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SAINT LAWRENCE SEAWAY
NAVIGATION-AID SYSTEM STUDY
Volume I - Text and Appendixes A and D

Jack W. Lewis
John J. Nelka

ARCTEC Inc.
9104 Red Branch Road
Columbia MD 21045

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FINAL REPORT

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Jack W. Lewis, John J. Nelka

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16. Abstract

The requirements for a navigation guidance system which will effect an increase in the ship processing capacity of the Saint Lawrence Seaway (Lake Ontario to Montreal, Quebec) are developed. The requirements include a specification of system positioning accuracy and the type and frequency of information which must be displayed to the master of each ship in the Seaway. A detailed development of the logic used to compute Seaway capacity as a function of the guidance system positioning accuracy is presented. A computer program is given which follows this logic and is used to compute Seaway capacity as a function of poitioning accuracy for two classes of ships. Various sensitivity analyses are presented. It is shown that the capacity of the Seaway could be increased by up to 30 percent through the use of a navigation guidance system. Volume II, 129 pages, contains Appendix B. Volume III, 108 pages, contains Appendix C.

17. Key Words
Saint Lawrence Seaway, Navigational Aids, Guidance Systems, All Weather Navigation, Electronic Navigation

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PREFACE

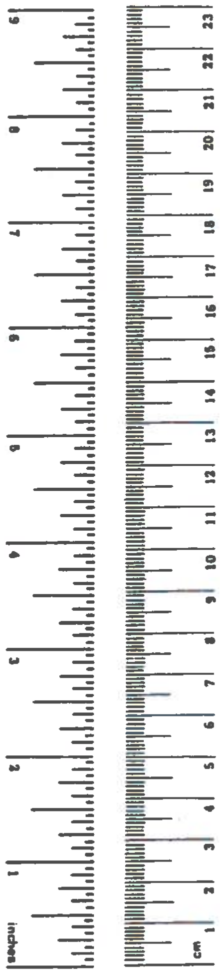
St. Lawrence Seaway is an inland waterway which carries ocean-going and lake-bound vessels from Montreal, Quebec to Lake Ontario. At the onset of winter as the ice begins to form, the floating aids to navigation are moved and conventional navigation comes to a halt until the advent of the annual spring thaw. With the possibility of ice breaking in the channels and ice removal at the locks becoming a reality, it is advantageous to provide an electronic navigation system for year round Seaway transits.

The first step in the implementation of an electronic navigation system is the establishment of the system's requirements. This report develops and defines this information.

METRIC CONVERSION FACTORS

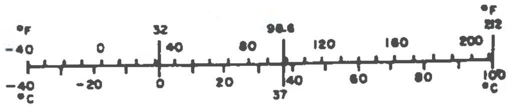
Approximate Conversions to Metric Measures

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



Approximate Conversions from Metric Measures

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



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x_o	Position of ship along channel centerline
$\dot{x}_o$	Forward velocity of ship
$\dot{x}_{o\text{initial}}$	Initial equilibrium value of X_o
$\ddot{x}_o$	Forward acceleration of ship
Y	Side force
Y_{wind}	Side force due to wind
y_o	Lateral distance from channel centerline to c.g. of ship
$(y_o)_{CG}$	Maximum excursion of ship's center of gravity from desired course
$\dot{y}_o$	Lateral velocity of ship
$\ddot{y}_{o\text{current}}$	Cross-current velocity
$\ddot{y}_o$	Lateral acceleration of ship
Δ	Ship displacement
δ	Angular displacement of rudder
ε	Navigation position accuracy
ϕ	Yaw angle
ϕ_{ss}	Yaw angle from steady state equations of motion
$\dot{\phi}$	Yaw angle velocity of ship
$\ddot{\phi}$	Yaw angular acceleration of ship

Subscripts

u	indicates partial derivative with respect to u
$\dot{u}$	" " " " " " $\dot{u}$
v	" " " " " " v
$\dot{v}$	" " " " " " $\dot{v}$
y_o	" " " " " " y_o
δ	" " " " " " δ
ϕ	" " " " " " ϕ
$\dot{\phi}$	" " " " " " $\dot{\phi}$
$\ddot{\phi}$	" " " " " " $\ddot{\phi}$

1. INTRODUCTION

1.1 Background and Purpose of Study

The Saint Lawrence Seaway Development Corporation (SLSDC) has endeavored over the years since the Saint Lawrence Seaway* opened to increase the ship processing ability of the Seaway. In 1975 the SLSDC published a system plan for all-year navigation (SPAN) [1]** in which specific concepts were developed which would remove the present impediments to year-round navigation. In this study it was specifically noted that the present practice of removing floating, lighted aids to navigation during the winter months (usually from 15 December through 1 April) significantly decreases the ability of the Seaway to process ships. Furthermore, the study pointed out that periods of low visibility further decreased the ability of the Seaway to process ships.

The SPAN study investigated several alternatives for removing this impediment to navigation including the installation of fixed, lighted aids and the installation of a precise radio-location system for ship navigation. The higher costs associated with the installation of fixed, lighted aids to navigation made the precise radio-location system appear more attractive. The SLSDC therefore decided that a more detailed study of this type of navigational aid system was warranted and that investigation is the subject of this report.

The purpose of this study was therefore established as being to develop and define navigational guidance system performance requirements which will effect improvements in the Capacity of the Seaway. By "navigational guidance system performance requirements" is meant the type, accuracy and frequency of information which must be made available to the master of a ship in order to facilitate safe passage of the ship through the Seaway. By "Capacity" is meant the number of ships which could be processed through the Seaway in a given period of time assuming that ships are always available for processing at both Montreal and Lake Ontario. The SPAN study was restricted to an investigation of navigational impediments during the extended season time period. As this did not address possible loss of Capacity during the normal season, the time period for this study was taken as one complete calendar year.

1.2 Basic Concepts and Study Approach

To present the methodology used to achieve the purpose of this study, it is first necessary to introduce several basic concepts used in modeling the Seaway. As mentioned above, the term "Capacity" as used in this report means the number of ships which could be processed through the Seaway in a given time period assuming ships are available for processing at both ends of the Seaway. If this assumption is met, then the term Capacity connotes an achievable figure because traffic into the Seaway

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*The Saint Lawrence Seaway refers to that section of the Saint Lawrence River between Montreal, Quebec and Lake Ontario.

**Numbers in brackets refer to references at end of report.

is regulated by Traffic Controllers. Of course, if the ship arrival rate at either end of the Seaway were to exceed the average processing rate of the Seaway during the time period under study, then queues would build and add to the transit delays associated with the Seaway. Inside the Seaway, however, transit times would remain near normal due to the regulation by the Traffic Controllers. It should also be noted that the term Capacity is not related to the present number of ship transits through the Seaway. Of course, one would expect the present number of ship transits to be less than or equal to the Capacity.

The detailed study of the processing of ships in the Seaway conducted in the SPAN study revealed that the Capacity in a small time increment (Δt) can be determined by the Capacity of the slowest lock in the Seaway, provided ships can move through every reach of the Seaway during this time increment. This is so because the rate of movement of ships through non-lock reaches of the Seaway can always be made greater than the rate of movement through locks. However, it may not always be possible for a ship to transit a non-lock reach because of fog, high winds, ice conditions, etc. When this occurs during the time interval, Δt, the Capacity of the Seaway is zero because no ships can be made available to a lock for lockage during this time interval.

The problem of computing Capacity of the Seaway thus becomes a problem of first determining if ships can proceed through every reach of the Seaway in the time interval, Δt. If not, the capacity is zero for this time interval. If so, then the problem becomes one of determining the capacity of the slowest lock in the system during the time interval. The time interval chosen for this study was three (3) hours which corresponded to the time interval between actual historic weather observations used in the study.

Determining When Non-Lock Reaches Constrain Capacity

To determine if a ship can proceed through a given reach, we first ask if the master can visually observe enough navigational aids to fix his position and maneuver his ship. If the answer is no, and he has no substitute guidance system, then the Seaway Capacity is zero for this time interval. If the answer is yes or if he has a substitute guidance system, we must then ask if the master can proceed safely through the reach considering the visibility, winds and currents in this reach. To determine this, we must take into consideration: (1) the maneuvering room requirements of the ship in the face of the winds and currents in the reach; (2) the accuracy with which the ships position in the channel is known; and (3) the width of the channel. Figure 1.1 shows this pictorially. For instance, when there is one way traffic, we first determine the maneuvering room requirements of the ship, M, in the face of the winds and currents. If the position of the ship in the channel is known to an accuracy of $\pm\varepsilon$, then we see that the channel width, W, must be greater than or equal to $M + 2\varepsilon$ for safe passage.

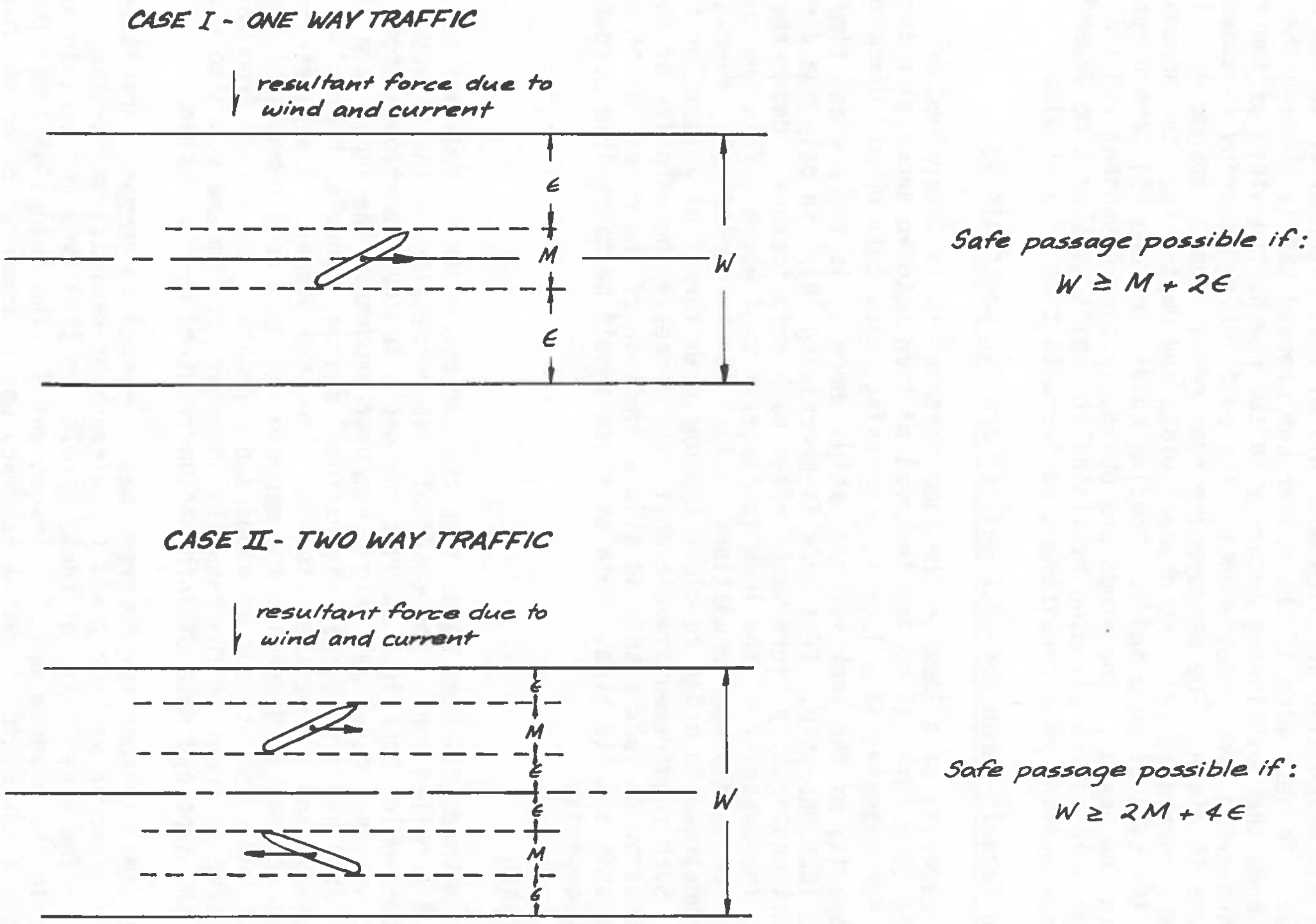


Figure 1.1. Method for Determining if Traffic Can Proceed Safely Through a Reach

To determine if the master can visually observe enough navigational aids to fix his position and maneuver his ship, we need to know the visibility in the reach, whether it is daytime or nighttime, the distances to navigational aids and which aids are lighted. All of this information varies with time of year. To determine if the master can proceed safely through the reach, we need to know the positioning accuracy in the reach, the width of the reach and the maneuvering room requirements. The positioning accuracy is assumed and the width is given. The maneuvering room requirements depends on: (1) the winds and currents; (2) the channel width and depth; (3) the speed of the ship; (4) the type of ship and its loading condition; and (5) the direction of travel in the Seaway. The winds are obviously time dependent and the speed of the ship can be affected by visibility which is also time dependent. Thus, the maneuvering room requirement varies with time of year also.

Determining Capacity when Non-Lock Reaches are not Constraining

The capacity of a lock in the time interval Δt is determined by dividing the time interval by the interval of time between successive lockages of ships. For example, if a lock is processing ships both up and downbound, then the capacity of the lock is $\Delta t/t_{\ell}$ ships where t_{ℓ} is the average time required to lock one ship. If a lock is processing ships in only one direction, the lock must continually "turn back" after each ship lockage. Under these conditions, the capacity of the lock is $\Delta t/(t_{\ell} + t_{tb})$ where t_{tb} is the turn back time. Under certain winter conditions, a lock may be periodically forced to lock ice downstream in order to clear the upstream throat of a lock for the next ship. Such requirements would obviously decrease the capacity of the lock. The time required to lock a ship is also a function of the direction of movement of the ship and its size. Both of these should be taken into account in determining capacity.

Study Approach

The methodology used to achieve the purpose of this study was as follows. A detailed logic flow chart of ship processing in the Seaway was developed which took into account the basic concepts mentioned above. This logic was then developed into a computer program. The input data requirements were obtained from Seaway navigational charts, manuals, hydraulic investigations, and the weather stations along the Seaway. A separate computer program was written to determine the maneuvering room requirements of the study ships under the actions of winds and currents. The output from this program became an input to the capacity computer program and was also used to determine the type and rate of information required by the master.

The capacity computer program was then used to compute capacities for each of the historic weather years for a range of navigational system accuracies. The sensitivity of these results to ship type and certain assumptions made in the program was also investigated. The output data was then analyzed and a navigational system accuracy was recommended based on this analysis.

1.3 Summary of the Work

The Seaway was divided into 103 reaches. Six of these reaches were the locks and the remainder the non-lock reaches. The number of reaches selected was based on the desire that each non-lock reach contain no course changes. Data on each reach consisting of channel bearing, channel width, speed limit, current, and location was assembled and tabulated. The minimum visibility to fix position visually in each reach using three navigational aids was also measured and tabulated under conditions of upbound/downbound, day/night, and extended/normal seasons. The visibility and wind for each non-lock reach and for each time increment was assembled from historic weather records for five years. These years were identical to the ones used in the SPAN study.

The ship maneuvering room requirements for each non-lock reach was computed by a ship maneuvering simulator developed specifically for this study. This simulator was developed by writing the equations of motion for a ship moving in the horizontal plane. Three groups of forces were considered in developing this simulator. The first group consisted of the hydrodynamic forces caused by motion of the ship through unconfined water and the hydrodynamic forces caused by the presence of banks and the channel bottom. The second group consisted of the control forces caused by movement of the rudder and increase or decrease in thrust of the propellers. The third group consisted of the forces caused by the winds and currents in a reach. The first group of forces vary for each study ship and for each reach. The second group depends upon the control law employed by the master; that is, the relationship between ordered rudder and propeller commands and observation of such variables as heading, rate of change of heading, position off track and rate of change of off track position. A separate study was made to devise a control law which would be representative of a prudent ship's master. The third group of forces vary from reach to reach and with time.

The above information was incorporated into a computer program for computing Seaway Capacity for each time interval associated with a new historic weather observation. Due to the importance of sunrise and sunset in determining when traffic will move in non-lock reaches during the extended season, a day was actually divided into 10 time intervals such that sunrise and sunset would fall at the beginning or end of a time interval. The computation of capacity for each of these time intervals followed the logic briefly explained in Section 1.2 and described in detail in Section 2.4.

The primary results obtained from the Capacity Computer Program are shown on the following page (Figure 1.2 repeated in section 3). This figure shows the percent increase in Seaway Capacity during all-year navigation of the Seaway due to utilizing an electronic navigational guidance system as a function of the positioning accuracy of the guidance system. These results indicate that no one particular value of positioning accuracy is obviously best for this application. It is recommended in Section 3.1 that the best accuracy to be chosen based on a

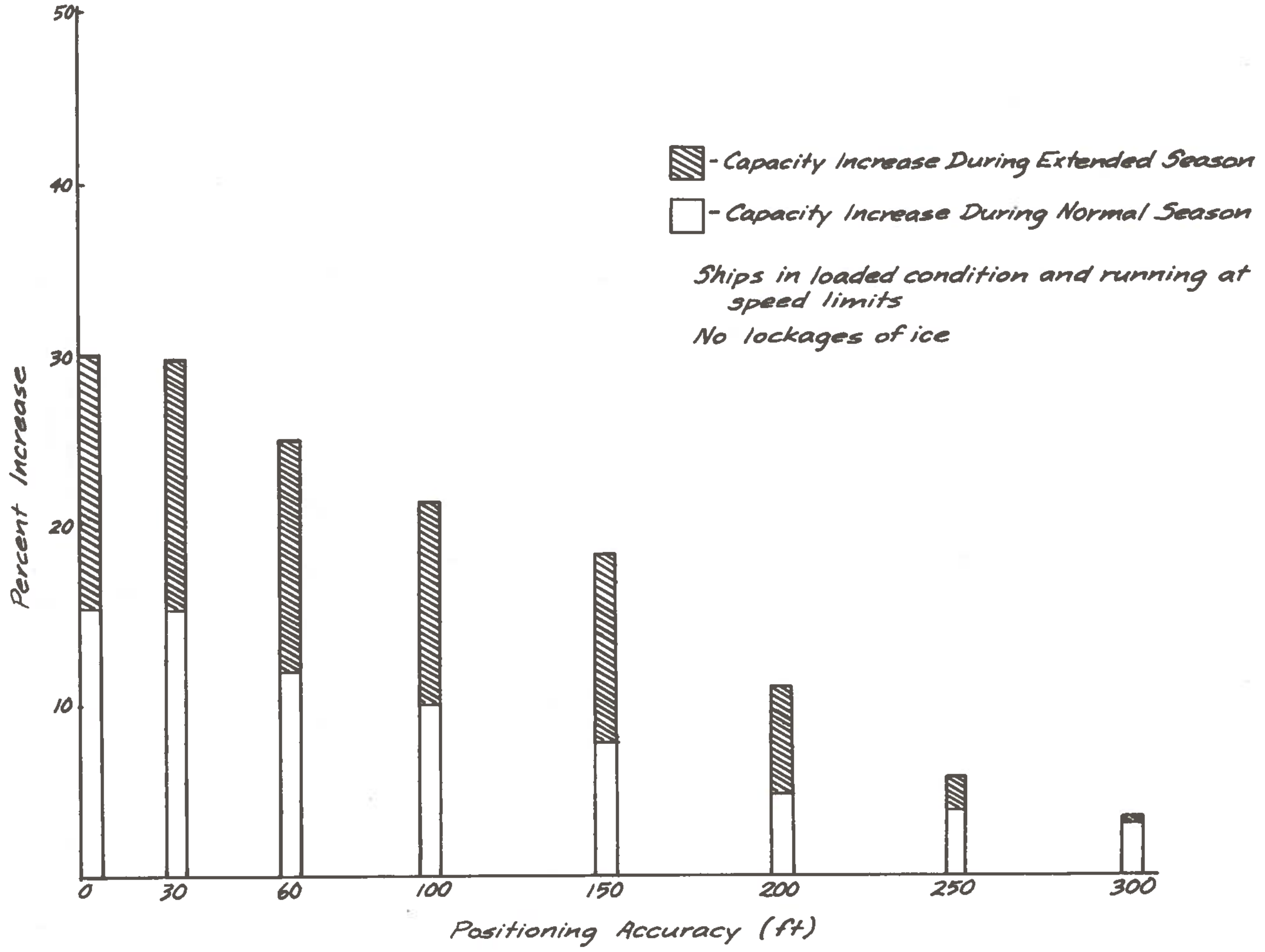


Figure 1.2. *Percentage Increase in Seaway Capacity for Salty Class Ships with Various Positioning Accuracies of the Navigational Guidance System Based on All-year Navigation of the Seaway*

cost/benefit analysis in which the costs associated with each system required to produce the indicated positioning accuracy be compared with the benefits to be derived from the increase in capacity associated with the positioning accuracy. The conduct of such a cost/benefit analysis was beyond the scope of this study and therefore another method was used to select the best positioning accuracy. This method involved an analysis of the number of constraining reaches associated with each positioning accuracy and an assessment of improving upon positioning accuracy by locating guidance system equipment near the reaches where accuracy is most critical. A positioning accuracy of ±100 feet was selected using this method.

The ship maneuvering simulator was used to determine the type and frequency of information required by the master to safely guide his ship through the Seaway. This was accomplished in two steps. In the first step the control law for the rudder was developed. This work indicated that stable control over the ship can be effected by observing both heading and heading rate but not by observing only one of these variables. The introduction of off track position into the control law was found to have a destabilizing effect on control and therefore must be offset by observing rate of change of off track position or increasing the gain on both heading variables. It was thus concluded from this first step that by observing heading, heading rate, off track position, and rate of change of off track position, satisfactory control of the ship could be achieved. In the second step, the required frequency of this information was analyzed. The type of display envisioned for this application would display three consecutive images of the ship's heading and off track position. Thus, mental computations of the control variables by the master could be made at a rate of 3 times the data update rate. It was concluded that an update rate of 5 seconds would be sufficient from a control point of view and reasonably achievable with present day electronic systems.

The data obtained from this study on type, accuracy and frequency of information required by a ship master was written into a navigation guidance system performance specification. This specification is given in Appendix A to this report.

2. SEAWAY CAPACITY MODEL

2.1 Methods Used to Describe Seaway Geometry

The Seaway was divided into 103 reaches. Six of these reaches were lock reaches one of which contained both the Melocheville and Beauharnois Locks. Of the remaining 97 reaches, 5 were used to describe bridges which did not constrain traffic due to their widths but did provide additional navigational aids. The remaining reaches represented straight-line course segments which provided for easier handling of maneuvering room calculations caused by winds and currents. All of these reaches are shown in Figures 2.1, 2.2, 2.3 and 2.4, and Table 2.1 provides navigational information for each of these reaches.

Table 2.2 lists twenty-two parameters used by the Capacity Computer Program to describe each reach. The first element indicates the type of reach as follows:

Reach Type	Meaning
0	Indicates that the reach is a lock.
1	Indicates that two-way traffic is allowed in the reach and that the maneuverability width is determined using the dynamic equations of motion for a ship following a course initially along the quarter channel.
2	Indicates that two-way traffic is allowed in the reach and that maneuverability width is determined using the steady state (static) equations of motion for a ship following a course along the quarter channel.
3	Indicates that only one-way traffic is allowed in the reach and that the maneuverability width is determined using the dynamic equations of motion for a ship following a course initially along the channel centerline.
4	Indicates that only one-way traffic is allowed in the reach and that the maneuverability width is determined using the static equations of motion for a ship following a course along the channel centerline.
5	Indicates a non-constraining reach. No capacity analysis of this type of reach is required. A reach type of 5 is used only to indicate the existence of a bridge.

(Text Continued on Page 20)

Figures 2.1 - 2.4. Seaway Charts Showing Reaches 1-103.

