AD-A113 691 WIND SHIP DEVELOPMENT CORP NORWELL MA F/G 13/10

ANALYSIS OF SAIL-ASSIST FOR NAVY OCEANOGRAPHIC RESEARCH SHIPS O--ETC(U)

MAR 82 L BERGESON, J YORK N00014-81-C-0823

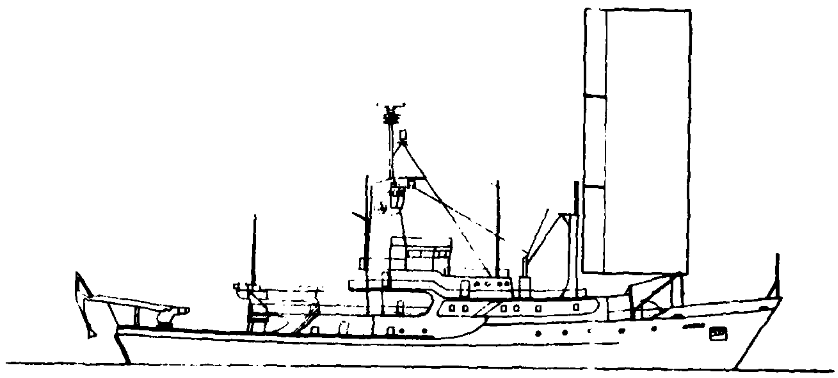
UNCLASSIFIED RR-2 NL

1 OF 2

AD A113691

RESEARCH REPORT

ANALYSIS OF SAIL-ASSIST FOR NAVY OCEANOGRAPHIC RESEARCH SHIPS OF THE AGOR-14 CLASS



WIND SHIP DEVELOPMENT CORPORATION

Norwell, Massachusetts

Final Report

March 1, 1982

DEPARTMENT OF THE NAVY
OFFICE OF NAVAL RESEARCH
OCEAN SCIENCE AND TECHNOLOGY DETACHMENT
NSTL STATION, MISSISSIPPI 39529

IN REPLY REFER TO
421SP:PF:mbf
Ser 421SP/161
15 Apr 82

From: ONRDET Code 421SP, Pat Fisher
To: Defense Technical Information Center/DDA, J. E. Condiff

Subj: Distribution Statement on Technical Document

Ref: (a) FONECON P. Fisher (ONR) and J. E. Condiff (DTIC) of 15 Apr 82

1. As discussed in reference (a), the Contractor, Wind Ship Development Corp., has advised our Office that the information provided on page 48 of the report prepared under ONR Contract N00014-81-C-0823 entitled, Analysis of Sail-Assist for Navy Oceanographic Research Ships of the AGOR-14 Class, is no longer considered to be proprietary. Therefore, the document is approved for public release with unlimited distribution.

K. W. Kaulum

K. W. KAULUM
Scientific Officer

Copy to:
Mr. Lloyd Bergeson

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: #2
2. GOVT ACCESSION NO.: AD-A117 341
3. RECIPIENT'S CATALOG NUMBER:
4. TITLE (and Subtitle): ANALYSIS OF SAIL-ASSIST FOR NAVY OCEANOGRAPHIC RESEARCH SHIPS OF THE AGOR-14 CLASS
5. TYPE OF REPORT & PERIOD COVERED: Final Research Report, Sept. 18, 1981–Jan. 21, 1982
6. PERFORMING ORG. REPORT NUMBER: #2
7. AUTHOR(s): Lloyd Bergeson & John York
8. CONTRACT OR GRANT NUMBER(s): #N00014-81-C-0823
9. PERFORMING ORGANIZATION NAME AND ADDRESS: Wind Ship Development Corporation, P. O. Box 440, Norwell, Mass. 02061
10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS:
11. CONTROLLING OFFICE NAME AND ADDRESS: Commanding Officer, Naval Ocean Research & Development Activities, NSTL Station, Mississippi 39529
12. REPORT DATE: January 21, 1982
13. NUMBER OF PAGES: 114
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office):
15. SECURITY CLASS. (of this report):
15a. DECLASSIFICATION/DOWNGRADING SCHEDULE:
16. DISTRIBUTION STATEMENT (of this Report):
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report):
18. SUPPLEMENTARY NOTES:
19. KEY WORDS (Continue on reverse side if necessary and identify by block number):

Naval auxiliary missions	Sail hardware	Naval engineering
Naval auxiliary vessels	Sail-assist retrofit	Oceanography
Ocean surveillance vessels	Alternative energy	Sail Wind
Oceanographic research operations	Fuel economy	Ship Design
Sail applications	Marine engineering	Ship Propulsion

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Mission requirements, fuel economy, design characteristics, and initial cost of a retrofit conversion of a AGOR-14 class oceanographic research vessel to a wing sail assisted ship are analyzed. Hardware alternatives to the wing sail are reviewed. Review and recommendations are given concerning new sail-assist vessels for the oceanographic missions and sail applications for transportation and surveillance missions.

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

Block 20. (cont'd.)

Operating statistics indicate that the AGOR-14 class R/V KNORR spends 30% of her time in transit. Conventional research vessel cruise planning leads to wind statistics which are favorable to sail assist.

A 3610 square foot wing sail retrofit to the KNORR would save 90 LT of fuel per year, and would not interfere with mission performance. Greater fuel savings would result for voyage scenarios with more time in transit. Potential benefits to oceanographic operations include increased fuel endurance, quiet propulsion, improved station keeping, motion reduction, and schedule reliability. Further consideration of sail-assist retrofit and/or new building is recommended. Retrofit is not recommended for the KNORR because the ship as is does not meet conventional stability criteria.

The Flettner rotor is identified as a promising hardware alternative for oceanographic applications. Study and development of silent towing under sail for acoustic surveillance and sail-assist for petroleum product transportation are recommended.

RESEARCH REPORT

ANALYSIS OF SAIL-ASSIST
FOR NAVY OCEANOGRAPHIC RESEARCH SHIPS
OF THE AGOR-14 CLASS

ACKNOWLEDGEMENT:

This report presents the results of research conducted for the Office of Naval Research under contract No. N0014-81-C-0823.

The authors would like to acknowledge the cooperation of the staff of the following government agencies and private institution: Office of Naval Research, Naval Sea Systems Command, National Science Foundation, and Woods Hole Oceanographic Institution.

Prepared By

Lloyd Bergeson & John York

Wind Ship Development Corporation

Norwell, Massachusetts

Final Report

March 1, 1982

ANALYSIS OF SAIL-ASSIST FOR AGOR-14 CLASS

TABLE OF CONTENTS

Chapter		Page
I.	INTRODUCTION	
	A. Background	1
	B. Outline	2
	C. Wind Ship Retrofit Analysis Model	3
II.	OPERATIONAL ANALYSIS	
	A. Introduction	5
	B. Research Vessel Design Characteristics	5
	C. Research Vessel Operations	6
	D. Voyage Scenarios	9
	E. Operating Statistics	16
	F Wind Statistics	18
	G Operating Costs	20
	H. Summary	22
III.	PARAMETRIC RETROFIT STUDY	
	A. Introduction	23
	B. Ship Parameters	23
	C. Retrofit Parameters	23
	D. Retrofit Optimization	25
	E. Performance of Selected Rig	28
	F. Cost of Selected Rig	30
	G. Summary	30
IV.	RETROFIT DESIGN CHARACTERISTICS	
	A. Introduction	31
	B. General Arrangement	31
	C. Structural Modifications & Wing Foundation	31
	D. Weight and Cost Estimates	36
	E. Wing Systems and Operation	36
	F Helm Balance	38
	G. Stability Before and After Retrofit	38
	H. Icing	40
	I. Visibility	40
	J. Navigation Lights	42
	K. Summary	43

TABLE OF CONTENTS

V. HARDWARE ALTERNATIVES

A. Introduction 44
B Cat Rig 44
C. Flettner Rotor 50
D. Wind Turbines for Auxiliary Power Generation 54
E. Summary 55

VI. NEW SAIL-ASSIST RESEARCH VESSELS

A. Introduction 57
B. Stability 57
C. Visibility 57
D. Engine Size 58
E. Deck Arrangements 58
F. Helm Balance 59
G. Smaller Research Vessels 61
H. Summary 62

VII. OTHER NAVAL MISSIONS

A. Introduction 63
B. Sensitivity of Annual Fuel Savings to Time in Transit 63
C. MSC Sealift Class Tankers 65
D. AGOS Ocean Surveillance Ships 65
E. Summary 67

VIII. SUMMARY

A. Introduction 69
B. Operational Analysis 69
C. Operational Benefits 69
D. Retrofit Analysis 70
E. New Vessels 71
F. Hardware Alternatives 71
G. Other Missions 72

IX. RECOMMENDATIONS

A. Introduction 73
B. Oceanographic Research Vessel Applications 73
C. Military Sealift Command 74
D. Ocean Surveillance Vessels 75

X. REFERENCES 77

A. APPENDIX DETAILED SHIP PERFORMANCE PREDICTIONS 79

ANALYSIS OF SAIL-ASSIST FOR AGOR-14 CLASS

LIST OF FIGURES

Figure #		Page
1.1	Retrofit analysis model	4
2.1	Voyage scenario No. 1 North Atlantic, General	10
2.2.	Voyage scenario No. 2 North Atlantic, East-West Transit	11
2.3	Voyage scenario No. 3 Atlantic, North-South Transit	12
2.4	Voyage scenario No. 4 Antarctic, General	13
2.5	Voyage scenario No. 5 Woods Hole-Panama Transit	14
2.6	Voyage scenario No. 6 Pacific, General	15
3.1	Chord length variation	26
3.2	Design wind speed variation	27
3.3	Sail area variation	27
4.1	Selected rig-outboard profile	32
4.2	Inboard profile	33
4.3	01 level and main deck	34
4.4	1st platform and hold	35
4.5	Wing sail systems and weight and cost estimates	37
4.6	Stability before and after retrofit	39
4.7	Visibility from pilot house	41
5.1	Rig alternatives	45
5.2	MINI LACE rig trials, Buzzard's Bay-August 24, 1981	46
5.3	Unstayed cat rig 3000 Sq. Ft. General Arrangement	47-48
5.4	Flettner Rotor	51
6.1	R/V Oceanus outboard profile	60
7.1	Fuel savings versus transit time R/V KNORR sail assist retrofit	64
A.1	Existing Ship Main engine power vs. true wind	90
A.2	Existing Ship Ship speed vs. true wind	91
A.3	Existing Ship Heel angle vs. true wind	92
A.4	Retrofit Ship Main engine power vs. true wind	100
A.5	Retrofit Ship Ship speed vs. true wind	101
A.6	Retrofit ship Heel angle vs. true wind	102
A.7	Retrofit Ship Rig power vs. true wind	103

LIST OF TABLES

Table #		Page
2.1	Research vessel activities and related assumptions for sail-assist study	8
2.2	Assumed annual schedule, R/V KNORR	17
2.3	Wind statistics for R/V KNORR voyage scenarios	19
2.4	R/V KNORR 1982 operating costs as proposed by WHOI and as assumed for retrofit study	21
3.1	R/V KNORR ship characteristics	24
3.2	R/V KNORR sail-assist retrofit fuel savings performance	29
A.1	R/V KNORR ship characteristics	84
A.2	Existing ship performance predictions	85-88
A.3	Performance program nomenclature	89
A.4	Retrofit ship performance predictions	94-99

I - INTRODUCTION

A. Background

The use of wind power to augment fossil fueled power plants and thereby reduce fuel costs for both commercial and naval ships has been given increased consideration throughout the world since the Arab oil crisis of 1973. A 1974 paper by Mavor[1] of the Woods Hole Oceanographic Institution (WHOI) suggests that wind propulsion may provide operational benefits of ship motion reduction, quiet ship propulsion and station keeping ability in addition to fuel economy for oceanographic research vessels.

In March of 1981 Wind Ship Development Corporation released a report giving the results of one year of government (U.S. Maritime Administration) and privately (Wind Ship) funded research into sail propulsion for commercial vessels[2]. The results presented in this report indicate that sail-assisted propulsion has potential economic benefits for new vessels and for retrofit of existing vessels. Although this research examined hardware alternatives and developed performance and economic analysis models which are applicable to a wide range of ship types and missions, the only application examined was commercial ships from 2,000 to 40,000 CDWT.

Because of the increasing fuel costs of operating oceonographic vessels, the Ocean Sciences Board of the National Academy of Sciences formed an ad hoc panel to consider the use of wind power for oceanographic ships. The panel published its conclusions in April, 1981[3] recommending further investigation of oceanographic ship applications of sail-assist and a more detailed preliminary design study sponsored by appropriate government agencies.

Wind Ship initiated correspondence with the Naval Sea Systems Command, the Office of Naval Research, and the Military Sealift Command on the potential of sail propulsion for several naval auxilliary vessel missions including oceanographic research, ocean surveillance, and petroleum product transportation. The Navy suggested that an AGOR-14[4] class research vessel might provide a good example of a naval auxiliary mission vessel. Wind Ship proposed a study of sail-assist retrofit for an AGOR-14 class vessel, and a review of other missions in light of the study results. The proposal was accepted and the following report presents the results of this study and review.

B. Outline

The work includes an analysis of mission requirements, fuel economy, net savings, design characteristics and initial cost of a retrofit conversion of an AGOR-14 Class ship to a wing-sail-assisted ship. Sail rig hardware alternatives to the wing sail are reviewed but not analyzed in detail. Review and recommendations are given concerning new sail-assist vessel characteristics for the AGOR mission and other naval missions which may benefit from sail propulsion.

An operational analysis outlines the requirements for sail-assist retrofit to be compatible with mission and operation of the AGOR-14 Class Ships. This analysis also provides typical voyage scenarios and corresponding wind statistics which will form the basis of the fuel economy and operating cost analysis.

Fuel economy and operating cost savings for a systematic variation of wing sail retrofits to the AGOR-14 Class ship R/V KNORR are investigated in a parametric retrofit study. Fuel consumption is derived for the present ship (without sail) and for the ship with each retrofit wing variation, using Wind Ship's computer-based Retrofit Analysis Model (q.v.).

Wing parameters are selected which optimize the trade-off between fuel savings and retrofit cost. Detailed performance predictions are presented for the existing ship and the optimum retrofitted ship. Retrofit design characteristics are illustrated with an outboard profile and deck plans, plus a cutaway profile showing rig subsystems. Weight and cost estimates are presented, and operational impact of the retrofit is discussed.

For purposes of brevity and efficiency, only wing sail rig configurations are included in the parametric retrofit study. The potential fuel economy and operational benefits of the cloth sail "Cat Rig", the Flettner rotor, and wind turbines are reviewed in light of the wing sail retrofit analysis results.

The operational performance and net savings resulting from the AGOR-14 retrofit can be improved in the design of a new sail-assist vessel to the AGOR mission objectives. Operational drawbacks of the retrofit are discussed and possible solutions in new vessel design are identified. Sail assist arrangement plan and details are suggested which may improve upon both the fuel economy of the retrofit and the mission performance of the existing ship.

Other oceanographic missions and the Military Sealift Command supply transport missions are reviewed in relation to the results of the retrofit study. The potential of unassisted sail propulsion for silent towing is discussed and developments required for implementation of sail towing are identified.

Recommendations for further research and development of wing sail retrofit for oceanographic vessels, hardware alternatives, new vessel design and construction, and wind propulsion for other naval missions are presented in the review of each of these subjects, and are summarized in the conclusions of the report.

C. Wind Ship Retrofit Analysis Model:

The Wind Ship Retrofit Analysis Model (flow chart, Figure 1.1) is a computer-based numerical analysis routine which derives annual operating and voyage costs for commercial ships before and after retrofit with sail-assist hardware (sailing rig). The difference between the annual costs before retrofit and those after retrofit is the net annual return of the retrofit conversion. The inputs to the analysis are voyage scenario, wind statistics, pre-retrofit ship parameters and retrofit sailing rig parameters.

The Performance Program predicts average speed and fuel consumption for a motor ship, motor-sailing ship, or pure sailing ship operating in the input wind statistics. Additional outputs of the performance analysis include heel angles, leeway angles, and optimized wing setting or sail trim for each 10^{o} point of sail and six wind speeds covering the range of the wind speed distribution. Included in the optimized sail trim is the requirement that the wing be feathered when the apparent wind speed would overload the rig structure if full sail were maintained.

The retrofit model combines the results of the pre-retrofit performance prediction with the logistics of the voyage scenario and the input pre-retrofit ship parameters. The resulting output is the annual transportation capacity and the annual operating cost of the existing analysis is rerun to give similar results for each retrofit rig option.

For commercial vessels results are presented for each rig option for two engine use strategies (target speeds) which give the retrofitted ship:

(1) the same annual transport capacity with annual cost savings

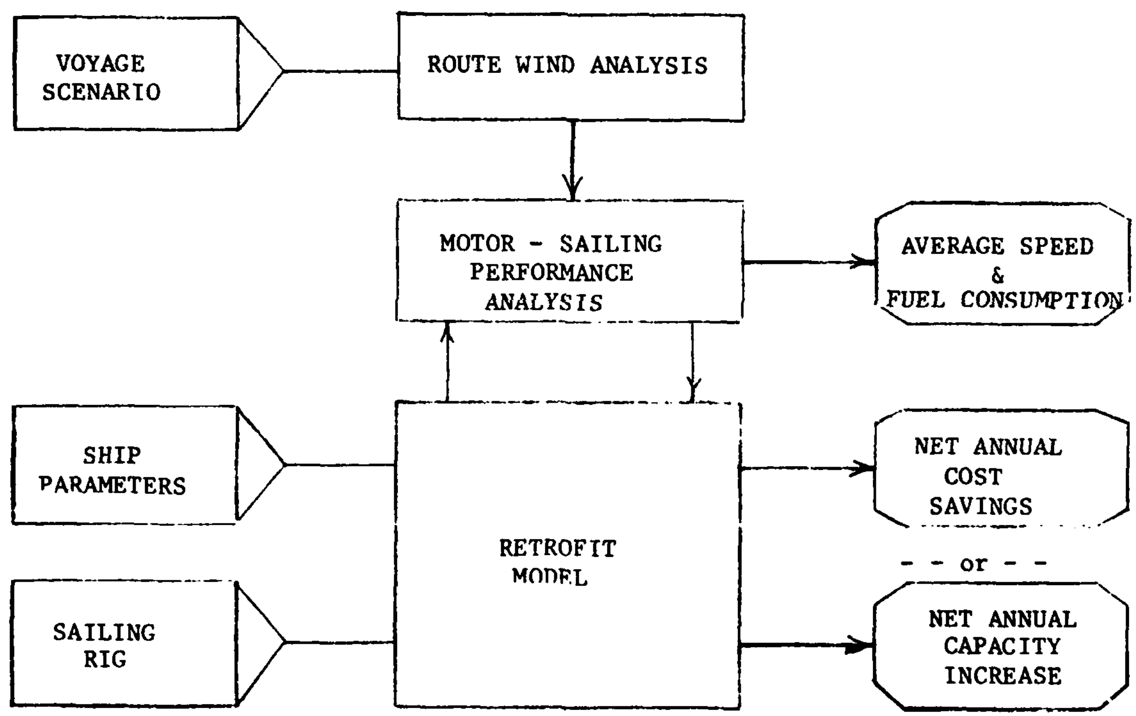
(2) the same annual cost with increase to annual transport capacity

The annual cost savings or the value of the increased cargo capacity is the "net annual return" of the sail assist retrofit.

For this study of oceanographic vessels, target speed is chosen to maintain a 10 knot average transiting speed, and operating cost reduction is the net annual return.

FIGURE 1.1

RETROFIT ANALYSIS MODEL



II - OPERATIONAL ANALYSIS

A. Introduction

In this chapter, the mission of the AGOR-14 class ships and mission requirements for sail-assist retrofit are analyzed. Research vessel utilization at the Woods Hole Oceanographic Institution (WHOI) forms the basis for interpreting the broadly stated mission of the AGOR-14 class:[3]

> "To conduct oceanographic research primarily at designated private and university laboratories supported by the Office of Naval Research, and at Naval Laboratories"

Representative voyage scenarios and operating statistics are developed from ship schedules for two vessels operated by WHOI and from nine year operating statistics for the AGOR-14 class R/V KNORR.[5,6,7,8] Wind statistics are derived according to the cruise tracks for each voyage scenario. Operating costs for the R/V KNORR are taken from proposed, estimated and actual operating costs provided by WHOI to the National Science Foundation for budgetary planning purposes.[9]

These operating statistics and wind statistics are used as inputs to the performance and economic analyses of the Parametric Retrofit Study (chapter III). Present operating costs are used for comparison of retrofit costs and fuel savings predicted in chapter III.

Research vessel activities described in this chapter dictate requirements for the retrofit design characteristics developed in chapter IV. These requirements and design solutions to meet them are discussed with respect to Hardware Alternatives (chapter V) and New Vessels (chapter VI).

B. Research Vessel Design Characteristics

The most important feature of a general purpose oceanographic vessel is operational flexibility. The ocean regions of interest, the subject matter of investigation, the method of investigation, the instruments and required support equipment change as breakthroughs and continuing evolution of the field of oceanography occur. It is not possible to specify exactly what equipment and deck hardware will be necessary to support future work. Research vessels must provide equipment flexibility so that new developments in oceanographic research are not impeded.

Tractor-trailer type containers are often used on deck as interchangeable laboratory units. Trailers work best on ships with plenty of open deck. Clear deck space with ample bolt down fixtures provides flexibility with respect to deck equipment.

The exposed deck area of the research vessel is the primary work area for research activities. On most multipurpose research vessels the active work area is the main deck aft, while the forecastle deck is seldom used for research work. Therefore, a sail power unit placed on the forecastle deck will have minimum impact on research activities and deck space utilization.

In the case of a retrofit installation, it is generally not possible or not cost effective to make extensive alterations of the existing general arrangement which may be required to accommodate sail units amidships or aft. Therefore, wing sail options examined in this retrofit analysis will be limited to a single wing sail stepped on the forecastle deck. The possibility of more extensive sail plans with wing sails or other types of sail power units will be examined in chapters V and VI, Hardware Alternatives and New Vessels.

A key feature of the AGOR-14 class general arrangement is a clear view from the pilot house to all working areas on deck. This visibility improves coordination of ship operations in support of scientific operations. The retrofit arrangement with single wing forward should not impair this view. (see Retrofit Design Characteristics).

C. Research Vessel Operations

The activities which a research vessel pursues while at sea are summarized as follows:

Station work includes drilling, coring, dredging, sampling, physical and chemical measurements, instrument and buoy tending, and submersible and diver support operations. Station keeping, low speed control, and minimum ship motions are essential to station activities. Drilling and coring are usually the work of special purpose vessels, not only because of dynamic positioning requirements, but also because of the extensive specialized drilling equipment. The predominant activity for multi-purpose vessels at WHOI is physical, chemical, and biological station work.

Buoy and bottom instruments are used for gathering long-term physical or chemical oceanographic data and meteological data. In buoy work, the ship would make a station at the buoy site, and deploy, maintain or pick up the buoy. Maintenance may include collection of recorded data.

The MELVILLE (AGOR-14, operated by Scripps Institute of Oceanography) is presently working as a support ship for the deep research vessel (DRV) "ALVIN". In this function, the DRV is handled by her own mothership, while the MELVILLE stands by for personnel, laboratory, and instrument support. In other cases the support ship would handle the DRV as well as providing personnel, lab and equipment support.

Slow towing of nets at speeds of 1 to 2 knots is typically used for biological sampling. Midwater instruments may also be towed at these slow speeds.

Moderate towing of acoustic arrays at speeds of 3 to 6 knots is used for geology and geophysics and oceanographic survey work. Towed sonar arrays may be as long as 10 miles. Ship speed control and directional control is required to maintain constant orientation when towing large arrays. Quiet ship operations are desirable for all acoustic work, and essential to certain operations. Although WHOI ships do very little towing work, towing is the predominant activity for some AGOR vessels.

Transits between stations at sea are usually of short duration (4 to 12 hours). Transits of one or two days are required from the home port or out port to working areas. Longer transits without oceanographic work are avoided by scheduling stations or towing work along the way. An occasional extended transit will occur when it is not possible to schedule work in a region the ship must transit.

Table 2.1 shows how these activities are grouped for the purpose of developing representative operating statistics from ship schedules and past operating statistics. The maintenance activity was added to separate ship maintenance from voyage related port activities.

The third column outlines the assumptions which are made for the analysis of sail-assist in the parametric retrofit study. Under these assumptions, the only benefit of the sail power unit is fuel savings while transiting. As shown by the retrofit design characteristics in chapter IV, it is possible to install a wing sail that has no significant negative impact on oceanographic research operations.

The fourth column of table 2.1 outlines possible benefits of sail-assist that are not included in the assumptions for the retrofit analysis. These possiblities are discussed in chapters V, VI and VII.

TABLE 2.1

RESEARCH VESSEL ACTIVITIES

AND RELATED ASSUMPTIONS FOR SAIL-ASSIST STUDY

ACTIVITY	DESCRIPTION	ASSUMPTION FOR AGOR-14 RETROFIT ANALYSIS	COMMENTS ON OTHER POSSIBILITIES FOR SAIL-ASSIST
Maintenance	shipyard maintenance, and repair, maintenance at home port	sail-assist hardware will not increase out-of-service maintenance, but will add an annual rig maintenance cost	sail provides back-up in case of engine failure at sea
Port	preparation for and unloading after voyage, ports of call	rig will not affect port operations. air draft limited to 135 feet to clear major bridges	increased endurance may reduce bunkering port calls
Station	oceanographic activities, with ship on station or slow towing (up to 2 knots)	no benefit from sail-assist while on station (wing is feathered)	sail power unit may provide station keeping capability (see Hardware Alternatives, Flettner rotor)
Towing	towing at moderate speed (3-6 knots) with sonar arrays	sail-assist not used while towing	fuel savings from sail-assisted towing would be additional to those predicted in this study. Quiet ship benefits could also result from sail-assisted towing. (see other Naval Missions)
Transit	cruising between ports, stations and/or towing sites	sail-assist employed for maximum fuel saving while maintaining 10 knot cruising speed (all fuel savings predicted by this study accrue while transiting)	(see other Naval Missions, sensitivity to transit time)

D. Voyage Scenarios

Six voyage scenarios are derived from the 1981 and 1982 ship schedules for the R/V KNORR and R/V ATLANTIS II,(5, 6, 7), two general purpose research vessels operated by WHOI. The two ships provide four ship-years of schedule data and thus present operating statistics which are representative of general purpose research vessel utilization. To eliminate remaining extremes due to the short sampling period, operating statistics from the voyage scenarios are adjusted to reflect nine year operating statistics for the KNORR (8) and to represent ocean regions which continue to be areas of extensive research.

Each voyage scenario consists of cruise tracks or an operating region for the ship, with corresponding operating statistics of port, station, towing and transit time and wind statistics of average wind speed and wind direction distribution. The six scenarios are chosen to represent the range of voyages included in the ship schedules, and are labeled according to their cruise tracks:

North Atlantic, General	(figure 2.1)
North Atlantic, East-West transit	(figure 2.2)
Atlantic, North-South transit	(figure 2.3)
Antarctic, General	(figure 2.4)
Woods Hole-Panama, transit	(figure 2.5)
Pacific, General	(figure 2.6)

The "general" voyage scenarios do not follow fixed voyage tracks but are specified by an ocean region in which the vessel is operating. Transit voyage scenarios typically occur when the ship is doing oceanograpic work en route during an otherwise extended transit to some general operating region (e.g., Woods Hole-Panama transit en route to Pacific), or when making a series of stations to gather data along a transect spanning an ocean basin (e.g., North Atlantic, East-West transit).

