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In this report, the panel set out to determine whether it is feasible and sensible to build an oceanographic research sailing ship that will: (1) perform all the needed scientific functions of a standard research ship; (2) save at least three quarters of the fuel that would be used by an entirely engine-powered ship; (3) perform essentially the same tasks as present ships without greatly extending the time at sea of the scientists and crew. The panel found that it is feasible to build a motor-assisted sailing ship for ocean research that will perform as well or better than many of the present ships while cutting fuel consumption by 50 to 80 percent, depending on the task, the part of the ocean traveled, and the operating strategy.

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The Use of Sailing Ships for Oceanography

Ad Hoc Panel on
the Use of Sailing Ships for Oceanography

Ocean Sciences Board

Assembly of Mathematical and Physical Sciences

National Research Council

NATIONAL ACADEMY PRESS
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This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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Preface

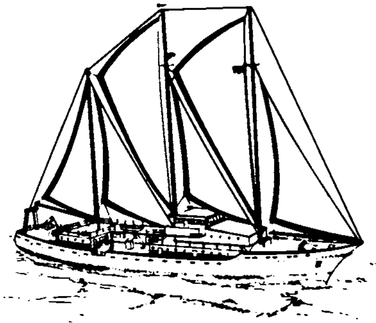
During its meeting of October 22-23, 1979, Ocean Sciences Board member Willard Bascom suggested that rising fuel costs, modern technology, and new design concepts might have combined to make the idea of a sailing research ship more attractive. Later, his preliminary investigation persuaded him that a more detailed examination would be worthwhile, and, at its February 20-21, 1980, meeting, the Board authorized him to form a small ad hoc group of experts to examine this question. They set out to determine whether it is feasible and sensible to build an oceanographic research sailing ship that will:

1. Perform all the needed scientific functions of a standard research ship.
2. Save at least three quarters of the fuel that would be used by an entirely engine-powered ship.
3. Perform essentially the same tasks as present ships without greatly extending the time at sea of the scientists and crew.

In addition, the group was asked to make a first estimate of the advantages and disadvantages (including comparable cost) and report back to the Board.

The group, consisting of naval architects and scientists with experience with sailing ships, met once in March 1980. This is their report. We hope that it will be useful to those considering the various alternatives for future oceanographic research ships.

Warren S. Wooster, Chairman
Ocean Sciences Board



1 Wind Power for Oceanographic Ships

The age of large sailing ships effectively came to a close in about 1910. Few have been built since then, and the few that are still being sailed are mostly square-rigged training ships. Until the last few decades a dozen or so oceanographic sailing ships were in service for some of the major institutions; these included Atlantis, Vema, Albatross, and E. W. Scripps. These have passed from the scene for the good reason that they were inefficient. No one wants to retrace those steps.

Now, circumstances have changed in a number of ways that make it worthwhile to reconsider whether a newly designed oceanographic ship that obtains much of its propulsion from the wind would be more efficient and satisfactory than other available choices.

The first factor to be considered is the recent great rise (and probable continuing rise) in the price of marine diesel fuel (Figure 1). Its per barrel cost rose from $3 in 1972 to $14 in 1978 to $34 in early 1980 to about $38 in late 1980. As of January 1981, spot prices for OPEC crude oil were at $43 per barrel and contract prices of $40 per barrel by spring were forecast. It has been estimated (by various oceanographic ship operators) that between 1978 and 1982 fuel costs of ships (in the 156-ft to 245-ft range) will increase by a factor of about 2.6 and that the percentage of operating cost in

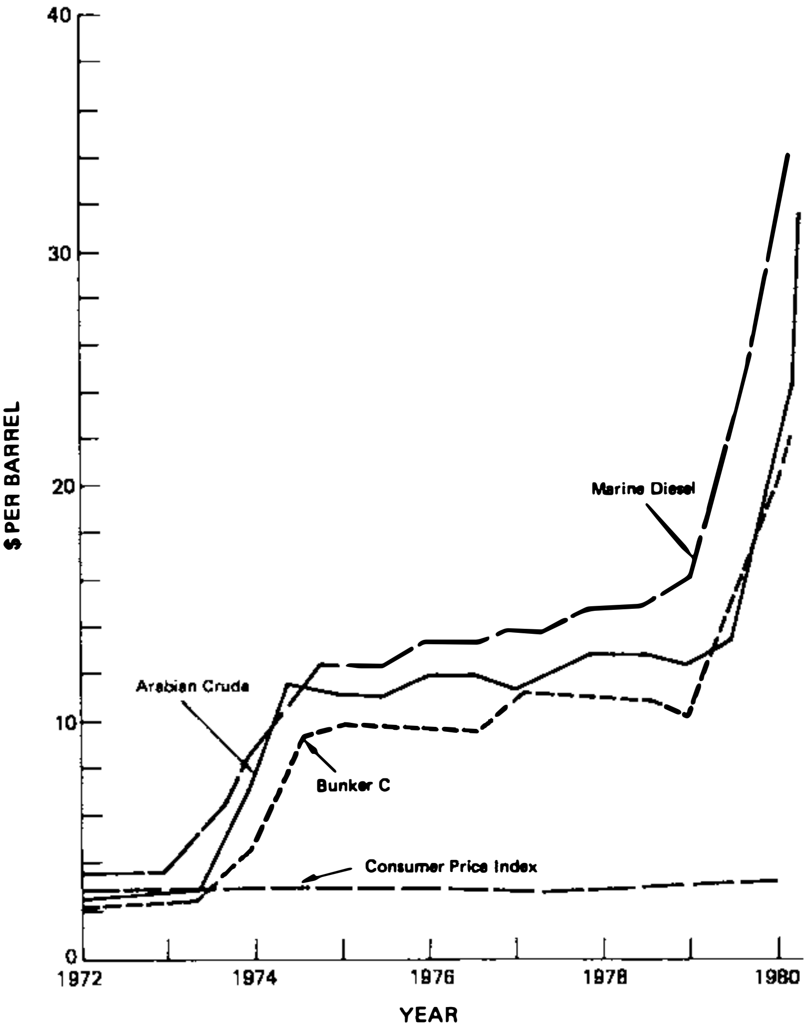


FIGURE 1 Oil prices in dollars per barrel (after Lloyd Bergeson). During the period when the consumer price index doubled, the price of marine diesel increased by a factor of 12.

fuel will rise from 135 to 264 percent. If the above estimates turn out to be correct, the average annual fuel cost per ship will be $424,000 (Table 1).

