DOE/R5/10288-2

IL-81-007

ECONOMIC FEASIBILITY OF SAIL POWER DEVICES

ON GREAT LAKES BULK CARRIERS

DOE/R5/10288--2

DE83 001119

SUBMITTED BY: GRAHAM & SCHLAGETER, INC.
444 N. Lake Shore Dr.
Chicago, Ill. 60611

DOE GRANT NO. DE-FG02-81R510288
9/22/82

DISCLAIMER

TABLE OF CONTENTS

LIST OF TABLES AND FIGURES

MAIN REPORT

APPENDIX I

LIST OF TABLES AND FIGURES (cont.)

FOREWARD

BACKGROUND

Since the tenfold increase in oil prices that started in the early 1970s, a subject of great concern to worldwide shipowners has been how to minimize the cost of fuel used in sea transport. With the daily fuel bill for global shipping approaching 120 million dollars , this subject is also of great concern to the industrialized countries.

Several studies have been conducted recently to investigate the feasibility of fitting ships with sail devices to augment the power plants. One such study done by Wind Ship Development Corp. concluded that such ships with sails as the primary source of driving power are in fact both economically and technically feasible on certain routes. The problem with this report is that it concentrated its efforts on new ship design and construction. Due to the global glut of ship capacity and the high interest rates, new ship construction is not really practical at the present time.

Other more practical studies are also being conducted at the present time. The Japanese have fitted a small freighter with a wing sail device and have reported fuel savings of as much as 50%. There is also a fleet of small freighters in the Caribbean that have been fitted with 3000 sq. ft. sails to save on fuel costs.

The idea of retro-fitting existing ships with sail devices is intriguing as it can be done relatively cheaply, costing hundreds of thousands of dollars rather then the tens of millions of dollars that new ship construction costs.

PURPOSE

As a research project, under the auspices of the Appropriate Technology Small Grants Program administered by the Department of Energy, the economic feasibility of retro-fitting existing Great Lakes bulk carriers with sail devices as an auxiliary power source will be investigated.

The purpose of this report is to outline the method used and the conclusions reached.

SUMMARY

MODELLING AND RESULTS

As discussed in more detail in the following pages, three ships were examined, the ED RYERSON, the ST. CLAIR, and the STEWART CORT to determine if retro-fitting these ships with a 3000 sq. ft. soft sail cat rig is economically feasible. By using existing weather data taken from recorded observations on Lake Michigan and Lake Superior and known performance characteristics of both the sailplan and hull, a computer program was written to model the problem.

The measure of merit for this study is the average annual cost (AAC). By estimating the extra costs involved in retro-fitting the chosen rig such as insurance, maintenance of the rig as well as the capital expenditure involved in purchasing the rig then comparing it to the amount of fuel that can be saved, we can measure the economic feasibility of the idea. If the AAC goes up, then the idea is not feasible, if on the other hand the AAC is reduced, then it is feasible economically. Three cases for each ship were estimated. The first was the average fuel savings, second was an optimistic estimate of fuel savings, and the third was a pessimistic estimate of fuel savings.

Several considerations had to be taken into account that had serious consequences for the economic viability of the idea. One was the fact that all of the aforementioned ships have self unloading equipment that require about 80% of the deck space to be clear. This limited the choice of sailplans to one per ship. Another consideration is that due to bridge clearance problems an air draft of less than 125' was required. These two factors limited the size and efficiency of the sail plan. The third consideration is that due to the very tight shipping channels on the Grat Lakes, there is no provision for altering course to take advantage of prevailing winds in order to maximize the usefulness of the sail device.

CONCLUSION

The conclusion of this report is supported in detail in subsequent pages.

The sail device on the ED RYERSON does not seem to be

economically feasible. Even at the lowest interest rate investigated in this study (8%) the average annual cost improves only in the optimistic estimates. At 12% interest even this slight advantage disappears. In order for the device to be advantageous on this ship fuel prices would have to jump substantially something that probably will not happen in the forseeable future, notwithstanding recent history.

The sail devices on the STEWART CORT and ST. CLAIR seem to be marginally feasible at low interest rates and the present cost of fuel. The STEWART CORT seems to benefit most from the fitting of a sail device. A modest increase in fuel prices, perhaps possible, will make both of these ships look substantially better.

ANALYSIS DESCRIPTION

In order to properly analyze the problem of the economic feasibility of sail devices on Great Lakes bulk carriers, three basic tasks had to be accomplished. They were:

1. Data Collection
2. Computer Simulation
3. Financial Analysis

Below is a detailed description of the basic tasks and how they relate to the overall problem.

DATA COLLECTION

For this study enough data was needed so that the physical problem of motor-sailing could be properly modelled and the financial aspects could be accurately estimated. To accomplish this data was needed in four general categories; ship performance data, sail performance data, weather data, and route data.

A. Ship Performance Data

The major source of ship performance data were references (3), (15), & (16) which are reproduced herein as figures 1, 2, & 3. These particular graphs are curves of various horsepowers versus speed. The horsepower numbers are calculated from model resistance data derived from towing tank tests. The service speed assumed for all the ships in this study is 15 mph, a standard steaming speed for Great Lakes bulk carriers.

The specific data needed from these graphs are effective horsepower (EHP), shaft horsepower (SHP), and propulsive efficiency (^{n}d). EHP is the horsepower needed to overcome the resistance of the ship. SHP is the horsepower that must be developed by the diesel engine to drive the ship at the given speed. The propulsive efficiency is the ratio of EHP/SHP. This efficiency is always less than one and takes into account power loss in the shaft, bearings, and propeller.

With the EHP value for each ship it is then possible to calculate the resistance of the ship in pounds using the formula:

$$R_t = \frac{550 \cdot EHP}{V}$$

FIGURE 1

HORSEPOWER VS.=SPEED

M/V ED RYERSON

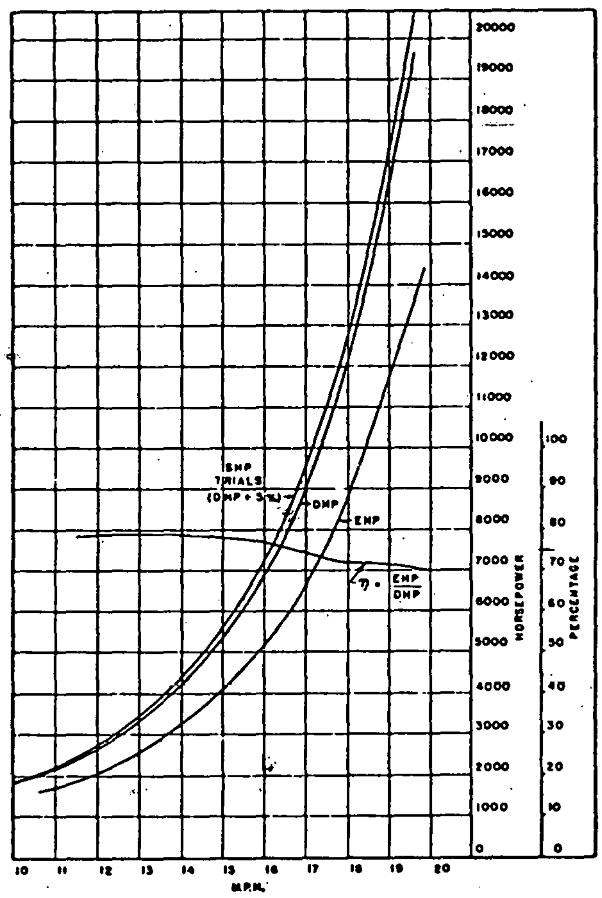


FIGURE 2

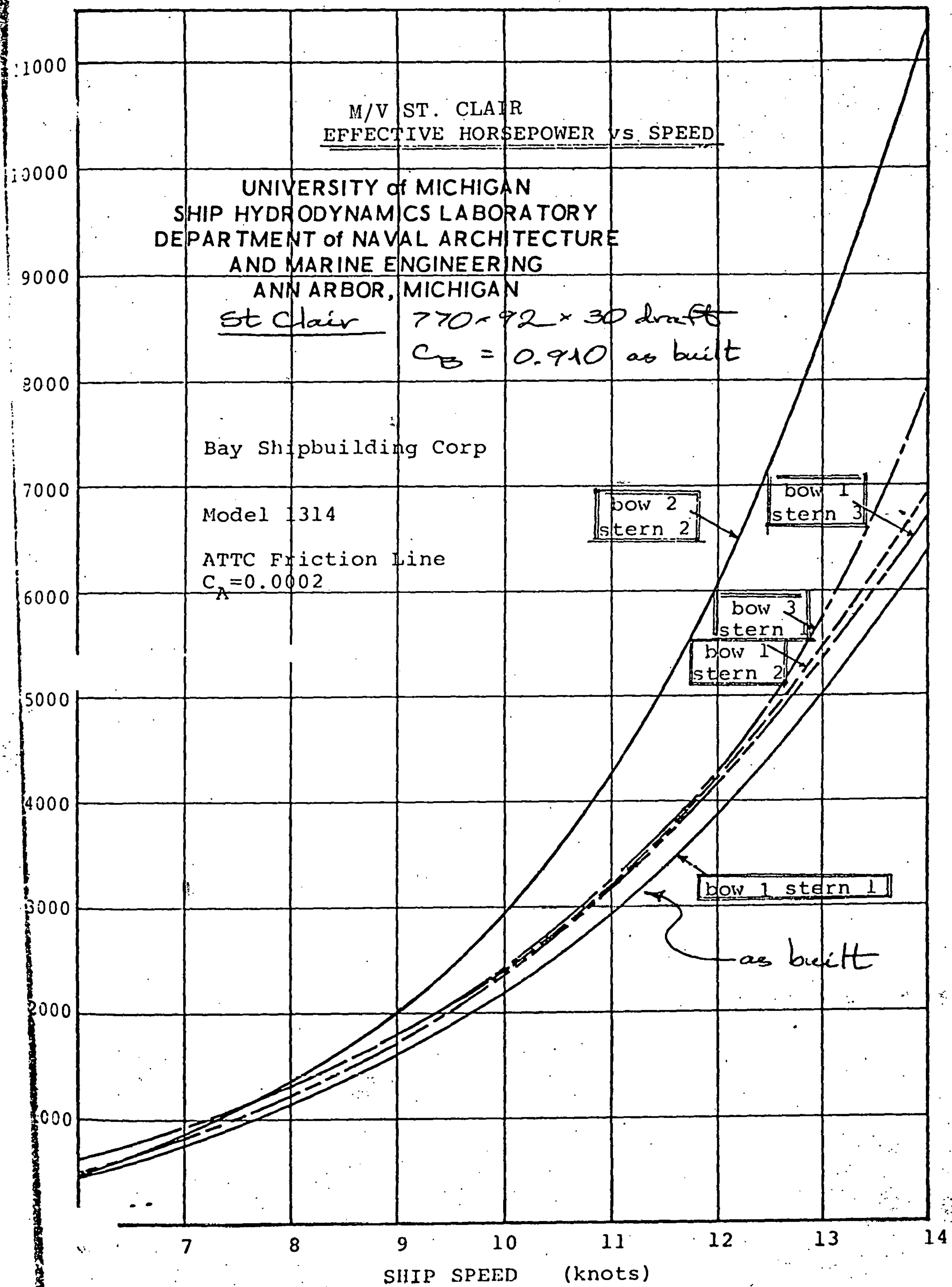
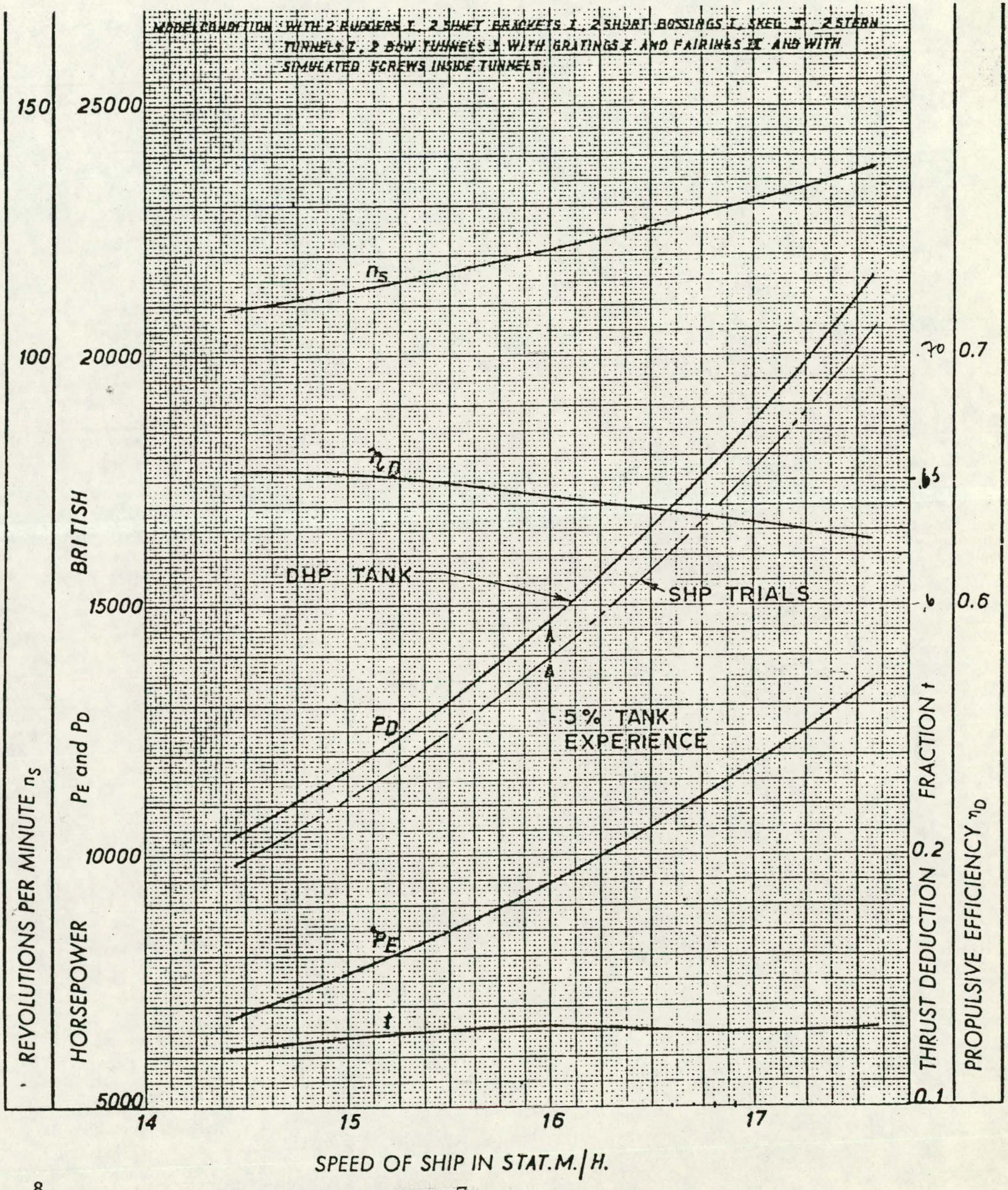

M/V ST. CLAIR
EFFECTIVE HORSEPOWER vs SPEED
UNIVERSITY of MICHIGAN
SHIP HYDRODYNAMICS LABORATORY
DEPARTMENT of NAVAL ARCHITECTURE
AND MARINE ENGINEERING
ANN ARBOR, MICHIGAN
St Clair 770 × 92 × 30 draft
C_B = 0.910 as built
Bay Shipbuilding Corp
Model 1314
ATTC Friction Line
C_A=0.0002
bow 2 stern 2
bow 1 stern 3
bow 3 stern 1
bow 1 stern 2
bow 1 stern 1
as built
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
11000
7
8
9
10
11
12
13
14
SHIP SPEED (knots)

FIGURE 3

M/V STEWART CORT



where: R_t = resistance of ship in lbs.

V = speed of ship in fps

The upright resistance of each ship is an important number because once the available thrust from the sailplan is calculated it is deducted from this resistance to yield a new horsepower that must be developed by the engine to overcome this resistance.

SHP is used to calculate the amount of fuel that is consumed by the engine since fuel use is directly proportional to the output horsepower. By calculating new EHPs (based on a lower resistance) it is possible to calculate SHP by using the propulsive efficiency, ^{n}d.

The values for resistance in pounds and the propulsive efficiencies for the three ships are as follows:

ED RYERSON:	Resistance = 102,500 lbs.	@15 mph
	n_d = .77	
STEWART CORT	Resistance = 191,250 lbs.	@15 mph
	n_d = .651	
ST. CLAIR	Resistance = 125,000 lbs.	@15 mph
	n_d = .67	

Note that the ED RYERSON has a substantially higher propulsive efficiency than the other two ships. This is because she was built in the early 60s and reflects a more hydrodynamically efficient hull shape. The other two ships were built in the 70s and sacrificed hydrodynamic efficiency for cargo carrying ability.

Other data needed to accurately model the ship's performance when under sail is data on the ship's characteristics when acted upon by a side force. This is due to the fact that a sail device, like any wing, produces a side force along with the forward driving force. The effect of this side force is twofold. First this side force, because it is working thru a center of effort above the ship, will cause the ship to heel a certain amount. The second effect is to cause the ship to 'crab' thru the water sideways so that the hull can produce an opposing side force. This sideways motion thru the water also causes additional drag call induced drag.