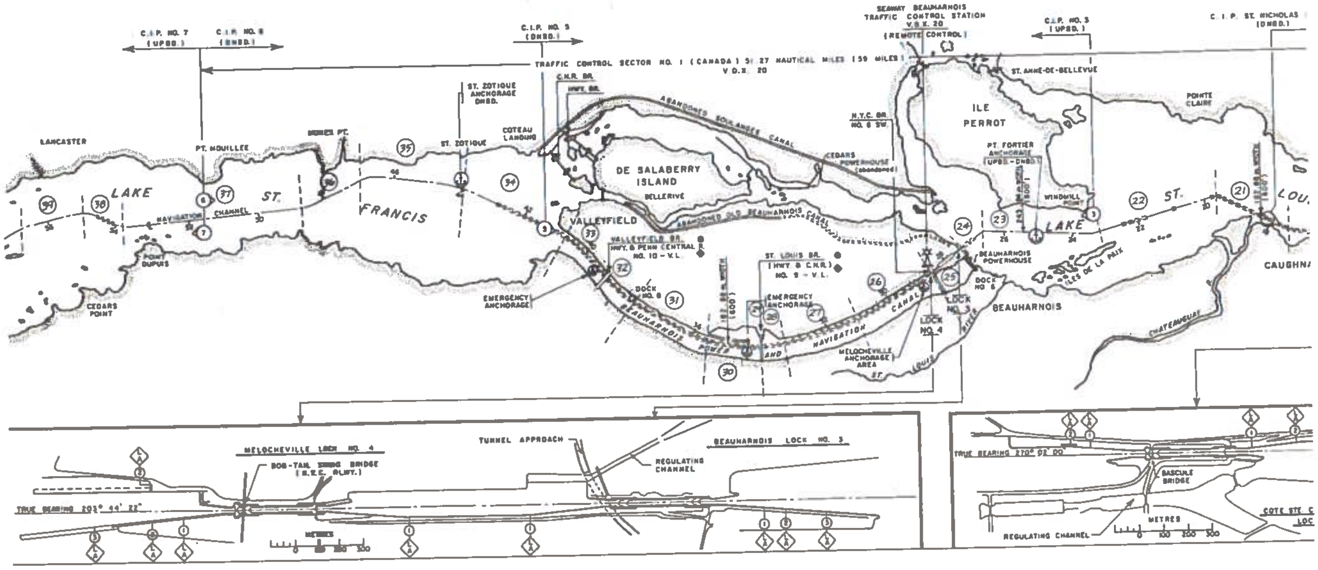
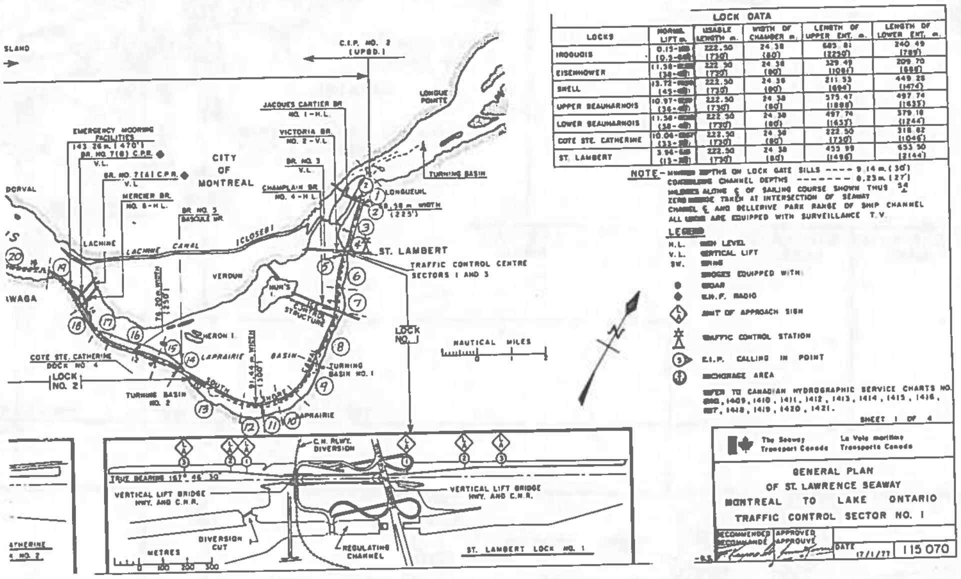


FIGURE 2.1. SEAWAY CHART SHOWING REACHES 1-39



LOCK DATA

LOCKS	NORMAL LIFT m.	USABLE LENGTH m.	WIDTH OF CHAMBER m.	LENGTH OF UPPER ENT. m.	LENGTH OF LOWER ENT. m.
IROQUOIS	0.15-[illegible] (0.5-[illegible])	222.50 (730')	24.38 (80')	685.81 (2250')	240.49 (789')
EISENHOWER	11.58-[illegible] (38-[illegible])	222.50 (730')	24.38 (80')	329.49 (1081')	209.70 (688')
SNELL	13.72-[illegible] (45-[illegible])	222.50 (730')	24.38 (80')	211.53 (694')	449.28 (1474')
UPPER BEAUHARNOIS	10.97-[illegible] (36-[illegible])	222.50 (730')	24.38 (80')	575.47 (1888')	497.74 (1633')
LOWER BEAUHARNOIS	11.58-[illegible] (38-[illegible])	222.50 (730')	24.38 (80')	497.74 (1633')	379.18 (1244')
COTE STE. CATHERINE	10.06-[illegible] (33-[illegible])	222.50 (730')	24.38 (80')	222.50 (730')	318.82 (1046')
ST. LAMBERT	3.96-[illegible] (13-[illegible])	222.50 (730')	24.38 (80')	455.99 (1496')	653.50 (2144')

NOTE - [illegible] DEPTHS ON LOCK GATE SILLS ---- 9.14 m. (30')
CONTROLLING CHANNEL DEPTHS -------- 8.23 m. (27')
MILEAGES ALONG ℄ OF SAILING COURSE SHOWN THUS 34
ZERO [illegible] TAKEN AT INTERSECTION OF SEAWAY
CHANNEL ℄ AND BELLERIVE PARK RANGE OF SHIP CHANNEL
ALL LOCKS ARE EQUIPPED WITH SURVEILLANCE T.V.

LEGEND

H.L.	HIGH LEVEL
V.L.	VERTICAL LIFT
SW.	SWING
	BRIDGES EQUIPPED WITH:
●	RADAR
◆	V.H.F. RADIO
◇	LIMIT OF APPROACH SIGN
	TRAFFIC CONTROL STATION
③	C.I.P. CALLING IN POINT
	ANCHORAGE AREA

REFER TO CANADIAN HYDROGRAPHIC SERVICE CHARTS NO. [illegible], 1409, 1410, 1411, 1412, 1413, 1414, 1415, 1416, [illegible], 1418, 1419, 1420, 1421.

SHEET 1 OF 4

The Seaway Transport Canada
La Voie maritime Transports Canada

GENERAL PLAN
OF ST. LAWRENCE SEAWAY
MONTREAL TO LAKE ONTARIO
TRAFFIC CONTROL SECTOR NO. 1

RECOMMENDED RECOMMANDÉ
APPROVED APPROUVÉ
DATE 17/1/77
115 070

FIGURE 2.1. (CONTINUED)

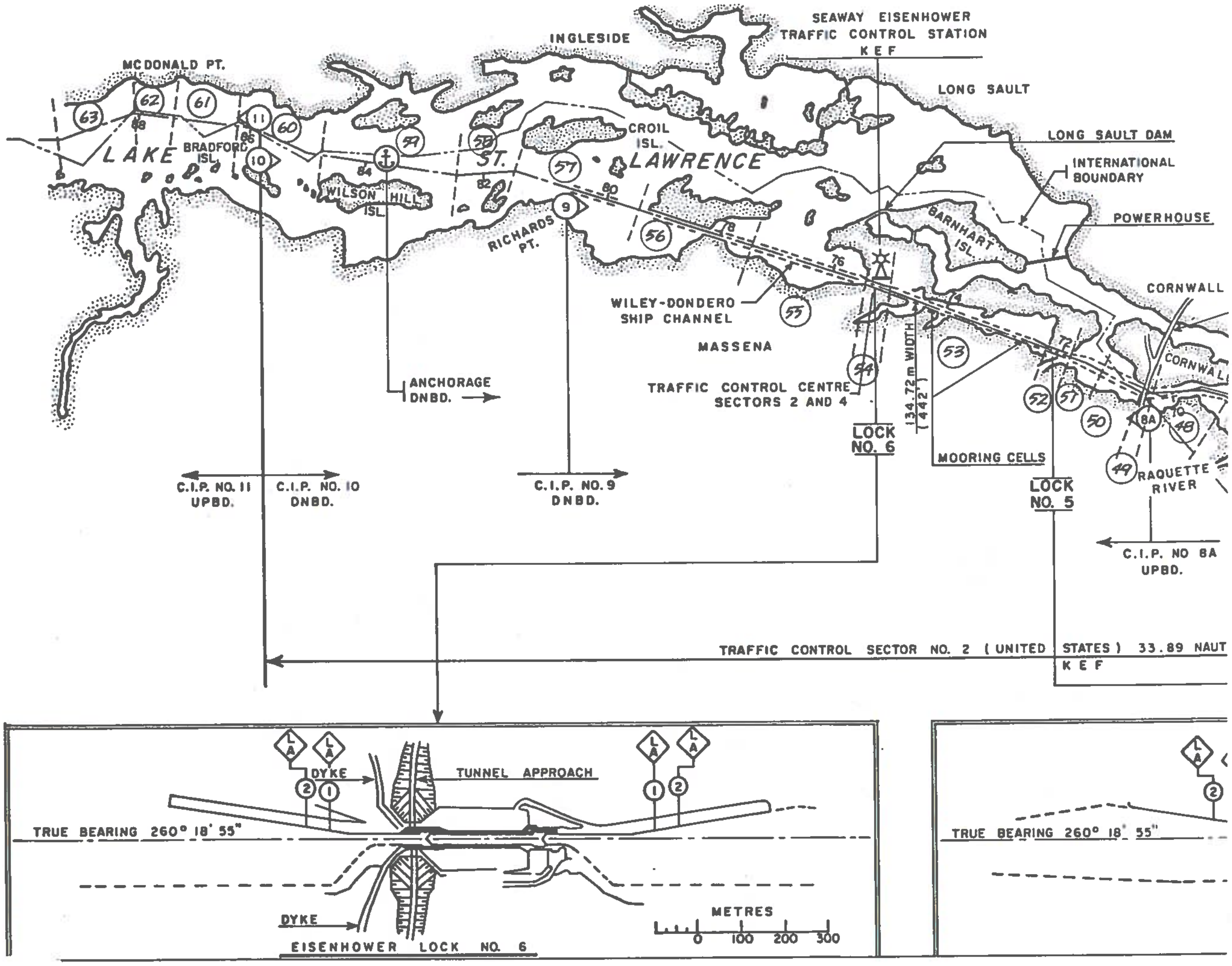


FIGURE 2.2. SEAWAY CHART SHOWING REACHES 40-63

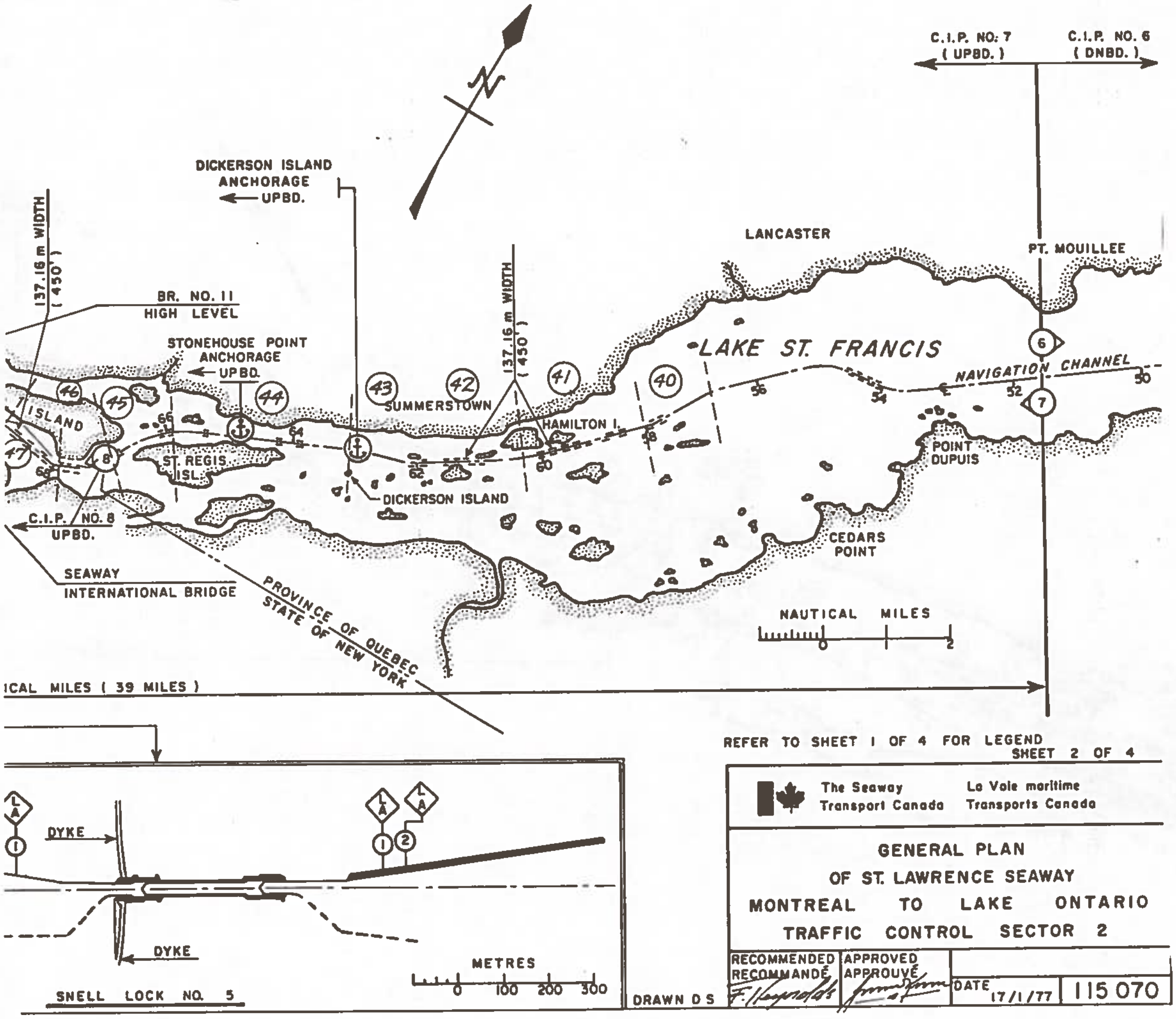


FIGURE 2.2. (CONTINUED)

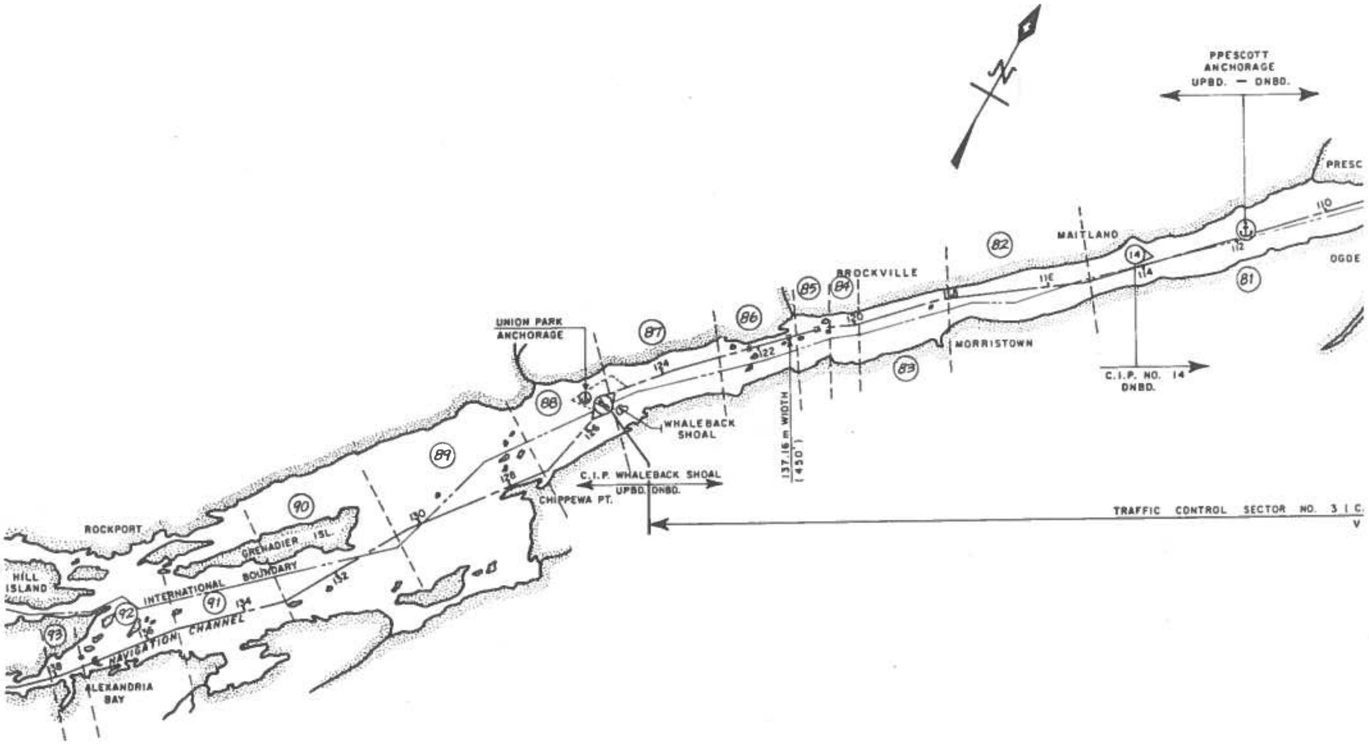


FIGURE 2.3. SEAWAY CHART SHOWING REACHES 64-93

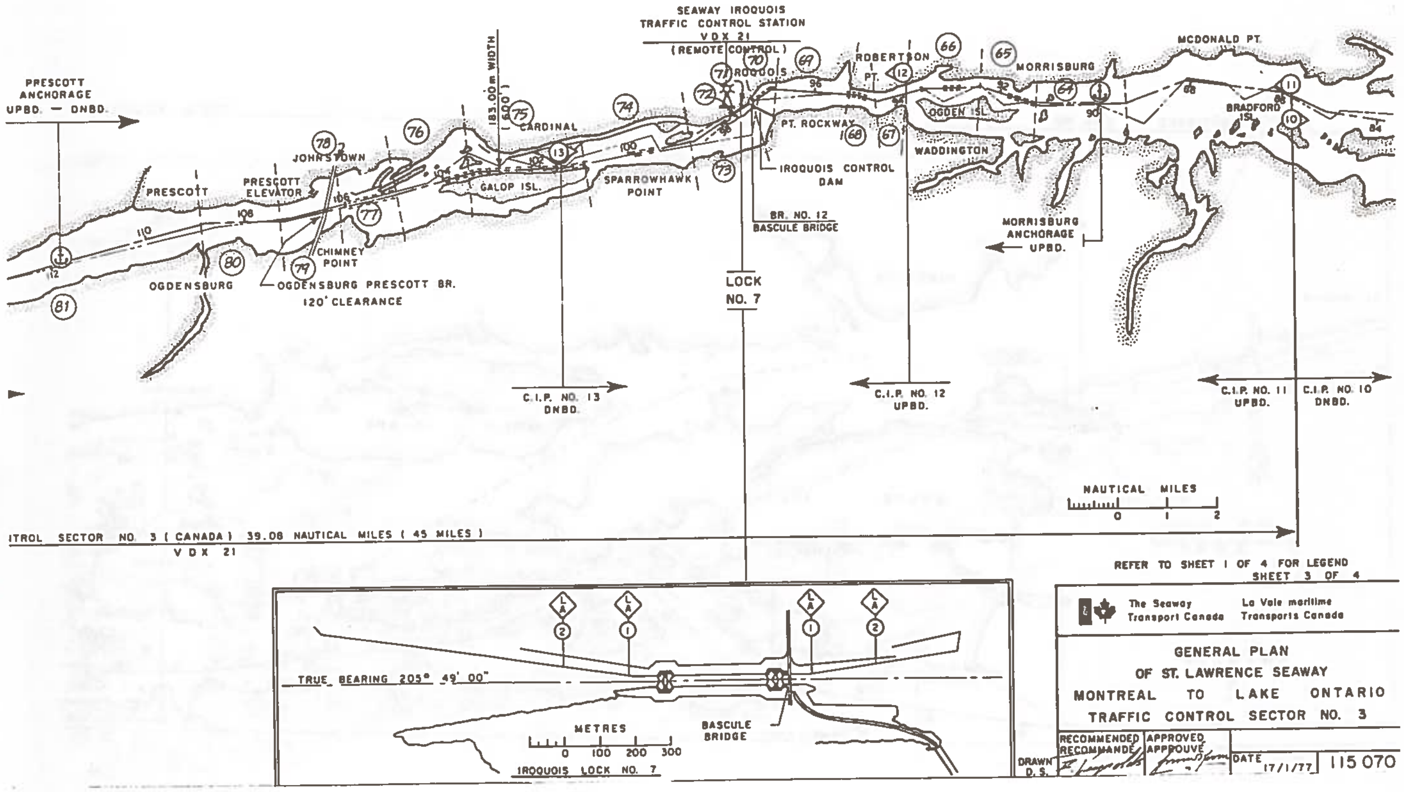


FIGURE 2.3. (CONTINUED)

TABLE 2.1 DESCRIPTION OF SEAWAY REACHES

Reach Description	Reach Number	Upbound Channel Bearing (°T)	Minimum Channel Width (ft)	Minimum Channel Depth (ft)	Beginning Channel Mileage*	Ending Channel Mileage*	Upbound Speed Limit (mph)	Down-Bound Speed Limit (mph)	Channel Current (fps)	Channel Current Direction* (°T)
Montreal Harbor	1	167	200	35	0	1.3	7	7	.5	
Cartier Bridge	2	167	200	27	1.3	1.3	7	7	.5	
South Shore Canal	3	167	225	27	1.3	3	7	7	.5	
St. Lambert Lock	4	167	80	27	3	3.25	7	7	.5	
Vertical Lift Bridge	5	167	80	27	3.25	3.25	7	7	.5	
South Shore Canal	6	165	280	27	3.25	4	7	7	.5	
	7	157	280	27	4	5.25	7	7	.5	
	8	177	280	27	5.25	7.85	7	7	.5	
	9	199	280	27	7.85	8.5	7	7	.5	
	10	221	280	27	8.5	9.25	7	7	.5	
	11	241	280	27	9.25	10	7	7	.5	
	12	260	280	27	10	10.5	7	7	.5	
	13	269	280	27	10.5	11.75	7	7	.5	
St. Catherine Lock	14	269	80	27	11.75	12	7	7	.5	

---

*STATUTE MILES

** A BLANK INDICATES NO CROSS CURRENTS IN THAT REACH

TABLE 2.1 DESCRIPTION OF SEAWAY REACHES (CON'T)

Reach Description	Reach Number	Upbound Channel Bearing (°T)	Minimum Channel Width (ft)	Minimum Channel Depth (ft)	Beginning Channel Mileage*	Ending Channel Mileage*	Upbound Speed Limit (mph)	Down-Bound Speed (mph)	Channel Current (fps)	Channel Current Direction** (°T)
South Shore Canal										
	15	269	250	27	12	13.25	7	7	.5	
	16	255	250	27	13.25	14.75	7	7	.5	
	17	277	250	27	14.75	15.75	7	7	.5	
	18	303	250	27	15.75	17.37	7	7	.5	
	19	278	225	27	17.37	18	7	7	.5	
South Shore Canal										
	20	249	250	27	18	20	7	7	.5	
Entrance to Lake St. Louis										
	21	266	500	28.5	20	22.3	12	12	3.2	053
	22	223	650	28.5	22.3	27	18	18	2	
	23	241.3	750	32	27	30	18	18	2	
	24	218	1400	42	30	31.5	18	18	1.5	030
Beauharnois and Melocheville Locks										
	25	209.3	80	27	31.5	32.5	0	0	0	
Beauharnois Canal										
	26	209.3	590	27	32.5	36	10	12	3.1	
	27	226	590	27	36.0	38.5	10	12	3.1	
	28	237	590	27	38.5	39.0	10	12	3.1	
St. Louis Bridge	29	237	180	27	38.5	38.5	10	12	3.1	
	30	248.3	590	27	39.0	40.5	10	12	3.1	
	31	270	590	27	40.5	44.5	10	12	3.1	

TABLE 2.1 DESCRIPTION OF SEAWAY REACHES (CON'T)

Reach Description	Reach Number	Upbound Channel Bearing (°T)	Minimum Channel Width (ft)	Minimum Channel Depth (ft)	Beginning Channel Mileage*	Ending Channel Mileage*	Upbound Speed Limit (mph)	Down-Bound Speed (mph)	Channel Current (fps)	Channel Current Direction** (°T)
Valley Field Bridge										
	32	287	180	27	44.5	44.5	10	12	3.1	
	33	287	590	27	44.5	47	10	12	3.1	
	34	263	500	28	47.0	51.4	18	18	2.4	062
Lake St. Francis										
	35	242.4	1160	28	51.4	54.2	18	18	2.4	
	36	209	1160	40	54.2	56.4	18	18	2.4	058
	37	234	1160	40	56.4	63	18	18	2.35	
	38	266	480	35	63	64.2	18	18	2.35	
Lancaster Bar	39	228.2	450	28.5	64.2	66.4	18	18	2.35	
	40	207.2	450	28.5	66.4	67.8	18	18	2.92	042
	41	225.55	450	28.5	67.8	70.3	10	12	2.92	
	42	239.15	460	28.5	70.3	72.5	10	12	2.80	
	43	262.5	480	35.7	72.5	73.6	10	12	2.80	
Glengary Anchorage										
	44	241.1	650	28.5	73.6	77.1	10	12	2.80	088
Cornwall and St. Regis Island										
	45	209	460	29.0	77.1	78.0	10	12	2.80	
Turn Cornwall Island										
	46	236	700	29	78.0	79	10	12	2.80	048
	47	278	460	29	79	80	10	12	5.06	
Turn Seaway International Bridge [Polly's Gut]										
	48	234	460	29	80	82	10	12	5.06	
	49	267	600	31	82	82	10	12	5.06	
	50	267	700	32	82	83	10	12	6.75	088
	51	267	700	29	83	84	10	12	10.1	103

TABLE 2.1 DESCRIPTION OF SEAWAY REACHES (CON'T)