Fuel costs are rising faster than available operating funds, and a consequence already observed is a steady decrease in operating days as major vessels are laid up.

It is quite clear that any measure taken to decrease these large fuel costs would be most welcome if the savings are not made at the expense of other costs, which may be in the form of additional crew, longer transit times, or less-efficient scientific operations.

Thus, the purpose of this discussion is to set forth the arguments for and against considering a new type of ship whose principal objective is to save 50 to 80 percent of the fuel costs without making corresponding sacrifices.

Readers who are not well informed about how sailing ships make use of the wind might first read Appendix B, Principles of Sailing.

The reason for believing that it is now possible to build a more efficient sailing ship than has been possible before is that substantial technological advances have been made in the last few decades that have not been utilized in large sailing ships. For example: (1) new materials are now available such as aluminum for cabins and masts, polyester fabrics for sails, Kelvar polyaramid fiber for lines, and improved paints to reduce fouling; (2) new sailing technology has been developed such as boomless and sparless fore-and-aft rig, combined engine and wind propulsion, powered furling, and tension-limited sheets; and (3) new kinds of electronic aids are available for navigation, positioning, weather routing, and steering. Finally, new standards have been adopted for safety and habitability that will make it easier to find crew members.

A new deep-sea research ship, designed from the keel up to save fuel by utilizing all those features will be able to do science efficiently at sea. Such a ship will be able to do all the kinds of work that large existing multipurpose research ships do on long cruises. It can be expected to be a better scientific platform for some kinds of investigation in some parts of the world than some of the present ships. It will be relatively quiet, and, therefore, the scientists aboard will have better "feel" for the winds and sea around them. Vibration will be minimal.

TABLE 1 Fuel Costs, U.S. Oceanographic Ships[a]

Length Research Vessel	Actual 1978 $	Actual 1978 %	Est. 1980 $	Est. 1980 %	Est. 1982 $	Est. 1982 %	Average $ 1982	Average $ 1978
156	80.8	11.0	259	27.8	360	30.7		48.5
170	22.4	9.5	257	22.7	335	24.9	335	
174	42.4	6.3	324	31.8	310	29.5		
177	81.4	13.4	498	36.7	475	33.9		121
177	167.	16.6	284	22.1	358	23.1	432	
177	116.	14.4	405	33.7	463	33.4		
208	180.	11.8	322	18.7				
210	122.	9.0	367	18.1	360	16.7		126
210	267.	19.2	684	31.6	508	25.1	434	
245	440.	23.3	446	23.8	485	22.5		228
245	245.	14.0	443	24.2	508	24.2	496	
Averages:	160.3	13.5	390[b]	26.4	416[c]	26.4	424	

[a] Estimates by the present institutional ship operators. All figures in thousands of dollars. Some of these data reconfirmed in July 1980 by George Shor of Scripps Institution of Oceanography. Percentages are the fuel part of the total operating cost.
[b] 2.43 x 1978 costs.
[c] 2.59 x 1978 costs.

Roll will be reduced by the steadying effect of the sails. Speed under power will be about the same as present oceanographic ships; that is, it will be able to move at 10 to 12 knots on the propeller alone. In winds of 20 knots, this ship will make 12-14 knots on some wind slants; in stronger winds on favorable points of sailing, it will drive at 16-18 knots.

One of the largest problems with sailing ships in the past has been the uncertainty of arrival time at the next port or station. However, the combined use of sail and engines, the knowledge of the winds and seas ahead based on satellite data and modern forecasts, and the help of computers to lay a course and steer it, will greatly reduce the uncertainties. It will be possible to automate many of the operations.

The first step in designing a new ship is to state exactly what it will be required to do (see Performance Specifications, page 19). The primary job of a research ship is to be a working platform at sea for trawling, coring, sampling, and measuring; it should also be a comfortable home for the scientists aboard. It must have long range, that is, be able to operate in remote oceans at reasonable speeds for extended periods. The sole purpose of the kind of ship discussed here is oceanographic research. These techniques probably are not suitable for commercial purposes.

There are many possible variations of hull shape, sail plans, auxilliary power plants, and sizes. It was not practical for our panel to do more than consider briefly the most likely combinations of these.

Our choice of the ship most likely to meet the performance specifications and become a practical addition to the U.S. oceanographic fleet is given in the accompanying design sketches (Figure 2). These show a single relatively broad hull, possibly with retractable centerboards. This gives spaciousness, stability, and the capability of entering shallow channels. Fore and aft roller-reefed sails have been selected for convenience and minimal manpower; a power plant of variable output makes electricity as required for propulsion, winches, electronics, and housekeeping. The proposed length is about 250 ft and the beam about 50 ft. This is partly so that its volume will be sufficient to carry all the people, supplies, and equipment that are necessary, partly so that its performance can be directly compared with the larger ships of the present fleet, and partly

