master station and the reference station. The position of the mobile unit is calculated using trigonometry and the positions of the master and reference stations.

For each position determination, MTS repeats the above sequence about 20 times and averages the results using filtering and quality control checks. It can track up to 24 transponders simultaneously and determine a round of positions every 30 seconds.

The MTS configuration during this experiment had the master station (R&D Control) located on the roof of the Sea Palms condominiums in Fort Pierce, FL. The northernmost of the two reference stations was located in Vero Beach on the southernmost tower of the Spires condominiums. The southern reference station was located on the meteorological tower for the Florida Light and Power Co. St. Lucie Nuclear Power Plant in Stuart, FL.

A survey error in the positions of the master and reference stations degraded the absolute geographical accuracy of the MTS. A position determined by the master station and one reference station was offset from the position as determined by the master station and the other reference station. The relative accuracy of the master and either reference station was not affected. Essentially the MTS became two separate navigational grids, one for each reference/master station pair. Alignment to true north of each grid was checked by comparing directions determined using LORAN-C. The directional error of the MTS grids was determined to be 1° from true. The relative accuracy of the MTS positions was ±30 meters for the same grid. For this study, relative distances and directions are important. The lack of absolute geographical accuracy prevents velocities from being calculated between positions determined using the two different grids.

The MTS used the Florida State Plane Coordinate System in meters in lieu of latitude and longitude. The coordinate plane is a Cartesian coordinate system with the x and y axes increasing to the east and north, respectively. The errors due to the curvature of the earth are insignificant for the small test area; therefore, the complexity of a spherical coordinate such as latitude and longitude may be avoided.

2.1.2 Test Craft's Instrument Packages

The wind data on the test craft were collected using two automated instrument systems each consisting of four components: a propeller-type anemometer and wind vane, a flux-gate compass, controlling circuits for the sensors, and a programmable microprocessor-controlled data logger. One data logger had 32K of internal memory, of which 15K was available for data storage. The other had 64K of internal memory with 47K available for data storage. The components of each package were interchangeable with the corresponding components of the other package. Each package was mounted on a plywood base with the wind sensor mounted at a height of six feet. The accuracy of wind measurements by these packages was ±10° and ±1.0 knot. The threshold of the wind sensor was two knots. Wind data consisting of 3-second averages were collected every 20 to 40 seconds depending on the data logger used in the package. The data were written out to a microcomputer at the end of each day.

Another wind instrument package used on the target test craft was a Brooks and Gatehouse Hercules System 190. It is a microprocessor-controlled instrument package designed primarily for sailing yachts and ocean racing. It uses a flux-gate compass, and a cup anemometer and wind vane. The wind sensor was mounted at a height of six feet. The accuracy of the system as mounted was approximately ±10° and ±2 knots. One-minute averages of the wind were recorded every 20 minutes by an FAU graduate student onboard the test craft. This wind measurement system was used only in fair weather.

2.1.3 R/V OCEANEER IV

Environmental observations were recorded by the R/V OCEANEER IV every 20 minutes when operations permitted. The environmental observations consisted of wind speed and direction, height and direction of the waves and swells, and a general description of the weather (cloud cover, visibility, fronts, etc.). The wind was measured with the R/V OCEANEER IV dead in the water using a Brooks and Gatehouse wind sensor similar to the one described in Section 2.1.2. The wind sensor was mounted at a height of 12 feet. This wind measurement was used only for a backup of the wind measured on the test craft. Swell and wave height were estimated by eye. Swell and wave directions were estimated using the R/V OCEANEER IV's magnetic compass. The R/V OCEANEER IV did not record environmental observations when the R/V BELLOWS was on scene.

2.1.4 R/V BELLOWS

During the joint R&DC and FAU part of the experiment, the R/V BELLOWS occupied stations around the drifting array. At the station locations the following measurements were taken: wind speed and direction, height and direction of wind waves and swells, currents, and a general description of the weather. The stations were spread approximately two miles in the north/south direction (along shelf) and one mile in the east/west direction (across shelf). Time intervals between stations ranged from 10 to 25 minutes. Once a day, an expendable bathythermograph (XBT) was used to determine sea temperature as a function of depth. Wind was measured using a hand-held anemometer while the vessel was dead in the water. The height of the wind measurements ranged from approximately 12 to 25 feet depending on where on the vessel the observer could get a clean exposure to the wind. This wind measurement was used only as a backup for the wind measurements made on the test craft. The heights of the swells and waves were estimated. Swell and wave directions were measured in reference to the R/V BELLOWS' compass. Current measurements were made at depths of 3, 6, 9, and 12 feet using a current meter with a deck readout.

2.1.5 Environmental Buoy

The environmental buoy was deployed from 3 through 15 April 1985 at position 27°33.24'N 80°05.91'W. Once an hour, the buoy measured the wind, air and water temperature, and relative humidity. The wind measurement consisted of a 10-minute vector average and the maximum gust during that 10-minute interval. The winds were measured at a height of 10 feet. The air temperature and relative humidity were measured at a height of eight feet. Water temperature was measured at a depth of three feet. Every three hours, the buoy sampled a 1-dimensional wave spectrum (height) for 20 minutes.

2.2 DRIFTERS

The MTS drifters, designed and constructed at the R&DC, consisted of a waterproof box between two 3-foot by 3-foot plexiglass sheets; the waterproof box protrudes through the top sheet (Figure 4). An MTS transponder with batteries was contained in the waterproof box and was connected by a flexible wave guides to an antenna on a pole which extended seven feet above the upper sheet. The drifters float with the upper sheet slightly submerged. A 40-pound lead weight suspended from a four-point bridle attached to the four corners of the lower sheet provides stability.

The MTS drifters were designed to have minimal leeway and to measure only the surface water current that would affect a life raft or a shallow draft vessel. This design was as effective as drift cards in marking the upper layer of the water (see Nash and Willcox, 1985). The drifters have an effective draft of nine inches. The total draft is approximately three feet with the counterweight. However, the surface area of the bridle and counterweight is negligible when compared to the main body of the drifter.

2.3 TEST CRAFT

Leeway data were collected on four canopied life rafts and three boats. The two circular life rafts with deep-draft ballast systems were the Switlik 4-man and Givens 6-man rafts. Both rafts were tested with and without drogues. The circular canopied life raft with ballast bags was the Avon 4-man raft, which was tested without drogue. The oblong canopied raft without any ballast system was the Winslow 4-man raft. It was tested with and without drogue. All rafts were loaded to capacity using a simulated weight of 160 pounds per person.

The three small boats tested were a 14-foot Boston Whaler-type outboard, a 19-foot center-console outboard, and a 20-foot cabin cruiser. All three were tested without drogues.

2.3.1 Simulation of Life Raft Complement

Five-gallon water jugs filled with fresh water were used to simulate survivors aboard the rafts. Water jugs were used instead of the traditional sandbags to prevent overloading if the raft took on water. Some of the added weight caused by water coming into the raft would be countered by the buoyancy of the people in the raft. Because sandbags do not float, a raft full of water with 640 pounds of sandbags is much more heavily loaded than the same raft full of water with 640 pounds (four 160-pound individuals) of semi-floating people. Other advantages are that a 5-gallon jug of water with a handle is much easier to load into a raft in 3-foot seas than a bag of sand. In addition, water jugs float when dropped over the side.

The jugs weighed approximately 40 pounds when filled; four jugs were used for each person. The variation in weight of individual jugs when filled was about 5 pounds. Therefore, a person was simulated at a weight of 160 pounds, ±20 pounds.

Each raft was equipped with a wind instrument package that weighed approximately 80 pounds. None of the rafts were deployed equipped with survival gear; that gear generally weighs 10 to 20 pounds.

2.3.2 Switlik 4-Man Life Raft

The Switlik 4-man raft was a circular raft with a toroidal ballast system. The raft had a T-shaped canopy with the door located at the head of the T (Figure 5). The ballast toroid was divided into eight sections by baffles. Each section had a metal bar at the bottom to aid in deploying and maintaining the bottom shape of the system. A towing bridle (not shown in Figure 5) was attached to the raft near the door and hangs down from the raft.

When deployed with a drogue, the drogue was attached under the canopy support tube opposite the door of the raft. A parachute type of drogue was used; its diameter, when laid out flat, was 31.5 inches. There were 8 lines, each 29 inches long. The lines connected into a single point to which 50 feet of parachute cord (550 pound test) was tied.

2.3.3 Givens Buoy 6-Man Life Raft

The Givens Buoy 6-man raft had a Y-shaped canopy and a hemispheric ballast system (Figure 6). A towing bridle is located on the side of the raft containing the door. This raft, manufactured in 1983 for the R&DC, was modified by Mr. Givens from the standard raft to include a deballasting slit in the bag opposite the towing bridle. The slit was closed by lacing and by sealing a flapper valve before deployment. The slit made recovery of the raft easier and reduced the risk of damage to the raft. The authors believe that the modification did not affect the performance of the raft.

When the raft was drogued, a drogue identical to the drogue for the Switlik 4-man raft (see Section 2.3.2) was used for the purpose of this experiment only. The original drogue was missing, and a replacement provided by Mr. Givens for this experiment was of a type less common than the parachute-type drogue. The same type drogue was used for both raft types to emphasize the difference in raft designs. The exact drogue carried by any brand of raft may vary as manufacturers or repackers switch drogues.

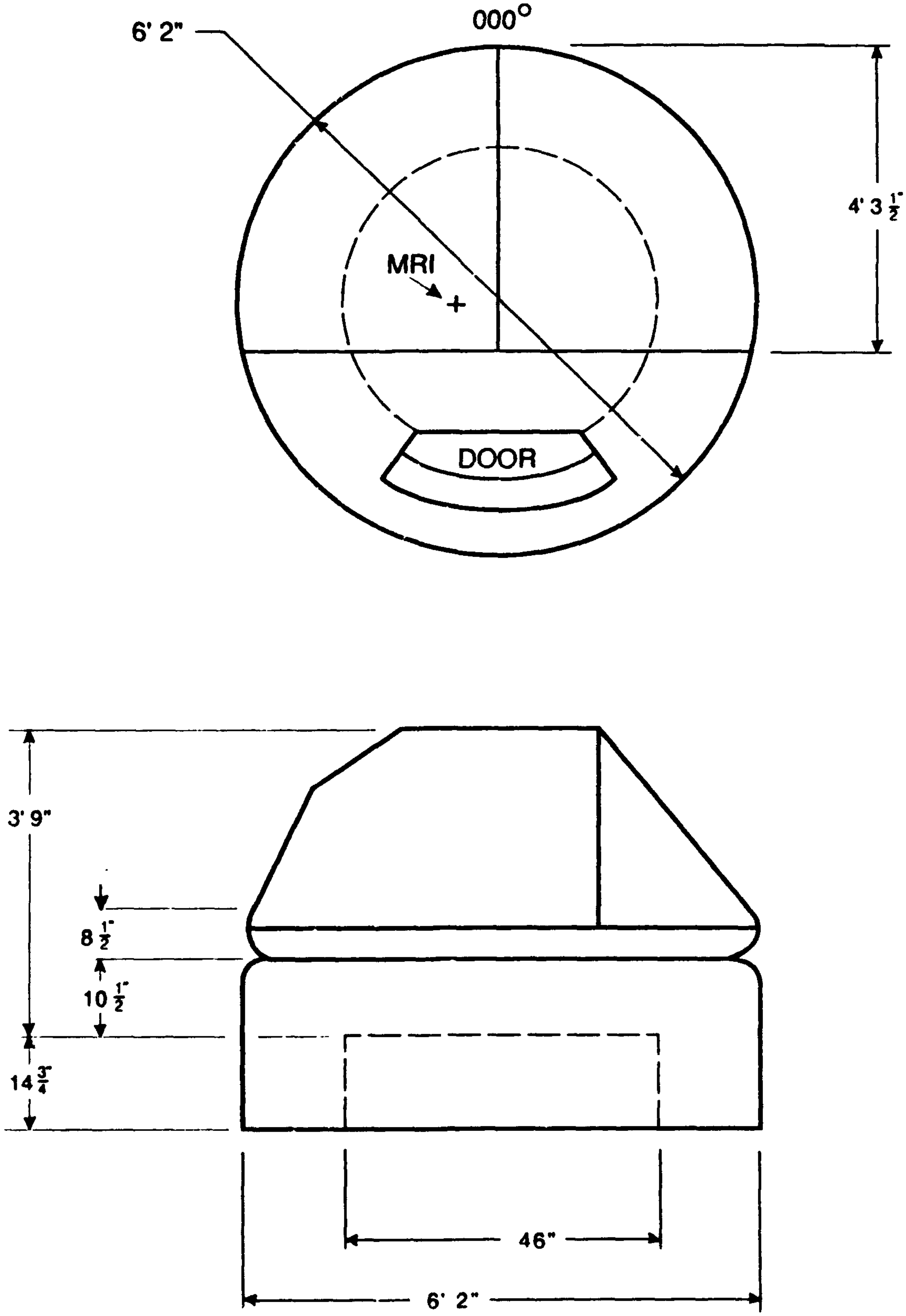


FIGURE 5. SWITLIK 4-MAN LIFE RAFT WITH TOROID BALLAST

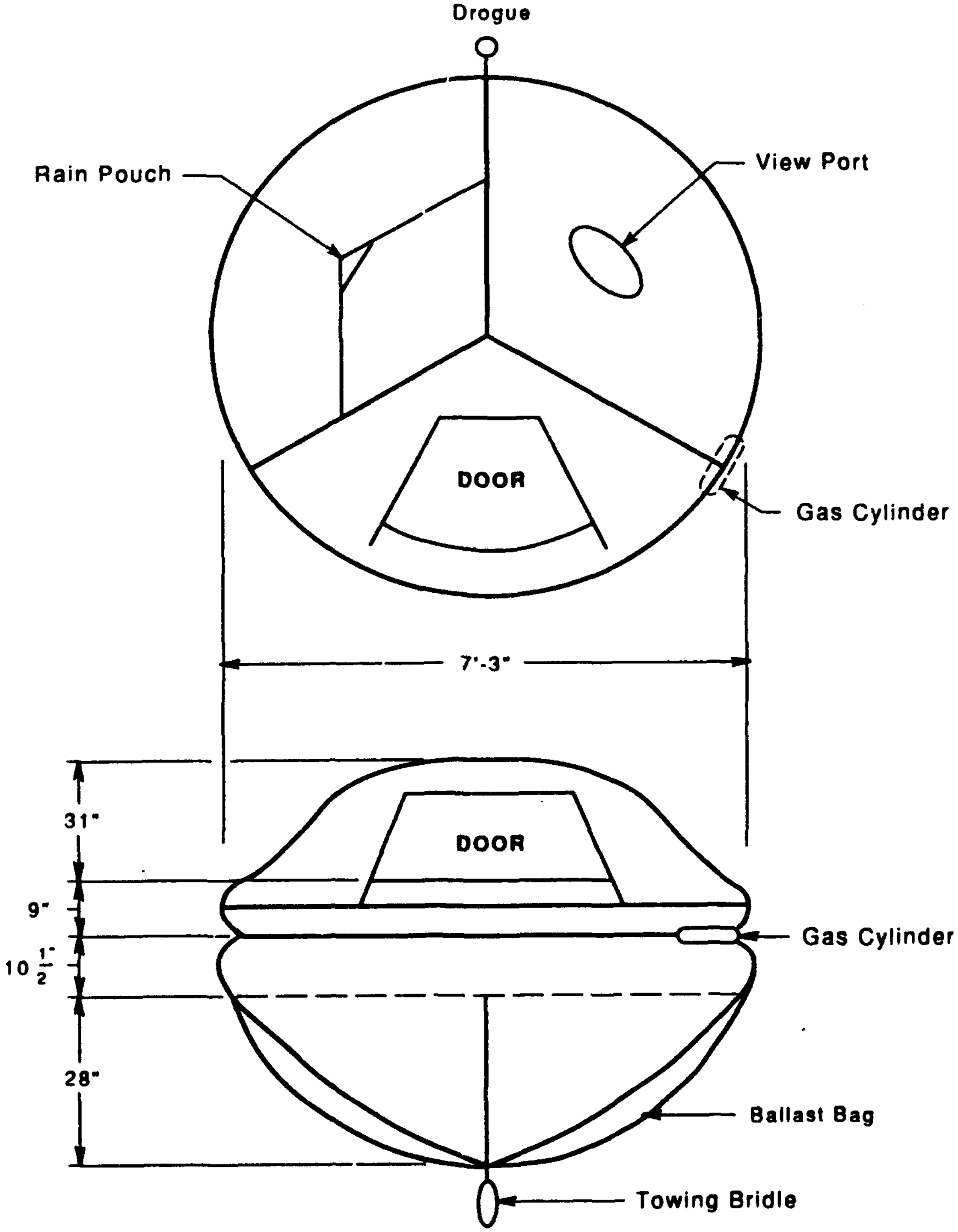


FIGURE 6. GIVENS BUOY 6-MAN LIFE RAFT

When deployed, the drogue was attached with 80 feet of parachute cord to the standard attachment point. This point is a webbed loop on the bottom tube located directly under the canopy support tube opposite the door of the raft.

2.3.4 Avon 4-Man Life Raft

The Avon 4-man raft has a canopy supported by a single tube dividing the raft into two equal parts (Figure 7). The raft had five ballast pockets (one larger than the others) distributed around the bottom of the raft in a manner that is approximately symmetric to the line marked by the canopy support tube. The raft was deployed without a drogue in this experiment. This raft was an older model and may not be representative of the rafts currently made by Avon. The date of manufacture, serial number, and any modifications are unknown. The ballast bags on the raft do not match in size, shape, or location with drawings dated 1977 provided by Imtra Corporation, Medford, Massachusetts.

2.3.5 Winslow 4-Man Life Raft

The Winslow 4-man life raft was an oblong raft with a canopy supported by an arch at each end of the raft (Figure 8). It lacked any type of ballast system and had only one base tube. Although not approved by the Coast Guard, it is typical of the rafts carried by many recreational and non-regulated vessels.

This raft used the soft carrying case as a drogue. Unfortunately, the outer casing of the drogue line chafed through during handling and parted when the drogue was deployed. Therefore, the drogue from the Switlik 4-man raft (see Section 2.3.2 for description) was used. The drogue was attached to the inflation pipes located on the base tube below the middle of the door.

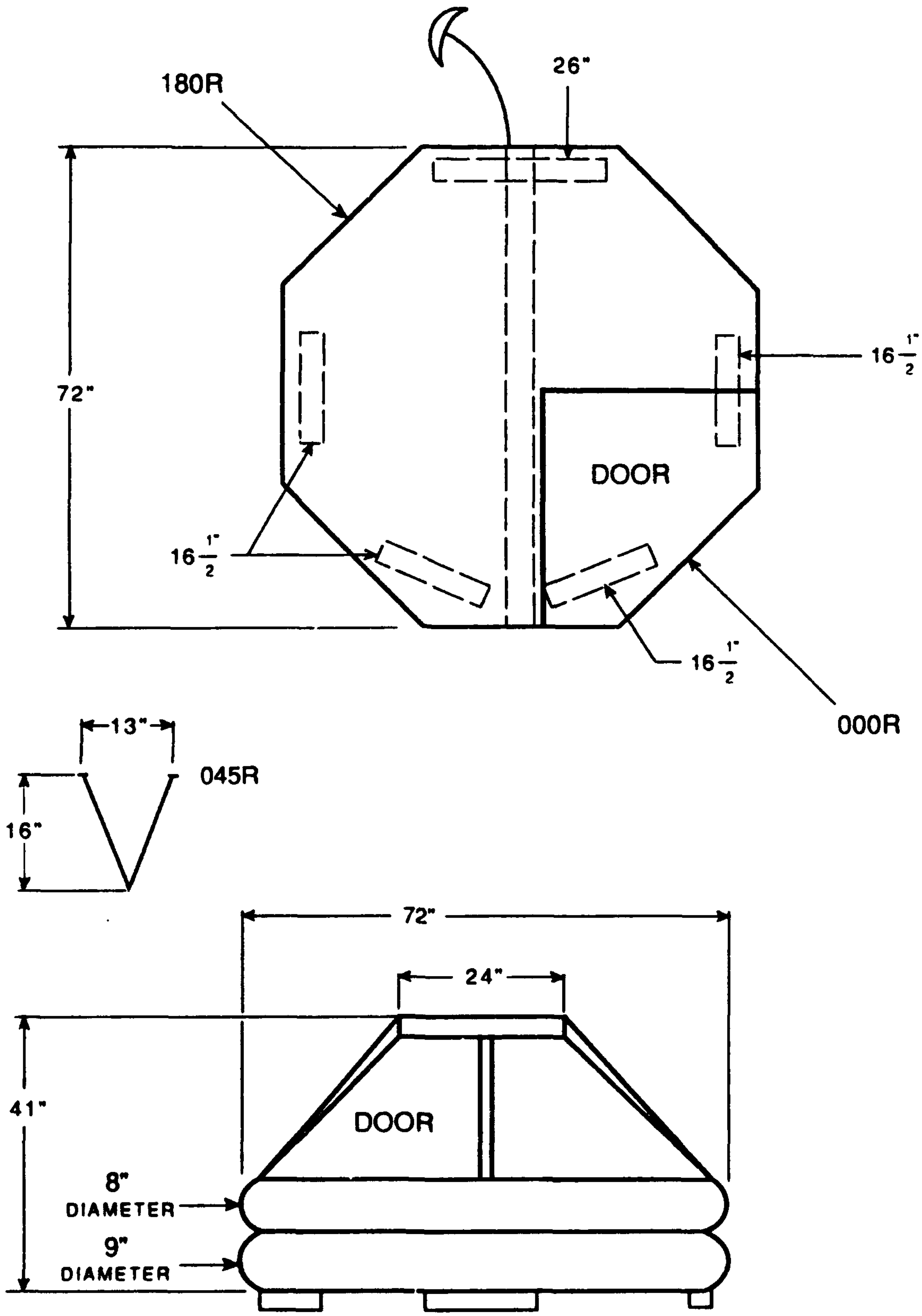


FIGURE 7. AVON 4-MAN LIFE RAFT

2.3.6 <u>14-Foot Outboard</u>

This vessel was a 14-foot Boston Whaler-type outboard with less than 6 inches of draft. It was equipped with a 25-horsepower outboard motor that was kept in the down position during the test. It was loaded with approximately 80 to 100 pounds of wind instrumentation and a 25-pound anchor. The boat should be considered either lightly loaded or empty.