Reach Description	Reach Number	Upbound Channel Bearing (°T)	Minimum Channel Width (ft)	Minimum Channel Depth (ft)	Beginning Channel Mileage*	Ending Channel Mileage*	Upbound Speed Limit (mph)	Down-Bound Speed (mph)	Channel Current (fps)	Channel Current Direction** (°T)
Snell Lock	52	272	80	27	84	84	0	0	0	
	53	261	442	27	84	87.5	7	7	0	
Eisenhower Lock										
	54	260	80	27	87.5	87.5	0	0	0	
	55	257	442	27	87.5	90.5	13	13	2	
Wiley-Dondero Channel										
	56	257	442	27	90.5	92.5	13	13	2.7	045
	57	257	442	29	92.5	95.0	13	13	1.76	125
Cat Island Shcal										
	58	233	610	46	95	96	15	15	1.4	
Morrisburg Section										
	59	248	730	37	96	99	15	15	1.4	
	60	262.15	730	44	99	100	15	15	1.4	
	61	233	730	48	100	101	15	15	1.4	
	62	255	730	37	101	102	15	15	1.7	
	63	220	730	36	102	104	15	15	1.7	
	64	237	600	29	104	106	13	13	3.16	
	65	255.25	630	27	106	108	13	13	3.44	
	66	237	610	29	108	109	13	13	3.72	
	67	227	600	56	109	110	15	15	3.40	
	68	248	600	48	110	110.75	15	15	3.50	
	69	242.5	580	29	110.75	112	15	15	3.50	032
	70	206.15	400	29	112	112.5	15	15	3.50	032
Iroquois Lock	71	209	80	27	112.5	112.75	0	0	0	
Rolling Lift Bridge										
	72	209	80	27	112.5	112.75	0	0	0	
	73	209	840	29	112.75	114	15	15	4.5	047
	74	227.2	500	29	114	117.5	15	15	4.75	
	75	237	400	29	117.5	119.5	15	15	4.88	
	76	221.45	400	29	119.5	121	15	15	3.88	
	77	238.35	450	29.5	121	123	15	15	4.22	

TABLE 2.1 DESCRIPTION OF SEAWAY REACHES (CON'T)

Reach Description	Reach Number	Upbound Channel Bearing (°T)	Minimum Channel Width (ft)	Minimum Channel Depth (ft)	Beginning Channel Mileage*	Ending Channel Mileage*	Upbound Speed Limit (mph)	Down-Bound Speed (mph)	Channel Current (fps)	Channel Current Direction** (°T)
Ogdensburg-Prescott Bridge										
	78	238.35	550	29.5	123	123	15	15	1.90	
	79	220	630	36	123	124.75	15	15	1.90	
	80	238	730	45	124.75	126.5	15	15	1.90	
	81	223	730	34	126.5	133.5	15	15	1.1	
	82	231	730	52	133.5	136.5	15	15	1.1	
McNair Island										
	83	220	730	57	136.5	138.25	15	15	1.4	
Skeleton Island										
	84	232	400	43	138.25	139	15	15	1.4	
Smith Island										
	85	236	300	29	139	140	15	15	4.9	
Brockville Narrows										
	86	222	300	29	140	142	15	15	4.9	
	87	217	550	38	142	144	15	15	1.4	
Whaleback Shoals										
	88	194	610	29	144	146.5	15	15	0.8	045
	89	218	610	29	146.5	151	13	13	0.8	032
	90	209	610	29	151	154	13	13	0.8	032
	91	225	600	39	154	157	13	13	0.8	
American Narrows										
	92	218	600	29	157	159	10	12	0.8	
	93	214	450	70	159	160	10	12	0.8	
	94	219	450	70	160	162	10	12	3.3	
	95	235	450	100	162	164.5	10	12	3.3	

TABLE 2.1 DESCRIPTION OF SEAWAY REACHES (CON'D)

Reach Description	Reach Number	Upbound Channel Bearing (°T)	Minimum Channel Width (ft)	Minimum Channel Depth (ft)	Beginning Channel Mileage*	Ending Channel Mileage*	Upbound Speed Limit (mph)	Down-Bound Speed (mph)	Channel Current (fps)	Channel Current Direction** (°T)
Thousand Islands Bridge										
	96	235	450	100	164.5	164.5	10	12	3.3	
	97	231	450	100	164.5	167	10	12	3.3	
	98	239	610	29	167	169.5	10	12	0.9	
	99	228	610	29	169.5	170.5	10	12	0.9	
	100	246	730	50	170.5	178	15	15	0.9	
	101	263	730	48	178	182	15	15	0.4	
	102	193.2	730	29	182	186	15	15	0.4	
Tibbetts Point										
	103	234	730	84	186	190	15	15	0.4	

TABLE 2.2 SEAWAY REACH PARAMETERS

Reach (I,N)

I = Reach Number (I = 1 to 103)

N	Element Description
1	Reach Type: 0 - lock 1 - two-way dynamic reach 2 - two-way static reach 3 - one-way dynamic reach 4 - one-way static reach 5 - non-constraining bridge
2	Upbound course, °T
3	Minimum width, ft
4	Minimum depth, ft
5	Beginning reach mileage, statute miles
6	Ending reach mileage, statute miles
7	Upbound speed limit, mph
8	Downbound speed limit, mph
9	Current speed, fps
10	Current direction, °T
11	Minimum visibility required to fix position visually from three navigational aids during the normal season, while upbound in daylight (statute miles)
12	Same as 11 - only downbound in daylight
13	Same as 11 - only during extended season, while upbound in daylight
14	Same as 11 - only during extended season, while downbound in daylight
15	Same as 11 - only during normal season, while upbound at night
16	Same as 11 - only during normal season, while downbound at night
17	Same as 11 - only during extended season, while upbound at night
18	Same as 11 - only during extended season, while downbound at night
19	Electronic navigation accuracy of reach, ft
20	Daytime visual navigation accuracy of reach, ft
21	Night-time visual navigation accuracy, ft
22	Indicator noting whether reach could have ice problems (no river steam when ice is present) during extended season operations 0 - No 1 - Yes

The reach parameters--upbound course direction, minimum channel width, minimum channel depth, upbound speed limit, downbound speed limit, current speed, and current direction (reach elements 2, 3, 4, 7, 8, 9 and 10 respectively)--are used in the static and dynamic equations of motion to determine the ship maneuverability width and the ship rudder angle required to achieve that width. Reach element 22, equal to 1, indicates that ice forms in the reach during the winter. This sets the maneuverability width equal to one-half the ship's beam and also indicates that no river steam exists when ice is present.

The course direction, channel dimensions, and ship speed limits were obtained from Charts 1409-1421 of the Canadian Hydrographic Office. References [1 and 2] provided information on the magnitude of reach currents and their direction. Currents are based on a flow rate of 310,000 cfs [2]. Ice formation data was obtained from the SPAN report [1].

In order for a ship to navigate visually, it must be capable of fixing its position using a sufficient number of navigation aids; i.e., lighted floating buoys, range lights, fixed lights, conspicuous land marks, etc. For this study, a sufficient number of navigation aids means that a ship must be able to fix its position using three navigational aids.

Analysis of the Seaway navigation aids indicated that the minimum visibility required to fix position visually at any point along a reach is a function of the time of the day, the direction of the ship, and the time of the year. Thus, eight categories of minimum visibilities required to fix position visually were identified as:

1. Normal season, day, upbound
2. Normal season, day, downbound
3. Extended season, day, upbound
4. Extended season, day downbound
5. Normal season, night, upbound
6. Normal season, night, downbound
7. Extended season, night, upbound
8. Extended season, night, downbound

The criteria for determining these distances were:

1. The navigation-aid distances determined must not be strictly distances between 3 nav-aids but rather reflect the minimum visibility required to fix position visually anywhere along a given course. Thus, with a visibility

equal to this distance, a pilot must be able to constantly fix his position anywhere along the course.

2. Whenever a course change occurs, the visibility required to fix position to change course must also be taken into account.

3. All navigation aids used to fix position must be forward of the beam.

Only lighted aids are used at night. During the normal season, the floating lighted aids, fixed lights, and range lights are the primary aids. Conspicuous land marks are secondary. During the extended season, fixed aids and range lights are the primary aids, and conspicuous land marks are secondary.

The required visibilities were determined by overlaying a transparent scaled template on the Seaway charts and determining the minimum distance that would include three navigational aids. The template was divided into distance increments consistent with the visibility increments used by weather stations. The template is shown in Figure 2.5.

A few reaches in the Seaway have very wide and deep channels with few lighted aids (Ogdensburg-Brockville). Navigation for those reaches would not be a problem if both shorelines could be seen during the day or night. This criteria was used to determine nav-aid distances for those reaches.

The required visibility for a lock or a bridge was set equal to zero because this distance was accounted for in the reach preceding the lock or bridge. Lock lights and bridge lights were used to determine the required visibility in the reach preceding a lock or bridge. This meant that if a pilot can see the lock (or bridge) light, his ship could proceed visually, both through the preceding reach and through the lock (or bridge).

Table 2.3 contains the required visibilities for reaches 20-103. The illuminated dike along the South Shore Canal (reaches 1-19) was used to determine the required visibilities for reaches 1-19. Tables 2.4 and 2.5 indicate the particular aids used in determining the required visibilities for each reach of the Seaway, excluding the South Shore Canal.

Reach element 19 in Table 2.2 is the navigation system electronic accuracy. For this study, the effect of system accuracies of 0', 30', 60', 100', 150', 200', and 300' on the yearly Seaway capacity was determined.

The reach elements 20 and 21 (day and night visual accuracy) were extimated to be ± 15 feet; i.e., if visual navigation was possible, then the ship's position in the channel was assumed known to within ± 15 feet.

(Text Continued on Page 33)

Figure 2.5. Template Used to Determine Distance to Fix Position Visually Using Three Navigational Aids (Numbers Denote Distances in Statute Miles)

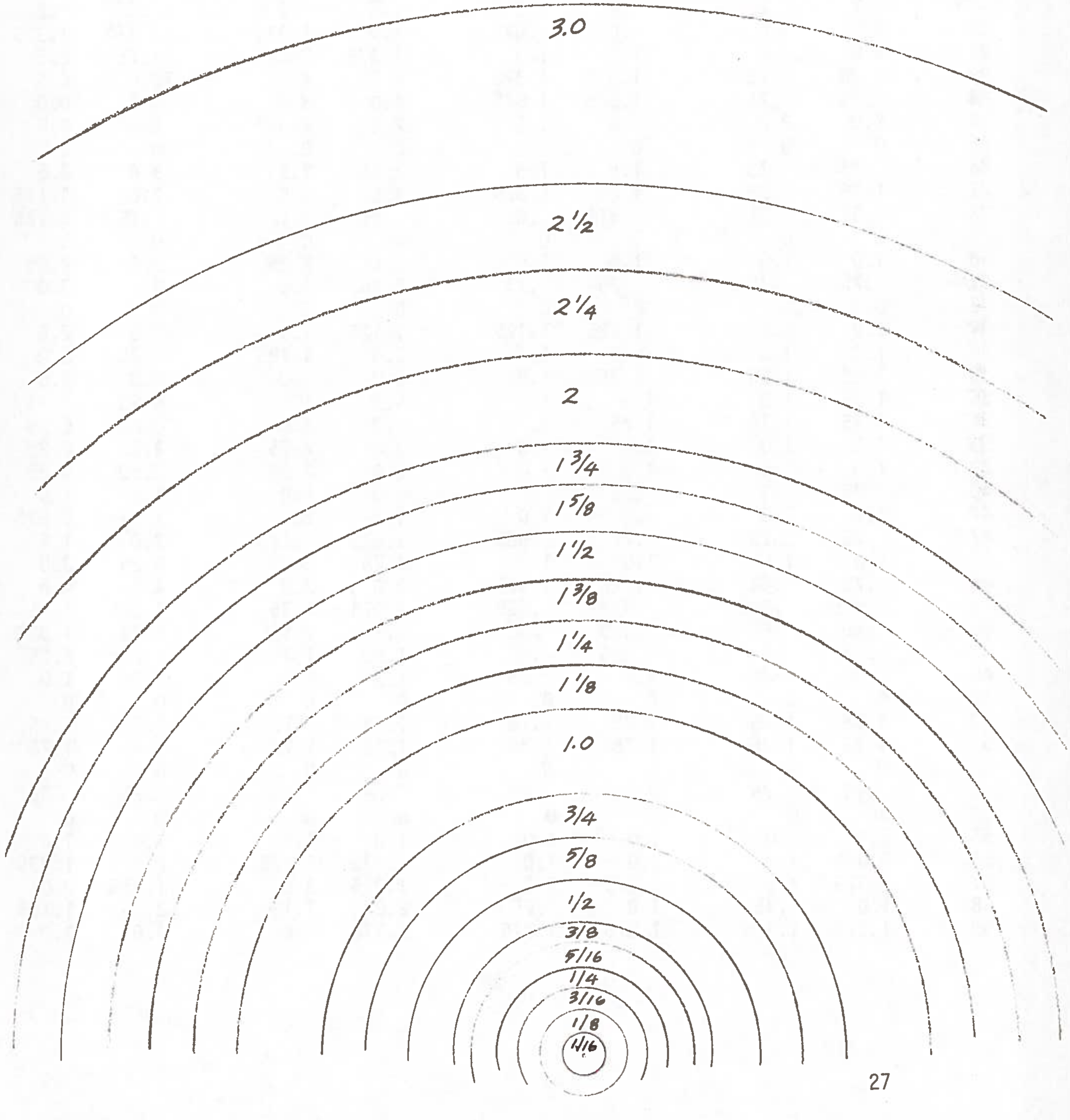


TABLE 2.3 MINIMUM VISIBILITY REQUIRED TO FIX POSITION VISUALLY USING THREE NAVIGATION AIDS (IN STATUTE MILES)

	NORMAL SEASON				EXTENDED SEASON			
	DAYTIME		NIGHT		DAYTIME		NIGHT	
Reach Number	Upbound	Downbound	Upbound	Downbound	Upbound	Downbound	Upbound	Downbound
1-19	.2	.2	.2	.2	.2	.2	.2	.2
20	1.0	1.0	1.0	.625	1.5	1.375	1.375	1.375
21	1.0	1.0	1.0	1.0	1.375	2.0	1.75	2.5
22	.75	.75	1.375	1.375	4.25	4.0	10.0	6.5
23	.75	.75	1.375	1.375	4.0	3.25	5.5	10.0
24	2.0	2.0	2.0	1.5	2.0	2.0	2.5	2.5
25	0	0	0	0	0	0	0	0
26	.75	.75	1.5	1.5	2.25	2.5	3.0	2.5
27	1.25	1.25	1.25	1.375	3.0	4.0	3.0	4.125
28	.313	.313	.313	.625	.75	3.125	.75	3.125
29	0	0	0	0	0	0	0	0
30	1.0	1.0	1.0	1.0	3.0	2.25	3.0	2.25
31	.75	.75	.75	.75	1.75	3.0	2.5	3.0
32	0	0	0	0	0	0	0	0
33	1.0	1.	1.125	1.125	1.125	1.5	2.5	2.5
34	1.0	1.0	1.0	1.0	3.0	4.125	6.25	6.0
35	1.25	1.25	1.25	1.25	4.0	5.0	4.0	7.5
36	1.25	1.0	1.0	1.0	4.0	1.5	4.25	1.75
37	1.75	1.75	1.75	1.75	4.0	3.0	6.25	6.25
38	1.0	1.0	1.0	1.0	3.0	2.25	2.25	2.25
39	1.0	1.0	1.0	1.0	2.0	2.25	2.50	4.25
40	.75	.5	.75	.5	1.0	1.0	1.0	1.0
41	1.0	1.0	1.0	1.0	1.75	2.5	1.75	2.625
42	.75	.625	.75	.625	1.625	1.125	2.0	1.5
43	1.0	1.0	1.0	1.0	3.75	2.25	5.25	3.0
44	.75	.625	1.125	1.375	3.0	3.0	4.0	4.5
45	.625	.625	.625	.625	1.375	1.25	1.375	1.75
46	.50	.50	.500	.50	.75	1.125	2.25	1.375
47	.625	.5	.625	.50	1.50	1.75	1.75	2.25
48	1.0	.75	1.0	.75	1.0	1.0	.75	1.0
49	0	0	0	0	0	0	0	0
50	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75
51	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75
52	0	0	0	0	0	0	0	0
53	.75	.75	.75	.75	.75	.75	.75	.75
54	0	0	0	0	0	0	0	0
55	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
56	1.0	1.0	1.0	1.0	1.375	1.375	2.0	1.375
57	1.375	1.5	1.375	1.5	1.375	3.0	1.375	3.0
58	1.0	.75	1.0	.75	2.25	1.125	2.25	1.125
59	1.375	1.375	1.375	1.375	3.375	3.0	4.0	3.0

TABLE 2.3 MINIMUM VISIBILITY REQUIRED TO FIX POSITION VISUALLY USING THREE NAVIGATION AIDS (IN STATUTE MILES) (CONT'D)

	NORMAL SEASON				EXTENDED SEASON			
	DAYTIME		NIGHT		DAYTIME		NIGHT	
Reach Number	Upbound	Downbound	Upbound	Downbound	Upbound	Downbound	Upbound	Downbound
60	.75	1.0	1.0	1.0	2.0	1.375	2.0	1.375
61	1.25	1.0	1.25	1.0	1.25	1.125	1.25	1.125
62	1.125	1.0	1.125	1.0	1.125	1.0	1.0	1.0
63	1.0	1.0	1.0	1.0	1.0	1.25	1.0	1.25
64	.625	.5	.625	.50	1.25	1.75	2.0	2.25
65	.625	.625	.625	1.0	1.0	1.0	1.0	1.125
66	.625	1.0	.625	1.0	3.75	1.5	4.0	1.375
67	1.0	.75	1.0	.75	3.0	2.0	3.375	2.0
68	.75	.625	.75	.625	2.5	3.0	2.5	3.0
69	1.25	1.0	1.25	1.0	1.625	2.25	1.625	4.0
70	.5	.625	.50	.625	.75	.75	.75	.75
71	0	0	0	0	0	0	0	0
72	0	0	0	0	0	0	0	0
73	1.25	.75	1.25	.75	1.375	1.25	1.75	1.25
74	1.25	1.125	1.25	1.125	1.75	1.75	2.5	3.75
75	1.625	.75	1.25	1.0	1.625	1.25	2.0	1.25
76	.75	.625	.75	.625	1.125	1.375	1.25	1.375
77	.625	.625	.625	.625	1.125	1.5	1.125	1.5
78	0	0	0	0	0	0	0	0
79	1.0	1.0	1.0	1.0	1.75	1.75	1.75	1.75
80	1.0	1.125	1.0	1.125	1.125	1.375	1.75	2.50
81	2.0	3.0	2.0	3.0	2.0	3.0	2.0	3.0
82	1.75	1.5	1.75	1.5	1.75	1.50	1.75	1.5
83	1.25	1.25	2.0	2.0	1.25	1.375	2.0	2.0
84	.75	.75	1.0	.75	1.625	1.75	1.625	2.0
85	.625	.50	.625	.50	.625	.625	.625	.625
86	.75	1.0	.75	1.0	1.125	1.0	1.125	1.0
87	1.0	1.0	1.125	1.0	2.0	1.5	2.0	2.0
88	1.5	1.5	1.5	1.5	3.0	3.0	3.25	3.0
89	1.375	1.375	1.375	1.375	3.0	2.25	4.25	3.25
90	1.75	1.75	1.75	2.0	3.5	2.0	5.0	4.5
91	1.5	1.5	1.5	1.5	2.25	2.25	2.25	2.75
92	1.25	1.125	.5	1.125	2.0	1.25	2.0	1.25
93	.75	.75	.75	.75	1.0	.75	1.0	.75
94	.75	1.5	.75	1.5	.75	1.5	.75	1.5
95	1.375	1.0	1.375	1.0	1.75	1.375	1.75	1.375
96	0	0	0	0	0	0	0	0
97	1.0	1.0	1.0	1.0	1.125	2.0	1.125	2.0
98	1.75	1.75	1.75	1.75	3.375	3.25	3.375	3.25
99	1.25	1.25	1.25	1.25	1.375	1.375	2.0	3.75
100	3.0	2.5	3.0	2.50	5.75	3.75	5.75	3.75
101	2.5	3.0	2.5	3.0	3.5	6.5	3.5	6.5
102	1.375	1.375	1.375	1.375	2.5	2.5	3.5	4.25
103	1.375	1.75	1.375	1.75	2.0	3.0	2.0	3.0

TABLE 2.4 IDENTIFICATION OF NAVIGATION AIDS USED TO DETERMINE MINIMUM VISIBILITY REQUIRED TO FIX POSITION VISUALLY FOR EACH REACH OF THE SEAWAY, NORMAL SEASON

Reach No.	Daylight						Night					
	Upbound Traffic			Downbound Traffic			Upbound Traffic			Downbound Traffic		
1-19	Illuminated Dike			Illuminated Dike			Illuminated Dike			Illuminated Dike		
20	1 A	2 A	Pt. Johnson Lt.	1 A	2 A	Pt. Johnson Lt.	Pt. Johnson Lt.	2 A	Dike Light	1 A	Dike Light	Flg 1/2A
21	10A	RB	13A	10A	RB	13A	10A	RB	13A	13A	9A	10A
22	22A	25A	24A	22A	25A	24A	22A	25A	28A	39A	33A	34A
23	39A	42A	41A	39A	42A	41A	39A	45A	46A	45A	39A	40A
24	Pt. Fortier	Lock Light	Flame	Pt. Fortier	Lock Light	Flame	Pt. Fortier	Lock Light	Flame	Anchor Flashing	Flashing Buoy	Flame
25	Beauharnois - Melocheville Locks											
26	8 B	10B	F34'	8 B	10B	F34'	8 B	12B	F34'	12B	8 B	Quick Fl Anchor Lt.
27	14B	16B	17B	14B	16B	17B	14B	16B	17B	16B	13B	L33'
28	19B	22B	FL	19B	22B	FL	19B	22B	FL	Bridge Light	19B	20B
29	St. Louis Bridge											
30	26B	L33'	29B	26B	L33'	29B	26B	L33'	29B	29B	26B	L33'
31	34B	35B	36B	34B	35B	36B	34B	35B	36B	34B	35B	36B
32	Valleyfield Bridge											
33	50B	52B	53B	50B	52B	53B	Bridge Light	52B	53B	50B	52B	53B
34	27F	28F	29F	27F	28F	29F	27F	28F	29F	27F	28F	20F
35	40F	5FL	6FL	40F	5FL	6FL	40F	5FL	6FL	40F	5FL	6FL
36	F73	FY34	46F	50F	73F	FY57	F73	FY34	46F	50F	73F	FY57
37	59F	63F	64F	59F	63F	64F	50F	63F	64F	59F	63F	64F
38	72F	75F	76F	72F	75F	76F	72F	75F	76F	72F	75F	76F
39	82F	84F	Unlighted Buoy	84F	F72	Floating Buoy	82	F72	84	F72	82	74

TABLE 2.4 IDENTIFICATION OF NAVIGATION AIDS USED TO DETERMINE MINIMUM VISIBILITY REQUIRED TO FIX POSITION VISUALLY FOR EACH REACH OF THE SEAWAY, NORMAL SEASON (CON'T)

Reach No.	Daylight						Night					
	Upbound Traffic			Downbound Traffic			Upbound Traffic			Downbound Traffic		
40	F58	L30'	F55	F55	88	F58	F58	L30'	F55	F55	88	F58
41	96F	98F	99F	98	95	96	96F	98F	99F	98	95	96
42	110F	116F	115F	116F	110F	111F	110F	116F	115F	116F	110F	111F
43	120F	122F	FLW	120F	119F	FLW	120F	122F	FLW	120F	119F	FLW
44	2 B	1 B	133F	133F	Chimney	Floating Buoy	FLW	133	134	133	128	FLW
45	142F	143F	140F	143F	F99	139F	142F	143F	140F	143F	F99	139F
46	Quick Fl Red	4	Flashing G5	5	3	2	Quick Fl Red	4	Flashing G5	5	3	2
47	FR8	L89	FRWG 54	9	8	7	FR8	L89	FRWG 54	9	8	7
48	FLG11	FLR14	FLG15	FLG15	FLR14	FLR13	FLG11	FLR14	FLG15	FLG15	FLR14	FLR13
49	Seaway International Bridge											
50	FLG17	FLR16	Bridge Lights	FLG17	FLG16	Bridge Lights	FLG17	FLR16	Bridge Lights	FLG17	FLG16	Bridge Lights
51	FLR16	FLG17	FLR18	21	20	18	FLR16	FLG17	FLR18	21	20	18
52	Snell Lock											
53	28	29	30	31	29	28	28	29	30	31	29	28
54	Eisenhower Lock											
55	40	41	42	Quick Flashing	39	40	40	41	42	Quick Flashing	39	40
56	48	49	50	50	49	48	48	49	50	50	49	48
57	55	57	FG58	FG58	55	54	55	57	FG58	FG58	55	54
58	57	58	60	58	FLG	FG28	57	58	60	58	FLG	FG28
59	Monument	67	FL15	63	FR	60	Monument	67	FL15	63	FR	60
60	68	70	71	71	70	68	68	70	71	71	70	68
61	72	73	74	73	FY56	72	72	73	74	73	FY56	72
62	74	75	77	75	74	FY33	74	75	77	75	74	FY33