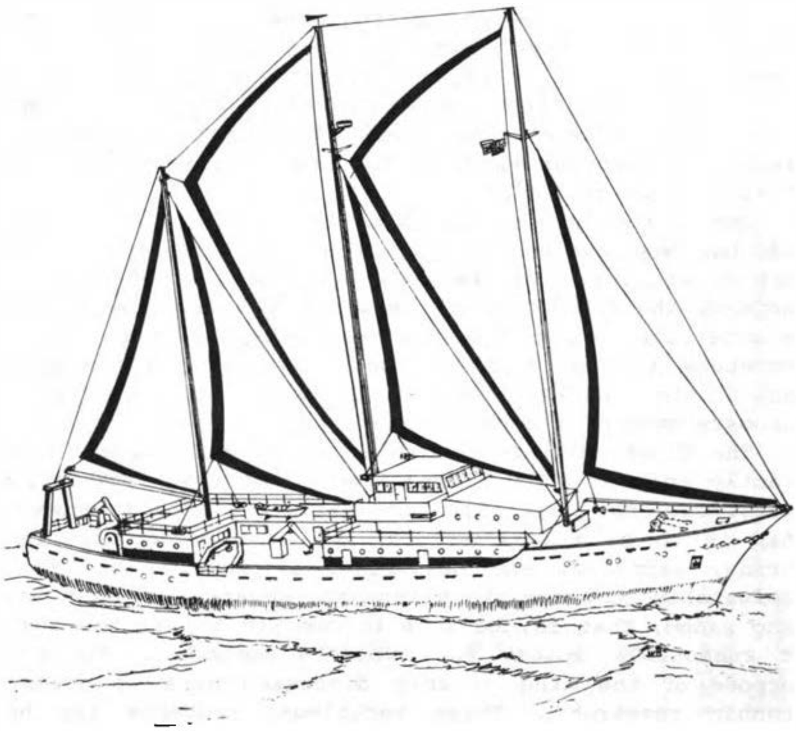


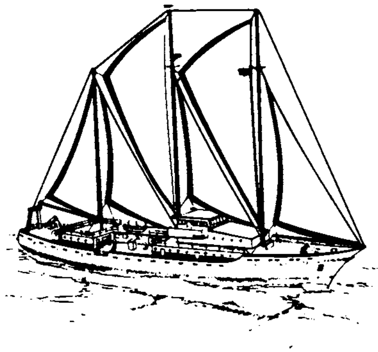
FIGURE 2 Design sketch of oceanographic motor-sailer.

because longer ships are faster. There will be three masts rising about 160 ft above the water (clearance under the Golden Gate and Verrazano-Narrows Bridges is 232 ft) and minimal standing rigging.

Of course, all the dimensions given undoubtedly will change as design work progresses, but these sketches and this outline of the characteristics give something tangible to discuss until our ideas are more explicit. It gives form to an otherwise amorphous idea.

We do not visualize that motor sailers like this would replace all engine-driven ships in the scientific fleet. We do expect that this ship will be more efficient for scientific operations in some waters than the ship it will replace. After the first oceanographic motor sailer is thoroughly tested, others would be built, each with improvements. The constraints of the more distant future cannot be foreseen.

We will be greatly surprised if oceanographers do not eagerly seek the opportunity to sail on this ship, and we foresee that there will be an increased willingness to undertake long voyages in more remote seas.

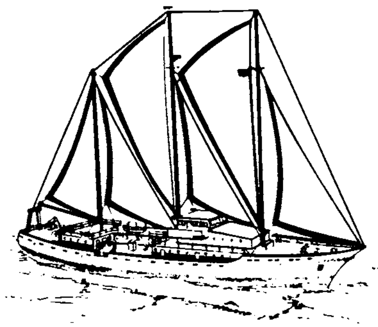


2 Panel Origin and Discussions

At an Ocean Science Board (OSB) meeting in 1979, Willard Bascom suggested that in view of the $6 million overrun in fuel costs for the U.S. oceanographic fleet in 1979, it might be wise to reconsider using wind-powered ships for oceanographic work. OSB Chairman Warren Wooster then requested that Bascom convene a small group to study the question of whether it is feasible and sensible to build a sailing ship for ocean research that would (1) be able to perform the usual kinds of ocean research while (2) saving about three quarters of the fuel that would be used by an engine-powered ship making the same stations (3) without greatly extending the time at sea of the scientists and crew.

Accordingly, an _ad hoc_ panel was formed that met on March 27, 1980, at the Explorers Club in New York to discuss the matter. The panelists all agreed that there is sufficient merit in the concept of a "large motor-assisted sailing ship" that it should be pursued further and a design developed.

Since that time we have exchanged letters and report drafts and talked by telephone on various occasions. We have reached substantial agreement on the points expressed here.



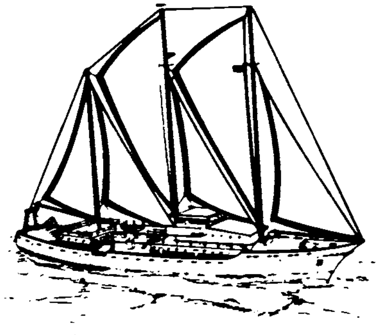
3 Summary of Conclusions and Recommendation

We believe that it is feasible to build a motor-assisted sailing ship for ocean research that will perform as well or better than many of the present ships while cutting fuel consumption by 50 to 80 percent, depending on the task, the part of the ocean traveled, and the operating strategy.

We believe that a modern sailing ship with ample auxilliary power will be quiet, have reduced vibration, and roll less than a motor ship of the same size and that it will find favor with the scientists who use it.

We believe that enough information has been assembled to justify the cost of a study of the characteristics that such a ship might have. This study would develop a preliminary hull design and plans for sail and engine arrangements, provide polar sailing diagrams, and make an economic comparison of fuel saving on typical scientific expeditions.

Therefore, we recommend that the Ocean Science Board take the lead in this matter by urging appropriate government agencies to sponsor a more detailed design.



4
Advantages of a Modern Motor-Sailing Ship over Sailing Ships of the Past

1. Triangular sails can be luff-roller furled around a head stay--and be remotely controlled. No pivoting spars and no men aloft are required. See Figure 3 for a description of roller furling.

2. Sails can be made of polyester fabric that will last longer and hold their shape better.

3. Sheets can also be remotely controlled. They will be steel and have tension-limiting releases (so ship cannot be blown over by a sudden strong gust).

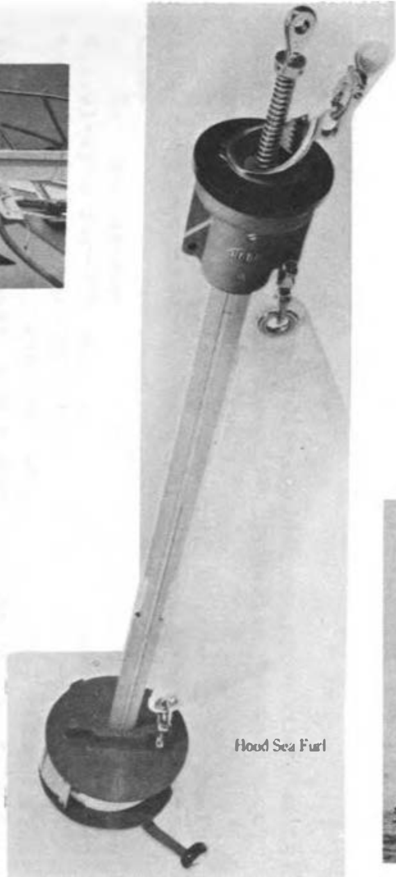
4. Ship can sail much closer to the wind (perhaps as close as 25°) while motor-sailing.