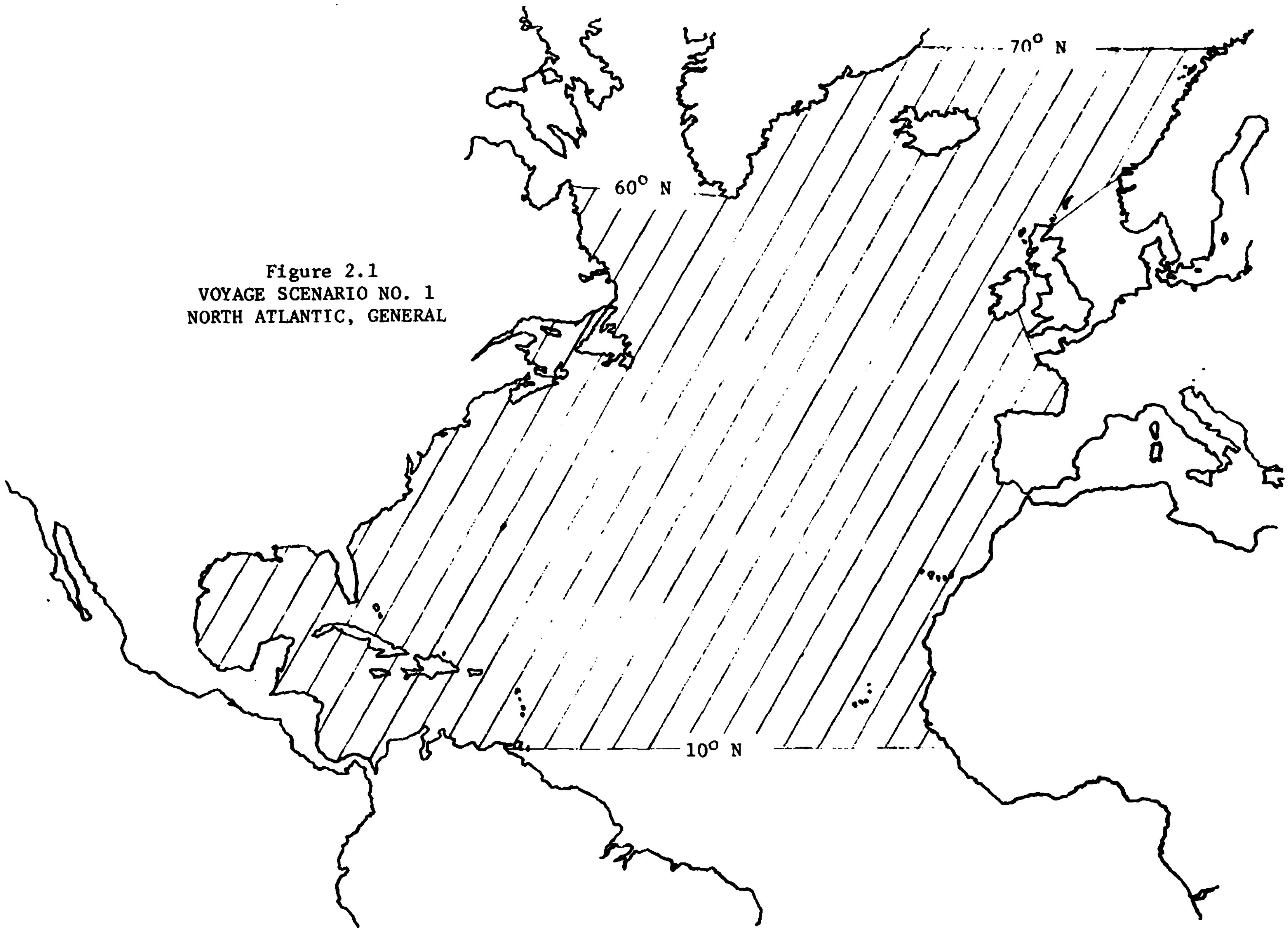


Figure 2.1
VOYAGE SCENARIO NO. 1
NORTH ATLANTIC, GENERAL

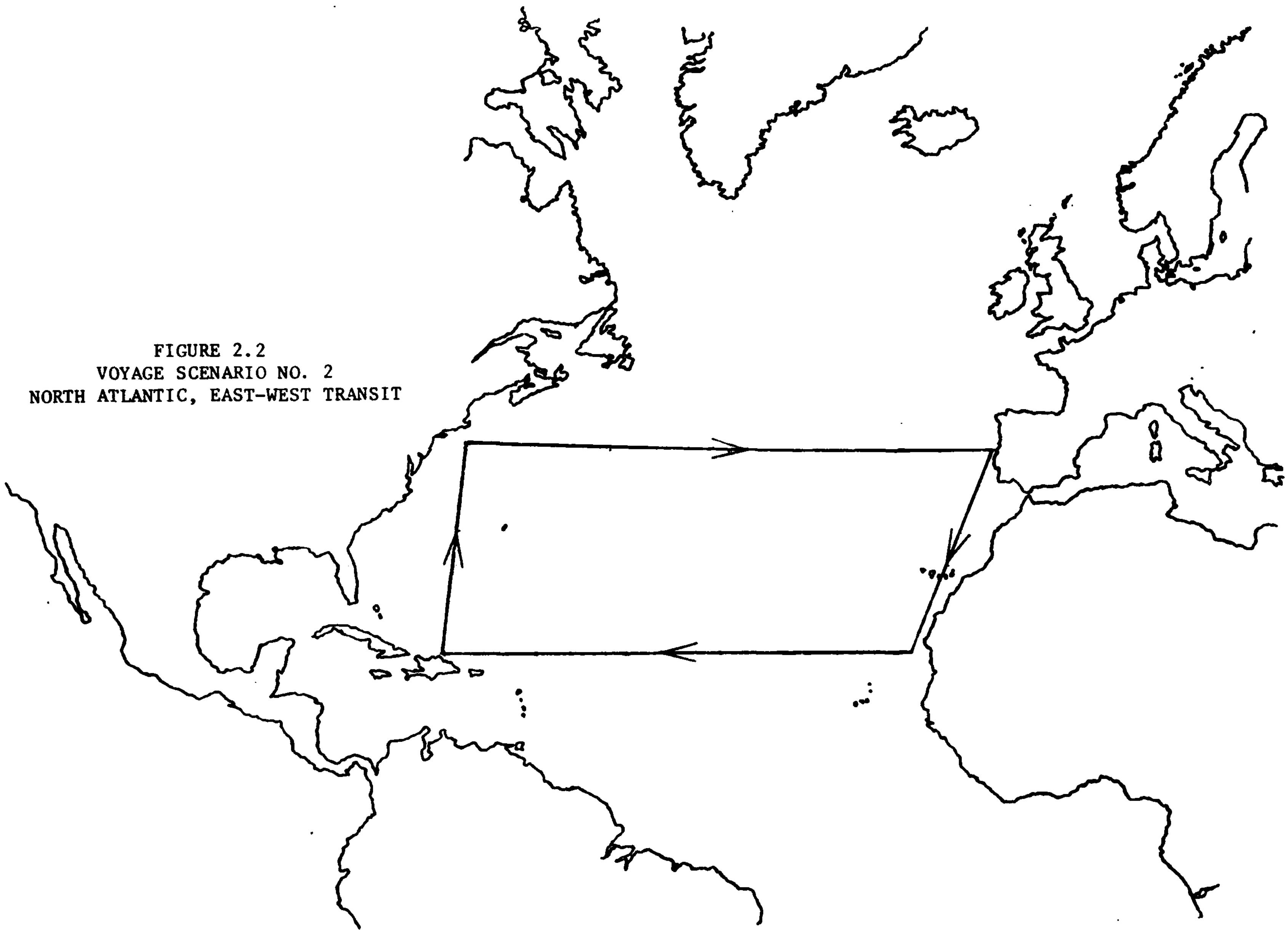
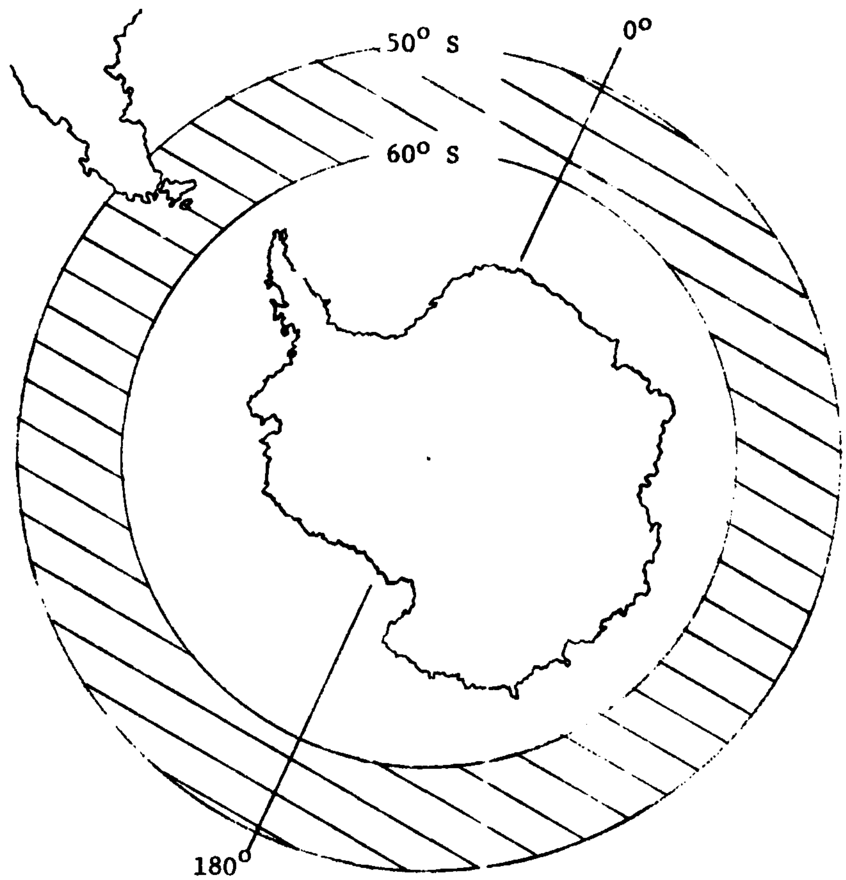


FIGURE 2.2
VOYAGE SCENARIO NO. 2
NORTH ATLANTIC, EAST-WEST TRANSIT

FIGURE 2.3
VOYAGE SCENARIO NO. 3
ATLANTIC, NORTH-SOUTH TRANSIT

FIGURE 2.4
VOYAGE SCENARIO NO. 4
ANTARCTIC, GENERAL



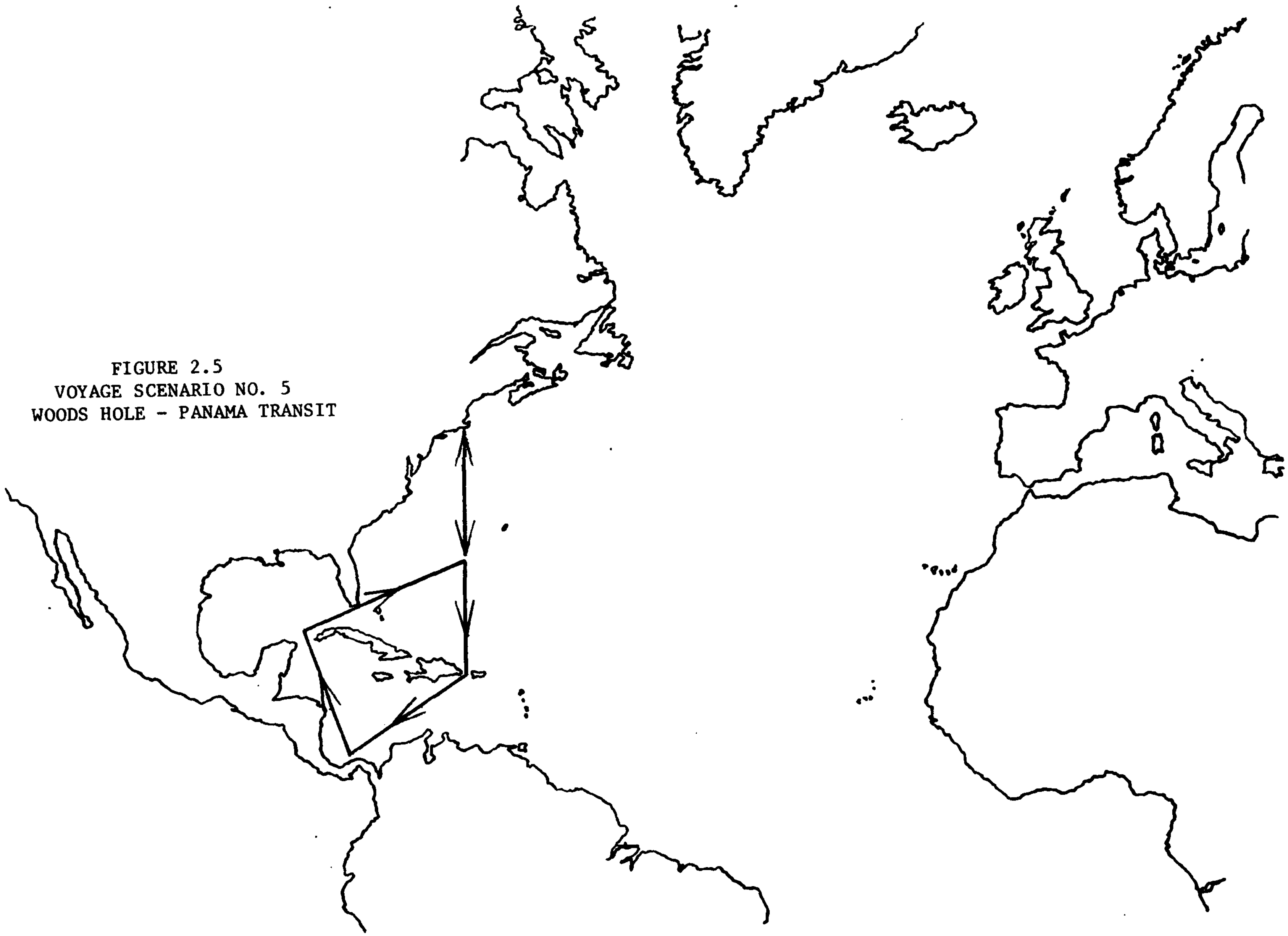
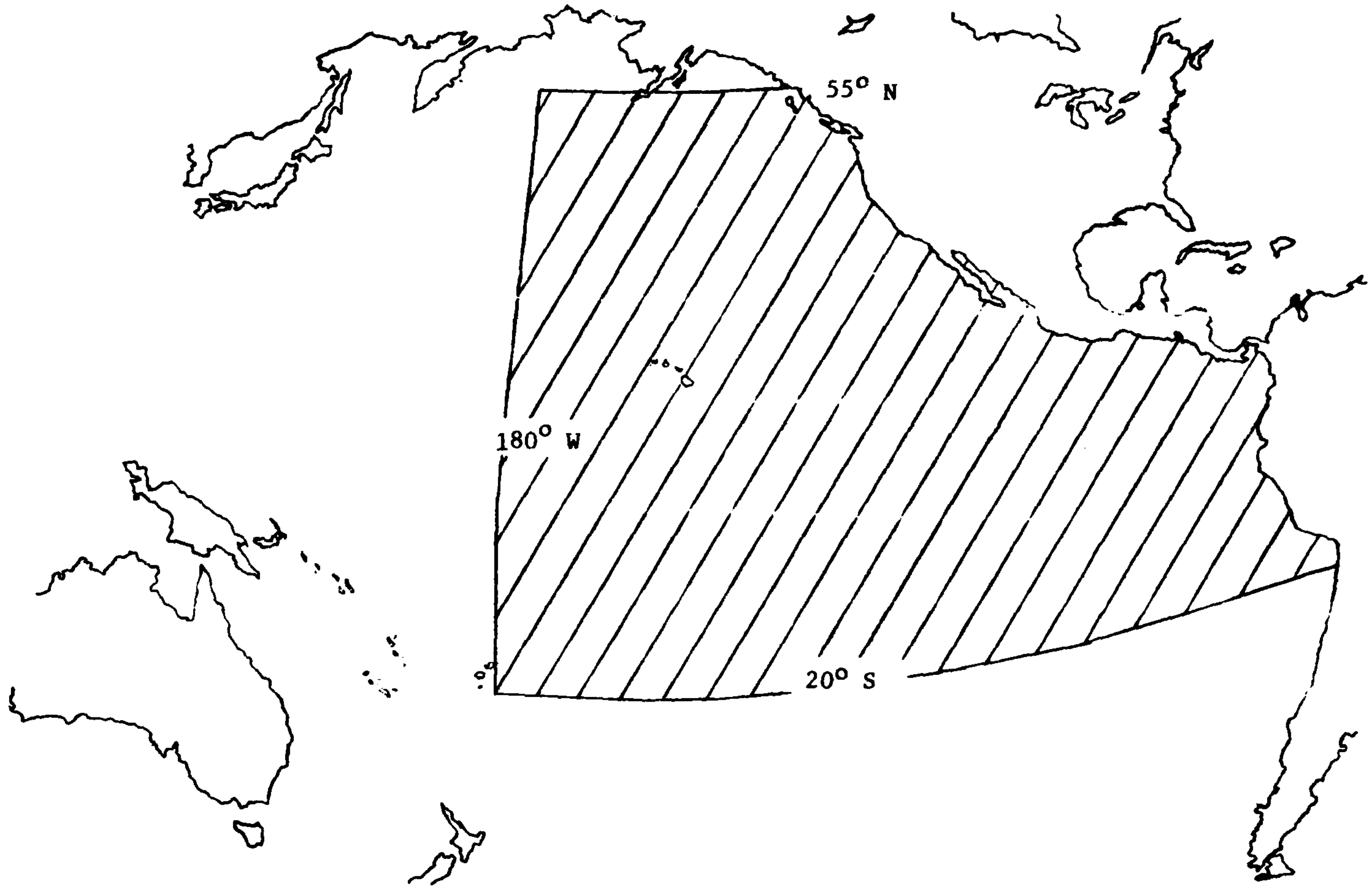


FIGURE 2.5
VOYAGE SCENARIO NO. 5
WOODS HOLE - PANAMA TRANSIT

Figure 2.6
VOYAGE SCENARIO NO. 6
PACIFIC, GENERAL



E. Operating Statistics

For each voyage scenario, ship activities are divided into port, station, towing and transit time according to the scheduled research discipline and methods according to the following assumptions:

> Port time is divided evenly between preceding and following voyages.
>
> Ship transits at cruising speed of 10 knots from port to target work area or first station, and from work area or last station to next port call.
>
> Physical and chemical oceanography or other routine station work is 50% station time, 50% transit time between stations @ 10 knots.
>
> Biology or other intense station work is 100% station time.
>
> Geology and geophysics survey work is 90% towing, 10% transiting.

Maintenance time is taken only when the ship is scheduled for shipyard repair or to be laid up at Woods Hole for maintenance independent of scientific outfitting. Maintenance time is not included in the six voyage scenarios but is totalled separately.

Because the ATLANTIS II is scheduled for extensive maintenance and refitting during the last quarter of 1981 and the first half of 1982, the average maintenance time derived from the schedules is atypically high. 1981 and 1982 scheduled maintenance for the KNORR averages 90 days per year, which agrees very well with 25% maintenance time derived from nine year operating statistics for the KNORR.

Statistics for the Antarctic General scenario are also inappropriate because this scenario is not properly represented in 1981 and 1982.

Table 2.2 shows the operating statistics with adjustments for maintenance time and Antarctic scenario according to actual nine year operating statistics for the KNORR (8). The first column shows percent of time at each scenario, and the second column shows the percent expressed as days per year. The remaining columns show the breakdown of days per year into maintenance, port, station, towing and transit time.

Actual nine year operating statistics for the KNORR are presented for comparison to the totals of the derived statistics. The close agreement is due to the use of the nine year statistics to adjust discrepancies in the 1981-82 schedule statistics. However, with the exceptions noted above, the necessary adjustments are very small.

The operating statistics presented in table 2.2 are those used for performance and economic predictions in the parametric retrofit study (chapter III). These statistics are believed to be representative of the utilization of AGOR class vessels at WHOI. These statistics do not represent research vessel operations at other institutions, particularly not those on the west coast of the United States, which would show much more time in the Pacific Ocean than the Atlantic Ocean. Institutions or vessels which do more survey work would show more towing time.

TABLE 2.2

ASSUMED ANNUAL SCHEDULE, R/V KNORR

SCENARIO	%	TOTAL DAYS	MAINT. DAYS	PORT DAYS	STATION DAYS	TOWING DAYS	TRANSIT DAYS
1	41.	150	--	34	60	6	50
2	7.	25	--	4	9	--	12
3	11.	42	--	6	16	--	20
4	8.	30	--	3	11	--	16
5	2.	7	--	1	--	1	5
6	6.	21	--	2	4	8	7
MAINT.	25.	90	90	--	--	--	--
TOTAL		365	90	50	100	15	110
%			25.	14.	27.	4.	30.

ACTUAL VOYAGE STATISTICS

(From nine years operation, April, 1970 - April, 1979)[8]

% OF TIME

MAINT.	PORT	STATION	TOWING & TRANSIT
25.	13.	28.	34.

F. Wind Statistics

Average wind speed for each voyage scenario is derived from wind speed data presented in the Marine Climatic Atlases (10, 11, 12, 13). For the general scenarios, mean wind speed is averaged over observation regions covering the operating area. For the transit scenarios, mean wind speed is averaged over observation regions which lie along the cruise tracks.

Wind direction statistics for the transit voyage scenarios are derived from a magnetic tape data base of weather statistics which covers all oceans of the world. The data tapes were supplied by the U.S. National Climatic Center at Asheville, N.C. which collected and compiled the data from years of shipboard and weather station observations. The data is broken down to statistics for every 5° by 5° square of latitude and longitude, and by month of observation.

Annual average true wind direction distribution relative to the cruise track is derived for each scenario according to the wind statistics in each 5° by 5° square which the ship will transit, the length of the course through each square, and the average heading in each square.

For the general scenarios, cruise tracks are not specified because the tracks do not repeat any typical pattern from one cruise to the next, and may be irregular on individual cruises. When several years of voyages are superposed, the direction of the cruise tracks will be nearly randomly distributed. For the North Atlantic and Pacific scenarios, wind direction is assumed to be evenly distributed with respect to ship heading. For the Antarctic General scenario, westerly cruise tracks are generally not scheduled to avoid adverse winds in the prevailing westerlies. The assumed wind direction distribution for the arctic scenario reflects the decrease in headwinds which results from this weather minded scheduling.

Wind statistics for each of the six voyage scenarios are presented in table 2.3. The typical wind statistics are the weighted average of the wind statistics for the six voyage scenarios adjusted to show slightly more headwinds than the strict weighted average. Transit time of each scenario is used as the weighting factor because this is the time when the wing sail will be deriving power from the wind.

A typical voyage scenario, combining the typical wind statistics with the totals of maintenance, port, station, locating and transit days per year from the operating statistics, is used in the optimization of retrofit wing parameters in chapter III. By analyzing the performance of a systematic variation of wing sail parameters on the typical scenario the optimum design parameters for wing sail retrofit are selected without analyzing each variation on each of six scenarios. Once selected, the optimum wing sail is analyzed on all six scenarios.

Wind direction distribution is shifted towards head winds to shift the parametric optimization towards a slightly higher rig design wind speed, which gives better performance on the six individual routes due to the wide spread of wind speeds on these six routes.

TABLE 2.3

WIND STATISTICS

For R/V KNORR Voyage Scenarios

	Scenario	Average Speed (Knots)	---Wind Direction Distribution------				
			Head	Close	Beam	Broad	Tail
1.	North Atlantic General	14.6	12.5%	25%	25%	25%	12.5%
2.	North Atlantic E-W Transit	13.4	5.5	12.8	19.0	34.5	28.2
3.	Atlantic N-S Transit	11.7	12.3	24.7	26.0	24.7	12.3
4.	Antarctic General	20.4	7.8	20.1	26.5	30.4	15.2
5.	Woods Hole Panama Transit	13.3	8.9	18.6	26.5	32.0	14.0
6.	Pacific General	13.0	12.5	25.0	25.0	25.0	12.5
	Typical	14.6	11.5	23.3	24.6	26.3	14.3

Because research vessel cruise tracks are often planned to avoid unnecessary head winds, the results of this wind analysis show wind direction distributions which are favorable for sail-assist. Thus, the voyage tracks as scheduled for conventional research vessels are also favorable to sail-assist vessels. For sail-assist vessels, an extension of the same practice could further improve voyage performance.

G. Operating Costs

Table 2.4 shows 1982 operating costs for the R/V KNORR, as proposed to the National Science Foundation by WHOI,[9] and as assumed for this study. The assumed costs differ from the proposed costs to reflect consistent discrepancies between proposed and actual costs over the last previous 3 years as cited in the comments column of table 2.4.

Annual fuel cost is not assumed but is output as a result of the retrofit analysis based on predicted fuel consumption and a fuel price of $1.25 per gallon. This fuel price is representative of the prices actually paid to fuel the KNORR with Marine Diesel Oil during the last quarter of 1981.[14] The annual fuel cost predicted in chapter III (q.v.) agrees closely with the proposed $482,000 for 1982.

From the cost breakdown presented in table 2.4 it is evident that fuel accounts for approximately 20% of the total operating costs. The value of fuel savings due to sail-assist will be some fraction of this 20% of operating cost. Wages and benefits for the ships company makes up approximately 40% of the operating cost, maintenance and supplies are approximately 20%, and the remaining 20% is on shore support personnel and facilities, insurance, and other indirect costs.

TABLE 2.4

R/V KNORR 1982 OPERATING COSTS

AS PROPOSED BY WHOI AND AS ASSUMED FOR RETROFIT STUDY

Item	WHOI Proposed (million $)	Assumed for Study (million $)	Comments: (based on proposed & actual costs for 1979, 1980 & 1981)
Maintenance	.225	.300	Typically 30 to 50% higher than proposed
Stores	.263	.250	} Typically 2 to 10% lower than proposed (Stores, Wages, Support Operations)
Wages	1.121	1.050	
Support Operations	.205	.200	
Insurance	.024	.024	As proposed
Other Indirect	.230	.230	As proposed
Total (less fuel)	2.068	2.054	
Fuel	.482	To be predicted in retrofit analysis (assumed fuel price $1.25 gallon)	
Total	2.550		

H. Summary

Flexibility is the most important operational consideration in multi-purpose research vessel design. A large, clear fantail deck with a grid of bolt down fixtures provides deck equipment flexibility. With sufficient space on the superstructure decks aft and on the forecastle deck, truck trailers or standard shipping containers can be used as interchangable laboratory units. A retrofit sail power unit on the forecastle deck with deck clearance for truck trailers will not interfere with research operations.

For the purpose of retrofit economic analysis, the only benefit of sail-assist is assumed to be fuel saving while transiting. Sail-assist benefits while on station or towing and reduced port time due to increased endurance are not quantified in this analysis, but are discussed in reviewing hardware alternatives, new vessels, and other naval missions.

Six voyage scenarios represent typical scheduling of the AGOR-14 class R/V KNORR, as operated by WHOI. Operating statistics for these scenarios indicate that the vessel spends 25% of her time in maintenance, 14% in port, 27% on station, 4% towing, and 30% in transit. Wind statistics indicate that present research cruise planning leads to wind direction distributions which are favorable to sail propulsion.

Operating costs for the KNORR are approximately 40% wages, 20% fuel, 20% maintenance and 20% support and indirect costs. Total operating costs in 1982 are expected to be 2.5 million dollars.

III - PARAMETRIC RETROFIT STUDY

A. Introduction

The purpose of this phase of the study is to determine the parameters of an economically optimum wing sail rig for the KNORR, as well as to estimate the benefits associated with that rig. The calculations are made using the Retrofit Analysis Model to predict ship performance for various rig configurations. By comparing these predictions with those for the ship without a sailing rig, the incremental effects on ship performance and fuel consumption are determined. A range of feasible rig parameters has been tried, and the most cost effective one selected. Some intermediate results of the process, as well as the final results are presented below.

B. Ship Parameters

In order to run the Retrofit Analysis Model, the parameters of the existing ship must be input. These are taken from the Plan Booklet[15] and the Trim and Stability Booklet,[16] and a Marine Technology article [17] and are summarized in Table 3.1.

C. Retrofit Parameters

A preliminary review of research vessel operations and the AGOR-14 general arrangement indicate that the most practical wing sail retrofit would be a single wing stepped on the 01 level deck (forecastle deck) forward of the 02 level deck. The base of the wing must be 8 feet above the 02 level deck to allow on deck storage under the tail swing, and an existing mast on the 02 deck must be moved aft of the tail swing.

With this arrangement, three wing parameters remain to be specified. Wing area, aspect ratio, and design wind speed are determined by systematic variation, analysis, and optimization as described below. The possible range of variation of these parameters is set by practical considerations of ship and wing arrangement. Air draft has been limited to 135 feet to allow the ship to pass under highway bridges over smaller ports and coastal waterways. Within this air draft limitation and the tail swing requirements described above, the maximum allowable wing span is 99 feet, and the maximum chord length is 45 feet.

TABLE 3.1

R/V KNORR SHIP CHARACTERISTICS

Hull:	
Displacement	2111.0 LT
Length (BP)	220.0 ft.
Beam	46.0 ft.
Draft	15.7 ft.
Block Coefficient	.465
GM	3.80 ft.
Power Plant:	
Rated Brake Horsepower	2500.0
Service Margin(@ 12 knots)	.79
Specific Fuel Consumption	.410 #/HP-Hr.
Propulsive Efficiency (@ 12 knots)	.51

D. Retrofit Optimization

Using the Retrofit Analysis Model, variations in aspect ratio, design wind speed, and sail area were investigated to determine an "optimum" wing sail rig for the KNORR. All rig optimization calculations were determined assuming the typical voyage scenario described under Operational Analysis (chapter II).

The first variation studied was aspect ratio. A wing span of 90 feet was assumed based on prior experience with wing sail optimizations. The chord length was then varied to determine the optimum ratio of span to chord (aspect ratio). For each assumed rig configuration, Wind Ship's Cost Estimating Model was used to determine installed rig cost, and the Retrofit Analysis Model determined fuel savings in long tons per year. These two variables are plotted in Figure 3.1 versus chord length. The ratio of rig cost to fuel savings ($/LT per year) is the cost of fuel savings, and we wish to minimize this cost. As seen from the plot, the minimum cost occurs at a chord length of approximately 36 feet. This is an aspect ratio of 2.5, which is used for the rest of the variations outlined below.

The aerodynamic loads associated with an apparent wind speed equal to the rig design wind speed are used to size structural members in the wing. At higher apparent wind speeds the wing must be feathered into the wind like a wind vane to control rig loads. This feathering is modeled by the Retrofit Analysis Model, as the design wind speed increases, the fuel savings also increase since the wing is being used a larger portion of the time. Of course, rig construction costs also increase with the heavier scantlings imposed by higher loads, and there is a point above which it is not desirable to increase the design wind. The cost of fuel savings is plotted versus design wind in figure 3.2 and the minimum is seen to be approximately 37.5 knots. Since the six operating scenarios have a wide range of average wind speeds, a slightly higher design wind of 40 knots was chosen for the balance of the rig variations.

The final variable optimized was rig size. Aspect ratio and design wind were held fixed at 2.5 and 40 knots respectively, and sail area was varied. Figure 3.3 shows the variation in fuel savings cost versus sail area, and the minimum is seen to occur for a sail area of approximately 3500 sq. ft. However, the curve is reasonably flat up to 3610 sq. ft. (corresponding to a wing span of 95 feet), and which is chosen as a suitably optimum sail area. The resulting air draft of 131 feet satisfies the bridge clearance requirements.