TABLE 2.4 IDENTIFICATION OF NAVIGATION AIDS USED TO DETERMINE MINIMUM VISIBILITY REQUIRED TO FIX POSITION VISUALLY FOR EACH REACH OF THE SEAWAY, NORMAL SEASON (CON'T)

Reach No.	Daylight						Night					
	Upbound Traffic			Downbound Traffic			Upbound Traffic			Downbound Traffic		
63	80	81	82	81	80	FR33	80	81	82	81	80	FR33
64	85	87	FLW	87	Flashing	85	85	87	FLW	87	Flashing	85
65	93	94	95	93	FY33'	Unlighted Buoy	93	94	95	93	33	92
66	96A	98	99	98	96A	F53	96A	98	99	98	96A	F53
67	99	100	101	100	99	98	99	100	101	100	99	98
68	102	103	104	103	102	101	102	103	104	103	102	101
69	105	107	F44	106	105	Tower	105	107	F44	106	105	104
70	108	109	110	108	107A	F33	108	109	110	108	107A	F33
71	Iroquois Lock											
72	Rolling Lift Bridge											
73	112	FR	FG	113	112	111	112	FR	FG	113	112	111
74	FR	FG	115	116	115	FG	FR	FG	115	116	115	FG
75	122	123	Old Lighthouse	124	FG60	123	122	123	124	122	124	123
76	124	125	126	FG28	Quick Flr 46	126A	124	125	126	FG28	Quick Flr 46	126A
77	130A	131	Bridge Light	128	129	FG	130A	131	Bridge Light	128	129	FG
78	Ogdensburg-Prescott Bridge											
79	131A	131B	Quick Flashing	131	Quick Flashing	131A	131A	131B	Quick Flashing	131	Quick Flashing	131A
80	FR	133	FR	Radio Tower	Chimney	FL92	FR	133	FR	FR	132	FL92
81	Storage Tank	Pr. Chimney	Old Lighthouse	Lights Chemical Plant	Lights Chemical Plant	Lights Chemical Plant	Storage Tank	Pr. Chimney	Old Lighthouse	Lights Chemical Plant	Lights Chemical Plant	Lights Chemical Plant

TABLE 2.4 IDENTIFICATION OF NAVIGATION AIDS USED TO DETERMINE MINIMUM VISIBILITY REQUIRED TO FIX POSITION VISUALLY FOR EACH REACH OF THE SEAWAY, NORMAL SEASON (CON'T)

Reach No.	Daylight						Night					
	Upbound Traffic			Downbound Traffic			Upbound Traffic			Downbound Traffic		
82	Chimney	Shoreline	Shoreline	Chimney	Shoreline	Shoreline	Shoreline	Shoreline	Shoreline	Shoreline	Shoreline	Shoreline
83	Chimney	FR	138	138	FR	Chimney	136	FR	138	138	FR	137
84	139	141	Unlighted Buoy	141	139	138	B9	141	142	141	139	138
85	142	143	144	143A	143	FR	142	143	144	143A	143	FR
86	146	146A	145A	147A	147	F31	146	146A	145A	147A	147	F31
87	149	150	151	151	150	149	149	150	151	151	150	149
88	160	162	163	159	160	162	160	162	163	159	160	162
89	165	167	166	167	168	165	165	167	166	167	168	165
90	172	177	178	177	172	Flagpole	172	177	178	177	172	173
91	179	180	182	182	181	179	179	180	182	182	181	179
92	189	181	Cupola	187	189	186	189	191	192	187	189	186
93	192	194	195	192	194	191	192	194	195	192	194	191
94	197	198	199	197	195	194	197	198	199	197	195	194
95	204	206	207	Bridge Lights	207	206	204	206	207	Bridge Lights	207	206
96	Thousand Islands Bridge											
97	210	211	212	212	211	210	210	211	212	212	211	210
98	217	218	219	219	218	217	217	218	219	219	218	217
99	219	222	224	224	222	219	219	222	224	224	222	219
100	229	FLG35	231	231	229	35T	229	FLG35	231	231	229	35T
101	234	235	237	235	234	233	234	235	237	235	234	233
102	240	238	231	241	230	238	240	238	231	241	230	238
103	OCCR	FL47	244	FL47	244	OCC69	OCCR	FL47	244	FL47	244	OCC69

TABLE 2.5 IDENTIFICATION OF NAVIGATION AIDS USED TO DETERMINE MINIMUM VISIBILITY REQUIRED TO FIX POSITION VISUALLY FOR EACH REACH OF THE SEAWAY, EXTENDED SEASON

Reach No.	Daylight						Night					
	Upbound Traffic			Downbound Traffic			Upbound Traffic			Downbound Traffic		
1-19	Illuminated Dike			Illuminated Dike			Illuminated Dike			Illuminated Dike		
20	Dike Light	Pt. Johnson	FLG27'	Pt. Johnson	Dike Light	FLG27	Dike Light	Pt. Johnson	FLG27'	Pt. Johnson	Dike Light	FLG27
21	FG32	FLG27	Pt. Johnson	Cross	Pt. Johnson	FG32	Pt. Johnson Lt.	FG32	FG75	FG32	FG75	Pt. Johnson
22	FG53	Croix Cross	Pt. Moulin	Pt. Moulin	Cross	FG53	Flame	Lock Light	L22'	FG53	FG32	FG75
23	Pt. Moulin	Pt. Fortier	Flame	Pt. Fortier	Flame	Pt. Moulin	Flame	Dike Light	L22'	FG53	FG32	FG75
24	52A	Lock Light	Flame	Flame	Pt. Fortier	L22	Flame	Dike Light	L22'	Flame	Dike Light	L22
25	Beauharnois - Melocheville Locks											
26	Quick Fl. Anchor Lt.	EINT	FY59	F34	FY25	Quick Fl. Anchor Lt.	FY25	Quick Fl Anchor Lt.	FY59	FY59	F34	Quick Fl. Anchor Lt.
27	FY59	EINT	Bridge Light	F34	FY59	EINT 33	FY59	L33	Bridge Light	L33'	FY59	F34
28	Bridge Light	Bridge Light	Bridge Light	Bridge Light	EINT 33	FY59	Bridge Light	Bridge Light	Bridge Light	Bridge Light	L33	FY59
29	St. Louis Bridge											
30	FY61	F58	EINT 33	Bridge Light	L33'	F58	F58	L33'	FY51	L33	F38	Bridge Light
31	FY61	F58	FL34'	FY61	EINT 33	F58	L34	F58	Bridge Light	FY61	L33	F58
32	Valleyfield Bridge											
33	Chimney	Bridge Lights	Bridge Lights	EINT	FG70	Bridge Light	F58	FG70	Bridge Light	L34	F58	Bridge Light
34	FLR10	FY56	FLR17	FLR17	FLR10	L35	FLR10	FLR17	FY56'	FLR17	FLR10	L35
35	FY57	FY34	FY73	FR	FR17	Conspicuous Tanks	FY57	FY34	FY73	FY56	FLR17	FLR10
36	FY57	FL25'	F73'	F78	F73	FY34	FY57	L25	L73	F38	F73	FY34
37	Pt. Moulee	Conspicuous Monument	FY57	FY57	Pt. Moulee	Conspicuous Monument	FY57	FY45	LY25	FY57	L25	F38

TABLE 2.5 IDENTIFICATION OF NAVIGATION AIDS USED TO DETERMINE MINIMUM VISIBILITY REQUIRED TO FIX POSITION VISUALLY ON EACH REACH OF THE SEAWAY, EXTENDED SEASON (CON'T)

Reach No.	Daylight						Night					
	Upbound Traffic			Downbound Traffic			Upbound Traffic			Downbound Traffic		
38	F33	Spire	F72	F33	FY45	FY30	F72	F33	F30	F33	FY30	FY45
39	F33	F72	Cairn Spire	Spire	Cairn	F72	F33	F72	F58	FY30	F72	F33
40	F58	F55	F30	F55	F58	EINT 30	F58	F55	F30	F55	F58	EINT 30
41	EINT 32	F59	F31	EINT 31	F58	EINT 32	F32	F59	F31	EINT 31	F58	EINT 32
42	116F	111F	108F	Spire	116	111	F32	111F	108F	116	111	108
43	116F	Chimney	124F	124	Spire	116	116F	124F	F66	111	108	116
44	124F	Abandoned Lt. House	Chimney	Chimney	124F	EINT 40	124F	F66	F99	EINT 40	124	116
45	F66	F99	QFLR	Light House	F66	F99	F66	F99	QFLR	EINT 40	F66	F99
46	2	4	FL11	4	2	Mast	2	4	11	4	2	F66
47	4	11	FR54	10	Mast	4	4	10	11	10	2	4
48	10	11	13	14	13	11	10	11	13	14	13	11
49	Seaway International Bridge											
50	14	15	Bridge Lights	Bridge Lights	Bridge Lights	Bridge Lights	14	15	Bridge Lights	Bridge Lights	Bridge Lights	Bridge Lights
51	20	21	QFR	21	18	Bridge Light	20	21	QFR	21	18	Bridge Lights
52	Snell Lock											
53	28	29	30	28	29	30	28	29	30	28	29	30
54	Eisonhower Lock											
55	40	41	42	40	41	42	40	41	42	40	41	42
56	48	L54	47	48	Tanks	47	48	55	47	48	55	47
57	55	FG58	57	55	54	48	55	FG58	57	55	54	48
58	57	FG28	63	FG28	FG48	QF	57	FG28	63	FG28	FG48	QF
59	63	Spire	Monument	63	FG28	FG58	63	68	70	63	FG28	FG58
60	75	FY33	FY56	71	F58	F33	75	FY33	FY56	71	F58	F33
61	FY33	FY56	FY75	75	F33	F56	FY33	FY56	FY75	75	F33	F56
62	FY33	FY56	FY75	79	75	F33	FY33	Fy56	FY75	79	75	F33
63	FR33	81	82	81	FR45	FR33	FR33	81	82	81	FR45	FR33

TABLE 2.5 IDENTIFICATION OF NAVIGATION AIDS USED TO DETERMINE MINIMUM VISIBILITY REQUIRED TO FIX POSITION VISUALLY FOR EACH REACH OF THE SEAWAY, EXTENDED SEASON (CON'D)

Reach No.	Daylight						Night					
	Upbound Traffic			Downbound Traffic			Upbound Traffic			Downbound Traffic		
64	85	Spire	Tower	Tower	Spire	85	85	FG28	FG52	85	81	82
65	F33	96	F38	FR	F33	F47	F33	96	F38	F33	F47	92
66	F44	Tower	107	F53	F38	96	107	F33	F44	F53	F38	96
67	F44	Tower	107	F38	96	F53	107	F33	F44	F38	F33	96
68	F44	Tower	107	Tower	96	F53	107	F33	F44	96	F33	F58
69	Tower	107	F44	107	Tower	Oil Terminal	F33	107	F44	96	F33	F38
70	110	F33	F432	FR32	F33	F44	110	F33	FR32	FG32	F33	F44
71	Iroquois Lock											
72	Rolling Lift Bridge											
73	111	FR	FG	114	111	Radio Tower	FG	111	FR	FG	111	FR
74	Radio Tower	Water Tower	Silo	Silo	Radio Tower	115	115	FG28	121	111	114	115
75	FG60	123	Old Light House	FG60	Old Light House	123	FG60	123	FG48	123	FG28	121
76	123	Old Lt. House	Old Light House	FG28	FG48	QFR46	123	FG28	QFR46	FG28	FG48	QFR46
77	F70	FG	FLR	FR	FG	EINT 70	F70	FG	FLR	FR	FG	EINT 70
78	Ogdensburg Prescott Bridge											
79	F92	QF	Bridge Light	FL92	QF	Bridge Light	F92	QF	Bridge Light	FL92	QF	Bridge Light
80	Radio Tower	Chimney	FL92	FR	Radio Tower	Chimney	FL92	FR	QF	FL92	QF	FR
81	Storage Tank	Pr. Chimney	Old Light House	Chemical Plant Lights	Chemical Plant Lights	Chemical Plant Lights	Storage Tank	Pr. Chimney	Old Light House	Chemical Plant Lights	Chemical Plant Lights	Chemica Plant Lights
82	Chimney	Shoreline	Shoreline	Chimney	Shoreline	Shoreline	Shoreline	Shoreline	Shoreline	Shoreline	Shoreline	Shoreline
83	137	Shimney	FR	138	FR	Chimney	137	138	FR	138	137	FR
84	FR	138	141	138	FR	Chimney	FR	138	141	138	137	FR

TABLE 2.5 IDENTIFICATION OF NAVIGATION AIDS USED TO DETERMINE MINIMUM VISIBILITY REQUIRED TO FIX POSITION VISUALLY FOR EACH REACH OF THE SEAWAY, EXTENDED SEASON (CON'T)

Reach No.	Daylight						Night					
	Upbound Traffic			Downbound Traffic			Upbound Traffic			Downbound Traffic		
85	133	144	145	144	143	132	133	144	145	144	143	132
86	145	146	146A	149	147	F31	145	146	146A	149	147	F31
87	150	151	156	150	151	149	150	151	156	150	151	149
88	156	160	Water Tower	156	151	160	163	160	FWAG	160	156	151
89	165	168	FWAG	Chimney	Flag-pole	168	165	168	178	168	165	FWRG
90	FLG	178	179	178	Flag-pole	168	182	178	179	179	178	168
91	179	182	183	179	183	182	179	182	183	179	183	182
92	186	187	189	189	186	187	186	187	189	189	186	187
93	194	195	197	194	192	191	194	195	197	194	192	191
94	197	198	199	197	195	194	197	198	199	197	195	194
95	204	206	207	207	206	204	204	206	207	207	206	204
96	Thousand Islands Bridge											
97	210	214	FG	210	209	Bridge Lights	210	214	FG	210	209	Bridge Lights
98	214	219	222	219	214	FLG	214	219	222	219	214	FLG
99	219	222	Tower	Tower	Signal Station	222	222	226	227	222	221	214
100	Flash	231	229				Flash	231	229	229	226	227
101	FR	FR70	FR35				FR	FR70	FR35	FR35	FR	231
102	OCCR	QF	FR	QF	Silo	Tower	OCCUR	FR	QF	QF	EINT	FR35
103	FR	FL47	OCCR	FL47	OCC 69	OCCR	FR	FL47	OCCR	FL47	OCC69	OCCR

2.2 Methods Used to Describe Meteorological Conditions

Winds and visibility affect the speed and maneuvering room requirements of ships in the Seaway. Five years of actual meteorological data consisting of three hourly observations of visibility, wind speed and direction, and dry bulb temperature were obtained from weather stations located near the Seaway at Montreal, Massena , and Watertown. The five years selected coincided with the years used in the SPAN study because this data had already been assembled for the extended season period and therefore only data for the normal season had to obtained. The SPAN study selected these five years based on the degree of winter severity as determined by the cumulative freezing degree days. For this study, however, the five years were considered to be random samples of weather from the set of all available weather data.

Data from the Canadian weather station was available on magnetic tape in US TDF 1440 format from the Atmospheric Environment Division of Environment Canada. Data from the two American stations was obtained from the National Climatic Center, Environmental Data Service, National Oceanic and Atmospheric Administration of the U.S. Department of Commerce, in Asheville, North Carolina. The data for the Massena station was available on magnetic tape; however, only one year of data for the Watertown station was on magnetic tape, the remainder was keypunched from photocopies of the hand-written original observations.

Five complete years of weather data were stored on magnetic tapes. The five years used were those years that contain the five winter seasons analyzed in the SPAN study [1]. These are shown in Table 2.6.

The Seaway was divided into three meteorological sectors as follows:

SECTOR 1 includes Reaches 1 to 41
SECTOR 2 includes Reaches 42 to 79
SECTOR 3 includes Reaches 80 to 103

Each reach within a given sector is subjected to the same meteorological conditions; that is, the visibility, wind speed, and wind direction at Reaches 1 through 41 are the same. This procedure allowed the simulation of a weather front moving through the Seaway.

The visibility due to river steam was calculated for each meteorological sector of the Seaway. The visibility due to river steam was calculated using the following equation, [1].

$$\text{Visibility}_{\text{river steam}} = (9\text{ mi})\left\{e^{-.0876}(\Delta T) + (1 - e^{-.0876}(\Delta T)\ \tan h(.38V_w)\right\}$$

where

$\Delta T = T_{\text{water}} - T_{\text{air}}$ (°F)

V_w = wind speed (mph)

TABLE 2.6 FIVE YEARS OF HISTORIC WEATHER DATA USED IN STUDY

YEAR NUMBER	YEAR
1	Oct. 1952 - Sept. 1953
2	Oct. 1965 - Sept. 1966
3	Oct. 1967 - Sept. 1968
4	Oct. 1968 - Sept. 1969
5	Oct. 1969 - Sept. 1970

Water temperature data for the five years of interest was incomplete, and records of water temperature for 1952-1953 could not be found. Therefore, water temperature data from 1965-1966 was used for river steam calculations for the year 1952-1953. Data was available for one location along the Seaway-Ogdensburg, New York [3]. This location corresponded to meteorological Sector 2 of the Seaway. Water temperatures for Sectors 1 and 3 were estimated in the following manner.

River steam occurs when the air temperature drops below the water temperature. Figure 2.6 [4] shows that this phenomenon occurs mid-August to late March for Montreal. During this period, the figure also shows that the maximum winter water temperature difference between Kingston and Montreal is approximately 6°F. The temperature at Sectors 1 and 3 were then estimated, with interpolation based on Seaway miles, using the following relationships:

SECTOR 1:

$$T_{\text{Montreal}} = (T_{\text{Ogdensburg}} - 2), \quad \text{if } (T_{\text{Ogdensburg}} - 2) > 32$$

$$= 32, \quad \text{if } (T_{\text{Ogdensburg}} - 2) \leq 32$$

SECTOR 3:

$$T_{\text{Kingston}} = T_{\text{Ogdensburg}} + 1$$

Six events occur on the Seaway during the winter which were significant for this study:

1. The floating lighted-navigation aids are pulled
2. Ice forms on the Seaway
3. Ice lockages begin
4. Ice lockages end
5. Ice disappears from the Seaway
6. The floating lighted aids are reinstalled

Table 2.7 lists the days after October 1 that these events occur for the five years of interest. Event 1 has an effect on visual navigation in that once the floating, lighted aids are pulled, the minimum required visibility increases significantly. Event 2, the formation of ice on the Seaway, is used to indicate that river steam will not occur when ice is present. Event 3, ice lockages begin, decreases capacity because of increase lockage time.*

$$t_{\text{Lock}} = t_{\text{Extended Season}} + t_{\text{Ice Lockage}}$$

Events 4, 5, and 6 signal the end of the winter season.

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*This study assumes that the Seaway is operating at a level of improvement that allows ships to proceed throughout the winter; that is, ice conditions do not stop ships.

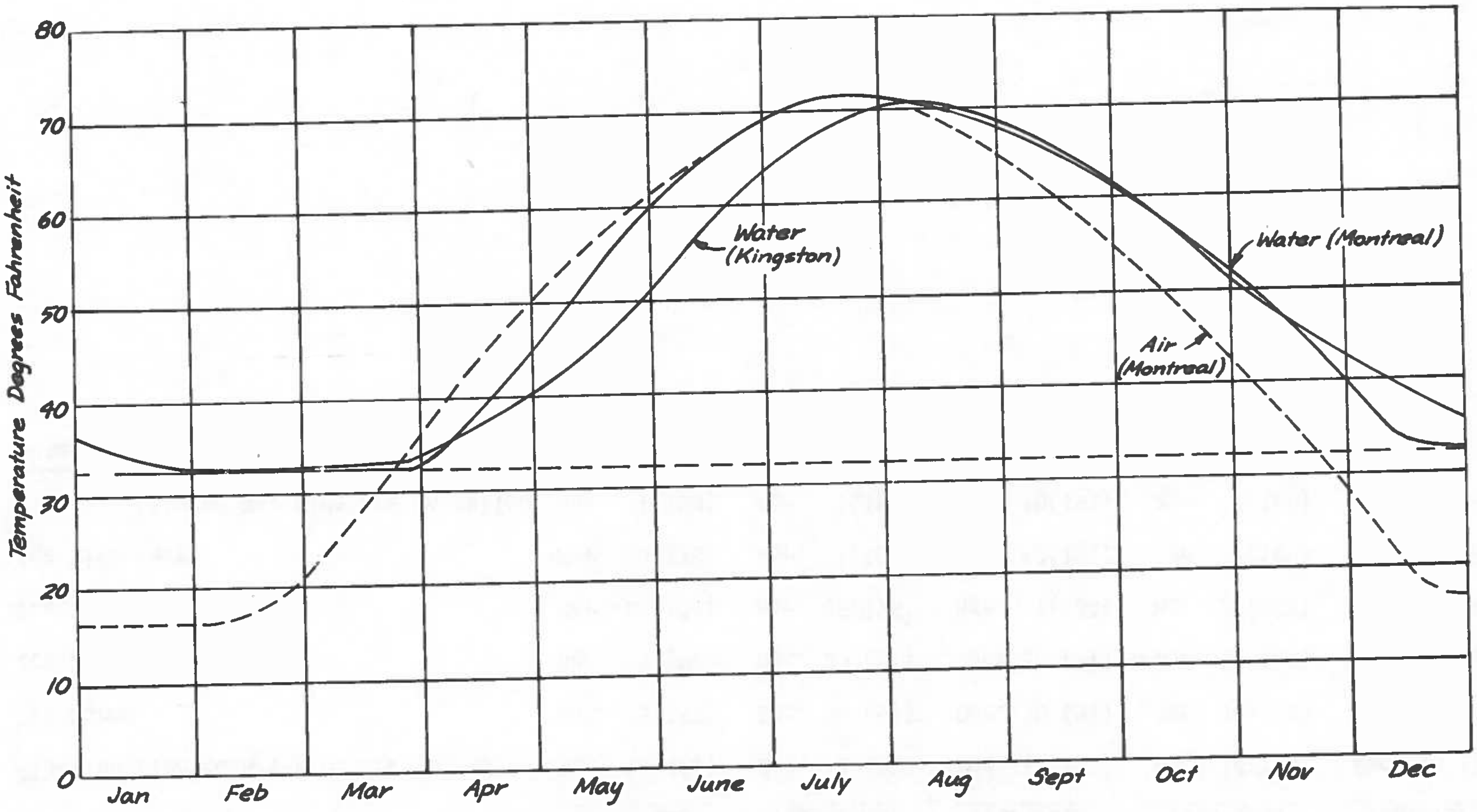


Figure 2.6. Air and Water Temperatures for Montreal, and Water Temperatures for Kingston

1963 - 1964 - 1965 Averages

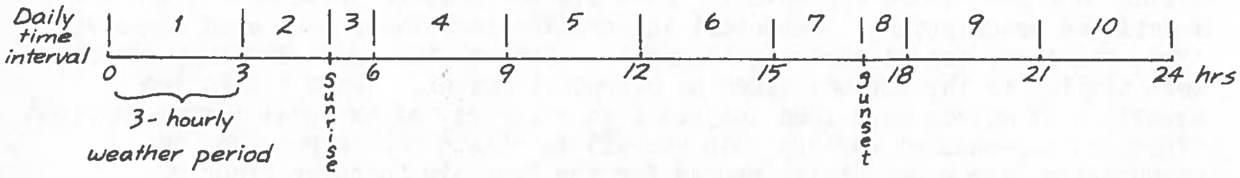
TABLE 2.7 DATES OF SIGNIFICANT EVENTS FOR EACH HISTORIC YEAR

	YEAR - 1	2	3	4	5
	1952-1953	1965-1966	1967-1968	1968-1969	1969-1970
Floating Lighted Nav-Aids are Pulled	Dec. 15 (76)	Dec. 3 (63)	Dec. 16 (77)	Dec. 14 (75)	Dec. 15 (76)
Ice Forms	Jan. 5 (97)	Dec. 30 (91)	Dec. 30 (91)	Dec. 14 (75)	Dec. 22 (83)
Ice Lockages Begin	Jan. 5 (97)	Dec. 30 (91)	Dec. 30 (91)	Dec. 21 (82)	Dec. 22 (83)
Ice Lockages End	Mar. 25(176)	Mar. 25(176)	Apr. 1(184)	Mar. 31(182)	Mar. 25(176)
Ice Disappears	Mar. 25(176)	Apr. 1(183)	Apr. 10(191)	Apr. 7(189)	Apr. 1(183)
Floating Lighted Nav-Aids are Installed	Apr. 1(183)	Apr. 1(183)	Apr. 10(191)	Apr. 7(189)	Apr. 1(183)

Note: Numbers in parenthesis denote number of days after October 1 that event occurs.

The Seaway year was divided into two periods, normal season and extended season. The normal and extended seasons are defined to be those periods between April 1 (0000 hours) and December 15 (2400 hours), and December 16 (0000 hours) and March 31 (2400 hours), respectively.

As listed in Section 2.1, the daylight and nighttime required visibilities are different. Therefore, each day had to be divided into periods of day and night. The time period of daylight was assumed to begin at sunrise and end at sunset. However, the beginning of 3-hourly weather periods, in general, do not coincide with either sunrise or sunset. Therefore, the two weather periods in which sunrise and sunset occur were divided into a period of day and one of night, resulting in a 24-hour day being divided into 10 daily time intervals as shown below:



Daily time periods 2 and 3 were analyzed using the weather period 2 data and time periods 7 and 8 were analyzed using the weather period 7 data.