5. Ship can have generous electric power supply with silicon-controlled rectifier (SCR) speed control (for motors) for all functions including auxilliary propulsion (which will drive the ship at 10 knots in windless conditions), bow thrusters (for stationkeeping), electronics, and housekeeping.

6. Modern hydrodynamic/aerodynamic knowledge can develop better hull lines and sail forms.

7. Hull can be made of mild steel, welded, protected from fouling (a big problem with early steel ships).

8. Weather can be forecast and/or obtained directly from satellites and the sailing route selected accordingly.



SEA FURL's high torque strength aluminum luff extrusions come in lengths which can easily be shipped anywhere in the world. These sections are assembled over the headstay and do not replace it. Consequently, the integrity of the headstay is retained and if a luff section is damaged, it can easily be replaced. Furthermore, the headstay can be set up tight to minimize luff sag but the bearings are not subjected to the resultant and constant headstay tension. This means fewer maintenance problems, easier reefing and furling of the jib in all wind conditions, plus peak performance when sailing to windward.

The sagging luff and sail storage problems of simple furlers stimulated development of grooved, one piece solid rod headstays. Hood Yacht Systems "Sea Stay" was a forerunner of these systems. Actually taking the place of the headstay, such systems can be set up as tight as desired to minimize sag. Grooves in the luff extrusions accept a special small diameter bolt rope so the sails can be raised or lowered quite easily for changing and bagging. Swivels and a furling drum permit the entire extrusion to rotate so the sail may be partially reefed or furled completely.

FIGURE 3 Luff-roller furling.

9. Ship can have all the comforts of other modern ships and meet modern safety standards.

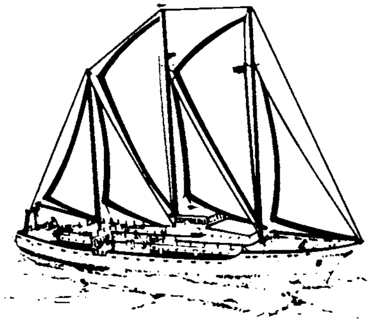
10. Instrumentation is now available for knowing position precisely, obtaining wind direction, watching for ice and land, and measuring water depth, stress on lines, and other factors.

11. Controllable pitch propellers or free-wheeling propellers are now available.

12. An oceanographic ship would be lightly loaded relative to cargo-carrying ships of the past.

13. Autopilot can be used to steer the ship, based on wind direction sensed at the top of the masts.

14. Computers can be used to lay an optimum course to reach a destination.



5 *Advantages and Disadvantages of a Modern Motor-Sailing Ship over a Modern Engine-Powered Ship*

ADVANTAGES

1. Vibrations and noise caused by propulsion units will be greatly reduced, making it easier to use microscopes, to think, and to rest.

2. Sails will reduce the roll of the ship, making life more comfortable, especially when hove-to on station.

3. Propulsion power can be readily adjusted with a diesel-electric-SCR control system to maintain the intended speed so that schedules can be kept.

4. Sails will save fuel while under way, permit ship to stay at sea longer, and reduce the change in stability caused by the changing load of fuel.

DISADVANTAGES

1. The largest problem to be overcome may be the state of mind of some scientists or administrators who know little about large sailing ships and may react negatively before investigating the possibilities. (There is a widespread image of square riggers rounding Cape Horn in a gale with men hanging on the yards that does not fit the ship we have in mind. See Figures 4 and 5.)

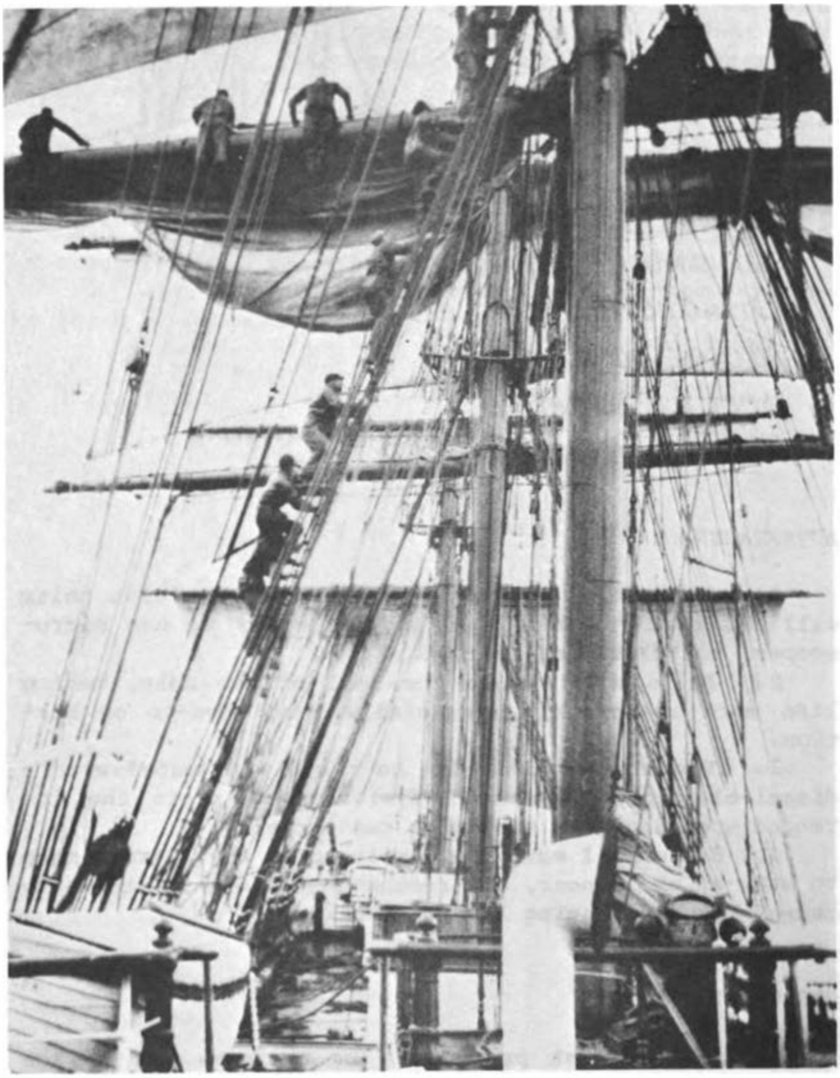
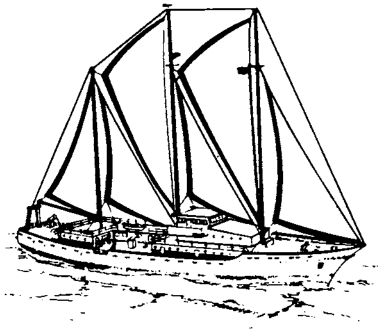