Since all motor sailing ships are designed to go thru the water in a straight line, little data was available for this information. The righting moment characteristics for the ships were estimated using the method outlined in reference (7). This particular method is widely used in preliminary design work. Righting moments were calculated for 1, 2, & 5 degrees of heel. A quadratic equation was then fitted to this data for calculation of intermediate values. Preliminary calculations of the heeling moments indicated that the heel angle would in most cases be less than 1^{o} so that additional drag due to heel angle could be ignored. The low heel angles are the result of two things; the relatively small size of the sail device and the relative beaminess of Great Lakes carriers.

A leeway angle and induced drag equation were developed from data in reference (1). Both of these characteristics were represented by quadratic equations so that intermediate values could be calculated. Although the leeway angles were very small, less than half a degree in most cases, the induced drag was not and therefore was taken into account in the computer program.

B. Sail Performance Data

With ship performance data collected the next task was to gather data on applicable sail devices. Two particular devices come to mind; a rigid wing sail device and a soft sail cat rig device. The latter device was used in this study.

There were several reasons for this. The rigid sail has the drawback that it cannot readily be furled or stowed when not in use. The de-powering of such a rig is done by 'feathering' the wing, i.e., turning it into the wind so no forward or side force is produced. This runs the potential risk of affecting manuvering characteristics in the sometimes tight channels found on the Great Lakes. Another drawback is that such a device would probably interfere with loading and unloading of the ship's cargo. A third drawback is that a wing sail costs about 25% more than a comparable soft sail device. In today's climate of high interest rates, capital expenditure must be kept to a minimum for this idea to work.

The soft sail cat rig is a fairly well tested device with at least one such device in the field at present being used. A couple of facts about the ships and routes being studied must also be considered when choosing a sailplan . All of these ships are self-loaders and as such about 80% of the deck space must be available for the loading equipment. The other fact is that due to bridge clearances the air draft available for a rig is 125'. These two factors combine to limit the size and efficiency of the proposed rig.

For this study a soft sail cat rig of 3000 sq. ft. area was chosen. The center of effort above the waterline for this rig is 65' for all ships, a reasonable assumption since they all float at basically the same freeboards. The frontal area (furled) is 292 sq. ft. Details of the size, weight, and cost of this rig are given later in the financial analysis section of this report.

Reference (2) gives further details of the design and performance characteristics of such a rig. Table 1 shows the lift and drag coefficients for this type of rig as a function of wind angle. The lift coefficient is used to calculate the amount of force available in a direction perpendicular to the wind flow. The drag coefficient is used to calculate the amount of force available in the direction of the wind flow. Details of these calculations are given in the computer simulation portion of this report.

C. Weather Data

The next set of data needed was information on what type of wind speeds and directions could be expected over the routes in question as this will have a big effect on the economic feasibility of this study. References (6) & (7) were the basis for this weather data. These two references are simply a statistical collection of the weather patterns observed over the Great Lakes region over a period of time. The precise set of data that was used in this study is given in appendix 3 with a detailed explanation.

The weather data is broken down into six separate areas. These areas are Southern Lake Michigan, Northern Lake Michigan, Eastern Lake Superior, East-Central Lake Superior, West-Central Lake Superior, and Western Lake Superior. For each of these areas the weather data was broken into 8 wind directions and 6 wind speed ranges plus the probability of calm. The weather data was given for the months of April thru November for a total of 48 different sets of possible weather patterns.

For the computer simulation we had to break the wind directions and wind ranges into discrete values in order to facilitate calculations. The values used for wind speed were 2, 7, 16, 27, 40, & 48 knots of wind speed plus 0 knots for calm. The values for wind direction are 0, 45, 90, 135, 180, 225, 270, & 315 degrees true. This weather data was stored on tape and accessed during the execution of the program based on the month and area, i.e., OCT1 calls up the weather data for the month of October when the ship is sailing thru area 1.

One assumption made was that for an individual calculation of fuel saved the wind direction and speed remained constant during the entire trip thru an area. At a service speed

TABLE 1

LIFT AND DRAG COEFFICIENTS FOR PROPOSED CAT RIG

WIND ANGLE (DEGREES)	LIFT COEFFICIENT	DRAG COEFFICIENT
25	1.5	.65
30	1.5	.61
35	1.5	.58
40	1.5	.56
45	1.5	.55
50	1.5	.54
55	1.5	.53
60	1.5	.52
65	1.5	.51
70	1.5	.505
75	1.5	.505
80	1.5	.505
85	1.5	.51
90	1.5	.55
95	1.5	.59
100	1.48	.66
105	1.45	.72
110	1.39	.76
115	1.30	.79
120	1.20	.81
125	1.10	.88
130	1.00	.99
135	.9	1.08
140	.8	1.20
145	.7	1.23
150	.6	1.19
155	.5	1.12
160	.4	1.05
165	.3	.90
170	.2	.75
175	.1	.64
180	0.0	.56

of 15 mph, most of the above mentioned areas can be traversed in 12 hours or less so this assumption seems to be valid. For the trip from Mackinac Bridge to Whitefish Bay (Area 7) the weather data used was the same data as used for area 3, Eastern Lake Superior.

D. Route Data

Route data was gathered from references (19), (20), (21), (22), & (23). This data consisted of specific sailing directions giving compass courses to be sailed as well as the distance to be sailed on the compass course. The compass course, when combined with the wind direction and speed enable an apparent wind to be calculated. If this wind will help drive the ship then the distance is used to obtain the fuel savings. The routes for the particular ships were obtained from reference (13).

In appendix 2, there is a detailed explanation of the routes and areas (which were chosen to coincide with the weather data areas) as well as the complete set of sailing directions used in the computer model.

COMPUTER SIMULATION

The program for simulating a ship traversing a given route with the given sailplan is the essence of this study. A flow chart for the program is shown in figure 4. The program listing itself is shown in Appendix IV. The program as listed was used only for modelling the motorsailing portion of the trips. The motor only portion of the trip from Whitefish Bay to the Mackinac Bridge was done with a simplified version of this program.

Shown in Table 2 is the ship data that was actually used in the program. Other data that was required to run the program included the weather data that was read from tape during the execution, route data that was read in for each ship, and the lift and drag coefficients for the sail device which is read in directly in the program.

The objective of the program was to calculate the mean (average) monthly fuel savings as well as a standard deviation for each month. This was accomplished by assuming that a trip from one port to another could be broken down into seven separate trips through seven distinct areas. Both averages and standard deviations had to converge to within 1% of a fixed value before the program would continue with another month.

After all the data has been read into memory the first task is to generate a reasonable approximation of the weather

FIGURE 4

FLOW CHART OF PERFORMANCE PROGRAM

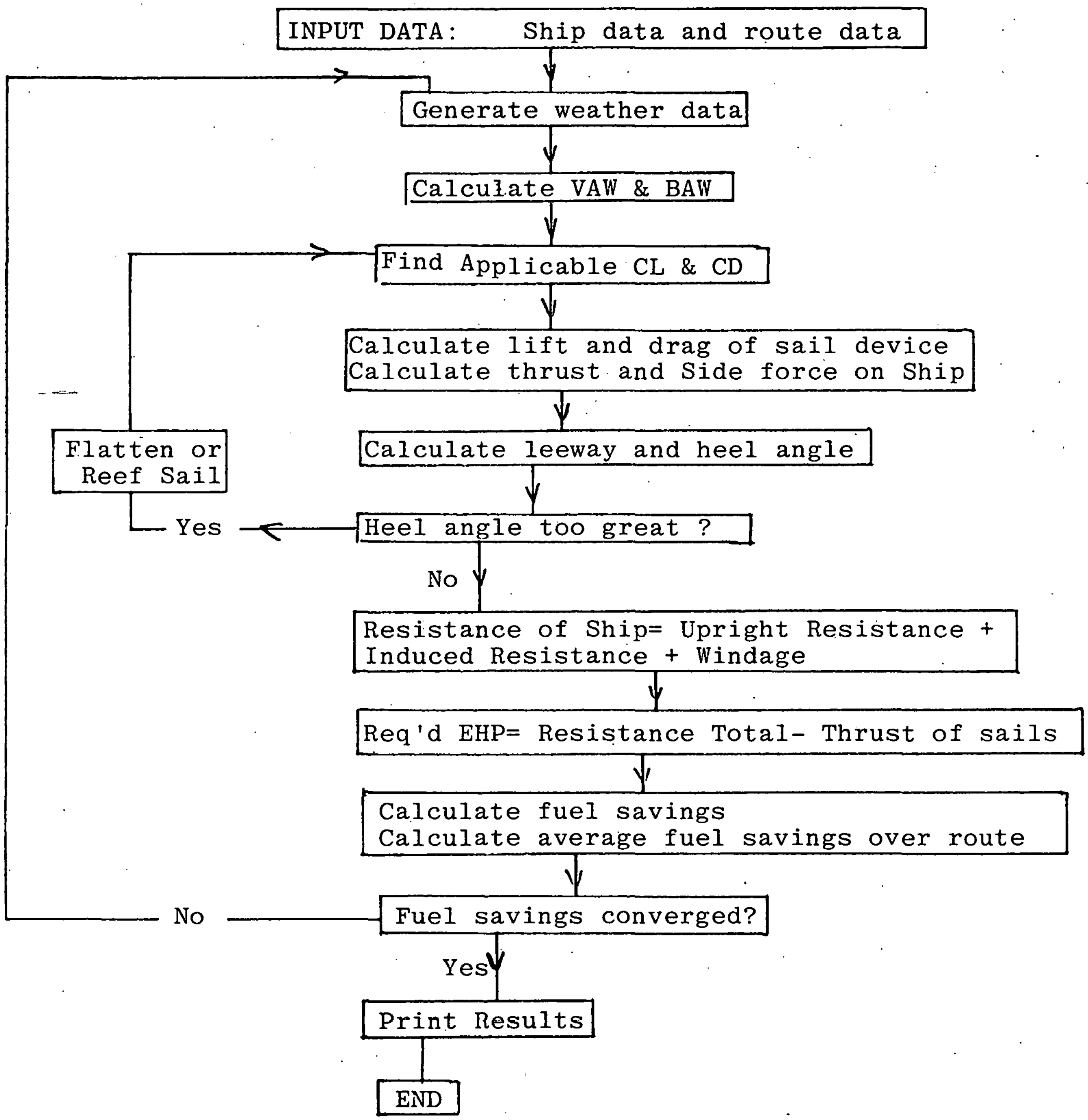


TABLE 2

SHIP DATA FOR PROGRAM

	ITEM	VARIABLE NAME	STEWART CORT	ED RYERSON	ST. CLAIR
1.	Ship's Name	B7$			
2.	Route Name	B8$			
3.	# of legs/area	N(I)			
4.	Course in degrees	C(I,J)			
5.	Distance in Miles	D(I,J)			
6.	3-letter Code for month	B$			
7.	Sail area	S1	3000	3000	3000
8.	C.E above DWL	C3	65	65	65
9.	Frontal area	S3	292	292	292
10.	Draft	T	25.8	26.5	30
11.	Length	L1	1000	730	770
12.	Service Speed	V1	15	15	15
13.	Delivered Efficiency	N8	.651	.77	.67
14.	Upright Resistance	R1	191,250	102,500	125,000
15.	Quadratic Constants for Righting Moment	A1	4.388E-5	1.983E-4	1.2438E-4
		A2	-5.293E-12	-6.725E-11	-4.239 E-11
16.	Quadratics Constants for Leeway angle	Z2	243.5	243.5	243.5
		Z3	-1050	-1050	-1050
17.	Quadratic Constants for Induced drag	Z4	5.866E-4	5.866E-4	5.866E-4
		Z5	6.666E-6	6.666E-6	6.666E-6

patterns that could be expected over the routes. To generate the proper mix of wind speeds and directions, i.e., to have the same mix of winds over a months time as the weather histories indicate probable, the program uses a Monte Carlo simulation with the machine's internal random number generator.

The random numbers produced by the machine are between 0 and 1. By subdividing the interval between 0 and 1 into subintervals of widths proportional to the probability of a certain wind speed and direction combination as detailed in the weather tables in appendix 3, the probability that the random number generated falls into any given interval is equal to the probability of that wind speed and direction. Thus for each time step (which is equal to the distance to be traveled in the area divided by service speed) and location a random number is generated that will give a corresponding wind speed and direction or calm.

With the wind direction and speed generated by the aforementioned method, we can then combine them with the ship's direction (given by the sailing directions) and its speed (always 15 mph) to calculate an apparent wind speed and angle. This is the wind that is seen and can be measured on the ship. Then a search routine locates the applicable lift and drag coefficients (C_l and C_d) as shown in table 1.

Once these coefficients are found the lift and drag of the sail device are calculated using standard aerodynamic theory:

$$\text{LIFT} = C_l \tfrac{1}{2} pAV^2$$

where:

- C_l = lift coefficient
- A = sail plan area = 3000 sq. ft.
- V = apparent wind speed
- P = mass density of air

The equation for drag is similar with the C_l being replaced by the applicable C_d.

The values of lift and drag, as discussed previously, are in a coordinate system defined by the apparent wind direction. Lift is in a direction perpendicular to the apparent wind direction and drag is in the same direction as the wind. These values must be translated into the coordinate system of the ship in terms of thrust, that is forward force, and side force, the force that is perpendicular to the ship's centerline. The equations for this translation are:

$$T = \text{Lift} \times \sin\Theta - \text{Drag} \times \cos\Theta$$

and $$S = \text{Lift} \times \cos\Theta - \text{Drag} \times \sin\Theta$$

where: T = thrust of sails in forward direction

S = side force perpendicular to ship's centerline

Lift = as calculated previously

Drag = as calculated previously

Θ = apparent wind angle as calculated

With the side force now calculated we can calculate the heeling moment and find the heel angle. The flow chart shows that if the heel angle is above some fixed value then the sails must be de-powered. No such case was ever run into on this simulation mainly due to the rather small size of the sail plan. Additionally with the side force calculated we can determine the leeway angle and associated induced drag.

With the above figures we can then calculate the required horsepower that the engine must produce to overcome the ship's resistance. The following formulas are used:

$$RT = R_t + R_i + R_w$$

where: RT = Total resistance of the ship

R_t = upright resistance from ship data

R_w = resistance due to windage

R_i = induced resistance due to side force

Note that the windage resistance is 0 when the sail is unfurled as the windage of the sail is accounted for in the drag coefficient. When the sail is furled then the induced resistance is assumed to be 0, as there is little if any side force due to the furled sail.

With the total resistance of the ship now calculated the effective resistance of the ship can be calculated. This is the resistance of the ship that must be overcome by the engine. The formula used is:

$$R_e = RT - T$$

where: R_e = effective resistance

RT = total resistance of ship as calculated

T = Thrust of sails as calculated

With the effective resistance of the ship thus determined we must determine the effective horsepower required.

$$EHP = \frac{R_e V}{550}$$

where: EHP= effective horsepower

V = speed of ship in fps

Next, we must calculate the SHP, that horsepower that the engine must provide to drive the ship at this speed. The following formula is used:

$$SHP = \frac{EHP}{n_d}$$

where: SHP= shaft horsepower

n_d= propulsive coefficient

A factor of 5% is generally added to the calculated SHP to account for the fact that towing tank resistance is ideal and does not take into account foul bottoms or less than optimal engine tune.

With shaft horsepower calculated the amount of fuel used is calculated using a formula from reference (2).

$$F = \frac{SHP}{1000}^{-.059} \times .4$$

where: F = specific fuel consumption in lb/HP·HR

This specific fuel consumption is then mulitplied by the number of horsepower and the hours spent on that particular leg of the course to come up with a total number of pounds of fuel used. The amount of fuel used when operating under normal conditions is also calculated. The difference between these two numbers is the amount of fuel saved (or excess used) by using the sail device.

A running average is calculated and when it converges to within 1% of a fixed number the same ship is run over the same course until the standard deviation converges to within 1% of a fixed value. To get these statistics to converge took on average about 400-500 runs over the given area. Had the tolerance been somewhat less tight on the standard deviation, convergence would have happened faster.

One other item that was printed out but is not documented in this report is the amount of time the sail is furled. Some runs obviously had the sail furled 100% of the time and coverged quickly to a negative fuel savings. There were some runs where the sail was only furled for about 20% of the time. The average seemed to be around 40% of the time, the implication of which will be discussed in the conclusion portion of this report.

The main reason for having such a reatively large amount of time with furled sails is that the shipping lanes on the Great Lakes are very tight and must be adhered to rigidly. These routes are not like those on the North Atlantic where the two ports are 3000 miles apart and the only thing the Captain must do is to get his ship to port. In that case the Captain would have the option to altering course in such a fashion so as to maximize the usefulness of the sail device. In the Great Lakes not only does the Captain have to worry about getting to port he must also make several intermediate way points to insure safe passage thru narrow channels. This is probably the biggest reason for the disappointing results of the study.

FINANCIAL ANALYSIS

The financial analysis aspect of this project is to simply estimate whether the savings in fuel costs by fitting a sail device are enough to offset the additional costs involved in fitting such a device. Such costs include the capital recovery of the investment, an increase in maintenance costs, and an increase in insurance costs.