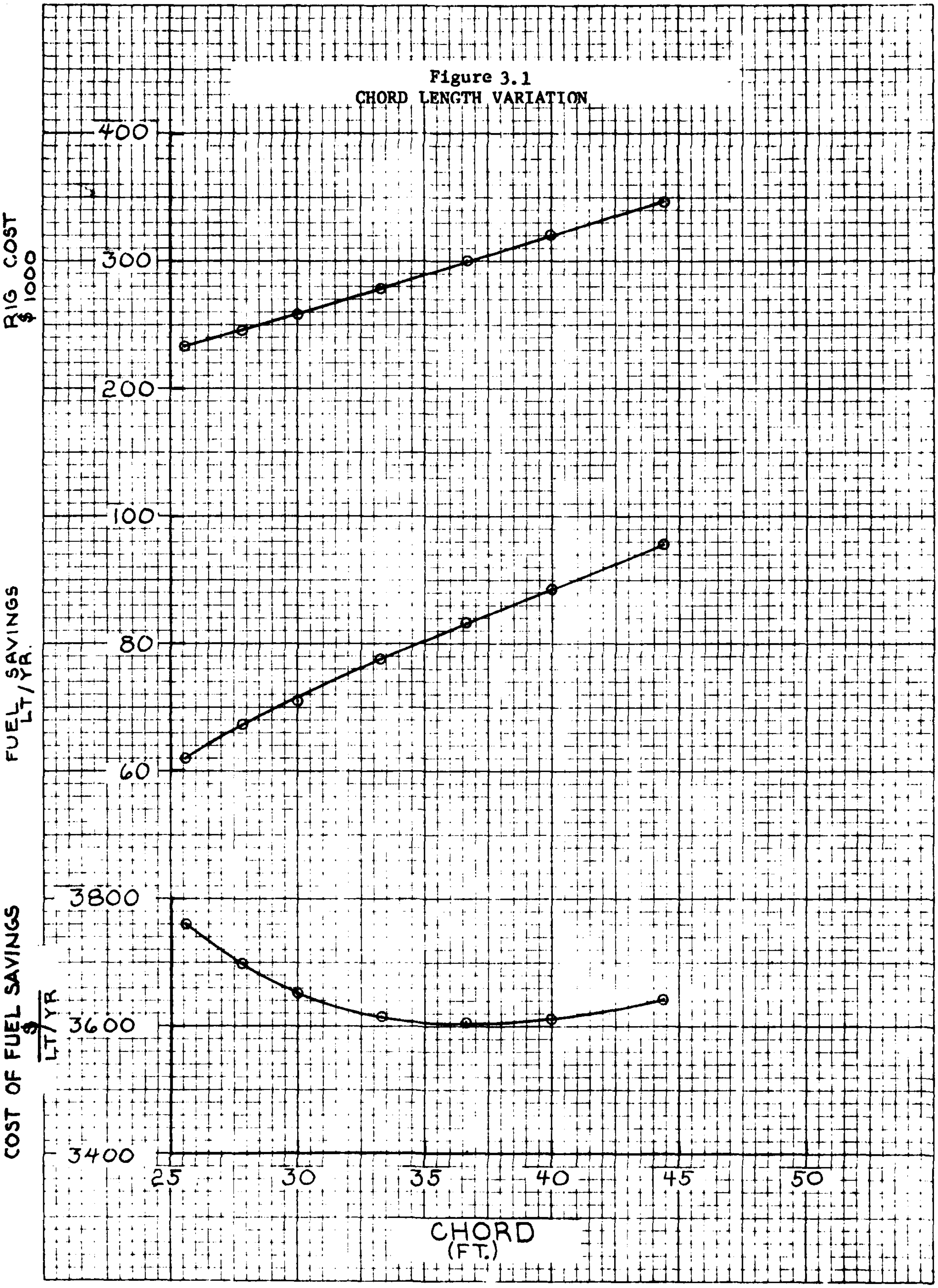


Figure 3.1
CHORD LENGTH VARIATION
RIG COST
$ 1000
400
300
200
FUEL SAVINGS
LT/YR.
100
80
60
COST OF FUEL SAVINGS
$
LT/YR
3800
3600
3400
25
30
35
40
45
50
CHORD
(FT.)

Figure 3.2
DESIGN WIND SPEED VARIATION

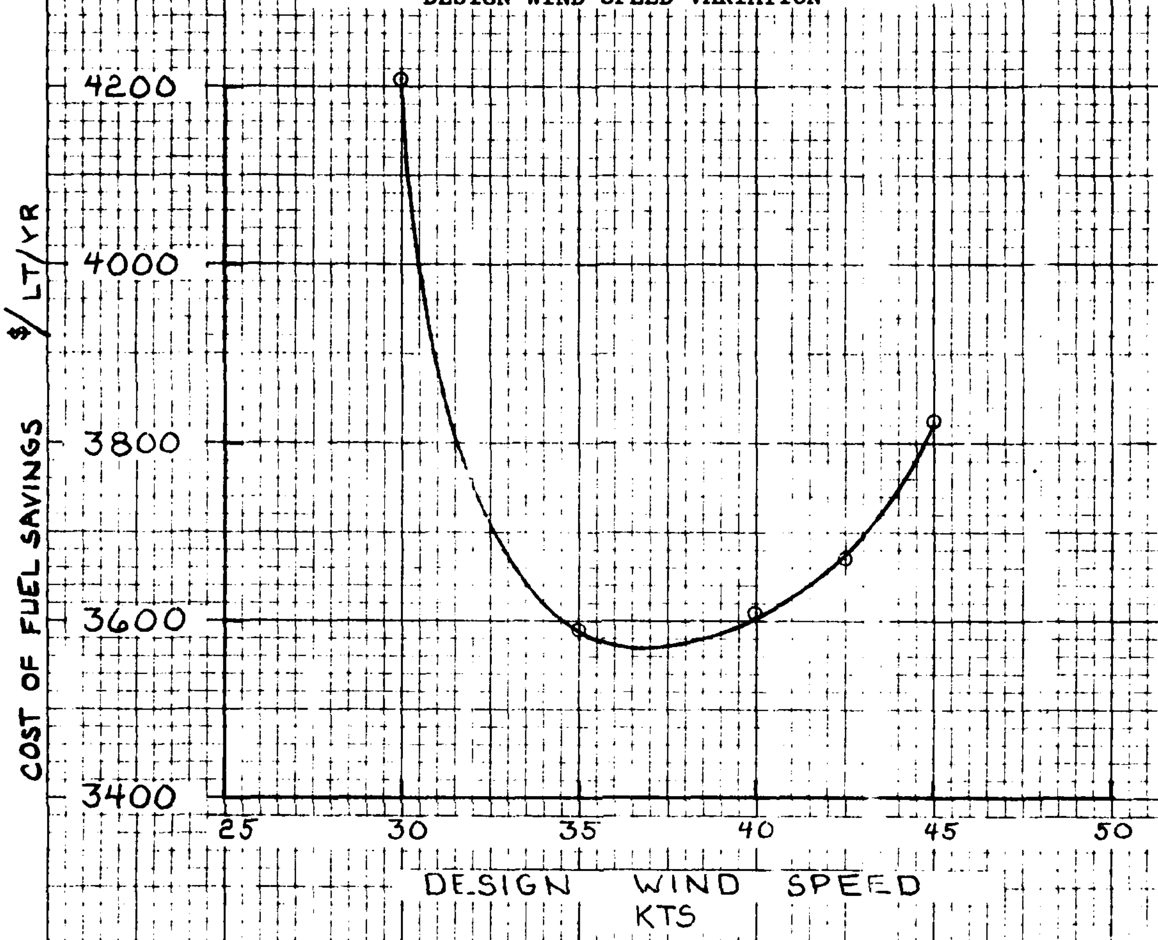
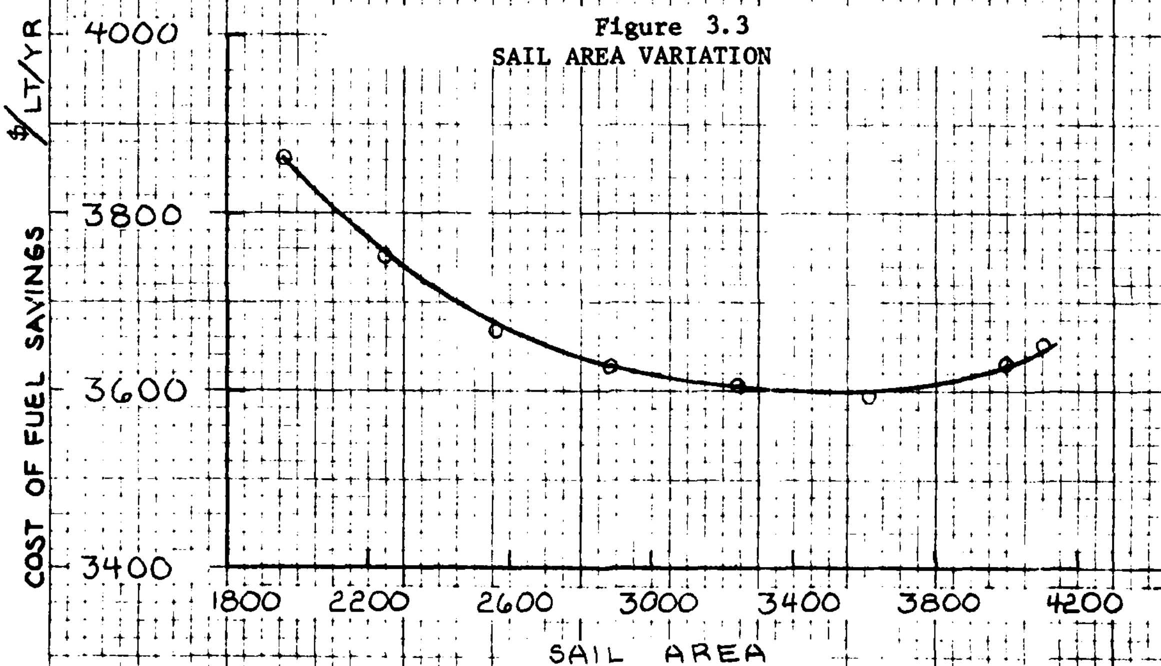


Figure 3.3
SAIL AREA VARIATION



E. Performance of Selected Rig

The fuel savings performance of the selected wing-sail was determined on each of the six operating scenarios, and is presented in Table 3.2. In addition, average performance was determined based on an appropriate weighting of the results of each scenario. On the average, the wing will save about 21 percent of the main engine propulsion requirement while transiting, or 90 long tons of Diesel fuel per year. At $1.25 per gallon, this is $36,000/yr. in fuel savings.

The value of fuel savings is based upon 1982 fuel prices and will escalate as fuel prices rise. The rate of increase of fuel prices is uncertain at this time, as is reflected by numerous conflicting predictions in support of one or another energy policy. Prices certainly will continue to increase, and probably will continue to increase faster than inflation of the economy as a whole.

The predicted annual fuel bill for the existing ship is $474,000 of which $176,000 is for propulsion requirements, and the remaining $298,000 is for auxiliary generators and station keeping. Because transiting fuel accounts for less than half of the total annual fuel consumption, the retrofit saves only 7.6% of the total.

The potential economic benefits of reduced lubrication oil consumption and reduced machinery maintenance due to the reduced propulsion requirements are not included in the predicted annual savings. A rough estimate of the magnitude of the potential reduction in maintenance cost may be derived from the total annual maintenance costs reported under Operating Costs in chapter II. Assuming that machinery maintenance accounts for 50% of the total maintenance cost, and that total machinery maintenance is reduced by the same percentage as total fuel consumption (7.6%), the net annual maintenance reduction will be 3.8% of $300,000 or approximately $11,000.

The estimated maintenance cost for the selected wing sail is $5,000/yr. On this basis it is reasonable to assume that rig maintenance cost will be covered by reduction in machinery maintenance, and that there may be additional savings of machinery maintenance and lubricating oil.

Detailed results of performance prediction for both the existing ship and the retrofitted ship are presented in Appendix A - Detail Performance Predictions. Of particular interest are the graphs of rig horsepower versus true wind for the retrofitted case, and heel angle versus true wind for both cases.

TABLE 3.2

R/V KNORR
Sail-Assist Retrofit
Fuel Savings Performance

Scenario	Main Engine Transit Fuel Savings (%)	Annual Fuel Savings LT/year	Annual Fuel Savings $/year *
1	20	74.8	29,900
2	20	101.3	40,500
3	16	79.0	31,600
4	28	174.0	69,600
5	21	158.5	63,400
6	18	64.8	25,900
Weighted Average	21	90.0	36,000

* Fuel price= $1.25/gallon or $400/LT.

F. Cost of Selected Rig

Based on the preliminary parametric cost estimates of the Retrofit Analysis Model, the selected rig would cost $327,000. The rig cost models have a generous allowance for wing foundation to account for unknown details of the existing ship configuration which are not included in the parametric description of the existing ship.

The estimate of rig cost presented in chapter IV is based on the modification characteristics as drawn for the AGOR-14. Because the wing foundation presented in chapter IV requires minimum modification of existing structure, the cost presented in chapter IV is less than the cost predicted by the retrofit model.

G. Summary

A systematic variation of retrofit parameters leads to the selection of a 3610 square foot wing sail for retrofit of an AGOR-14 class vessel. The optimum wing parameters are span of 95 feet, chord of 38 feet, and a 40 knot structural design wind speed.

The selected wing saves 90 long tons of fuel per year, worth $36,000 at 1982 fuel prices. The cost of wing-sail maintenance may be offset by reduced machinery maintenance and reduced lubricating oil consumption.

Based on the $327,000 rig cost predicted by the retrofit model, the cost of fuel saving is $3,600 for each long ton per year of savings. Retrofit design characteristics presented in the next chapter indicate that the wing foundation will cost less than predicted by the model.

IV - RETROFIT DESIGN CHARACTERISTICS

A. Introduction

In this chapter, a conceptual design of the wing sail retrofit including wing subsystems and required modifications to the existing ship, is presented to demonstrate practical considerations of a retrofit installation. General arrangement, compatibility with research operations, structural modifications, wing systems, stability, visibility, and helm balance are discussed in reference to study sketches of wing arrangement, wing foundation, and wing systems.

B. General Arrangement

Figure 4.1 is an outboard profile of the KNORR with retrofit wing sail as selected in chapter III. The wing arrangement and structure are designed to be compatible with existing deck and structural arrangements. The only required modification of the existing outboard arrangement is that an existing mast is relocated to a position just aft of the wing The new location in figure 4.1 is approximately 15 feet aft of the existing location shown as a dashed line in figure 4.2.

As described in chapter II, the wing sail located on the forecastle deck should not interfere with oceanographic research operations. The base of the wing is more than 8 feet above all points on the 02 level deck to avoid interference with trailers which are occasionally placed on this deck for temporary laboratory space.

C. Structural Modifications & Wing Foundation

Figure 4.2 is an inboard profile sketch showing the foundation which is simply a continuation of the fixed mast from the weather deck down to the second platform. Figures 4.3 and 4.4 show the deck arrangement and structural modifications at each deck or platform. The four foot diameter mast passes through the 01 level (weather) deck between an existing booby hatch stairwell and the anchor windlasses. The 01 deck is reinforced with heavy deck beams (of angle or "I" section) and mast partners (plate) welded to the underside of the deck in way of the mast. The main deck and first platform are reinforced with doubler plates to tie the mast foundation to the deck and to the bulkhead just forward of the mast.

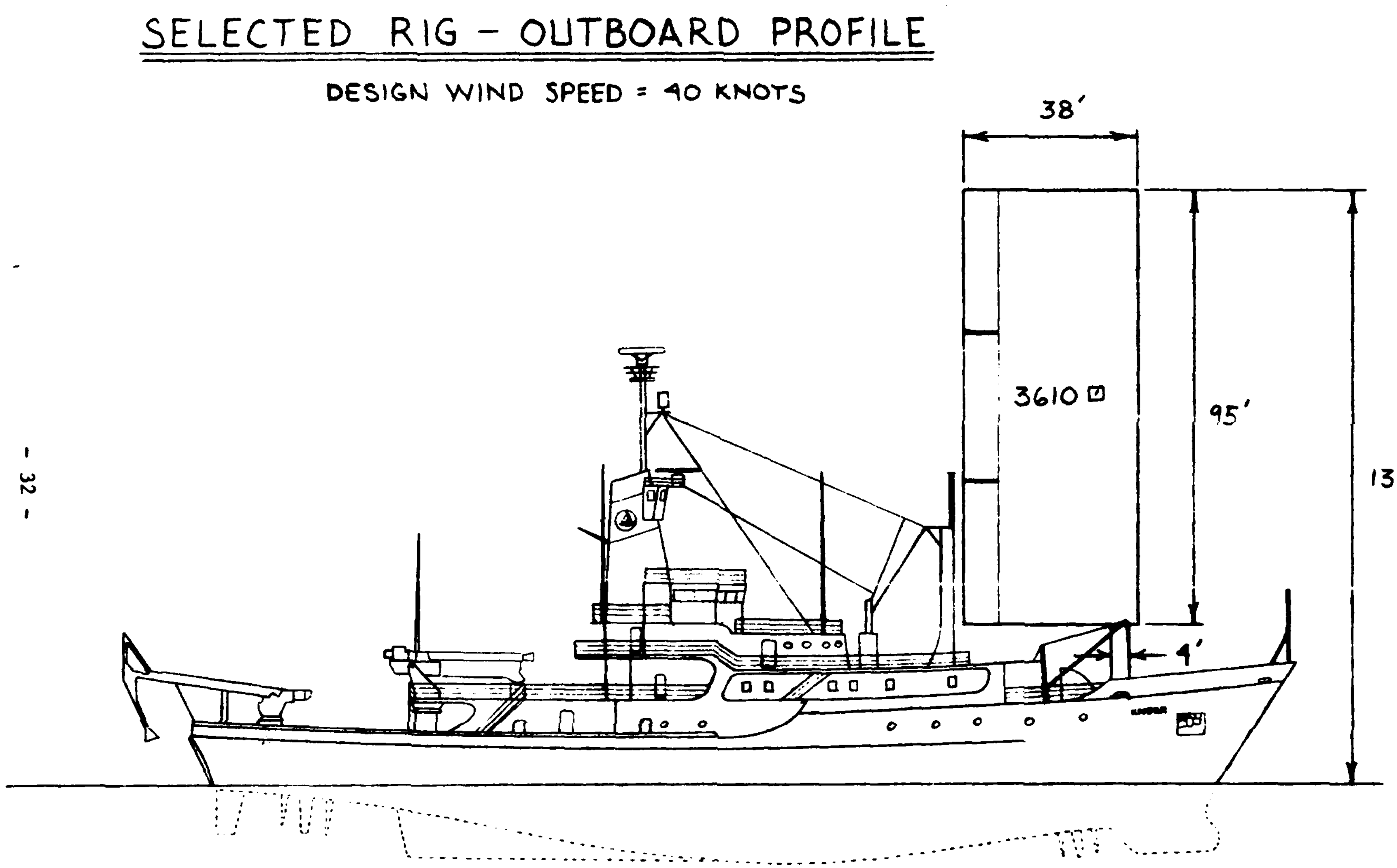


FIGURE 4.1
R/V KNORR
SAIL ASSIST RETROFIT
STUDY SKETCH
SCALE $\frac{1}{32}$" = 1′-0"

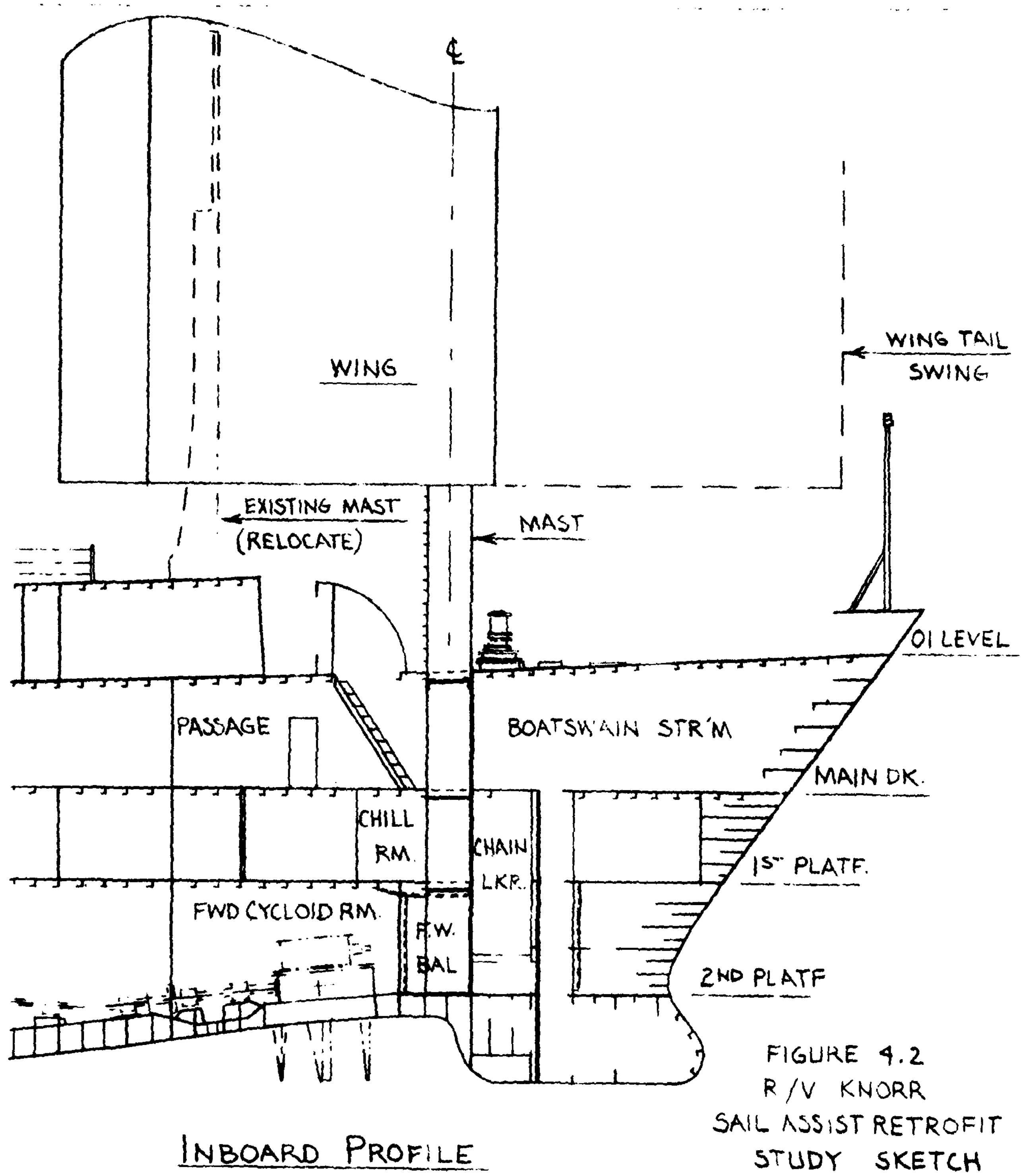


FIGURE 4.2
R/V KNORR
SAIL ASSIST RETROFIT
STUDY SKETCH

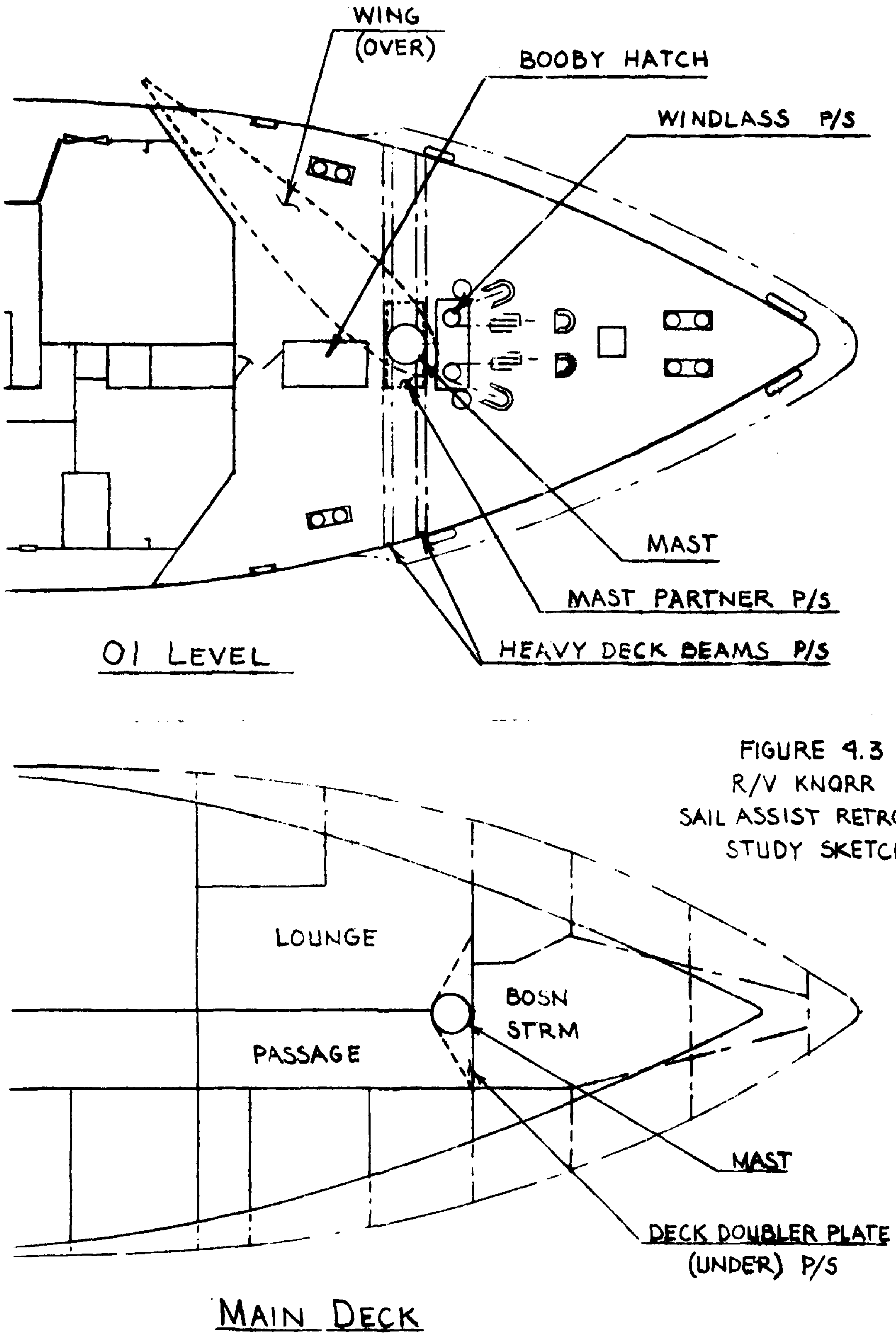


FIGURE 4.3
R/V KNORR
SAIL ASSIST RETROFIT
STUDY SKETCH

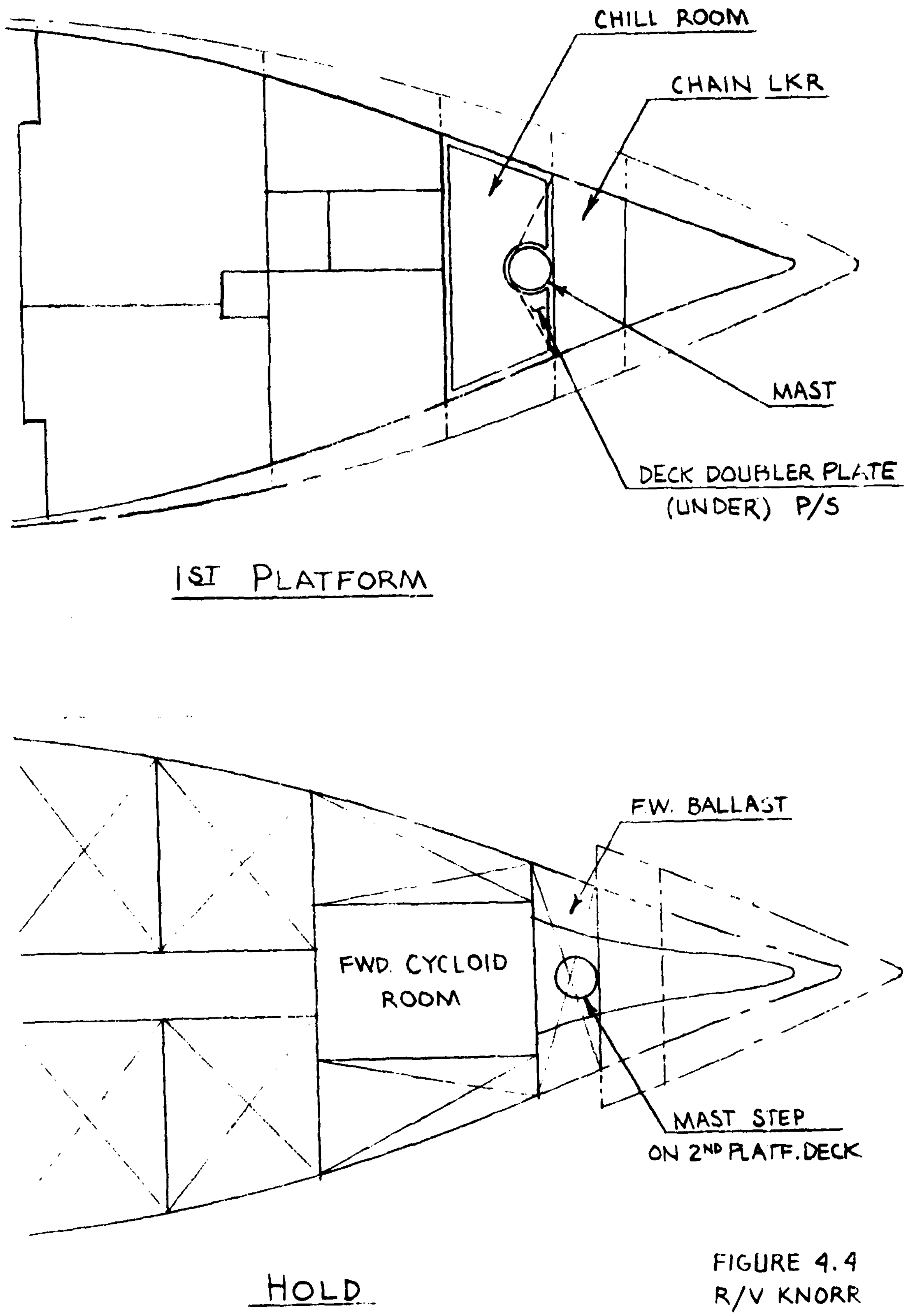


FIGURE 4.4
R/V KNORR
SAIL ASSIST RETROFIT
STUDY SKETCH

The base of the mast foundation is butted to the second platform in the forward fresh water ballast tank. The mast would be fabricated of eight or twelve foot sections of rolled plate welded at the seam and butt welded at the ends. A diaphragm would be included at the butt weld above the ballast tank, and penetrations through the mast plate would allow the volume inside the mast to be recovered as ballast capacity. On the first platform, the mast foundation passes through a chill room where it should be insulated as are the existing walls. The foundation and insulation occupies about 10% of the present chill room space. At the main deck, mast occupies an insignificant amount of space in a corner of the crew's lounge and a passage.