FIGURE 4 These days are gone. On a modern sailing ship there will be no spars, little rigging, no men aloft, and powered sail furling.

FIGURE 5 The square rigged ships of 80 years ago were handsome but demanding.

2. There may be some uncertainty about whether a complex scientific program can be carried out on schedule, or that a sailing ship can hold station, or steer a proper course, or that it will suddenly heel in beam winds, or that its rigging will be in the way of deck operations. Mast height may prevent using some harbors where bridge clearances are low. Masts and rigging give additional unwanted windage when the ship is moving into the wind under power. Those are reasonable problems to raise, and the prospective operator must be assured that they can be overcome or minimized.

3. We believe that most problems can be resolved in the proposed design/study and that those remaining can be resolved during actual operations at sea.



6
Designing a New Class of Ship

It is difficult to discuss the virtues and problems of a ship that does not exist. Although it may not be difficult to get agreement on design principles, it often turns out that when a generalized plan becomes specific there are many objections. Therefore, it is useful to have a specific ship design to consider so those involved can visualize how it would be used in various circumstances. Each scientist or sailor can then think about what his own cabin or laboratory or actions will be like during a voyage.

Our panel began by listing what should be expected of a general-purpose long-range oceanographic ship, regardless of its method of propulsion. We believe that the sailing ship should meet all those requirements and otherwise perform comparably with the best of the existing ships whose fuel costs are cited in Table 1.

TABLE 2 Design Characteristics of an Oceanographic Sailing Ship (Bascom Sketch Plan)

Length	250 ft
Beam	50 ft
Mast Height	160 ft
Tonnage (est. for steel hull)	1400 ft
Crew	16
Cadets	3
Scientists	18
Wet laboratory	800 ft^2
Dry laboratory	2800 ft^2
Instrument laboratory	2500 ft^2
Afterdeck working space	900 ft^2
Side deck working space	1500 ft^2
Electric plant 3 - 400-HP diesel (all purposes)	
Main prop 400-HP	
Bow thruster 200-HP	
Sail area to wetted surface: about 1.3:1	
Crane, after deck	
Crane, side deck	
Main winch	
Hydro winch	

Sail plan: 3 masts, fore and aft luff-roller furled sails. Furling and sheets controlled from the bridge. Probable speed on favorable point of sailing--14 knots. Navigation by satellite, Omega, Loran C, radar.

TABLE 3 Roster

Scientists' berths	24
Captain	1
Mates	3
Bosun	1
Able seamen	3
Cadets[a]	3
Chief engineer	1
Engineer officers	2
Mechanic	1
Winch engineer	1
Cook	1
Mess cook	1
	42

[a]A cadet is a volunteer apprentice seaman who works without pay while learning how to sail and navigate a ship. We think there would be many volunteers.

Performance specifications (apply to most deep-sea research ships):

1. Must be able to operate safely in any part of the ocean for at least 2 months. It must be able to survive all weather and be able to do useful work in a State 5 sea.

2. Must carry 12-24 scientists in comfort with at least 150 ft^2 of laboratory space for each scientist in the following forms:

Wet laboratory (on deck for overside gear);
Dry laboratory (paperwork, microscopes, etc.);
Instrument/computer laboratory (both of the latter should be air conditioned)

3. Must have adequate electrical power for housekeeping, instrumentation, winches, and additional necessary uses.

4. Must have an average under-way speed of about 12 knots.

5. Must carry coring winch (40,000 ft of 9/16-in. wire), hydrographic winch (30,000 ft of 1/4-in. wire), proper A frames, and cranes for handling heavy gear overside.

6. Should be quiet both accoustically and electrically.

To which we have added for a sailing ship:

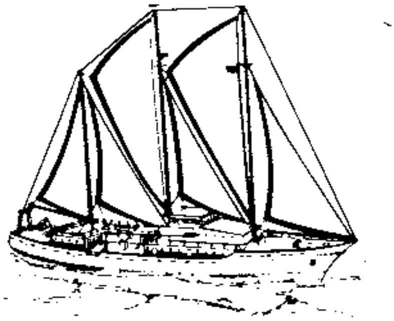
1. Should save 50 to 80 percent of fuel of a comparable-size motor ship.

2. Should not require much more crew than a comparable-size motor ship.

3. Heel of ship should not exceed 10° in normal conditions.

4. Sails and working decks should be in convenient view of the bridge.

Tables 2 and 3 summarize some tentative design characteristics and outline a possible roster of the crew.



7
The Strategy of Motor-Sailing

The relative efficiency of sailing improves with the amount of wind available. The wind usually is better in the winter and at higher latitudes; it decreases in the equatorial doldrums. Only enough auxilliary power was installed in early ships to give maneuvering capability in harbors and channels or to traverse calms. Ships designed to move along routes with strong winds had small engines; those meant to sail in variable winds carried more installed power. The reason why large square-rigged ships never tried to use much auxilliary power was that the huge aerodynamic drag of the masts, spars, and rigging made such propulsion inefficient. A fore-and-aft sail plan with relatively little rigging greatly decreases that drag, but the fact that the drag (of both air and water) increases as the square of the velocity is always on the mind of the designer. Most large sailing ships were built to carry cargo; for that purpose their principal advantage (in addition to saving fuel) over ships with engines, was that cargo could be carried in the engine room space.