2.3.7 <u>19-Foot Outboard</u>

This vessel was a 19-foot center-console sport fisherman with an outboard motor. This test craft always held one or two persons and was fully equipped, including fishing gear. The engine was always in the down position. The load on this vessel should be considered normally loaded.

2.3.8 <u>20-Foot Cabin Cruiser</u>

The 20-foot cabin cruiser was a Beachcomber manufactured by Cruisers (Figure 9). It had a cubbyhole cabin in the bow. The cockpit area, which was closed in by a canopy snapped onto a frame, remained open to the stern. It was equipped with an inboard/outboard motor. In the configuration used during the experiment, the outboard drive was kept in the down position and oriented amidships, and the cockpit was covered by the canopy. The tracking and environmental instrument package was placed in the stern. The vessel had a 7- to 8-foot beam and a 2- to 2.5-foot draft. Other than some boat gear and the instrument package, the vessel was empty.

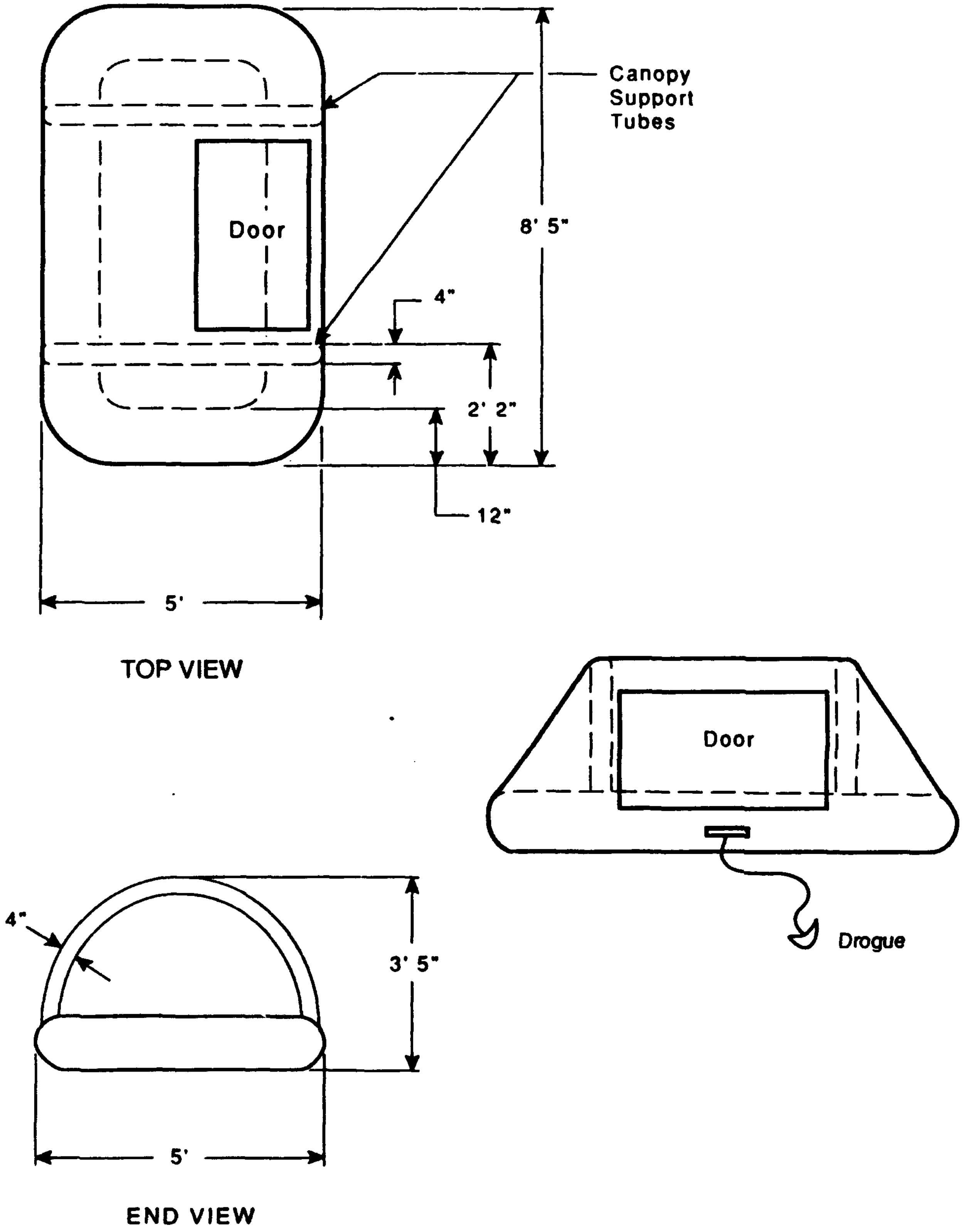


FIGURE 8. WINSLOW 4-MAN LIFE RAFT

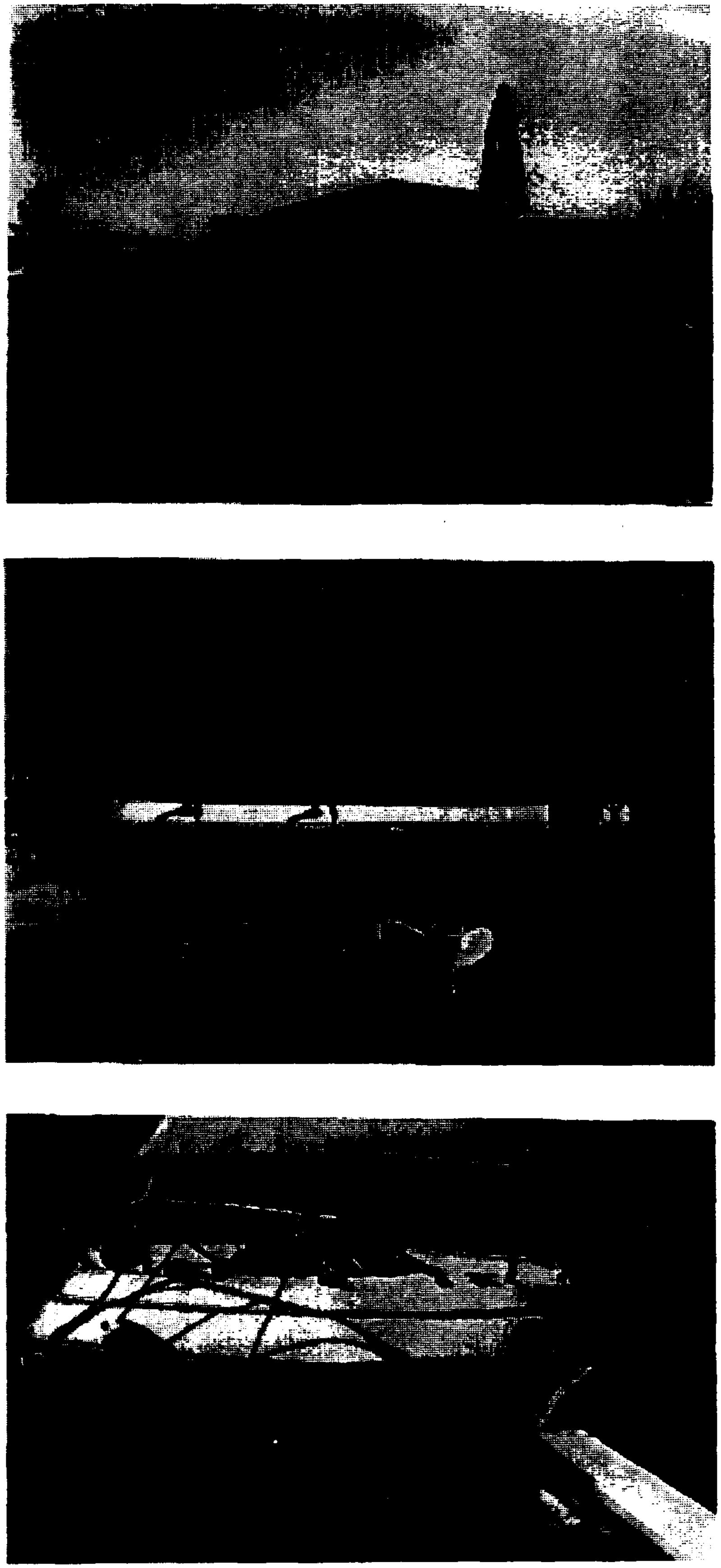


Figure 9. Photographs of 20-foot cabin cruiser

CHAPTER 3
DATA PROCESSING

3.1 INTRODUCTION

This chapter outlines the data inputs, the data processing methods used, and the results obtained. The details are presented in Appendix A.

The raw data included:

a. Position data for drifters,
b. Position data for test craft,
c. Output from environmental instruments, and
d. Craft code and configuration information.

3.2 CALCULATION OF CURRENTS, TEST CRAFT VELOCITIES, AND LEEWAY

Position data from drifters and test craft were edited to include only those positions when the platforms were drifting freely and when positions were all provided by a single MTS reference station. (Reasons for using a single reference station are given in Section 2.1.1) A piecewise linear regression method was used to eliminate questionable data points and to interpolate for position data between known positions. Interpolated platform position records for 4-minute intervals were created.

Current velocity components for each drifter were calculated from the drifter position record by using a time-centered finite difference algorithm. Currents for each drifter were combined using regression equations to produce a current field in the area of the test craft. The current at the test craft was obtained by entering the craft's position into the regression equations.

Test craft velocities were calculated from craft position data using the same time-centered finite difference algorithm used to calculate the current components at the drifters. Subtracting the current at the test craft from the craft's velocity yielded leeway speed and direction.

3.3 WIND DATA

Wind data collected onboard the test craft were used in the leeway calculations. Automated instrument packages, used on all test craft except the 19-foot outboard, provided analog voltages from the compass, wind vane, and anemometer. Initial processing included changing analog readings to engineering units, computing wind direction in degrees true, and compensating for differences in instrument orientation.

Wind data from the automated instrument packages were checked and edited to remove erroneous data points, to correct for passage of the wind direction through the discontinuity at 360°/000°, and to compensate for an offset caused by an equipment problem. Average values for compass heading, relative wind direction (RWD), and wind velocity were determined; these values were used to create 4-minute averages that corresponded in time to drifter position records. (Relative wind direction is the direction from which the wind blows, measured in degrees clockwise about some chosen axis on the test platform.)

The Hercules 190 wind station, used aboard the 19-foot outboard, provided 1-minute averages (recorded every 20 minutes) for compass heading, wind direction in degrees magnetic, and wind speed. Relative wind direction was computed, and wind direction was converted to degrees true. A wind record for every minute was created by assigning the nearest values in time to each minute.

3.4 DATA COLLATION

Records for each day for a single craft were tabulated. The records included the code for the craft, the date and time of the individual data points, the craft's configuration (weight of water jugs, deployment of drogue, engine in up or down position, etc.), leeway speed and direction, wind direction, wind speed, relative wind direction, compass heading, and number of drifters used in current calculations.

3.5 LEEWAY ANGLE

Subtracting the wind direction from the leeway direction yields leeway angle; leeway angles are chosen to be positive for deflection to the right of downwind and negative for deflection to the left of downwind.

[THIS PAGE INTENTIONALLY LEFT BLANK]

CHAPTER 4
ANALYSIS

4.1 INTRODUCTION

The objective of this analysis is to quantify the relationship between leeway and wind for the craft tested. Specifically, the following questions are considered:

1. How does the drifting craft orient itself to the wind?

2. Does the craft drift directly downwind or at some angle to the wind? Is the angle unique?

3. What is the relationship between wind speed and the craft's speed?

The parameters that provide answers to these questions include relative wind direction (RWD), leeway angle, leeway speed and leeway rate.

4.1.1 Significance of Parameters

1. Relative wind direction (RWD) is the direction from which the wind blows, measured in degrees clockwise about some chosen axis and point on the test craft. The convention for ships is to measure from the fore-and-aft line using the bow as a reference point. RWD quantifies the orientation of the craft to the wind and permits differences in leeway attributable to orientation to be identified. A rough example of how the craft's orientation to the wind is related to leeway angle can be seen in Figure 10. A RWD of 225°R results in a negative leeway angle (to the left of downwind), a RWD of 135°R results in a positive leeway angle (to the right of downwind).

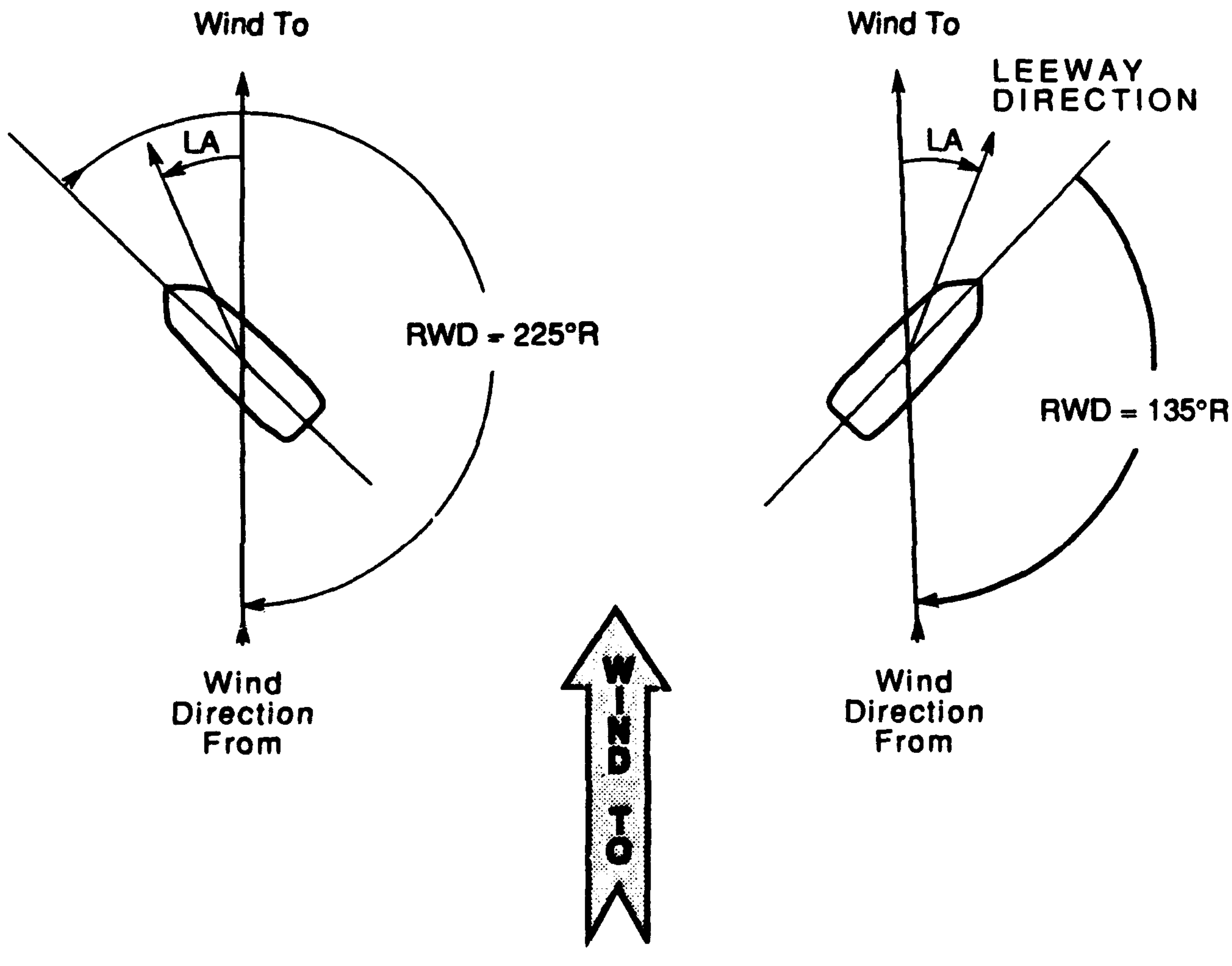


FIGURE 10. RELATION OF RELATIVE WIND DIRECTION (RWD) AND LEEWAY ANGLE (LA)

The distribution of RWDs also indicates whether the craft drift is influenced by the wind. If the craft is bouncing in the waves and unaffected by the wind, the RWDs will vary considerably as either the wind direction or the craft's heading changes. Variation in RWD will decrease as the craft's response to the wind increases. Thus, RWD can help identify the threshold value of wind speed needed to affect the craft's orientation.

2. Leeway angle is defined as leeway direction minus wind direction, with a deflection to the right of downwind being positive. The leeway angle parameter combines wind direction and leeway direction. A leeway angle of 0° indicates that the craft drifts directly downwind. Positive or negative values quantify how far to the right or left of downwind the craft is drifting. Realistic values of leeway angle are bounded by -90° and +90° for measurable leeway speeds. Leeway angles for very low wind speeds may exceed those bounds due to the measured leeway being less than the measurement errors. Leeway angle estimates are no better than the wind measurements, which were good to ±10 degrees.

3. Leeway speed is the magnitude of the leeway velocity. Most of the analysis will use the leeway velocity separated into orthogonal components oriented parallel and perpendicular to the downwind direction. Leeway speed cannot be less than zero; however, leeway components may lead to negative values for downwind leeway speed. Coefficients of leeway models determined using leeway speed instead of the leeway speed components will result in higher estimates of predicted leeway drift for a given wind speed.

4. Leeway rate is defined as the leeway speed divided by the wind speed.

4.1.2 Leeway Models

Three leeway models (regression equations of leeway speed as a function of wind speed) were considered in this analysis to quantify the relationship of craft speed to wind speed. The models are:

$$L = b*W \qquad \text{Equation 4-1}$$

$$L = a+b*W \qquad \text{Equation 4-2}$$

$$L = d*W^{c} \qquad \text{Equation 4-3}$$

where: L is the leeway speed,
W is the wind speed, and
a, b, c, and d are regression coefficients.

Equations 4-1 and 4-2 are standard leeway equations used in previous studies and currently in use in search planning. The third equation, known as a power curve, is a departure from the assumption of a linear relationship between leeway speed and wind speed. In some cases, the non-linear model produced the result that the leeway rate increased as the wind speed increased, which is not reasonable. In other cases, the non-linear model produced reasonable results that were not sufficiently better than the results of the linear models to justify the increased complexity. Only the results of the linear models are reported here.

Methods of fitting the linear models to the data and the error analysis are described in Appendix B.

4.2 SWITLIK 4-MAN LIFE RAFT

4.2.1 Switlik 4-Man Raft With Drogue

Data for the Switlik 4-man raft with drogue consist of 328 data points collected over 4.5 days. Wind speed ranged from 2.5 to 13.6 knots. Sea conditions ran from calm to 2.5-foot waves and 3-foot swells. There was considerable overlap of environmental conditions from day to day.

The drogue was attached to the main bottom tube at a point located just below the canopy support tube opposite the door (Figure 11). For this discussion, the convention for relative bearings will be that the door is at the bow (000°R) and the point of attachment of the drogue to the raft is at 180°R.

The RWD data show considerable scatter for wind speeds under 8 knots; however, the scatter in the RWDs is much less for winds greater than 8 knots (Figure 12). As the force of the wind on the Switlik 4-man raft increases, the Switlik 4-man raft increases its pull on the drogue. The increasing strain on the drogue line holds its point of attachment to the raft into the wind; however, the Switlik 4-man raft without drogue will never have that canopy support tube (180°) up wind (Nash and Willcox, 1985). The strain on the drogue line holds the raft in that position when the wind speed increases to about 6 knots (Figure 13a and 13b). The bottom line of Figure 13a is the RWD plotted using the left-hand scale; the top line is the wind direction in degrees true plotted using the right-hand scale. The wind speed (Figure 13b) dropped below 5 knots early in the drift, increased to over 6 knots, and then dropped steadily to below 3 knots. When the wind speed increased to 6 knots, the RWD approached 180°R (Figure 13a) where it stayed as long as the wind was 6 knots or greater. When the wind speed decreased below 5 knots toward the end of the experiment, the RWD no longer held at 180°R.

The Switlik 4-man raft, when drogued, has no measurable leeway movement for winds under 12 knots (Figure 14). Leeway speed does not vary with increased wind speed and the values of leeway speed are low and scattered around zero leeway speed (Figure 14). This data base does not permit extrapolation for winds above 12 knots.