D. Weight and Cost Estimates

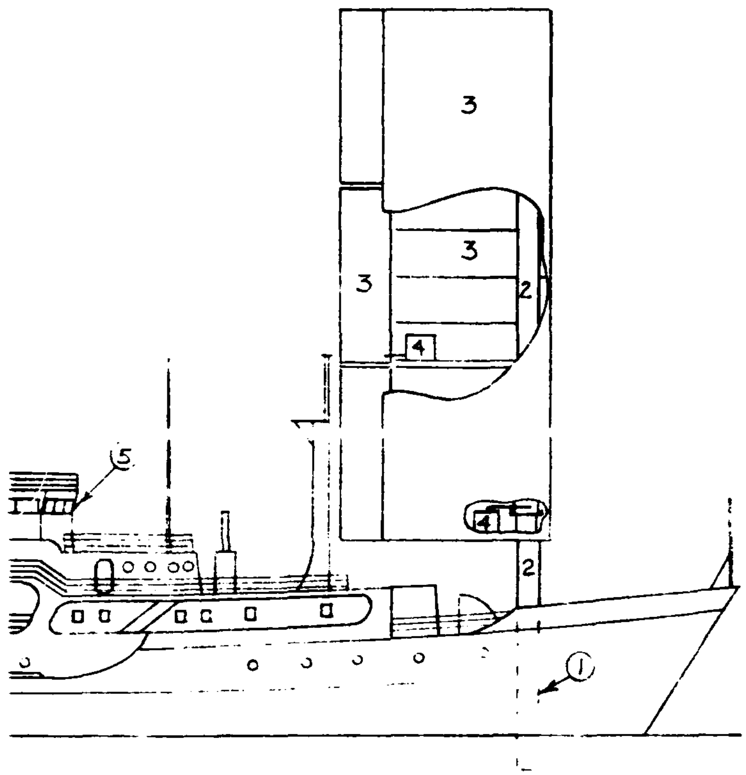
Figure 4.5 shows a cutaway profile of the wing sail, and weight and cost estimates broken down into six cost groups. The design features are based on Wind Ship's proprietary wing sail designs (patents applied for). The estimate of total installed cost (less design and engineering) is $300,000.

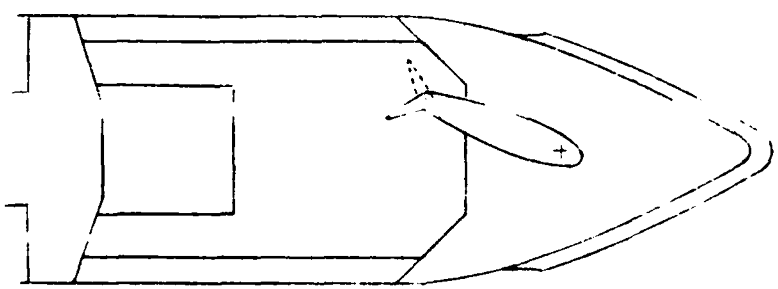
E. Wing Systems and Operation

Details of the Foundation group are described above. The Spar and Fixed Mast group includes the fixed mast from above deck to its top one-third of the way up the wing, the pivot bearings located at the base of the wing and the top of the fixed mast, and the rotating spar which is mounted on the pivot bearings and extends the full wing span along the leading edge. The fixed mast is fabricated as described for the foundation. The rotating spar is welded steel with a box cross section.

The laminated wood trusswork framework is bolted to the rotating spar and supports the molded plywood skin which forms the aerodynamic surface of the wing. The three flaps of molded plywood over wood framework are included in the Framework and Skin group.

Each flap is individually driven and may be deflected to 45° either side of the wing centerline. Flap deflection causes an increase in aerodynamic lift, similar to the effect of camber (wing section curvative). For maximum thrust in most sailing conditions, all three flaps will be deflected to the maximum 45°. When the apparent wind is less than 35° off the bow, optimum performance is achieved with the flaps set at less than maximum deflection. When the wind is directly ahead, windage drag of the wing is minimized with the flaps centered and the wing aligned with the ship centerline.





WEIGHT AND COST ESTIMATES

FOR SELECTED RIG

ITEM GROUP	WEIGHT (LT)	COST (1982 $)	% COST
1 Foundation	8.0	50,000	17
2 Spar and Fixed Mast	13.4	44,000	15
3 Framework & Skin	7.2	80,000	27
4 Power & Drives	5.1	70,000	23
5 Controls	.3	12,000	4
6 Procurement & Supervision of Installation	---	44,000	15
Total	34.0	300,000	

FIGURE 4.5
WING SAIL SYSTEMS
AND
WEIGHT AND COST ESTIMATES

When apparent wind speeds exceed the 40 knot structural design wind speed, the flaps must be centered and the wing aligned with the wind to prevent structural loads from exceeding the design loads. Because the pivot axis located only 10% of the chord length aft of the leading edge, the wing will self-align (feather) with the wind when the main drive system is disengaged and the wing is allowed to rotate freely about the pivot axis. In this passive feathering mode, the flaps must be centered.

Three flaps are used instead of one full length flap because the flap structural loads are much less for the one-third length individual flaps. Reduced loads allow lighter weight flaps which improve the feathering response of the wing and are less expensive. The three flaps are driven independently to provide redundancy so that the wing will feather if [illegible] of the flaps fails to lock on centerline.

Three flap drives, the main slewing drive system with feathering clutch, and power supplies therefore make up the Power and Drive group. The estimate for the Controls group includes remote control of all wing functions from the pilot house, but does not include an automatic control system.

F. Helm Balance

The forward location of the single wing on the AGOR-14 retrofit is chosen to coincide with the approximate center of lateral resistance (CLR) as well as to avoid interference with oceanographic work. Experience with side thrust applied to the forward cycloid indicates that the selected wing location should have minimal impact on ship steering, and may actually improve steering in beam winds. The existing ship has trouble in beam winds because the windage of the superstructure is aft of the CLR and the ship tends to veer towards the wind unless corrected by side thrust from the cycloids.

G. Stability Before and After Retrofit

Figure 4.6A shows righting arm versus heel angle for the R/V KNORR in typical arrival condition.[18] without free surface correction (therefore, passive roll stabilization tank not in use) and an assumed wind heeling arm versus heel angle, calculated for 100 knot beam wind following the method of Sarchin & Goldberg,[19]. The equilibrium heel angle is in the intersection of the curves at 23° heel, where the righting arm, $\overline{GZ}_s$, is 1.6 ft.

According to the stability criteria presented by Sarchin & Goldberg, the equilibrium righting arm, GZ_s, should be no more than .6 of the maximum righting arm, $GZ_{max.}$, and the area A_1, between the two curves to the right of the equilibrium point should be at least 1.4 times the area A_2, between the two curves out to 25° to the left of the equilibrium point. From Figure 1 for the R/V KNORR GZ_s is .74 of $GZ_{max.}$, and A is 1.02 times A_2. According to the above criteria, the existing vessel has neither sufficient margin of stability in the equilibrium condition, nor sufficient reserve stability when rolling about the equilibrium heel angle.

FIGURE 4.6
R/V KNORR
Stability Before and After Retrofit

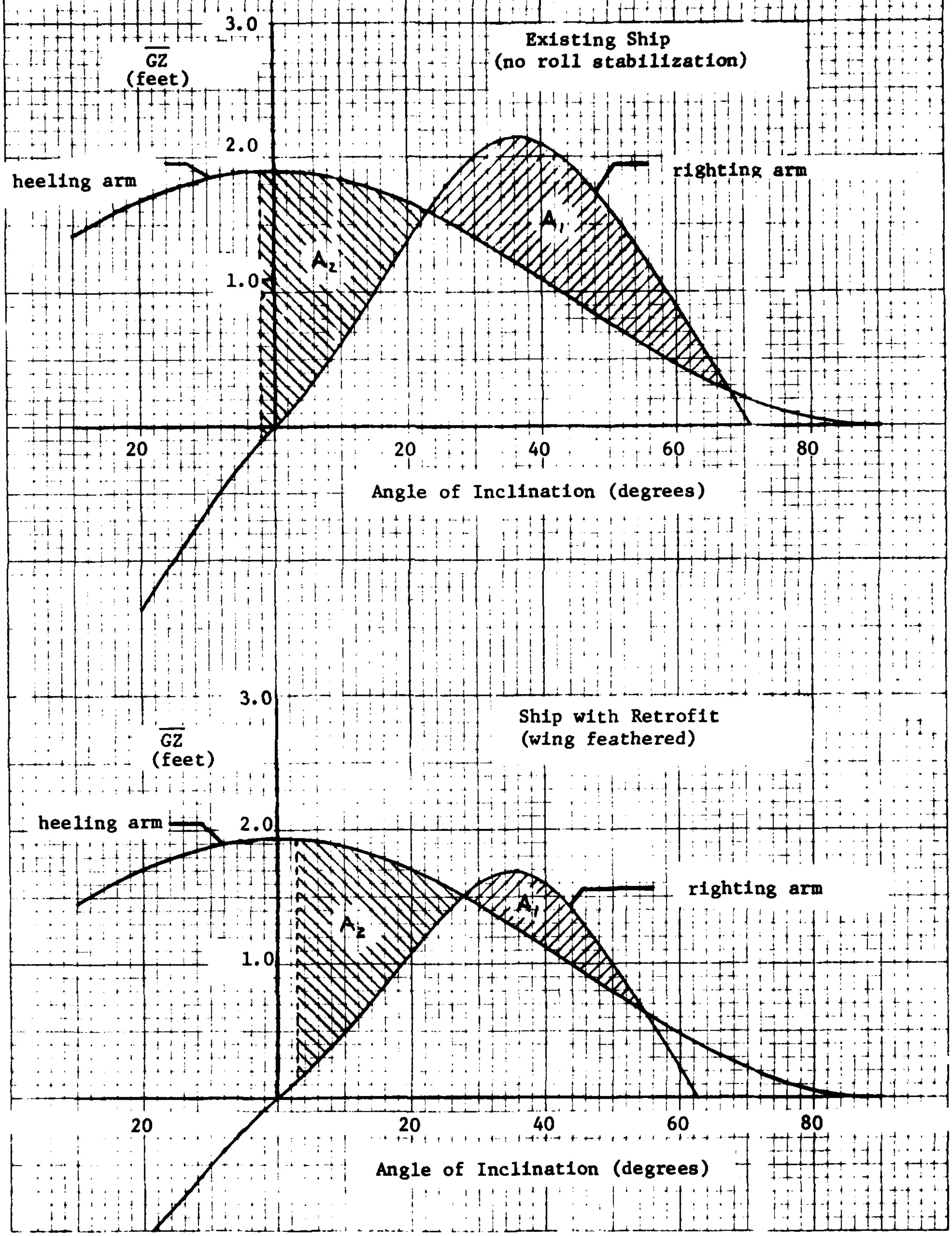


Figure 2 is a similar presentation of righting arm and wind heeling arm for the R/V KNORR with retrofit wing sail. The wing weight aloft increases the KG of the ship by .76 feet and therefore reduces the righting arm from figure 1 as shown. When feathered, the streamlined wing increases the 100 knot heeling arm by only 2% of the existing ship wind heeling arm. Because of the reduced righting moment curve after retrofit, the retrofitted ship has a larger equilibrium heel angle (28°) and is farther from meeting the stability criteria than the existing ship.

A ship which does not meet stability criteria before retrofit is not suitable for retrofit without additional modification to provide adequate stability. This does not mean that sail-assist retrofit causes an unacceptable decrease in stability. For the case examined here, the .76 foot increase in KG has an effect on stability which is roughly equivalent to the free surface effect of the AGOR-14's passive roll stabilization tank. Thus, design of a new sail-assist vessel or modification of a vessel for sail-assist retrofit would require stability allowances similar to those required for designs to incorporate passive roll stabilization.

Although the KNORR does not meet conventional storm wind stability criteria before or after retrofit, the detail performance predictions (q.v.) show that heel angles under sail reach a maximum of 12.4 degrees in a true wind speed of 32 knots. Above this wind speed wing sail feathering reduces heel angle until the wind becomes so strong that hull and superstructure windage will produce greater heel angles. Therefore, excessive heel angles will not occur when sailing.

H. Icing

The wing sail retrofit adds considerable surface area on which ice may form when icing conditions occur. The weight of ice on the wing surface not only creates a stability hazard, but also degrades the feathering response of the wing by increasing its pivoting inertia. Further wing sail design work should address possible solutions to prevent ice formation and/or to allow de-icing the wing.

I. Visibility

Although the wing does not impair the pilot house view of oceanographic work on the fantail or of line and anchor handling on the forecastle deck, it does create a significant blind sector on the horizon ahead of the ship when viewed from a fixed point in the pilot house. In the worst case, with the wing perpendicular to the mean sight line, the occluded sector is 25°. However, the pilot house enclosure spans the full beam of the ship (46 ft.) so that the operator may move from one side to the other and gain a view of any point on the horizon.

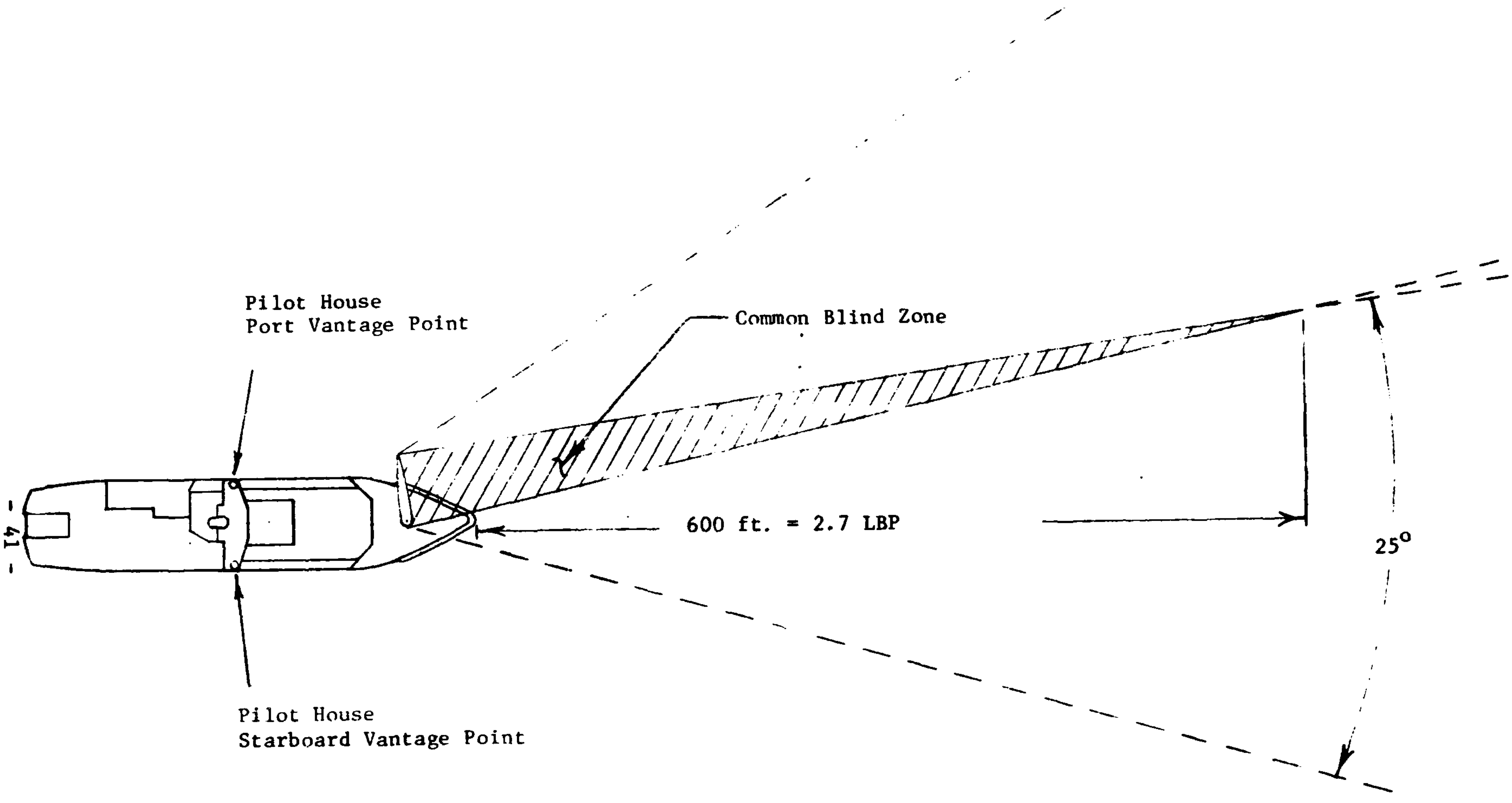


FIGURE 4.7

VISIBILITY FROM PILOT HOUSE

R/V KNORR

SAIL-ASSIST RETROFIT

not to scale

Figure 4.7 shows the views from the two best vantage points at the extremes of the pilot house. There remains a common blind zone which extends 2.75 ship lengths forward of the bow.

Present U. S. Coast Guard policy is to restrict vessels to a blind zone extending no more than 1.25 ship lengths forward of the bow. An alternative policy does exist for certain types of container ships and liquified gas carriers. The chief of the U. S. Coast Guard Ship Design Branch has indicated that neither policy adequately addresses the visibility problems encountered on large commercial vessels with sail. Comments of the Ship Design Branch on this wing-sail retrofit indicate that the master should have a complete view of the horizon, the loss of which is only partially compensated by his ability to move to the extremes of the pilot house to see around the wing.

Raising the base of the wing by ten feet would place it seven feet above the pilot house deck and eliminate the visibility problems associated with the retrofit. This adjustment would reduce the wing area by 380 sq. ft. The lost area could be recovered by extending the top of the wing 4 feet to the maximum 135 feet above the load water line and extending the chord to 40 feet. The parameters of this wing correspond to the 40 feet chord wing in the chord length variation (chapter III, figure 3.1) which shows 89 long tons per year fuel savings.

J. Navigation Lights

The wing sail also occludes the navigation range lights when viewed from certain directions from ahead. The jackstaff at the bow could be replaced by a larger mast to support both the anchor light and the forward range light which is presently located on the foremast.

The aft range light in its present location on the mainmast above the exhaust stack is not "clear of and above all other lights and obstructing superstructures" as required by the international rules of the road. The rules also require that the horizontal distance between the two range lights be at least three times the vertical distance, which is not satisfied if the aft light is placed on top of the wing. Further consultation with the appropriate authorities could determine if either the present location of the aft range light or the location on top of the wing would provide a sufficiently recognizable range light pattern to merit a waiver from strict compliance with the rules.

The navigation light problems which arise with the single wing retrofit would not occur with a multiple wing sail arrangement such as may be desirable for a new building. With two or more wing sails, the aft range light could be placed atop the aft wing.

K. Summary

This conceptual design indicates that a wing sail can be retrofit to a multipurpose oceanographic research vessel without impeding research operations and with minimal modification of existing arrangement and structure . The forward position of the center of lateral resistance is a fortunate property of most ship hull forms that allows retrofit of a single wing sail stepped on the forecastle deck. In this position the wing is removed from interference with research operations and the foundation may take advantage of the existing watertight bulkhead.

Visibility of the horizon is partially occluded by the retrofit wing, but this can be avoided by setting the base of the wing higher than shown. In the future, visibility should be considered before setting a limit on the lower extent of the wing for parametric optimization and retrofit design work.

The AGOR-14 class RV KNORR is not suitable for sail-assist retrofit because the existing ship does not have adequate stability. However. the stability requirements for sail-assist retrofit are not large and should not present serious difficulties on most vessels. In new buildings, design for sail-assist would require a margin in stability similar to that required to accommodate passive roll stabilization tanks.

Except for inadequate stability, the AGOR-14 class appears to be an excellent opportunity for sail-assist retrofit of an oceanographic vessel, and would achieve fuel savings with no detriment and possible benefit to oceanographic operations.

In light of the potential advantages to be gained by sail-assist retrofit, consideration of other research vessels for retrofit is justified.

V - HARDWARE ALTERNATIVES

A. Introduction

Although detailed performance and economic analysis has been limited to the wing sail retrofit, other types of sail-assist hardware may merit consideration.[20] Figure 5.1 shows eight sail-assist hardware alternatives, including the wing sail which is described above. Two of these rigs, the unstayed cat rig and the Flettner rotor, are considered in this chapter with the results from the wing sail retrofit analysis as a reference point for comparison. Wind turbines are also discussed in this case not for sail propulsion, but for auxiliary power generation.

B. Cat Rig

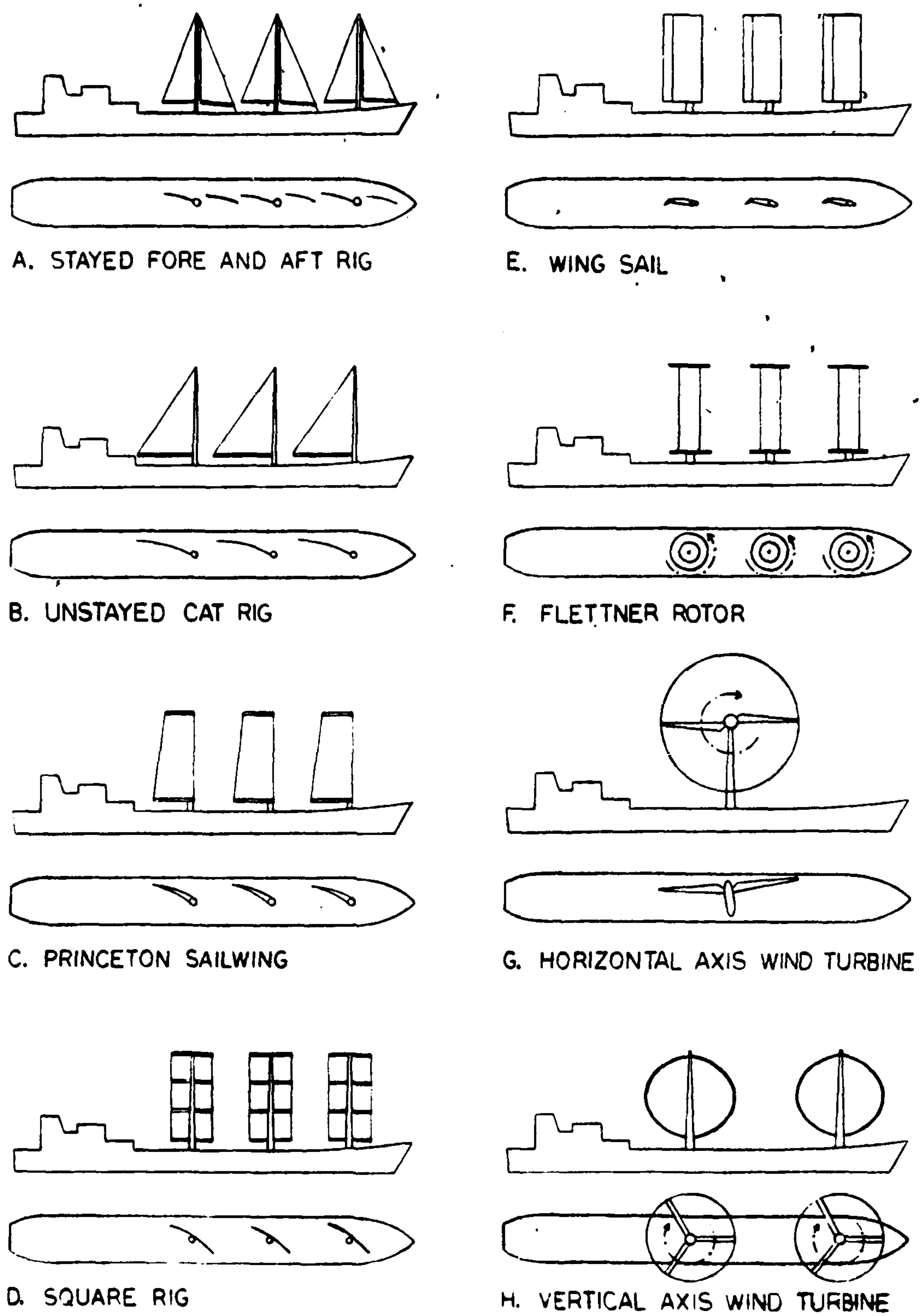
An unstayed cat rig is presently in commercial service in Caribbean trade aboard the 3,000 DWT general cargo vessel MINI LACE. Figure 5.2 is a picture of the MINI LACE with retrofit cat rig on sea trials in Buzzards Bay. This rig has operated successfully since the ship returned to service in September, 1981, and has verified the performance predictions made previous to the installation using the Wind Ship Retrofit Analysis Model. The dacron sail is 3,000 square feet in area, and the mast stands 116 feet above deck. This rig was designed to operate with full sail in winds up to 35 knots, and to survive storm winds up to 150 knots with sail furled.

Figure 5.3 is a general arrangement drawing of the MINI LACE Cat Rig The unstayed mast is mounted in bearings to permit furling and unfurling of the sail by mast rotation. The boom is cantelivered on bearings from the mast support to allow trimming in the horizontal plane. Hydraulic sheet winches mounted on the boom pay out and take in sheet lines to swing the boom to the desired position. A hydraulic motor rotates the mast in relation to the boom so that the sail may be reefed without changing the position of the boom, and so that swinging of the boom also causes a corresponding rotation of the mast. Therefore, a change in position of the boom does not change the amount of exposed sail.

The loose footed triangular sail sets on sliders from a track on the mast Tension on the clew of the sail is provided by an outhaul and a downhaul which operate independently of each other The outhaul line is paid out and taken in under continuous tension in conjunction with the rotation of the mast to take in or let out sail. The downhaul mechanism is mounted on the boom and connected to the clew, and travels in and out along the boom with movement of the clew, maintaining downhaul tension during such movement. Adjustment of tension on the outhaul and downhaul are provided by hydraulic winches and cylinders.