A sailing ship for worldwide oceanographic research (perhaps with an increased likelihood of assignments in higher latitude) must be expected to encounter the maximum variation in winds. Therefore, it is necessary to design a ship that will optimize the use of wind power while maintaining overall voyage speed at that of an equivalent motor ship. As long as there is ample room for scientific work, the space used for the engine room is of no concern, especially since increased length gives more speed. (Hull speed, the upper practical limit of speed for a displacement hull in ideal winds, is approximately 1.0 to 1.3 times the square root of the waterline length--in the case of a 250-ft overall ship, this is about 15 to 18 knots.)

The strategy for optimizing speed and minimizing fuel costs by using the best combination of sail and engine power needs to be carefully thought out after a final design is agreed on and more data are available. However, it may be something like this:

1. All sails spread (up to safe limits) on all courses except those within 25° of the wind direction.

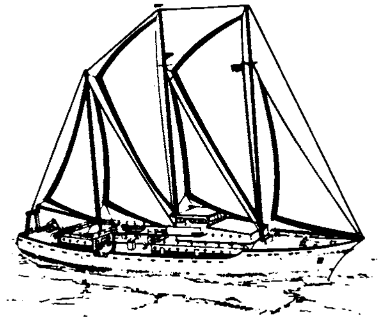
2. Propeller to free-wheel or be feathered until forward speed drops below 10 knots. At that time, the propeller is engaged and motor is run to bring ship up to 10 knots or desired speed.

3. On certain wind slants the "course made good" can be substantially improved by running the motor-propulsion enough so that the sails "see" the wind differently and the ship can sail closer to the wind.

4. On courses directly downwind, the ship may have to tack to develop enough wind slant to make the sails effective.

5. With electric propulsion and SCR control of motors, electric (or hydraulic) control of sail furling and sheets, routing data from satellites and elsewhere, wind vanes aloft, and autopilot steering, it will be possible to use a computer to optimize course and minimize fuel expenditure.

6. Once under way at sea the watch officers will be largely concerned with watching for obstacles and seeing that the electronics functions properly.



8 *Why Not Start with a Smaller Ship?*

Several reviewers who favor the principle of using sail to save fuel have suggested that it might be better to begin with a ship smaller than the one described. Presumably their thought is that the idea of doing oceanographic research from a sailing ship should be tested with a vessel that is less expensive to build. Then, if it worked out well, one could step up to a larger ship.

There are several kinds of answers to that. One is that a similar but smaller ship (Audela) 125 ft long (Figure 6) already exists; it served as a partial model for the one proposed. It sails well with a small crew, but it is not designed for oceanographic work. Such a ship could make long voyages, but it could not carry the people, equipment, or supplies needed for useful scientific work in distant seas. It is possible that in some specific part of the world a small sailing ship would be useful in coastal work. Windward and Young America (each about 100 ft on deck) are examples of small oceanography training ships now in use. However, they do not meet the requirement of a deep-sea research ship. It would be a mistake to build a sailing ship either to prove the obvious (that sails will move a ship) or for a demonstration in a size or for a use that puts the technology at a disadvantage. In restricted waters, or if many stops and starts are needed, a motor ship is probably best.

A better answer to the comment about size is that all ships (and all engineering projects) are designed to meet a set of performance specifications that are established before design begins. These specifications are usually aimed at maximizing the most promising features of the technique to be exploited--in this case the use of sails to save fuel. So we set up performance specifications for a ship that would compete exactly with the ships in the present oceanographic fleet that are used for deep-sea research on long voyages. In addition to making sail and motor ships directly comparable, this tends to maximize the value of wind power without giving up other val-

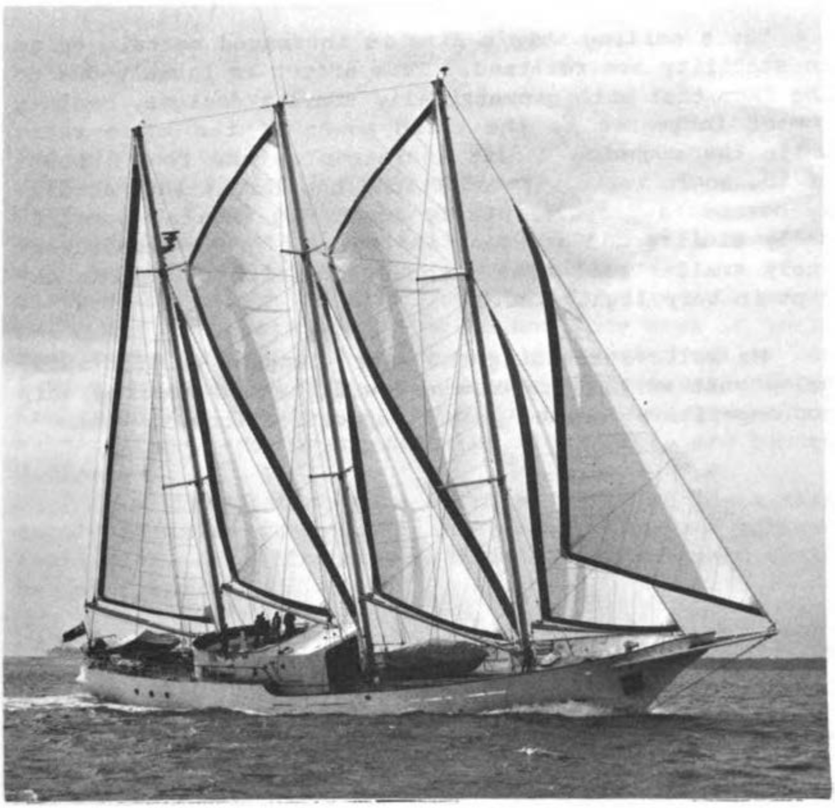


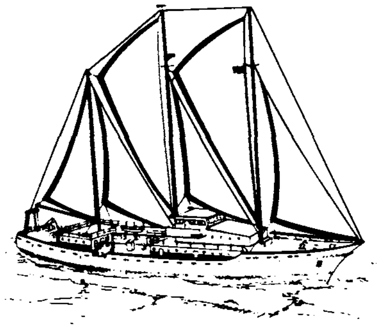
FIGURE 6 Audela, a 125-ft English yacht sailing into the wind.

ues; that is, both kinds of ships will perform any ocean-science function. Moreover, since good speed through the water is a valuable asset and this is related to length, it is sensible to have a hull at least as long as the competition. Furthermore, since the volume (displacement) of a ship varies as the cube of the length, a small change in length makes a great difference in its carrying capacity. For example, a 250-ft-long ship is twice as large as a 200-ft-long ship and four times as large as a 160-ft-long ship. So, if we were to go to the latter size there would be about one quarter the space and the hull speed would drop by about 25 percent.