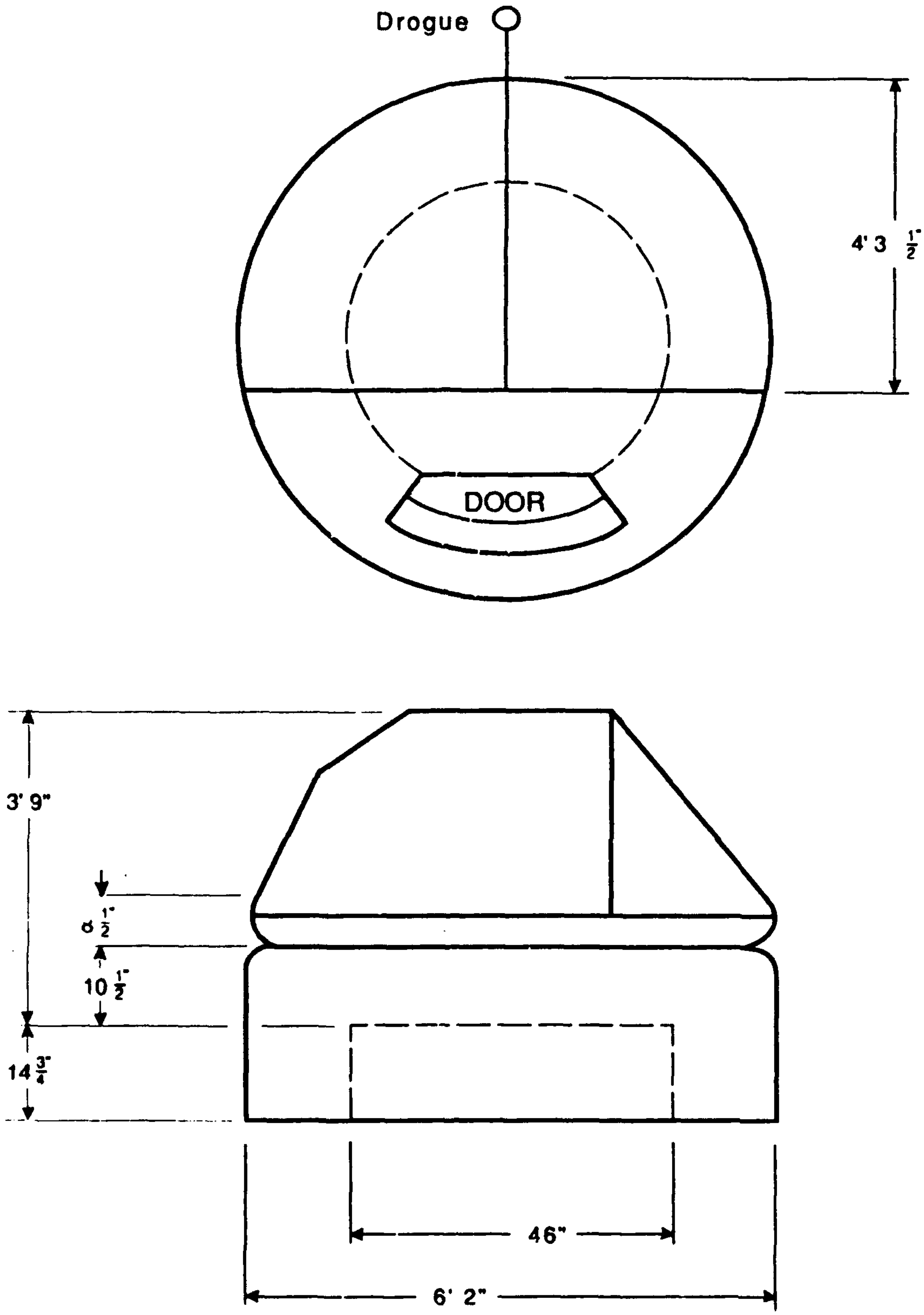


FIGURE 11. SWITLIK 4-MAN LIFE RAFT WITH TOROID BALLAST

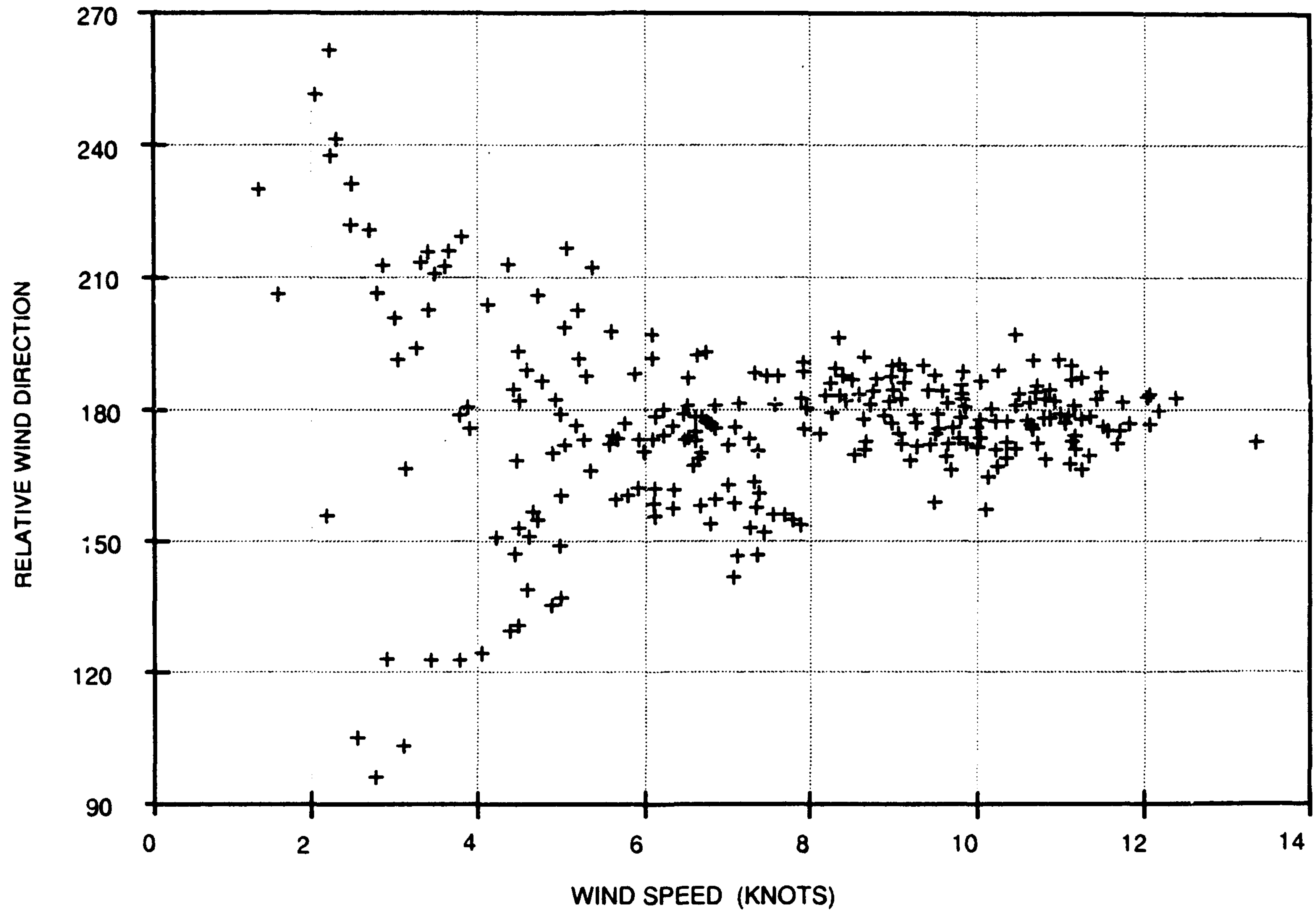
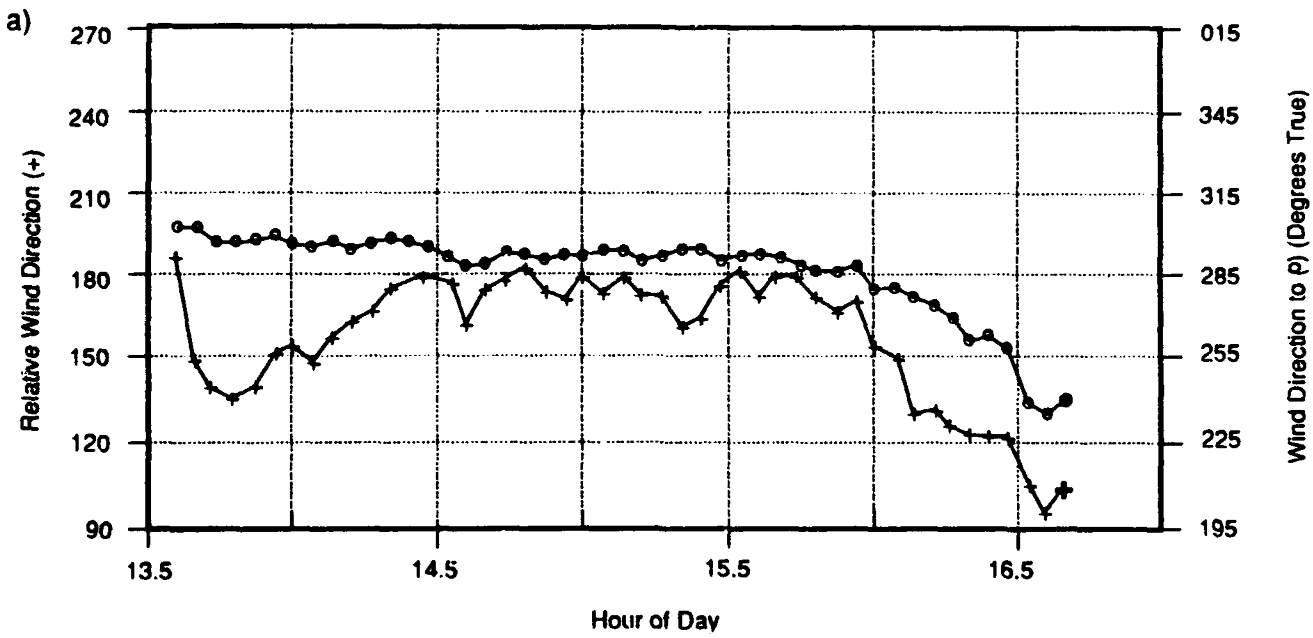


FIGURE 12. RWD VERSUS WIND SPEED FOR SWITLIK 4-MAN RAFT WITH DROGUE



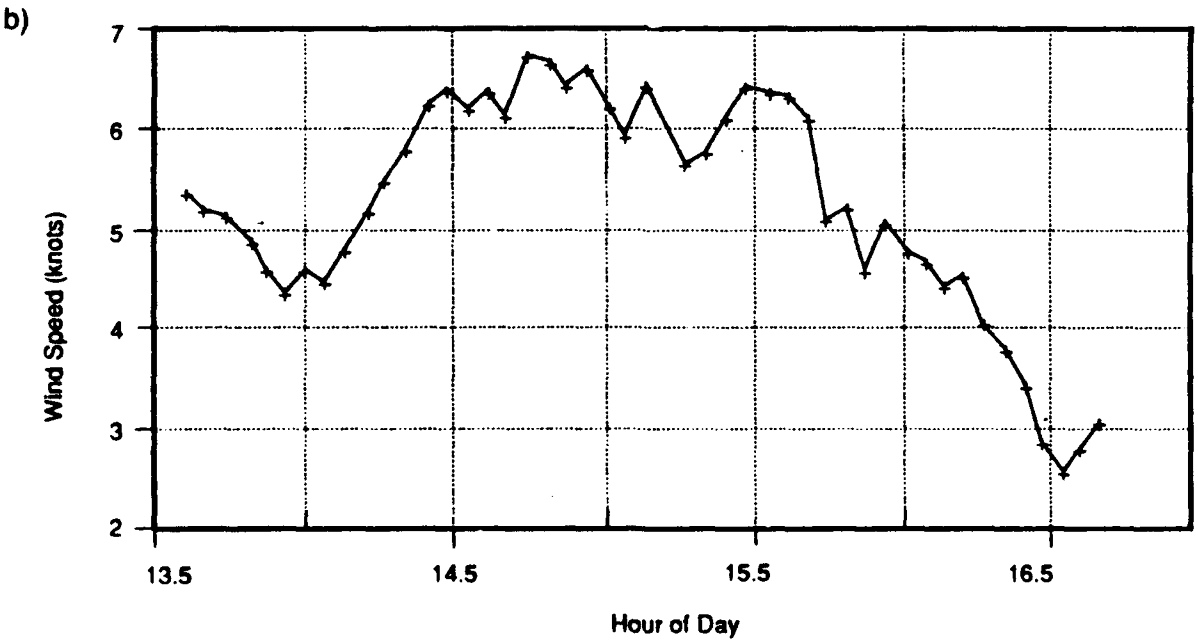


FIGURE 13. DATA OF 6 APRIL 1985 FOR SWITLIK 4-MAN RAFT WITH DROGUE

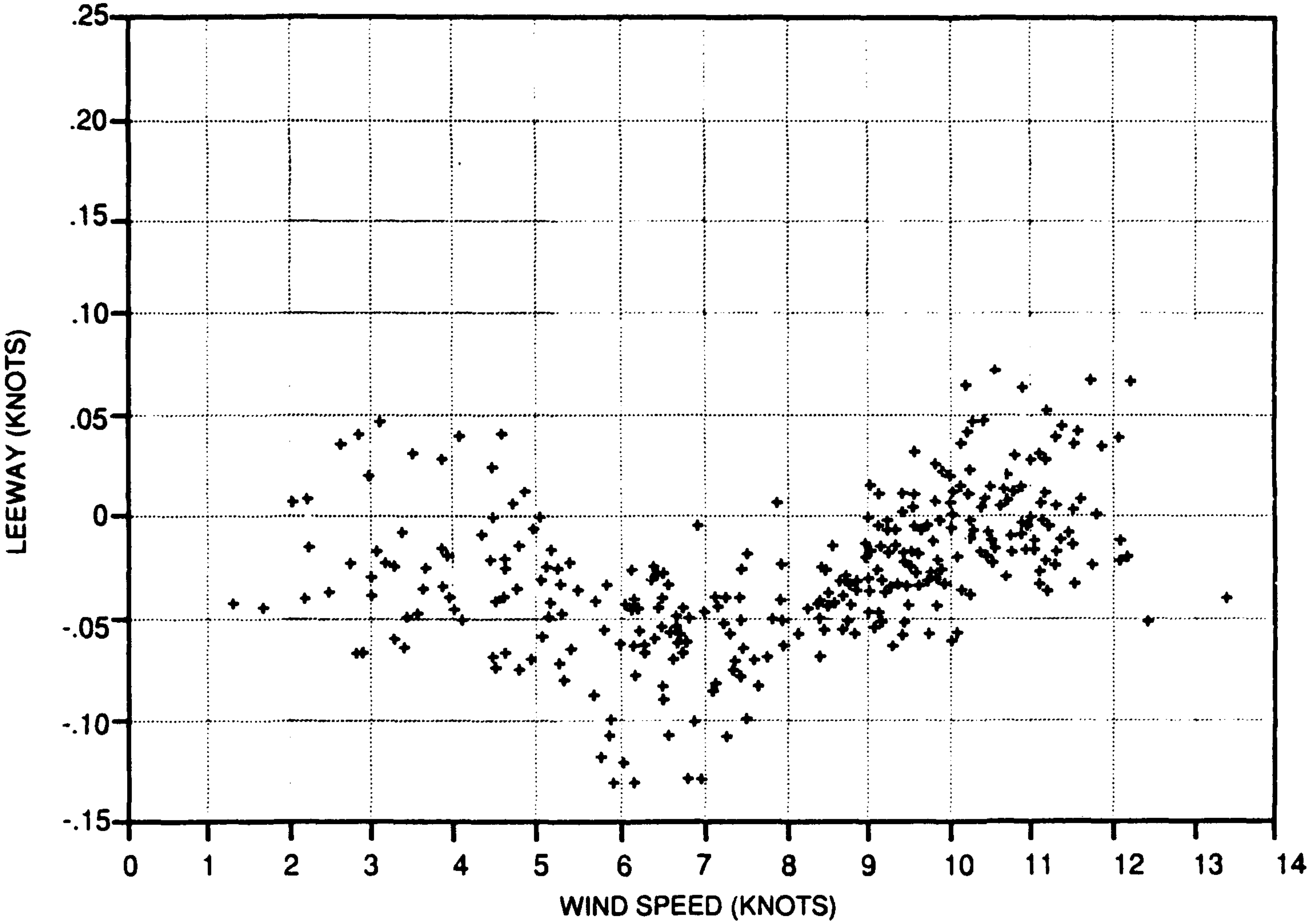


FIGURE 14. DOWNWIND COMPONENT OF LEEWAY VERSUS WIND SPEED
FOR SWITLIK 4-MAN RAFT WITH DROGUE

4.2.2 Switlik 4-Man Raft Without Drogue

The data base for the Switlik 4-man raft without drogue consists of 113 data points collected over 1.5 days. There is almost no overlap of environmental conditions from one day to the next day. One day had winds of 4.7 to 8.0 knots, waves of 1 foot or less, and swells of 1 to 2 feet. The other day had winds of 8.7 to 13.6 knots, waves of 2 to 3 feet, and swells of 2 to 6 feet.

The RWD stayed in two sectors, 080°R to 120°R and 215°R to 225°R. The RWD of 180°R observed when the Switlik 4-man raft was drogued was never observed when the raft did not have a drogue. The RWD changed sectors three times during the longest drift. This is similar to the behavior noticed in the Summer 1983 Experiment (Nash and Willcox, 1985). RWD was found to have no correlation to the leeway angle or to any component of leeway.

The crosswind component of leeway was less than 0.1 knots to the right and left of downwind. The crosswind component was not correlated with wind speed. This confirms the conclusion from the Summer 1983 Experiment that the Switlik 4-man raft drifts downwind (Nash and Willcox, 1985).

The downwind component of leeway (L) is presented in Figure 15. Small negative values of leeway speed at wind speeds of 5 knots represent variations in the data due to measurement errors. The leeway models discussed in Section 4.1 and Appendix B were fitted to these data (see Table 8). The standard error of the slope is presented so that confidence limits can be obtained. The standard error of the estimate is indicative of the scatter of the data around the regression line. The percent variance explained is the percentage of the total variance, in the downwind data leeway component, that is attributable to wind speed. This percent variance is the coefficient of determination multiplied by 100.

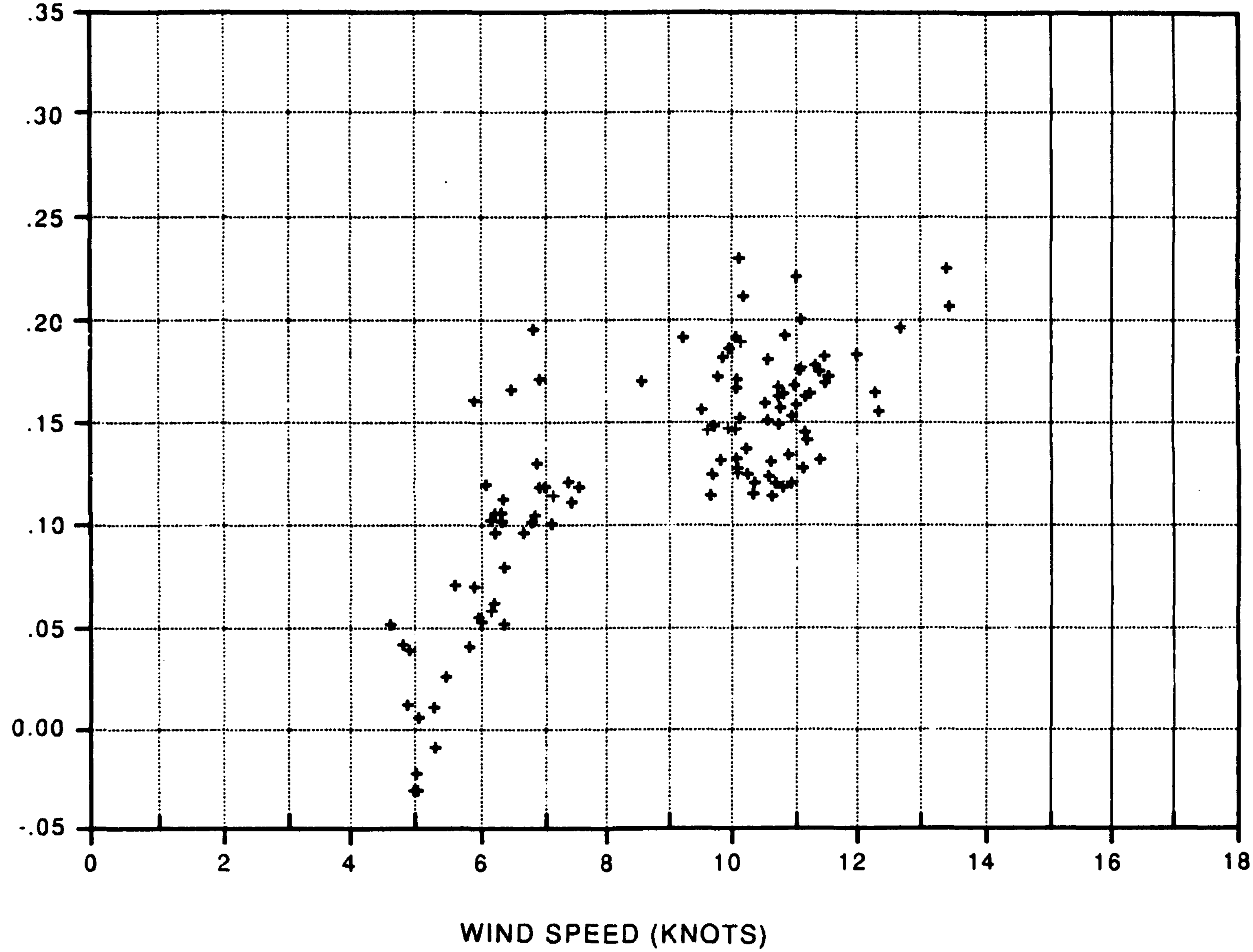


FIGURE 15. DOWNWIND COMPONENT OF LEEWAY VERSUS WIND SPEED FOR SWITLIK 4-MAN RAFT WITHOUT DROGUE

TABLE 8

RESULTS OF LEEWAY MODELS FITTED TO DOWNWIND COMPONENT OF LEEWAY (L) FOR SWITLIK 4-MAN RAFT WITHOUT DROGUE (Values for L are in knots. W is wind speed in knots.)