The measure of merit for this study is average annual cost (AAC). We wish to calculate the average annual cost of the sail device. More specifically we actually want to calculate the change in the average annual cost. If the cost increases, then the idea is not economically feasible, if on the other hand the average annual cost decreases then the idea is economically feasible.

The basic equation for AAC is:

$$\Delta AAC = \Delta Y + (CR\text{-}1\%\text{-}N) \cdot P$$

Where: ΔY = change in annual operating costs

ΔY = Δ(fuel cost) + Δ(insurance) + Δ(maintenance)

Δ(fuel costs) = from tables 5, 6, & 7

Δ(Insurance) = 1.5% of rig cost per year

Δ(Maintenance) = 1% of rig cost+ 25% of sail cost per year

(CR-i%-N) = capital recovery factor for i% over N years. This is how much must be recovered per year.

For our study we have made some assumptions to simplify the analysis. The period N is assumed to be 20 years, a reasonable life to expect from the capital expenditure. We have also not taken into account inflation of fuel prices. This is seen as too difficult to forecast, but probably makes the sail device look less advantageous than it is. For this study we are also going to examine interest rates in the range of 8% - 18% in 2% increments.

Tables 3 & 4 show the weight and costs of the proposed cat rig. These estimates are from reference (2). The capital expenditure necessary for the entire rig is shown as $120,641. However, with a 10% tax credit the actual expenditure is less. Therefore in the above equation:

P = capital expenditure
= 90% of rig cost
= $108,578

Since the insurance costs and maintenance costs are based on the rig cost they are as follows.

Δ(Insurance) = $1809.63/yr.

Δ(Maintenance) = $4956.42/yr.

Breaking down the insurance and maintenance costs on a monthly basis (8 month sailing season) the monthly change in operating costs is $845.76/month.

The following capital recovery factors are used.

(CR-8%-20) = .1018
(CR-10%-20)= .1175
(CR-12%-20)= .1339
(CR-14%-20)= .1510
(CR-16%-20)= .1687
(CR-18%-20)= .1868

The above factors are based on a per year pay back schedule. We wish to compare on a monthly basis so the above numbers must be divided by 8.

TABLE 3

WEIGHT OF CAT RIG

WEIGHT GROUP	COMPONENTS INCLUDED	WEIGHT PER MAST (LONG TONS)	WEIGHT FOR THIS MAST
*POWER	POWER GENERATION AND DISTRIBUTION EQUIPMENT	$2.104\text{x}10^{-7}(SA_m H)^{3/4} V_{max}^{2}$	.9176
WINCHES	WINCHES AND DRIVE MOTORS	$1.036\text{x}10^{-7}(HV_{max})^2$	2.3375
TRIM	SAIL TRIMMING AND HANDLING GEAR	$4.186\text{x}10^{-8}(HV_{max})^2$	.9445
BOOM	BOOM STRUCTURAL MEMBER	$2.472\text{x}10^{-8} SA_m^{5/3} H^{-1/3} V_{max}^{4/3}$	.6227
MAST	MAST, MAST SUPPORT STRUCTURE, BEARINGS & ROLLER FURLING EQUIPMENT	$1.511\text{x}10^{-7} SA_m^{2/3} H^{5/3} V_{max}^{4/3}$	11.4510
CONTROL	WINCH & DRIVE CONTROLS AND INSTRUMENTATION		.3571

SA_m = sail area per mast (sq. ft.) = 3000 sq. ft.

H = mast height = 95 ft.

V_{max} = rig design wind speed = 50 knots

*SOURCE: Above data taken from "Wind Propulsion for Ships of the American Merchant Marine", a report prepared by Wind Ship Development Corp. for the U.S. Department of Commerce, March 1981

TABLE 4

COST OF CAT RIG

COST GROUP	COMPONENTS INCLUDED	COST PER MAST (DOLLARS)	COST FOR THIS MAST
*SAILS	SAILS AND SAIL HARDWARE		$15,000
**POWER	POWER GENERATION AND DISTRIBUTION EQUIPMENT	$.5057(SA_m H)^{\frac{1}{2}} V_{max}$	$13,498
WINCHES	WINCHES AND DRIVE MOTORS	$.4238\ (H\ V_{max})^{1.3}$	$25,518
TRIM	SAIL TRIMMING AND HANDLING GEAR	5669 per ton	$ 5,354
BOOM	BOOM STRUCTURAL MEMBER	2802 per ton	$ 1,744
MAST	MAST, MAST SUPPORT STRUCTURE, BEARINGS & ROLLER FURLING EQUIPMENT	3306 per ton	$37,857
PAINT	SANDBLASTING AND PAINTING	$9.073 \times 10^{-3} SA_m^{1/3} H^{4/3} V_{max}^{2/3}$	$ 770
CONTROL	WINCH & DRIVE CONTROLS AND INSTRUMENTATION	20,900	$20,900
		TOTAL CAPITAL EXPENDITURE	$120,641

*SOURCE: HOOD Sailmakers, Marblehead, Mass.

**SOURCE: Above data taken from "Wind Propulsion for Ships of the American Merchant Marine", a report prepared by the Wind Ship Development Corp. for the U.S. Department of Commerce, March 1981

SA_m = sail area per mast = 3000 sq. ft

H = mast height = 95 ft.

V_{max} = rig design speed = 50 knots

The table below shows the amount of the various factors that must be recovered versus interest rate as well as the break-even point for fuel savings.

INTEREST RATE	(CR-i%-20)·P	ΔY	FUEL NEEDED TO BE SAVED
8%	$1381.65/mth	$845.76	$2227.41/mth
10%	$1594.74	$845.76	$2440.50
12%	$1817.32	$845.76	$2663.08
14%	$2049.41	$845.76	$2895.17
16%	$2289.64	$845.76	$3135.40
18%	$2535.30	$845.76	$3381.06

The cost of fuel saved is shown in tables 5, 6, & 7. These costs are calculated based on the cost of fuel indicated at the top of the page. These tables were developed from the results of the computer simulation. The detailed results from the computer runs are shown in Appendix I.

Subtracting the numbers from the right hand column from the fuel savings shown will net the change in average annual costs. A negative number indicates an increase in costs while a positive one indicates that the cost has decreased.

Tables 8 thru 13 are a compilation of these costs and represent the final analysis of this project. Discussion of the results and conclusions are contained in the next portion of this report.

TABLE 5

COST OF FUEL SAVED PER MONTH

COST OF FUEL = $281/ metric ton = $.1275/lb

Based on cost of diesel fuel as of August, 1982
(Source: Marine Engineering/Log; Aug. 1982)

SHIP: ST. CLAIR
ROUTE: BURNS HARBOR/THUNDERBAY/BURNS HARBOR

MONTH	PESSIMISTIC	AVERAGE	OPTIMISTIC
APRIL	1322.67	2352.77	3382.87
MAY	1058.24	2016.00	2951.27
JUNE	603.09	1351.88	2100.68
JULY	458.33	1161.50	1864.67
AUGUST	664.50	1472.05	2279.59
SEPTEMBER	1239.66	2239.45	3239.24
OCTOBER	1888.93	3080.48	4272.03
NOVEMBER	2470.50	3788.84	5107.18

TABLE 6

COST OF FUEL SAVED PER MONTH

COST OF FUEL= $281/metric ton = $ .1275/ lb.

Based on cost of Diesel Fuel as of August, 1982
(Source: Marine Engineering/Log; Aug. 1982)

SHIP: STEWART CORT
ROUTE: BURNS HARBOR/TACONITE HARBOR/BURNS HARBOR

MONTH	PESSIMISTIC	AVERAGE	OPTIMISTIC
APRIL	1294.39	2395.94	3497.53
MAY	1021.73	1960.75	2899.77
JUNE	576.73	1317.43	2058.13
JULY	560.16	1252.89	1945.62
AUGUST	608.59	1406.67	2204.75
SEPTEMBER	1378.94	2436.40	3493.87
OCTOBER	2088.68	3406.80	4724.92
NOVEMBER	2623.16	3835.80	5048.44

TABLE 7

COST OF FUEL SAVED PER MONTH

COST OF FUEL= $281/metric ton = $.1275 / lb

Based on cost of diesel fueal as of August, 1982
(Source: Marine Engineering/Log; Aug. 1982)

SHIP: ED RYERSON
ROUTE: BURNS HARBOR/PT. SUPERIOR/BURNS HARBOR

MONTH	PESSIMISTIC	AVERAGE	OPTIMISTIC
APRIL	937.70	1864.45	2791.20
MAY	692.25	1603.73	2515.20
JUNE	313.65	951.05	1588.45
JULY	419.96	977.33	1534.69
AUGUST	448.86	1107.13	1765.41
SEPTEMBER	1005.28	1931.59	2857.90
OCTOBER	1684.03	2771.46	3858.90
NOVEMBER	2131.24	3372.43	4613.61

TABLE 8

AAC CALCULATIONS

The following tables show the net gain or loss in dollars per month as well as the sailing season total

INTEREST RATE= 8 %

SHIP: ST. CLAIR
ROUTE: BURNS HARBOR/THUNDERBAY/BURNS HARBOR

MONTH	PESSIMISTIC	AVERAGE	OPTIMISTIC
APRIL	- 904.75	125.35	1155.45
MAY	-1169.18	- 211.42	723.85
JUNE	-1624.33	- 875.54	- 126.74
JULY	-1769.09	-1065.92	- 326.75
AUGUST	-1562.92	- 755.37	52.17
SEPTEMBER	- 987.76	12.03	1011.82
OCTOBER	- 338.49	853.06	2044.61
NOVEMBER	243.08	1561.42	2879.76
TOTALS FOR SEASON	-8113.44	- 356.39	7414.17

SHIP: ED RYERSON
ROUTE: BURNS HARBOR/PT. SUPERIOR/BURNS HARBOR

MONTH	PESSIMISTIC	AVERAGE	OPTIMISTIC
APRIL	-1289.72	- 362.97	563.78
MAY	-1535.17	- 623.69	287.78
JUNE	-1913.77	-1276.37	- 638.97
JULY	-1807.46	-1250.09	- 692.73
AUGUST	-1778.56	-1120.29	- 462.01
SEPTEMBER	-1222.14	- 295.83	630.48
OCTOBER	- 543.39	544.04	1631.48
NOVEMBER	- 96.18	1145.01	2386.19
TOTALS FOR SEASON	-10,186.39	-3240.10	3706.00

SHIP: STEWART CORT
ROUTE: BURNS HARBOR/TACONITE HARBOR/BURNS HARBOR

MONTH	PESSIMISTIC	AVERAGE	OPTIMISTIC
APRIL	- 933.03	168.52	1270.11
MAY	-1205.69	- 266.67	672.35
JUNE	-1650.69	- 909.99	- 169.29
JULY	-1667.26	- 974.53	- 281.80
AUGUST	-1618.83	- 820.75	- 22.67
SEPTEMBER	- 848.48	208.98	1266.45
OCTOBER	- 138.74	1179.38	2497.50
NOVEMBER	395.74	1608.38	2821.02
TOTALS FOR SEASON	-7666.98	193.32	8053.67

TABLE 9

AAC CALCULATIONS

The following tables show the net gain or loss in dollars per month as well as the sailing season total.

INTEREST RATE= 10%

SHIP: ST. CLAIR
ROUTE: BURNS HARBOR/THUNDERBAY/BURNS HARBOR

MONTH	PESSIMISTIC	AVERAGE	OPTIMISTIC
APRIL	-1117.83	- 87.73	942.37
MAY	-1382.26	- 424.50	510.77
JUNE	-1837.41	-1088.62	- 339.82
JULY	-1982.17	-1279.00	- 575.83
AUGUST	-1776.00	- 968.45	- 160.91
SEPTEMBER	-1200.84	- 201.05	798.74
OCTOBER	- 551.57	639.98	1831.53
NOVEMBER	30.00	1348.34	2666.68
TOTALS FOR SEASON	-9818.08	-2061.03	5673.53

SHIP: ED RYERSON
ROUTE: BURNS HARBOR/PT. SUPERIOR/BURNS HARBOR

MONTH	PESSIMISTIC	AVERAGE	OPTIMISTIC
APRIL	-1502.60	- 576.05	350.70
MAY	-1748.25	- 836.77	74.70
JUNE	-2126.85	-1489.45	- 852.05
JULY	-2020.54	-1463.17	- 905.81
AUGUST	-1991.64	-1333.37	- 675.09
SEPTEMBER	-1435.22	- 508.91	417.40
OCTOBER	- 756.47	330.96	1418.40
NOVEMBER	- 309.26	931.93	2173.11
TOTAL FOR SEASON	-11,891.05	-4944.83	2001.36

SHIP: STEWART CORT
MONTH: BURNS HARBOR/TACONITE HARBOR/BURNS HARBOR

MONTH	PESSIMISTIC	AVERAGE	OPTIMISTIC
APRIL	-1146.11	- 44.56	1057.03
MAY	-1418.77	- 479.75	459.27
JUNE	-1863.77	-1123.07	- 382.37
JULY	-1880.34	-1187.61	- 494.88
AUGUST	-1831.91	-1033.83	- 235.75
SEPTEMBER	-1061.56	- 4.10	1053.37
OCTOBER	- 351.82	966.30	2284.42
NOVEMBER	182.66	1395.30	2607.94
TOTAL FOR SEASON	-9371.62	-1511.32	6349.03

TABLE 10

AAC CALCULATIONS

The following tables show the net gain or loss in dollars per month as well as the sailing season total.

INTEREST RATE = 12%

SHIP: ST. CLAIR
ROUTE: BURNS HARBOR/THUNDERBAY/BURNS HARBOR

MONTH	PESSIMISTIC	AVERAGE	OPTIMISTIC
APRIL	-1340.41	- 310.31	719.79
MAY	-1604.84	- 647.08	288.19
JUNE	-2059.99	-1311.20	- 562.40
JULY	-2204.75	-1501.58	- 798.41
AUGUST	-1998.58	-1191.03	- 383.49
SEPTEMBER	-1423.42	- 423.63	576.16
OCTOBER	- 774.15	417.40	1608.95
NOVEMBER	- 192.58	1125.76	2444.10
TOTAL FOR SEASON	-11,598.72	-3841.67	3892.89

SHIP: ED RYERSON
ROUTE: BURNS HARBOR/PT. SUPERIOR/BURNS HARBOR

MONTH	PESSIMISTIC	AVERAGE	OPTIMISTIC
APRIL	-1725.38	- 798.63	128.12
MAY	-1970.83	-1059.35	- 147.88
JUNE	-2349.43	-1712.03	-1074.63
JULY	-2243.12	-1685.75	-1128.39
AUGUST	-2214.22	-1555.95	- 897.67
SEPTEMBER	-1657.80	- 731.49	194.82
OCTOBER	- 979.05	108.38	1195.82
NOVEMBER	- 531.84	709.35	1950.53
TOTAL FOR SEASON	-13,671.67	-6725.47	220.72

SHIP: STEWART CORT
ROUTE: BURNS HARBOR/TACONITE HARBOR/BURNS HARBOR

MONTH	PESSIMISTIC	AVERAGE	OPTIMISTIC
APRIL	-1368.69	- 267.14	834.45
MAY	-1641.35	- 702.33	236.69
JUNE	-2086.35	-1345.65	- 604.95
JULY	-2102.92	-1410.19	- 717.46
AUGUST	-2054.49	-1256.41	- 458.33
SEPTEMBER	-1284.14	- 226.68	830.79
OCTOBER	- 574.40	743.72	2061.84
NOVEMBER	- 39.92	1172.72	2385.36
TOTAL FOR SEASON	-11,152.26	-3291.96	4568.39

TABLE 11

AAC CALCULATIONS

The following tables show the net gain or loss in dollars per month as well as the sailing season total

INTEREST RATE = 14%

SHIP: ST. CLAIR
ROUTE: BURNS HARBOR/THUNDERBAY/BURNS HARBOR

MONTH	PESSIMISTIC	AVERAGE	OPTIMISTIC
APRIL	-1572.50	- 542.40	487.70
MAY	-1863.93	- 879.17	56.10
JUNE	-2292.08	-1543.29	- 794.49
JULY	-2436.84	-1733.67	-1030.50
AUGUST	-2230.67	-1423.12	- 615.58
SEPTEMBER	-1655.51	- 655.72	344.07
OCTOBER	-1006.24	185.31	1376.86
NOVEMBER	- 424.67	893.67	2212.01
TOTAL FOR SEASON	-13,482.44	-5698.39	2036.17

SHIP: ED RYERSON
ROUTE: BURNS HARBOR/PT. SUPERIOR/BURNS HARBOR

MONTH	PESSIMISTIC	AVERAGE	OPTIMISTIC
APRIL	-1957.47	-1030.72	- 103.97
MAY	-2202.92	-1291.44	- 379.97
JUNE	-2581.52	-1944.12	-1306.72
JULY	-2475.21	-1917.84	-1360.48
AUGUST	-2446.31	-1788.04	-1129.76
SEPTEMBER	-1889.89	- 963.58	- 37.27
OCTOBER	-1211.14	- 123.71	963.73
NOVEMBER	- 763.93	477.26	1718.44
TOTAL FOR SEASON	-15,528.39	-8582.19	-1636.00