Figure 5.1

Rig Alternatives



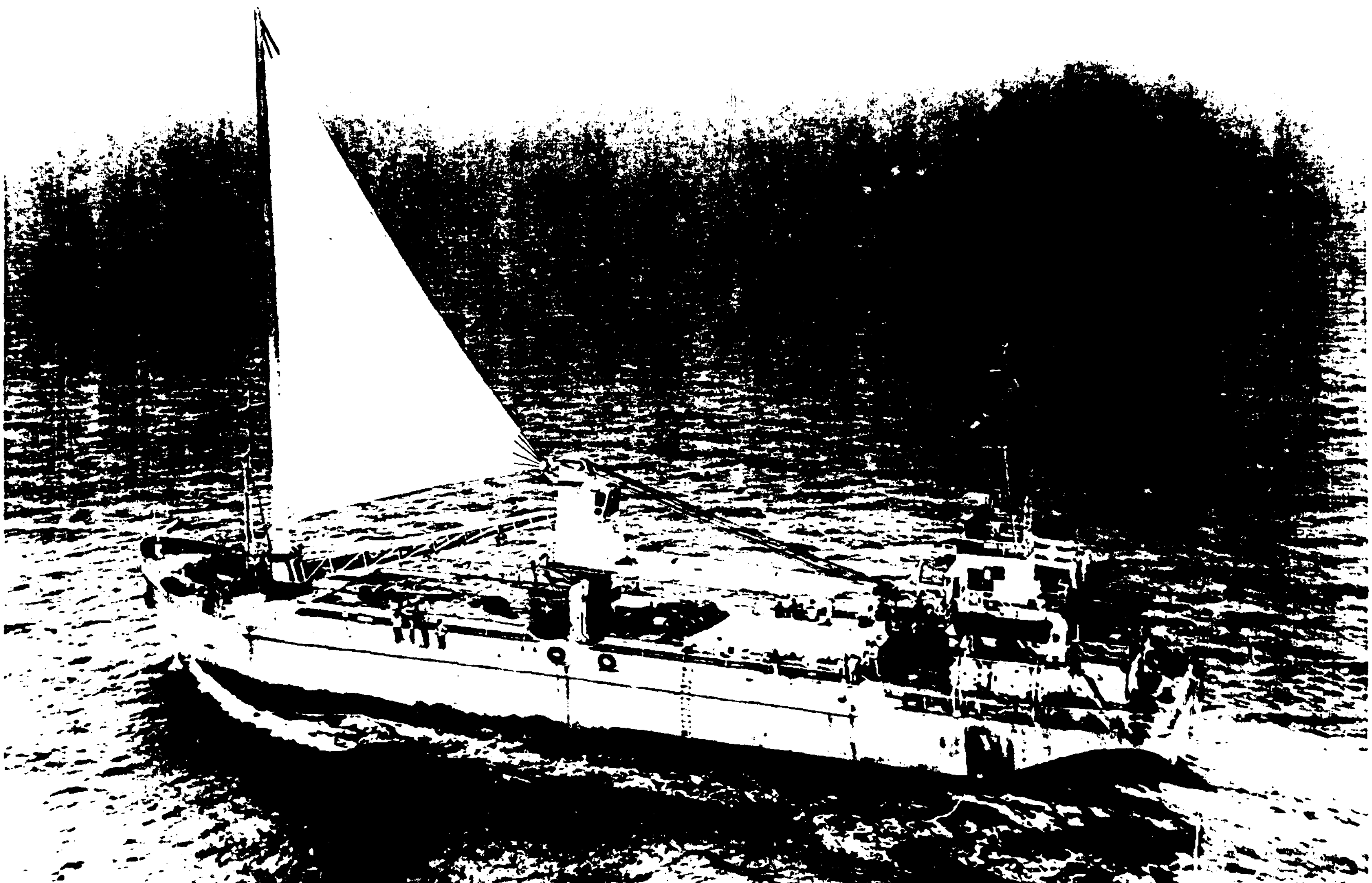
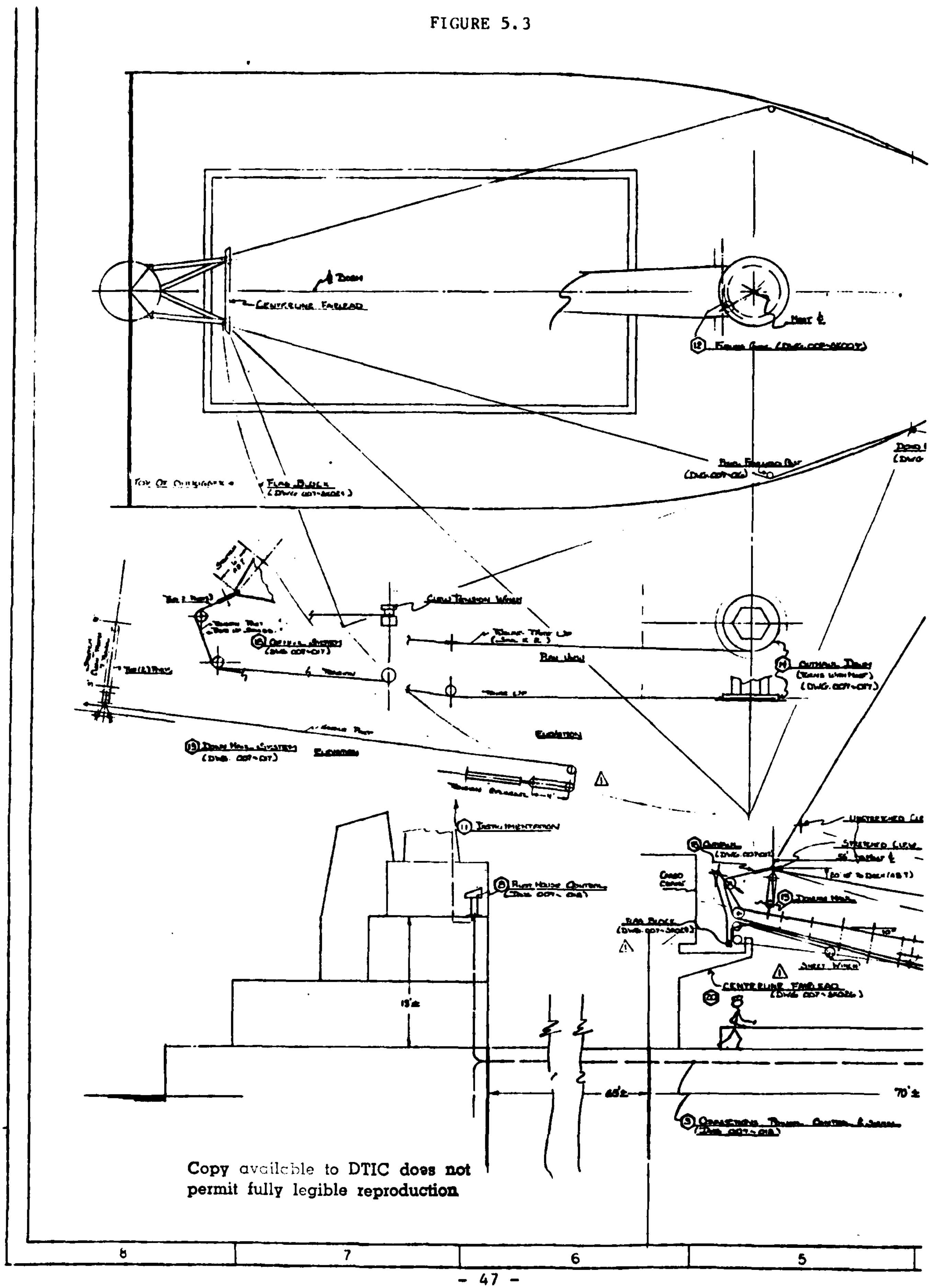


FIGURE 5.2

MINI LACE Rig Trials, Buzzard's Bay - August 24, 1981

FIGURE 5.3



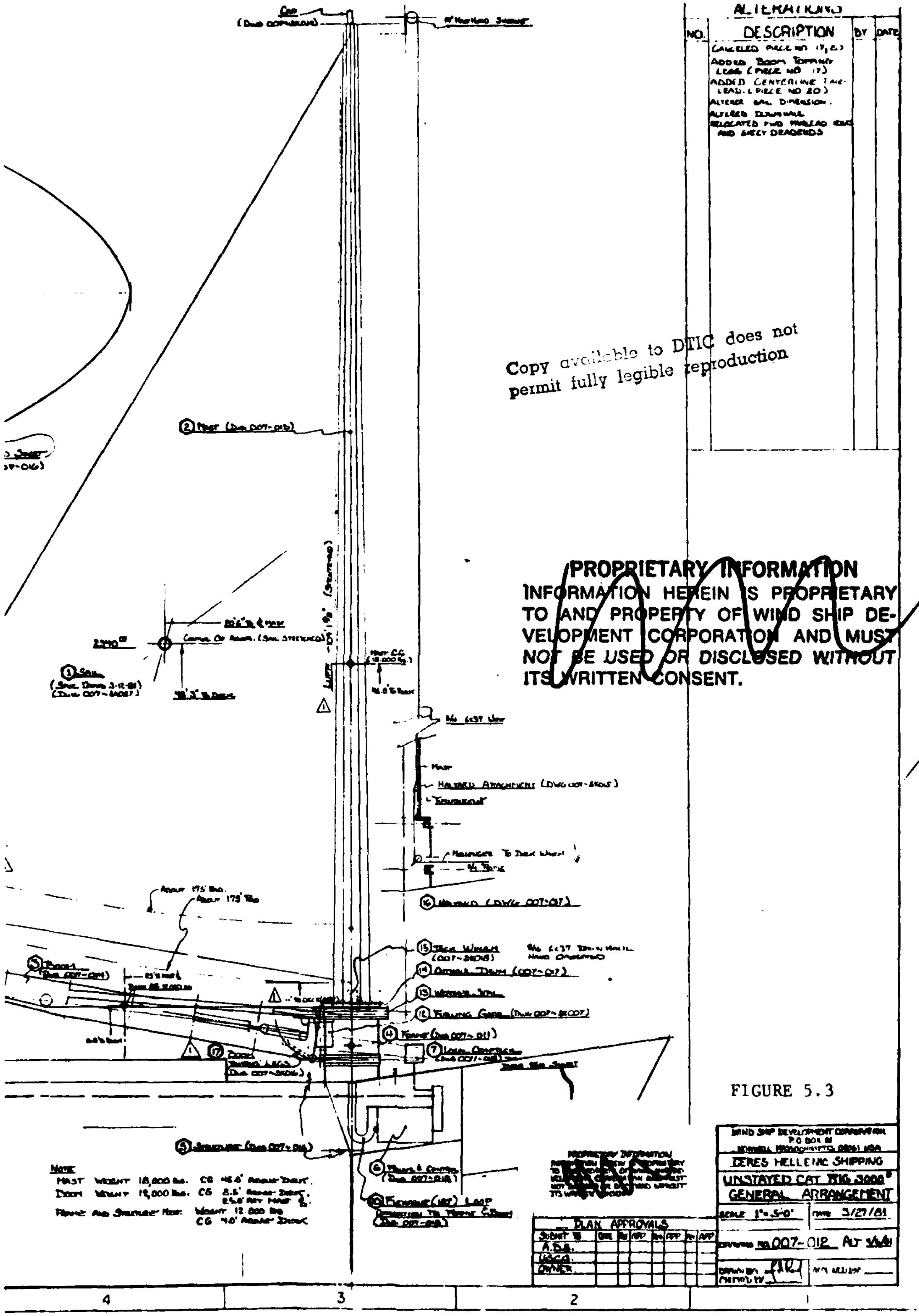

ALTERATIONS
NO.
DESCRIPTION
BY
DATE
CANCELED PIECE NO 17, 20
ADDED BOOM TOPPING LEAD (PIECE NO 17)
ADDED CENTERLINE FAIRLEAD (PIECE NO 20)
ALTERED SAIL DIMENSION.
ALTERED DOWNHAUL
RELOCATED FWD FAIRLEAD ... AND ... DEADENDS
Mast (Dwg 007-016)
Sail
Boom
Note:
MAST WEIGHT 18,000 lbs.
PLAN APPROVALS
A.B.S.
U.S.C.G.
OWNER
WIND SHIP DEVELOPMENT CORPORATION
CERES HELLENIC SHIPPING
UNSTAYED CAT RIG 3000
GENERAL ARRANGEMENT
SCALE 1"=5'-0"
DATE 3/27/81
DRAWING NO 007-012
4
3
2
1

FIGURE 5.3

All rig functions are controlled from the bridge, so that no manual handling of the rigging is required. Wind Ship has applied for patents on the proprietary features of the rig.

The Cat Rig is an attractive alternative to the Wing Sail when the objective of the retrofit is to gain experience at sea with sail-assist operation before pursuing a significant hardware development program. The cat rig hardware has already been developed and tested in service to the point where it could be retrofit to an AGOR-14 or similar size vessel with a minimum of rig redesign. Retrofit with a wing sail would involve more hardware development before the wing could be installed. It may be desirable to gain operating experience at sea with a cat rig before committing to, or in parallel with, design development of the wing sail.

The performance of the cat rig would be less than the performance of the wing (e.g. approximately 90% of the fuel savings). The reduction in performance is due to lower maximum thrust and greater aerodynamic drag compared to the wing sail. The cost of the cat rig would be similar to the cost of a wing sail of equal size. Maintenance cost for the cat rig would be higher due to replacement of the sail every 4 - 5 years. For test operation as described above, a cat rig of the size installed on the MINI LACE (3,000 sq. ft.) could provide about 70% of the performance of the 3,610 sq. ft. wing sail, would cost about $250,000, and would be of adequate size to provide the desired operational experience.

In consideration of obstructed deck space, simplicity of control, and response time when setting or furling, the cat rig would not be as well suited to research vessel operation as the wing sail would be. The boom and sheeting system of the cat rig would take up more space on deck and overhead of the deck. In cases where it may be desirable to put more than one sail unit on a research vessel, the deck and overhead obstruction of the cat rig would be prohibitive.

The amount of time and operator attention required to set or "furl" the rig will be of some importance where the ship may be making stations with short steaming intervals in between. Setting or furling a 3,000 sq. ft. cat rig sail takes about 3 minutes. Trimming the wing sail from zero lift to maximum lift should take less than 20 seconds and engaging the wing clutch should take less than 5 seconds. The three minutes to set the cat rig would not detract significantly from the fuel savings between stations which are an hour or more apart, as most stations are. However, the operator attention required for three minutes of setting or furling a non-automatic cat rig while departing or arriving at a station would be an inconvenience at least, and may discourage use of the rig for short transits.

Because sail trimming requires more control inputs and more complex feedback sensors than wing trim, automated control of the cat rig would be more complex.

C. Flettner Rotor

The Flettner rotor is a circular cylinder set upright above the deck of the ship, supported by an internal mast with bearings, and rotated by an electric or hydraulic motor. The Flettner rotor generates aerodynamic lift (force at a right angle to the wind direction) by means of the Magnus effect.

As shown in figure 5.4a, cylinder rotation causes more air to flow around one side of the cylinder than around the other. This assymetrical flow pattern causes reduced pressure on the side of the rotor which is moving in the same direction as the wind, and increased pressure on the side which is moving towards the wind. The result of this pressure distribution is a component of force perpendicular to the direction of the wind. Rotor lift increases as rotational speed is increased. When the speed at the surface of the rotor is about four times the wind speed, maximum lift is achieved, equal to about five times the maximum lift of a flapped wing of chord length equal to rotor diameter. Alternatively, to produce the same lift as a wing sail, the diameter of a Flettner rotor would be only one-fifth the chord length of the wing.

The rotor also experiences aerodynamic drag similar to that experienced by a non-rotating circular section, plus lift induced drag similar to that induced by other lift generating devices such as a wing or a sail. When the rotor is used for sail-assist propulsion, lift and drag forces act on the vessel in the same manner as lift and drag forces generated by a conventional sailing rig or wing sail (figure 5.4b).

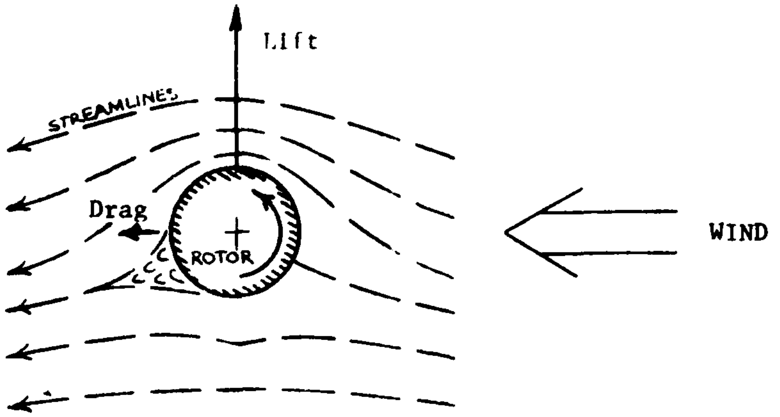
A drive motor is required to turn the rotor against air friction of the rotor surface and mechanical friction in the support bearings. For maximum lift, rotor RPM should be proportional to the wind speed. The maximum rotor RPM (limited by the maximum horsepower of the drive motor) limits high wind performance. However, this limit on performance also limits structural loads, allowing rotor operation at partial load in strong winds without danger of sudden overload due to a gust. Unfortunately, available aerodynamic data on the power required for cylinder rotation is derived from small models and may not be valid for full scale rotors.

The Flettner rotor does not furl or feather, which has caused some concern over the safety of this rig in extreme storm conditions. However, the enhanced performance of this device allows a rotor much smaller than a sail or wing which produces the same thrust. Thus, the storm wind forces on a Flettner rotor may be similar to those on the mast and yards of an equivalent soft sail rig.

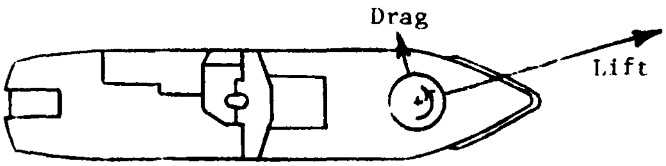
The Flettner rotor is attractive for research vessel applications because of its ease of control and relatively quick response time compared to the wing sail or cloth sail rigs, and because of its small profile which provides minimum restriction of visibility and minimum obstruction of deck space. The rotor has only one control variable (rotor RPM), so that automated control could be very simple. The rotor's position does not change so that the obstruction of visibility and deck space does not change with varying wind directions.

FIGURE 5.4

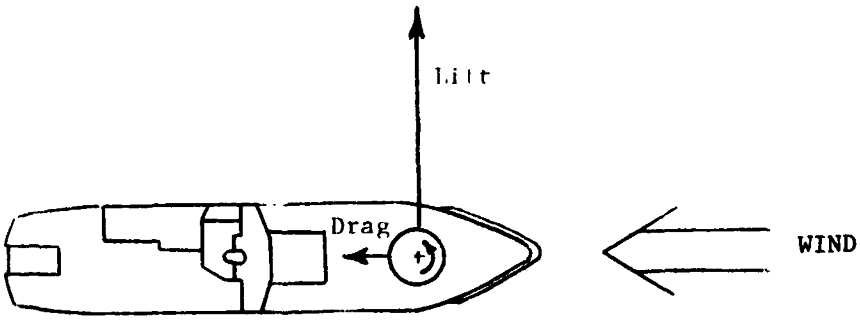
FLETTNER ROTOR



A. Magnus Effect



B. Flettner Rotor
as Sail-Assist Propulsion



C. Flettner Rotor
as Bow Thruster

Although the rotor has the operational advantages mentioned above, it does have more wind resistance when not operating than the minimum resistance of the feathering streamlined wing sail. This windage reduces fuel savings by requiring slightly more main engine power when steaming into headwinds, and produces an increase in windage forces when on station or in storm conditions. The windage of the rotor would be the same as or slightly more than that of a cat rig of equivalent maximum thrust.

Mavor (1) reviewed the potential of the Flettner rotor for oceanographic vessels, and suggested that a forward mounted rotor may be used as bow thruster when the ship is on station and headed into the wind (see figure 5.4c). This application of the rotor would not be necessary on the AGOR-14 which already has excellent station keeping due to her fore and aft cyloidal propellors. However, on conventional screw propelled ships, an 8-foot diameter rotor, 100 foot tall, in a 20 knot head wind, would provide bow thrust similar to that of the AGOR-14's forward cycloid. Thus, a rotor sized for sail-assist propulsion (similar in performance the wing sail shown for AGOR 14 retrofit) would provide ample station keeping ability in head winds.

The rotor would not provide adequate station keeping with wind near the beam. However, present practice is to make most oceanographic stations with the ship head to wind or a few degrees away from head to wind. Of course, the rotor would not provide station keeping in calms or very light wind.

The rotor would have an advantage over conventional bow thrusters in that available thrust would increase as wind speed increased, and that available thrust would not decrease if the ship were making headway. Thus, station keeping ability would, to some extent, increase as station keeping requirements increase. The rotor would have a disadvantage in that response time (time required to reverse rotation of the rotor to reverse thrust) might be somewhat longer than that of a bow thruster or cycloid.

The wing sail could provide similar bow thrust as the rotor, with less attendant windage drag, but would have slower response.

Some indication of the initial cost of a Flettner rotor may be taken by comparison with the wing sail and its cost estimate. The foundation and bearing requirements should be similar for both structures and so roughly the same price. The diameter of the rotor (8') is slightly larger than the thickness of wing available for the main spar structure, so that the cost of the rotor and support mast should not be greater than the cost of the wing spar and fixed mast. The rotor has no additional skin or framework.

Most of the uncertainty in this rough comparison lies in the drive system for the rotor, but this might cost about the same as the total wing and flap drives. The controls for the rotor should cost about half of the controls cost for the wing. In addition to fewer control variables, slip rings are not required to transmit control signals to the rotating parts.

The resulting rough cost estimate is tabulated below. From the table it is clear that the Flettner rotor has significant potential for cost effective performance.

FLETTNER ROTOR ROUGH COST ESTIMATE (± 50%!!)

GROUP	COST (1982 $)	% COST
Foundation	50,000	25
Mast and Rotor	44,000	22
Power and Drive	70,000	35
Controls	6,000	3
Procurement and Supervision of Installation	30,000	15
Total	200,000	

A Flettner rotor system design study with preliminary detailing of system components, fabrication and installation requirements could provide more accurate weight and cost estimates. This study should also include a more thorough literature search on drive power requirements, and aerodynamic testing if sufficient data is not found. The rotor design study is justified in light of the indicated performance potential.

D. Wind Turbines for Auxiliary Power Generation

Because research vessels spend a significant portion of their time on station and have relatively large auxiliary power requirements, the fuel which may be saved by reducing propulsion requirements is generally less than half of the total fuel consumption. Therefore, one might consider the possibility of wind assisted auxiliary power generation. However, the present study is concerned with wind assisted propulsion (sail-assist) and not with stationary wind power conversion. The generation of auxiliary power through the use of horizontal or vertical axis wind turbines is outside of the scope of the present study, but a few comments may be made on this topic.

If a wind turbine were sized to save the same amount of fuel as saved by the wing sail presented in this study, and assuming that the turbine would be operating all of the time the ship is at sea (in transit, towing, and on station) to generate auxiliary power, the turbine would have a diameter approximately equal to the span of the wing sail (95 ft.) and a projected area of about 7,000 sq. ft. (about twice the area of the wing). Thus, even with less than half of the at sea time as transit time, sail-assisted propulsion is a more effective means of wind energy extraction than continuous wind turbine power generation on a size for size basis.

The relative cost and reliability of the wind turbine will not be considered here, but could be approximated by examining land based wind turbine technology and the hardware and operational requirements for shipboard applications. The development of wind turbines for shipboard auxiliary power does not seem as promising as development of sail-assist technology except where the ship (or other sea-going platform) spends nearly all of its time on station. If the subject were to be pursued, it should be considered in terms of present land based wind turbine technology, and additional requirements for marine service.

E. Summary

A 3000 square foot cloth sail "cat-rig" prototype is operating successfully in continuous commercial service. As an alternative to the wing sail, the cat rig offers a short lead time and minimum development expense to implement a retrofit installation and begin gaining operating experience with a sail-assist oceanographic research vessel. However, in the long term the cat rig is less attractive than the wing sail for oceanographic operations because it occupies more deck space and has slower response time when setting and furling.

Other cloth sail rigs can be considered as discussed in reference (20). Of the cloth sail rigs, the cat rig minimizes operational disadvantages.

For oceanographic operations the Flettner rotor has several advantages over the wing sail and cat rig. The rotor occupies the least deck space, restricts the least visibility, and is the most amenable to automated control. The Flettner rotor also may have economic advantages, but these are uncertain because rotor design has not been developed to the extent of present wing sail and cat rig technology. A Flettner rotor design study is recommended to provide a basis for cost estimates and to expose practical design considerations.

Wind turbines for auxiliary power generation are not as promising as sail-assist for propulsion, except where a ship or other ocean-going platform spends nearly all of its time on station.

In order of economic and operational potential for the AGOR mission, the hardware alternatives are ranked Flettner rotor first, wing sail second and cat rig third. Based on the status of present development, the ranking is reversed. In view of this difference, it is recommended that a design study of the Flettner rotor be undertaken to bring rotor design to a level sufficient for economic and operational comparison with present wing sail designs.

VI - NEW SAIL-ASSIST RESEARCH VESSELS

VI - NEW SAIL-ASSIST RESEARCH VESSELS

A. Introduction

In chapter IV, practical consideration of the wing sail retrofit reveals several difficulties which are related to the characteristics of the AGOR-14 class, but are not inherent in the concept of sail-assist. In addition, many of the ship design variables which are predetermined in the case of a retrofit may be adjusted to utilize the full potential of sail-assist in a new vessel design.

In this chapter, new vessel characteristics are suggested to avoid the stability and visibility problems of the AGOR-14 retrofit. Engine size, deck arrangement and hull characteristics to make better advantage of sail-assist are presented and discussed. A conventional research vessel, somewhat smaller than the AGOR-14, is presented as an example which incorporates many characteristics which are desirable for a sail-assist vessel.

B. Stability

As noted in chapter IV, the sail power unit raises the center of gravity of the ship and decreases stability. The stability decrease is roughly equivalent to the free surface effect caused by passive roll stabilization tanks which are included in many vessel designs. Therefore, the stability allowance required in the design of a sail-assist vessel can be achieved through minor design allowances such as slight increase in beam or addition of ballast.

C. Visibility

The AGOR-14 retrofit suffered from impaired visibility from the pilot house. The solution suggested in chapter IV for the retrofit is to raise the base of the wing to above the level of the pilot house. Because the AGOR-14 pilot house is quite far above the water, this solution places the wing farther above deck than would otherwise be necessary, and limits the wing span to less than the optimum.

In a new vessel design more space can be made available for the wing sail by lowering the pilot house deck one deck level. This feature would also reduce the windage of the superstructure and lower its center of gravity.

D. Engine Size

In the AGOR-14 retrofit examined in detail in this study, fuel savings are the only savings available to recoup the cost of the retrofit wing-sail. In new sail-assist design and construction, the main engine may be smaller than that required by a motor vessel to achieve the same average service speed. Engine size reduction provides another means to offset the cost of the sail-assist hardware. However, engine size reduction is not possible if some criterion other than average transit speed determines the main propulsion requirements.

Where engine size reduction is possible, the net cost of sail-assist is less than for the retrofit analyzed in this study. The trade off between rig initial cost and fuel savings benefit will not lead to the same rig as selected in the retrofit analysis. Because the initial cost has effectively been reduced, the rig optimization will lead to larger sail area and possibly a higher rig design wind speed. Thus, an optimized vessel designed and built for sail-assist would take greater advantage of wind propulsion than an optimized retrofit sail-assist vessel, not only through engine size reduction, but also through deriving a larger part of its propulsion requirements from the wind than is derived by the retrofit vessel.

E. Deck Arrangements

The single wing retrofit optimized for the R/V KNORR is very close to the maximum dimensions within the limits defined by most height and tail swing limitations. It may be possible to increase the area of a single wing to 4,000 square feet in the design of a new sail-assist vessel of AGOR-14 size by reducing the superstructure height in way of the wing and increasing the span.

Multiple wing sails for greater sail area require design reconsiderations which are avoided by the single wing rig. Two wing sails could be arranged with one forward as shown for the AGOR-14 retrofit, and one aft of the pilot house. The pilot house would have to be further forward than on the AGOR-14 to allow space for the aft wing without excessive loss of working deck space. The aft wing would have deck clearance sufficient to allow trailers as temporary labs underneath the tail swing. Cranes would have to be located outside of the tail swing, but hydrographic trawl or instrument winches could be accommodated in this area.

The view of working deck space from the pilot house is a valuable feature of the AGOR-14 class ships, which allows coordination of ship operations in support of oceanographic activities. This view would not be occluded by the aft wing sail, but would be diminished by the pilot house location further forward.

The benefits of increased sail-assist would have to outweigh the reduced working versatility of the space about the aft wing in order to justify the use of two wing sails. Because Flettner rotors have less impact on deck arrangement (see "Hardware Alternatives"), rotors are better suited to multiple installations.

F. Helm Balance

The location of additional sail power units may cause steering problems due to sideforce acting aft of the center of lateral resistance. The following factors may be used to avoid these steering problems in the design of new sail assist vessels.

Inspection of ship model manuevering test data indicates that the effective "center of lateral resistance" (CLR) is not a fixed point on the hull underbody. This center actually shifts position depending upon the relative magnitude of the sideforce applied to the hull. For light sideforce, such as is applied by a single wing sail or the side thrust of the forward cycloid on the AGOR-14, the CLR is near the forward perpendicular (or in some cases forward of the bow). As the sideforce is increased the CLR moves aft, towards the lateral center of the underbody profile.

The movement of the CLR should reduce the discrepancy between CLR and the center of the rig sideforce when more sail is added. However, this effect is not likely to result in a perfectly balanced helm. In most cases the CLR will not be as far aft as the rig center. For any given ship the CLR will vary as the rig sideforce varies due to varying wind conditions. A sail-assist ship with conventional screw propulsion may require increased rudder area to overcome the turning moments due to shifting position of CLR.

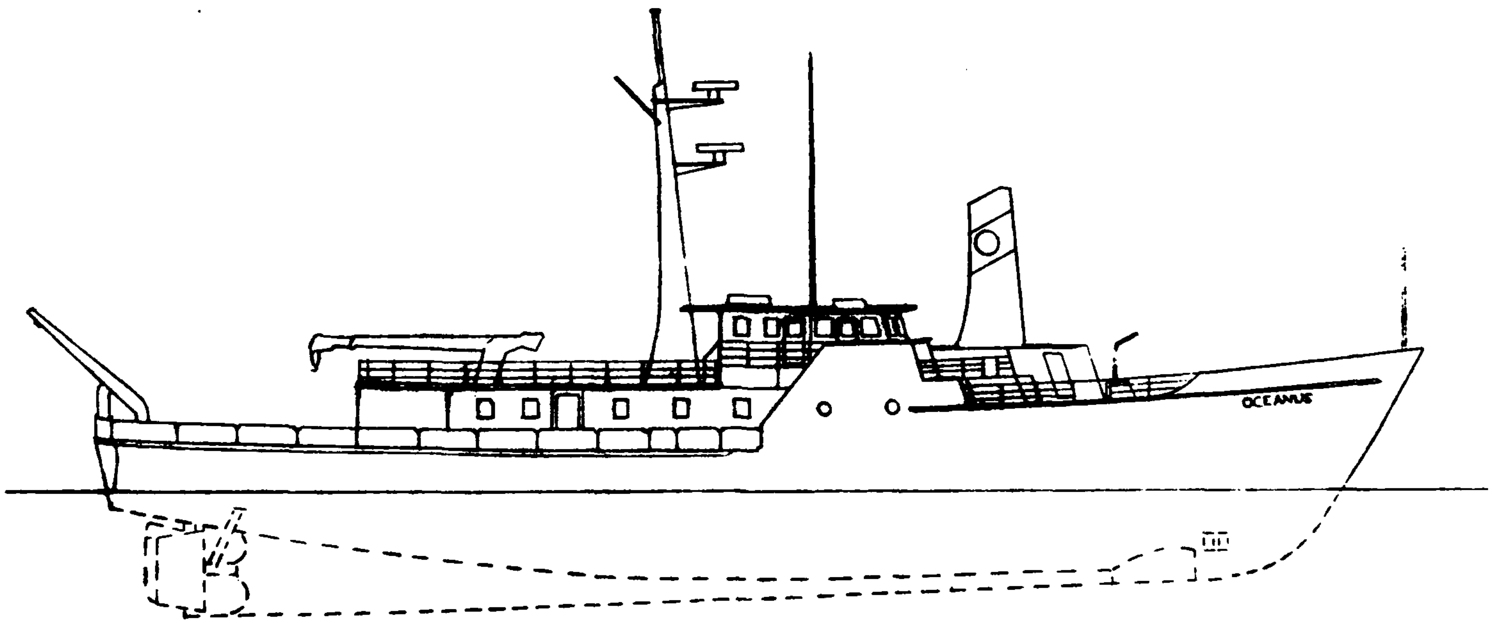
The underbody shape can be designed such that the CLR range is further aft by introducing "drag" to the keel as is typical of the fishing trawler hull form. The R/V OCEANUS (figure 6.1) and her sister ship (R/V WECOMA, R/V ENDEAVOR) are examples of a successful research vessel design with this feature.