Model	Standard Slope	Error of: Estimate	% Variance Explained
L = 0.0144W	0.00036	0.03581	58
L = -0.0393 + 0.0183W	0.00139	0.03466	61

Both models provide similar answers over the data range. The negative values produced by the second (L=a+b*W) at wind speeds under 2 knots make it less realistic. Therefore, the first model (L = b*W) is recommended.

The leeway equation derived during the Summer 1983 Experiment was L = 0.100 + 0.0083W, where L (leeway) and W (wind) are in knots. That equation was for a virtually empty raft and was derived using the total leeway speed instead of the downwind component. Therefore, one would expect higher leeway values for that equation. For 3 knots of wind, the leeway speed using the equation L = 0.100 + 0.0083W is 0.08 knots higher than a leeway calculated using the new equation of L = 0.0144W. The difference between the two equations decreases as the wind speed increases, until eventually the new equation provides a higher leeway speed than the 1983 equation. This crossover will take place at a wind speed higher than the data range found during these experiments. Both equations have the Switlik 4-man raft with slower leeway at wind speeds above 6 knots than the equation L = -0.12 + 0.05W given by Scobie and Thompson (1979).

4.3 GIVENS 6-MAN LIFE RAFT

4.3.1 Givens 6-Man Raft With Drogue

The data base for the Givens 6-man raft with drogue includes

142 data points collected over 1.5 days. Wind speed ranged from 2.3 to 13.5 knots with waves and swells of 1 foot or less. The wind speeds on the half day of drift fell within the wind range for the full day of drift.

The drogue was attached to the main bottom tube at a point located just below the canopy support tube opposite the door (Figure 16). For this discussion, the convention for relative bearings will be that the door is at the bow (000°R), and the point of attachment of the drogue to the raft is at 180°R.

The RWD data show considerable scatter for wind speeds under 8 knots; however, the scatter in the RWDs is much less for winds greater than 8 knots (Figure 17). The raft appears to drift with the stern (and the point of attachment of the drogue) nearly toward the wind (170°R) when wind speeds exceed 8 knots. This result is similar to results for the Switlik 4-man raft with drogue (Section 4.2.1).

The downwind component of leeway is essentially zero for wind speeds up to 13 knots (Figure 18). The Givens 6-man raft, when drogued, has no measurable leeway movement for winds up to 13 knots. This data base does not permit extrapolation to winds above 13 knots.

4.3.2 Givens 6-Man Raft Without Drogue

The data base for the Givens 6-man raft without drogue has sizable, with 320 data points collected over 4.5 days. Wind speed ranged from 1.4 to 13.6 knots. Sea conditions ranged from calm to 2.5-foot waves and to 3-foot swells. There was considerable overlap of environmental conditions from day to day; no one day had unique conditions.

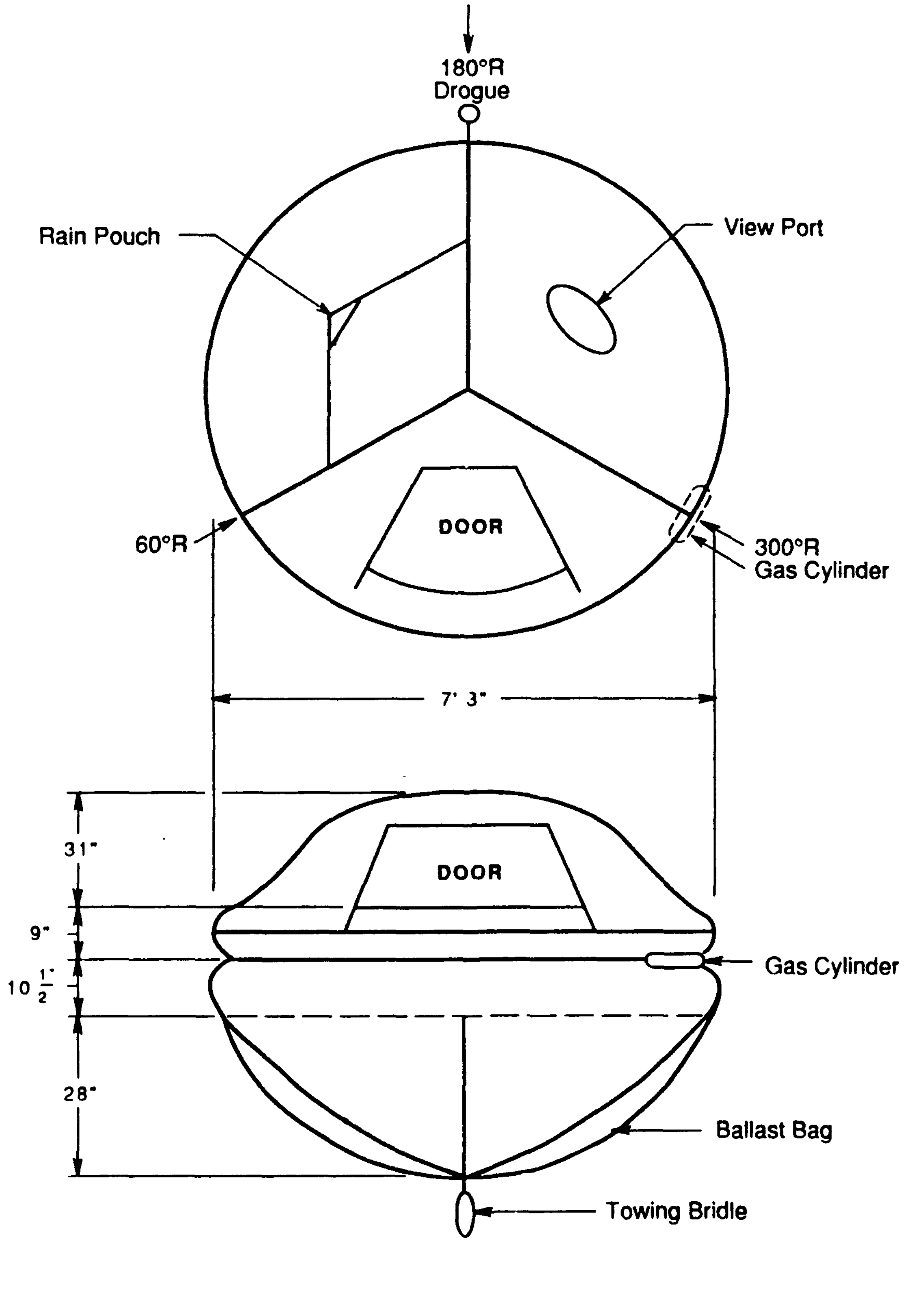


FIGURE 16. GIVENS BUOY 6-MAN LIFE RAFT

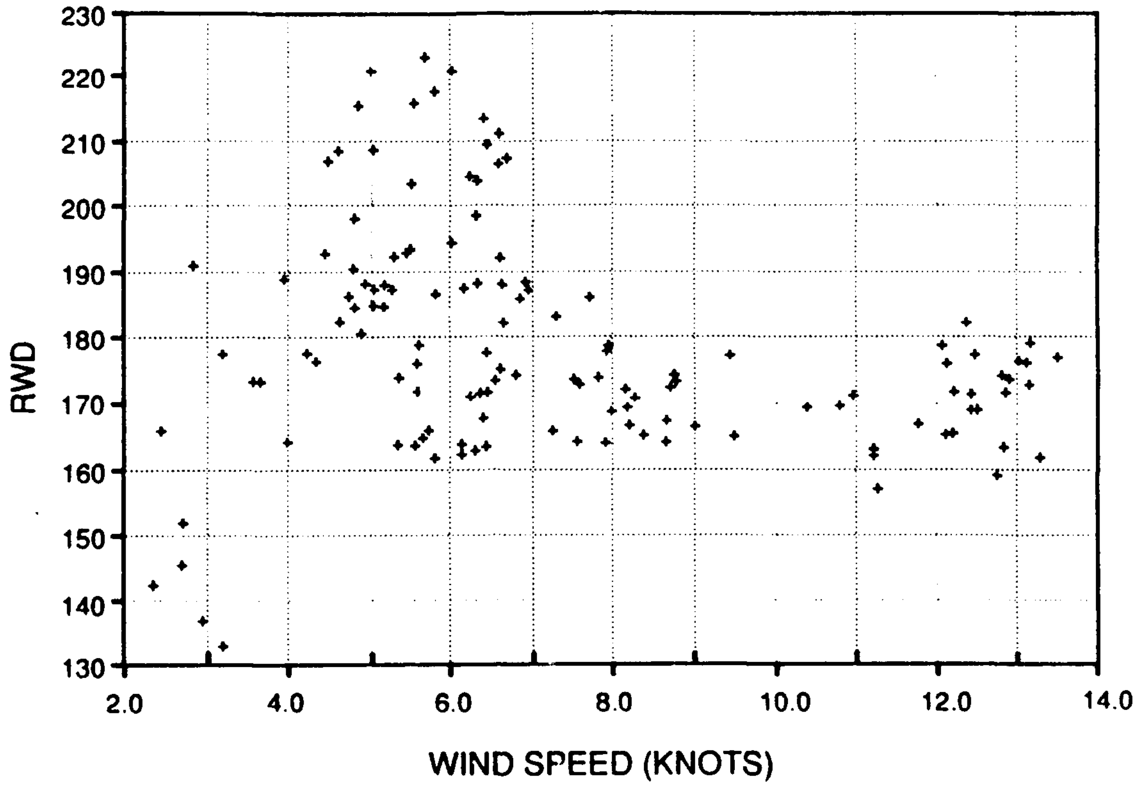


FIGURE 17. RWD VS WIND SPEED FOR 6-MAN RAFT WITH DROGUE

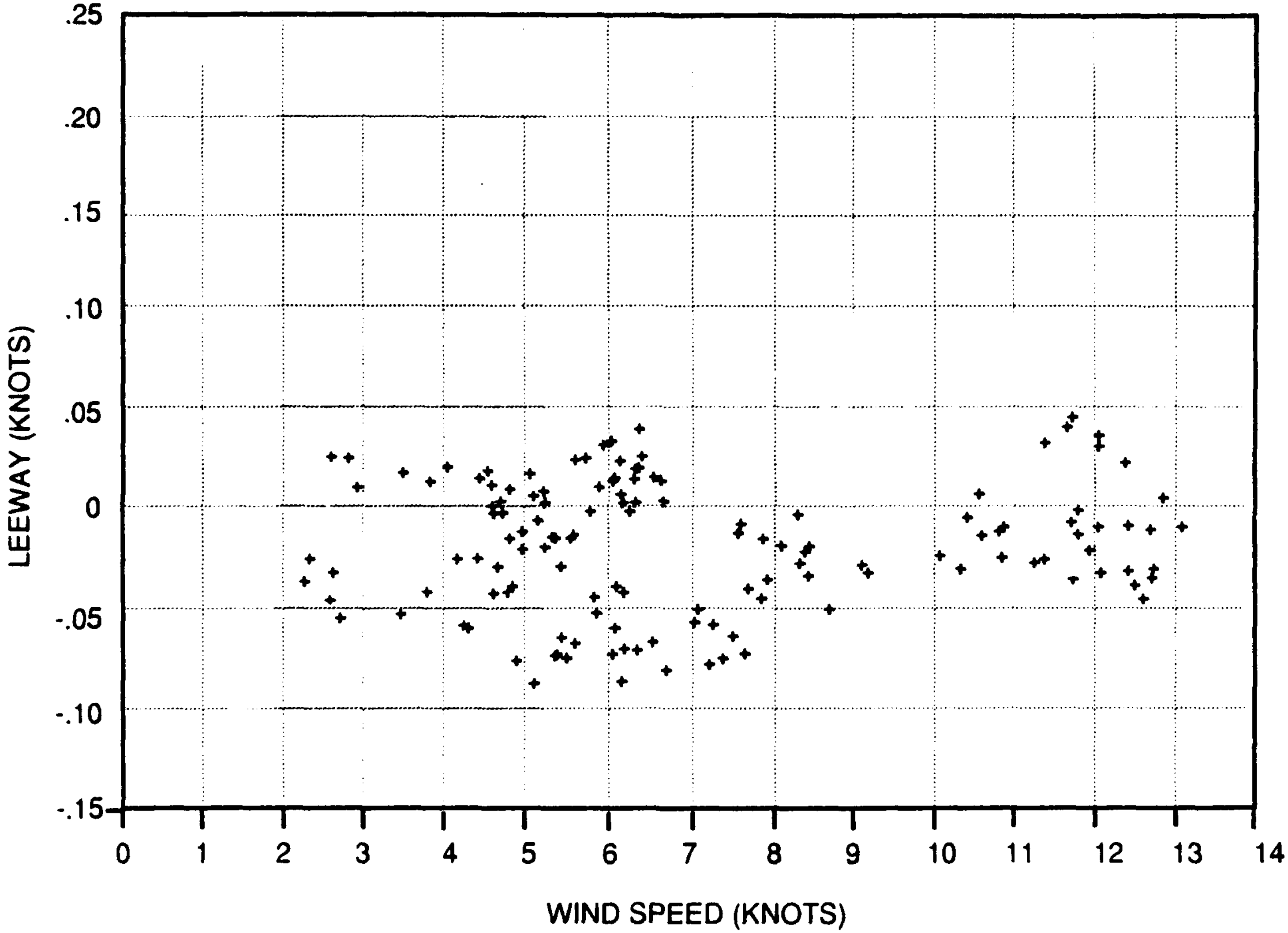


FIGURE 18. DOWNWIND COMPONENT OF LEEWAY SPEED VERSUS WIND SPEED
FOR GIVENS 6-MAN RAFT WITH DROGUE

The discussion of RWD will use the convention that the door of the raft is located at 000°R and the canopy support tubes are located at 060°R, 180°R, and 300°R (Figure 16). The RWDs were predominantly in three sectors: 340°R to 020°R, 090°R to 130°R, and 230°R to 270°R. These sectors correspond to the areas between the canopy support tubes. RWD changed sectors from one to three times a day for winds greater than 6 knots. For winds of 6 knots or less, the RWD varied with the wind direction. An example of the variation of the RWD with wind speed and direction can be seen in Figure 19.

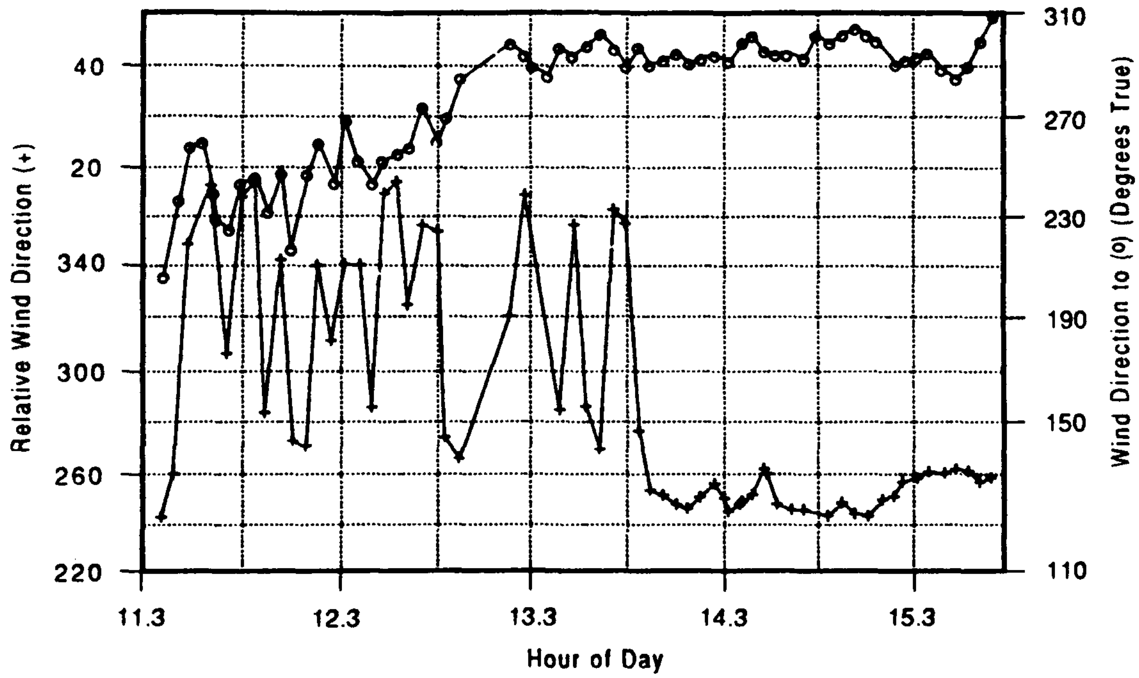
The top line of Figure 19a is the wind direction "to" in degrees true using the right-hand scale. The bottom line of Figure 19a is the RWD using the left-hand scale. Figure 19b is the wind speed in knots.

The horizontal axis is the hour of the day for 24 March 1985. The change in the RWD record when the wind speed increases above 6 knots is striking. At wind speeds above 6 knots, RWD becomes very steady at 240°R to 260°R (Figures 19a and 19b). This suggests that the raft is not strongly affected by winds under 6 knots.

The sector affected by the RWD had no effect on the components of leeway or the leeway angle. There was no correlation between the crosswind component of leeway and the wind speed. The raft drifts nearly directly downwind.

The downwind component of leeway (L) is presented in Figure 20. The negative values around 5.2 knots and the positive values for winds less than 5.2 knots are from two different days. Additional data would be needed to define the leeway for wind speeds less than 5 knots.

a)



b)

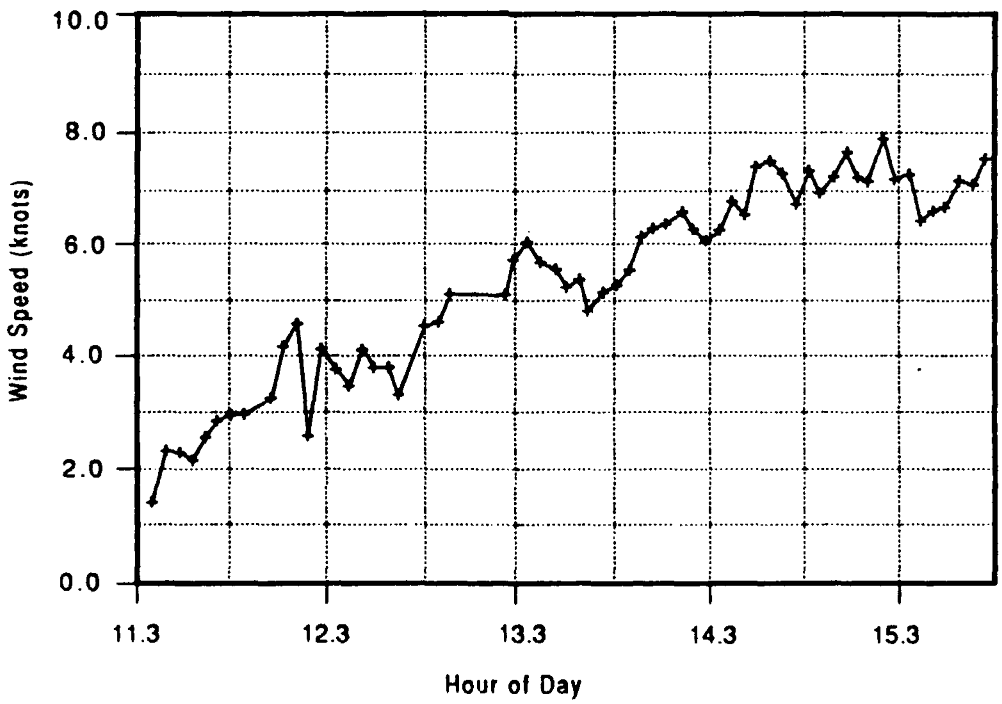


FIGURE 19. DATA OF 24 MARCH 1985 FOR GIVENS 6-MAN RAFT WITHOUT DROGUE

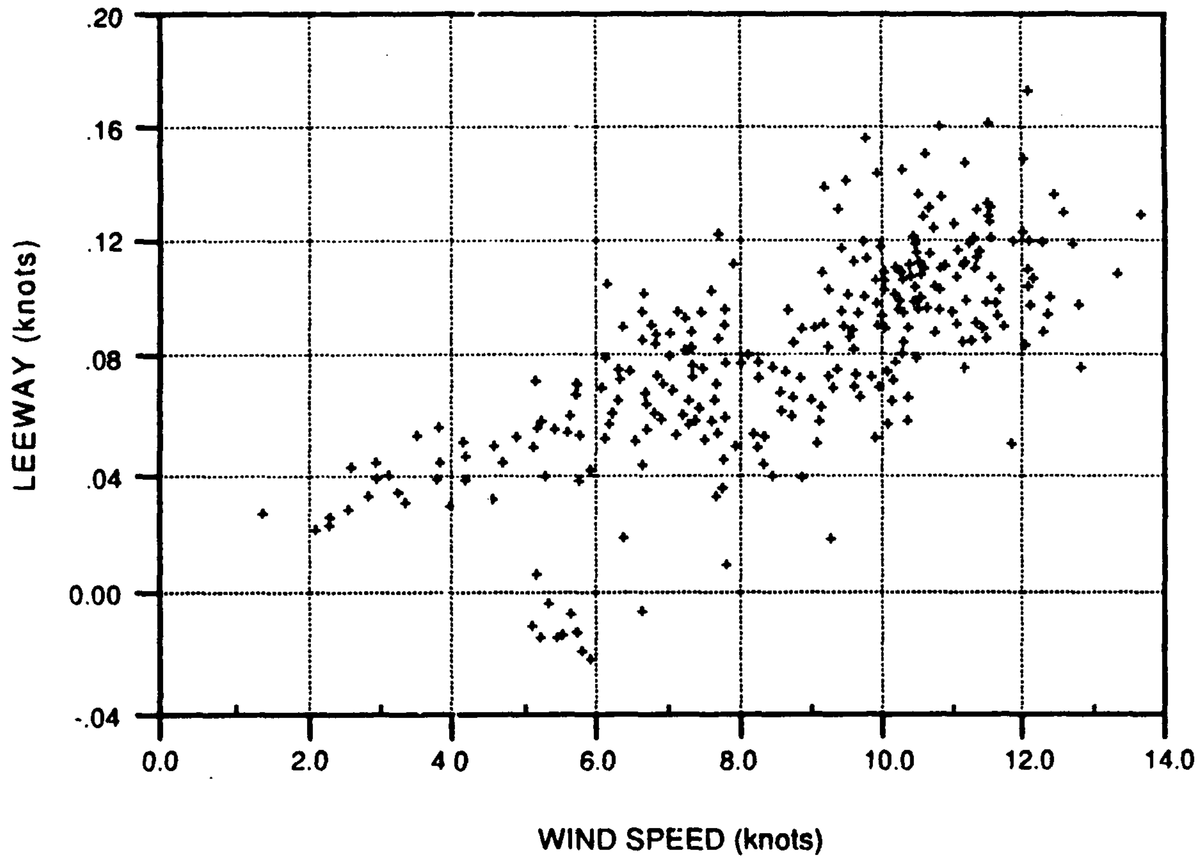


FIGURE 20. DOWNWIND COMPONENT OF LEEWAY VERSUS WIND SPEED
FOR GIVENS 6-MAN RAFT WITHOUT DROGUE

The leeway models discussed in Section 4.1 and Appendix B were fitted to the Givens raft data (Table 9). Both models explained 52% of the variance in the data set. The model $L = a + b*W$ has a value of (a) that is negligible. The first model, $L = b*W$, is chosen for this data set.