2.3 Determination of Ship Maneuvering Requirements

The importance of having a methodology whereby the maneuvering room requirements for the study ships would be a function of the weather conditions and reach parameters was briefly discussed in Section 1.1. Without such a functional relationship, it would have been impossible to determine if a given reach constrained the capacity at any given time.

The approach used to develop a functional relationship between maneuvering room requirements and the weather conditions and reach parameters consisted of developing equations of motion to describe the movement of a ship in the horizontal plane when subjected to external disturbance forces (winds, currents, bank suctions, etc.) and control forces (rudder and propeller). This development followed the method given in Reference 5. The equations of motion were programmed for solution on a digital computer (see Appendix C for a detailed description). Numerical integration techniques were used to solve these equations due to their nonlinearity. Control laws were developed which were similar to the actions taken by a prudent master. These controlled equations of motion were then subjected to a variety of external forces (various winds and currents at various ship speeds) to obtain the information on maneuvering room requirements needed for the Capacity Computer Program.

Two classes of ships were investigated in this study. These were referred to as a "LAKER" and a "SALTY." Typical principal particulars of these two ship types are given in Table 2.8.

The equations of motion which describe the uncontrolled movement of these ships in the horizontal planes are:

$$(m - Y_{\dot{v}})\,\ddot{y}_o = Y_{\text{wind}} + Y_\delta \delta + Y_{yo} y_o + (\dot{y}_o - \dot{y}_{o\text{current}})Y_v \tag{1}$$

$$- Y_v(\dot{x}_o - \dot{x}_{o\text{current}})\phi + (Y_{\dot{\phi}} - Y_{\dot{v}} x_o)\dot{\phi} + (Y_{\ddot{\phi}} - m x_G)\ddot{\phi}$$

$$(I_z - N_{\ddot{\phi}})\ddot{\phi} = N_{\text{wind}} + N_\delta \delta + N_{yo} y_o + N_v(\dot{y}_o - \dot{y}_{o\text{current}}) + (N_{\dot{v}} - m x_G)\ddot{y}_o \tag{2}$$

$$+ N_v(\dot{x}_o - \dot{x}_{o\text{current}})\phi + (N_{\dot{\phi}} - N_{\dot{v}}\dot{x}_o)\dot{\phi}$$

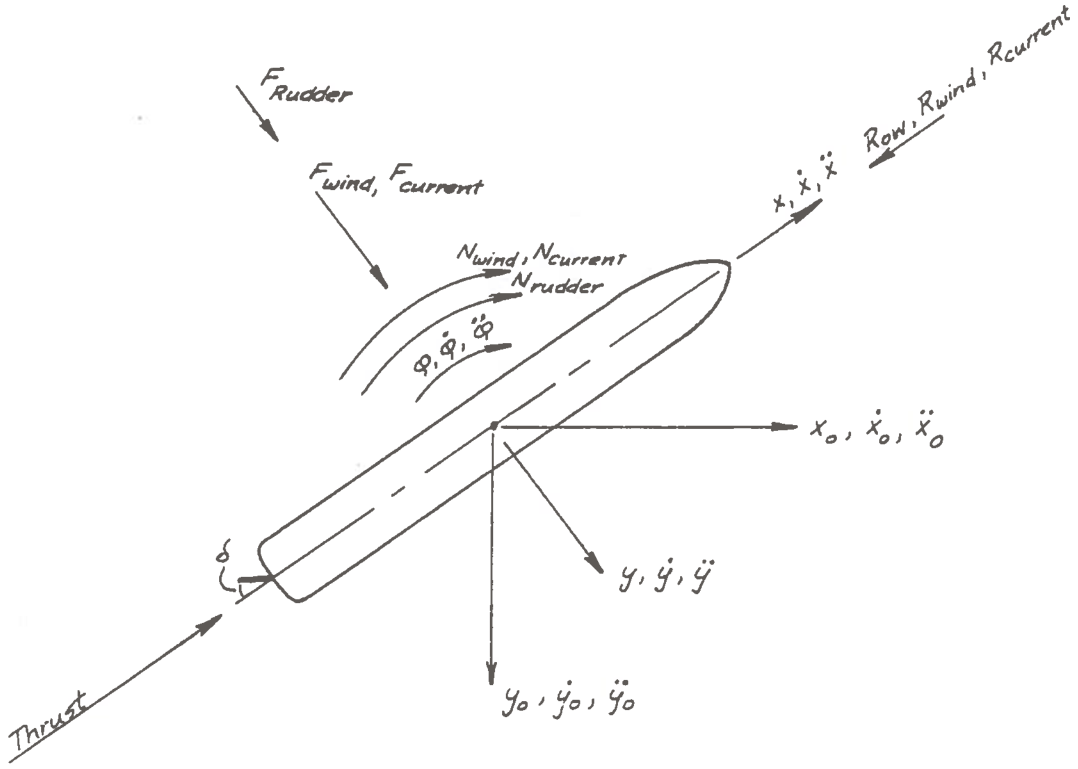
$$(m - X_{\dot{u}})\ddot{x}_o = X_{\text{wind}} + X_\delta \delta + X_{yo} y_o + (\dot{x}_o + \dot{x}_{\text{initial}})X_u \tag{3}$$

Definitions of the coordinate system and motion variables are given in Figure 2.7. The symbols $Y_{\dot{v}}$, $N_{\ddot{\phi}}$, etc., refer to linearized hydrodynamic force coefficients. They are functions of hull form, channel geometry and ship speed. Reference 5 was used as the source of information to determine these coefficents.

TABLE 2.8 PRINCIPAL SHIP PARTICULARS

	Quebecois (LAKER)	Partignies (SALTY)
Length, overall, ft	730.0	600.0
Beam, ft	75.0	75.0
Seaway draft, ft	25.5	25.5
Displacement, F.W., tons	32,526	22,932

Fig. 2.7 Ship Coordinate System, Motion Variables and Forces



A controlled set of motion equations can be obtained by adding to the above equations, an equation which describes the rudder angle as a function of certain motion variables normally observed and used by the master to control his ship. In this study, the following controller equation was employed:

$$\delta = a(y_o - y_{course}) + b\dot{y}_o + c(\phi - \phi_{desired}) + d\dot{\phi} \quad \text{for } \delta \leq 35° \qquad (4)$$

That is, the rudder command was made equal to the sum of four terms, which were proportional to off track position, cross track velocity, heading, and rate of change of heading respectively. The constants of proportionality in this equation were determined by conducting an analysis of the roots of a linearized version of equations (1) through (4) as a function of various values of the constants (Root-Locus method). Stable controllers which gave response times typical of a prudent master's actions were selected and used in the maneuvering width computations.

For computing the maneuvering widths, the non-lock reaches were first divided into two groups depending upon the nature of the currents and winds expected in the reaches. In reaches where the currents were steady over the length of the reach and the winds were not variable due to changes in terrain contours, a steady state solution to the equations of motion was used. This allowed the direct computation of yaw angle for these "STATIC" reaches using the steady state equations in the Capacity Computer Program. The maneuvering width was then computed using:

$$M = 1/2(L\sin\phi_{ss} + B\cos\phi_{ss}) \qquad (5)$$

where

L = ship's length

B = ship's beam

ϕ_{ss} = steady state yaw calculated from the steady state equations using the winds, currents, and channel geometry for the reach being studied.

In reaches where the currents were not steady over the length of the reach, channel width varied, or winds could possibly vary due to changes in terrain contours, detailed solutions to the controlled differential equations of motion were obtained. Eleven of these "DYNAMIC" reaches were initially selected for study. After several initial runs, this list was narrowed to three reaches: (1) Reach No. 44 (along St. Regis Island); (2) Reach No. 50 (along Polly's Gut); and (3) Reach No. 56 (Copeland Cut). Numerous runs were then made for each of these reaches using various ship speeds, wind velocities and ship direction of motion. From each of these runs, the maximum excursion of the ship's center of gravity from the desired course, $(y_o)_{CG}$, and the yaw angle, ϕ, at that point was obtained. The maneuvering width was then computed using:

$$M = (y_o)_{CG} + 1/2(L\sin\phi + B\cos\phi) \qquad (6)$$

A table of these maneuvering widths as a function of wind, ship speed, and ship direction was then prepared and used in a table "look-up" fashion in the Capacity Computer Program. Tables 2.9, 2.10, and 2.11 show the results for each of the three DYNAMIC reaches.

It can be seen from the above discussion that the ship's speed through a particular reach must be known before the maneuvering width for that reach can be determined. The ship's speed is assumed to be equal to the speed limit in the reach unless it is reduced by consideration of visibility in the reach. Rule 15 of the "Rules of the Road, Great Lakes" [6] states "Every vessel shall, in thick weather, by reason of fog, mist, falling snow, heavy rainstorms, or other causes, go at *moderate* speed." The term "moderate speed" has been interpreted by the courts [7] to mean that a ship must proceed at a speed which will allow it to stop at a distance equal to one-half the visibility.

Stopping distance was calculated using the following equation: [5]

$$S = \frac{106.2V_o^2}{(T_1/\Delta)} - \frac{34.4V_o^2(R_o/\Delta)}{(T_1/\Delta)^2} + 16.9V_o \qquad (7)$$

where

S = stopping distance, ft

Δ = ship displacement

R_o = ship resistance at V_o

T_1 = astern thrust

V_o = ship speed, in knots, when the stopping maneuver begins

The stopping distance S for a number of ship speeds V_o were calculated and a relationship of the form

$$V_o = K_1 S^{K_2} \qquad (8)$$

was developed which would allow direct computation of the maximum allowable speed given the desired stopping distance. The desired stopping distance under low visibility must be one half the visibility; therefore

$$V_o = K_1 \left(\frac{\text{VISIBILITY}}{2}\right)^{K_2} \qquad (9)$$

TABLE 2.9 DYNAMIC MANEUVERING RESULTS FOR SEAWAY REACH 44 (ALONG ST. REGIS ISLAND) FOR A SALTY AND A LAKER

			Salty		Laker	
Wind Direction (°T)	Wind Speed (mph)	Ship Speed (mph)	Upbound M (ft)	Downbound M (ft)	Upbound M (ft)	Downbound M (ft)
331.17	0	3	819.10	1,331.40	819.78	1,334.21
		6	464.05	627.47	464.32	635.03
		9	316.57	394.74	317.64	399.18
		12	249.49	285.74	250.19	288.67
	15	3	831.82	1,379.06	834.29	1,408.58
		6	466.97	641.85	467.24	651.12
		9	317.59	397.89	318.39	402.76
		12	249.93	286.79	250.48	289.93
	30	3	865.13	1,138.14	903.10	1,200.84
		6	475.98	690.23	478.32	706.74
		9	321.99	412.91	322.26	419.77
		12	252.46	293.18	252.57	297.34
	45	3	30,457.00	3,080.05	∞	∞
		6	490.90	1,220.61	496.77	1,229.00
		9	329.67	443.07	331.79	454.86
		12	257.08	304.82	258.32	310.80
151.17	15	3	824.00	1,981.75	825.70	∞
		6	462.98	606.08	464.08	611.40
		9	316.82	387.89	318.28	391.44
		12	248.29	282.67	249.21	285.20
	30	3	5,500.70	3,217.50	∞	∞
		6	475.64	1,397.76	479.10	1,400.01
		9	322.55	369.35	325.19	370.41
		12	250.60	273.96	252.23	275.27
	45	3	35,760.30	∞	∞	∞
		6	751.47	3,207.50	771.30	3,223.50
		9	332.01	795.46	336.63	811.39
		12	256.09	271.24	258.90	273.25

TABLE 2.10 DYNAMIC MANEUVERING RESULTS FOR SEAWAY REACH 50 (POLLY'S GUT) FOR A SALTY AND A LAKER

			Salty		Laker	
Wind Direction (°T)	Wind Speed (mph)	Ship Speed (mph)	Upbound *M* (ft)	Downbound *M* (ft)	Upbound *M* (ft)	Downbound *M* (ft)
357	0	3	452.21	617.72	454.22	627.56
		6	317.73	350.86	321.32	355.44
		9	232.04	248.84	235.63	251.35
		12	183.27	192.98	185.58	194.72
	15	3	463.83	1,070.65	471.26	1,087.10
		6	321.31	402.14	325.46	408.29
		9	233.49	262.64	237.03	265.88
		12	183.87	198.16	187.41	200.11
	30	3	489.12	5,512.92	499.20	5,525.00
		6	331.76	600.08	338.25	612.71
		9	238,74	315.52	242.91	321.02
		12	287.06	219.95	189.90	223.08
	45	3	3,277.64	17,079.67	3,295.14	17,200.00
		6	351.35	3,227.82	374.06	3,300.00
		9	248.37	412.55	253.62	421.95
		12	192.77	258.67	196.34	263.70
177	15	3	453.26	255.47	459.08	259.99
		6	315.40	294.71	318.56	296.87
		9	230.34	232.41	233.49	234.37
		12	182.21	186.38	184.39	187.81
	30	3	443.64	5,686.79	446.96	5,700.00
		6	306.95	180.07	308.92	184.36
		9	224.92	187.38	226.11	188.28
		12	178.89	163.91	180.59	164.10
	45	3	14,804.23	17,260.94	14,850.00	17,300.00
		6	297.82	3,974.76	298.80	4,000.00
		9	218.33	142.35	218.62	146.77
		12	173.45	143.92	174.37	148.34

TABLE 2.11 DYNAMIC MANEUVERING RESULTS FOR SEAWAY REACH 56 (COPELAND CUT) FOR A SALTY AND A LAKER

			Salty		Laker	
Wind Direction (°T)	Wind Speed (mph)	Ship Speed (mph)	Upbound *M* (ft)	Downbound *M* (ft)	Upbound *M* (ft)	Downbound *M* (ft)
347	0	3	225.87	225.62	228.05	228.24
		6	225.26	226.44	230.59	232.55
		9	201.67	211.74	252.49	217.85
		12	144.71	147.28	213.19	153.75
		15	117.00	118.59	126.44	122.49
	15	3	225.27	225.30	228.24	249.83
		6	226.26	226.36	230.39	230.12
		9	197.75	204.92	252.56	214.73
		12	142.64	144.83	203.20	150.89
		15	115.20	117.46	115.99	121.63
	30	3	225.47	267.29	261.52	265.00
		6	225.27	225.07	226.76	237.71
		9	189.57	186.78	249.73	193.62
		12	137.04	137.31	172.26	141.94
		15	111.83	113.56	112.12	116.98
	45	3	225.03	227.33	260.91	235.00
		6	226.88	226.09	243.29	258.12
		9	214.39	225.78	253.84	229.97
		12	129.02	126.09	131.41	128.50
		15	106.75	107.35	107.34	109.50
167	15	3	225.71	225.46	231.67	242.50
		6	229.17	225.36	235.26	231.33
		9	210.16	215.88	293.90	227.39
		12	190.00	148.88	234.29	155.68
		15	179.02	119.34	187.18	123.89
	30	3	227.38	267.29	232.08	270.00
		6	230.04	225.45	238.75	236.84
		9	217.17	225.04	314.14	237.34
		12	205.00	156.54	252.93	164.73
		15	193.61	123.07	203.77	128.36
	45	3	229.67	300.76	264.99	350.00
		6	228.91	225.66	246.68	253.01
		9	228.71	225.34	245.72	237.94
		12	224.00	172.16	264.91	182.86
		15	220.34	130.41	233.99	137.04

2.4 Logic for Flow of Traffic and Capacity Computation

The capacity of the Seaway for a time interval Δt is determined by the slowest lock provided ships can transit every reach of the Seaway. Capacity of that time period is zero if ship traffic is stopped. Traffic is stopped when: (1) a pilot of a ship, not equipped with an electronic navigation system, cannot fix his position visually; or (2) the ship maneuvering requirements exceed the channel width. When traffic is not stopped, ships may be processed through a lock in both directions (two-way traffic) or in only one direction (one-way traffic). This means that for a given time interval Δt, one of three values of Seaway capacity can be achieved:

1. CAPACITY = $\Delta t/t_\ell$ (two-way traffic)
2. CAPACITY = $\Delta t/(t_\ell + t_{tb})$ (one-way traffic)
3. CAPACITY = 0 (traffic is stopped)

The logic of program AWCAP determines, for a given time interval, if a lock can process ships both upbound and downbound (two-way traffic), in one direction only (one-way traffic), or not at all (traffic is stopped).

The ship positioning accuracy, ε, is linked to the Seaway capacity in the following manner. The positioning accuracy ε, the ship maneuvering width M, and the channel width W; determine which type of traffic exists and then the capacity achieved during time interval Δt; that is, if $2M + 4\varepsilon \leq W$ (refer to Figure 1.1) then two-way traffic exists and the capacity is equal to $\Delta t/t_\ell$; if $M + 2\varepsilon \leq W$ then one-way traffic exists with the capacity equal to $\Delta t/(t_\ell + t_{tb})$; if $M + 2\varepsilon > W$ then traffic stops and the capacity is equal to zero.
A discussion of the logic of program AWCAP using the flow chart presented in Figure 2.8 follows:

1.* After reading the control and input cards, the first computation that occurs is the determination of the maximum distance throughout the Seaway which includes three navigational aids to fix position visually. This computation is done by subroutine MAXDIS for the normal season day, normal season night, extended season day, and extended season night. These results are used later to determine if an overall Seaway check can be implemented; that is, if low winds and high visibility levels exist throughout the Seaway for a given time interval then the capacity can be determined without analyzing each Seaway reach.

---

* Numbers correspond to numbers in boxes in Figure 2.8.

2. Daily water temperatures are read for the entire year for meteorological Sector 2. Water temperatures for Sectors 1 and 3 are calculated later in the program.

3. Eight 3-hourly observations of the weather for the three meteorological sectors are read for each day.

4. Time of sunrise and time of sunset are calculated using subroutine SUNRS.

5. The day is then divided into periods of daylight and nighttime. The 3-hour weather periods in which sunrise and sunset occur are divided into periods of day and night of less than 3 hours. The day and night distinctions are necessary because the distance-to-navigation aids are a function of day and night.

6. Water temperatures for Sectors 1 and 3 are calculated and riversteam visibility is computed for the three Seaway sectors.

7. For each sector, the prevailing visibility level is the minimum of the riversteam visibility and the observed visibility.

8. Beam winds are computed for the South Shore and Beauharnois canals. Earlier calculations indicated that a beam wind of 29 mph or greater will stop traffic at the bridges in the Beauharnois canal. Beam winds of 17.5 mph or greater in the St. Lambert Lock portion (reaches 6-13) and 13.5 or greater in the St. Catherine Lock portion (reaches 15-20) of the South Shore canal will cause traffic to be one-way.

9. Events occur during the winter months which affect capacity. These events are the following:

1) The floating lighted-navigation aids are pulled.
2) Ice forms in the river.
3) Ice lockages occur at Seaway locks.

The program logic determines if any of these events have occurred for the day being analyzed.

10. If the visibility throughout the entire Seaway is greater than the maximum distance-to-navigation aids throughout the entire Seaway, then the overall Seaway check can be made; if not, a reach-by-reach check must be made to determine the constraining reach and capacity.

11. As part of the overall Seaway check, the prevailing beam winds in the Beauharnois and South Shore canals are calculated to determine if traffic is stopped, two-way, or one-way. After an overall Seaway check is made, the variable NTIME is incremented by 1 to begin capacity analysis for the next time period.

12. The reach-by-reach analysis of the Seaway begins by identifying the reach as either a lock, a non-constraining bridge, or a non-lock reach. If the reach is a lock, the variable SUM is set to zero and, since the capacity of a lock is already known, no further analysis is required of this reach. The variable NREACH is incremented by 1 to begin identification of the next reach. For a non-constraining bridge, no analysis is required and the variable NREACH is incremented by 1 to begin identification of the next reach.

13. If a reach is a non-lock reach, the sector in which this reach is located is determined and the prevailing visibility, wind speed, and wind direction are computed.

14. A check is again made to determine the following:

1) Upbound and downbound distance-to-navigation aids for the reach.
2) Has ice formed in this reach?
3) Do ice lockages occur?

15. Next, a check is made to determine if the ship is equipped with an electronic navigation system. If not, the traffic can be stopped due to low visibility or insufficient maneuvering clearance. If the ship possesses an electronic system, traffic may be stopped because of insufficient maneuvering clearance only.

16. Consider a ship without an electronic navigation system. Checks are made to determine if the ship can proceed visually upbound or downbound. If it cannot proceed visually in either direction, the capacity for this reach is equal to zero. No additional reaches need to be analyzed since a capacity of zero is the minimum value for any time period. If the ship can proceed in both directions, or in just one direction, the reach maneuvering requirements are calculated to determine capacity.

17. Consider a ship with an electronic navigation system. If the visibility is greater than the nav-aid distance, the ship can proceed using the visual system accuracy; if not, it then proceeds, implementing the electronic accuracy.

18. The ship speed is calculated based on the visibility law discussed in Section 2.3. If this visibility speed exceeds the upbound or downbound speed limits, the ship speed is then set equal to these speed limits; otherwise, the upbound and downbound speeds are set equal to this calculated ship speed. The visibility law, when implemented, indicates that a ship must stop if the visibility is zero.

19. An event check and a reach check are made to determine if ice has formed and if the reach is part of the South Shore Canal. If both checks are positive, the maneuvering requirements for this reach are based on the one-way traffic mode. If the reach is not part of the South Shore Canal, a check is made to determine if the reach is one-way due to Seaway regulations. After the above checks have been made, the reach maneuvering requirements and reach capacity can be calculated.

20. If the traffic pattern becomes one-way, an additional check is made. The time, SUM, to transit sequential one-way reaches is calculated and compared to the lockage time for two-way traffic. If SUM is greater than the two-way lockage time, the capacity decreases to the one-way traffic capacity.

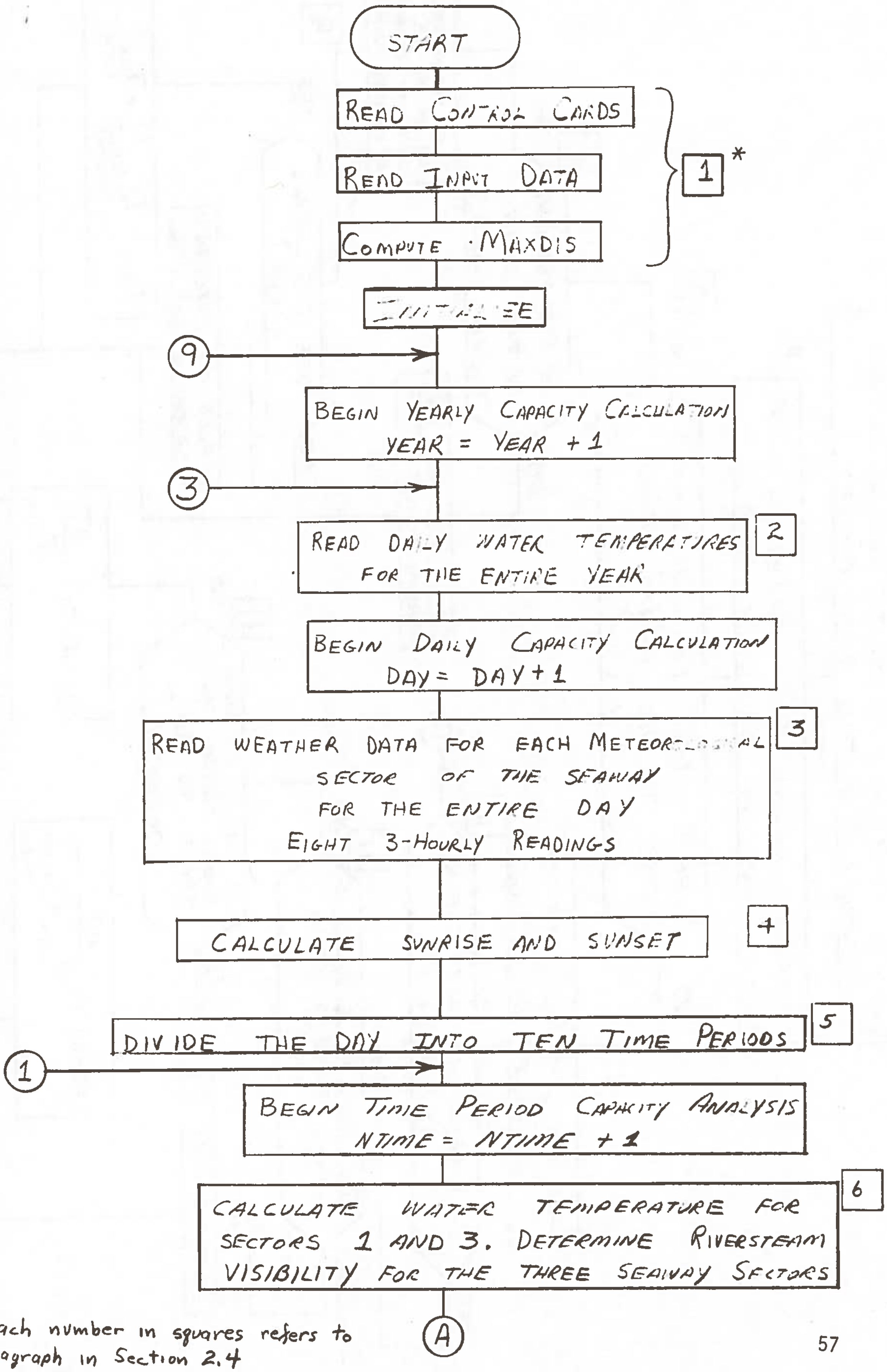
21. For the reach-by-reach analysis, the capacity for a given daily time period is the minimum of all the reach capacity results.