FIGURE 6.1

R/V OCEANUS OUTBOARD PROFILE

LOA	177'0"
LBP	157'8"
Depth of Hull	15'0"
Draft (fore)	12'6"
Draft (aft)	17'6"

Displacement	1150 LT
Light Ship	590 LT
Scientific Outfit	100 LT
Crew,Stores,Fuel,etc.	205 LT
Ballast	255 LT



Approx. Scale 1:300

G. Smaller Research Vessels

Sail power unit cost and weight per square foot increase with sail area because structural moments which are the dominant design loads increase faster than sail area. On the other hand, conventional propulsion systems cost per horsepower and specific fuel consumption decrease as engine size increases. Because of these scaling effects, the economics of sail assist are more favorable in smaller vessels. In addition to consideration of helm balance and of scaling effects of the slight decrease in size, operational efficiency and general arrangement may be more compelling reasons to consider a design similar to the OCEANUS for sail-assist retrofit or new building.

In the present economic environment, the moderate sized vessels often perform their research mission more cost effectively than the larger AGOR ships. In planning for new building of a multi-purpose research vessel, it would be prudent to give the smaller vessel complete consideration before deciding that a larger vessel is necessary to meet the required oceanographic capabilities. Increased endurance, enhanced station keeping ability, and quiet ship capabilities of sail-assist could combine with the operational and economic advantages already inherent in the smaller design to provide oceanographic capabilities of the larger AGOR-14 class and acoustic capability which is presently available only with special purpose vessels. Of course, the capacity (in terms of number of scientists or tons of payload) would be less than that of the larger vessels, yet the potential exists for improved capabilities and lower operating cost per capacity.

The arrangement of the OCEANUS has proven to be versatile and efficient, and would be compatible with sail power units. The deck layout could accommodate wing sails or Flettner rotors fore and aft. The pilot house deck is low enough so that the base of the wings could be above the operators' eye level, allowing unobstructed view of the horizon and the decks. Flettner rotors could be similarly elevated, but might extend down to deck level without undue obstruction of visibility. The existing mast and stacks might be modified and/or relocated and the pilot house might be extended to the maximum beam to improve visibility.

H. Summary

New sail-assist vessel design offers several opportunities to improve upon the benefits of retrofit. Stability and visibility problems are easily avoided in new vessel design. The initial cost of the sailing rig may be partially offset by engine size reduction. For new vessels, the increased benefit of sail propulsion may lead to sail plans more extensive than the single wing retrofit selected for the AGOR-14 class. The flexibility of new vessel design allows configuration of deck arrangement and hull characteristics to suit both oceanographic operations and sail plan requirements.

The OCEANUS is a successful conventional research vessel with many of the characteristics suggested for a new sail-assist vessel. The operational and economic success of the OCEANUS is reflected by the subsequent construction of two sister ships, and indicates that many of the desirable characteristics for sail-assist are mutually desirable for oceanographic operations.

The OCEANUS represents a type of vessel which will continue to play a major role in oceanographic research, particularly in the present and foreseeable future economic environment. Plans for new building of this type of vessel should consider the potential benefits of sail-assist.

VII - OTHER NAVAL MISSIONS

A. Introduction

The preceding analysis and discussions have been limited to sail-assist retrofits for or new buildings of vessels for multipurpose oceanographic research, the mission of the AGOR class. This chapter will discuss some possible applications for other U. S. Navy auxiliary missions - T-AO Military Sealift Command (MSC) and AGOS Ocean Surveillance. MSC tankers and other supply ships have deck plans and operating procedures which are compatible with sail-assist, and spend a large portion of time in transit. Silent operation at towing speed is essential to the AGOS surveillance mission.

The sensitivity of fuel savings to transit time is presented and discussed with respect to the T-AO supply and transport mission, oceanographic missions, and ocean survey missions. Characteristics and operation of existing MSC tankers are discussed with respect to sail-assist retrofit or new building. Unassisted sail propulsion for silent towing is considered and developments necessary to meet control requirements for towing large acoustic arrays are identified.

B. Sensitivity of annual fuel savings to time in transit:

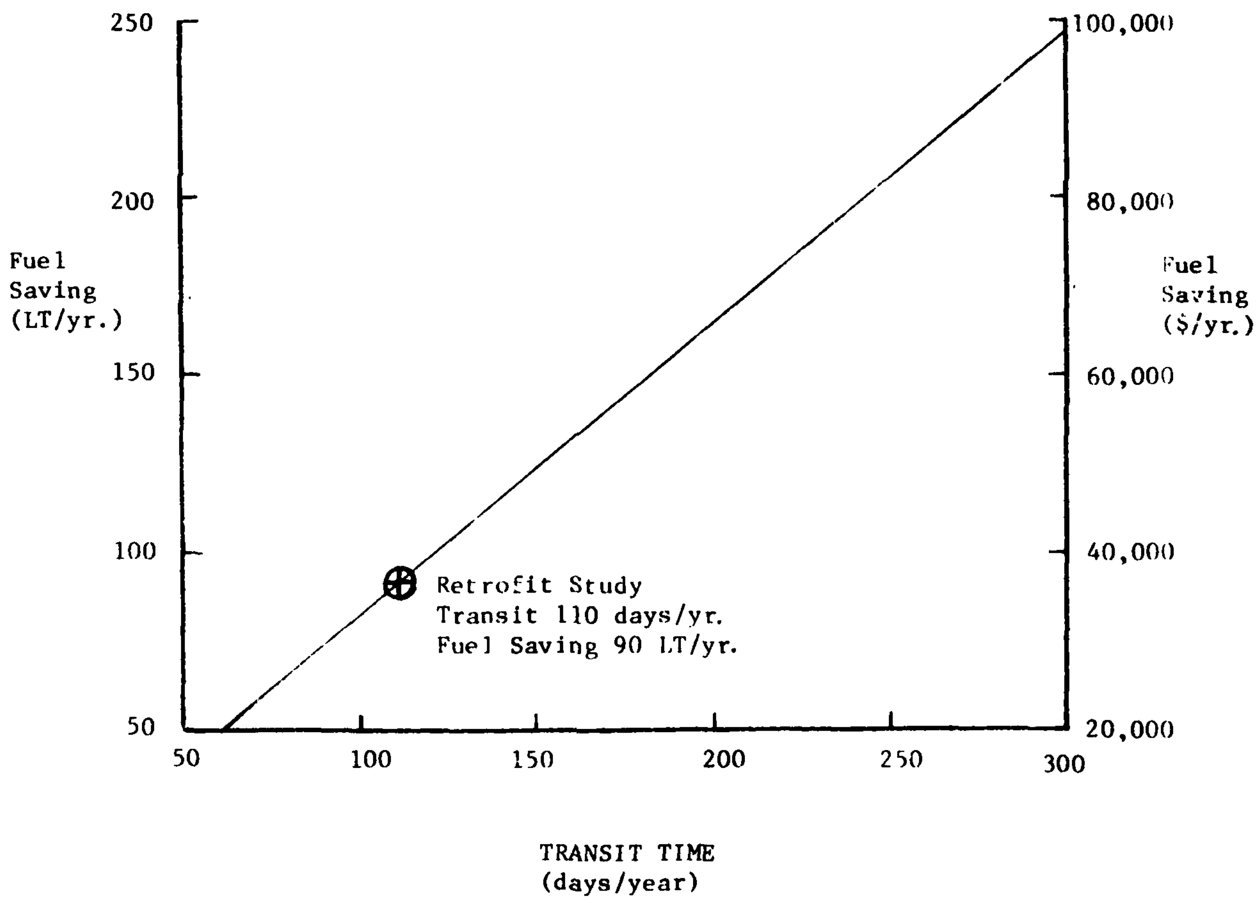
According to the assumptions made for the retrofit analysis, the retrofit provides fuel savings only while the ship is transiting. The results of the analysis indicate that the wing sail retrofit saves .82 LT of fuel each day of transit time. With the assumed ship schedule (transit 110 days/year) and fuel price ($1.25/gallon, $400/LT) the AGOR-14 retrofit saves 90 LT per year, or $36,000 worth of fuel. Figure 7.1 is a graph of annual fuel savings in LT and 1982 dollars per year for other schedules with 50 to 300 transit days per year assuming the same daily fuel savings and fuel price.

This graph indicates the fuel savings which would accrue to a retrofitted AGOR-14 class vessel operating in the same wind conditions as used in the analysis but spending more time in transit. If ship operations include more days in transit, fuel savings increase. For the purpose of operations analysis, the AGOR-14 class mission was interpreted in terms of vessel utilization at WHOI. The same mission may result in different operating statistics when interpreted in terms of the operations of other institutions. Vessels which pursue other oceanographic missions would also show varying operating statistics.

FIGURE 7.1

FUEL SAVINGS VERSUS TRANSIT TIME
R/V KNORR
SAIL-ASSIST RETROFIT

ASSUMPTIONS:
Fuel Price $1.25/gal. ($400/LT)
Fuel Saving .82 LT/transit day
Based upon performance prediction for
R/V KNORR with 3610 sq. ft. wing sail.



C. MSC Sealift Class Tankers

Tankers of the SEALIFT Class (e.g. SEALIFT PACIFIC, 25,000 DWT) are operated by the Military Sealift Command to transport petroleum products in support of Navy and Department of Defense operations. The mission is similar to commercial tanker operations which would have 200 to 250 transit days per year. Plans of the SEALIFT PACIFIC (21) show several characteristics which increase compatibility with sail-assist and/or potential fuel savings. Most of the deck has no superstructure, leaving ample space for sail power units.

Machinery characteristics of the SEALIFT Class Tankers are nearly ideal for sail-assist retrofit. Twin medium-speed Diesel engines drive a single shaft and controllable pitch propeller. When sufficient power is derived from the wind, the power plant could be operated efficiently at half power or less with one engine shut down. The controllable pitch propeller allows proper engine loading over the range of speed and power levels which might occur during sail-assisted operations.

The bow thruster reduces port turn around time, thereby reducing the time when sail power units would be idle. Also, any increase in windage due to the sail units should be easily compensated by the bow thruster.

A study similar to chapters II, III and IV of this report would determine typical operating and wind statistics, optimum sail rig, bottom line fuel savings, preliminary design and practical considerations of a retrofit for a SEALIFT Class Tanker. These results would present the potential of retrofit not only for the MSC tanker mission, but also for similar auxiliary supply missions.

D. AGOS Ocean Surveillance Ships

AGOS ships conduct ocean surveillance with towed arrays of sonar equipment. The AGOS mission definition (22) states:

> "Water borne acoustic noise is to be minimized to the maximum extent possible."
> "Both airborne and waterborne noise levels should be kept to a minimum."

This instruction also notes that with a diesel engine, cylinder firing frequency and harmonics thereof are within the acoustic range utilized by sonar.

Present practice in AGOS ship design has a diesel generator plant driving an electric motor for propulsion. This arrangement has been adopted to isolate engine and generator noise from the hull structure and propeller. Isolation of the diesel engine does remove one major component of waterborne noise, but propeller generated noise is still radiated directly into the water. The engine also creates airborne noise which may be indirectly carried to the water via hull structures. Although the mission definition calls for maximum possible reduction of waterborne noise, the acceptable noise levels specified in the instruction are based upon those which are achievable with diesel-electric propulsion.

Sail propulsion introduces the possibility of eliminating propeller generated noise and significantly reducing airborne engine noise by eliminating most of the generator output requirements. However, towing acoustic arrays with pure sail propulsion also introduces design and control considerations which are not required for sail-assisted propulsion. Constant position and orientation of the array with respect to the towing vessel are essential to sonar surveillance operations. Constant orientation requires that the towing vessel maintain constant speed, and that the tow point be steady in all degrees of freedom.

When towing with sail as the only source of propulsion, speed must be controlled by controlling the thrust generated by the sailing rig. Sail power units (sails, wings or rotors) generate not only forward thrust but side thrust as well. At slow towing speeds, rig side force will cause the ship to make significant leeway. If this leeway is not controlled and steady, constant orientation of the array will not be maintained. It is not always possible to control both forward and side thrust independently because only certain combinations of aerodynamic lift and drag forces may be generated by the rig.

To reduce leeway under pure sail at low speed and to control leeway as sideforce varies, one or more movable centerboards or daggerboards should be added as control surfaces. As a part of the sail power system, these control surfaces not only allow independent control of forward and side thrust, but also improve propulsive performance by increasing the efficiency of the hull in resisting leeway and leeway induced drag.

With two control surfaces similar to large rudders placed one forward and one aft, and two sail power units one forward and one aft, controlled constant speed towing can be achieved without leeway. Operation of these sail power units and control surfaces requires an automated control system designed to maintain constant speed and zero leeway.

The control surfaces and control system required for sail towing are relatively simple hardware and software technology when compared to sophisticated ship systems such as hydrofoil vessels. The development of this hardware would require little expense compared to development of the hydrofoil, and could borrow extensively from active stabilization control surface and hydrofoil technologies which have already been developed.

In this application sail propulsion is intended to provide superior mission performance as opposed to reduced cost with equivalent performance. The control surfaces incre se the construction cost of the sail system. However, the operating cost is reduced because the rig will meet the full propulsion requirement most of the time while towing. Diesel-engine screw propulsion would be used with sail-assist in transit and for the surveillance mission in light winds or calms.

According to the mission requirements the desired operating statistics for AGOS ships are:

Towing (0-3 knots)	306-312 days/year
Transit (10-11 knots)	17-23 days/year
Port & Maintenance	36 days/year

Although the primary reason for this application is not fuel savings, it is evident that there is great potential for savings. The reduced operating costs may balance the increased initial cost to provide superior mission performance with equal or reduced life cycle costs.

E. Summary

The mission variable which has the greatest impact on the economics of sail-assist is time in transit. The AGOR-14 mission as implemented by WHOI is at the lower end of the scale of transit time, with 110 days per year of transit. Other missions may require up to 330 days under way per year, which would triple the per annum fuel savings predicted for the R/V KNORR.

The MSC operated SEALIFT class tankers spend 200 to 250 days per year steaming, and have machinery and arrangement characteristics which are nearly ideal for sail-assist. A SEALIFT class tanker retrofit analysis is recommended.

For AGOS surveillance ships, acceptable noise levels are presently dictated by those achievable with Diesel-electric screw propulsion. Sail propulsion offers a degree of silent operation which is unattainable with screw propulsion. Towing with pure sail propulsion at low speed requires specialized control surfaces and an automated control system which are primarily an application of existing hardware and software technologies but require development as would any new application.

VIII - SUMMARY

VIII - SUMMARY

A. Introduction

Mission requirements, fuel economy, net savings, design characteristics and initial cost of a retrofit conversion of an AGOR-14 Class ship to a wing sail assisted ship are analyzed. Sail rig hardware alternatives to the wing sail are reviewed but not analyzed in detail. Review and recommendations are given concerning new sail-assist vessel characteristics for the AGOR mission and other naval missions which may benefit from sail propulsion.

B. Operational Analysis

Flexibility is the most important operational consideration in multi-purpose research vessel design. A large, clear fantail deck with a grid of bolt down fixtures provides deck equipment flexibility. With sufficient space on the superstructure decks aft and on the forecastle deck, truck trailers or standard shipping containers can be used as interchangeable laboratory units. A retrofit wing sail on the forecastle deck with deck clearance for truck trailers does not interfere with research operations, provides proper helm balance, and may take advantage of existing structural arrangement. Visibility of the horizon is partially occluded by the wing sail unless the lower edge of the wing is above pilot house eye level.

Six voyage scenarios represent typical scheduling of the AGOR-14 class R/V KNORR, as operated by WHOI. Operating statistics for these scenarios indicate that the vessel spends 25% of her time in maintenance, 14% in port, 27% on station, 4% towing, and 30% in transit. Wind statistics indicate that present research cruise planning leads to wind direction distributions which are favorable to sail propulsion.

C. Operational Benefits

For the purpose of retrofit economic analysis, the only benefit of sail-assist is assumed to be fuel saving while transiting. However, wind propulsion may provide operational benefits of ship motion reduction, quiet ship propulsion and station keeping ability in addition to fuel economy for oceanographic research vessels. Fuel economy may also result in the additional operational benefit of reduced bunkering port calls and therefore more time at sea for mission operations and greater flexibility in voyage planning.

For quiet ship operations, a sail-assist vessel can shut down main engine and proceed down wind or across the wind propelled by sail alone. For a sail-assist vessel without an enlarged rudder and neither a centerboard nor a deep keel, pure sail towing operations are limited to a downwind course.

A forward mounted sail power unit (wing sail or Flettner rotor) may be used as bow thruster when the ship is on station. A rig which is modest in terms of sail-assist propulsion will provide ample ability to keep the ship head to wind or at some desired position near head to wind. The sail power unit would not provide adequate station keeping with wind near the beam. Present oceanographic practice is to make most stations with the ship head to wind or a few degrees away from head to wind.

The sail power unit has distinct advantage over conventional thrusters in that available sail thrust increases as wind speed increases and available thrust does not decrease when the ship is making headway. Thus, station keeping ability increases as station keeping requirements increase. Of course, the unit would not provide station keeping in calms or very light wind.

The sail power unit has a disadvantage in that response time (time required to change the orientation of the wing or the rotation of the rotor) is somewhat longer than the response time of a conventional bow thruster or cycloid. The Flettner rotor has a faster response than the wing sail.

A sail power unit will provide some aerodynamic damping of ship roll motions. However, sail propulsion will also cause an offset of equilibrium heel angle while underway. Whether or not the reduced motions improve shipboard habitability and working efficiency more than the heel angle degrades these qualities remains to be observed in practice.

Experience with the commercial sail-assist vessel MINI LACE indicates that sail-assist may improve a ship's ability to maintain schedule. Sail-assist provides the greatest propulsive boost in strong winds when high seas slow most motor vessels. As long as the wind is not directly ahead and does not exceed the rig design speed, sail-assist provides the extra power required to maintain service speed in heavy seas.

D. Retrofit Analysis

Analysis of fuel economy and operating cost savings for a systematic variation of wing sail retrofits to the R/V KNORR leads to selection of optimum retrofit wing parameters:

Sail Area	3610 sq. ft.
Design Wind Speed	40 knots
Mast Height (above L.W.L.)	131 ft.
Span	95 ft.
Chord	38 ft.

The selected wing saves 90 long tons of fuel per year, worth $36,000 at 1982 fuel prices. The estimated cost of the wing-sail retrofit is $300,000 including installation but not including design and engineering.

The AGOR-14 class R/V KNORR is not suitable for sail-assist retrofit because the ship as is does not meet conventional stability criteria. However, the stability requirements for sail-assist retrofit are not large and should not present serious difficulties on most vessels. Except for inadequate stability, the AGOR-14 does appear to be an excellent opportunity for sail-assist retrofit of an oceanographic vessel, and would achieve fuel savings with no detriment and possible benefit to oceanographic operations. In light of the potential advantages to be gained by retrofit, consideration of sail-assist for other research vessels is recommended.

E. New Vessels

New sail-assist vessel design offers several opportunities to improve upon the benefits of retrofit. Stability and visibility problems are easily avoided in new vessel design. The initial cost of the sailing rig may be partially offset by engine size reduction. For new vessels, the increased benefit of sail propulsion may lead to sail plans more extensive than the single wing retrofit selected for the AGOR-14 class. The flexibility of new vessel design allows configuration of deck arrangement and hull characteristics to suit both oceanographic operations and sail.

The OCEANUS is a successful conventional research vessel with many of the characteristics suggested for a new sail-assist vessel. The operational and economic success of the OCEANUS is reflected by the subsequent construction of two sister ships, and indicates that many of the desirable characteristics for sail-assist are mutually desirable for oceanographic operations.

The OCEANUS represents a type of vessel which will continue to play a major role in oceanographic research, particularly in the present and foreseeable future economic environment. Plans for new building of this type of vessel should consider the potential benefits of sail-assist.

F. Hardware Alternatives

A 3000 square foot cloth sail "cat-rig" prototype is operating successfully in continuous commercial service. As an alternative to the wing sail, the cat rig offers a short lead time and minimum development expense to implement a retrofit installation and begin gaining operating experience with a sail-assist oceanographic research vessel. However, in the long term the cat rig is less attractive than the wing sail for oceanographic operations because it occupies more deck space and has slower response time when setting and furling.

Other cloth sail rigs can be considered as discussed in chapter 2 of reference (2). Of the cloth sail rigs, the cat rig minimizes operational disadvantages.

For oceanographic operations the Flettner rotor has several advantages over the wing sail and cat rig. The rotor occupies the least deck space, restricts the least visibility, and is the most amenable to automated control. The Flettner rotor also may have economic advantages, but these are uncertain because rotor design has not been developed to the extent of present wing sail and cat rig technology. A Flettner rotor design study is recommended to provide a basis for cost estimates and to expose practical design considerations.

Wind turbines for auxiliary power generation are not as promising as sail-assist for propulsion, except where a ship or other ocean-going platform spends nearly all of its time on station.

G. Other Missions

The mission variable which has the greatest impact on the economics of sail-assist is time in transit. The AGOR-14 mission as implemented by WHOI is at the lower end of the scale of transit time, with 110 days per year of transit. Other missions may require up to 330 days under way per year, which would triple the per annum fuel savings predicted for the R/V KNORR.

The MSC operated SEALIFT class tankers spend 200 to 250 days per year steaming, and have machinery and arrangement characteristics which are nearly ideal for sail-assist. A SEALIFT class tanker retrofit analysis is recommended.

For AGOS surveillance ships, acceptable noise levels are presently dictated by those achievable with Diesel-electric screw propulsion. Sail propulsion offers a degree of silent operation which is unattainable with screw propulsion. Towing with pure sail propulsion at low speed requires specialized control surfaces and an automated control system which are primarily an application of existing hardware and software technologies but require development as would any new application.

IX - RECOMMENDATIONS

A. Introduction

Recommendations for further research and development are summarized below. The recommendations are divided into three groups according to mission application:

- oceanographic research vessels
- military sealift command (MSC)
- ocean surveillance vessels (AGOS)

Within the oceanographic mission group, recommendations are presented in suggested chronological order, which is also the order of perceived priority. No attempt is made to assign relative priorities to the three mission groups.

B. Oceanographic Research Vessel Applications

In order of economic and operational potential for the AGOR mission, the hardware alternatives are ranked Flettner rotor first, wing sail second, and cat rig third. Based on the status of present development, the order is reversed. Therefore, the first priority for research vessel applications is to bring a Flettner rotor design to a level sufficient for economic and operational comparison with the wing sail.

Existing vessels and proposed new buildings should consider examining the potential advantages of sail-assist for both fuel economy and oceanographic operations. Sail assist can be evaluated following the voyage scenario analysis, parametric study and conceptual design procedures presented in this report. Flettner rotor or wing sail hardware alternatives may be considered, the choice depending upon the results of the suggested first priority rotor design study. If there is a compelling reason for applications in the very near term, or for use of a cloth sail rig, the cat rig or conventional yacht type rigs may be considered.

The R/V OCEANUS is an example of an existing type of oceanographic vessel which is sensible for new building, is well suited to sail-assist either as a retrofit or a new building, and may gain significant advantage from sail-assisted oceanographic operations. In addition to vessel characteristics, scheduled time in transit should be considered in anticipating the economic bottom line of a sail-assist study.

Any investigations which lead to plans for sail-assist retrofit or new building will require development of sail-assist hardware technology for the application.

The Flettner rotor is an inherently simple mechanical mechanism which was demonstrated in marine service more than 50 years ago.[23] The rotor control system involves only one control variable - rotor RPM. Rotor hardware development should require primarily conventional mechanical and marine engineering design.

The greatest barrier to rotor development is lack of aerodynamic data for the Magnus effect in full scale flow regimes. Because the Magnus effect depends upon viscous boundary layer flow, viscous scale effects may produce significant differences between model tests and full scale rotor behavior. Wind tunnel or other aerodynamic testing in a range of flow regimes from typical model scale to as close to full scale as possible is recommended to determine scale effects on lift, drag, and torque coefficients. Valid torque data is particularly scarce for the Flettner rotor, although this data is required to determine drive system power requirements and to size the drive motor.

The wing sail requires drive and control system development to be suitable for application to a modern research vessel. Feather behavior must be incorporated into wing sail design using aerolastic analysis techniques and should be verified with prototype hardware. A 300 square foot (approx. 1/10 full scale area) wing sail prototype operated on land would be of sufficient size to provide the real world effects necessary to breadboard automatic control system and to test feathering behavior and aeroelastic analysis. The wing would be small enough to be transportable on a flat bed trailer truck, which would allow testing at various suitably windy and gusty locations.

It is not expected that the oceanographic applications should bear the entire burden of sail-assist hardware development. However, the oceanographic ship community should play a part in the development of sail-assist hardware. If this development activity is coordinated with that of other sail propulsion applications, hardware development will not lag unnecessarily far behind investigation of the potential of sail-assist for research vessel operations.

C. Military Sealift Command

A study similar to chapters II, III and IV of this report is recommended to determine typical operating and wind statistics, optimum sail rig, bottom line fuel savings, preliminary design and practical considerations of a retrofit for a SEALIFT Class Tankers operated by MSC. The results would indicate the potential of retrofit not only for the MSC tanker mission, but also for similar auxiliary supply missions.

Machinery characteristics of the SEALIFT Class Tankers are nearly ideal for sail-assist retrofit. Twin medium-speed Diesel engines drive a single shaft and controllable pitch propeller. When sufficient power is derived from the wind, the power plant could be operated efficiently at half power or less with one engine shut down. The controllable pitch propeller allows proper engine loading over the range of speed and power levels which might occur driving sail-assisted operations.

The bow thruster reduces port turn around time, thereby reducing the time when sail power units would be idle. Also, any increase in windage due to the sail units should be easily compensated by the bow thruster.

D. Ocean Surveillance Vessels

The maximum possible reduction of waterborne and airborne noise is essential to the AGOS mission of ocean surveillance with towed sonar arrays. With Diesel-engine screw propulsion, propeller generated noise is radiated directly into the water, and the engine radiates airborne noise which may also be transmitted to the water. Both propeller and engine generate noise within the frequency range utilized by sonar. Accepted noise levels are presently dictated by those achievable with Diesel-electric screw propulsion.

Sail propulsion introduces the possibility of eliminating propeller generated noise and significantly reducing airborne engine noise by eliminating most of the generator output requirements. In this application sail propulsion is intended to provide superior mission performance as opposed to reduced cost with equivalent performance. The wing sail is the appropriate hardware alternative for this application because its superior aerodynamic performance provides the greatest operational capability in terms of course headings.

The control surfaces and control system required for sail towing are relatively simple hardware and software technology when compared to other advanced ship systems such as retractable hydro foils. The development of this hardware would require little expense compared to development of the hydro foil, and could borrow extensively from active stabilization control surface and hydrofoil technologies which have already been developed.

If near silent noise levels which are not attainable with present AGOS technology are of value to Naval operations, development of sail towing hardware and control system is recommended.

X - REFERENCES

X - REFERENCES

(1) J. W. Mavor, Jr., and J. S. Tochko, "A Revival of the Flettner Rotorship for Oceanography", Marine Technology Society Tenth Annual Conference Proceedings, pp. 783-802, 1974.

(2) L. Bergeson, et al, Wind Propulsion for Ships of the American Merchant Marine, U. S. Maritime Administration report number MA-RD-940-81-034, National Technical Information Service document number PB-81-162455, NTIS, Springfield, Va., March, 1981

(3) Bascom, W., et al, The Use of Sailing Ships for Oceanography, National Academic Press, Washington, D. C., 1981.

(4) OPNAV INST 9010.249-CH-1, "Approved Characteristics for Oceanographic Research Ship (T-AGOR), SCB Project No. 710.66", Office of the Chief of Naval Operations, Department of the Navy, Washington, D. C., July, 1966.

(5) Tentative Research Vessel Operating Schedules, 1981, University-National Oceanographic Laboratory System Office, Woods Hole Oceanographic Institution, Woods Hole, Mass., November, 1980.

(6) Tentative Research Vessel Operating Schedules, 1982, University-National Oceanographic Laboratory System Office, Woods Hole Oceanographic Institution, Woods Hole, Mass., August, 1981.

(7) 1981 & 1982 Woods Hole Oceanographic Institution Ship Schedule, WHOI, Woods Hole, Mass., September, 1981.

(8) E. H. Hiller, "Voyage to the Ice", Woods Hole Notes, Vol. XI, No. 2, August, 1979.

(9) Actual Estimated, Proposed and Projected operating cost data for R/V KNORR, as submitted by WHOI to National Science Foundation, Woods Hole, Mass., June, 1979, June, 1980, and June, 1981.

(10) J. M. Meserve, "U. S. Navy Marine Climatic Atlas of the World, Vol. 1, North Atlantic," U. S. Department of Commerce, National Climatic Center, U. S. Gov. Printing Office, Washington, D. C., December, 1974.

(11) J. M. Meserve, "U. S. Navy Marine Climatic Atlas of the World, Vol. 4, South Atlantic," U. S. Department of Commerce, National Climatic Center, U. S. Gov. Printing Office, Washington, D. C., March, 1978.

(12) J. M. Meserve," U. S. Navy Marine Climatic Atlas of the World, Vol. 2, North Pacific," U. S. Department of Commerce, National Climatic Center, U. S. Gov. Printing Office, Washington, D. C., March, 1977.