SHIP: STEWART CORT
ROUTE: BURNS HARBOR/TACONITE HARBOR/BURNS HARBOR

MONTH	PESSIMISTIC	AVERAGE	OPTIMISTIC
APRIL	-1600.78	- 499.94	602.36
MAY	-1873.44	- 934.42	4.60
JUNE	-2318.44	-1577.74	- 837.04
JULY	-2335.01	-1642.28	- 949.55
AUGUST	-2286.58	-1488.50	- 690.42
SEPTEMBER	-1516.23	- 458.77	598.70
OCTOBER	- 806.49	511.63	1829.75
NOVEMBER	- 272.01	940.63	2153.27
TOTAL FOR SEASON	-13,008.98	-5149.39	2711.67

TABLE 12

AAC CALCULATIONS

The following tables show the net gain or loss in dollars per month as well as the sailing season total

INTEREST RATE = 16%

SHIP: ST. CLAIR
ROUTE: BURNS HARBOR/THUNDERBAY/BURNS HARBOR

MONTH	PESSIMISTIC	AVERAGE	OPTIMISTIC
APRIL	-1812.73	- 782.63	247.47
MAY	-2077.16	-1119.40	- 184.13
JUNE	-2532.31	-1783.52	-1034.72
JULY	-2677.07	-1973.90	-1270.73
AUGUST	-2470.90	-1663.35	- 855.81
SEPTEMBER	-1895.74	- 895.95	-103.84
OCTOBER	-1246.47	- 54.92	1136.63
NOVEMBER	- 664.90	653.44	1971.78
TOTAL FOR SEASON	-15,377.28	-7620.23	114.33

SHIP: ED RYERSON
ROUTE: BURNS HARBOR/PT. SUPERIOR/BURNS HARBOR

MONTH	PESSIMISTIC	AVERAGE	OPTIMISTIC
APRIL	-2197.70	-1270.95	- 344.20
MAY	-2443.15	-1531.67	- 620.20
JUNE	-2821.75	-2184.35	-1546.95
JULY	-2715.44	-2158.07	-1600.71
AUGUST	-2686.54	-2028.27	-1369.99
SEPTEMBER	-2130.12	-1203.81	- 277.50
OCTOBER	-1451.37	- 363.94	723.50
NOVEMBER	-1004.16	237.03	1478.21
TOTAL FOR SEASON	-17,450.23	-10,504.03	-3557.84

SHIP: STEWART CORT
ROUTE: BURNS HARBOR/TACONITE HARBOR/BURNS HARBOR

MONTH	PESSIMISTIC	AVERAGE	OPTIMISTIC
APRIL	-1841.01	- 739.46	362.13
MAY	-2113.67	-1174.65	- 235.63
JUNE	-2558.67	-1817.97	-1077.27
JULY	-2575.24	-1882.51	-1189.78
AUGUST	-2526.81	-1728.73	- 930.65
SEPTEMBER	-1756.46	- 699.00	- 358.47
OCTOBER	-1046.72	271.40	1589.52
NOVEMBER	- 512.24	700.40	1913.04
TOTAL FOR SEASON	-14,930.82	-7070.52	72.89

TABLE 13

AAC CALCULATIONS

The following tables show the net gain or loss in dollars per month as well as the sailing season total.

INTEREST RATE = 18%

SHIP: ST. CLAIR
ROUTE: BURNS HARBOR/THUNDERBAY/BURNS HARBOR

MONTH	PESSIMISTIC	AVERAGE	OPTIMISTIC
APRIL	-2058.39	-1028.29	1.81
MAY	-2322.82	-1365.06	- 429.79
JUNE	-2777.97	-2029.18	-1280.38
JULY	-2922.73	-2219.56	-1516.39
AUGUST	-2716.56	-1909.01	-1101.47
SEPTEMBER	-2141.40	-1141.61	- 141.82
OCTOBER	-1492.13	- 300.58	890.97
NOVEMBER	- 910.56	407.78	1726.12
TOTAL FOR SEASON	-17,342.56	-9585.51	-1850.95

SHIP: ED RYERSON
ROUTE: BURNS HARBOR/PT. SUPERIOR/BURNS HARBOR

MONTH	PESSIMISTIC	AVERAGE	OPTIMISTIC
APRIL	-2443.36	-1516.61	- 589.86
MAY	-2688.81	-1777.33	- 865.86
JUNE	-3067.41	-2430.01	-1792.61
JULY	-2961.10	-2463.73	-1846.37
AUGUST	-2932.20	-2273.93	-1615.65
SEPTEMBER	-2375.78	-1449.47	- 523.16
OCTOBER	-1697.03	- 609.60	477.84
NOVEMBER	-1249.82	- 8.63	1232.55
TOTAL FOR SEASON	-19,415.51	-12,529.31	-5523.12

SHIP: STEWART CORT
ROUTE: BURNS HARBOR/TACONITE HARBOR/BURNS HARBOR

MONTH	PESSIMISTIC	AVERAGE	OPTIMISTIC
APRIL	-2086.67	- 985.12	116.47
MAY	-2359.33	-1420.31	- 481.29
JUNE	-2804.33	-2063.63	-1322.93
JULY	-2820.90	-2128.17	-1435.44
AUGUST	-2772.47	-1974.39	-1176.31
SEPTEMBER	-2002.12	- 944.66	112.81
OCTOBER	-1292.38	25.74	1343.86
NOVEMBER	- 757.74	454.74	1667.38
TOTAL FOR SEASON	-16,896.10	-9035.80	-1175.44

DISCUSSION AND CONCLUSION

Tables 8 thru 13 in the previous section show the final calculations of average annual cost used to determine the economic feasibility of retro-fitting these ships with a sail device. Three cases are shown for each ship and route; an average case, an optimistic case, and a pessimistic case. Negative values in the total row indicate that the annual costs increased, while a positive value in this row indicates the average annual cost dropped and the idea is an economically viable one.

At best, the economic feasibility of fitting these ships with sail devices is marginal. In the worst cases, the idea doesn't even come close to paying for itself. A basic reason for this is because of problems inherent with the geography and routes of the Great Lakes. The sailing strategy employed in the computer simulation allows no deviation from the specified courses. This strategy is in strict adherence to the tight shipping lanes on the Great Lakes. The captain of the ship has no option to alter course even slightly to take advantage of the prevailing wind.

If the wind is 5 degrees too far forward to be effective with the sailplan, the sail must be furled. This sort of sailing strategy puts the motor-sailing vessel at a serious disadvantage. On other longer routes, such as ocean routes, deviations from course could be tolerated. In fact, present motor vessels on ocean routes regularly deviate from the shortest course, not so much to take advantage of weather systems but to avoid head winds and seas. A sailing strategy employing some decision making on the part of the captain would probably yield much higher fuel savings. However, due to the relatively short distances and tight channels on Great Lakes routes, such a strategy cannot be employed for the studied vessels.

With regards to specific ships; at no time does the sail device pay for itself when it is fitted to the ED RYERSON. Only in the most optimistic at interest rates of 8% and 10% does the annual cost decrease. Even this slight advantage all but disappears at an interest rate of 12%. One difference between this ship and the others is that it has a much higher propulsive effciency, about 20% higher than the other vessels. This implies that decreases in the effective resistance (which is what the sail device does) translate to relatively small decreases in the SHP and therefore fuel consumption.

The other ships, the ST. CLAIR and the STEWART CORT have a better chance of making this idea pay off. The CORT is the best of the two ships with a decrease in annual costs in the average column at 8% interest. It is only a slight advantage, but an advantage nonetheless. One would have to believe the optimistic column to make a strong case for fitting a sail device to the ST. CLAIR.

One possible reason for the sail device working well on the STEWART CORT and not the other ships is the fact that she has the lowest propulsive efficiency of all the ships. She was built in the mid-1970s when hydrodynamic efficiency was sacrificed for cargo capacity. Therefore changes in the effective horsepower are translated to relatively large changes in the shaft horsepower and thereby the fuel consumption. One can draw the conclusion from this fact that prime candidates for successful retro-fitting of sail devices are full, inefficient hull forms found on ships constructed during the 1970s.

The conclusion from this report then, is that retro-fitting sail devices to Great Lakes bulk carriers is marginally feasible in some cases. Any change in the price of diesel fuels, such as a 10% increase could in fact make the idea feasible for a few, well chosen ships.

APPENDIX I

The following tables are a compilation of the results of the computer program used to simulate the problem.

Tables 1 thru 6 are the results for the individual ships, on the specified routes (both upbound and downbound), for each month of the sailing season. For the specified route and month, the table shows the average amount of fuel saved in pounds for one trip thru each area of the route. Also shown is the standard deviation for the particular areas.

The standard deviation is surprising high. The reason for this is that the fuel savings can go negative as well as positive. The program allows no deviation from the specified course. This is in strict adherence to the shipping lanes in the Great Lakes. There is no modelling of what might happen if the Captain could alter course to take advantage of the prevailing wind. This results in the sails having to be furled and using extra fuel in the process to overcome the extra drag of the sailplan. In some runs as much as 70% of the time the sail has to be furled. That is why the financial results are based on three seperate cases; pessimistic, optimistic, and the average case.

Tables 7 thru 9 show the extra fuel that is used when motoring between the Mackinac Bridge and Whitefish Bay as well as the reverse course. For each ship the average fuel used is shown in pounds as well as the standard deviation.

Table 10 shows the number of round trips that can be completed each month based on the voyage length. Each round trip is based on spending two days at the dock for loading/unloading and other reasons. This seems to be fairly close to the actual case as the self-unloading capabilities of these ships is amazing.

Tables 11 thru 13 shows how much fuel can be saved per month. This is simply a summation of the previous tables. The following equations are used for these tables;

$$\text{Average Fuel savings} = (\Sigma AVSAV - AVUSE) \times \text{\# of round trips/mth}$$

where:

AVSAV= amount of fuel saved for particular month. (Sum of fuel savings of areas)

AVUSE= amount of fuel used in both upbound and downbound trips thru area 7.

The optimistic column reflects the average savings with the standard deviations of fuel saved per area is added to AVSAV and the standard deviations for area 7 are subtracted from AVUSE. The pessimistic column reflects the

the average fuel savings with the standard deviations of fuel saved per are is subtracted from AVSAV and the standard deviations for area 7 are added to AVSAV.

TABLE 1

PREDICTED FUEL SAVINGS

SHIP: ST. CLAIR
ROUTE: BURNS HARBOR TO THUNDERBAY

MONTH: APRIL

	Area 1	Area 2	Area 3	Area 4	Area 5
Average	390.67	363.19	237.87	355.66	125.87
Std. Dev.	168.49	145.39	124.39	141.75	46.44

MONTH: MAY

	Area 1	Area 2	Area 3	Area 4	Area 5
Average	362.95	360.28	180.42	265.19	165.75
Std. Dev.	156.09	116.51	83.99	125.26	42.81

MONTH: JUNE

	Area 1	Area 2	Area 3	Area 4	Area 5
Average	196.15	278.95	145.78	220.80	82.81
Std. Dev.	101.95	98.47	88.04	125.83	39.96

MONTH: JULY

	Area 1	Area 2	Area 3	Area 4	Area 5
Average	215.66	217.44	99.31	171.23	65.50
Std. Dev.	134.67	65.83	77.64	95.17	37.45

MONTH: AUGUST

	Area 1	Area 2	Area 3	Area 4	Area 5
Average	235.57	271.62	135.67	269.59	69.39
Std. Dev.	157.02	95.63	86.67	128.21	29.37

TABLE 1 (cont.)

PREDICTED FUEL SAVINGS

SHIP: ST. CLAIR
ROUTE: BURNS HARBOR TO THUNDERBAY

MONTH: SEPTEMBER

	Area 1	Area 2	Area 3	Area 4	Area 5
Average	388.46	433.82	200.93	272.19	105.24
Std. Dev.	204.73	135.95	104.33	97.58	29.74

MONTH: OCTOBER

	Area 1	Area 2	Area 3	Area 4	Area 5
Average	529.40	680.35	302.41	332.48	119.87
Std. Dev.	176.16	215.72	114.32	138.60	39.67

MONTH: NOVEMBER

	Area 1	Area 2	Area 3	Area 4	Area 5
Average	674.52	771.21	357.45	425.74	139.27
Std. Dev.	315.23	286.33	141.67	111.45	40.57

Notes: Fuel Savings are given in Lbs. of fuel saved per trip thru given area

Average fuel savings per month = Sum of fuel savings of areas

Optimistic fuel savings = Average + Std. Dev.

Pessimistic fuel savings= Average - Std. Dev.

TABLE 2

PREDICTED FUEL SAVINGS

SHIP: ST. CLAIR
ROUTE: THUNDERBAY TO BURNS HARBOR

MONTH: APRIL

	Area 1	Area 2	Area 3	Area 4	Area 5
Average	354.27	402.50	209.09	378.51	124.38
Std. Dev.	185.23	164.64	95.15	81.36	48.52

MONTH: MAY

	Area 1	Area 2	Area 3	Area 4	Area 5
Average	281.74	241.79	176.51	315.26	100.65
Std. Dev.	104.09	101.36	88.53	109.88	30.70

MONTH: JUNE

	Area 1	Area 2	Area 3	Area 4	Area 5
Average	188.05	155.73	144.82	217.64	88.85
Std. Dev.	133.44	64.47	56.49	126.60	40.44

MONTH: JULY

	Area 1	Area 2	Area 3	Area 4	Area 5
Average	157.17	135.41	125.79	186.38	77.87
Std. Dev.	104.32	89.46	67.46	93.96	25.80

MONTH: AUGUST

	Area 1	Area 2	Area 3	Area 4	Area 5
Average	188.58	202.84	168.41	191.37	83.47
Std. Dev.	112.63	112.91	76.86	82.19	28.46

TABLE 2 (cont.)

PREDICTED FUEL SAVINGS

SHIP: ST. CLAIR
ROUTE: THUNDERBAY TO BURNS HARBOR

MONTH: SEPTEMBER

	Area 1	Area 2	Area 3	Area 4	Area 5
Average	352.75	365.16	230.83	340.41	111.41
Std. Dev.	175.39	148.72	95.00	128.42	49.70

MONTH: OCTOBER

	Area 1	Area 2	Area 3	Area 4	Area 5
Average	457.87	460.46	282.90	410.09	121.67
Std. Dev.	135.92	227.94	127.59	136.89	34.39

MONTH: NOVEMBER

	Area 1	Area 2	Area 3	Area 4	Area 5
Average	688.85	553.21	342.89	535.90	184.15
Std. Dev.	179.44	206.61	85.89	131.39	49.40

Notes: Fuel savings are given in lbs. of fuel saved per trip thru given area

Average fuel savings per month = Sum of fuel savings of areas

Optimistic fuel savings = Average + Std. Dev.

Pessimistic fuel savings= Average - Std. Dev.

TABLE 3

PREDICTED FUEL SAVINGS

SHIP: ED RYERSON
ROUTE: PORT SUPERIOR TO BURNS HARBOR

MONTH: APRIL

	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6
Average	219.42	324.15	185.38	260.41	100.40	62.60
Std. Dev.	122.09	174.37	63.87	108.15	76.96	100.10

MONTH: MAY

	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6
Average	166.45	209.54	158.07	220.80	117.70	56.24
Std. Dev.	99.26	99.48	99.52	98.46	95.93	60.62

MONTH: JUNE

	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6
Average	91.31	128.46	107.11	131.94	85.40	52.97
Std. Dev.	77.28	89.76	54.08	98.77	51.62	66.94

MONTH: JULY

	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6
Average	98.52	110.22	87.08	174.87	119.90	80.41
Std. Dev.	95.94	78.16	33.36	86.64	37.46	41.31

MONTH: AUGUST

	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6
Average	110.52	122.36	119.40	132.40	118.64	82.81
Std. Dev.	116.25	81.46	44.60	62.80	29.66	45.35

TABLE 3 (cont.)

PREDICTED FUEL SAVINGS

SHIP: ED RYERSON
ROUTE: PORT SUPERIOR TO BURNS HARBOR

MONTH: SEPTEMBER

	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6
Average	259.67	281.48	182.17	260.81	179.41	160.55
Std. Dev.	168.84	100.97	119.88	87.86	71.30	83.78

MONTH: OCTOBER

	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6
Average	326.51	388.99	218.56	361.24	264.95	255.85
Std. Dev.	158.21	180.63	87.24	93.66	88.40	123.54

MONTH: NOVEMBER

	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6
Average	475.27	449.45	313.42	418.90	322.50	331.47
Std. Dev.	206.77	177.45	92.25	130.94	107.86	110.71

Notes: Fuel savings are given in lbs. of fuel saved per trip thru given area

Average fuel savings per month = Sum of fuel savings of areas

Optimistic fuel savings = Average + Std. Dev.

Pessimistic fuel savings = Average - Std. Dev.

TABLE 4

PREDICTED FUEL SAVINGS

SHIP: ED RYERSON
ROUTE: BURNS HARBOR TO PORT SUPERIOR

MONTH: APRIL

	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6
Average	311.99	335.41	190.66	315.77	203.32	196.76
Std. Dev.	145.64	100.07	77.26	89.59	97.52	112.60

MONTH: MAY

	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6
Average	308.35	304.03	158.19	253.94	176.18	137.28
Std. Dev.	155.76	106.94	68.94	164.01	78.22	76.74

MONTH: JUNE

	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6
Average	165.30	203.50	108.31	183.42	84.84	81.81
Std. Dev.	96.99	84.46	65.32	108.10	34.50	38.34

MONTH: JULY

	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6
Average	172.10	218.79	86.34	143.48	58.95	60.73
Std. Dev.	89.69	68.12	42.13	70.99	43.21	46.68

MONTH: AUGUST

	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6
Average	189.76	279.21	122.44	170.16	76.21	65.46
Std. Dev.	107.80	130.58	69.65	93.99	48.40	35.43

TABLE 4 (cont.)