22. After all of the reaches have been analyzed, or when the capacity drops to zero, NTIME is incremented by 1 to begin capacity analysis of the next time period.

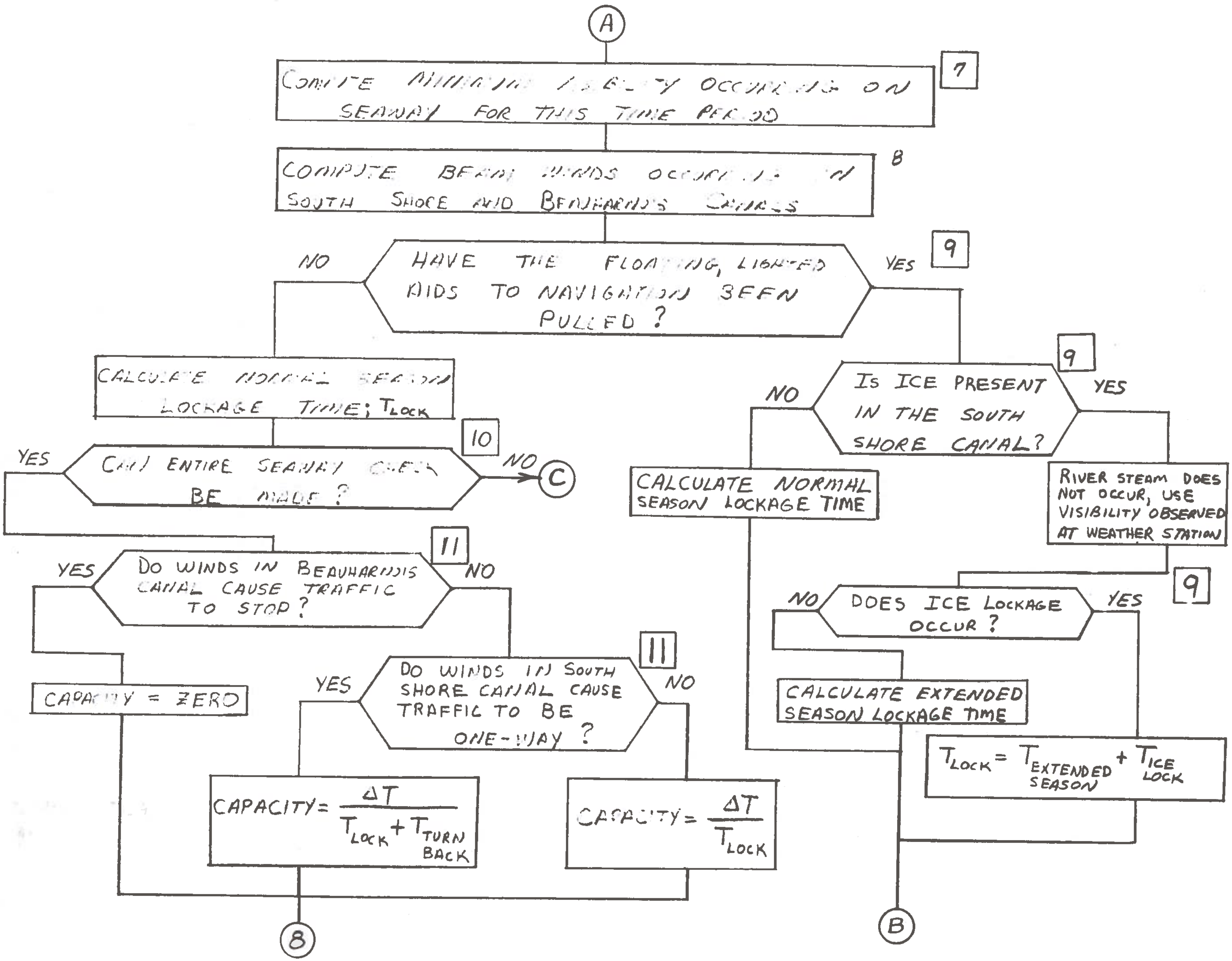
23. Capacity calculations continue until all the time periods in a day, and all the days in a year have been analyzed.

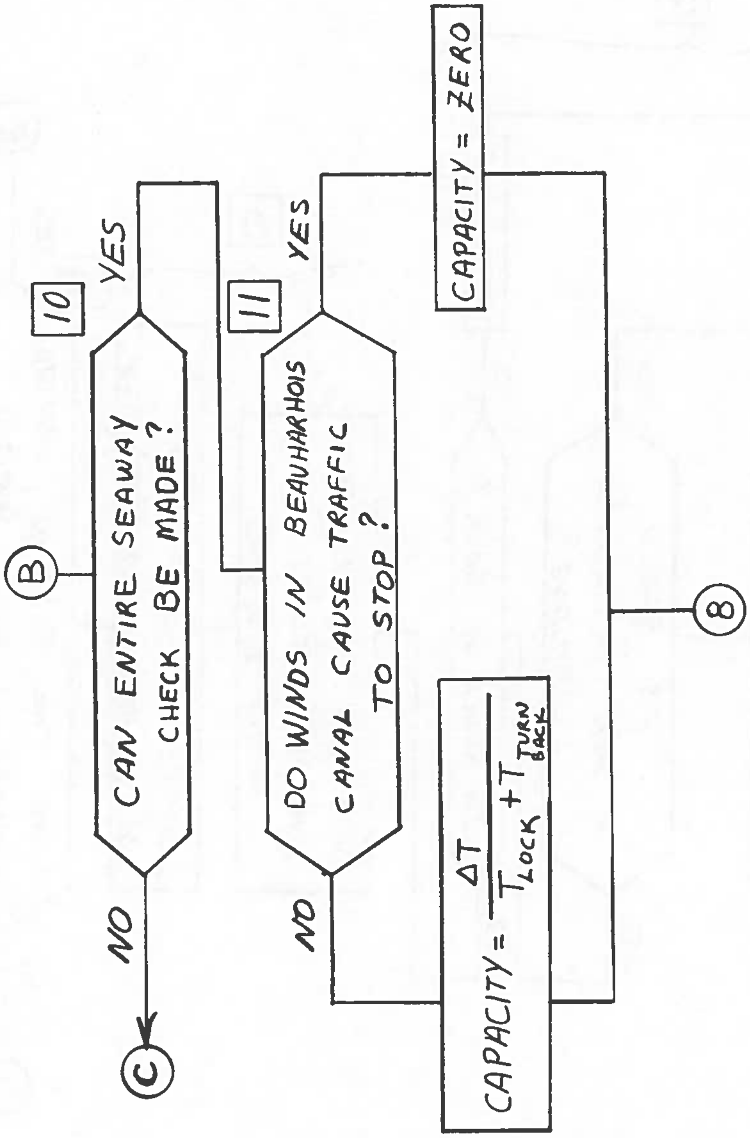
This concludes Section 2 of the report. In the next Section we will present and discuss the results obtained from the models developed in this Section.

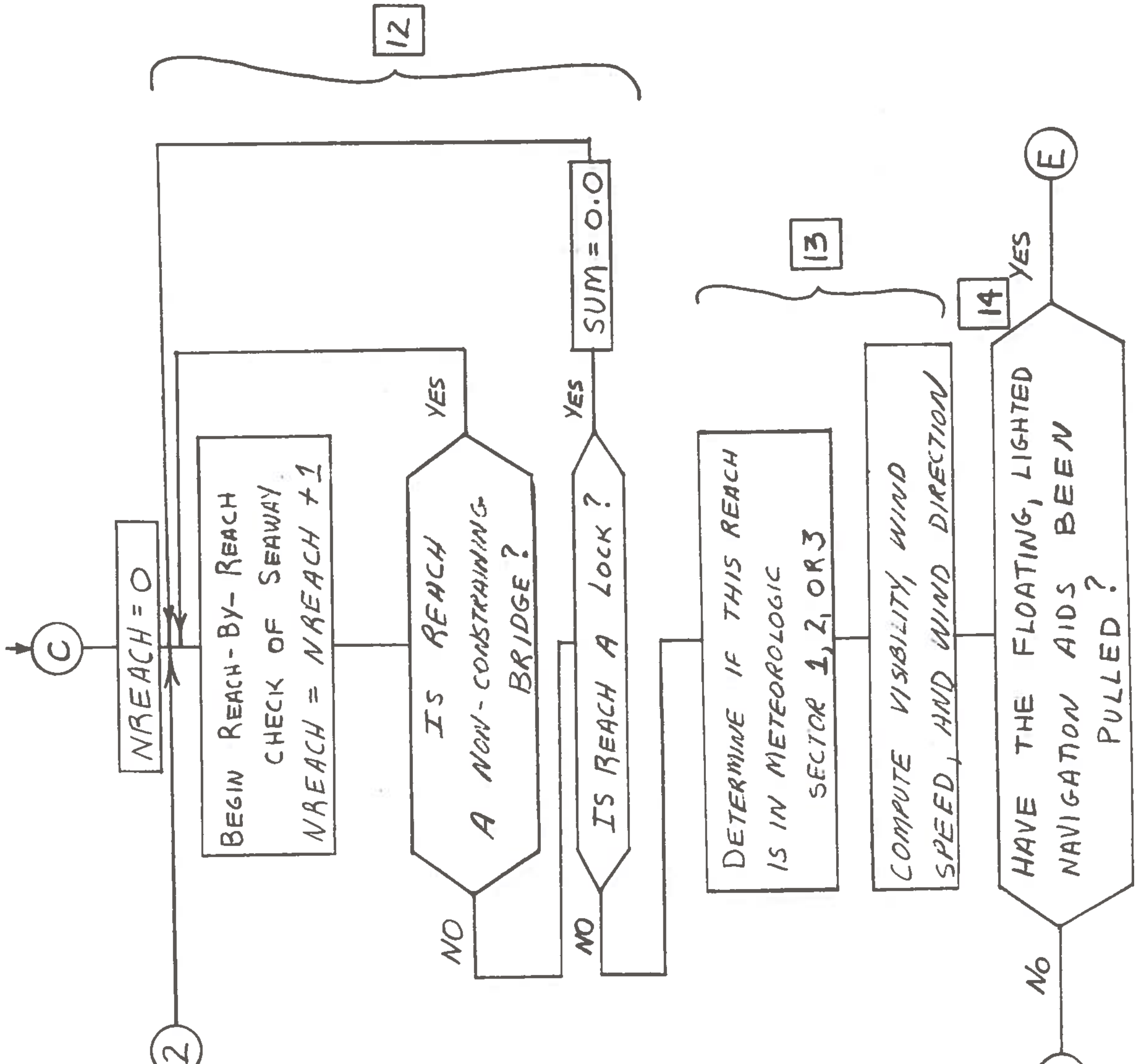
FIGURE 2.8 FLOW CHART OF AWCAP

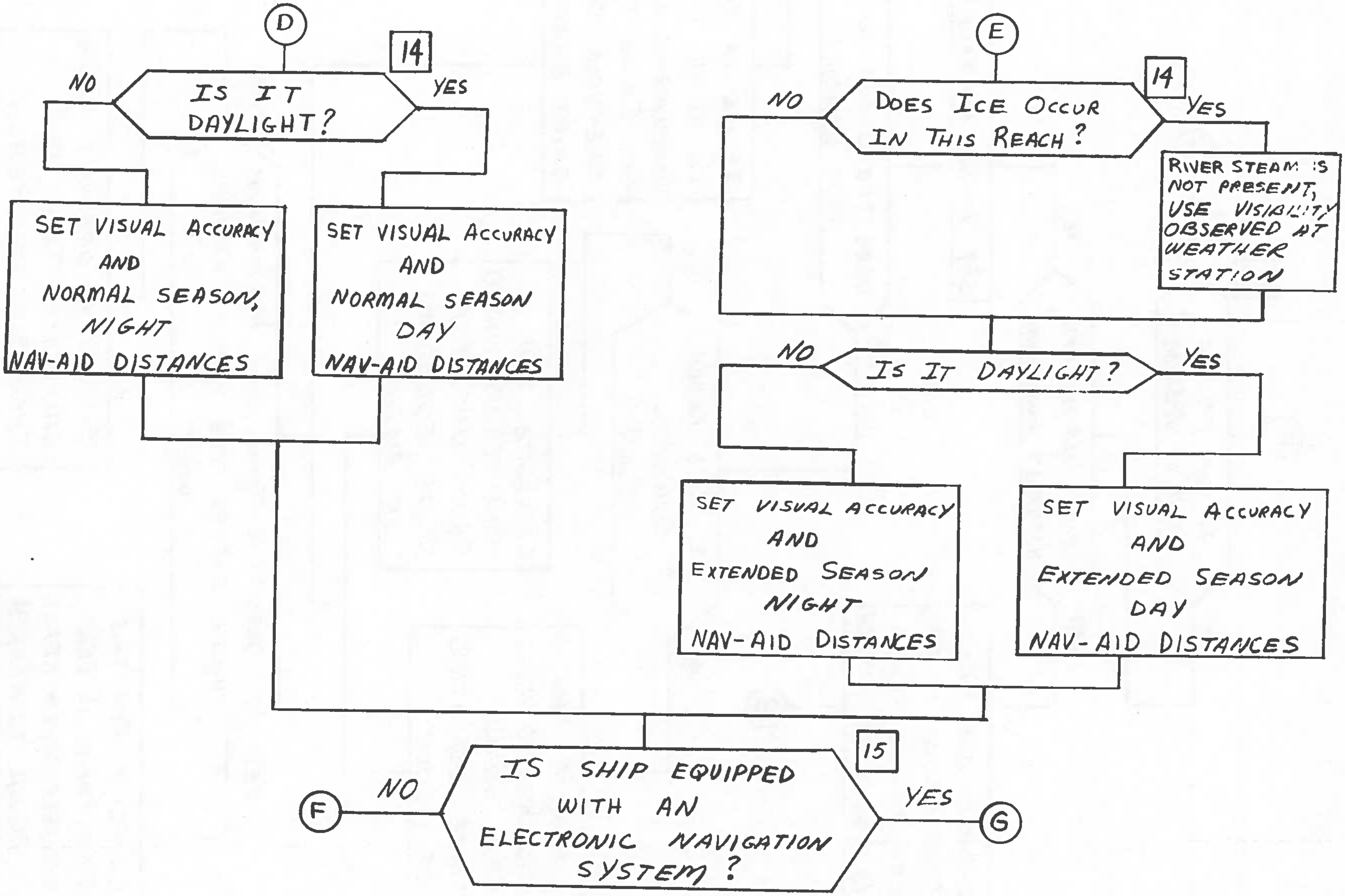


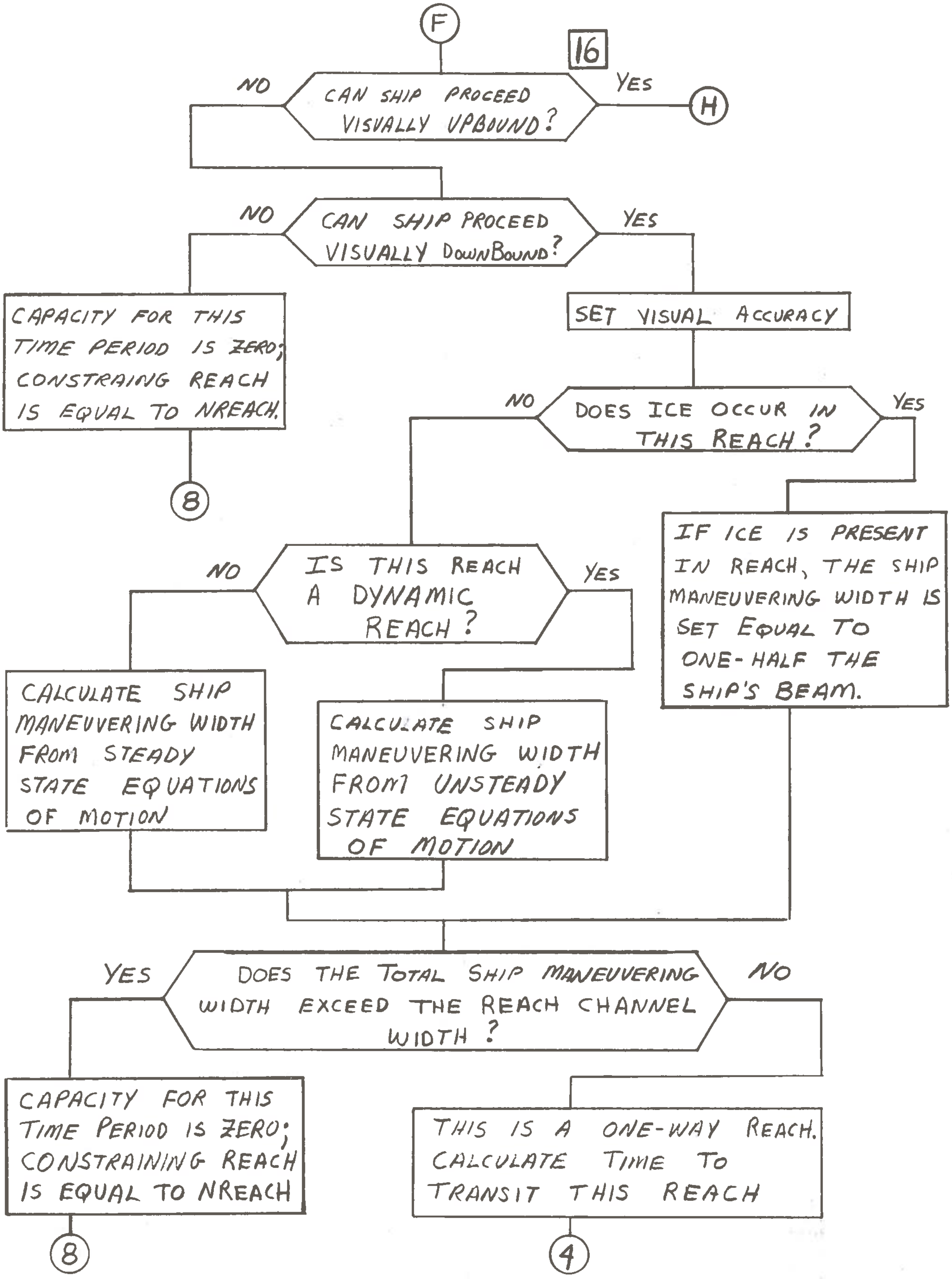
* Each number in squares refers to Paragraph in Section 2.4

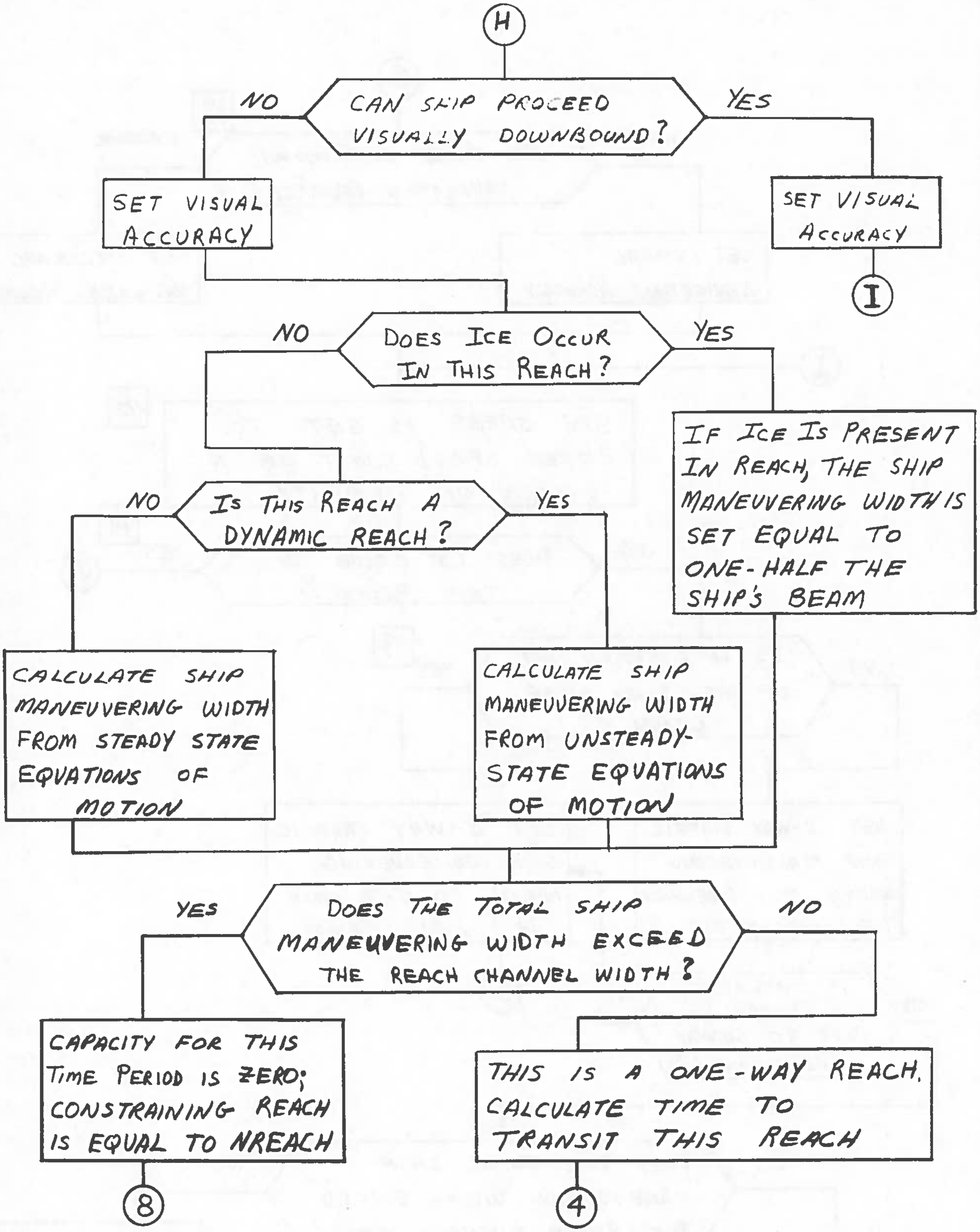

A
COMPUTE MINIMUM VISIBILITY OCCURRING ON SEAWAY FOR THIS TIME PERIOD
7
COMPUTE BEAM WINDS OCCURRING ON SOUTH SHORE AND BEAUHARNOIS CANALS
8
HAVE THE FLOATING, LIGHTED AIDS TO NAVIGATION BEEN PULLED ?
NO
YES
9
CALCULATE NORMAL SEASON LOCKAGE TIME; T_{LOCK}
CAN ENTIRE SEAWAY CHECK BE MADE ?
10
YES
NO
C
DO WINDS IN BEAUHARNOIS CANAL CAUSE TRAFFIC TO STOP ?
11
YES
NO
CAPACITY = ZERO
DO WINDS IN SOUTH SHORE CANAL CAUSE TRAFFIC TO BE ONE-WAY ?
11
YES
NO
$CAPACITY = \frac{\Delta T}{T_{LOCK} + T_{TURN BACK}}$
$CAPACITY = \frac{\Delta T}{T_{LOCK}}$
8
IS ICE PRESENT IN THE SOUTH SHORE CANAL?
9
NO
YES
CALCULATE NORMAL SEASON LOCKAGE TIME
RIVER STEAM DOES NOT OCCUR, USE VISIBILITY OBSERVED AT WEATHER STATION
DOES ICE LOCKAGE OCCUR ?
9
NO
YES
CALCULATE EXTENDED SEASON LOCKAGE TIME
$T_{LOCK} = T_{EXTENDED SEASON} + T_{ICE LOCK}$
B