(13) J. M. Meserve," U. S. Navy Marine Climatic Atlas of the World, Vol. 5, South Pacific," U. S. Department of Commerce, National Climatic Center, U. S. Gov. Printing Office, Washington, D. C., October, 1979.

(14) Conversation with E. H. Hiller, master, R/V KNORR, Woods Hole, Mass., October, 1981.

(15) AGOR-15 Booklet of General Plans, Defoe Drawing No. AGOR15-845-28 Navships No. AGOR 15-845-2582295, Defoe Shipbuilding Co., Bay City, MI.

(16) R/V KNORR Trim and Stability Booklet, Defoe Drawing No. AGOR 15-845-29, Navships No. AGOR 15-845-2582305, Defoe Shipbuilding Co., Bay City, MI., October, 1969.

(17) S. C. Reed, et al, "New Concepts Applied to Research Ship Design," Marine Technology, April, 1969, SNAME

(18) R/V KNORR Trim and Stability Booklet, Sheet No. 33

(19) T. H. Sarchin & L. L. Goldberg, "Stability Criteria for U. S. Naval Surface Ships," Transactions of SNAME, Vol. 70, New York, N. Y., 1962.

(20) Reference (2), chapter 2

(21) 25,000 DWT tanker for charter to Military Sealift Command, Booklet of General Plans, Todd Drawing No. H9-145-01, Todd Shipyards Corp., Los Angeles Division, San Pedro, California, June, 1973.

(22) OPNAV Instruction 9010.315, 15 Nov. 1976, "Top Level Requirement for T-AGOS", (unclassified).

(23) G. Whittlesey, Jr., "Crossing the Atlantic in a Rotorship", Yachting, June, 1926.

APPENDIX A

DETAILED SHIP PERFORMANCE PREDICTIONS

		Page
I	INTRODUCTION	78
II	APPROACH	79
III	EXISTING SHIP	
	Table A.1 - Ship Characteristics	81
	Table A.2 - Ship Performance Predictions	
	Table A.3 - Performance Program Nomenclature	
	Figure A.1 - Main Engine Power vs. True Wind	
	Figure A.2 - Ship Speed vs. True Wind	
	Figure A.3 - Heel Angle vs. True Wind	
IV	RETROFIT SHIP	91
	Table A.4 - Ship Performance Predictions	
	Figure A.4 - Main Engine Power vs. True Wind	
	Figure A.5 - Ship Speed vs. True Wind	
	Figure A.6 - Heel Angle vs. True Wind	
	Figure A.7 - Rig Power vs. True Wind	

INTRODUCTION

This appendix presents detailed performance predictions for two ship configurations: the KNORR as presently configured; and the ship retrofitted with a wing sail rig of 3,610 square feet in area. These predictions are derived using Wind Ship's Retrofit Analysis Program. A brief summary of the approach used is provided, along with tabular and graphical presentations of the results. For a more detailed description of the methodology used, see chapter 3 of reference (2).

APPROACH

The performance of a motor sailing ship is a function of wind condition. The wind condition is specified by wind velocity and angle. Wind velocity is measured at a 10 meter reference height, relative to the water's surface; angle is measured relative to the course-made-good by the ship (a wind angle of 0 degrees indicates a head wind, a wind angle of 180 degrees indicates a tail wind). In order to bring aerodynamic forces and moments acting on the above water portion of the ship into equilibrium with hydrodynamic forces and moments acting on the hull, the ship assumes an equilibrium sailing condition defined by ship speed, engine power, heel angle, and leeway angle. Ship speed is measured in the course-made-good direction. Heel angle is measured relative to perpendicular from the ship's coordinate system; the ship heels until hull righting moments balance the rig-imposed heeling moments. Leeway angle is measured between the course steered, and course-made-good; the hull operates with a leeway angle to generate hull lift which balances side force imposed by sail forces and hull windage.

The Performance Program is used to solve for the equilibrium sailing conditions. The following effects are taken into account when determining aerodynamic forces and moments:

1. sail section lift and drag performance
2. sail induced drag
3. benefits to be obtained by trimming sails to optimize performance.
4. reefing imposed by rig structural limits
5. dependence of sail heeling moments on sail plan
6. windage forces and heeling moments generated by topsides and superstructure.

The following effects are taken into account when determining hydrodynamic forces and moments:

1. hull resistance curve - determined from reference (2)
2. hull leeway and induced drag dependence on side force
3. propulsive efficiency - determined from reference (2)
4. hull righting moment dependence on heel angle - from reference (3)

An equilibrium sailing condition can often be improved upon by adjusting sail trim. In a simple example, with a true wind of 0 degrees (on the bow), ship speed will clearly be greater with the wing sail feathered. A more subtle example is partial trimming to unload the wing in moderate breezes when close reaching.

The wing sail has an operational wind speed range of zero to 40 knots. In higher winds, rig loads could exceed the design loads, and sail loading must be reduced from the maximum obtainable to protect the rig. The Program models this in the following way: For each wind condition, sail trim is first optimized for maximum ship speed. If the resulting apparant wind speed exceeds the rig design wind speed of 40 knots, the rig is unloaded progressively until either:

a) the ship slows enough for the apparent wind speed to drop to 40 knots, or

b) the wing is fully feathered.

This model results in conservative predictions, since in practice a wing load management system will allow the sail to operate safely in winds somewhat above the rig design speed.

A target speed engine use strategy has been used. Under this strategy, a speed of 10 knots is maintained if it can be attained with a power setting between 10 and 80 percent of the maximum continuous rating. If 80% power will not maintain the floor speed, the ship speed drops to the achievable level. If the required throttle setting for a 10 knot speed would be less than 10%, ship speed is allowed to increase to that resulting for a 10% throttle setting. This throttle range is chosen since there are significant problems inherent in modeling lower power performance of the machinery and propeller. With this strategy the rig is serving primarily to reduce fuel consumption.

EXISTING SHIP

Table A.1 presents a summary of the ship characteristics assumed when preparing performance predictions for the existing ship. Detail results for the ship operating in wind speeds of 0, 8, 16, 24, 32, 40 and 48 knots are presented in Table A.2. A target speed of 10 knots was employed for these predictions. Each line of Table A.2 summarizes the equilibrium sailing condition associated with the given wind speed and angle. A summary of the nomenclature used for these line outputs appears in Table A.3.

Figure A.1 is a plot of engine power vs. wind direction for wind speeds of 0 through 48 knots. Figure A.2 is a polar plot of ship speed vs. wind direction for the same wind speeds. The ship is seen to maintain the target speed of 10 knots for most wind conditions. In a 48 knot wind the ship is forced to slow down for wind angles of 10 to 90 degrees because the engine power has reached the 80% limit, as shown in Figure A.1. In fact, the ship is unable to make progress for wind angles between 40 and 80 degrees due to the power limit and hull windage forces. To make progress between these wind angles the ship is assumed to tack at wind angles of 30 and 90 degrees, and the speed made good is shown on Figure A.2 as a straight line between 30 and 90 degrees.

Figure A.3 presents a plot of static heel angle vs. wind direction for the same range of wind velocities. The maximum heel angle is seen to be about 6 degrees. There is a break in the curve for 48 knots between 40 and 90 degrees, since no equilibrium exists for the wind conditions as described above.

TABLE A.1

R/V KNORR SHIP CHARACTERISTICS

Hull:

Displacement	2111.0 LT
Length (BP)	220.0 ft.
Beam	46.0 ft.
Draft	15.7 ft.
Block Coefficient	.465
GM	3.80 ft.

Power Plant:

Rated Brake Horsepower	2500.0
Service Margin(@ 12 knots)	.79
Specific Fuel Consumption	.410 #/HP-Hr.
Propulsive Efficiency (@ 12 knots)	.51

Table A.2

EXISTING SHIP PERFORMANCE PREDICTIONS

WIND SHIP DEVELOPMENT CORPORATION PERFORMANCE PROGRAM RELEASE DATE: 4/6/81
R/V KNORR NO RIG SHIP NUMBER1206 RUN DATE: 11/12/81 13:27

HULL PARAMETERS

DISP(LT):	2111.	LBP:	220.00	BEAM:	46.00	DRAFT:	15.70	WSA:	13000.		
L/VOL^1/3:	5.24	CB:	0.465	CP:	0.533	CM:	0.872	B/T:	2.93		
GM:	3.80	RM2:	140.	RM25:	156.	RAILDN:	1.29	HEEL:	0.0	DESIGN WIND:	0.
FREEBOARD:	9.30	ALAT:	7804.	ATRANS:	1440.	ZCELAT:	25.00	CROUGH:	0.0		

POWER PLANT

SERSPD:	12.00	SHP:	2500.	SFC:	0.410		
PROP DIA:	10.00	PPA:	30.00	CDPROP:	1.00000	PROP EFF SS:0.51	PROP EFFMAX:0.63

UPRIGHT RESISTANCE

V(KTS):	4.00	6.00	8.00	9.00	10.00	11.00	12.00	13.00	14.00	15.00	16.00	17.00
R(LT):	0.94	2.10	3.71	4.64	5.76	7.05	8.62	10.58	13.13	16.88	22.54	31.03

VTW	BTW	VAW	BAW	V	HP-ME	HP-RIG	HEEL	LWY	REEF	FLAT
0.0	0.	10.00	0.	10.00	844.	0.	0.0	0.0	0.0	0.0
8.0	180.	2.00	0.	10.00	810.	0.	0.0	0.0	0.0	0.0
8.0	170.	2.54	33.	10.00	810.	0.	0.0	0.0	0.0	0.0
8.0	160.	3.69	48.	10.00	809.	0.	0.0	0.1	0.0	0.0
8.0	150.	5.04	52.	10.00	809.	0.	0.1	0.1	0.0	0.0
8.0	140.	6.44	53.	10.00	810.	0.	0.1	0.2	0.0	0.0
8.0	130.	7.82	51.	10.00	811.	0.	0.2	0.2	0.0	0.0
8.0	120.	9.17	49.	10.00	814.	0.	0.2	0.3	0.0	0.0
8.0	110.	10.45	46.	10.00	818.	0.	0.3	0.4	0.0	0.0
8.0	100.	11.67	42.	10.00	825.	-0.	0.3	0.5	0.0	0.0
8.0	90.	12.81	38.	10.00	835.	0.	0.4	0.5	0.0	0.0
8.0	80.	13.85	34.	10.00	847.	0.	0.4	0.6	0.0	0.0
8.0	70.	14.79	30.	10.00	863.	-0.	0.4	0.6	0.0	0.0
8.0	60.	15.62	26.	10.00	879.	-0.	0.4	0.6	0.0	0.0
8.0	50.	16.34	22.	10.00	895.	-0.	0.3	0.5	0.0	0.0
8.0	40.	16.93	17.	10.00	908.	0.	0.3	0.4	0.0	0.0
8.0	30.	17.39	13.	10.00	916.	0.	0.2	0.3	0.0	0.0
8.0	20.	17.73	9.	10.00	921.	0.	0.1	0.2	0.0	0.0
8.0	10.	17.93	4.	10.00	923.	0.	0.1	0.1	0.0	0.0
8.0	0.	18.00	0.	10.00	923.	0.	0.0	0.0	0.0	0.0

Table A.2

EXISTING SHIP PERFORMANCE PREDICTIONS

SHIP NUMBER: 1206 PAGE: 2 RUN DATE: 11/12/81 13:27

VTW	BTW	VAW	BAW	V	HP-ME	HP-RIG	HEEL	LWY	REEF	FLAT
16.0	180.	6.00	180.	10.00	797.	0.	0.0	-0.0	0.0	0.0
16.0	170.	6.39	154.	10.00	798.	0.	0.1	0.1	0.0	0.0
16.0	160.	7.44	132.	10.00	806.	0.	0.1	0.2	0.0	0.0
16.0	150.	8.88	115.	10.00	809.	0.	0.2	0.3	0.0	0.0
16.0	140.	10.53	102.	10.00	811.	0.	0.2	0.5	0.0	0.0
16.0	130.	12.26	91.	10.00	814.	0.	0.2	0.7	0.0	0.0
16.0	120.	14.00	82.	10.00	818.	-0.	0.2	0.9	0.0	0.0
16.0	110.	15.70	72.	10.00	823.	-0.	0.7	1.1	0.0	0.0
16.0	100.	17.33	64.	10.00	830.	-0.	0.9	1.3	0.0	0.0
16.0	90.	18.87	57.	10.00	841.	-0.	1.0	1.5	0.0	0.0
16.0	80.	20.28	49.	10.00	857.	-0.	1.1	1.6	0.0	0.0
16.0	70.	21.57	43.	10.00	882.	-0.	1.1	1.7	0.0	0.0
16.0	60.	22.71	36.	10.00	917.	-0.	1.1	1.6	0.0	0.0
16.0	50.	23.70	30.	10.00	959.	-0.	1.0	1.5	0.0	0.0
16.0	40.	24.52	24.	10.00	1000.	-0.	0.8	1.3	0.0	0.0
16.0	30.	25.16	18.	10.00	1029.	-0.	0.6	0.9	0.0	0.0
16.0	20.	25.63	12.	10.00	1043.	0.	0.4	0.6	0.0	0.0
16.0	10.	25.91	6.	10.00	1046.	0.	0.2	0.3	0.0	0.0
16.0	0.	26.00	0.	10.00	1046.	0.	0.0	0.0	0.0	0.0
24.0	180.	14.00	180.	10.00	743.	0.	0.0	-0.0	0.0	0.0
24.0	170.	14.26	163.	10.00	744.	0.	0.2	0.3	0.0	0.0
24.0	160.	15.00	146.	10.00	774.	-0.	0.4	0.6	0.0	0.0
24.0	150.	16.13	131.	10.00	807.	-0.	0.6	1.0	0.0	0.0
24.0	140.	17.56	117.	10.00	826.	-0.	0.8	1.3	0.0	0.0
24.0	130.	19.17	105.	10.00	840.	-0.	1.1	1.6	0.0	0.0
24.0	120.	20.88	95.	10.00	855.	-0.	1.1	1.9	0.0	0.0
24.0	110.	22.62	85.	10.00	873.	-0.	1.1	2.3	0.0	0.0
24.0	100.	24.33	74.	10.00	893.	-0.	1.7	2.6	0.0	0.0
24.0	90.	25.99	65.	10.00	913.	-0.	1.9	2.8	0.0	0.0
24.0	80.	27.54	56.	10.00	938.	-0.	2.1	3.0	0.0	0.0
24.0	70.	28.97	48.	10.00	971.	-0.	2.2	3.2	0.0	0.0
24.0	60.	30.26	40.	10.00	1018.	-0.	2.2	3.1	0.0	0.0
24.0	50.	31.37	33.	10.00	1079.	-0.	2.0	2.9	0.0	0.0
24.0	40.	32.30	26.	10.00	1145.	-0.	1.7	2.5	0.0	0.0
24.0	30.	33.04	19.	10.00	1195.	-0.	1.3	1.9	0.0	0.0
24.0	20.	33.57	13.	10.00	1216.	-0.	0.8	1.2	0.0	0.0
24.0	10.	33.89	6.	10.00	1216.	-0.	0.4	0.6	0.0	0.0
24.0	0.	34.00	0.	10.00	1213.	0.	0.0	0.0	0.0	0.0

Table A.2

EXISTING SHIP PERFORMANCE PREDICTIONS

SHIP NUMBER:1206 PAGE: 3 RUN DATE: 11/12/81 13:27

VTW	BTW	VAW	BAW	V	HP-ME	HP-RIG	HEEL	LWY	REEF	FLAT
32.0	180.	22.00	180.	10.00	646.	0.	0.0	-0.0	0.0	0.0
32.0	170.	22.22	165.	10.00	648.	-0.	0.3	0.5	0.0	0.0
32.0	160.	22.86	150.	10.00	708.	-0.	0.8	1.3	0.0	0.0
32.0	150.	23.87	136.	10.00	803.	-0.	1.3	1.9	0.0	0.0
32.0	140.	25.17	123.	10.00	870.	-0.	1.6	2.4	0.0	0.0
32.0	130.	26.68	110.	10.00	917.	-0.	2.0	2.9	0.0	0.0
32.0	120.	28.33	99.	10.00	960.	-0.	2.3	3.4	0.0	0.0
32.0	110.	30.06	92.	10.00	1006.	-0.	2.3	3.9	0.0	0.0
32.0	100.	31.80	82.	10.00	1053.	-0.	2.3	4.3	0.0	0.0
32.0	90.	33.48	68.	10.00	1097.	-1.	3.2	4.7	0.0	0.0
32.0	80.	35.09	59.	10.00	1138.	-1.	3.4	4.9	0.0	0.0
32.0	70.	36.60	50.	10.00	1182.	-1.	3.6	5.1	0.0	0.0
32.0	60.	37.96	42.	10.00	1237.	-1.	3.5	5.0	0.0	0.0
32.0	50.	39.16	34.	10.00	1307.	-1.	3.3	4.7	0.0	0.0
32.0	40.	40.16	27.	10.00	1381.	-1.	2.9	4.1	0.0	0.0
32.0	30.	40.96	20.	10.00	1434.	-0.	2.2	3.1	0.0	0.0
32.0	20.	41.54	13.	10.00	1447.	-0.	1.4	2.0	0.0	0.0
32.0	10.	41.88	7.	10.00	1434.	-0.	0.7	0.9	0.0	0.0
32.0	0.	42.00	0.	10.00	1425.	0.	0.0	0.0	0.0	0.0
40.0	180.	30.00	180.	10.00	504.	0.	0.0	-0.0	0.0	0.0
40.0	170.	30.20	166.	10.00	512.	-0.	0.5	0.9	0.0	0.0
40.0	160.	30.79	152.	10.00	620.	-0.	1.3	2.1	0.0	0.0
40.0	150.	31.73	138.	10.00	817.	-0.	2.1	3.2	0.0	0.0
40.0	140.	32.95	125.	10.00	977.	-0.	2.7	4.0	0.0	0.0
40.0	130.	34.39	113.	10.00	1090.	-1.	3.2	4.7	0.0	0.0
40.0	120.	35.98	101.	10.00	1187.	-2.	3.7	5.3	0.0	0.0
40.0	110.	37.69	96.	10.00	1283.	-2.	3.7	5.9	0.0	0.0
40.0	100.	39.43	86.	10.00	1375.	-2.	3.7	6.5	0.0	0.0
40.0	90.	41.09	69.	10.00	1459.	-5.	4.9	6.9	0.0	0.0
40.0	80.	42.74	59.	10.00	1526.	-6.	5.2	7.2	0.0	0.0
40.0	70.	44.29	50.	10.00	1582.	-6.	5.3	7.4	0.0	0.0
40.0	60.	45.72	4[illegible].	10.00	1638.	-6.	5.3	7.3	0.0	0.0
40.0	50.	46.98	34.	10.00	1699.	-5.	4.9	6.9	0.0	0.0
40.0	40.	48.05	26.	10.00	1753.	-3.	4.3	6.0	0.0	0.0
40.0	30.	48.90	20.	10.00	1774.	-1.	3.3	4.6	0.0	0.0
40.0	20.	49.51	13.	10.00	1748.	-0.	2.1	2.9	0.0	0.0
40.0	10.	49.88	7.	10.00	1702.	-0.	1.0	1.4	0.0	0.0
40.0	0.	50.00	0.	10.00	1680.	0.	0.1	0.0	0.0	0.0

AD-A113 691 WIND SHIP DEVELOPMENT CORP NORWELL MA F/G 13/10
ANALYSIS OF SAIL-ASSIST FOR NAVY OCEANOGRAPHIC RESEARCH SHIPS O--ETC(U)
MAR 82 L BERGESON, J YORK N00014-81-C-0823
UNCLASSIFIED RR-2 NL

2 of 2
AD
A113691

END
DATE
FILMED
5-82
DTIC

Table A.2

EXISTING SHIP PERFORMANCE PREDICTIONS

SHIP NUMBER: 1206 PAGE: 4 RUN DATE: 11/12/81 13:27

VTW	BTW	VAW	BAW	V	HP-ME	HP-RIG	HEEL	LWY	REEF	FLAT
48.0	180.	38.00	180.	10.00	318.	0.	0.0	-0.0	0.0	0.0
48.0	170.	38.19	166.	10.00	337.	-0.	0.8	1.3	0.0	0.0
48.0	160.	38.75	152.	10.00	521.	-0.	2.0	3.0	0.0	0.0
48.0	150.	39.63	138.	10.00	877.	-1.	3.2	4.7	0.0	0.0
48.0	140.	40.79	125.	10.00	1187.	-2.	4.1	5.8	0.0	0.0
48.0	130.	42.16	113.	10.00	1412.	-4.	4.8	6.8	0.0	0.0
48.0	120.	43.69	101.	10.00	1600.	-7.	5.5	7.6	0.0	0.0
48.0	110.	45.36	98.	10.00	1775.	-9.	5.5	8.4	0.0	0.0
48.0	100.	47.09	88.	10.00	1938.	-10.	5.5	9.0	0.0	0.0
48.0	40.	54.58	23.	8.36	2000.	-11.	5.8	10.9	0.0	0.0
48.0	30.	56.03	18.	9.10	2000.	-3.	4.4	7.4	0.0	0.0
48.0	20.	57.11	12.	9.60	2000.	-0.	2.8	4.3	0.0	0.0
48.0	10.	57.81	6.	9.93	2000.	-0.	1.3	1.9	0.0	0.0
48.0	0.	58.00	0.	10.00	1979.	0.	0.1	0.0	0.0	0.0

TABLE A.3

PERFORMANCE PROGRAM NOMENCLATURE

Symbol	Description
VTW	TRUE WIND SPEED (knots). Measured relative to the water at a height of 10 meters.
BTW	TRUE WIND ANGLE (degrees). Measured relative to the course made good by the ship.
VAW	APPARANT WIND SPEED (knots). Measured relative to the ship at the center of effort of the rig, and incorporating the effects of ship speed and heel angle.
BAW	APPARENT WIND ANGLE (degrees). Measured relative to the ship center line at the rig center of effort.
V	SHIP SPEED (knots). Measured relative to the water along the course made good by the ship.
HP-ME	MAIN ENGINE POWER (horsepower). Engine power required to propel the ship at the given speed.
HP-RIG	RIG POWER (horsepower). The net reduction in main engine power over that required if the rig were not fitted to the ship.
HEEL	HEEL ANGLE (degrees). Measured relative to the verticle.
LWY	LEEWAY ANGLE (degrees). The angle between the course steered and the course made good by the ship.
REEF	SAIL REEFING PARAMENTER. For the Wind Sail, Reef = 1 indicates that the sail is being trimmed for optimum performance. Reef = 0 indicates that the sail is feathering passively in the wind.
FLAT	SAIL TRIMMING PARAMETER. When Flat = 1, the sail is being trimmed to obtain the maximum sail forces available for the given apparent wind, fractional values of Flat indicate that the sail forces have been reduced by trimming to that fraction of the maximum.

FIGURE A.1

EXISTING SHIP

MAIN ENGINE POWER VS. TRUE WIND

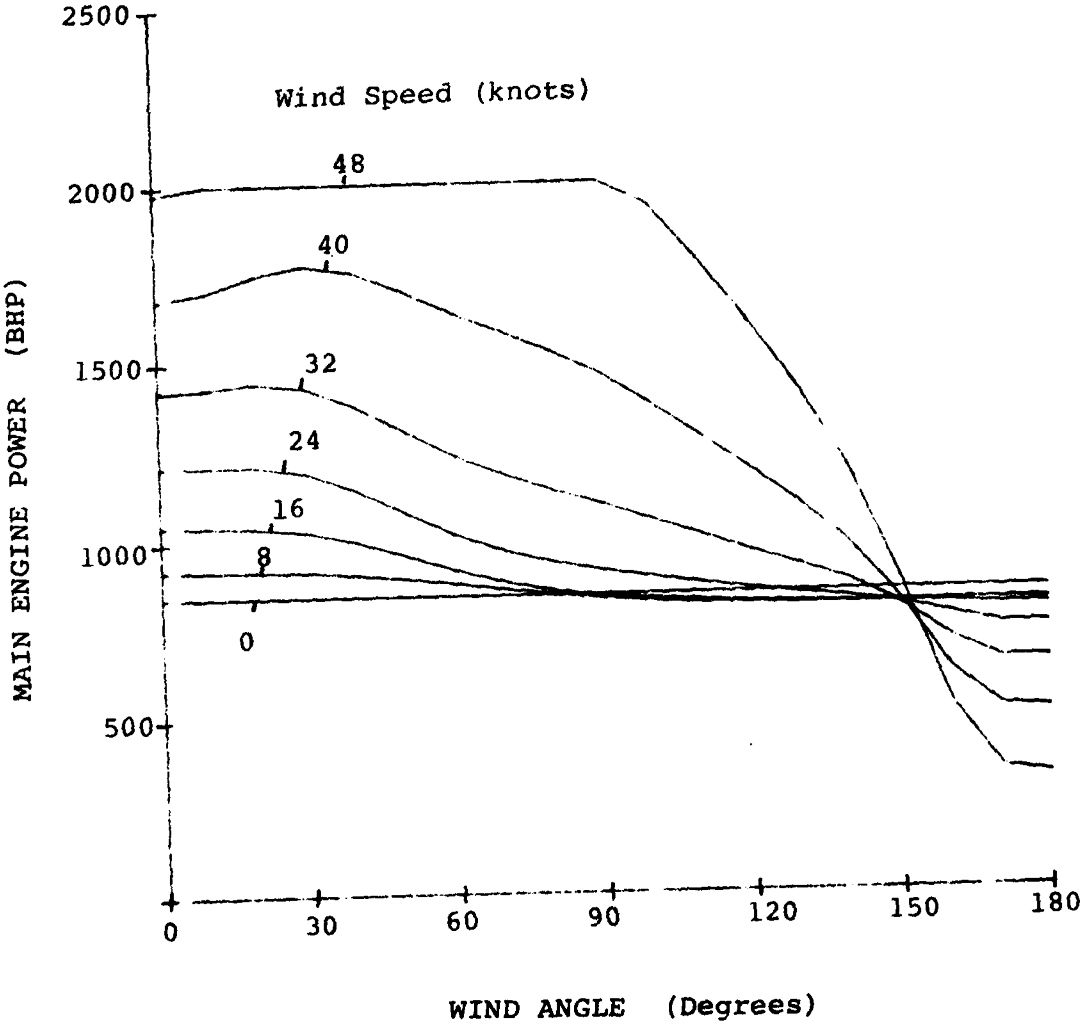


FIGURE A.2

EXISTING SHIP

SHIP SPEED VS. TRUE WIND

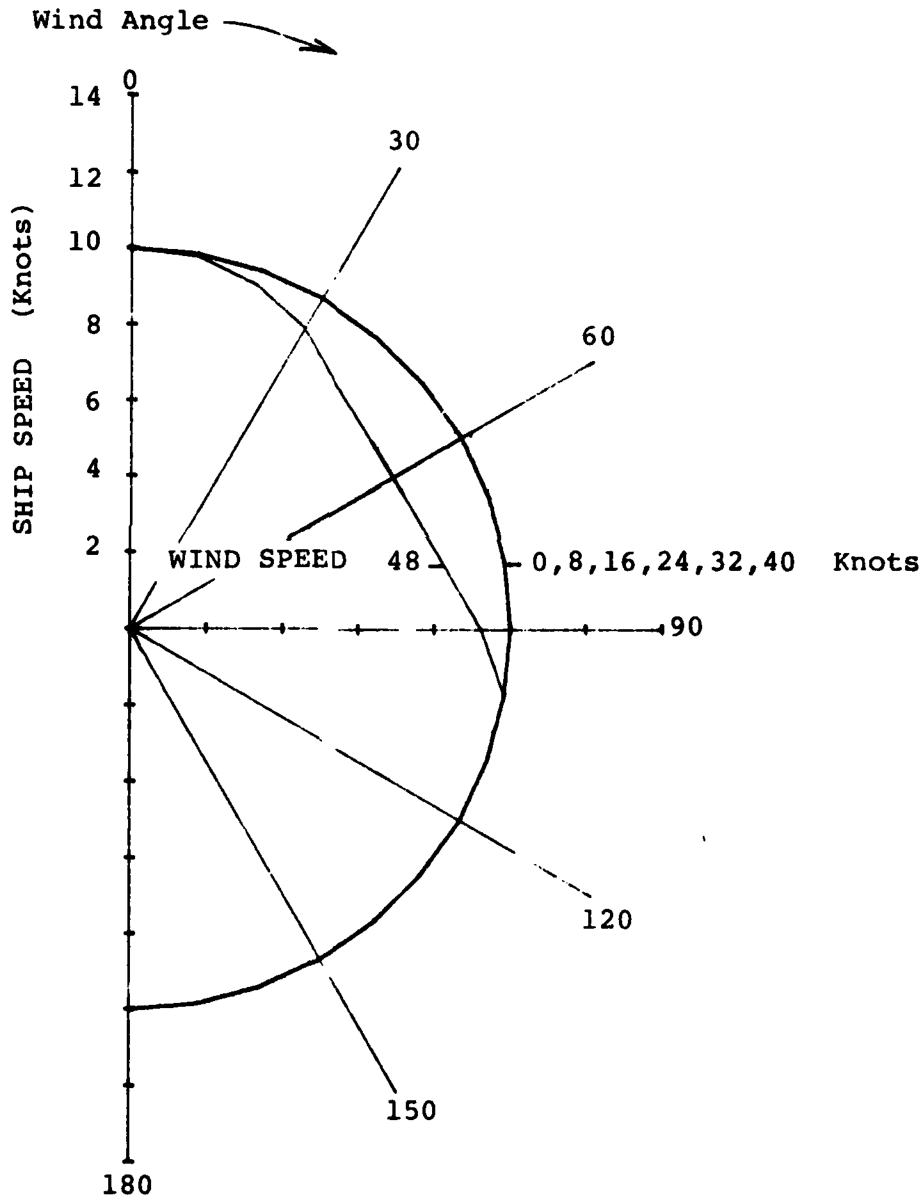
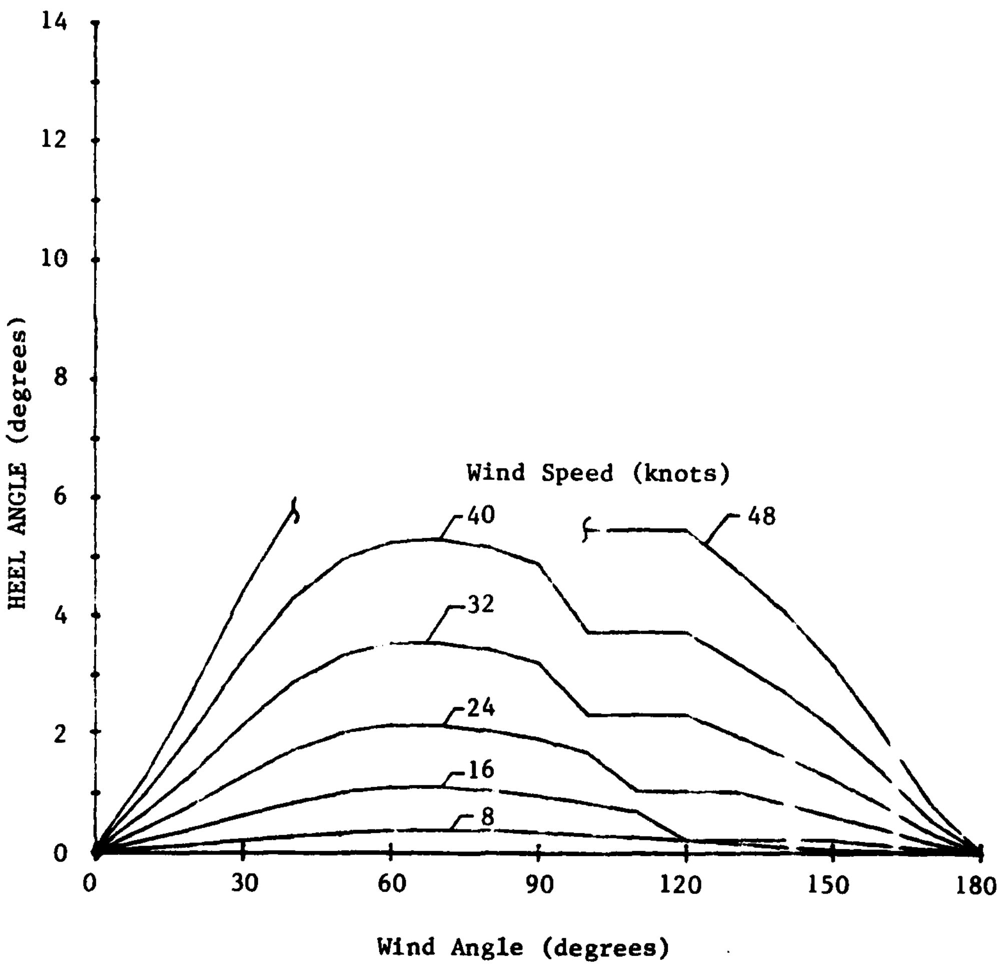


FIGURE A.3

EXISTING SHIP

HEEL ANGLE VS. TRUE WIND



RETROFIT SHIP

The following performance predictions are derived assuming a retrofitted wing sail rig with the following characteristics:

Sail Area	3610 sq. ft.
Design Wind Speed	40 knots
Mast Height (above L.W.L.)	131 ft.
Span	95 ft.
Chord	38 ft.
Section Thickness	18% of chord
Flaps	20% of chord
Flaps Articulated	$\pm 45^{o}$

Table A.4 presents the detail performance predictions for the retrofitted ship operating in wind speeds of 0, 8, 16, 24, 32, 40 and 48 knots. Each line of Table A.4 summarizes the equilibrium sailing condition associated with the given wind speed and angle (for a summary of the nomenclature used see table A.3).