PREDICTED FUEL SAVINGS

SHIP: ED RYERSON
ROUTE: BURNS HARBOR TO PORT SUPERIOR

MONTH: SEPTEMBER

	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6
Average	351.24	439.30	154.37	265.59	136.07	133.27
Std. Dev.	104.65	177.12	68.39	111.44	83.93	91.91

MONTH: OCTOBER

	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6
Average	529.92	550.92	224.01	337.84	231.48	174.83
Std. Dev.	199.62	205.43	49.78	78.39	74.72	95.71

MONTH: NOVEMBER

	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6
Average	605.24	731.70	249.86	330.68	325.49	267.62
Std. Dev.	234.41	284.63	117.32	69.57	77.31	94.25

Notes: Fuel savings are given in Lbs. of fuel saved per trip thru given area

Average fuel savings per month = Sum of fuel savings of areas

Optimistic fuel savings = Average + Std. Dev.

Pessimistic fuel savings= Average - Std. Dev.

TABLE 5

PREDICTED FUEL SAVINGS

SHIP: STEWART CORT
ROUTE: BURNS HARBOR TO TACONITE HARBOR

MONTH: APRIL

	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6
Average	424.72	386.38	200.34	351.98	184.27	143.00
Std. Dev.	182.22	141.50	99.52	140.28	72.47	57.75

MONTH: MAY

	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6
Average	330.73	335.52	158.09	277.96	201.83	90.59
Std. Dev.	157.82	138.79	77.37	107.95	92.89	32.33

MONTH: JUNE

	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6
Average	181.26	282.48	132.71	213.51	115.04	70.99
Std. Dev.	122.88	83.94	60.31	107.24	92.31	35.42

MONTH: JULY

	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6
Average	214.52	213.35	100.62	173.07	71.99	36.73
Std. Dev.	100.48	213.35	59.59	84.24	57.84	20.82

MONTH: AUGUST

	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6
Average	244.24	248.66	120.21	193.80	79.03	43.32
Std. Dev.	86.99	119.12	56.33	106.98	81.40	23.56

TABLE 5 (cont.)

PREDICTED FUEL SAVINGS

SHIP: STEWART CORT
ROUTE: BURNS HARBOR TO TACONITE HARBOR

MONTH: SEPTEMBER

	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6
Average	426.37	514.58	162.98	312.38	185.97	73.88
Std. Dev.	165.94	172.62	72.15	110.35	110.85	40.35

MONTH: OCTOBER

	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6
Average	569.51	659.57	260.38	468.59	216.82	92.66
Std. Dev.	186.72	276.23	52.05	176.79	88.02	31.31

MONTH: NOVEMBER

	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6
Average	676.68	778.20	286.77	424.59	357.83	110.03
Std. Dev.	178.39	263.36	111.98	98.08	147.87	56.60

Notes: Fuel savings area given in lbs. of fuel saved per trip thru given area.

Average fuel savings per month = Sum of fuel savings of areas

Optimistic fuel savings = Average + Std. Dev.

Pessimistic fuel savings= Average - Std. Dev.

TABLE 6

PREDICTED FUEL SAVINGS

SHIP: STEWART CORT
ROUTE: TACONITE HARBOR TO BURNS HARBOR

MONTH: APRIL

	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6
Average	351.22	423,86	222.36	364.93	159.15	39.29
Std. Dev.	172.40	206.17	94.73	112.34	93.81	38.75

MONTH: MAY

	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6
Average	254.04	263.12	172.80	301.00	175.88	37.19
Std. Dev.	122.41	109.35	86.28	121.41	81.22	34.47

MONTH: JUNE

	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6
Average	169.98	153.64	146.95	198.59	129.21	40.94
Std. Dev.	109.49	86.83	81.24	90.95	54.00	27.50

MONTH: JULY

	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6
Average	145.03	159.16	143.22	232.09	155.66	40.52
Std. Dev.	117.27	79.70	54.24	110.68	66.04	31.96

MONTH: AUGUST

	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6
Average	198.51	193.64	164.54	206.36	163,96	34.05
Std. Dev.	126.59	132.72	80.71	93.69	52.57	22.01

TABLE 6 (cont.)

PREDICTED FUEL SAVINGS

SHIP: STEWART CORT
ROUTE: TACONITE HARBOR TO BURNS HARBOR

MONTH: SEPTEMBER

	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6
Average	349.65	365.46	229.92	360.64	259.72	69.04
Std. Dev.	174.48	156.24	96.17	117.23	115.00	30.69

MONTH: OCTOBER

	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6
Average	475.58	533.04	298.67	422.99	347.14	106.18
Std. Dev.	209.09	196.35	109.26	169.16	102.61	41.11

MONTH: NOVEMBER

	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6
Average	569.20	601.34	396.85	470.62	357.83	125.55
Std. Dev.	185.43	193.39	111.11	87.14	90.03	32.26

Notes: Fuel savings are given in lbs. of fuel saved per trip thru given area

Average fuel savings per month = sum of fuel savings of areas

Optimistic fuel savings = Average + Std. Dev.

Pessimistic fuel savings= Average - Std. Dev.

TABLE 7

Extra fuel used (in lbs.) to overcome added resistance of sail device per trip.

SHIP: STEWART CORT
ROUTE: WHITEFISH BAY TO MACKINAC BRIDGE

MONTH	AVERAGE	STD. DEV.
APRIL	55.28	12.10
MAY	60.94	13.36
JUNE	62.58	13.75
JULY	56.06	13.42
AUGUST	58.43	10.83
SEPTEMBER	66.95	15.62
OCTOBER	81.45	13.86
NOVEMBER	77.21	14.76

ROUTE: MACKINAC BRIDGE TO WHITEFISH BAY

MONTH	AVERAGE	STD. DEV.
APRIL	64.23	15.94
MAY	57.42	12.23
JUNE	50.59	2.37
JULY	44.97	9.15
AUGUST	52.42	16.09
SEPTEMBER	58.80	14.62
OCTOBER	60.00	14.89
NOVEMBER	64.08	14.75

TABLE 8

Extra fuel used (in lbs.) to overcome added resistance of sail device per trip

SHIP: ST. CLAIR
ROUTE: WHITEFISH BAY TO MACKINAC BRIDGE

MONTH	AVERAGE	STD. DEV.
APRIL	62.96	12.65
MAY	65.35	13.01
JUNE	56.98	11.46
JULY	62.64	14.45
AUGUST	63.60	11.37
SEPTEMBER	66.64	9.78
OCTOBER	73.12	14.03
NOVEMBER	70.65	10.04

ROUTE: MACKINAC BRIDGE TO WHITEFISH BAY

MONTH	AVERAGE	STD. DEV.
APRIL	66.08	17.58
MAY	53.07	12.77
JUNE	46.29	8.11
JULY	45.49	7.22
AUGUST	50.09	12.85
SEPTEMBER	57.07	16.01
OCTOBER	60.87	17.16
NOVEMBER	72.60	18.19

TABLE 9

Extra fuel used (in lbs.) to overcome added resistance of sail device per trip

SHIP: ED RYERSON
ROUTE: WHITEFISH BAY TO MACK BRIDGE

MONTH	AVERAGE	STD. DEV.
APRIL	52.21	10.43
MAY	52.69	12.87
JUNE	57.52	11.51
JULY	52.07	10.19
AUGUST	52.63	11.70
SEPTEMBER	60.18	12.36
OCTOBER	73.88	19.26
NOVEMBER	62.80	13.17

ROUTE: MACKINAC BRIDGE TO WHITEFISH BAY

MONTH	AVERAGE	STD. DEV.
APRIL	56.70	12.40
MAY	49.21	13.68
JUNE	41.95	10.29
JULY	39.99	8.53
AUGUST	42.18	10.96
SEPTEMBER	52.86	8.01
OCTOBER	49.92	13.38
NOVEMBER	60.68	12.45

TABLE 10

CALCULATION OF ROUND TRIPS PER MONTH

BASIC EQUATION:

$$\text{\# of Round Trips/mth} = \frac{(\text{\# of days in month})}{\frac{\text{Voyage Length}}{360} + 2}$$

Above Equation based on a 15 mph service speed with 2 days of in port time per round trip:

SHIP: STEWART CORT
ROUTE: BURNS HARBOR/TACONITS HARBOR/BURNS HARBOR

TOTAL LENGTH: 1080.6 miles

MTH:	APR.	MAY	JUNE	JULY	AUG.	SEP.	OCT.	NOV.
# of Trips:	6.0	6.2	6.0	6.2	6.2	6.0	6.2	6.0

SHIP: ED RYERSON
ROUTE: BURNS HARBOR/PORT SUPERIOR/BURNS HARBOR

TOTAL LENGTH: 1199.85 miles

MTH:	APR.	MAY	JUNE	JULY	AUG.	SEP.	OCT.	NOV.
# of trips:	5.63	5.81	5.63	5.81	5.81	5.63	5.81	5.63

SHIP: ST. CLAIR
ROUTE: BURNS HARBOR/THUNDERBAY/BURNS HARBOR

TOTAL LENGTH: 925.73 miles

MTH:	APR.	MAY	JUNE	JULY	AUG.	SEP.	OCT.	NOV.
# of trips:	6.56	6.78	6.56	6.78	6.78	6.56	6.78	6.56

TABLE 11

TOTAL FUEL SAVED PER MONTH IN LBS.

SHIP: ST. CLAIR
ROUTE: BURNS HARBOR/THUNDERBAY/BURNS HARBOR

MONTH	PESSIMISTIC	AVERAGE	OPTIMISTIC
APRIL	10,373.85	18,453.08	26,532.31
MAY	8,299.94	15,811.77	23,147.19
JUNE	4,730.09	10,602.99	16,475.90
JULY	3,594.76	9,109.81	14,624.87
AUGUST	5,211.79	11,545.46	17,879.13
SEPTEMBER	9,722.84	17,564.33	25,405.83
OCTOBER	14,815.11	24,160.60	33,506.08
NOVEMBER	19,376.47	29,716.41	40,056.34

TABLE 12

TOTAL FUEL SAVED PER MONTH IN LBS.

SHIP: ED RYERSON
ROUTE: BURNS HARBOR/PT. SUPERIOR/BURNS HARBOR

MONTH	PESSIMISTIC	AVERAGE	OPTIMISTIC
APRIL	7,354.53	14,623.14	21,891.75
MAY	5,429.45	12,578.24	19,727.04
JUNE	2,459.97	7,459.19	12,458.40
JULY	3,293.81	7,665.31	12,036.81
AUGUST	3,520.45	8,683.39	13,846.33
SEPTEMBER	7,884.54	15,149.71	22,414.89
OCTOBER	13,208.05	21,736.95	30,265.86
NOVEMBER	16,715.64	26,450.42	36,185.19

TABLE 13

TOTAL FUEL SAVED PER MONTH IN LBS.

SHIP: STEWART CORT
ROUTE: BURNS HARBOR/TACONITE HARBOR/BURNS HARBOR

MONTH	PESSIMISTIC	AVERAGE	OPTIMISTIC
APRIL	10,152.06	18,791.70	27,431.58
MAY	8,013.56	15,378.42	22,743.27
JUNE	4,523.40	10,332.78	16,142.16
JULY	4,393.38	9,826.57	15,259.75
AUGUST	4,773.26	11,032.71	17,292.17
SEPTEMBER	10,815.18	19,109.04	27,402.90
OCTOBER	16,381.83	26,720.02	37,058.21
NOVEMBER	20,573.82	30,084.72	39,595.62

APPENDIX II

The following tables are the sailing directions for the three routes that are being examined in this study. The routes for these ships all originate in Burns Harbor, Ind. The destinations are Port Superior in Minnesota, Taconite Harbor also in Minnesota, and Thunderbay located in Ontario. All three of the ports are sources of iron ore used in the steel industry located in and around Burns Harbor.

The tables show, for each particular route, the compass course in degrees (true) and the distance that must be sailed on that course. In additon the table shows what area is being traversed. This area corresponds with the weather data areas. The geographic location of these areas is shown at the bottom of each page.

Areas 1 thru 6 are all areas where the ships have the potential to be motor sailing. In addition to these areas all the ships must traverse the route from Mackinac Bridge to Whitefish Bay. Because of the frequent course changes and narrow width of the channels, this is an area that must be motored through only. This is called area 7. The sailing directions for this area are also shown in the tables.

TABLE 1

SAILING DIRECTIONS

LAKE MICHIGAN

MACKINAC BRIDGE TO BURNS HARBOR

BURNS HARBOR TO MACKINAC BRIDGE

AREA	MACK BRIDGE TO BURNS HARBOR		BURNS HARBOR TO MACK BRIDGE	
1	191°	166 miles	11°	166
2	191	4	11	4
2	193.5	45	13.5	45
2	209	17.5	29	17.5
2	241.75	14.5	61.75	14.5
2	216.50	64.75	36.5	64.75
2	186	5	6	5
2	276	20	96	20
	TOTAL DISTANCE	336.75		336.75

SAILING DIRECTIONS:

Compass course (degrees true), distance (statue miles)
LOCATION OF AREAS

AREA 1: Lake Michigan south of Latitude 44° 0'
AREA 2: Lake Michigan north of Latitude 44° 0'

TABLE 2

SAILING DIRECTIONS

LAKE SUPERIOR

PORT SUPERIOR TO WHITEFISH BAY

WHITEFISH BAY TO PORT SUPERIOR

AREA	WHITEFISH BAY TO PORT SUPERIOR		PORT SUPERIOR TO WHITEFISH BAY	
3	319°	7 st. mi.	138.75	9.75
3	328	14.5	147.5	14.75
3	279.25	14.25	114	63
3	292	46.5		
4			114	68.5
4	292	86.75	105.25	18.25
4	265.75	14	85.75	14
5	257.75	87.5	77.75	88.25
6	257.75	36	77.75	35.
6	243.25	67.75	63	72
6			45.25	19.75
TOTAL DISTANCE		374.25		383.50

SAILING DIRECTIONS:

Compass course (degrees true) distance (statue miles)
LOCATION OF AREAS:
AREA 3: Lake Superior east of longitude 86° 10'
AREA 4: Lake Superior between longitude 86° 10' and 88° 10'
AREA 5: Lake Superior between longitude 88° 10' and 90° 0'
AREA 6: Lake Superior west of longitude 90° 0'

TABLE 3

SAILING DIRECTIONS

LAKE SUPERIOR

TACONITE HARBOR TO WHITEFISH BAY

WHITEFISH BAY TO TACONITE HARBOR

AREA		WHITEFISH BAY TO TACONITE HARBOR		TACONITE HARBOR TO WHITEFISH BAY	
3		319	7	138.75	9.75
3		328	14.25	147.5	14.75
3		279.25	14.25	114	63.50
3		292.25	46.25		
4		292.25	87	114	68
4		308.25	17.75	112.75	34.25
5		261.25	87	82.5	87.5
6		261.25	34.5		
6		299	10.75	82.5	42
	TOTAL DISTANCE		318.75		319.75

SAILING DIRECTIONS:

Compass Course (degrees true), Distance (statue miles)
LOCATIONS OF AREAS:

AREA 3: Lake Superior east of longitude 86° 10'
AREA 4: Lake Superior between longitude 86° 10' and 88° 10'
AREA 5: Lake Superior between longitude 88° 10' and 90° 0'
AREA 6: Lake Superior west of longitude 90° 0'

TABLE 4

SAILING DIRECTIONS

LAKE SUPERIOR

THUNDERBAY TO WHITEFISH BAY

WHITEFISH BAY TO THUNDERBAY

AREA	WHITEFISH BAY to THUNDERBAY		THUNDERBAY TO WHITEFISH BAY	
3	318.75°	8.63 st. mi	138.57°	9.75
3	339.75	13	147.5	14.75
3	300.00	71.25	118.75	65.75
4	300	109.75	118.75	109.75
5	300	14.0	148.	15
5	277	26	98	26
TOTAL DISTANCE		242.63		241.00

SAILING DIRECTIONS GIVEN IN:

Compass course (degrees true) distance (statue miles)

LOCATIONS OF AREAS:

AREA 3: Lake Superior East of Longitude 86° 10'
AREA 4: Lake Superior between longitude 86° 10' and 88° 10'
AREA 5: Lake Superior between longitude 88° 10' and 90°

TABLE 5

SAILING DIRECTIONS

WHITEFISH BAY TO MACKINAC BRIGDE

MACKINAC BRIDGE TO WHITEFISH BAY

AREA	WHITEFISH BAY TO MACKINAC BRIDGE		MACKINAC BRIDGE TO WHITEFISH BAY	
7	127°	7 miles	68°	6.25 miles
7	55	7	90	20
7	90	4	61	14
7	145	2.6	0	14
7	167	13	318	3.75
7	128	9.5	295	4.25
7	115	4.25	308	9.5
7	138	3.75	347	13
7	180	14	325	2.6
7	241	14	270	4
7	270	20	235	7
7	248	6.25	307	7
Total distance		105.35		105.35

SAILING DIRECTIONS:

Compass course (degrees true) distance (statue miles)

APPENDIX III

WEATHER DATA

The following tables show the weather data that was used in the simulation model. This data is taken from references (5) & (6). The tables are broken down into six seperate areas and by the months of April thru November, the sailing season for the Great Lakes.