The following comments from Woodward _et al_., in a University of Michigan study for the Maritime Administration in 1975, may be helpful in the consideration of the question of size.

"As a sailing ship's size is increased certain gains in stability are realized. This effect is largely due to the fact that with geometrically similar designs, heeling moment increases as the third power of the scale ratio while the righting moment increases as the fourth power of the scale ratio. In addition, the larger ship actually carries a proportionately lower rig than a geometrically similar one and can, in general, use a proportionately smaller sail area without sacrifice of speed, except in very light wind."

We believe reducing the size (length) substantially below what we have recommended will make a sailing ship noncompetitive for the present specifications.



9 Capital Costs

The plan layout (Figure 7) by Willard Bascom given here approximates the hull shape and sail plan that would be used. The final design may be shallower or deeper, the masts may be shorter, the sails and cabins will undoubtedly be arranged differently. The intention was to stimulate a discussion of ship characteristics not to get a basis for cost estimates. We do not know what it would cost to build such a ship, and no large motor-sailer exists today that we know of. We warn against anyone trying to make a usable cost estimate until the size, characteristics, and arrangements of such a ship are better defined.

This presentation puts forth a series of ideas that should minimize fuel costs and maximize range, working facilities, and efficiency. It is directed toward optimal operations.

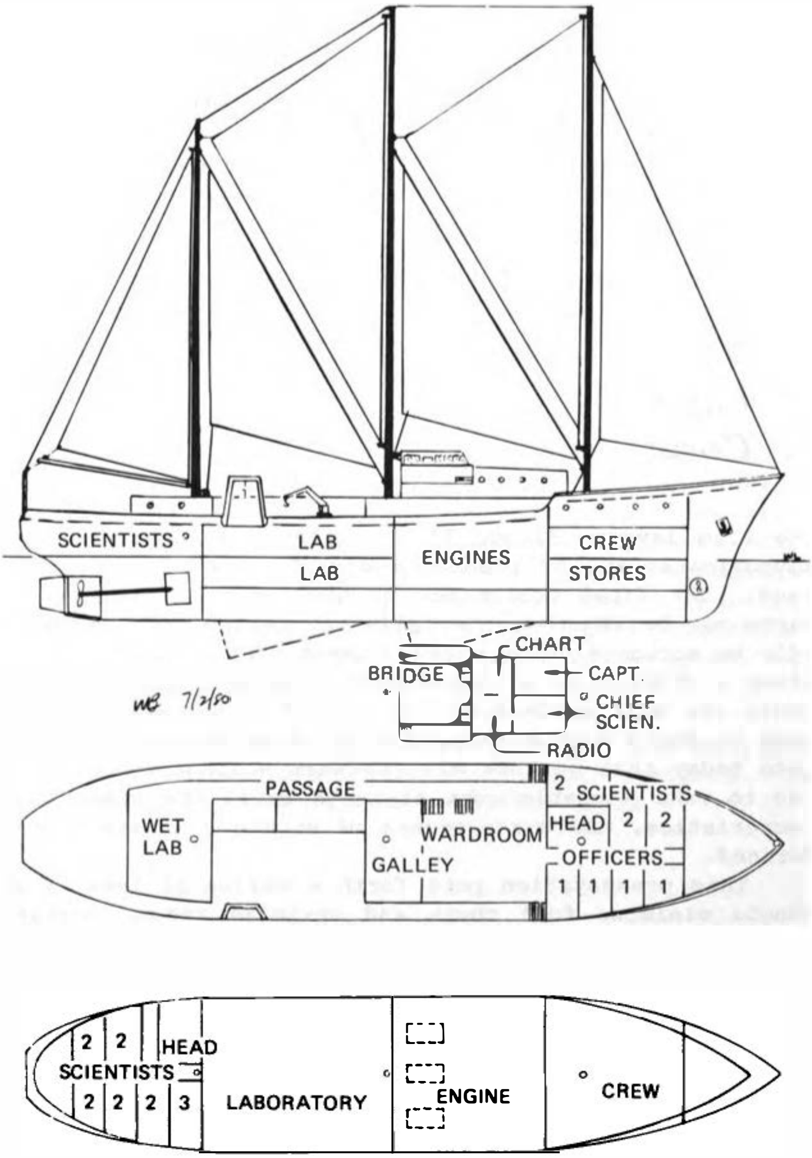
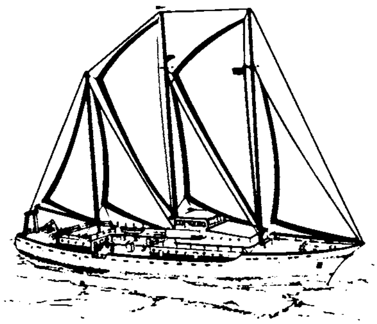


FIGURE 7 Plan layout of oceanographic motor-sailer.



10 Recommendation

We have considered the possibilities of using motor-sailer ships for oceanographic research and believe that the possibilities are promising relative to other kinds of ships, considering the needs and the probability of increasing cost of fuel.

We recommend that the Ocean Science Board take the lead in proposing further investigation of the possibilities for using sailing ships for oceanographic research by urging the appropriate government agencies to sponsor a more detailed preliminary design study.

This study would better define requirements, relation to the rest of the oceanographic fleet, size, hull form, sail plan, automation possibilities, and fuel savings on various voyages and make preliminary capital and operating-cost estimates.

APPENDIX A Background of Panelists

Willard Bascom, chairman Sometime sailor on trading schooners and yachts, some experience in designing and operating motor ships, student of ancient sailing ships.