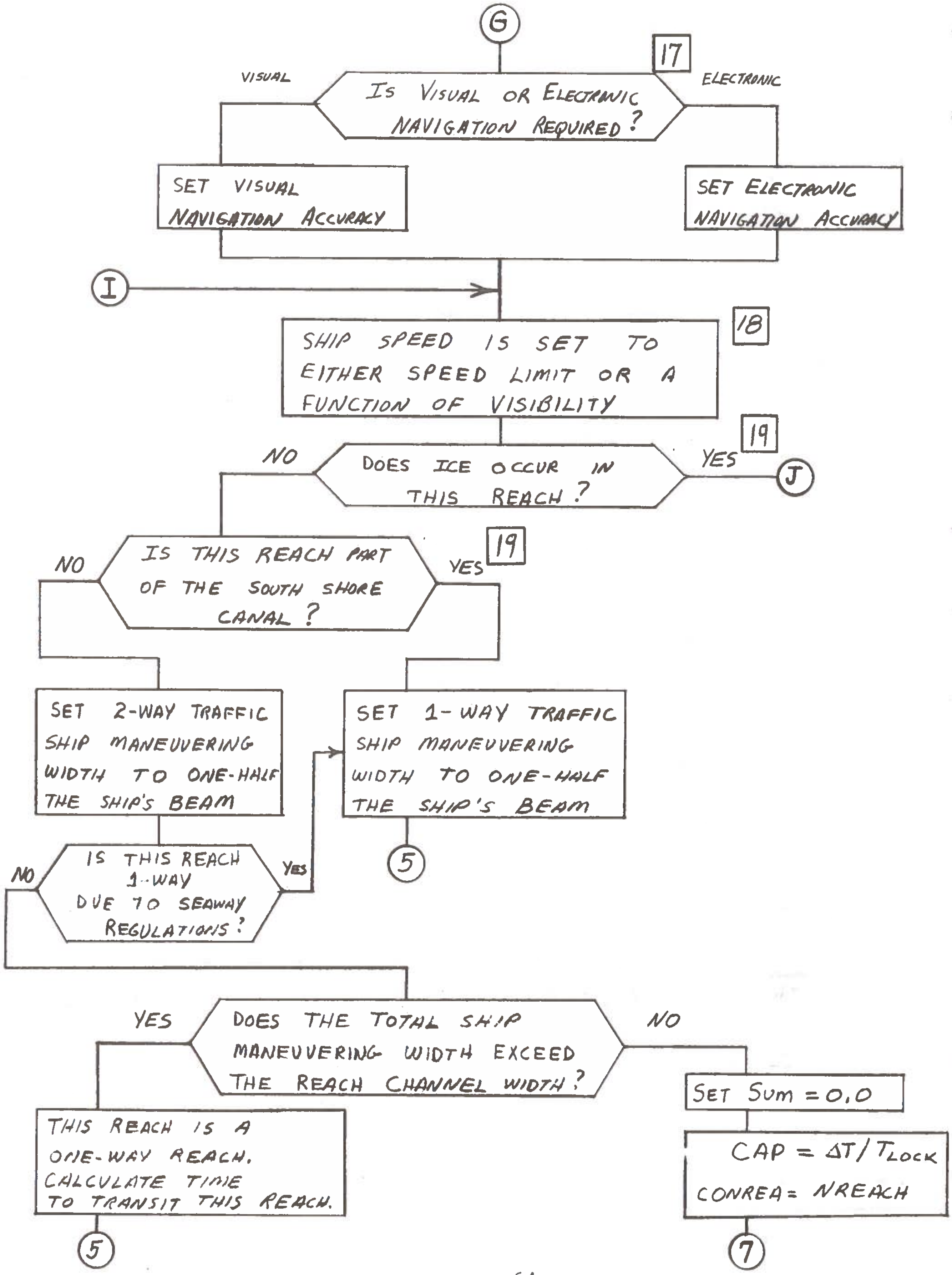

B
10
CAN ENTIRE SEAWAY CHECK BE MADE ?
YES
NO
C
11
DO WINDS IN BEAUHARNOIS CANAL CAUSE TRAFFIC TO STOP ?
YES
NO
CAPACITY = ZERO
CAPACITY = $\frac{\Delta T}{T_{LOCK} + T_{TURN\ BACK}}$
8

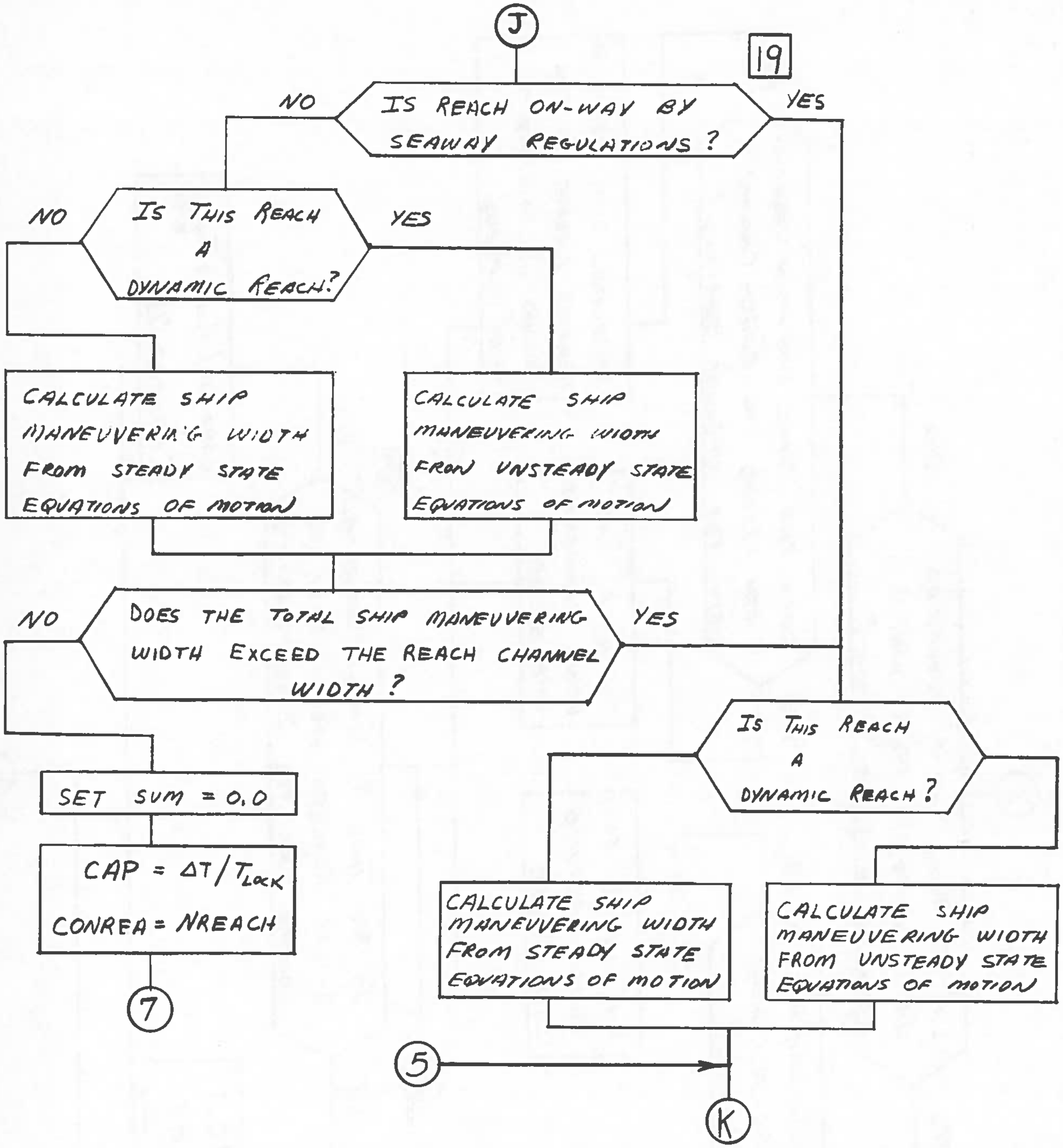

C
NREACH = 0
BEGIN REACH-BY-REACH
CHECK OF SEAWAY
NREACH = NREACH + 1
2
12
IS REACH
A NON-CONSTRAINING
BRIDGE ?
YES
NO
IS REACH A LOCK ?
YES
NO
SUM = 0.0
13
DETERMINE IF THIS REACH
IS IN METEOROLOGIC
SECTOR 1, 2, OR 3
COMPUTE VISIBILITY, WIND
SPEED, AND WIND DIRECTION
14
HAVE THE FLOATING, LIGHTED
NAVIGATION AIDS BEEN
PULLED ?
YES
NO
E
D

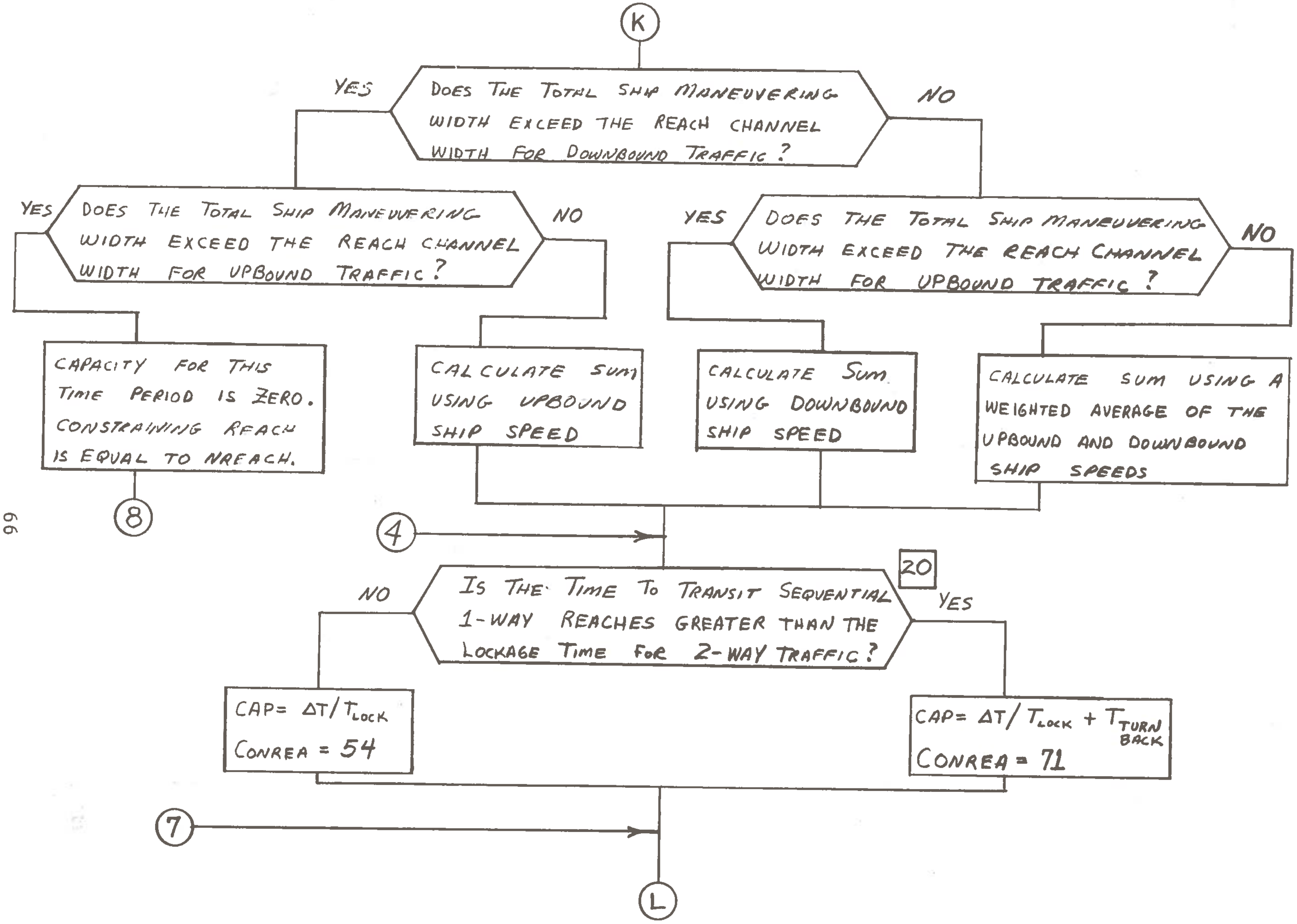

D
14
IS IT DAYLIGHT?
NO
YES
SET VISUAL ACCURACY AND NORMAL SEASON, NIGHT NAV-AID DISTANCES
SET VISUAL ACCURACY AND NORMAL SEASON DAY NAV-AID DISTANCES
E
14
DOES ICE OCCUR IN THIS REACH?
NO
YES
RIVER STEAM IS NOT PRESENT, USE VISIBILITY OBSERVED AT WEATHER STATION
IS IT DAYLIGHT?
NO
YES
SET VISUAL ACCURACY AND EXTENDED SEASON NIGHT NAV-AID DISTANCES
SET VISUAL ACCURACY AND EXTENDED SEASON DAY NAV-AID DISTANCES
15
IS SHIP EQUIPPED WITH AN ELECTRONIC NAVIGATION SYSTEM?
NO
F
YES
G

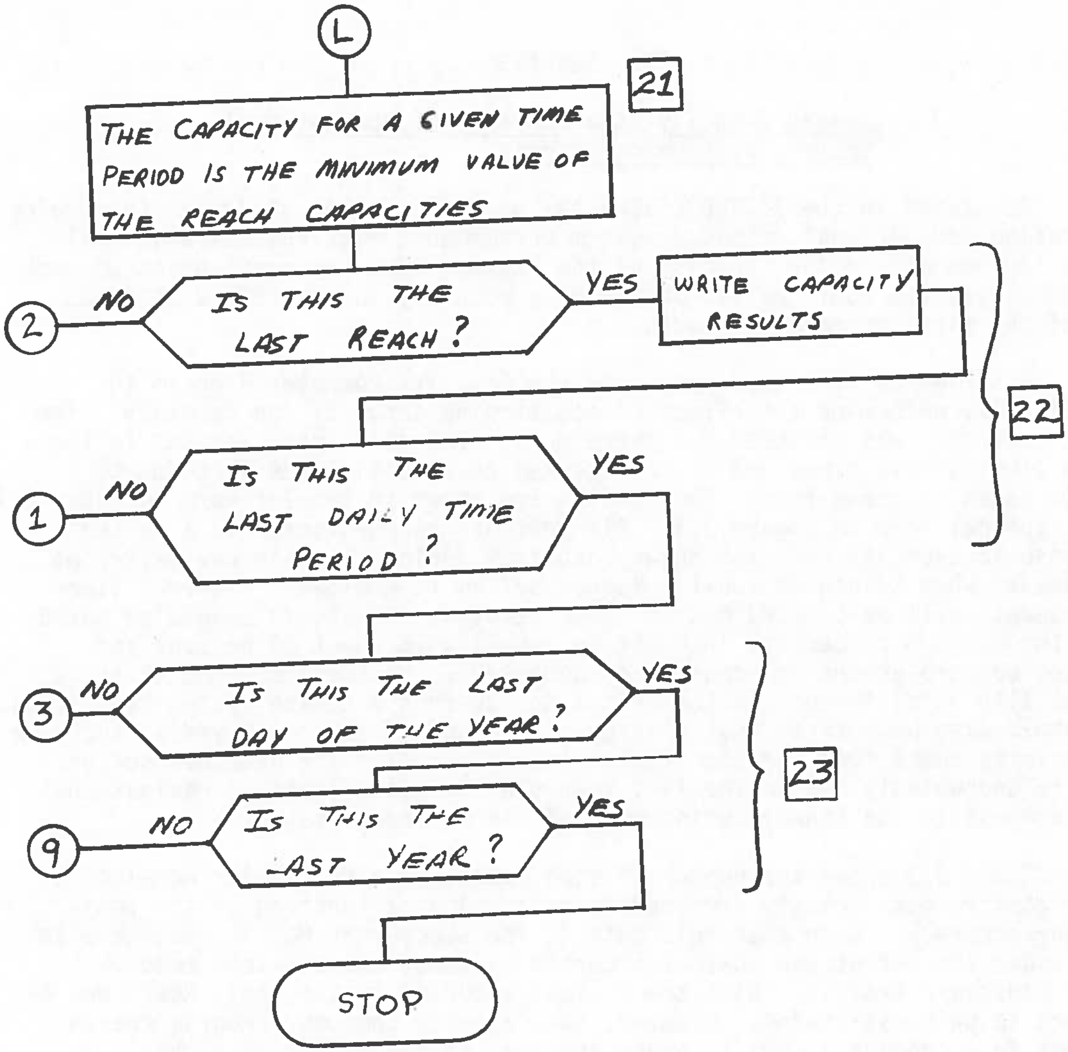

F
16
CAN SHIP PROCEED VISUALLY UPBOUND?
NO
YES
H
CAN SHIP PROCEED VISUALLY DOWNBOUND?
NO
YES
CAPACITY FOR THIS TIME PERIOD IS ZERO; CONSTRAING REACH IS EQUAL TO NREACH.
8
SET VISUAL ACCURACY
DOES ICE OCCUR IN THIS REACH?
NO
YES
IF ICE IS PRESENT IN REACH, THE SHIP MANEUVERING WIDTH IS SET EQUAL TO ONE-HALF THE SHIP'S BEAM.
IS THIS REACH A DYNAMIC REACH?
NO
YES
CALCULATE SHIP MANEUVERING WIDTH FROM STEADY STATE EQUATIONS OF MOTION
CALCULATE SHIP MANEUVERING WIDTH FROM UNSTEADY STATE EQUATIONS OF MOTION
DOES THE TOTAL SHIP MANEUVERING WIDTH EXCEED THE REACH CHANNEL WIDTH?
YES
NO
CAPACITY FOR THIS TIME PERIOD IS ZERO; CONSTRAINING REACH IS EQUAL TO NREACH
THIS IS A ONE-WAY REACH. CALCULATE TIME TO TRANSIT THIS REACH
8
4


H
CAN SHIP PROCEED VISUALLY DOWNBOUND?
NO
YES
SET VISUAL ACCURACY
SET VISUAL ACCURACY
I
DOES ICE OCCUR IN THIS REACH?
NO
YES
IF ICE IS PRESENT IN REACH, THE SHIP MANEUVERING WIDTH IS SET EQUAL TO ONE-HALF THE SHIP'S BEAM
IS THIS REACH A DYNAMIC REACH?
NO
YES
CALCULATE SHIP MANEUVERING WIDTH FROM STEADY STATE EQUATIONS OF MOTION
CALCULATE SHIP MANEUVERING WIDTH FROM UNSTEADY-STATE EQUATIONS OF MOTION
DOES THE TOTAL SHIP MANEUVERING WIDTH EXCEED THE REACH CHANNEL WIDTH?
YES
NO
CAPACITY FOR THIS TIME PERIOD IS ZERO; CONSTRAINING REACH IS EQUAL TO NREACH
THIS IS A ONE-WAY REACH. CALCULATE TIME TO TRANSIT THIS REACH
8
4


G
17
VISUAL
IS VISUAL OR ELECTRONIC NAVIGATION REQUIRED?
ELECTRONIC
SET VISUAL NAVIGATION ACCURACY
SET ELECTRONIC NAVIGATION ACCURACY
I
18
SHIP SPEED IS SET TO EITHER SPEED LIMIT OR A FUNCTION OF VISIBILITY
19
NO
DOES ICE OCCUR IN THIS REACH?
YES
J
19
NO
IS THIS REACH PART OF THE SOUTH SHORE CANAL?
YES
SET 2-WAY TRAFFIC SHIP MANEUVERING WIDTH TO ONE-HALF THE SHIP'S BEAM
SET 1-WAY TRAFFIC SHIP MANEUVERING WIDTH TO ONE-HALF THE SHIP'S BEAM
5
NO
IS THIS REACH 1-WAY DUE TO SEAWAY REGULATIONS?
YES
YES
DOES THE TOTAL SHIP MANEUVERING WIDTH EXCEED THE REACH CHANNEL WIDTH?
NO
THIS REACH IS A ONE-WAY REACH. CALCULATE TIME TO TRANSIT THIS REACH.
SET SUM = 0.0
CAP = ΔT/T_LOCK
CONREA = NREACH
5
7


J
19
NO
IS REACH ON-WAY BY SEAWAY REGULATIONS ?
YES
NO
IS THIS REACH A DYNAMIC REACH?
YES
CALCULATE SHIP MANEUVERING WIDTH FROM STEADY STATE EQUATIONS OF MOTION
CALCULATE SHIP MANEUVERING WIDTH FROM UNSTEADY STATE EQUATIONS OF MOTION
NO
DOES THE TOTAL SHIP MANEUVERING WIDTH EXCEED THE REACH CHANNEL WIDTH ?
YES
SET SUM = 0.0
CAP = ΔT/T_LOCK
CONREA = NREACH
7
IS THIS REACH A DYNAMIC REACH?
CALCULATE SHIP MANEUVERING WIDTH FROM STEADY STATE EQUATIONS OF MOTION
CALCULATE SHIP MANEUVERING WIDTH FROM UNSTEADY STATE EQUATIONS OF MOTION
5
K


K
DOES THE TOTAL SHIP MANEUVERING WIDTH EXCEED THE REACH CHANNEL WIDTH FOR DOWNBOUND TRAFFIC ?
YES
NO
DOES THE TOTAL SHIP MANEUVERING WIDTH EXCEED THE REACH CHANNEL WIDTH FOR UPBOUND TRAFFIC ?
YES
NO
DOES THE TOTAL SHIP MANEUVERING WIDTH EXCEED THE REACH CHANNEL WIDTH FOR UPBOUND TRAFFIC ?
YES
NO
CAPACITY FOR THIS TIME PERIOD IS ZERO. CONSTRAINING REACH IS EQUAL TO NREACH.
CALCULATE SUM USING UPBOUND SHIP SPEED
CALCULATE SUM USING DOWNBOUND SHIP SPEED
CALCULATE SUM USING A WEIGHTED AVERAGE OF THE UPBOUND AND DOWNBOUND SHIP SPEEDS
8
4
20
IS THE TIME TO TRANSIT SEQUENTIAL 1-WAY REACHES GREATER THAN THE LOCKAGE TIME FOR 2-WAY TRAFFIC ?
NO
YES
CAP= ΔT/T LOCK
CONREA = 54
CAP= ΔT/T LOCK + T TURN BACK
CONREA = 71
7
L


L
21
THE CAPACITY FOR A GIVEN TIME PERIOD IS THE MINIMUM VALUE OF THE REACH CAPACITIES
2
NO
IS THIS THE LAST REACH ?
YES
WRITE CAPACITY RESULTS
22
1
NO
IS THIS THE LAST DAILY TIME PERIOD ?
YES
3
NO
IS THIS THE LAST DAY OF THE YEAR ?
YES
23
9
NO
IS THIS THE LAST YEAR ?
YES
STOP

3. RESULTS

3.1 Seaway Capacity as a Function of Navigational System Positioning Accuracy

As stated in the INTRODUCTION, the purpose of this study was to develop and define navigational guidance system performance requirements which will allow improvement in the Capacity of the Seaway. One key requirement of such a guidance system would be its positioning accuracy and therefore this was one of the first parameters studied.

A series of runs were made with the Capacity Computer Program to specifically determine the effect of positioning accuracy on capacity. The SALTY type ship was selected for these runs. The ship speed was set to the speed limit at all times and it was assumed that no time was lost due to ice lockages in these runs. The results are shown in tabular form in Table 3.1 and graphical form in Figure 3.1*. All percentages used refer to a percent increase in capacity over the Seaway capacity during all-year navigation of the Seaway when no navigational guidance system is employed. Several items of interest will be pointed out in these results. First, it should be noted that the maximum percentage increase in capacity is about 30 percent and reduces to zero around an accuracy of 300+ feet. Notice also that there is essentially no difference in the 0-foot and 30-foot accurate system capacities. It should also be noticed that a large percentage of the total yearly increase in capacity comes from the significant increase during the extended season. This is undoubtedly due to the fact that the lighted, floating, navigational aids are not in the Seaway during most of the extended season.

Table 3.2 shows the number of time intervals a particular non-lock reach constrained capacity (reduced it to zero) as a function of the positioning accuracy. Note that this data is for study year No. 3. Notice also that under the 0-foot and 30-foot accurate systems, the non-lock reaches never constrain traffic. With the 60-foot accurate system, only Reach No. 44 appears to be constraining. However, the Capacity Computer Program checks reaches in ascending numerical order and for efficiency purposes checks no further once the capacity is determined to be zero. This means that if Reach No. 44 were changed to have an accuracy of 30-feet while all others remained at 60-feet, all we can be certain of is that Reach No. 44 will no longer constrain the 111 ships. We would not know until we made such a run if reaches further upstream would constrain these 111 ships during those time intervals when Reach 44 was constraining.

Figure 3.2 shows the effect on percent improvement in Seaway capacity of the ships' speeds varying with visibility as described in Section 2.3. The tabular results of these runs are given in Table 3.3 and the frequency analysis of the number of time intervals a non-lock reach constrained capacity is given in Table 3.4. The percent improvement in Seaway Capacity does not appear to be greatly affected by the requirement that the ships proceed at a speed which would allow them to stop within 1/2 the distance of visibility.

(Text Continued on Page 71)

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*Figure 3.1 also appears in the text as Figure 1.2.