Figure A.4 is a plot of engine power versus wind direction for wind speeds of 0 through 48 knots. For certain wind angles in wind speeds of 24, 32 and 40 knots, the wing sail generates enough thrust that main engine power is set to the 10% minimum. In these cases the ship exceeds the target speed of 10 knots as shown in Figure A.5. The abrupt increases in engine power (for instance in 40 knots of wind between wind angles of 120 and 110 degrees) correspond to feathering of the wing when the apparent wind exceeds the design wind speed of 40 knots. This also shows up in Figure A.5 as a sharp reduction in ship speed. In a 48 knot wind, ship performance is very much the same as it is for the existing ship since the wing sail is always feathered, and the feathered drag is small compared to windage forces on the ship's hull and superstructure.

Figure A.6 presents a plot of static heel angle versus wind direction for the same range of wind speeds. The maximum heel angle is about 12^{o} and occurs in wind of 40 knots. In higher wind speeds, the wing is feathered so that heel angles are not as great. There is a break in the curve for 48 knots, since no equilibrium exists for these wind conditions and the ship is assumed to tack as described in the existing ship performance prediction section.

Figure A.7 is a plot of Rig Power versus True Wind. Rig Power is the net reduction in required engine output achieved with the sailing rig in a specified wind condition.

Table A.4

RETROFIT SHIP PERFORMANCE PREDICTIONS


```
WIND SHIP DEVELOPMENT CORPORATION PERFORMANCE PROGRAM                                       RELEASE DATE:    4/6/81
R/V KNORR                                 AR=2.5 BS=95 VAWMAX=40              SHIP NUMBER1207  RUN DATE: 11/12/81 13:31
---------------------------------------------------------------------------------------------------------------------
HULL PARAMETERS
  DISP(LT):  2111.     LBP:         220.00   BEAM:        46.00   DRAFT:      15.70   WSA:      13000.
  L/VOL^1/3:  5.24     CB:           0.465   CP:          0.533   CM:         0.872   B/T:        2.93
  GM:         3.04     RM2:           112.   RM25:         129.   RAILDN:      1.29   HEEL:      16.69   DESIGN WIND: 40.
  FREEBOARD:  9.30     ALAT:         7804.   ATRANS:      1440.   ZCELAT:     25.00   CROUGH:  0.0
POWER PLANT
  SERSPD:    12.00     SHP:          2500.   SFC:         0.410
  PROP DIA:  10.00     PPA:          30.00   CDPROP:    1.00000   PROP EFF SS:0.51    PROP EFFMAX:0.63
RIG
  SA:        3610.     NMAST:            1   MASTHT:     121.70   WINDAGE:     63.9   ZCE:       83.50   ZRB:        36.00
  RIG BASE:   0.0      BASE SPAN:    95.00   WINDG/SA:  0.0177
  CLMAX:     1.700     CDMAX:        1.180   CDQ:           0.0   CDCL2:   0.0      CDCL4:    0.0050   RGLAU:       0.0
---------------------------------------------------------------------------------------------------------------------
UPRIGHT RESISTANCE
V(KTS):   4.00    6.00    8.00    9.00   10.00   11.00   12.00   13.00   14.00   15.00   16.00   17.00

R(LT):    0.94    2.10    3.71    4.64    5.76    7.05    8.62   10.58   13.13   16.88   22.54   31.03
---------------------------------------------------------------------------------------------------------------------
RIG POLAR
  BAW:              0.     10.     20.     30.     40.     50.     60.     70.     80.     90.    100.    110.
                  120.    130.    140.    150.    160.    170.    180.
  CL:            1.700   1.700   1.700   1.700   1.700   1.700   1.700   1.700   1.700   1.700   1.662   1.549
                 1.360   1.133   0.907   0.680   0.453   0.227   0.0
  CD:            0.000   0.000   0.000   0.000   0.000   0.000   0.000   0.000   0.000   0.000   0.104   0.209
                 0.321   0.470   0.732   0.956   1.087   1.158   1.180
  SPAN RATIO:    1.000   1.000   1.000   1.000   1.000   1.000   1.000   1.000   1.000   1.000   1.000   1.000
                 1.000   1.000   1.000   1.000   1.000   1.000   1.000
---------------------------------------------------------------------------------------------------------------------
```

Table A.4

RETROFIT SHIP PERFORMANCE PREDICTIONS

SHIP NUMBER: 1207 PAGE: 2 RUN DATE: 11/12/81 13:31

VTW	BTW	VAW	BAW	V	HP-ME	HP-RIG	HEEL	LWY	REEF	FLAT
0.0	0.	10.00	0.	10.00	846.	-2.	0.0	0.0	1.00	0.0
8.0	180.	1.19	0.	10.00	810.	-0.	0.0	0.0	1.00	0.0
8.0	170.	2.02	49.	10.00	806.	3.	0.0	0.0	1.00	1.00
8.0	160.	3.47	60.	10.00	797.	12.	0.1	0.1	1.00	1.00
8.0	150.	5.00	62.	10.00	785.	25.	0.2	0.2	1.00	1.00
8.0	140.	6.53	60.	10.00	769.	41.	0.4	0.3	1.00	1.00
8.0	130.	8.02	57.	10.00	754.	58.	0.6	0.4	1.00	1.00
8.0	120.	9.46	53.	10.00	740.	74.	0.8	0.6	1.00	1.00
8.0	110.	10.83	49.	10.00	731.	87.	1.1	0.7	1.00	1.00
8.0	100.	12.13	45.	10.00	729.	96.	1.3	0.9	1.00	1.00
8.0	90.	13.33	40.	10.00	736.	99.	1.6	1.1	1.00	1.00
8.0	80.	14.43	36.	10.00	753.	94.	1.9	1.2	1.00	1.00
8.0	70.	15.42	31.	10.00	780.	83.	2.2	1.3	1.00	0.99
8.0	60.	16.30	27.	10.00	813.	66.	2.1	1.2	1.00	0.85
8.0	50.	17.06	22.	10.00	846.	49.	1.9	1.1	1.00	0.72
8.0	40.	17.68	18.	10.00	875.	32.	1.7	1.0	1.00	0.58
8.0	30.	18.17	13.	10.00	899.	17.	1.3	0.8	1.00	0.44
8.0	20.	18.53	9.	10.00	916.	5.	0.9	0.5	1.00	0.30
8.0	10.	18.74	4.	10.00	925.	-3.	0.5	0.3	1.00	0.15
8.0	0.	18.81	0.	10.00	929.	-5.	0.0	0.0	1.00	0.0

Table A.4

RETROFIT SHIP PERFORMANCE PREDICTIONS

SHIP NUMBER: 1207 PAGE: 3 RUN DATE: 11/12/81 13:31

VTW	BTW	VAW	BAW	V	HP-ME	HP-RIG	HEEL	LWY	REEF	FLAT
16.0	180.	7.63	180.	10.00	743.	53.	0.0	-0.0	1.00	1.00
16.0	170.	7.97	157.	10.00	739.	59.	0.1	0.1	1.00	1.00
16.0	160.	8.91	137.	10.00	730.	76.	0.1	0.2	1.00	1.00
16.0	150.	10.27	121.	10.00	691.	118.	0.2	0.3	1.00	1.00
16.0	140.	11.86	107.	10.00	630.	181.	0.4	0.5	1.00	1.00
16.0	130.	13.57	95.	10.00	573.	241.	0.8	0.8	1.00	1.00
16.0	120.	15.31	84.	10.00	526.	292.	1.3	1.1	1.00	1.00
16.0	110.	17.02	75.	10.00	493.	329.	1.9	1.5	1.00	1.00
16.0	100.	18.68	66.	10.00	478.	352.	2.6	1.9	1.00	1.00
16.0	90.	20.24	58.	10.00	488.	353.	3.3	2.3	1.00	1.00
16.0	80.	21.69	50.	10.00	526.	331.	4.1	2.7	1.00	1.00
16.0	70.	23.00	43.	10.00	595.	287.	4.7	3.1	1.00	1.00
16.0	60.	24.18	36.	10.00	693.	223.	5.3	3.3	1.00	0.99
16.0	50.	25.21	29.	10.00	802.	157.	4.8	3.0	1.00	0.82
16.0	40.	26.08	23.	10.00	900.	99.	4.1	2.5	1.00	0.64
16.0	30.	26.75	17.	10.00	976.	53.	3.3	2.0	1.00	0.48
16.0	20.	27.24	11.	10.00	1025.	18.	2.2	1.3	1.00	0.32
16.0	10.	27.53	6.	10.00	1050.	-4.	1.1	0.7	1.00	0.16
16.0	0.	27.63	0.	10.00	1058.	-12.	0.0	0.0	1.00	0.0
24.0	180.	16.44	180.	10.00	495.	248.	0.0	-0.0	1.00	1.00
24.0	170.	16.68	164.	10.00	486.	258.	0.2	0.2	1.00	1.00
24.0	160.	17.38	148.	10.00	487.	286.	0.4	0.6	1.00	1.00
24.0	150.	18.47	133.	10.00	476.	331.	0.5	0.8	1.00	1.00
24.0	140.	19.85	120.	10.00	379.	447.	0.7	1.1	1.00	1.00
24.0	130.	21.42	107.	10.00	251.	589.	1.3	1.6	1.00	1.00
24.0	120.	23.04	95.	10.47	250.	716.	2.2	2.0	1.00	1.00
24.0	110.	24.86	84.	10.71	250.	795.	3.3	2.5	1.00	1.00
24.0	100.	26.66	74.	10.72	250.	816.	4.6	3.2	1.00	1.00
24.0	90.	28.30	64.	10.47	250.	772.	5.9	3.9	1.00	1.00
24.0	80.	29.66	56.	10.00	274.	660.	7.0	4.9	1.00	1.00
24.0	70.	31.08	47.	10.00	430.	536.	8.2	5.4	1.00	1.00
24.0	60.	32.41	39.	10.00	632.	381.	8.7	5.6	1.00	0.93
24.0	50.	33.62	32.	10.00	830.	246.	7.9	5.2	1.00	0.74
24.0	40.	34.63	25.	10.00	998.	144.	6.7	4.4	1.00	0.57
24.0	30.	35.43	18.	10.00	1121.	73.	5.2	3.4	1.00	0.41
24.0	20.	35.99	12.	10.00	1193.	23.	3.5	2.3	1.00	0.27
24.0	10.	36.33	6.	10.00	1225.	-9.	1.8	1.1	1.00	0.13
24.0	0.	36.44	0.	10.00	1234.	-20.	0.0	0.0	1.00	0.0

Table A.4

RETROFIT SHIP PERFORMANCE PREDICTIONS

SHIP NUMBER: 1207 PAGE: 4 RUN DATE: 11/12/81 13:31

VTW	BTW	VAW	BAW	V	HP-ME	HP-RIG	HEEL	LWY	REEF	FLAT
32.0	180.	24.52	180.	10.74	250.	583.	0.0	-0.0	1.00	1.00
32.0	170.	24.70	165.	10.79	250.	600.	0.3	0.4	1.00	1.00
32.0	160.	25.42	151.	10.75	250.	648.	0.8	1.0	1.00	1.00
32.0	150.	26.57	137.	10.65	250.	714.	1.0	1.4	1.00	1.00
32.0	140.	27.66	123.	11.13	250.	907.	1.2	1.7	1.00	1.00
32.0	130.	29.01	110.	12.01	250.	1232.	2.2	1.9	1.00	1.00
32.0	120.	30.88	97.	12.57	250.	1493.	3.7	2.4	1.00	1.00
32.0	110.	32.97	86.	12.80	250.	1634.	5.5	3.0	1.00	1.00
32.0	100.	35.01	75.	12.69	250.	1629.	7.6	3.8	1.00	1.00
32.0	90.	36.82	66.	12.25	250.	1485.	9.6	4.8	1.00	1.00
32.0	80.	38.13	57.	11.12	250.	1149.	11.2	6.5	1.00	1.00
32.0	70.	39.09	47.	10.00	431.	733.	12.4	8.4	1.00	0.99
32.0	60.	38.44	42.	10.00	1258.	-23.	4.5	5.1	0.0	0.0
32.0	50.	39.65	34.	10.00	1330.	-25.	4.2	4.8	0.0	0.50
32.0	40.	40.66	27.	10.00	1406.	-26.	3.6	4.1	0.0	0.0
32.0	30.	41.47	20.	10.00	1460.	-26.	2.7	3.1	0.0	0.0
32.0	20.	42.05	13.	10.00	1474.	-27.	1.7	2.0	0.0	0.0
32.0	10.	42.40	7.	10.00	1461.	-27.	0.9	0.9	0.0	0.0
32.0	0.	42.51	0.	10.00	1452.	-28.	0.1	0.0	0.0	0.0
40.0	180.	31.47	180.	12.60	250.	1091.	0.0	-0.0	1.00	1.00
40.0	170.	31.68	166.	12.66	250.	1121.	0.5	0.5	1.00	1.00
40.0	160.	32.52	151.	12.59	250.	1204.	1.3	1.1	1.00	1.00
40.0	150.	33.86	138.	12.44	250.	1314.	1.6	1.7	1.00	1.00
40.0	140.	35.18	124.	12.87	250.	1631.	1.8	2.0	1.00	1.00
40.0	130.	36.71	111.	13.77	250.	2186.	3.3	2.3	1.00	1.00
40.0	120.	38.76	99.	14.29	250.	2615.	5.5	2.9	1.00	1.00
40.0	110.	38.22	90.	10.00	1290.	-10.	5.4	6.0	0.0	0.0
40.0	100.	39.93	79.	10.00	1390.	-17.	5.8	6.6	0.0	0.0
40.0	90.	41.62	69.	10.00	1478.	-25.	6.2	7.0	0.0	0.0
40.0	80.	43.27	60.	10.00	1551.	-32.	6.5	7.3	0.0	0.0
40.0	70.	44.83	50.	10.00	1613.	-38.	6.7	7.5	0.0	0.0
40.0	60.	46.28	42.	10.00	1673.	-42.	6.6	7.4	0.0	0.0
40.0	50.	47.57	34.	10.00	1737.	-43.	6.2	7.0	0.0	0.0
40.0	40.	48.67	26.	10.00	1792.	-42.	5.4	6.0	0.0	0.0
40.0	30.	49.53	20.	10.00	1812.	-40.	4.1	4.6	0.0	0.0
40.0	20.	50.15	13.	10.00	1787.	-39.	2.6	2.9	0.0	0.0
40.0	10.	50.52	7.	10.00	1741.	-39.	1.3	1.4	0.0	0.0
40.0	0.	50.64	0.	10.00	1719.	-39.	0.1	0.0	0.0	0.0

Table A.4

RETROFIT SHIP PERFORMANCE PREDICTIONS

SHIP NUMBER: 1207 PAGE: 5 RUN DATE: 11/12/81 13:31

VTW	BTW	VAW	BAW	V	HP-ME	HP-RIG	HEEL	LWY	REEF	FLAT
48.0	180.	38.77	180.	10.00	295.	23.	0.0	-0.0	0.0	0.0
48.0	170.	38.96	166.	10.00	315.	22.	1.1	1.3	0.0	0.0
48.0	160.	39.51	152.	10.00	501.	20.	2.5	3.1	0.0	0.0
48.0	150.	40.38	138.	10.00	861.	14.	4.0	4.7	0.0	0.0
48.0	140.	41.51	125.	10.00	1178.	7.	5.1	5.9	0.0	0.0
48.0	130.	42.85	113.	10.00	1410.	-3.	6.1	6.8	0.0	0.0
48.0	120.	44.33	101.	10.00	1606.	-15.	6.9	7.7	0.0	0.0
48.0	110.	45.91	90.	10.00	1793.	-29.	7.6	8.5	0.0	0.0
48.0	100.	47.55	79.	10.00	1969.	-44.	8.3	9.1	0.0	0.0
48.0	30.	56.59	18.	8.88	2000.	-55.	5.6	7.8	0.0	0.0
48.0	20.	57.72	12.	9.44	2000.	-51.	3.5	4.5	0.0	0.0
48.0	10.	58.43	6.	9.79	2000.	-52.	1.6	2.0	0.0	0.0
48.0	0.	58.68	0.	9.91	2000.	-52.	0.0	0.0	0.0	0.0

FIGURE A.4

RETROFIT SHIP

MAIN ENGINE POWER VS. TRUE WIND

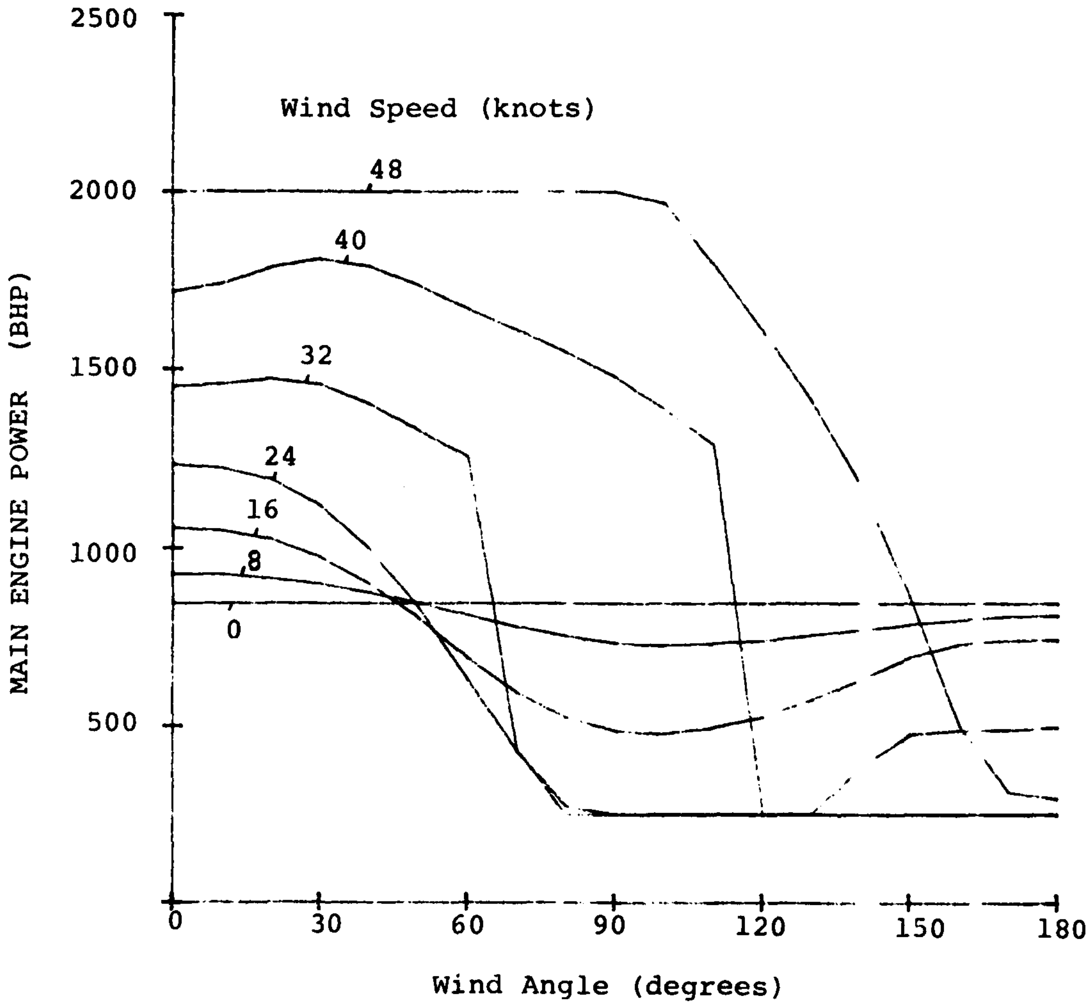


Figure A.5

RETROFIT SHIP

SHIP SPEED VS. TRUE WIND

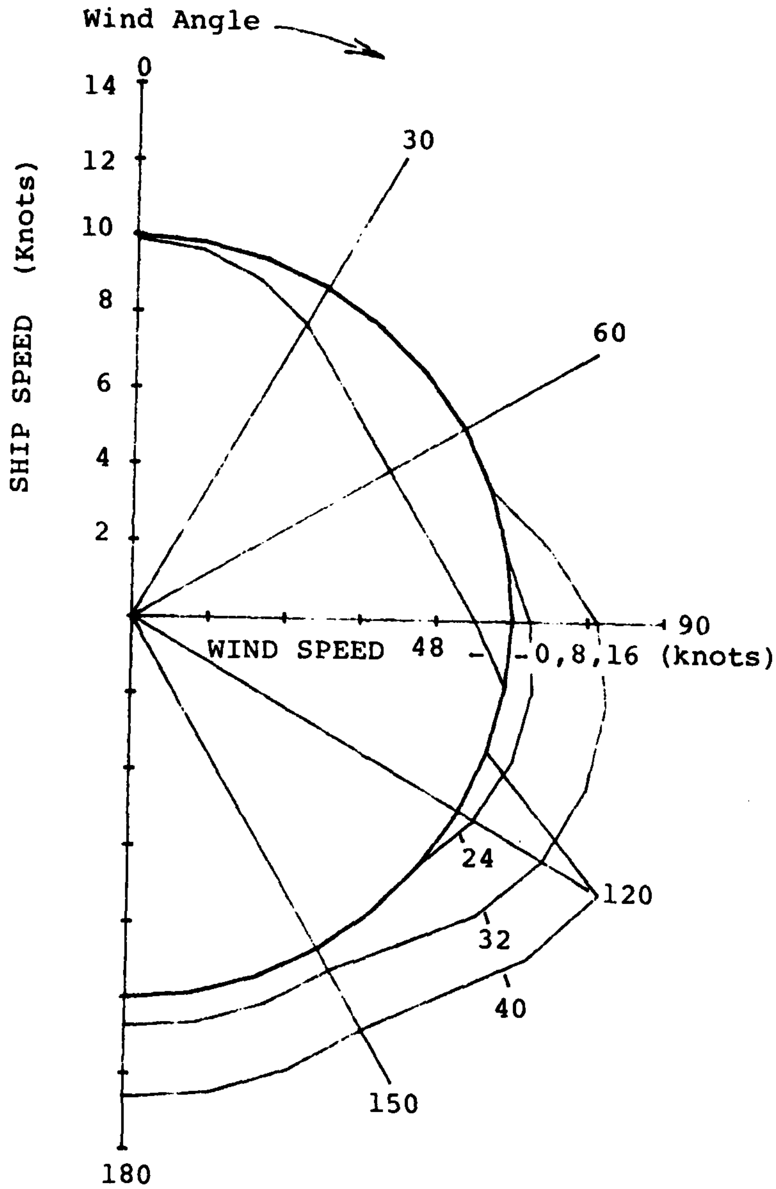


FIGURE A.6

RETROFIT SHIP

HEEL ANGLE VS. TRUE WIND

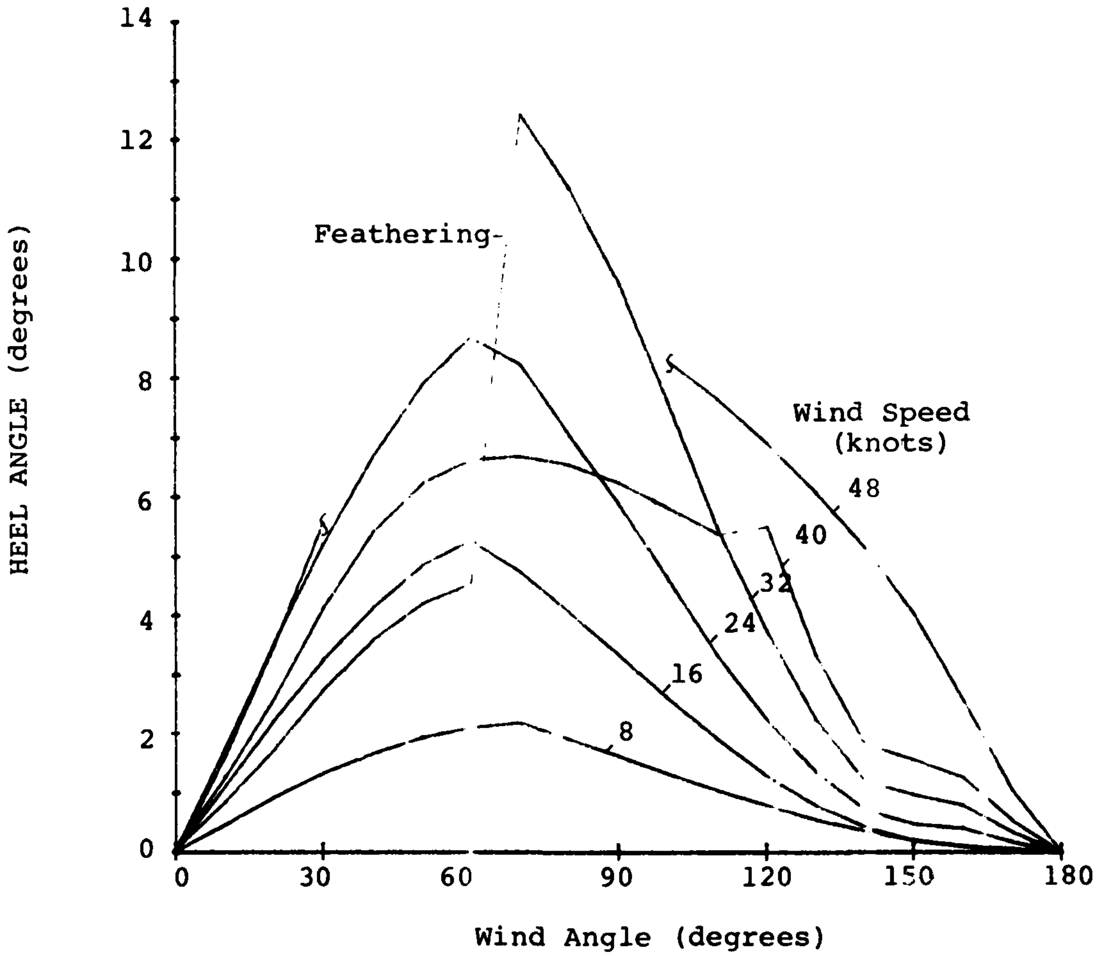


FIGURE A.7

RETROFIT SHIP

RIG POWER VS. TRUE WIND