The location of the areas are as follows:

Area 1: Southern Lake Michigan
Lake Michigan south of Latitude 44° 0' N.

Area 2: Northern Lake Michigan
Lake Michigan North of Latitude 44° 0' N.

Area 3: Eastern Lake Superior
Lake Superior east of longitude 86° 10' W.

Area 4: East-Central Lake Superior
Lake Superior between longitude 86° 10' W and 88° 10' W.

Area 5: West-Central Lake Superior
Lake Superior between longitude 88° 10' W. and 90° 0' W.

Area 6: Western Lake Superior
Lake Superior west of longitude 90° 0' W.

The tables show the historical wind speeds and directions based on observations over the past twenty years. For each month the tables show the per centage of time that one can expect the wind to blow from a specific direction in the given wind range. Also included at the bottom of each table is the per centage of time the wind is expected to be calm.

Since the computer program depends on having a specifc number for both direction and speed, discrete values for these two variables had to be chosen. The values for wind speed were 2,7,16,27,40, & 48 knots of wind speed plus 0 knots for calm. The values for direction were 0,45,90,135,180,225,270, & 315 degrees (true). This gives a 6 x 8 matix of potential wind speeds and direction.

TABLE 1

WEATHER CONDITIONS

SOUTHERN LAKE MICHIGAN (AREA 1)

AUGUST

WIND SPEED (KNOTS) WND DIR	0 -3	4- 10	11- 24	22- 33	34- 47	48+
N	.4	2.9	5.7	3.2	.3	0.0
NE	.3	3.9	4.7	1.3	0.0	0.0
E	.4	3.5	4.0	.4	0.0	0.0
SE	.5	4.1	6.5	.7	.1	0.0
S	.6	6.8	11.0	1.9	.1	0.0
SW	.4	5.3	9.4	1.3	0.0	0.0
W	.6	2.8	5.3	.9	0.0	0.0
NW	.2	2.6	5.1	1.8	.1	0.0
CALM	.9					

SEPTEMBE

WIND SPEED (KNOTS) WND DIR	0 -3	4- 10	11- 24	22- 33	34- 47	48+
N	.3	2.3	4.7	3.4	.2	0.0
NE	.2	2.7	4.9	1.7	.1	0.0
E	.3	2.7	4.7	1.1	0.0	0.0
SE	.2	3.5	9.7	2.7	.1	0.0
S	.1	3.9	13.4	4.0	.2	0.0
SW	.1	2.7	6.4	1.8	.1	0.0
W	.2	2.3	4.8	2.1	.4	0.0
NW	.1	2.0	5.7	3.5	.1	0.0
CALM	.6					

OCTOBER

WIND SPEED (KNOTS) WND DIR	0 -3	4- 10	11- 24	22- 33	34- 47	48+
N	.1	1.8	4.7	3.7	.5	0.0
NE	.1	1.9	2.6	1.1	.1	0.0
E	.2	1.7	3.9	.8	0.0	0.0
SE	.1	2.8	6.8	2.5	.2	0.0
S	.3	3.2	11.7	7.4	.5	0.0
SW	.2	2.3	6.9	4.2	.3	0.0
W	.2	1.9	6.0	3.8	.5	0.0
NW	.1	2.0	6.2	5.5	1.1	0.0
CALM	.1					

NOVEMBER

WIND SPEED (KNOTS) WND DIR	0 -3	4- 10	11- 24	22- 33	34- 47	48+
N	.2	1.7	4.2	3.5	.4	0.0
NE	.2	1.5	3.1	2.1	.1	0.0
E	.1	1.7	1.9	.8	.1	0.0
SE	.1	1.7	4.1	2.1	.3	0.0
S	.1	1.8	8.0	6.4	.7	0.0
SW	.1	2.2	7.7	5.4	.3	0.0
W	.1	1.9	7.5	6.4	.7	0.0
NW	.1	2.0	8.0	8.8	1.4	.1
CALM	.4					

APRIL

WIND SPEED (KNOTS) WND DIR	0 -3	4- 10	11- 24	22- 33	34- 47	48+
N	.2	2.1	8.7	4.4	.3	0.0
NE	.3	3.1	5.3	.8	0.0	0.0
E	.3	3.3	5.8	1.5	.2	0.0
SE	0.0	3.0	8.7	3.6	.2	0.0
S	.5	3.2	11.0	6.8	.2	.1
SW	.2	1.5	5.2	1.3	0.0	0.0
W	.3	2.4	3.5	1.0	.1	0.0
NW	.2	3.0	4.9	2.3	.2	0.0
CALM	.3					

MAY

WIND SPEED (KNOTS) WND DIR	0 -3	4- 10	11- 24	22- 33	34- 47	48+
N	.5	3.3	8.3	3.3	.2	0.0
NE	.2	2.8	6.7	.9	.1	0.0
E	.3	2.6	5.6	1.4	0.0	0.0
SE	.2	3.4	9.0	2.5	0.0	0.0
S	.3	3.3	11.7	4.0	.1	0.0
SW	.2	2.7	8.2	1.2	0.0	.1
W	.2	1.8	5.1	1.0	.1	0.0
NW	.1	2.5	4.5	1.1	0.0	0.0
CALM	.4					

JUNE

WIND SPEED (KNOTS) WND DIR	0 -3	4- 10	11- 24	22- 33	34- 47	48+
N	.3	4.0	9.3	2.0	.2	0.0
NE	.3	3.2	5.4	.6	.1	0.0
E	.1	3.5	5.3	.4	0.0	0.0
SE	.2	3.2	8.0	.6	0.0	0.0
S	.5	3.8	15.1	2.7	0.0	0.0
SW	.2	2.9	9.1	.7	.1	0.0
W	.4	2.8	5.2	.5	0.0	0.0
NW	.4	3.3	4.2	.8	0.0	0.0
CALM	.6					

JULY

WIND SPEED (KNOTS) WND DIR	0 -3	4- 10	11- 24	22- 33	34- 47	48+
N	.3	4.5	5.8	1.3	.1	0.0
NE	.3	4.1	4.6	.4	0.0	0.0
E	.5	4.0	3.9	.6	0.0	0.0
SE	.2	5.4	5.6	.4	0.0	0.0
S	.3	5.7	11.7	2.0	.1	0.0
SW	.4	6.3	8.7	.9	.1	0.0
W	.4	3.8	5.8	.7	0.0	0.0
NW	.3	4.6	4.6	1.0	0.0	0.0
CALM	.6					

TABLE 2

WEATHER CONDITIONS

NORTHERN LAKE MICHIGAN (AREA 2)

AUGUST

WND DIR	WIND SPEED (KNOTS) 0 -3	4- 10	11- 24	22- 33	34- 47	48+
N	.3	3.3	6.9	2.9	.2	0.0
NE	.7	2.9	4.2	.9	0.0	0.0
E	.2	3.2	2.8	.5	0.0	0.0
SE	.3	3.7	4.1	.7	0.0	0.0
S	.4	5.9	13.9	4.3	.1	0.0
SW	.4	6.1	10.2	2.9	0.0	0.0
W	.5	3.4	4.1	.8	0.0	0.0
NW	.2	3.0	4.2	1.1	.2	0.0
CALM	.5					

SEPTEMBER

WND DIR	WIND SPEED (KNOTS) 0 -3	4- 10	11- 24	22- 33	34- 47	48+
N	.2	2.1	6.7	4.5	.6	0.0
NE	.2	1.8	4.6	1.1	.1	0.0
E	.3	2.3	4.4	1.0	0.0	0.0
SE	.2	3.1	6.3	1.7	.1	0.0
S	.2	3.4	13.1	4.3	.2	0.0
SW	.3	3.6	7.9	3.2	.4	0.0
W	.2	2.2	4.4	2.6	.2	0.0
NW	.3	1.6	6.3	3.8	.2	0.0
CALM	.3					

OCTOBER

WND DIR	WIND SPEED (KNOTS) 0 -3	4- 10	11- 24	22- 33	34- 47	48+
N	.2	2.2	5.5	3.4	.6	.1
NE	.1	1.7	2.3	1.0	.1	0.0
E	.2	2.0	2.9	.8	.1	0.0
SE	.1	2.5	5.3	2.3	.1	0 0
S	.1	2.5	10.2	7.7	.8	0.0
SW	.2	2.3	7.8	5.3	.8	0.0
W	.1	2.0	5.8	4.0	.6	.1
NW	.2	2.2	6.5	5.7	1.2	0.0
CALM	.4					

NOVEMBER

WND DIR	WIND SPEED (KNOTS) 0 -3	4- 10	11- 24	22- 33	34- 47	48+
N	.2	1.8	5.8	4.4	.6	.2
NE	.1	1.6	2.8	1.3	.1	0.0
E	.1	1.4	2.3	.5	0.0	.1
SE	0.0	1.0	4.3	2.2	.1	0.0
S	.1	1.4	8.6	5.2	.7	0.0
SW	.1	2.3	6.4	5.5	.9	.1
W	.2	2.2	7.4	6.5	.8	0.0
NW	.2	2.4	8.0	8.7	1.0	.1
CALM	.3					

APRIL

WND DIR	WIND SPEED (KNOTS) 0 -3	4- 10	11- 24	22- 33	34- 47	48+
N	.3	3.0	8.1	3.5	.6	0.0
NE	.3	3.9	7.9	1.8	.2	0.0
E	.3	3.1	5.5	1.7	.3	0.0
SE	.2	2.9	5.6	1.8	.1	0.0
S	.3	2.8	9.7	4.6	.1	0.0
SW	.1	3.5	5.7	1.0	0.0	0.0
W	.2	2.8	4.2	.8	.1	0.0
NW	.1	2.6	7.0	2.4	.3	.1
CALM	.5					

MAY

WND DIR	WIND SPEED (KNOTS) 0 -3	4- 10	11- 24	22- 33	34- 47	48+
N	.2	3.6	7.7	2.7	.3	0.0
NE	.4	3.4	7.2	1.4	.1	0.0
E	.2	3.4	5.5	.8	.1	0.0
SE	.2	3.1	5.9	1.2	0.0	0.0
S	.2	3.5	10.8	5.1	.1	0.0
SW	.3	3.6	8.1	2.4	0.0	0.0
W	.2	2.3	3.9	.6	.1	0.0
NW	.1	2.7	5.7	1.7	.2	0.0
CALM	1.0					

JUNE

WND DIR	WIND SPEED (KNOTS) 0 -3	4- 10	11- 24	22- 33	34- 47	48+
N	.4	3.4	7.9	1.9	0.0	0.0
NE	.4	3.8	6.0	1.0	0.0	0.0
E	.2	3.4	4.1	.5	0.0	0.0
SE	.2	3.0	4.2	.7	0.0	0.0
S	.4	4.8	14.5	4.2	.1	0.0
SW	.4	5.0	10.8	1.8	.1	0.0
W	.3	3.4	3.6	.3	0.0	0.0
NW	.3	2.9	4.0	.9	.1	0.0
CALM	1.0					

JULY

WND DIR	WIND SPEED (KNOTS) 0 -3	4- 10	11- 24	22- 33	34- 47	48+
N	.3	4.4	7.1	1.6	.1	0.0
NE	.3	3.7	4.0	.6	0.0	0.0
E	.6	3.1	2.1	.1	0.0	0.0
SE	.3	4.1	3.5	.4	0.0	0.0
S	.5	6.5	13.2	3.0	.1	0.0
SW	.5	6.0	11.3	1.4	0.0	0.0
W	.5	3.9	5.8	.4	0.0	0.0
NW	.2	3.4	4.8	1.1	0.0	0.0
CALM	1.1					

TABLE 3

WEATHER CONDITIONS

EASTERN LAKE SUPERIOR
(AREA 3)

AUGUST
WIND SPEED (KNOTS)

WND DIR	0 -3	4- 10	11- 24	22- 33	34- 47	48+
N	.2	3.8	5.0	1.8	.1	0.0
NE	.5	2.8	2.9	1.0	.1	0.0
E	.3	4.3	3.2	.2	0.0	0.0
SE	.8	3.8	7.2	1.1	0.0	0.0
S	.6	4.7	9.8	1.6	0.0	0.0
SW	.4	5.1	6.8	1.3	0.0	0.0
W	.5	4.7	6.7	.8	.2	0.0
NW	.3	5.5	7.8	2.8	.2	0.0
CALM	1.1					

SEPTEMBER
WIND SPEED (KNOTS)

WND DIR	0 -3	4- 10	11- 24	22- 33	34- 47	48+
N	.3	2.9	5.3	2.5	.2	.1
NE	.3	2.8	3.7	1.2	.1	0.0
E	.4	2.5	3.1	.8	0.0	0.0
SE	.2	3.4	8.9	2.7	.2	0.0
S	.1	3.2	9.4	2.6	.2	0.0
SW	.2	3.0	6.7	2.0	.2	0.0
W	.2	3.2	5.6	2.3	.3	0.0
NW	.5	4.1	7.8	6.0	.5	0.0
CALM	.3					

OCTOBER
WIND SPEED (KNOTS)

WND DIR	0 -3	4- 10	11- 24	22- 33	34- 47	48+
N	.1	2.5	5.4	3.7	.9	0.0
NE	.1	1.5	3.3	1.6	.4	.1
E	.3	2.1	2.5	.9	.1	0.0
SE	.2	2.8	8.8	5.4	.9	0.0
S	0.0	2.3	10.3	5.1	.4	0.0
SW	.1	1.9	5.8	3.2	.2	0.0
W	.1	2.4	3.6	2.5	.5	0.0
NW	.3	2.0	6.8	7.3	1.3	0.0
CALM	.3					

NOVEMBER
WIND SPEED (KNOTS)

WND DIR	0 -3	4- 10	11- 24	22- 33	34- 47	48+
N	.1	2.4	6.0	4.5	1.0	.1
NE	.1	2.4	6.4	3.6	.5	.1
E	.2	1.5	2.5	1.5	.1	0.0
SE	.2	2.1	4.7	3.5	.6	.1
S	0.0	2.0	6.7	4.1	.3	0.0
SW-	.1	1.9	5.6	4.1	.4	0.0
W	.2	2.0	4.6	3.7	.7	0.0
NW	.1	1.8	6.6	8.8	1.6	.1
CALM	.4					

APRIL
WIND SPEED (KNOTS)

WND DIR	0 -3	4- 10	11- 24	22- 33	34- 47	48+
N	.3	2.7	6.6	3.6	.4	0.0
NE	.2	3.3	6.7	4.0	.5	0.0
E	.4	2.9	5.6	1.4	.1	0.0
SE	.5	3.8	8.2	3.2	.8	0.0
S	.2	2.2	4.7	2.0	.2	0.0
SW	.1	2.5	3.6	.5	.1	0.0
W	.2	2.8	4.8	1.7	.1	.1
NW	.4	5.1	7.6	4.5	.3	0.0
CALM	1.1					

MAY
WIND SPEED (KNOTS)

WND DIR	0 -3	4- 10	11- 24	22- 33	34- 47	48+
N	.2	3.0	6.5	2.5	.1	0.0
NE	.2	3.3	5.1	1.3	.4	.1
E	.2	3.3	5.0	1.2	0.0	0.0
SE	.4	4.0	9.5	3.1	.2	0.0
S	.2	3.1	6.0	1.7	0.0	0.0
SW	.3	2.9	5.1	.9	0.0	0.0
W	.3	3.2	6.6	1.7	.3	0.0
NW	.3	3.9	9.2	3.1	.4	.1
CALM	1.1					

JUNE
WIND SPEED (KNOTS)

WND DIR	0 -3	4- 10	11- 24	22- 33	34- 47	48+
N	.6	4.0	4.9	1.1	.1	0.0
NE	.4	3.2	3.5	.7	0.0	0.0
E	.4	4.4	4.2	.6	0.0	0.0
SE	.4	4.4	9.6	1.9	0.0	0.0
S	.5	3.6	8.1	2.4	0.0	0.0
SW	.4	3.8	5.6	1.3	.2	0.0
W	.4	5.6	7.3	1.3	.1	0.0
NW	.4	5.0	6.7	1.5	0.0	0.0
CALM	1.4					

JULY
WIND SPEED (KNOTS)

WND DIR	0 -3	4- 10	11- 24	22- 33	34- 47	48+
N	.7	4.6	4.9	.4	0.0	0.0
NE	.7	3.7	2.8	.2	0.0	0.0
E	.5	3.3	2.6	.2	0.0	0.0
SE	.3	4.9	6.6	.9	0.0	0.0
S	.5	3.1	8.7	1.7	0.0	0.0
SW	.4	4.7	7.1	1.4	0.0	0.0
W	.4	6.5	8.7	1.4	0.0	0.0
NW	.6	5.8	8.9	1.7	0.0	0.0
CALM	1.1					

TABLE 4

WEATHER CONDITIONS

EAST-CENTRAL LAKE SUPERIOR
(AREA 4)

AUGUST
WIND SPEED (KNOTS)