TABLE 9

RESULTS OF LEEWAY MODELS FITTED TO DOWNWIND COMPONENT OF LEEWAY (L) FOR GIVENS 6-MAN RAFT WITHOUT DROGUE (Values for L are in knots. W is wind speed in knots.)

Model	Standard Slope	Error of: Estimate	% Variance Explained
L = 0.0099W	0.00015	0.02337	52
L = - 0.0023 + 0.0102W	0.00055	0.02338	52

No correlation was found between the downwind component of leeway rate and wind speed, thus confirming the linear nature of the leeway model.

The leeway equation from the Summer 1983 Experiment was $L = 0.100 + 0.0064W$, where L (leeway) and W (wind speed) are in knots. That equation was for a virtually empty raft and was derived using the total leeway speed instead of the downwind component. Therefore, one would expect higher leeway values for that equation. In fact, for 3 knots of wind, that equation is 0.1 knots higher than the new equation of $L = 0.0099W$. The difference between the two equations decreases as the wind speed increases, until eventually the new equation provides a higher leeway speed than the old. However, this happens at a wind speed of 28 knots, which is well beyond the range of the data. When wind speeds exceed 6 knots, both experiments have the Givens 6-man raft with much slower leeway than the equation $L = -0.12 + 0.05W$ (Scobie and Thompson, 1979).

4.4 AVON 4-MAN LIFE RAFT

The Avon 4-man raft was tested without a drogue; 127 data points were collected over 3 days. There was considerable variation in the swell conditions; most of the data were collected with either no swells or 4- to 5-foot swells (Table 10). The swells were traveling downwind within approximately 30° of the downwind direction.

TABLE 10

ENVIRONMENTAL CONDITIONS REPRESENTED IN DATA FOR AVON 4-MAN RAFT

Number of Points	Date	Wind Speed	Waves (feet)	Swells (feet)
75	8 April 1985	3.9 to 13.6 knots	0.5 to 2	0
48	10 April 1985	9.1 to 14.2 knots	2	4 to 5
4	14 April 1985	3.9 to 6.6 knots	1	2 to 3

The convention for RWD is that the center of the door is at 000°R, and the 045°R to 225°R line runs along the canopy support tube (Figure 21). There are two distinct patterns for RWD data for wind speeds greater than 8 knots (Figure 22). The first pattern of RWD, starting around 165°R for 10 knots of wind and decreasing to 125°R for 14 knots of wind, was for swells of 4 to 5 feet. The second pattern from the upper left-hand corner of the plot to the lower right-hand corner consists mostly of data from 8 April 1985 (i.e., no swells).

The RWDs of 080°R and 135°R may have some significance with respect to swell or no swell at the higher wind speeds. Looking back at Figure 21, an RWD of 135°R corresponds to a line perpendicular to the canopy support tube and running through a ballast bag. An RWD of 080°R also corresponds to a line drawn from the center of the raft through a ballast bag. A silhouette of the raft viewed from 135° would be greater than one viewed

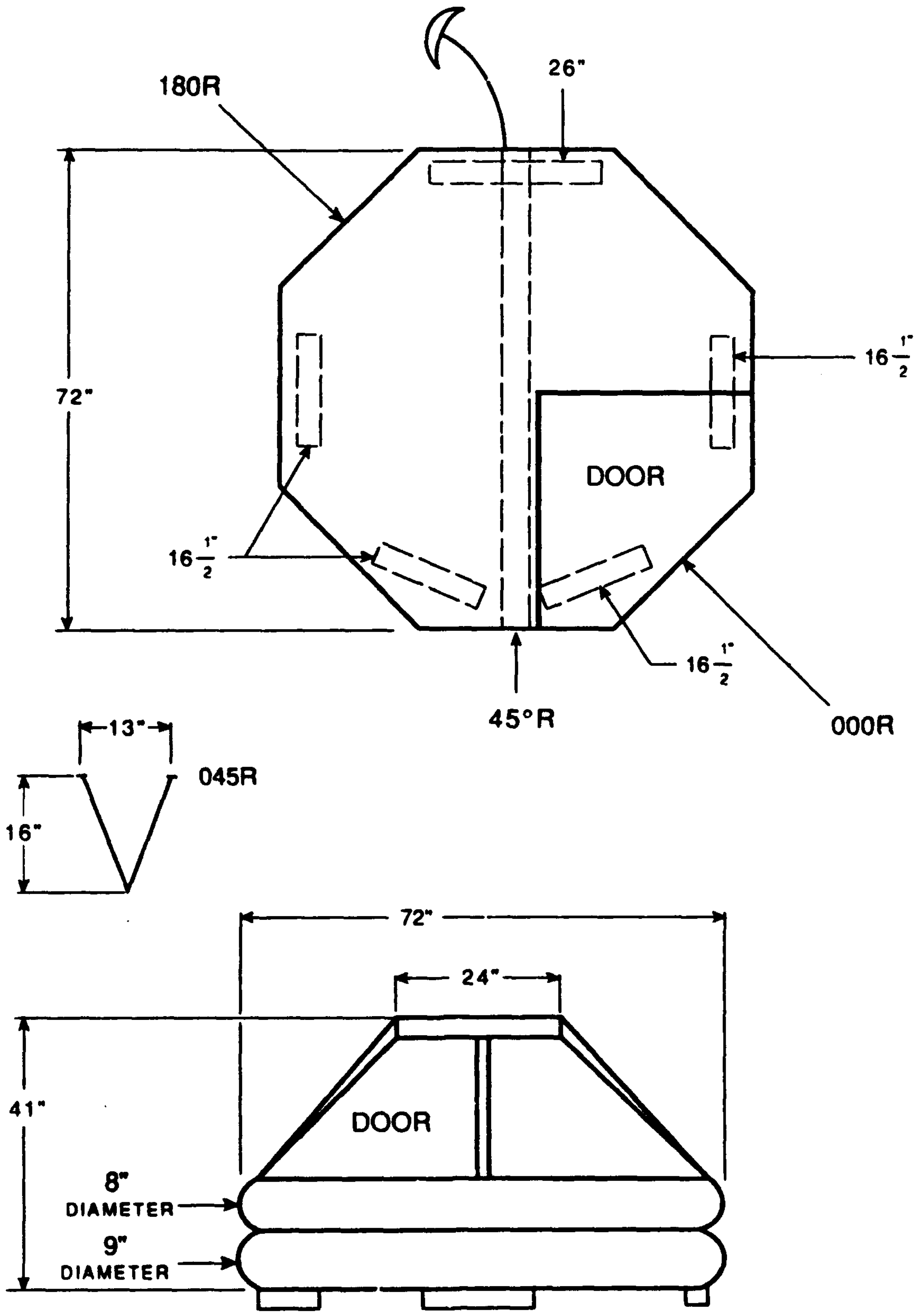


FIGURE 21. AVON 4-MAN LIFE RAFT

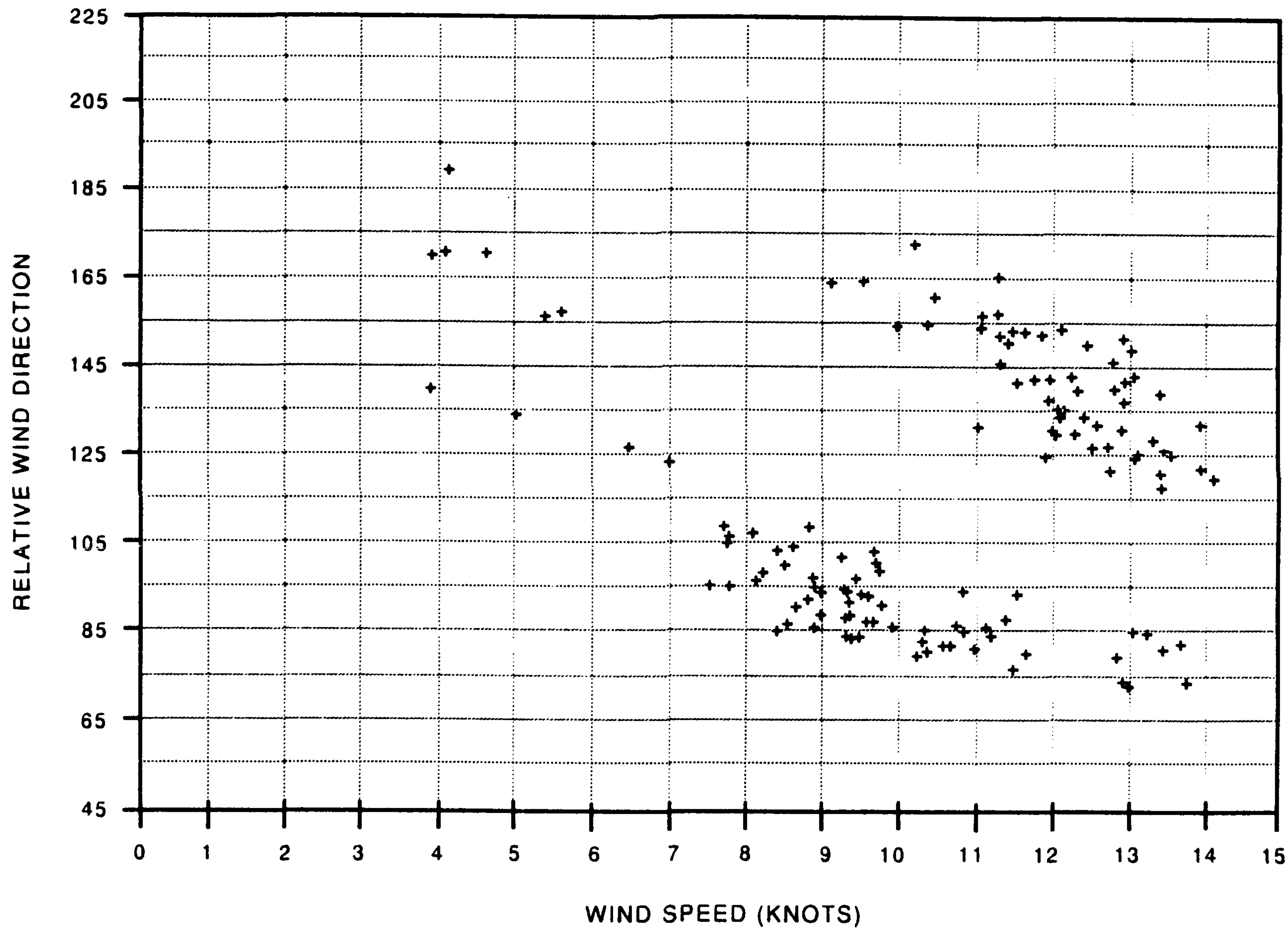


FIGURE 22. RWD VERSUS WIND SPEED FOR AVON 4-MAN RAFT WITHOUT DROGUE

from 080°R. The area of the silhouette corresponds to the sail area available for the wind to push. Thus, a wind from 135°R would exert a greater force on the raft than the same wind from 080°R.

The presence of swell appeared to affect the raft's orientation to the wind. Differences in orientation might produce differences in leeway. The effects of swell and raft orientation cannot be separated in this data set. The data were combined for analysis.

The downwind component of leeway (L) for the Avon 4-man raft without drogue is presented in Figure 23. Leeway models discussed in Section 4.1.2 and Appendix B were fitted to these data (Table 11). The second model (L = a+b*W) provides the best fit to the data.

4.4.1 Summary for Avon 4-Man Raft

The Avon 4-man raft exhibits at least two patterns of orientation to the wind.

TABLE 11

RESULTS OF LEEWAY MODELS FITTED TO DOWNWIND COMPONENT OF LEEWAY (L) FOR AVON 4-MAN RAFT WITHOUT DROGUE (Values for L are in knots. W is wind speed in knots.)

Model	Standard Slope	Error of: Estimate	% Variance Explained
L = 0.0081W	0.00055	0.06508	51
L = -0.1412 + 0.0213W	0.00217	0.05704	66

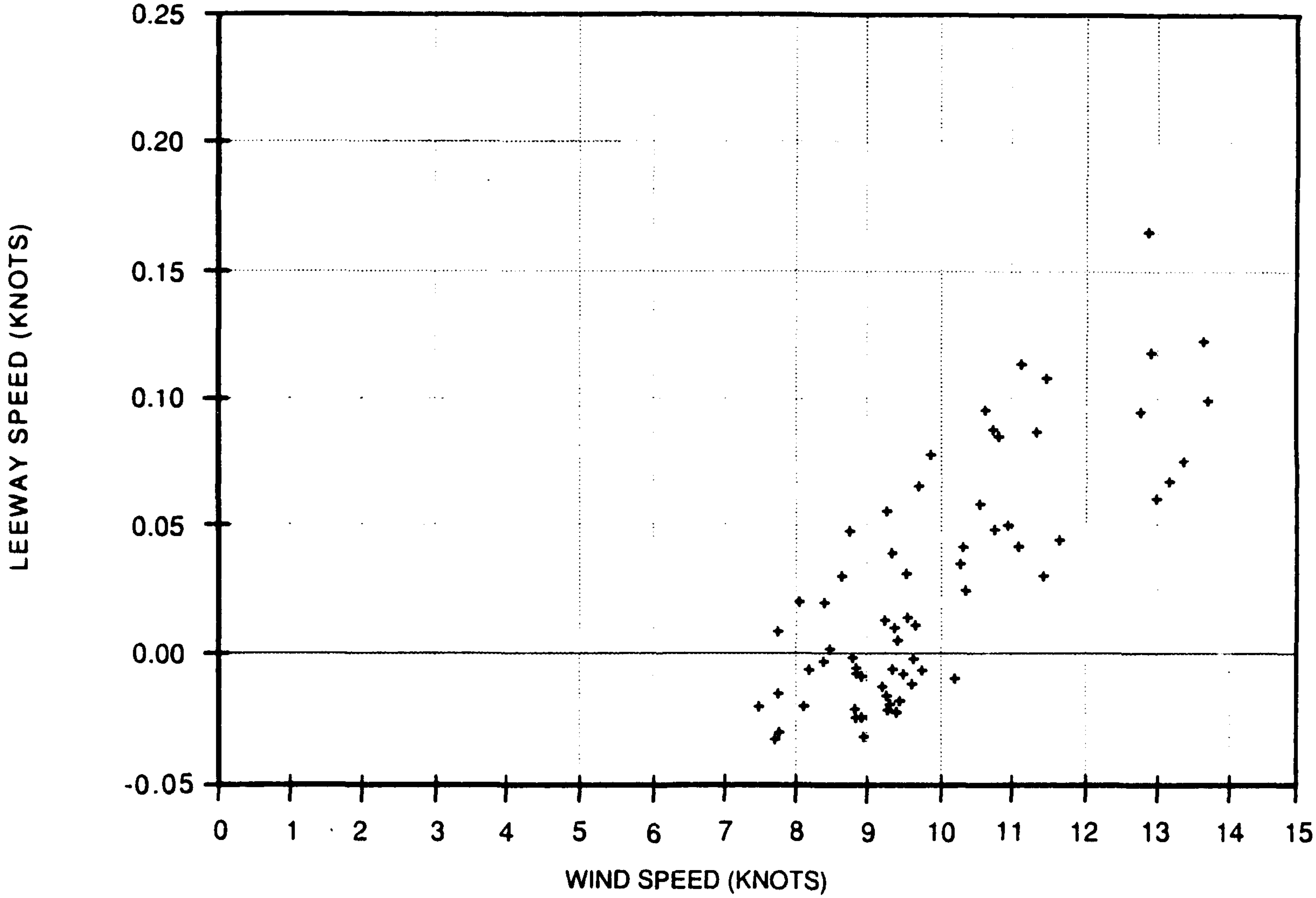


FIGURE 23. DOWNWIND COMPONENT OF LEEWAY SPEED VERSUS WIND SPEED
FOR AVON 4-MAN RAFT (RWD<115R)

Leeway speeds calculated using the Avon 4-man raft model from this experiment are consistently and substantially lower than leeway speeds calculated using the CASP leeway rate of 0.07. Because of the high negative leeway values predicted at low wind speeds and the high variability of leeway angle the results are questionable.

The CASP leeway rate of 0.07 represented the class of raft used in the Summer 1983 Experiment (Nash and Willcox, 1985) fairly well; however, the Avon 4-man raft has more ballast (more and larger bags) and is smaller than the 6-man raft used in the Summer 1983 Experiment. The results suggest that the class description "raft with canopy and ballast bags" is too broad a classification.

4.5 WINSLOW 4-MAN LIFE RAFT

The testing period for the Winslow 4-man raft coincided with that of the Avon 4-man raft. These data were also collected in the disparate weather conditions presented in Table 10, Section 4.4. The Winslow 4-man raft was deployed without a drogue on 8 through 10 April 1985. It was deployed with a drogue on 14 April 1985 but only four data points were collected on that day.

The Winslow 4-man raft is an oblong canopied raft without any ballast system or bags (see Section 2.3.5 for description). The convention for RWD is that one end of the raft is the bow (000°R), the other is the stern (180°R), and the door is on the starboard side at 090°R (Figure 24). Except for the door, the raft is completely symmetrical about the centerline. The Winslow 4-man raft drifted with the wind at 090°R and 270°R (beam to the wind).

4.5.1 Winslow 4-Man Raft With Drogue

Data for the Winslow 4-man raft with drogue consist of four data points with winds of 3.9 to 6.8 knots. The drogue was attached below the door (090°R). The RWDs were approximately 090°R with the drogue upwind. The downwind component of leeway was negligible.

4.5.2 Winslow 4-Man Raft Without Drogue

The Winslow 4-man raft without a drogue drifted fast enough that it needed to be recovered and redeployed during each day to prevent the drifter array from becoming too large. There was less load on the second deployment due to leakage from the water jugs. The full load was approximately 720 pounds: 640 pounds of water jugs and 80 pounds of equipment. The lighter load was unknown and variable. Because leeway varies with the loading condition, the data were separated by loading condition. Only the data for the fully loaded raft are presented here.

4.5.3 Winslow 4-Man Raft Without Drogue, Fully Loaded

Data for the Winslow 4-man raft without drogue, fully loaded, consist of 44 data points in no swell conditions and 11 data points with 4- to 5-foot swells. The downwind component of leeway for swell height conditions of 0 feet and 4 to 5 feet is presented in Figure 25. A multiple linear least-squares regression of the downwind component of leeway (L) as a function of wind speed (W) and swell height (S) explained 86% of the variance in data (Table 12). Leeway was found to increase with increasing wind speed and swell height.