Lloyd Bergeson, naval architect. Involved in the development of ships, including nuclear submarines and LNG carriers; one-time general manager of two large shipyards. Trans-Atlantic crossing single handed. Now president of Wind Ships Development Corporation, which is actively planning modern sail-cargo ships.

Corey Cramer, Executive Director of Sea Education Association. Operator of the auxilliary staysail schooner Westward, used for oceanographic training. Long-distance sailor, ex-Coast Guard skipper. Sailed on the WHOI ship Atlantis.

R. T. Dinsmore, Ex-Coast Guard. Licensed for 700-ton sailing ships. Instructor in oceanography and sailing on U.S. Coast Guard sailing ship Eagle. At present, ship superintendent at Woods Hole Oceanographic Institution.

Gustaf Arrhenius. Sailed around the world on the Swedish Albatross deep-sea scientific expedition in 1947-1948. Professor of Oceanography at Scripps Institution of Oceanography.

Frank MacLear, of MacLear & Harris, Inc., New York City. Naval architect; designer of short-handed sailing yachts and motor-sailing commercial vessels; long-distance sailor; specialist in automated sail handling.

James Mays, naval architect. Expert on ship motions; makes computer models of sailing ship forms and responses for Wind Ships Development Corporation.

APPENDIX B *Principles of Sailing*

This elementary discussion of the principles of sailing was added after the rest of this report was completed for the benefit of those who do not understand how a sailing ship can sail in any direction it wishes as long as there is wind. As one astute reviewer put it: "But the wind blows every which way." So it does, and for about 5000 years men have known how to use it to go where they wished.

Some very early ships with flat bottoms and square cross-ways sails could only sail in the same direction in which the wind was blowing. But thousands of years ago the lateen rig, the keel, and the rudder were invented so that ships could sail toward the wind. Not directly into it, but perhaps as "close to the wind" direction as 60°. Very much later, the schooner fore-and-aft sail plan improved on that somewhat.

The reason they could do that, although no sailor would have put it into these words, was that a cloth sail, secured at the leading edge to a straight spar forms an airfoil section and "lifts" the ship horizontally. In other words, a ship moves into the wind for the same reason that a glider flies. Both get "lift" from the air flowing over these airfoils. Even square-rigged ships could set their spars so that the sails were nearly parallel to the keel and sail into the wind.

The keel, which extends downward below the hull, is essential because it prevents the ship from slipping sideways excessively. Without it, the ship would drift with the wind; with it to take up the reaction, the lift of the sail can be applied usefully. Once the ship is under way, the rudder is used to move the stern from side to side and change the direction of the keel (the ship).

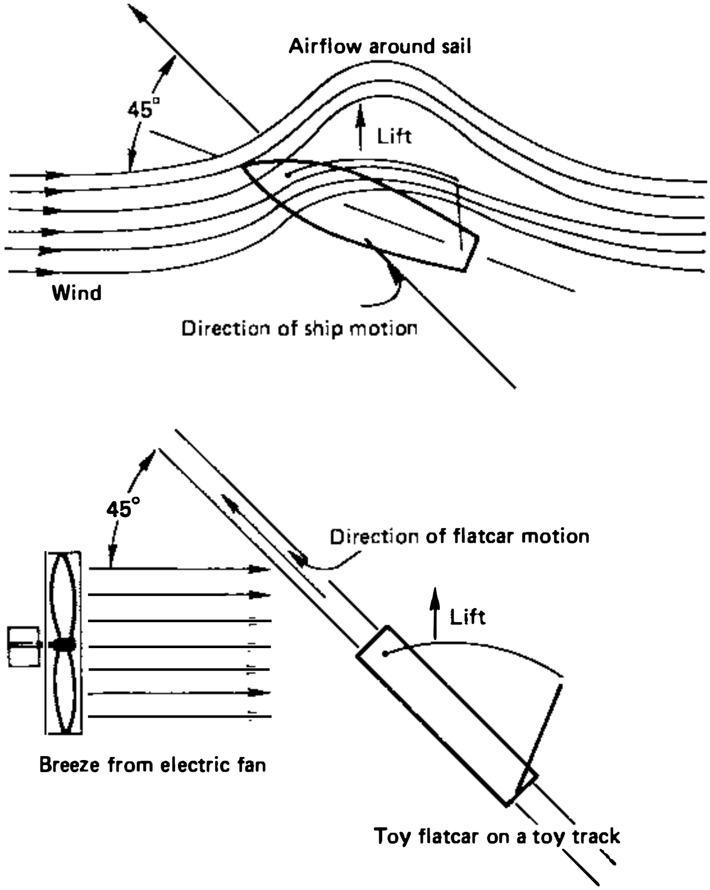


FIGURE B.1 Sailing upwind with airfoil lift from a sail.

Figure B.1 is a sketch of a toy train-track, an electric fan, and a sail mounted on a toy flat car. When the fan is turned on, the flat car will "sail" up the track. If the angle of the track relative to the breeze from the fan is changed until it becomes too small, eventually the car will be driven backwards. Modern sailing yachts act as shown in the upper drawing to sail up to about 45° off the wind.

Sailing in any downwind direction is easier to understand but likely to be slower; yachts often raise large additional sails called parachutes or spinnakers to improve their speed when they run "before the wind." Sailing cross wind ("on the reach") is most convenient; the sheets (lines that control the angle of the sail to the keel) are adjusted so that there is the best possible angle between wind and sail and the best airfoil develops. A yacht's best "point of sailing" (angle with the wind where it goes fastest) is somewhere between the reach and the closest it can sail into the wind, because it gets the most lift when sailing partly into the wind.

Now we have covered all wind directions except the 45° on each side of the direction from which the wind is blowing. In order to sail into that quadrant it is necessary to tack, that is, to sail into the wind as closely as possible, alternating sides at regular intervals. The distance sailed is greater, but the ship reaches its destination.

In sailing upwind, motor sailers have the same advantage over an unpowered sailing ship that a powered aircraft has over a glider. The apparent wind is stronger, and there is more lift from the sails. Thus, the ship proposed here is expected to sail up to about 25° off the wind with motor assistance, reducing the zone that requires tacking to 50° (about 14 percent of the compass).

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