WND DIR	0 -3	4- 10	11- 24	22- 33	34- 47	48+
N	.4	3.5	5.3	1.4	.1	0.0
NE	.3	2.6	3.2	.7	.1	0 0
E	.5	3.1	2.3	.4	0.0	0.0
SE	.4	4.9	6.1	.7	0.0	0.0
S	.3	5.4	11.7	2.4	0.0	0.0
SW	.3	4.9	8.8	1.4	.1	0.0
W	.4	4.9	7.4	1.2	.1	0.0
NW	.3	4.9	7.4	1.2	.1	0.0
CALM	.8					

SEPTEMBER
WIND SPEED (KNOTS)

WND DIR	0 -3	4- 10	11- 24	22- 33	34- 47	48+
N	.1	3.1	6.3	3.3	.3	0.0
NE	.2	2.2	3.4	1.3	.2	0.0
E	.2	2.6	3.7	.5	.1	0 0
SE	.4	3.0	7.6	1.7	.1	0.0
S	.3	3.2	12.8	4.6	.2	0.0
SW	.2	2.9	7.1	2.0	.1	0.0
W	.3	3.2	6.0	3.4	.4	0.0
NW	.3	2.5	6.2	3.0	.3	0 0
CALM	.7					

OCTOBER
WIND SPEED (KNOTS)

WND DIR	0 -3	4- 10	11- 24	22- 33	34- 47	48+
N	.2	2.4	6.3	3.9	1.1	0.0
NE	.2	2.2	3.1	1.4	.2	.1
E	.2	1.9	2.4	1.1	.1	0.0
SE	.1	2.4	6.4	3.8	.3	0.0
S	.1	2.5	10.4	6.7	.3	0.0
SW	.2	2.7	6.7	3.0	.4	0.0
W	.2	2.3	5.2	3.2	.5	.2
NW	.2	2.7	6.2	4.9	1.2	.1
CALM	.3					

NOVEMBER
WIND SPEED (KNOTS)

WND DIR	0 -3	4- 10	11- 24	22- 33	34- 47	48+
N	.1	2.4	7.0	5.9	.9	0.0
NE	.3	1.8	5.6	3.7	.6	0.0
E	.1	1.6	2.7	.9	.1	0.0
SE	.2	1.5	3.5	2.3	.4	0.0
S	.2	1.5	6.4	4.8	.7	0.0
SW	.1	2.0	6.5	3.8	.8	0.0
W	.1	1.6	5.6	4.1	.8	.1
NW	.2	2.1	7.1	8.0	1.5	.1
CALM	.3					

APRIL
WIND SPEED (KNOTS)

WND DIR	0 -3	4- 10	11- 24	22- 33	34- 47	48+
N	.5	2.9	6.7	5.8	.6	0.0
NE	.2	1.9	5.8	4.4	.7	0.0
E	.1	2.3	6.4	4.2	.7	0.0
SE	.3	2.8	6.1	3.5	.1	0.0
S	.2	2.1	7.1	2.3	.3	0.0
SW	.2	2.0	4.6	.5	.2	.1
W	.2	2.5	4.6	1.7	.1	.1
NW	.2	3.5	8.0	2.7	.5	0.0
CALM	.3					

MAY
WIND SPEED (KNOTS)

WND DIR	0 -3	4- 10	11- 24	22- 33	34- 47	48+
N	.3	3.0	6.5	3.5	.4	0.0
NE	.3	2.3	5.6	2.8	.6	0.0
E	.3	3.0	5.9	1.8	.2	0.0
SE	.2	2.9	8.1	2.3	.1	0.0
S	.2	2.6	7.3	2.8	.1	0.0
SW	.2	2.9	5.3	1.1	0.0	0.0
W	.3	2.9	5.6	2.4	.2	.1
NW	.3	4.0	7.5	3.3	.2	0.0
CALM	.6					

JUNE
WIND SPEED (KNOTS)

WND DIR	0 -3	4- 10	11- 24	22- 33	34- 47	48+
N	.3	3.4	4.5	1.2	.1	0.0
NE	.1	2.8	4.6	1.1	.1	0.0
E	.3	3.6	4.7	.9	0.0	0.0
SE	.3	3.8	7.6	1.7	0.0	0.0
S	.3	3.9	10.2	2.8	.1	0.0
SW	.4	4.2	7.2	1.7	0.0	0.0
W	.5	4.5	7.0	1.4	.1	0.0
NW	.4	4.2	7.3	1.6	.1	0.0
CALM	1.0					

JULY
WIND SPEED (KNOTS)

WND DIR	0 -3	4- 10	11- 24	22- 33	34- 47	48+
N	.3	2.8	4.2	.9	0.0	0.0
NE	.3	2.5	3.0	.4	0.0	0.0
E	.3	2.5	2.7	.2	0.0	0.0
SE	.3	4.1	7.2	1.0	0.0	0.0
S	.3	4.2	11.2	2.9	0.0	0.0
SW	.4	4.4	7.9	2.2	0.0	0.0
W	.3	5.4	9.7	2.1	.1	0.0
NW	.4	5.0	8.0	1.3	0.0	0.0
CALM	1.5					

TABLE 5

WEATHER CONDITIONS

WEST-CENTRAL LAKE SUPERIOR (AREA 5)

AUGUST

WND DIR	0 -3	4- 10	11- 24	22- 33	34- 47	48+
N	.6	3.9	4.4	1.0	0.0	0.0
NE	.6	4.3	5.2	1.2	.1	0.0
E	.7	4.2	4.2	.3	0.0	0.0
SE	.4	3.8	5.2	.4	0.0	0.0
S	.5	5.1	7.2	1.4	0.0	0.0
SW	.4	6.9	13.0	2.7	.2	0.0
W	.4	4.6	6.0	1.8	.1	0.0
NW	.3	3.6	3.4	.6	0.0	0.0
CALM	1.3					

SEPTEMBER

WND DIR	0 -3	4- 10	11- 24	22- 33	34- 47	48+
N	.3	2.3	5.3	2.1	.2	0.0
NE	.2	2.9	4.9	1.2	.3	0.0
E	.4	3.3	4.5	.7	0.0	0.0
SE	.4	2.9	6.2	1.2	.1	0.0
S	.4	3.9	9.4	2.9	.1	0.0
SW	.3	4.0	10.4	3.6	.3	0.0
W	.5	2.8	7.2	3.7	.4	0.0
NW	.2	2.7	4.9	2.2	.2	0.0
CALM	.5					

OCTOBER

WND DIR	0 -3	4- 10	11- 24	22- 33	34- 47	48+
N	.1	2.0	5.8	3.3	.7	.1
NE	.2	1.9	4.5	1.3	0.0	0.0
E	.3	3.3	3.4	1.1	.1	0.0
SE	.1	2.9	6.4	2.1	.2	0.0
S	.3	2.9	8.4	2.6	.1	0.0
SW	.3	2.8	8.3	4.4	.9	0.0
W	.3	2.5	6.6	4.0	1.0	0.0
NW	.2	2.4	6.2	5.0	.8	0.0
CALM	.2					

NOVEMBER

WND DIR	0 -3	4- 10	11- 24	22- 33	34- 47	48+
N	.1	2.4	8.9	5.6	.8	0.0
NE	.1	2.0	6.0	3.4	.7	0.0
E	.2	2.0	3.1	1.2	.1	0.0
SE	.1	1.7	3.3	1.3	.1	0.0
S	.1	1.6	4.9	3.0	.1	0.0
SW	.1	1.8	6.7	4.3	1.1	.1
W	.1	1.6	5.5	4.3	.6	0.0
NW	.2	2.7	8.3	8.1	1.4	.1
CALM	.2					

APRIL

WND DIR	0 -3	4- 10	11- 24	22- 33	34- 47	48+
N	.4	2.8	5.8	3.8	.6	0.0
NE	.1	4.1	9.7	6.1	.8	.1
E	.6	3.7	7.1	3.0	.6	0.0
SE	.5	3.3	5.1	1.4	.1	0.0
S	.4	3.7	4.7	.9	0.0	0.0
SW	.2	4.5	5.9	1.2	.6	0.0
W	.2	3.0	5.3	1.7	.3	0.0
NW	.1	2.0	4.2	.6	.2	0.0
CALM	.6					

MAY

WND DIR	0 -3	4- 10	11- 24	22- 33	34- 47	48+
N	.4	2.6	6.2	2.5	.4	0.0
NE	.2	3.6	8.7	2.9	.4	0.0
E	.4	4.0	7.5	1.6	.2	0.0
SE	.2	4.0	5.8	1.3	.1	0.0
S	.4	3.2	5.8	1.5	.1	0.0
SW	.2	4.3	8.8	2.6	.1	0.0
W	.4	3.7	5.6	1.9	.1	0.0
NW	.3	2.8	3.2	1.0	0.0	0.0
CALM	1.0					

JUNE

WND DIR	0 -3	4- 10	11- 24	22- 33	34- 47	48+
N	.5	3.8	3.5	1.0	0.0	0.0
NF	.4	3.9	8.6	1.6	.1	0.0
E	.5	3.9	6.8	.5	0.0	0.0
SE	.4	3.5	5.2	.7	.1	0.0
S	.5	3.7	6.6	1.6	.1	0.0
SW	.2	5.6	11.8	2.9	.1	0.0
W	.6	5.0	6.6	1.5	.1	0.0
NW	.3	3.1	3.2	.3	0.0	0.0
CALM	1.2					

JULY

WND DIR	0 -3	4- 10	11- 24	22- 33	34- 47	48+
N	.2	2.8	2.9	.3	0.0	0.0
NE	.2	4.1	4.5	.3	0.0	0.0
E	.4	4.0	4.0	.3	0.0	0.0
SE	.2	3.1	5.7	.4	0.0	0.0
S	.4	3.9	8.1	1.5	.1	0.0
SW	.3	7.0	14.5	3.5	.2	0.0
W	.3	5.0	9.3	2.3	.1	0.0
NW	.4	3.7	4.4	.5	0.0	0.0
CALM	1.0					

TABLE 6

WEATHER CONDITIONS

WESTERN LAKE SUPERIOR
(AREA 6)

AUGUST

WND DIR	0 -3	4- 10	11- 24	22- 33	34- 47	48+
N	.5	4.4	4.1	.2	0.0	0.0
NE	.4	6.6	8.9	2.3	0.0	0.0
E	.6	4.4	5.2	.8	0.0	0.0
SE	.5	4.6	2.6	.2	0.0	0.0
S	.6	4.8	5.7	.5	0.0	0.0
SW	.5	7.3	11.4	1.9	.1	0.0
W	.6	4.6	5.2	1.2	0.0	0.0
NW	.4	3.6	3.6	.4	0.0	0.0
CALM	1.3					

SEPTEMBER

WND DIR	0 -3	4- 10	11- 24	22- 33	34- 47	48+
N	.4	3.0	4.7	1.3	.1	0.0
NE	.5	5.0	7.7	1.6	.1	0.0
E	.5	4.1	4.5	1.5	.2	0.0
SE	.3	3.3	4.0	.4	.1	0.0
S	.3	4.3	7.0	1.3	0.0	0.0
SW	.5	5.0	10.4	2.7	0.0	0.0
W	.3	3.5	7.0	2.2	.1	0.0
NW	.4	2.8	5.8	2.1	.1	0.0
CALM	.9					

OCTOBER

WND DIR	0 -3	4- 10	11- 24	22- 33	34- 47	48+
N	.4	2.3	5.7	1.6	.1	0.0
NE	.3	3.8	6.7	2.6	.3	0.0
E	.2	3.6	4.8	1.8	.1	0.0
SE	.3	3.2	4.0	.7	0.0	0.0
S	.4	2.9	6.3	1.2	0.0	0.0
SW	.2	3.8	9.4	4.3	.5	.2
W	.2	2.8	6.3	2.6	.6	0.0
NW	.3	2.5	7.4	4.4	.5	0.0
CALM	.6					

NOVEMBER

WND DIR	0 -3	4- 10	11- 24	22- 33	34- 47	48+
N	.1	2.9	7.6	3.1	.3	0.0
NE	.3	3.0	6.2	2.3	.2	0.0
E	.3	3.2	4.5	2.5	.2	0.0
SE	.1	1.8	2.8	.4	0.0	0.0
S	0.0	1.9	3.7	1.8	.3	0.0
SW	.1	2.1	7.3	4.1	.6	0.0
W	.3	2.9	6.3	2.9	.7	.1
NW	.1	2.9	12.1	7.0	.5	.1
CALM	.4					

APRIL

WND DIR	0 -3	4- 10	11- 24	22- 33	34- 47	48+
N	.6	4.0	5.0	1.2	.2	0.0
NE	.3	6.7	13.6	11.5	1.4	0.0
E	.4	2.9	4.0	4.2	.7	0.0
SE	.1	1.8	2.5	.2	0.0	0.0
S	.1	3.1	3.6	.6	0.0	0.0
SW	.4	3.9	8.0	1.7	.1	0.0
W	.3	2.2	3.4	1.4	.3	0.0
NW	.2	2.8	3.8	1.4	.3	0.0
CALM	1.1					

MAY

WND DIR	0 -3	4- 10	11- 24	22- 33	34- 47	48+
N	.5	5.3	6.5	1.0	.1	0.0
NE	.4	8.2	17.3	5.8	1.1	0.0
E	.5	4.6	5.0	1.3	.1	0.0
SE	.3	2.6	2.9	.6	0.0	0.0
S	0.0	3.0	3.7	.3	0.0	0.0
SW	.3	2.9	6.6	1.1	.1	0.0
W	.4	3.0	4.2	1.1	0.0	0.0
NW	.4	2.8	3.9	.8	.1	0.0
CALM	1.2					

JUNE

WND DIR	0 -3	4- 10	11- 24	22- 33	34- 47	48+
N	.4	5.3	5.7	.5	0.0	0.0
NE	.3	7.9	15.0	3.9	.4	0.0
E	.3	4.2	4.5	.5	0.0	0.0
SE	.2	3.5	2.5	.2	0.0	0.0
S	.3	3.4	2.9	.6	0.0	0.0
SW	.4	4.6	9.5	3.0	.1	0.0
W	.3	4.1	4.9	1.0	.1	0.0
NW	.2	3.4	3.6	.3	0.0	0.0
CALM	2.0					

JULY

WND DIR	0 -3	4- 10	11- 24	22- 33	34- 47	48+
N	.5	5.3	4.3	.3	0.0	0.0
NE	.6	7.6	9.8	1.3	0.0	0.0
E	.4	4.4	2.9	.4	0.0	0.0
SE	.3	3.3	2.0	.1	0.0	0.0
S	.2	3.9	4.7	.5	0.0	0.0
SW	.3	7.0	12.3	1.8	.1	0.0
W	.7	5.2	7.6	1.3	.1	0.0
NW	.5	4.0	4.3	.3	0.0	0.0
CALM	1.7					

APPENDIX IV

COMPUTER LISTING

The following pages contain the listing of the computer program used to simulate the problem of motor-sailing Great Lakes bulk carriers. The program is written in HP Basic and was used on an HP-85 computer. The program takes approximately 13,700 bytes of memory. Also needed to run the program is a tape full of weather data. This data is accessed in the program for the different months and areas.

Running time for the program totaled about 120 hours due to the rather slow convergence of the statistics and the limitations of the machine itself. One possible improvement might be to let the standard deviation converge to within 5% of a fixed value rather than the exceptionally tight tolerance of 1% used in the program.

A couple of notes about this listing as it does not represent all the computer work done for this study. First note is that this listing shows the months of April thru October only as being used in the simulation. The HP tapes used to store the weather data can only have 42 files per tape while 48 files were need to store all the weather data (6 areas and 8 months). To keep the program self tending it was written to run the first seven months of the sailing season, then the tapes were changed and the pertinent statements were changed in the program so that the month of November was run by itself.

This particular listing implies that area 7 fuel usage calcualtions were being done. That is not the case. The math involved in calculatiing fuel used to overcome the extra drag while motoring only between Whitefish Bay and Mackinac Bridge is much simpler than the math involved in the simulation of motor sailing. Therefore to save time the program was simplified. That program was similar in execution just simipler to run. The weather data used for the calculations in area 7 was the weather data for area 3.