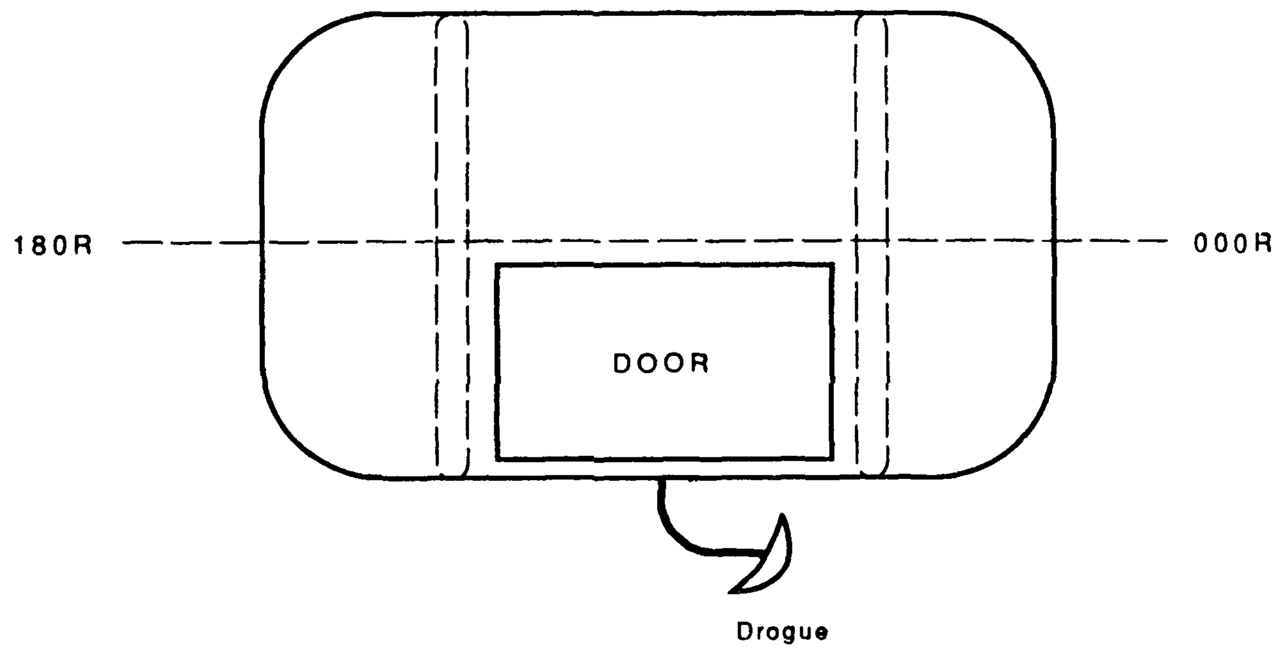


FIGURE 24. WINSLOW 4-MAN RAFT

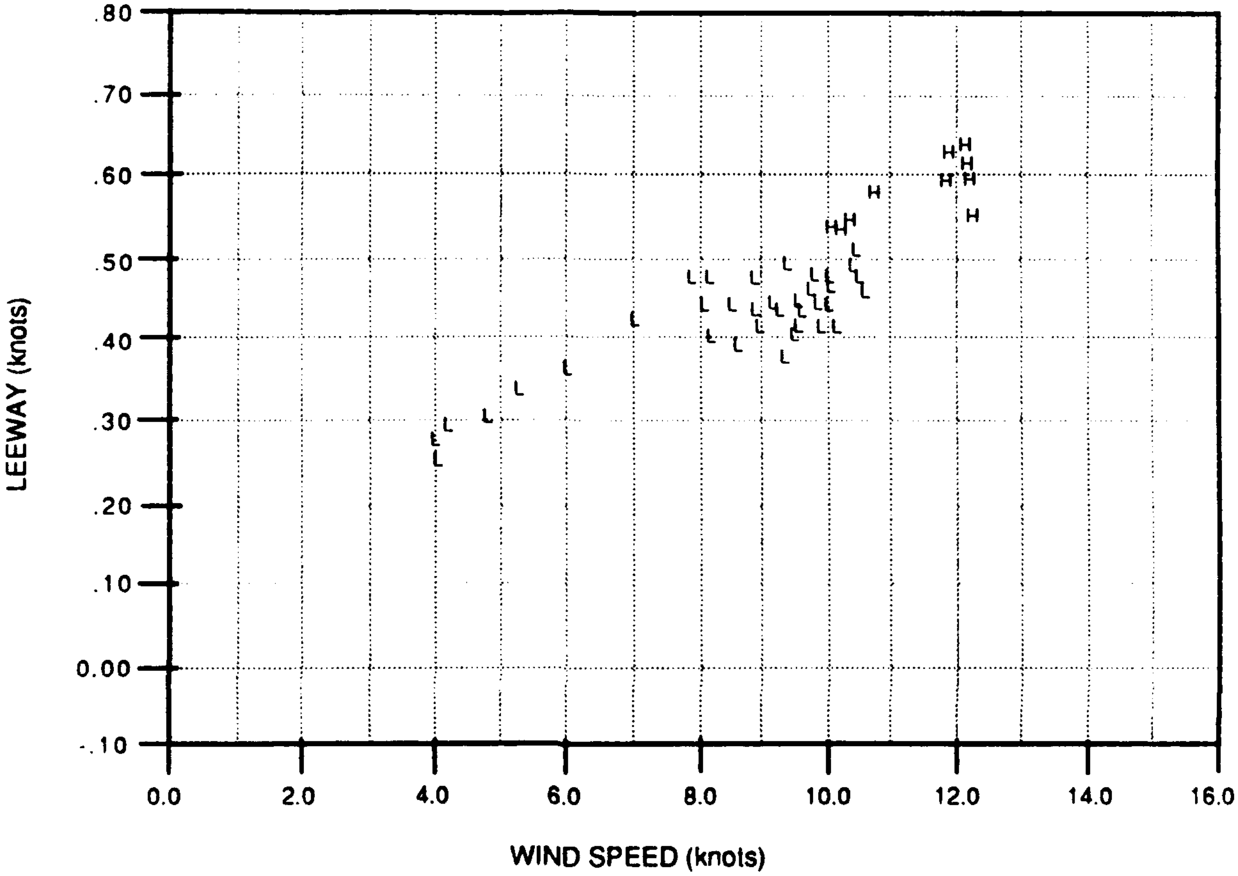


FIGURE 25. DOWNWIND COMPONENT OF LEEWAY VERSUS WIND SPEED FOR WINSLOW 4-MAN RAFT WITHOUT DROGUE, FULLY LOADED. (SWELL HEIGHT: L FOR NO SWELL, H FOR 4 TO 5 FOOT SWELL)

TABLE 12

RESULTS OF LEAST-SQUARES FIT OF DOWNWIND COMPONENT OF LEEWAY (L) AS A FUNCTION OF WIND SPEED (W) AND SWELL HEIGHT (S) TO MODEL L = a+b*W+e*S FOR WINSLOW 4-MAN RAFT WITHOUT DROGUE, FULLY LOADED.

Coefficient		95% Confidence Limits		Units
a	0.17951	0 13646	0.22257	knots
b	0.02796	0.02303	0.03289	
e	0.01747	0.01238	0.02256	knots/feet

While a regression analysis that explains 86% of the variance is a very good fit to the data, a regression on the same data using the downwind component of leeway as a function of wind speed alone explained 75% of the variance (Table 13). The consistency of the results can be checked by inserting a swell height into the equation from Table 12 and comparing the result with the corresponding equation for the same swell conditions from Table 13. The comparison for swell heights of 4 to 5 feet (using a swell height of 4.5 feet) is:

From Table 12: $L = 0.25813 + 0.02796W$,

From Table 13: $L = 0.23793 + 0.02992W$,

where L and W are in knots.

TABLE 13

RESULTS OF LEAST-SQUARES FIT OF DOWNWIND COMPONENT OF LEEWAY (L) AS A FUNCTION OF WIND SPEED (W) TO MODEL L = a+b*W FOR DIFFERENT SWELL HEIGHTS FOR WINSLOW 4-MAN RAFT WITHOUT DROGUE, FULLY LOADED

(Wind speed and leeway speed are in knots.)

Swell Height (feet)	a	b	% Variance Explained
0	0.18044	0.02785	70
4 to 5	0.23793	0.02992	53
Combined	0.11228	0.03715	75

Table 14 provides the results of the leeway models for the fully loaded Winslow 4-man raft, without drogue, for combined swell conditions.

Although the model L = a+b*W explains 75% of the variance for combined swell conditions, it produces a leeway of 0.1 knots at zero wind speed. Therefore, the model L = b*W is recommended.

TABLE 14

RESULTS OF LEEWAY MODELS FITTED TO DOWNWIND COMPONENT OF LEEWAY (L) FOR FULLY LOADED WINSLOW 4-MAN RAFT WITHOUT DROGUE FOR COMBINED SWELL CONDITIONS

(Values for L are in knots. W is wind speed in knots.)

Model	Standard Slope	Error of: Estimate	% Variance Explained
L = 0.0490W	0.00068	0.04679	67
L = 0.1123 + 0.0371W	0.00292	0.04102	75

4.6 SMALL BOATS

Three small boats were tested for three days as part of the joint FAU and R&DC effort. Due to equipment problems, there were only two days with adequate wind data for analysis. For these two days, the winds ranged from 1.4 to 12.2 knots, waves ranged from 1 to 2 feet, and swells ranged from 0 to 3 feet. There was considerable duplication of weather conditions between the two days.

The convention for RWD for the three craft is the conventional one for boats and ships. The bow is 000°R and the stern is 180°R.

Leeway results for the 14-foot outboard are discussed in Section 4.6.1. Leeway for the 19-foot outboard is discussed in Section 4.6.2, and results for the 20-foot cabin cruiser are discussed in Section 4.6.3.

4.6.1 14-Foot Outboard

Data for the 14-foot Boston Whaler-type outboard consist of 120 data points, of which 45 points have RWD. An additional 45 points were collected without RWD, but with the wind direction.

The RWDs were predominantly concentrated between 070°R and 080°R, and also between 265°R and 275°R. This indicates that the 14-foot outboard drifts beam to the wind.

The leeway angles divided into two groups as wind speed increased past 7 knots (Figure 26). For the first group, the leeway angles had a mean of +14° (14° to the right of the downwind), and the RWDs were between 265°R and 275°R. The second group of leeway angles had a mean of -24° (24° to the left of downwind). The RWDs for the second group are unknown.

The difference of leeway angles between the two data groups is unexplained and could be due to a different RWD for the second group.

The primary components of leeway for both groups of leeway angles are shown in Figure 27. Both leeway models fitted to the primary component of leeway (Table 15) have about the same fit to the data. Therefore, the model L = b*W is recommended for simplicity. As would be expected from the fit of the model L = b*W to the data, there were no significant correlations of the primary leeway rate to wind speed.

TABLE 15

RESULTS OF LEEWAY MODELS FITTED TO PRIMARY COMPONENT OF LEEWAY (L) FOR 14-FOOT OUTBOARD
(Values for L are in knots. W is wind speed in knots.)

Model	Standard Slope	Error of Estimate	% Variance Explained
L = 0.0398W	0.00045	0.03718	78
L = 0.0427 + 0.0344W	0.00155	0.03537	81

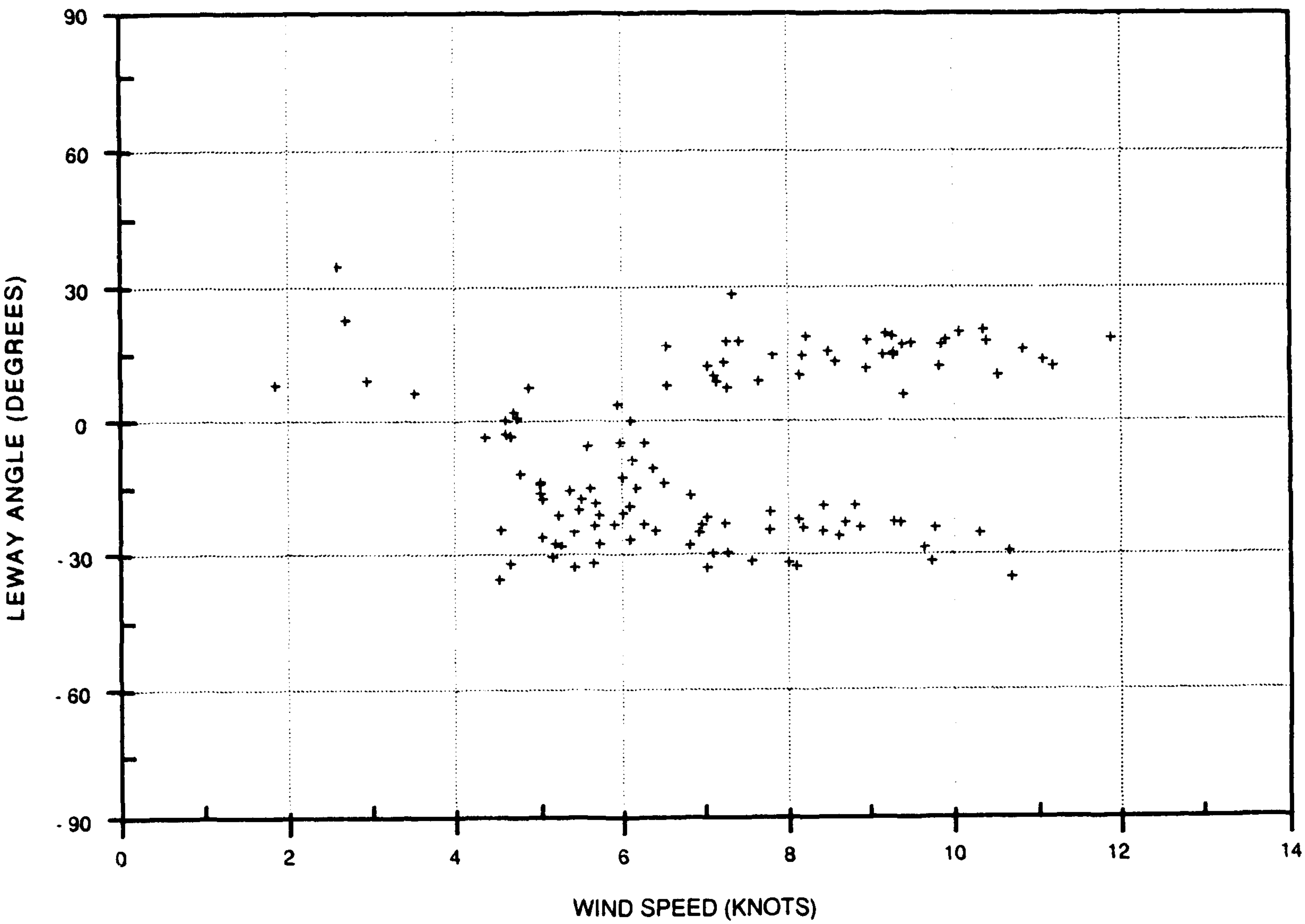


FIGURE 26. LEEWAY ANGLE VERSUS WIND SPEED FOR 14 - FOOT OUTBOARD

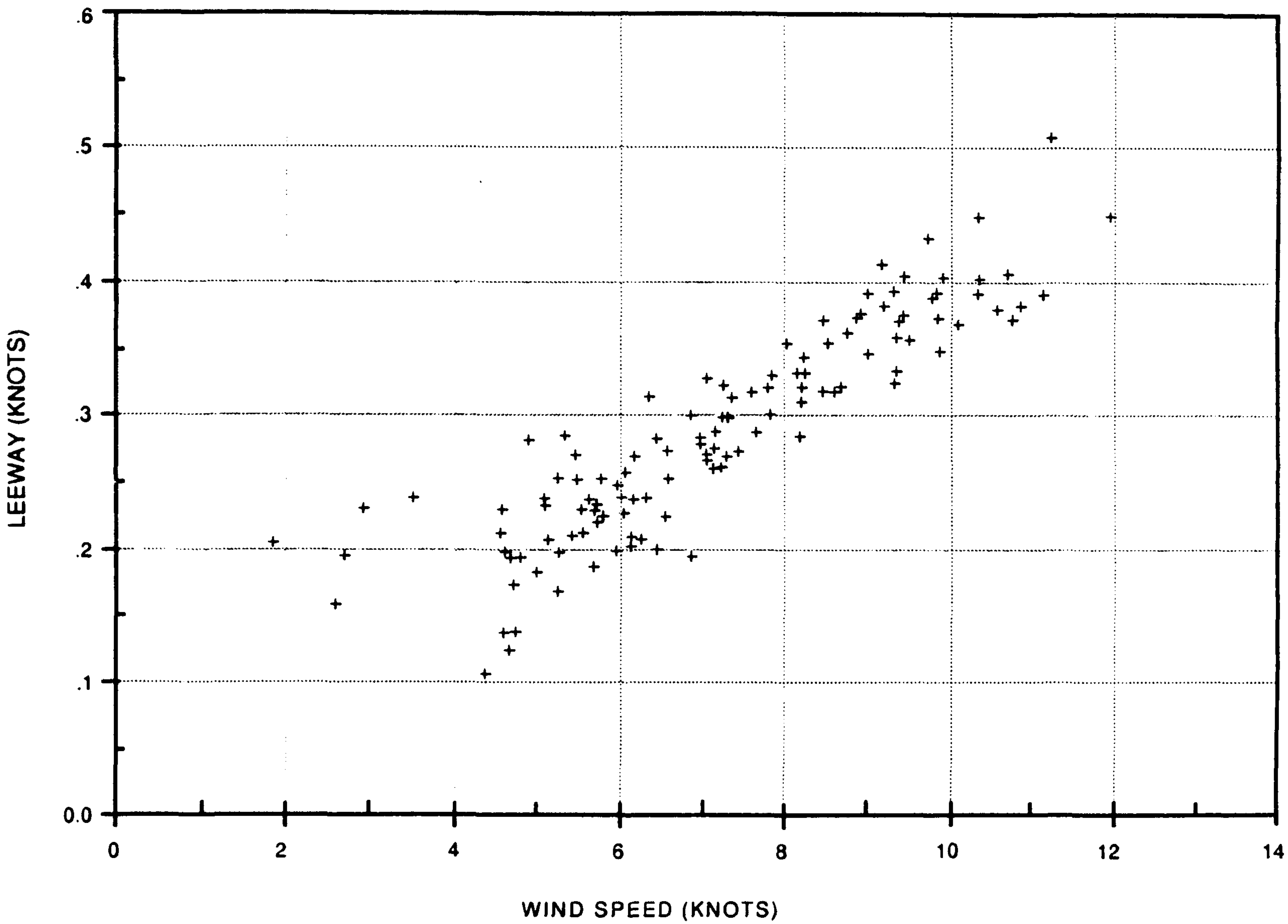


FIGURE 27. PRIMARY COMPONENT OF LEEWAY VERSUS WIND SPEED FOR 14-FOOT OUTBOARD

4.6.2 19-Foot Outboard

Data for the 19-foot outboard consist of 141 data points collected over two days. All but four data points utilize wind information from the Brooks and Gatehouse wind instrument.

The engine on the 19-foot outboard was always in the down position and oriented amidships. The FAU student generally used this craft for fishing; therefore, it was fully equipped. The load on the craft should be typical for one or two persons going out for a day's fishing.

The RWD and leeway angle data are rough because a single wind reading covered several data records. The majority of the RWDs were between 110°R and 220°R, but the tendency was toward 180°R, indicating that the 19-foot outboard drifts stern to the wind.

Leeway angles ranged from 39° to the left of downwind to 32° to the right of downwind (Figure 28), with half the leeway angles to the right of downwind. (The grouping of the leeway angles into vertical lines on Figure 28 is the result of a single wind reading serving for several drift intervals). A linear least-squares regression of leeway direction as a function of wind direction (in degrees true) explained 81% of the variance in leeway direction. The addition of RWD into the regression did not add to the explained variance. All indications that the craft has some leeway angle are weak and inconclusive. Resolution of leeway angle requires more data of a higher quality. The rest of the analysis will assume that the 19-foot outboard drifts downwind.

The downwind component of leeway ranged up to 0.7 knots for 11 knots of wind (Figure 29). Both leeway models provide a good fit to the data (Table 16); therefore, the model L = b*W is recommended for simplicity.

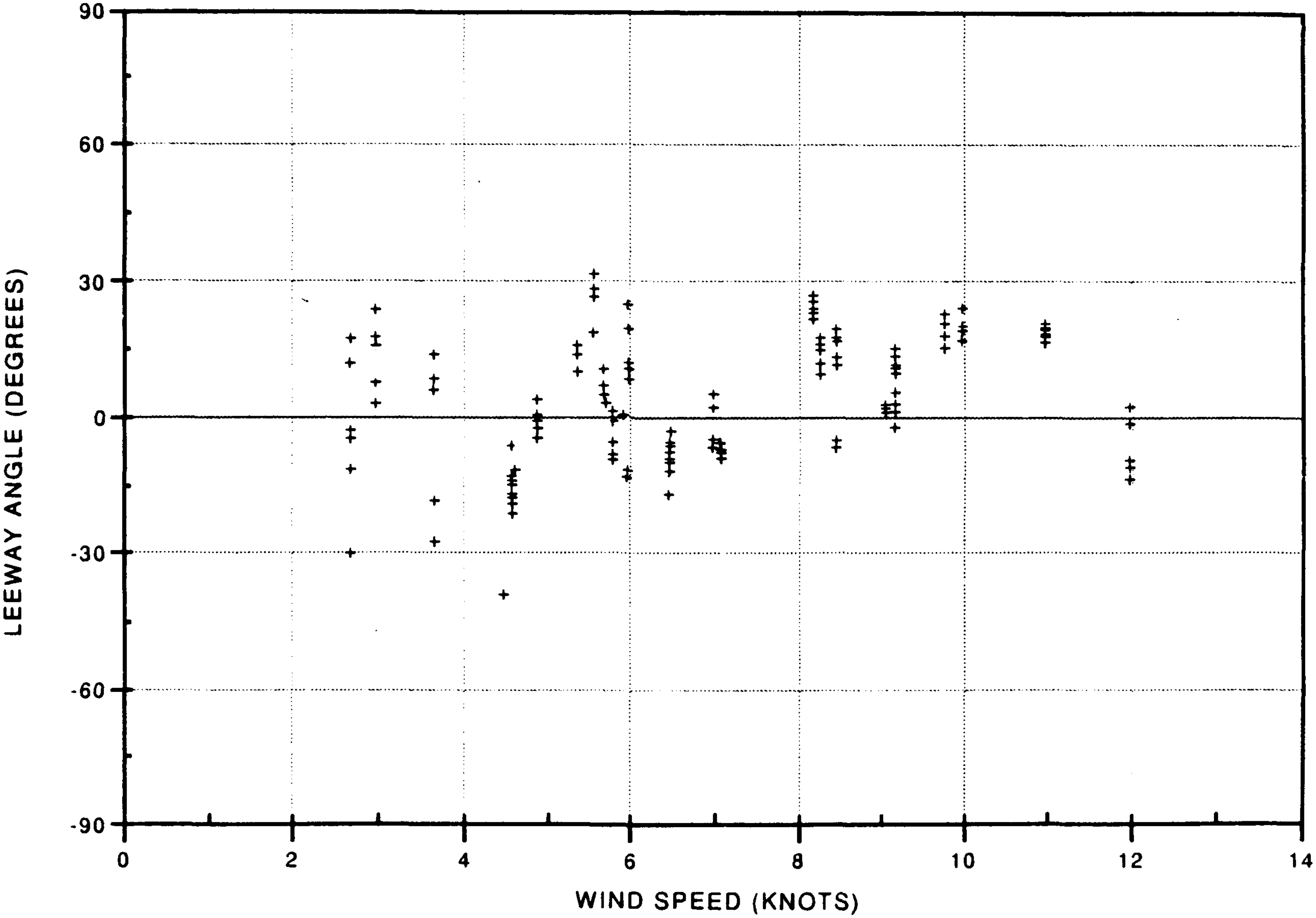


FIGURE 28. LEEWAY ANGLE VERSUS WIND SPEED FOR 19-FOOT AQUASPORT

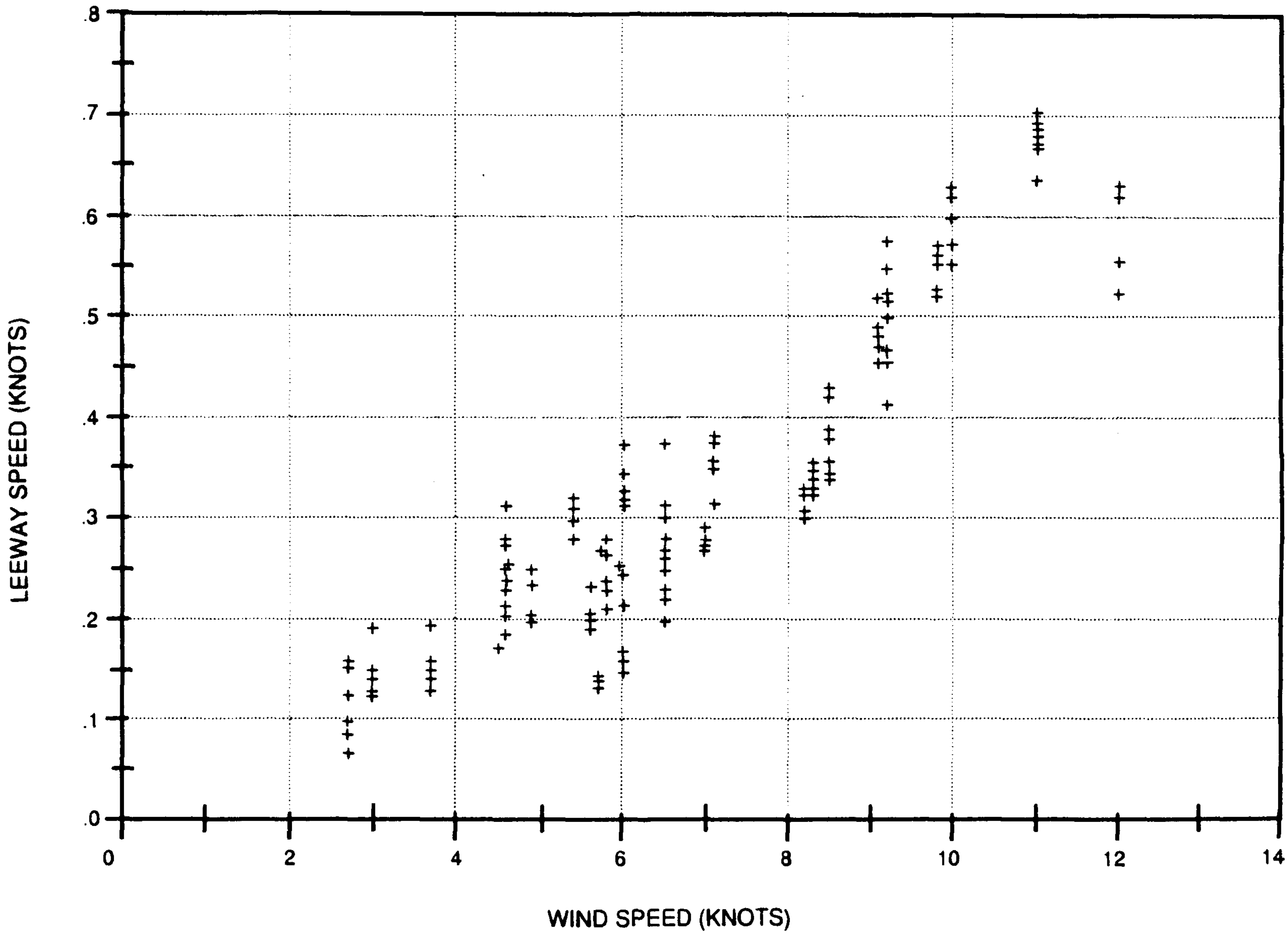


FIGURE 29. DOWNWIND COMPONENT OF LEEWAY VERSUS WIND SPEED FOR 19 - FOOT AQUASPORT

TABLE 16

RESULTS OF LEEWAY MODELS FITTED TO DOWNWIND COMPONENT OF LEEWAY (L) FOR 19-FOOT OUTBOARD
(Values for L are in knots. W is wind speed in knots.)

Model	Standard Slope	Error of: Estimate	% Variance Explained
L = 0.0493W	0.00080	0.07003	81
L = -0.0851 + 0.0602W	0.00225	0.06448	84

4.6.3 20-Foot Cabin Cruiser

Leeway data for the 20-foot cabin cruiser consist of 146 data points collected over two days. An additional 45 data points were collected; however, there was no suitable wind direction information.

The 20-foot cabin cruiser drifted primarily stern to the wind with RWDs lying between 120°R and 220°R. There is a weak correlation between leeway angle and RWD caused by the craft not responding to quick changes in wind direction. The leeway angles ranged between 26° to the left and 27° to the right of downwind (Figure 30). On average the 20-foot cabin cruiser appears to drift downwind with little or no leeway angle.

Leeway speed appears to be a linear function of wind speed (Figure 31). Both leeway models provide equivalent fits to the downwind component of leeway (Table 17). The correlation between the downwind component of leeway rate and wind speed is negligible, as would be expected from the fit of the model L = b*W to the leeway speed. Again, the model L = b*W is recommended for simplicity, as the goodness-of-fits are similar.

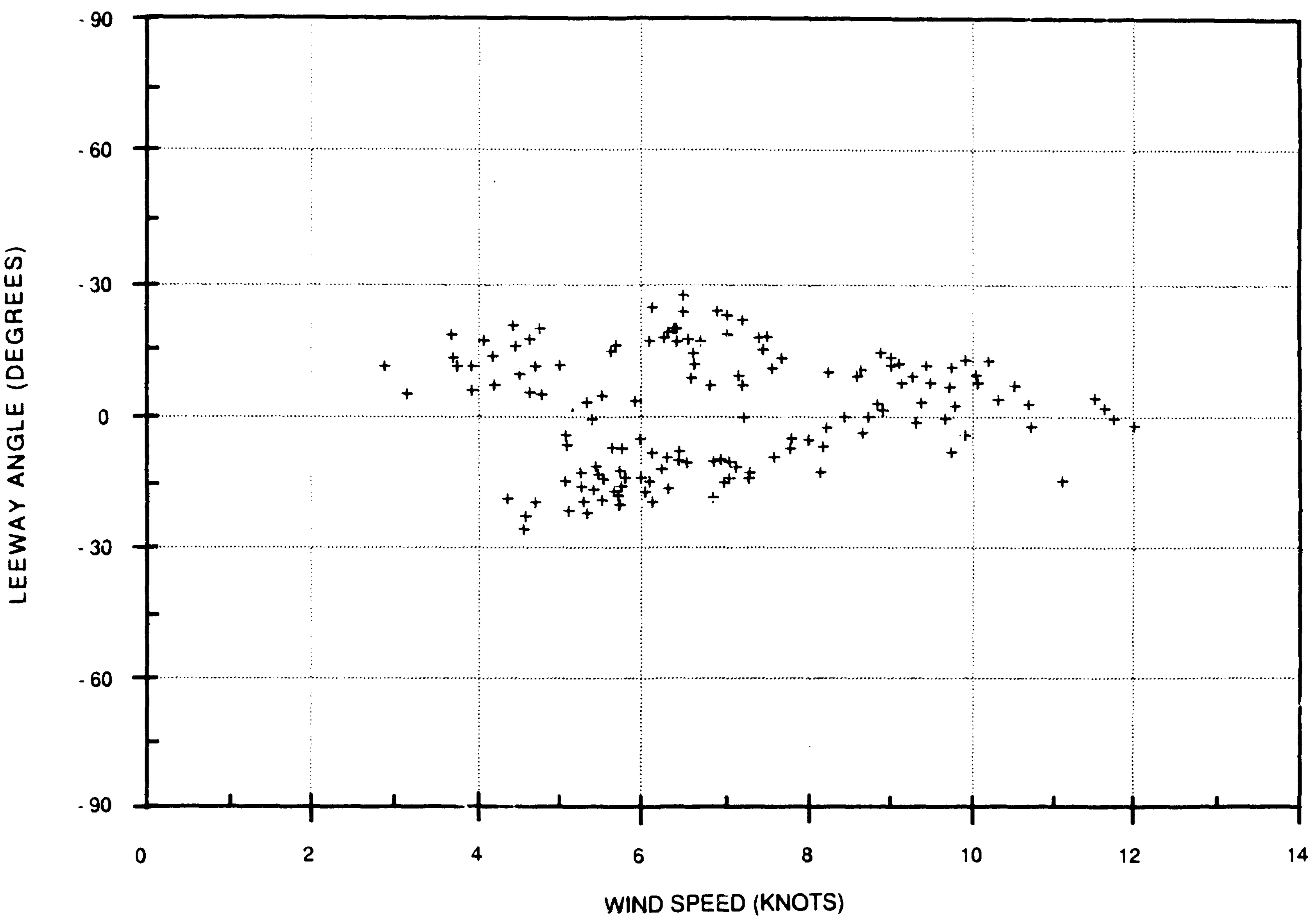


FIGURE 30. LEEWAY ANGLE VERSUS WIND SPEED FOR 20 - FOOT BEACHCOMBER

TABLE 17

RESULTS OF LEEWAY MODELS FITTED TO DOWNWIND COMPONENT OF LEEWAY (L) FOR 20-FOOT CABIN CRUISER
(Values for L are in knots. W is wind speed in knots.)

Model	Standard Slope	Error of: Estimate	% Variance Explained
L = 0.0582W	0.00070	0.06066	84
L = -0.0813 + 0.0690W	0.00228	0.05631	86

CHAPTER 5
CONCLUSIONS

5.1 SUMMARY

The first step of this analysis was to identify the equilibrium RWD for a craft due to its size and shape. The second step was to determine the leeway angle and to compute the component of leeway in the true leeway direction. The third step was to fit a set of leeway models to that component of leeway.

Leeway equations for the craft tested are summarized in Table 18. Canopied rafts with deep-draft ballast systems and drogue (Switlik 4-man and Givens 6-man Rafts) are not included in Table 18. These two rafts when drogued were found to have zero or near zero leeway for winds up to 13 knots. These rafts with drogues may have some as yet undetermined leeway speed for winds greater than 13 knots.

5.2 IMPLICATIONS FOR CASP

Current leeway information available in CASP for the craft tested is presented in this section. The CASP system uses leeway rate, rate uncertainty, and leeway angle for search planning (Section 1.2.1). Leeway rate is the ratio of leeway speed to wind speed. For the craft tested in this experiment, (except the Avon 4-man Raft) leeway rate is given in Table 18 as the coefficient of W. Results of this experiment are used to evaluate the leeway rates in CASP and to recommend changes.

There are seven classes of targets for leeway in the current search planning doctrine. The leeway rates (Table 3) range from a person in the water with zero leeway up to a light displacement vessel without drogue which drifts at approximately 7% of the windspeed. There are rules for adjusting leeway for the addition of a canopy and ballast buckets on life rafts.

TABLE 18

SUMMARY OF LEEWAY EQUATIONS AND ANGLES BY CRAFT

(L = leeway speed; W = wind speed in knots. Positive leeway angles denote deflection to the right of downwind.)

Class	Craft	Equation	Leeway Angle(s) (degrees)
Canopied Raft with deep-draft ballast system	Switlik 4-Man Raft without drogue	$L = 0.0144W$	0
	Givens 6-Man Raft without drogue	$L = 0.0099W$	0
Canopied Raft with ballast buckets	Avon 4-Man Raft without drogue	$L = -0.1412+0.0213W$* *questionable equation	0
Canopied Raft with no ballast system	Winslow 4-Man Raft without drogue, full load, combined swell	$L = 0.0490W$	0
Light displacement vessels	14-Foot outboard	$L = 0.0398W$	+14, -24
	19-Foot outboard	$L = 0.0493W$	0
	20-Foot Cabin Cruiser	$L = 0.0582W$	0

Craft representing light displacement vessels with and without drogues were tested in this experiment. In addition, an entirely new class of craft was tested. The new class was canopied rafts with deep-draft ballast system and drogue.

5.2.1 Canopied Rafts with Deep-Draft Ballast System and Drogue

CASP does not currently include this type of craft in its classification system. Leeway rates for the two rafts tested from this classification (Switlik 4-man and Givens 6-man rafts) were negligible at wind speeds below 13 knots. Leeway at wind speeds in excess of 13 knots is unknown. The maximum deflection from downwind for these rafts with drogue is not expected to exceed 10°.

5.2.2 Canopied Rafts with Deep-Draft Ballast System (No Drogue)

Current leeway doctrine classifies the undrogued Switlik 4-man and Givens 6-man rafts (canopied rafts with deep-draft ballast systems) as light displacement vessels with drogue. CASP uses a leeway rate of 0.05 and an uncertainty of 0.33 for these vessels. This is equivalent to using a range of leeway rates from 0.0335 to 0.0665. Leeway rates for the undrogued Switlik 4-man and Givens 6-man rafts did not fall into that range (Table 18). This confirms the results from the Summer 1983 Experiment that these rafts drift more slowly than previously believed (Nash and Willcox, 1985).

The leeway rate for the Switlik 4-man raft was 0.0144 and the rate for the Givens 6-man raft was 0.0099 in this experiment. The average of the two is 0.0122 with a rate uncertainty of 0.25, well below values used in CASP. The rafts were found to have a deflection off the downwind direction of 0° ± 10°.

5.2.3 Canopied Rafts with Ballast Buckets

The raft with canopy and ballast bags tested in this experiment was the Avon 4-man raft. Current leeway doctrine has this raft drifting at the same rate as an unballasted raft without canopy, i.e., 7% of the wind. CASP uses a range of leeway rates from 0.0469 to 0.0931 when the uncertainty is applied to the base leeway rate.

The leeway equation for the Avon 4-man raft gives leeway speeds well below speeds calculated using the 0.07 base leeway rate used by CASP. (Leeway speeds for CASP and the leeway equation for the Avon 4-man raft are compared in Table 11, Section 4.4.1). In the Summer 1983 experiment, however, the leeway of a raft with different ballast bags and canopy style was found to be within present doctrine.

The authors recommend expanding the range of leeway rates to cover both data sets. The recommended base rate is 0.05 with a rate uncertainty of 0.96. No change is recommended for the leeway angles.

5.2.4 Canopied Rafts without Ballast or Drogue

The Winslow 4-man raft tested in this experiment was an oblong canopied raft without any ballast system. Leeway rates used by CASP range from 0.056 to 0.112. (The base rate of 0.07 is increased by 20% to compensate for the addition of a canopy. The range is calculated by applying the uncertainty of ± 0.33 to the new base rate of 0.084).

Leeway rates for the fully loaded Winslow 4-man raft are slightly below the range used by CASP. Increasing the uncertainty from 0.33 to 0.40 and using a base rate of 0.08 for a canopied raft without ballast or drogue will provide a range of leeway rates that will include the rates observed for the undrogued Winslow 4-man raft in this experiment. (The value 0.08 is based on a leeway of 0.0667 plus 20% for the addition of a canopy). Leeway angles were within the recommended limits.

5.2.5 Light-Displacement Small Craft and Outboards

The three small boats tested (14-foot outboard, 19-foot outboard and 20-foot cabin cruiser) fit into the classification of light displacement vessels. The leeway rates used by CASP for this classification are 0.0469 through 0.0931. Of the three small craft, only the 14-foot outboard fell outside that range (Table 18).

The 19-foot outboard and the 20-foot cabin cruiser drifted downwind with their sterns to the wind. The 14-foot outboard drifted beam to the wind and off the downwind direction by +14° to -24°, ±10°. This deflection off downwind is well within the present doctrine for leeway angle, i.e., 35° on either side of downwind.

Because one of the three small craft used in this experiment had leeway rates lower than the present doctrine, the authors recommend expansion of the rate limits. The proposed base rate is 0.062 with a rate uncertainty of 0.50. No change in leeway angles is recommended.

[THIS PAGE INTENTIONALLY LEFT BLANK]

APPENDIX A

DATA PROCESSING METHODS

A.1 INTRODUCTION

This appendix discusses methods used to process the raw data to obtain leeway. The steps for reducing the data to a useful form are:

1. Edit position records and screen for bad positions.

2. Create interpolated position records using 2-minute intervals.

3. Calculate the current at the test craft.

4. Calculate the test craft's velocities.

5. Calculate the leeway velocities of a test craft by subtracting the current from the test craft's velocities.

6. Screen the wind records for bad data and create 4-minute vector averages of the wind.

7. Collate the leeway data, craft configurations, and wind data into files suitable for analysis.

8. Calculate the leeway angle.

The processing of the position data through the calculation of leeway is discussed in Section A.2 and its subsections. The processing of the wind data is discussed in Section A.3 and its subsections. The details of the collation of the leeway and wind data with the associated parameters are discussed in Section A.4. Leeway angle computations are discussed in Section A.5, and leeway components are addressed in Section A.6.

A.2 POSITION DATA

For this discussion, a platform may be either a drifter or a test craft. A position refers to a data point consisting of a time (T) and a corresponding location given in state plane coordinates. The x-coordinate (X) of a position is similar to longitude, and the y-coordinate (Y) is similar to latitude. A position record refers to a series of positions for a particular platform corresponding to a continuous drift. For example, if a drifter is deployed at 0900 and recovered at 1700 the same day, all positions and their corresponding times, from 0900 to 1700, would represent a single position record.

Position records were edited to contain only the time interval during which the platform was freely drifting, and only those positions provided by a single reference station of the MTS. For reasons explained in Section 2.1.1, a position determined using one reference station would differ from the position determined using the other reference station.

Next, a piecewise linear regression method was used to screen position records for bad positions. This method is described in Section A.2.1. Raw positions were compared to their corresponding positions calculated from the regression equations. If the difference between the raw and the calculated positions was greater than 32.8 yards, the raw position was flagged as a possible bad position. These candidates were checked and removed if erroneous.

Finally, the results of the linear regression were used to create interpolated-in-time position records for all platforms. The interpolation served three purposes. The first was to make the position records suitable for velocity calculations by ensuring that the time increment between a platform's successive positions was constant (i.e., 120 seconds). The second purpose was to produce position records for all platforms calculated at exactly the same times, e.g., 12:00:00, 12:02:00, 12:04:00, etc. The third purpose was to fill in data gaps of 6 minutes or less caused by missing or deleted positions. Details of the interpolation are discussed in Section A.2.1.

A.2.1 Piecewise Linear Regression Method

Position data were screened and interpolated using a piecewise linear least-squares regression method. The term "piecewise" means that the regression used segments or pieces of the data instead of using the entire data or position record. For each segment of a position record, a linear regression equation of each component of position (X,Y) as a function of time (T) is fitted to the data using the method of least squares. The method of least squares is a regression method that seeks to ensure the best fit of the regression equation to the data by minimizing the squares of the differences between the regression line and the data. A full discussion of the method can be found in most basic statistics books (e.g., Leplin, 1975). The regression equations used are:

$$X = i+j*T \qquad \text{Equation A-1}$$

$$Y = k+l*T \qquad \text{Equation A-2}$$

where:

X is the east-west component of position,
Y is the north-south component of position, and
i, j, k, and l are the coefficients determined by the method of least squares.

For the screening, each position within the segment was compared to its interpolated counterpart. The position would be flagged as a possible bad position if the distance between the raw position and its corresponding interpolated position was greater than a critical value. After all possible bad positions were flagged, another segment would be used so that each data point was screened in at least two segments. Any data point flagged twice would be checked prior to deletion.

The screening program had five adjustable parameters. Typical values for these parameters for the final screening are presented in Table A-1. The regression was generally performed on drift segments of 20 minutes. Segments of 10 minutes were used when it appeared that the current was changing rapidly. The minimum for the number of points required and maximum permissible gap ensured that there were always adequate data for a regression. If the segment contained fewer than the minimum number of points or contained a gap in the record greater than the maximum permissible gap, another segment would be chosen. A time increment of 10 minutes would mean that a segment would start 10 minutes after the start time of the previous segment. Thus, if the first segment started at 1015, the next segment

TABLE A-1

PARAMETERS AND VALUES USED TO SCREEN AND INTERPOLATE POSITION RECORDS

SCREENING VALUES

Segment Length: 1200 seconds (20 minutes)
Minimum Number of Points: 5
Maximum Permissible Gap: 360 seconds (6 minutes)
Time Increment: 600 seconds (10 minutes)
Maximum Distance for Flag: 32.8 yards

INTERPOLATION VALUES

Regression Interval: 1200 seconds (20 minutes)
Minimum Number of Points: 7
Maximum Permissible Gap: 360 seconds (6 minutes)
Increment Interval: 120 seconds (2 minutes)
Maximum Distance for Flag: 32.8 yards

---

would start at 1025. The time increment was usually chosen to be half of the segment length to screen each data point twice.