TABLE 1

```
 10 OPTION BASE 1
 20 DEG
 30 DIM C(7,12),D(7,12),N(7),C1(
    37),C2(37),P(49),B1(49),V2(4
    9),F1(7),B7$[34],B8$[34]
 40 REM READ IN LIFT AND DRAG DA
    TA FOR SAILS
 50 DATA 1.6,1.15,1.5,.92,1.5,.7
    8,1.5,.71,1.5,.65
 60 DATA 1.5,.61,1.5,.58,1.5,.56
    ,1.5,.55,1.5,.54,1.5,.53,1.5
    ,.52
 70 DATA 1.5,.51,1.5,.505,1.5,.5
    05,1.5,.505,1.5,.51,1.5,.55
 80 DATA 1.5,.59,1.48,.66,1.45,.
    72,1.39,.76,1.3,.79,1.2,.81
 90 DATA 1.1,.88,1,.99,.9,1.08,.
    8,1.2,.7,1.23,.6,1.19
100 DATA .5,1.12,.4,1.05,.3,.9,.
    2,.75,.1,.64,0,.56
110 FOR I=5 TO 180 STEP 5
120 READ C1(I/5),C2(I/5)
130 NEXT I
140 REM READ IN WEATHER CONDITIO
    NS
150 DATA 2,0,7,0,16,0,27,0,40,0,
    48,0
160 DATA 2,45,7,45,16,45,27,45,4
    0,45,48,45
170 DATA 2,90,7,90,16,90,27,90,4
    0,90,48,90
180 DATA 2,135,7,135,16,135,27,1
    35,40,135,48,135
190 DATA 2,180,7,180,16,180,27,1
    80,40,180,48,180
200 DATA 2,225,7,225,16,225,27,2
    25,40,225,48,225
210 DATA 2,270,7,270,16,270,27,2
    70,40,270,48,270
220 DATA 2,315,7,315,16,315,27,3
    15,40,315,48,315
230 FOR I=2 TO 49
240 READ V2(I),B1(I)
250 NEXT I
260 DISP "THE FOLLOWING AREAS AR
    E ASSUMED:"
270 DISP "AREA 1: SOUTHERN LAKE
    MICHIGAN"
280 DISP "AREA 2: NORTHERN LAKE
    MICHIGAN"
290 DISP "AREA 3: EASTERN  LAKE
    MICHIGAN"
300 DISP "AREA 4: EAST-CENTRAL
                      LAKE SUPER
    IOR"
310 DISP "AREA 5: WEST-CENTRAL
                      LAKE SUPER
    IOR"
320 DISP "AREA 6: WESTERN LAKE S
    UPERIOR"
330 DISP "AREA 7: WHITEFISH BAY
                       MACKINAC B
    RIDGE"
340 DISP "DATA WILL BE READ IN
                AUTOMATICALLY"
350 DISP "PRESS *CONT* TO START
    PROGRAM"
360 PAUSE
440 FOR Q=1 TO 6
450 ON Q GOTO 460,600,760,900,10
    50,1200
460 DATA "M/V CORT","TACONITE HA
    RBOR TO BURNS HARBOR",3000,6
    5,292
470 DATA 25.8,1000,15,.651,19125
    0,.00004388549
480 DATA -5.79211E-12,243.5,-105
    0,.0005866667,.00000666667
490 READ B7$,B8$,S1,C3,S3,T,L1,V
    1,N8,R1,Z0,Z1,Z2,Z3,Z4,Z5
500 DATA 1,1,2,3,7,1
510 READ N(6),N(5),N(4),N(3),N(2
    ),N(1)
520 DATA 191,166,191,4,193.5,45,
    209,17.5,241.75,14.5,216.5,6
    4.75,186,5,276,20
530 DATA 138.75,9.75,147.5,14.75
    ,114,63.5,114,68,112.75,34.2
    5,82.5,87.5,82.5,42
540 FOR I=1 TO 6
550 FOR J=1 TO N(I)
560 READ C(I,J),D(I,J)
570 NEXT J
580 NEXT I
590 GOTO 1500
600 DATA "ED RYERSON","PORT SUPE
    RIOR TO BURNS HARBOR",3000,6
    4
610 DATA 292,26.5,730,15,.77,102
    500,.0001983501
620 DATA -6.725473E-11,243.5,-10
    50,.005866667,.0000066667
630 READ B7$,B8$,S1,C3,S3,T,L1,V
    1,N8,R1,Z0,Z1,Z2,Z3,Z4,Z5
640 DATA 3,1,3,3,7,1
650 READ N(6),N(5),N(4),N(3),N(2
    ),N(1)
670 DATA 191,166,191,4,193.5,45,
    209,17.5,241.75,14.5,216.5,6
    4.75,186,5,276,20
680 DATA 138.75,9.75,147.5,14.75
    ,114,63,114,68.5,105.25,18.2
    5,85.75,14
690 DATA 77.75,88.25,77.75,35.63
    ,72,45.25,19.75
700 FOR I=1 TO 6
710 FOR J=1 TO N(I)
720 READ C(I,J),D(I,J)
730 NEXT J
740 NEXT I
```

```
750 GOTO 1500
760 DATA "ST. CLAIR","THUNDERBAY
     TO BURNS HARBOR",3000,65
770 DATA 292,30,770,15,.67,12500
    0,.0001243866
780 DATA -4.239809E-11,243.5,-10
    50,.00058666667,.00000666667
790 READ B7$,B8$,S1,C3,S3,T,L1,V
    1,N8,R1,Z0,Z1,Z2,Z3,Z4,Z5
800 DATA 0,2,1,3,7,1
810 READ N(6),N(5),N(4),N(3),N(2
    ),N(1)
820 DATA 191,166,191,4,193.5,45,
    209,17.5,241.75,5,216.5,64.7
    5,186,5,276,20
830 DATA 138.75,9.75,147.5,14.75
    ,118.75,65.75,118.75,109.5,1
    48,15,98,26
840 FOR I=1 TO 6
850 FOR J=1 TO N(I)
860 READ C(I,J),D(I,J)
870 NEXT J
880 NEXT I
890 GOTO 1500
900 DATA "M/V CORT","BURNS HARBO
    R TO TACONITE HARBOR",3000,6
    5
910 DATA 292,25.8,1000,15,.651,1
    91250,.00004388549
920 DATA -5.79211E-12,243.5,-105
    0,.0005866667,.000006666667
930 READ B7$,B8$,S1,C3,S3,T,L1,V
    1,N8,R1,Z0,Z1,Z2,Z3,Z4,Z5
940 DATA 1,7,4,2,1,2
950 READ N(1),N(2),N(3),N(4),N(5
    ),N(6)
960 DATA 11,166,11,4,13.5,45,29,
    17.5,61.75,14.5,36.5,64.75,6
    ,5,96,20
970 DATA 319,7,328,14.25,279.25,
    14.25,292,46.25,292.25,87
980 DATA 308.25,17.75,261.25,87,
    261.25,34.5,299,10.75
990 FOR I=1 TO 6
1000 FOR J=1 TO N(I)
1010 READ C(I,J),D(I,J)
1020 NEXT J
1030 NEXT I
1040 GOTO 1500
1050 DATA "ED RYERSON","BURNS HA
     RBOR TO PORT SUPERIOR",3000
     ,65
1060 DATA 292,26.5,730,15,.77,10
     2500,.0001983501
1070 DATA -6.725473E-11,243.5,-1
     050,5.866666667E-4,.0000066
     66667
1080 READ B7$,B8$,S1,C3,S3,T,L1,
     V1,N8,R1,Z0,Z1,Z2,Z3,Z4,Z5
1090 DATA 1,7,4,2,1,2
1100 READ N(1),N(2),N(3),N(4),N(
     5),N(6)
1110 DATA 11,166,11,4,13.5,45,29
     ,17.5,61.75,14.5,36.5,64.75
     ,6,5,96,20
1120 DATA 319,7,328,14.5,279.25,
     14.25,292,46.5,292.25,86.75
     ,265.75,14
1130 DATA 257.75,87.5,257.75,36,
     243.25,67.75
1140 FOR I=1 TO 6
1150 FOR J=1 TO N(I)
1160 READ C(I,J),D(I,J)
1170 NEXT J
1180 NEXT I
1190 GOTO 1500
1200 DATA "ST. CLAIR","BURNS HAR
     BOR TO THUNDERBAY",3000,65
1210 DATA 292,30,770,15,.67,1250
     00,.0001243866
1220 DATA -4.239809E-11,243.5,-1
     050,.000586667,.00000666666
     7
1230 READ B7$,B8$,S1,C3,S3,T,L1,
     V1,N8,R1,Z0,Z1,Z2,Z3,Z4,Z5
1240 DATA 1,7,3,1,2,0
1250 READ N(1),N(2),N(3),N(4),N(
     5),N(6)
1260 DATA 11,166,11,4,13.5,45,29
     ,17.5,61.75,14.5,36.5,64.75
     ,6,5,96,20
1270 DATA 318.75,8.63,339.75,13,
     300,71.25,300,109.75,300,14
     ,277,26
1280 FOR I=1 TO 6
1290 FOR J=1 TO N(I)
1300 READ C(I,J),D(I,J)
1310 NEXT J
1320 NEXT I
1330 GOTO 1500
1500 FOR Q1=1 TO 7
1505 PRINT USING 1506 ; B7$,B8$
1506 IMAGE "SHIP:",4X,20A,/,"ROU
     TE:",/,34A
1510 ON Q1 GOTO 1520,1530,1540,1
     550,1560,1570,1580
1520 B$="APR" @ GOTO 1590
1530 B$="MAY" @ GOTO 1590
1540 B$="JUN" @ GOTO 1590
1550 B$="JUL" @ GOTO 1590
1560 B$="AUG" @ GOTO 1590
1570 B$="SEP" @ GOTO 1590
1580 B$="OCT" @ GOTO 1590
1590 FOR I=1 TO 6
1600 FOR J=1 TO 6
1610 F1(J)=0
1620 NEXT J
1630 A3,A4,A5=0
1640 GOSUB 3000
1650 REM PRINT RESULTS
```

TABLE 1 (cont.)

```
1660 PRINT "NO. OF RUNS=";N2
1670 PRINT USING 1680 ; I,A8,A5
1680 IMAGE "FOR AREA=",2D,/,"CON
     VERGED AVG.=",4D.2D,/,"CONV
     ERGED STD. DEV.=",4D.2D
1690 NEXT I
1700 NEXT Q1
1710 NEXT Q
1720 END
3000 REM SUBROUTINE FOR PERFORMA
     NCE PREDICTION
3010 REM READ WEATHR DATA FROM T
     APE
3020 IF N(I)=0 THEN RETURN
3030 C$=B$&VAL$(I)
3035 PRINT ;C$
3040 ASSIGN# 1 TO C$
3050 READ# 1 ; C$
3060 FOR N1=1 TO 49
3070 READ# 1 ; P(N1)
3080 NEXT N1
3090 ASSIGN# 1 TO *
3100 RANDOMIZE
3110 A3,A4,A5=0
3120 FOR N2=1 TO 50
3130 X9,M1=0
3140 FOR N1=1 TO 200
3150 REM GET WEATHER DATA
3160 X=RND
3170 IF X<=P(1) THEN V2(1)=0 @ G
     OTO 3230
3180 V2(1)=1
3190 FOR E=2 TO 49
3200 IF X>P(E-1) AND X<=P(E) THE
     N GOTO 3220
3210 NEXT E
3220 REM CALCULATE APPARENT WIND
      AND ANGLE
3230 FOR J=1 TO N(I)
3240 IF V2(1)=0 THEN GOTO 3610
3250 V2(E)=V2(E)*1.1516
3260 D=ABS(C(I,J)-B1(E))
3270 IF D>=0 AND D<=180 THEN A=1
     80-D @ GOTO 3290
3280 IF D>180 AND D<=360 THEN A=
     D-180
3290 A1=SQR(V1*V1+V2(E)*V2(E)-2*
     V1*V2(E)*COS(A))
3300 B2=ACS((A1*A1+V1*V1-V2(E)*V
     2(E))/(2*A1*V1))
3310 V2(E)=V2(E)/1.1516
3320 IF I=7 OR B2<=28 THEN X9=X9
     +1 @ GOTO 3400
3330 REM GET CLs AND CDs
3340 FOR I2=5 TO 180 STEP 5
3350 IF B2-I2<=5 THEN GOTO 3370
3360 NEXT I2
3370 C5=C2(I2/5)-(B2-I2)/5*(C2(I
     2/5)-C2((I2+5)/5))
3380 C4=C1(I2/5)-(B2-I2)/5*(C1(I
     2/5)-C1((I2+5)/5))
3390 GOTO 3430
3400 T2=-(.002549*COS(B2)*A1*COS
     (B2)*A1*1.2*S3)
3410 S2=.002549*SIN(B2)*A1*SIN(B
     2)*A1*1.2*S3
3420 GOTO 3480
3430 REM CALCULATE THRUST AND SI
     DE FORCE
3440 L=.002549*A1*A1*C4*S1
3450 D=.002549*A1*A1*C5*S1
3460 T2=L*SIN(B2)-D*COS(B2)
3470 S2=L*COS(B2)+D*SIN(B2)
3480 REM CALCULATE LEEWAY AND HE
     EL ANGLE
3490 H1=(S2*C3+S2*T/2)/2240
3500 H2=Z0*H1+Z1*H1*H1
3510 C6=S2/(2.838121*V1*V1*L1*T)
3520 L2=Z2*C6+Z3*C6*C6
3530 C7=Z4*L2+Z5*L2*L2
3540 R4=2.838121*L1*T*V1*C7
3550 R3=R1+R4-T2
3560 E1=R3*1.4667*V1/550/N8*1.05
3570 E2=R1*1.4667*V1/550/N8*1.05
3580 F4=(E2/1000)^(-.059)*.4*E2*
     (D(I,J)/V1)
3590 F5=(E1/1000)^(-.059)*.4*E1*
     (D(I,J)/V1)
3600 F1(J)=F4-F5 @ GOTO 3620
3610 F1(J)=0
3620 NEXT J
3630 F9=0
3640 FOR P=1 TO N(I)
3650 F9=F9+F1(P)
3660 NEXT P
3670 M1=M1+F9
3680 A=M1/N1
3690 IF N1<4 THEN GOTO 3720
3700 IF A=0 THEN GOTO 3720
3710 IF ABS((A-A0)/A)<=.01 THEN
     GOTO 3740
3720 A0=A
3730 NEXT N1
3740 PRINT "NO. OF RUNS=";N1
3750 PRINT USING 3760 ; I,A
3760 IMAGE "FOR AREA=",2D,/,"CON
     VERGED AVG.=",4D.2D
3770 X9=X9/N1/N(I)*100
3780 PRINT USING 3790 ; X9
3790 IMAGE "SAIL FURLED",2X,2D.2
     D,"% OF RUNS"
3800 A3=A3+A
3810 A8=A3/N2
3820 A4=A4+A*A
3830 IF N2<2 THEN GOTO 3860
3840 A5=SQR((A4-A3*A3/N2)/(N2-1)
     )
3850 IF ABS((A8-A6)/A8)<=.01 AND
      ABS((A5-A7)/A5)<=.01 THEN
     RETURN
3860 A7=A5
```

TABLE 1 (cont.)

```
3870 A6=A8
3880 NEXT N2
3890 PRINT "N2=50"
3900 RETURN
```

REFERENCES

1. Woodward, John B., et al
"Feasibility of Sailing Ships for the American Merchant Marine", Prepared for the U.S. Dept. of Commerce, Maritime Administration by the University of Michigan, 1975

2. Bergeson, Lloyd, et al
"Wind Propulsion for Ships of the American Merchant Marine", Prepared for the U.S. Dept. of Commerce, Maritime Administration by Wind Ship Development Corp., 1981

3. Fisher, Peter A.
"Model Test Program for the M/V St. Clair", Presented to the Great Lakes and Great Rivers Section of the Society of Naval Architects and Marine Engineers, 1976

4. Swift, Peter, et al
"Estimation of Great Lakes Bulk Carrier Resistance Based on Model Test Data Regression", Marine Technology, Oct. 1973

5. Copperman, Art, et al
Summary of Synoptic Meteorlogical Observations for the Great Lakes, Volume 4, Lake Superior, Published by the National Oceanic and Atmospheric Administration, 1975

6. Cooperman, et al
Summary of Synoptic Meteorlogical Observations for the Great Lakes, Volume 3, Lake Michigan, Published by the National Oceanic and Atmospheric Administration, 1975

7. Comstock, John P. Editor
Principals of Naval Architecture, Published by the Society of Naval Architects and Marine Engineers, 1967

8. Dennis, Lawrence
"Greek Shippers Catch Wind of Sail Power", Soundings Magazine, Aug. 1981

9. Bergeson, Lloyd
"Sail Power for the World's Cargo Ships", Technology Review, March/April, 1979

10. Carson, Jay
"Sailing Bulk Carrier Design", Presented to the New England section of the Society of Naval Architects and Marine Engineers, November, 1976

11. Myers, Hugo
"Theory of Sailing Applied to Ocean Racing Yachts", Marine Technology, July 1975

12. Lawrence, Hugh
"The Western Flyer Project, A Modern Sailing Cargo Ship", Presented to the Northern California Section of the Society of Naval Architects and Marine Engineers, Sept. 1976

13. Greenwood, John O.
Greenwood's Guide to Great Lakes Shipping, Freshwater Press, Inc. April 1976

14. Milgram, J.H.
"Effect of Masts on the Aerodynamics of Sail Sections", Marine Technology, Jan. 1978

15. Model Test Data of the M/V Stewart J. Cort, prepared by the University of Michigan, Ship Hydrodynamics Laboratory, Dept. of Naval Architecture and Marine Engineering

16. Model Test Data of the SS Edward L. Ryerson, Prepared by the University of Michigan, Ship Hydrodynamics Laboratory, Dept. of Naval Architecture and Marine Engineering.

17. Marine Engineering/Log, Simmons-Boardman Publishing Co. August, 1982

18. Maclear, Frank
"Booms are Obsolete" Paper presented to the Chesapeake Section of the Society of Naval Architects and Marine Engineers, Jan. 1974

19. Chart Number 14900 (Lake Michigan) Published by the National Oceanic and Atmospheric Administration.

20. Chart Number 14960 (Lake Superior), Published by NOAA

21. Chart Number 14882 (Detour Passage to Munuscong Lake) Published by NOAA

22. Chart Number 14883 (St. Mary's River; Lake Munuscong to Sault Ste. Marie), Published by NOAA

23. Chart Number 14881 (De Tour Passage to Waugoshance Pt.), Published by NOAA