The interpolated records were created after the screening for questionable values. Each interpolated point was calculated as the center point of a 20-minute segment with a 2-minute incremental step. If the segment had less than seven points or a gap greater than six minutes, the preceding interpolated point was marked as the end of a drift and a new drift record started. For the rest of the analysis, the two drift records were treated as if they were of two different drifters.

A.2.2. Current Calculations

The current at each drifter was calculated for 4-minute intervals from the interpolated drifter position records. Because the interpolated drifter positions were spaced two minutes apart, each 4-minute interval contained three positions. The data from each drifter that was not drifting continuously during the interval were discarded. The U and V components of velocity for each remaining drifter were then calculated using a time-centered finite difference algorithm. This means that U and V were calculated as the difference between the first (T = t-2) and last (T = t+2) positions for that time interval, ie.,

$$U_{(t)} = \frac{X_{(t+2)} - X_{(t-2)}}{4 \text{ minutes}} \qquad \text{Equation A-3}$$

$$V_{(t)} = \frac{Y_{(t+2)} - Y_{(t-2)}}{4 \text{ minutes}} \qquad \text{Equation A-4}$$

where: t is the time of the center position,
t-2 is the time of the first position, and
t+2 is the time of the last position.

Then $U_{(t)}$ and $V_{(t)}$ were assigned to be the velocity components of the drifter at the central time (t) of the interval. The output for each active drifter consists of $U_{(t)}$, $V_{(t)}$, $X_{(t)}$, and $Y_{(t)}$.

A.2.3 Current Field Calculations

Current velocities at each drifter were combined to produce a current field around the test craft. It was assumed that, for each 4-minute interval, the rate of change of the current velocity over the area covered by the drifters is constant. Mathematically stated, the assumptions for each 4-minute interval are:

$$dU/dX = \alpha \qquad \text{Equation A-5}$$

$$dU/dY = \beta \qquad \text{Equation A-6}$$

$$dV/dX = \delta \qquad \text{Equation A-7}$$

$$dV/dY = \tau \qquad \text{Equation A-8}$$

where: U is the east/west component of current,
V is the north/south component of current,
X is the east/west component of position,
Y is the north/south component of position, and
α, β, δ and τ are constants.

The following regression equations were fitted to the drifter velocity and position components ($U_{(t)}$, $V_{(t)}$, $X_{(t)}$, and $Y_{(t)}$) by the method of least squares:

$$U_{(t)} = \alpha * X_{(t)} + \beta * Y_{(t)} + \chi \qquad \text{Equation A-9}$$

$$V_{(t)} = \delta * X_{(t)} + \tau * Y_{(t)} + \gamma \qquad \text{Equation A-10}$$

where α, β, δ and τ are the constants defined above, and χ and γ are constants determined by the regression for time (t).

These regression equations, when fitted to the data centered on a time interval, were taken to represent the current field for that interval. The current at each test craft was calculated using the center position of the test craft in the regression equations.

The adequacy of the regression fit to the data was checked by comparing the regression derived velocity for each drifter to the observed velocities. If this difference for any component of velocity for any active drifter was greater than 0.058 knots, the regression in question was repeated for each test craft, excluding the data for the drifter farthest from that test craft. This procedure was repeated for each test craft until all differences were 0.058 knots or less. The regression equations will give a perfect fit to the data if there are three drifters. Data were discarded for any interval with less than three drifters continuously drifting.

A.2.4 Velocity Calculations

Test craft position data for 4-minute intervals were generated from the interpolated position records produced by the piecewise linear regression method described in Section A.2.1. Test craft velocity components were calculated in the same manner as the drifter velocity components. The position data were used as inputs to the time-centered finite difference algorithm (Equations A-3 and A-4) described in Section A.2.2. The information generated for each test craft was $U_{(t)}$, $V_{(t)}$, $X_{(t)}$, and $Y_{(t)}$ for each 4-minute interval.

A.2.5 Leeway Calculations

Leeway for each test craft was calculated for each 4-minute interval by subtracting the current at the test craft from the velocity of the test craft. The calculation yields leeway speed and leeway direction.

A.3 WIND DATA

Wind data were collected from several sources during the experiment, but only the data collected onboard the test craft were used in the leeway calculations. Data from other sources were used for quality control. All the test craft, except the 19-foot outboard, were equipped with automated instrument packages. Onboard the 19-foot outboard, a student manually recorded 1-minute averages of the wind every 20 minutes using the Hercules 190 wind system. Data collected by the automated instrument packages were recorded every 20 to 40 seconds, depending on the package's memory capacity.

A.3.1 Automated Instrument Package Data

Data from the automated instrument packages consist of individual records of time and three analog voltages from the compass, wind vane, and anemometer. Analog readings were converted into engineering units. The wind direction was computed in degrees true. All craft used the same convention for the bow of the craft and the orientation of the instrument package. The instrument packages were installed with different orientations based on expected wind direction to avoid the 5° dead zone of the wind vane potentiometer between 355° and 360° relative.

Wind data were visually checked and edited. Data from the research vessels and the environmental buoy were used to quality control data from the test craft. Suspect data values were replaced by a missing value "flag" except when the problem could be identified as one of two special cases. The first case occurred when the compass heading or the relative wind direction crossed the area of discontinuity between 355° and 360°. A directional change from 359° to 000° for the wind or the boat is a 1° shift; however, for numbers and analog voltages, the apparent shift is much greater. Even an averaging period of less than three seconds was long enough for the wind vane sensor to enter or cross the discontinuity area during a reading. Since the average of a high number and a low number is a number in between, the reading from the sensor can be in error up to 180° . Whenever this was identified to be the case, the bad value was replaced by a default value corresponding to the middle of the discontinuity. The maximum error associated with the substituted value should be no more than 5°. The second case was caused by a manufacturing defect in one of the wind vanes. The vane's housing and the potentiometer could became misaligned during handling, resulting in a 19° offset. However, the data were recoverable since the change in alignment could only occur when the sensor was being mounted. The alignment of the installation was checked before each run by taking several readings with the vane aligned with the test craft.

The last step in processing the wind data was to create 4-minute vector averages which corresponded in time to the drifter data record. These values were computed using compass heading, relative wind direction, and wind speed. When the compass heading or the relative wind direction was missing, only average wind speed was determined.

A.3.2 Brooks and Gatehouse Hercules 190 Data

Data from the Hercules 190 wind station consisted of 1-minute averages of compass heading, wind direction, and wind speed. These data were recorded every 20 minutes. The data were compared with wind information from the other sources and found to require no editing. Relative wind direction was computed. Wind direction was converted to degrees true. A wind record with values for every minute was created by assigning the nearest values in time to each minute.

A.4 DATA COLLATION

After processing, the data consisted of 4-minute averages of leeway speed and direction and the wind records. The wind records included wind direction, wind speed, relative wind direction, and compass heading. Data for each craft were collated a day at a time. Records were combined only if their times matched exactly. The combined records consisted of leeway speed and direction, wind records, number of drifters used in current calculations, and craft configuration parameters. (A craft's configuration consists of variables that may affect the leeway of the craft, such as the combined weight of the water jugs onboard, deployment of a drogue, engine in the up or down position, rudder position, etc.). Also included in the file are record-keeping items, such as the code for the craft and the date and time of the individual data points.

A.5 LEEWAY ANGLE

The last computation was the leeway angle. For this report, leeway angle is defined as the leeway direction minus the wind direction with the convention of positive leeway angles for the deflection to the right of downwind and negative to the left of downwind.

A.6 LEEWAY COMPONENTS

Leeway speed was resolved into components. In most cases, the components used were the downwind and crosswind components of leeway speed.

The only test craft with a non-zero leeway angle was the 14-foot outboard. For the analysis of data for the 14-foot outboard leeway speed was resolved into two components. One component was in the leeway direction and the other component was perpendicular to the leeway direction rather than in the downwind and crosswind directions. The primary component of leeway was taken to be the component of the leeway speed in the leeway direction (wind direction plus leeway angle). The secondary component is perpendicular to the primary component and positive in direction to the right of the primary component.

[THIS PAGE INTENTIONALLY LEFT BLANK]

APPENDIX B

LEEWAY MODELS AND ERROR ANALYSIS

B.1 INTRODUCTION

The purpose of this appendix is to explain the various relationships which are possible between leeway speed and wind speed for different types of test craft and to determine the angle of the drift with respect to the downwind direction.

Previous studies have assumed a linear relationship between leeway speed and wind speed. This can be expressed mathematically as:

$$L = b*W \qquad \text{Equation B-1}$$

where: L is the leeway speed,
W is the wind speed, and
b is the slope of the line (or leeway rate).

This is an equation for a straight line passing through the origin. In terms of leeway, it means that when the wind speed is zero, leeway speed will be zero.

A second linear equation that has been used to express the relationship between leeway speed and wind speed is:

$$L = a+b*W \qquad \text{Equation B-2}$$

where: L is the leeway speed,
W is the wind speed,
a is the y-intercept, and
b is the slope of the line.

This is an equation for a straight line that may cross the y-axis (or leeway axis) at some point other than zero. Equation B-2 allows for leeway cases where leeway speed is negligible below a threshold wind speed and increases with increasing wind speed above the threshold wind speed.

When the value of a (the y-intercept) is close to zero, Equations B-1 and B-2 will produce similar results.

To investigate the possibility that the relationship between leeway speed and wind speed is not linear, a third equation, known as a power curve, was used in this analysis. The relationship is:

$$L = d*W^{c} \qquad \text{Equation B-3}$$

where: L is the leeway speed,
W is the wind speed, and
d and c are constants.

Equation B-3 removes the requirement implicit in the previous two equations that the data (leeway as a function of wind speed) lie along a straight line. When the value of c is close to one, Equations B-1 and B-3 will produce similar results. The non linear case in Equation B-3 was examined, but the results were not significantly better than the linear results.

Methods used to determine a, and b are discussed in Section B.2, and an error analysis is presented in Section B.3.

B.2 FITTING OF LEEWAY MODELS

The linear leeway models used for this analysis are repeated below for convenience:

$$L = b*W \qquad \text{Equation B-1}$$

$$L = a+b*W \qquad \text{Equation B-2}$$

where: L is the leeway speed (or a component),
W is the wind speed, and
a and b are regression coefficients.

The models were fitted to the data using the least-squares method. This means that all coefficients were chosen to minimize the sum of the squares of the differences between the observed and predicted leeway values. Equations B-1 and B-2 were solved completely using the least-squares method.

The models all used the same definitions of degrees of freedom (d.f.), standard error of estimate (Se), and coefficient of determination (r^2). The term degrees of freedom (d.f.) is defined as the number of data points minus the number of coefficients in the regression equation. The mathematical definitions of Se and r^2 are presented below:

$$Se = \left(\frac{\sum (Y - \hat{Y})^2}{n-2} \right)^{1/2} \qquad \text{Equation B-4}$$

$$r^2 = 1 - \frac{\sum (Y - \hat{Y})^2}{(Y - \bar{Y})^2} \qquad \text{Equation B-5}$$

where: Y is an observed value of the dependent variable,
$\hat{Y}$ is a predicted value of the dependent variable,
$\bar{Y}$ is the mean of the dependent variable,
Σ is the summation sign, and
n is the number of points used in fitting the line.

The dependent variable is the variable which is predicted, i.e., leeway. The standard error of estimate (Se) is a measure of the variability of the dependent variable around the regression line with 68% and 95.5% of the observations lying within one or two (Se) of the regression line. The coefficient of determination (r^2) is the ratio of the variability in the dependent variable explained by the regression equation to the original variability around the mean observations. A value for r^2 of 1.0 would be a perfect fit of the data. The value of r^2 lies between 0.0 and 1.0. Generally, regressions with r^2 values of less than 0.1 are useless, of 0.2 to 0.4 are poor, of 0.5 or greater are good, and of greater than 0.8 are excellent.

Next, the fitting of the leeway models is described separately. The descriptions will use the standard notations of X and Y instead of W and L to avoid confusion. W can be substituted for X and L for Y.

L = b*W or Y = b*X

A good reference for this regression equation is Snedecor and Cochran (1980). The coefficient (b) for the method of least-squares is defined as that value of b which minimizes the sum of the squares of differences between the observed and predicted values of the dependent variable (Y). Mathematically stated:

$$\sum (Y - \hat{Y}) = 0 \qquad \text{Equation B-6}$$

$$\text{and} \quad \sum (Y - \hat{Y})^2 \text{ is a minimum}$$

where: Y is an observed value of the dependent variable,
$\hat{Y}$ is a predicted value of the dependent variable, and
b is the regression coefficient.

The standard error of the slope (Sa) is calculated by the following equation (Snedecor and Cochran, 1980, page 155):

$$Sa = Se/\sqrt{\Sigma x^2} \qquad \text{Equation B-7}$$

where: (Se) is the standard error of estimate.

The standard error of the slope is a measure of the variability of the slope of the regression. It is used to calculate the confidence limits on the slope.

<u>L = a+b*W or Y = a+b*X</u>

The standard regression equations for this model are (Laplin, 1975):

$$b = \frac{\sum XY - N\bar{X}\bar{Y}}{\sum X^2 - N\bar{X}^2} \qquad \text{Equation B-8}$$

$$a = \bar{Y} - b\bar{X} \qquad \text{Equation B-9}$$

$$Sa = \frac{Se}{(\sum X^2 - N\bar{X}^2)^{1/2}} \qquad \text{Equation B-10}$$

where: a is the regression coefficient of the intercept,
b is the regression coefficient of the slope,
N is the number of data points,
X is the independent variable (wind speed),
Y is the dependent variable (leeway speed),
$\sum$ is the summation sign,
$\bar{X}$, $\bar{Y}$ are the average or mean values of X and Y,
Se is the standard error of estimate, and
Sa is the standard error of the slope (b).

The standard error of the slope is a measure of the variability of the slope of the regression. It is used to calculate the confidence limits on the slope.

B.3 ERROR ANALYSIS

Section 2.1.1 and Appendix A discussed the sources of error involving the tracking system and wind instruments. Both were calibrated just before the experiment and checked during and after the experiment. The remaining errors arose from normal measurement errors and assumptions made during data reduction and analysis. This analysis will attempt to estimate the magnitude of the errors associated with the leeway and wind velocities.

Errors associated with leeway velocities are determined by estimating the error in the current value at the test craft. Data for 8 April 1985 were chosen to check the current calculations because of the long drift records and the large number of drifters. Each drifter was treated as a test craft, and the current was estimated from the remaining drifter array. The current was separated into north-south and east-west components. The absolute differences between predicted and observed components of current were recorded for 222 predictions. The predicted current explained about 55% of the variability in the observed current for both components. The maximum magnitudes of the observed east-west and north-south components of current were 0.23 knots and 0.76 knots respectively. The maximum errors were ± 0.087 knots and ± 0.105 knots. The magnitude of the errors had no correlation with the magnitude of either component of the predicted or observed current, magnitude of the other error component, or the number of drifters used to make the prediction. The root mean square (rms) of the errors was ± 0.031 knots for the east-west component and ± 0.037 knots for the north-south component. To estimate the propagation of the errors through the leeway calculation, it is assumed that the addition of two errors (E_1 and E_2) is as follows:

$$\text{Sum of Errors} = \sqrt{E_1^{\,2}+E_2^{\,2}} \qquad \text{Equation B-11}$$

This leads to an estimate of the error in the current calculations of ±0.049 knots. A very conservative estimate of the error in the test craft velocity is that it is the same as the error in the current calculations. Using Equation B-11, the error associated with the leeway velocities is ±0.068 knots.

The accuracy of the wind measurements is given in Section 2.1.2 for the automated instrument packages as better than ±10° and ±0.97 knots. The component of leeway used to calculate the relationship of leeway to wind speed is computed on the basis of the wind direction. A 10° error in wind direction would lead to the leeway being underestimated by 2%. Assuming that a craft drifts at 7% of the wind and the wind speed is 19.4 knots, the total error in the leeway from the angular and speed errors would be ±0.097 knots.

Two approximations were made in the data reduction and analysis that may not be obvious. First, the wind is assumed to be the apparent wind relative to the current, i.e., the wind as measured by an object drifting with the current. Using this apparent wind eliminates the need to consider such cases as wind with and wind opposing the current. The fact that the wind instrument is on a craft with leeway is ignored as the leeway speed is assumed to be 10% or less of the wind speed.

The second assumption is that a steady-state situation exists over each 4-minute time step. Reality is that the craft was probably accelerating during these intervals and was never in perfect balance with the wind. Both of these approximations are thought to have little or no effect on the results.

[THIS PAGE INTENTIONALLY LEFT BLANK]

APPENDIX C
OBSERVATIONS AND RECOMMENDATIONS

C.1 PROPOSED EXPERIMENTAL METHOD OF DETERMINING LEEWAY

During this experiment, leeway was determined indirectly from other parameters. An electromagnetic current meter, which determines the water current flowing through a magnetic field, may provide a method of measuring leeway directly without a tracking system and the large number of personnel currently required. The electromagnetic current meter can accurately measure very small velocities needed for leeway experiments. Previous current meter designs suffered from wave pumping or could not measure very small velocities.

The new method consists of equipping the test craft with both a wind instrument, as is done currently, and a current meter suspended under the craft. The current meter would measure the motion of the craft through the water, i.e., leeway, directly. The data would be contaminated by wave motion, which would have to be filtered out. The filtering could be done by either spectral analysis or vector averaging over a 10- to 15-minute period.

The drag of the current meter would be negligible for craft such a sailboats with keels, cabin cruisers, and larger vessels. Conducting a test of the proposed method while using the current method would permit any effect of the additional drag of the current meter to be identified.

The proposed method would require development of an instrument package onboard the test craft suitable to support a current meter and wind instrument. If successful, the method would permit the collection of leeway data without the constant maintenance of a drifter array and tracking system. Leeway data for high wind conditions could be collected by deploying a test craft before the experiment begins and leaving it unattended. Tracking could be done either by satellite (Murphy and Allen, 1985) or by a LORAN-C receiver and relay.

C.2 RESEARCH TOPICS

The following leeway topics need further research.

1. Variations in leeway caused by different degrees of loading on a craft should be determined. The maximum and minimum leeway values should be obtained by testing the craft fully loaded and empty.

2. The leeway of a craft greater than 25 feet in length should be checked. The authors know of no successful work done in this area since 1960 (Chapline, 1960).

3. The rafts referred to as canopied rafts with ballast buckets need to be researched as a group. Regulations have required the addition of more ballast to this type of raft than they had in the early 1970's. Variations in ballast configurations for this group could affect leeway.

4. Leeway data need to be collected for higher wind speeds to gain a better understanding of leeway. This may require the development of new or modified methods of determining leeway.

REFERENCES

National Search and Rescue Manual, 1986. U. S. Coast Guard, COMDTINST M16120.5 dtd 1 August 1986.

Allen, A.A., S. L. Eynon, and R. Q. Robe. 1987. "Descriptions of HF and VHF Loran-C Buoys and Evaluations as Potential Datum Marker Buoys." U.S. Coast Guard Report CG-D-02-88.

Central Tactics and Trial Organization (CTTO). 1974. "Life Raft Drift Rates." CTTO/10756/44/LRMP, Canada.

Chapline, W.E. 1960. "Estimating the Drift of Distressed Small Craft." Coast Guard Alumni Association Bulletin, U.S. Coast Guard Academy, New London, CT. Vol. 22, No. 2, March-April 1960, p. 39-42.

Edwards, N.C., Jr., S.R. Osmer, T.J. Mazour, and G.L. Hover. 1981. "Factors Affecting Coast Guard SAR Unit Visual Detection Performance." U.S. Coast Guard Report CG-D-09-82.

Hufford, G.L., and S. Broida. 1974. "Determination of Small Craft Leeway." U.S. Coast Guard Research and Development Center Report No. 39/74, December 1974.

Laplin, L. 1975. STATISTICS, Meaning and Method, Harcourt Brace Jovanovich, Inc., New York, NY.

Nash, L., and J. Willcox. 1985. "Summer 1983 Leeway Drift Experiment." U.S. Coast Guard Report CG-D-35-85.

Morgan, C.W. 1978. "Seven-Man Life Raft Leeway Study." U.S. Coast Guard Oceanographic Unit Technical Report 78-1, Washington, D.C.

REFERENCES (Cont'd)

Morgan, C.W., S.E. Brown, and R.C. Murrell. 1977. "Experiments in Small Craft Leeway." U.S. Coast Guard Oceanographic Unit Technical Report 77-2, Washington, D.C.

Murphy, D.L., and Allen, A.A. 1985. "An Evaluation of CASP Drift Predictions Near the New England Shelf/Slope Front." U.S. Coast Guard Report CG-D-16-85.

Osmer, S.R., N.C. Edwards, Jr., and A.L. Breiter. 1982. "An Evaluation of Life Raft Leeway, February 1982." U.S. Coast Guard Report No. CG-D-10-82 .

Pingree, F. deW. 1944. "Forethoughts on Rubber Rafts." Woods Hole Oceanographic Institution, 26pp.

Scobie, R.W., and D.L. Thompson. 1979. "Life Raft Study, February 1978." U.S. Coast Guard Oceanographic Unit Technical Report 79-1, Washington, D.C.

Snedecor, W., and W.G. Cochran. 1980. Statistical Methods, Seventh Edition. Iowa State University Press, Ames, Iowa.