TABLE 3.1 SALTY SEAWAY CAPACITY AS A FUNCTION OF NAVIGATIONAL SYSTEM POSITIONING ACCURACY

RUN		CAPACITY								
Salty Class Ship $T_{ice\ lock}=0$ $V_{ship} = V_{speed\ limit}$		NORMAL			EXTENDED			ALL YEAR		
Year	Condition	Yearly	4 yr avg	% Increase Over 4 yr avg	Yearly	4 yr avg	% Increase Over 4 yr avg	Yearly	4 yr avg	% Increase Over 4 yr avg
1	No electronic navigation aids	8131	8059	NA	1762	1636	NA	9893	9695	NA
2		8163			1723			9886		
3		8227			1631			9858		
4		7715			1428			9143		
1	0'	9555	9564	18.7	3134	3017	84.4	12689	12581	29.8
2		9586			3019			12605		
3		9557			3035			12592		
4		9558			2881			12439		
1	30'	9541	9557	18.6	3129	3016	84.4	12670	12573	29.7
2		9581			3020			12601		
3		9550			3035			12585		
4		9555			2881			12435		
1	60'	9257	9202	14.2	2934	2912	78.0	12191	12114	25.0
2		9286			2895			12181		
3		9188			2938			12126		
4		9078			2880			11958		
1	100'	9066	9025	12.0	2748	2752	68.2	11814	11777	21.5
2		9133			2767			11900		
3		9072			2768			11840		
4		8829			2724			11553		
1	150'	8918	8813	9.4	2709	2672	63.3	11627	11485	18.5
2		8887			2642			11529		
3		8875			2667			11542		
4		8572			2670			11242		

TABLE 3.1 SALTY SEAWAY CAPACITY AS A FUNCTION OF NAVIGATIONAL SYSTEM POSITIONING ACCURACY (Continued)

R U N		C A P A C I T Y								
Salty Class Ship $T_{ice\ lock}=0$ $V_{ship}=V_{speed\ limit}$		NORMAL			EXTENDED			ALL YEAR		
Year	Condition	Yearly	4 yr avg	% Increase Over 4 yr avg	Yearly	4 yr avg	% Increase Over 4 yr avg	Yearly	4 yr avg	% Increase Over 4 yr avg
1	200'	8711	8524	5.8	2470	2205	34.8	11181	10729	10.7
2		8605			2216			10821		
3		8586			2131			10717		
4		8194			2003			10197		
1	250'	8554	8434	4.7	1930	1789	9.4	10484	10223	5.4
2		8537			1863			10400		
3		8573			1754			10327		
4		8072			1609			9681		
1	300'	8462	8325	3.3	1771	1661	1.5	10233	9986	3.0
2		8409			1761			10170		
3		8499			1656			10155		
4		7930			1456			9386		

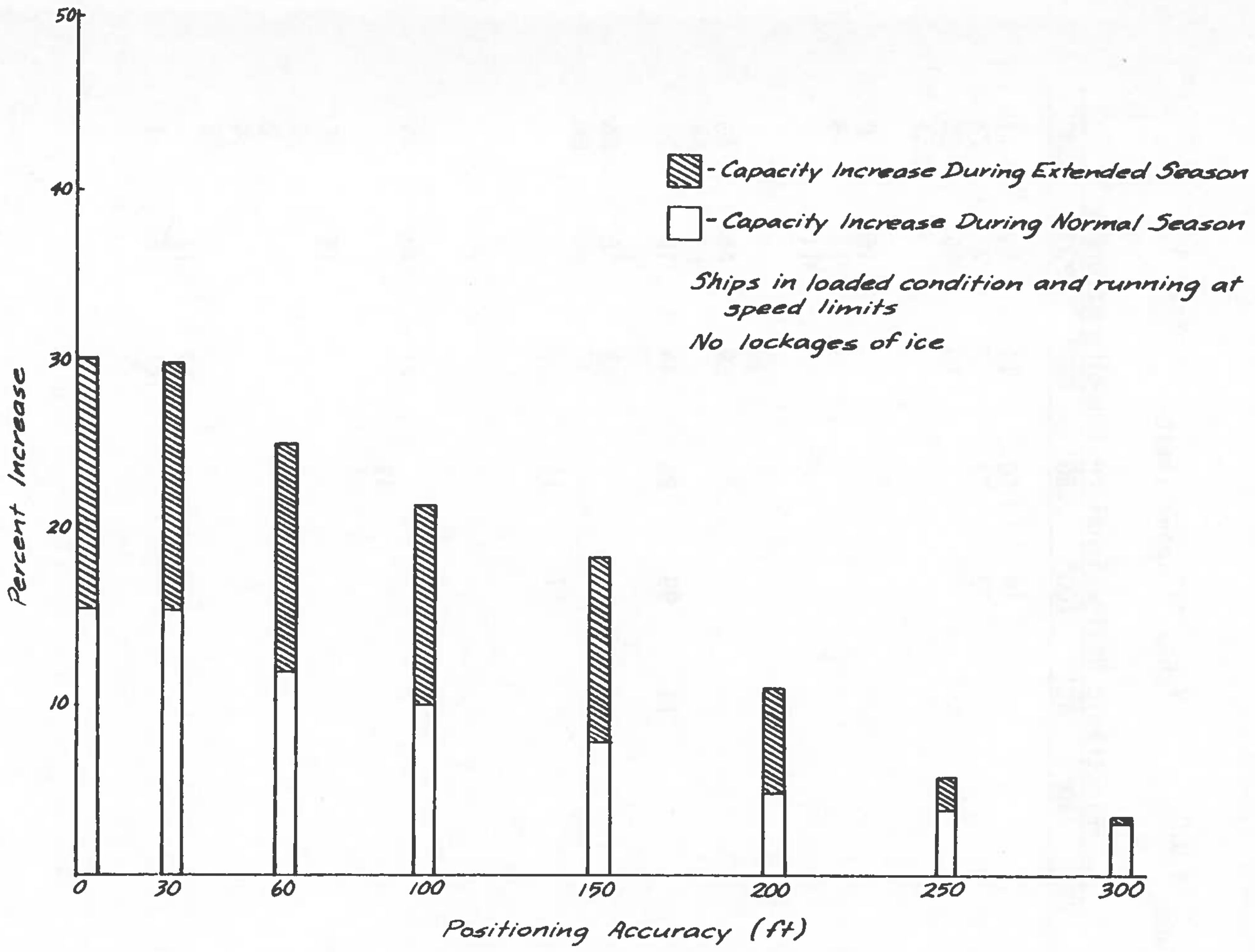

Figure 3.1. Percentage Increase in Seaway Capacity for Salty Class Ships with Various Positioning Accuracies of the Navigational Guidance System Based on All-year Navigation of the Seaway

TABLE 3.2 FREQUENCY ANALYSIS OF NUMBER OF TIME INTERVALS A NON-LOCK REACH CONSTRAINED SALTY SEAWAY CAPACITY

Salty, Loaded $T_{ice\ lock} = 0.0$ $V_{ship} = V_{speed\ limit}$ Year 3

Constraining Reaches	No Elec Nav-Aid	Electronic Navigational Positioning Accuracy							
		0'	30'	60'	100'	150'	200'	250'	300'
1	14				14	14	14	14	14
20	77				77	77	77	77	77
21	25						10	25	25
22	251								251
24	57								
26								16	8
27								13	5
34								211	
37	6								
39							94		
42	41						59	44	43
43	59							68	65
44	19			111	99	99	44	10	19
47							6		
48	56						62	56	56
50	56						77	66	66
56					11	11			
73	4								
80	70								
81	49								
83	2								
84	3						51	39	35
85						33			
86						24			
87								16	16
88	6								20
89	2								2
90	5								14
92									20
93							17	17	
95							21	5	1
100	24								

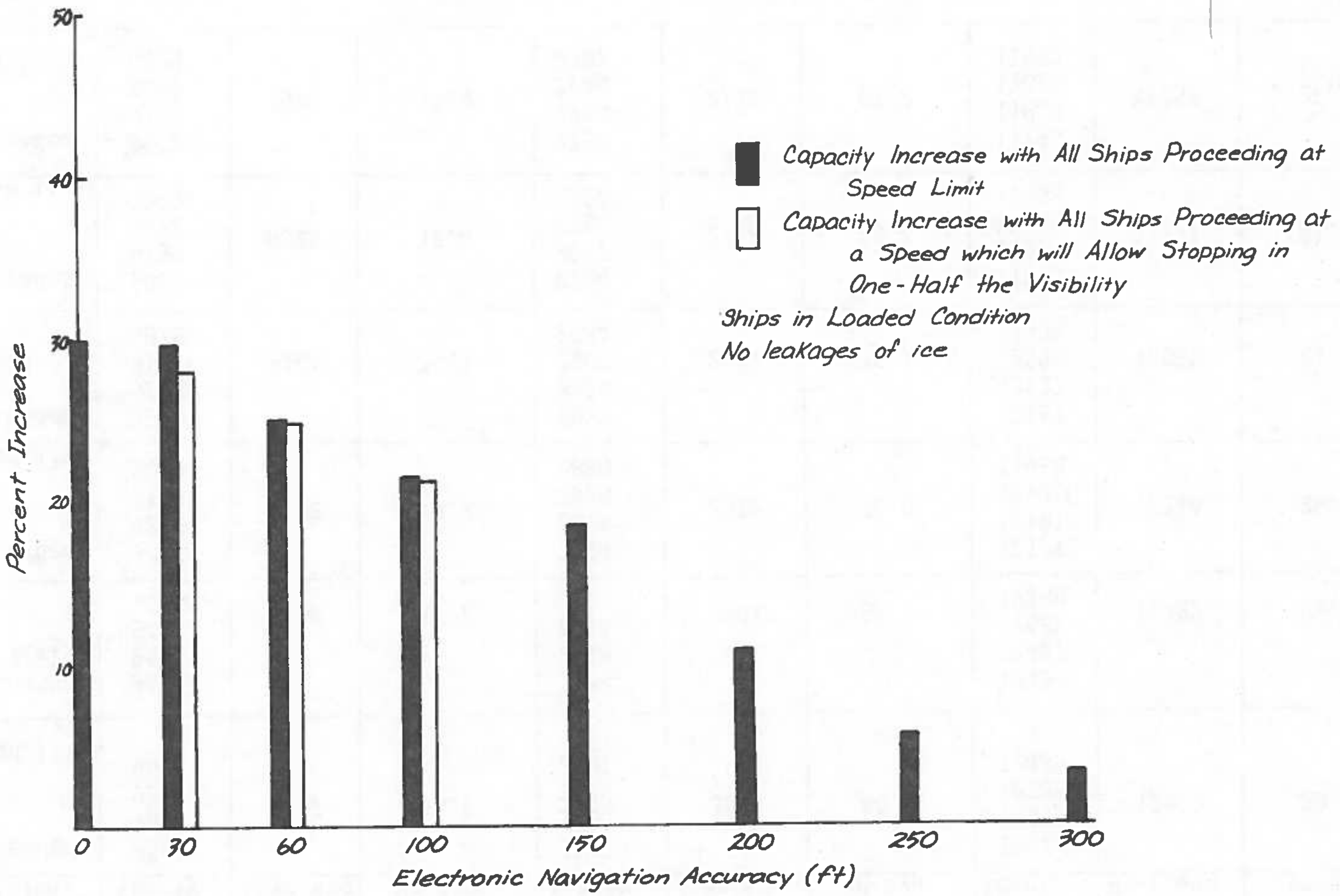

Figure 3.2. Percent Increase in Seaway Capacity for Salty Class Ships with Various Positioning Accuracies of the Navigational Guidance System Based on All-year Navigation of the Seaway Showing Effect of Different Speed Rules

TABLE 3.3 SALTY SEAWAY CAPACITY AS A FUNCTION OF SHIP SPEED ASSUMPTION

RUN		CAPACITY								
$T_{ice\ lock} = 0$		NORMAL			EXTENDED			ALL YEAR		
Year	Condition	Yearly	4 yr avg	% Increase Over yr avg	Yearly	4 yr avg	% Increase Over yr avg	Yearly	4 yr avg	% Increase Over yr avg
1 2 3 4	Salty, Loaded 30' $V = V_{speed\ limit}$	9541 9581 9550 9555	9557	18.6	3129 3020 3035 2881	3016	84.4	12670 12601 12585 12435	12573	29.7
1 2 3 4	Salty, Loaded $V_{ship} = f(VIS)$ 30'	9421 9481 9438 9426	9442	17.2	3078 2986 2994 2864	2981	82.2	12499 12467 12432 12289	12422	28.1
1 2 3 4	Salty, Loaded 60' $V = V_{speed\ limit}$	9257 9286 9188 9078	9202	14.2	2934 2895 2938 2880	2912	78.0	12191 12181 12126 11958	12114	25.0
1 2 3 4	Salty, Loaded 60' $V = f(VIS)$	9250 9263 9187 9075	9194	14.1	2917 2874 2907 2864	2891	76.7	12167 12137 12095 11939	12085	24.7
1 2 3 4	Salty, Loaded 100' $V = V_{speed\ limit}$	9066 9133 9072 8829	9025	12.0	2784 2767 2768 2724	2752	68.2	11814 11900 11840 11553	11777	21.5
1 2 3 4	Salty, Loaded 100' $V = f(VIS)$	9062 9115 9072 8829	9020	11.9	2734 2753 2748 2707	2736	67.2	11796 11868 11820 11537	11755	21.2

TABLE 3.4 FREQUENCY ANALYSIS OF NUMBER OF TIME INTERVALS A NON-LOCK REACH CONSTRAINED SALTY SEAWAY CAPACITY SHOWING EFFECT OF SHIP SPEED ASSUMPTION

Salty, Loaded Year 3 $T_{ice\ lock} = 0.0$

Constraining Reach	No Elec Nav-Aid	Electronic Navigation Positioning Accuracy					
		$V_{ship} = f(\text{VISIBILITY})$			$V_{ship} = V_{speed\ limit}$		
		30'	60'	100'	30'	60'	100'
1	14	6	6	14			14
20	77			77			77
21	25						
22	251						
24	57						
26							
27							
34							
37	6						
39							
42	41	8	8	6			
43	59						
44	19	12	105	95		111	99
47							
48	56						
50	56						
56		2		11			11
73	4						
80	70	11	11	7			
81	49						
83	2						
84	3						
85							
86							
87							
88	6						
89	2						
90	5						
92							
93							
95							
100	24						

An analysis of the improvement in Seaway Capacity as a function of positioning accuracy was also made for the LAKER class ship. This analysis was similar to the SALTY class analysis only briefer in that fewer accuracies were run. The results are listed in Tables 3.5 and 3.6. A graph of the results is given in Figure 3.3. It can be seen that in general the Seaway Capacity is reduced with the LAKER class ship. This is due to its greater length requiring greater maneuvering widths. On a percentage basis, however, the navigational guidance system appears to give almost identical improvements in the Seaway Capacity.

An analysis of the improvement in Seaway Capacity as a function of loading condition of the two study ships was also made. The results are shown in Tables 3.7 and 3.8. It appears from these results that the improvements to capacity are not significantly affected by the loading condition of the ships.

One overall result of this "capacity versus accuracy" analysis is that no one positioning accuracy stands out as being "best" for the Seaway. One logical method of selecting the "best" positioning accuracy would be to conduct a cost/benefit study using these capacity versus accuracy results as a data base. This could be done in a manner similar to that used in the SPAN study [1] and could be conducted as follows. The dollar benefits to be derived from the increased capacities associated with each positioning accuracy would be estimated. Next, the dollar cost of the system required to produce each positioning accuracy would be estimated. Finally, the benefit/cost ratio and/or net worth of the system for each positioning accuracy would be determined and the accuracy selected which gave the largest benefit/cost ratio or largest net worth. The conduct of a benefit/cost study was not included in the scope of work for this study. Therefore, we selected a positioning accuracy of ±100-feet based on the following reasoning. The most accurate system consistent with existing technology should be employed as the capacity increases as the positioning accuracy improves. Positioning accuracies in the order of ±100-feet are achievable and may be better than this in certain reaches by careful location of guidance system equipment. With ±100-foot positioning accuracy system, Reaches No. 20, 44, and 45 appear to be the major constraining reaches and therefore guidance equipment required to cover these reaches appears to be consistent with the probable number of monitors that would be employed in the Saint Lawrence System.

Additional runs were made with the Capacity Computer Program to determine the probable effect on capacity of a guidance system with 100-foot positioning accuracy along the Seaway except in certain reaches where the accuracy might be improved through location of guidance system equipment. The results showed that if Reaches No. 1, 20 and 56 could be made to have a 60-foot positioning accuracy and Reach No. 44 a 30-foot positioning accuracy, then the capacity could be made almost equal to that associated with a guidance system having 60-foot positioning accuracy in all reaches. The results of these runs are shown in Table 3.9.

This concludes the analysis of Seaway Capacity as a function of Navigational System Positioning Accuracy. The next section will address the remaining Navigational System Performance Requirements.

(Text Continued on Page 78)

TABLE 3.5 LAKER SEAWAY CAPACITY AS A FUNCTION OF NAVIGATIONAL SYSTEM POSITIONING ACCURACY

RUN		CAPACITY								
$T_{ice\ lock} = 0$		NORMAL			EXTENDED			ALL YEAR		
Year	Condition	Yearly	4 yr avg	% Increase Over 4 yr avg	Yearly	4 yr avg	% Increase Over 4 yr avg	Yearly	4 yr avg	% Increase Over 4 yr avg
1	Laker, Loaded No Electronic Navigational Aids	7462	7396	-	1645	1531	-	9107	8927	-
2		7490			1613			9103		
3		7550			1527			9076		
4		7081			1340			8421		
1	Laker, Loaded $V=V_{speed\ limit}$ 30'	8751	8764	18.5	2915	2819	84.1	11666	11583	29.7
2		8785			2821			11606		
3		8757			2836			11592		
4		8761			2702			11463		
1	Laker, Loaded $V_{ship} = f(VIS)$ 30'	8639	8639	16.8	2868	2785	81.9	11507	11424	28.0
2		8693			2790			11483		
3		8622			2797			11419		
4		8600			2686			11286		
1	Laker, Loaded $V = V_{speed\ limit}$ 60'	8492	8439	14.1	2736	2723	77.9	11228	11162	25.0
2		8515			2707			11222		
3		8426			2745			11172		
4		8323			2702			11025		
1	Laker, Loaded $V_{ship} = f(VIS)$ 60'	8486	8431	14.0	2720	2703	76.6	11206	11134	24.7
2		8493			2688			11182		
3		8425			2716			11141		
4		8320			2686			11006		
1	Laker, Loaded $V = V_{speed\ limit}$ 100'	8325	8293	12.1	2565	2574	68.1	10889	10867	21.7
2		8393			2588			10980		
3		8333			2588			10922		
4		8119			2555			10674		
1	Laker, Loaded $V_{ship} = f(VIS)$ 100'	8321	8287	12.0	2551	2558	67.1	10872	10845	21.5
2		8375			2574			10949		
3		8333			2567			10900		
4		8119			2539			10658		

TABLE 3.6 FREQUENCY ANALYSIS OF NUMBER OF TIME INTERVALS A NON-LOCK REACH CONSTRAINED LAKER SEAWAY CAPACITY SHOWING EFFECT OF SHIP SPEED ASSUMPTION

Laker, Loaded Year 3 $T_{ice\ lock} = 0.0$

Constraining Reach	No Elec Nav-Aid	Electronic Navigation Positioning Accuracy $V_{ship} = f(\text{VISIBILITY})$ 30'	 60'	 100'	 $V_{ship} = V_{speed\ limit}$ 30'	 60'	 100'
1	14	6	6	14			14
20	77			77			77
21	25						
22	251						
24	57						
29						6	
37							
42	41	8	8	6			
43	59						
44	19	23	105	95		111	99
48	56						
50	56	2					
56				11			11
73	4						
80	70	11	11	7			
81	49						
83	2						
84	3						
88	6						
89	2						
90	5						
100	24						

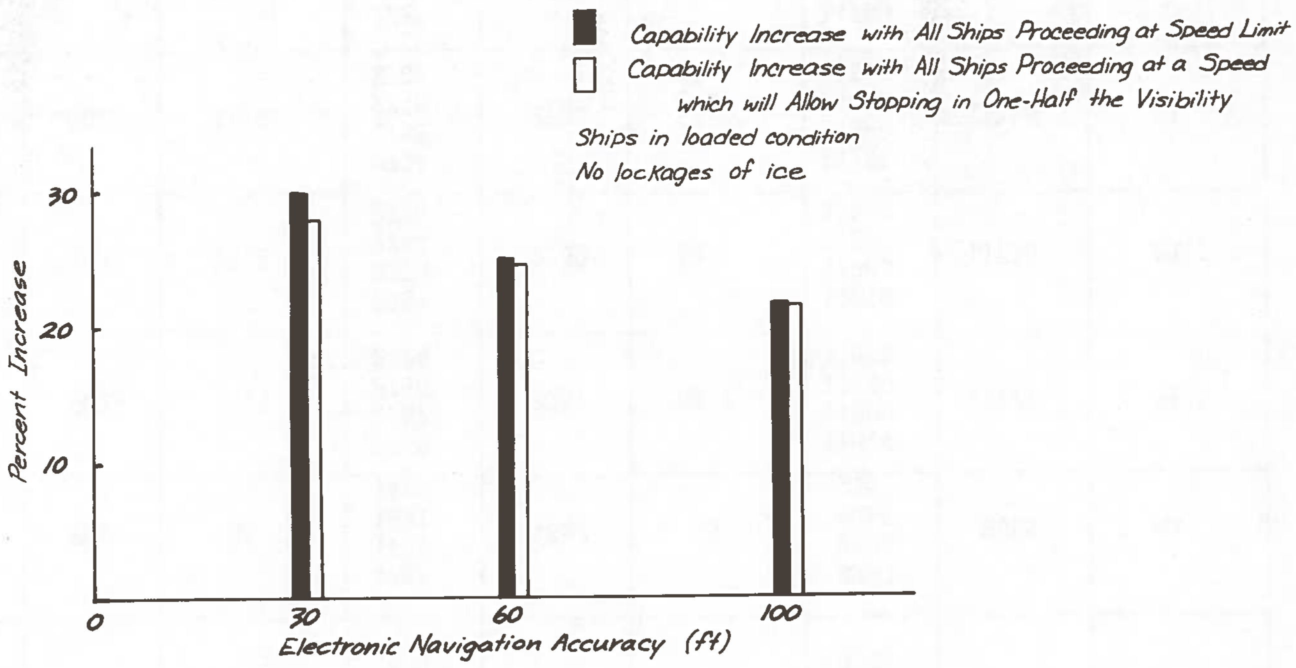

Figure 3.3. Percentage Increase in Seaway Capacity for Laker Class Ships with Various Positioning Accuracies of the Navigational Guidance System Based on All-year Navigation of the Seaway

TABLE 3.7 SALTY SEAWAY CAPACITY AS A FUNCTION OF LOADING CONDITION

RUN		CAPACITY								
$T_{ice\ lock} = 0$		NORMAL			EXTENDED			ALL YEAR		
Year	Condition	Yearly	4 yr avg	% Increase Over 4 yr avg	Yearly	4 yr avg	% Increase Over 4 yr avg	Yearly	4 yr avg	% Increase Over 4 yr avg
1 2 3 4	Salty, Loaded No electronic navigation aids	8131 8163 8227 7715	8959	NA	1762 1723 1631 1438	1636	NA	9893 9886 9858 9143	9695	NA
1 2 3 4	Salty, Ballast No electronic vavigation	8131 8163 8225 7715	8059	NA	1762 1727 1631 1428	1637	NA	9893 9890 9856 9143	9696	NA
1 2 3 4	Salty, Loaded $V = V_{speed\ limit}$ 100'	9066 9133 9072 8829	9025	12.0	2748 2767 2768 2724	2752	68.2	11814 11900 11840 11553	11777	21.5
1 2 3 4	Salty, Ballast 100' $V = V_{speed\ limit}$	9065 9133 9070 8829	9024	11.9	2751 2770 2764 2724	2752	68.1	11816 11903 11834 11553	11776	21.5
1 2 3 4	Salty, Loaded 100' V = f(VIS)	9062 9115 9072 8829	9020	11.9	2734 2753 2748 2707	2736	67.2	11796 11868 11820 11537	11755	21.2
1 2 3 4	Salty, Ballast 100' V = f(VIS)	9061 9115 9070 8829	9019	11.9	2737 2757 2744 2707	2736	67.1	11798 11872 11814 11536	11755	21.2

TABLE 3.8 LAKER SEAWAY CAPACITY AS A FUNCTION OF LOADING CONDITION

RUN		CAPACITY								
		NORMAL			EXTENDED			ALL YEAR		
Year	Condition	Yearly	4 yr avg	% Increase Over 4 yr avg	Yearly	4 yr avg	% Increase Over 4 yr avg	Yearly	4 yr avg	% Increase Over 4 yr avg
1 2 3 4	Laker, Loaded No Electronic Navigation Aids	7462 7490 7550 7081	7396	NA	1645 1613 1627 1340	1531	NA	9107 9103 9076 8421	8927	NA
1 2 3 4	Laker, Ballast No Electronic Navigation Aids	7462 7490 7550 7081	7396	NA	1645 1615 1526 1340	1532	NA	9107 9105 9076 8421	8928	NA
1 2 3 4	Laker, Loaded $V=V_{\text{speed limit}}$ 100'	8325 8393 8333 8119	8293	12.1	2565 2588 2588 2555	2574	68.1	10889 10980 10922 10674	10867	21.7
1 2 3 4	Laker, Ballast $V=V_{\text{speed limit}}$ 100'	8325 8392 8334 8119	8293	12.1	2567 2591 2587 2555	2575	68.1	10892 10983 10921 10674	10868	21.7
1 2 3 4	Laker, Loaded $V = f(VIS)$ 100'	8321 8375 8333 8119	8287	12.0	2551 2574 2567 2539	2558	67.1	10872 10949 10900 10658	10845	21.5
1 2 3 4	Laker, Ballast $V = f(VIS)$ 100'	8321 8375 8334 8118	8287	12.0	2554 2577 2568 2539	2560	67.1	10875 10952 10902 10657	10847	21.5

TABLE 3.9 SEAWAY CAPACITY FOR A SYSTEM WITH 100-FOOT ACCURACY EXCEPT IN REACHES NOTED

RUN		CAPACITY								
Salty, Loaded		NORMAL			EXTENDED			ALL YEAR		
Year	$V = V_{\text{speed limit}}$ Condition	Yearly	4 yr avg	% Increase Over 4 yr avg	Yearly	4 yr avg	% Increase Over 4 yr avg	Yearly	4 yr avg	% Increase Over 4 yr avg
1 2 3 4	Reach Accuracy 1 60 ft 20 60 ft 44 30 ft 56 60 ft others 100 ft	9375 9432 9402 9354	9391		3041 2973 2996 2881	2973		12416 12405 12397 12235	12364	27.5

3.2 Navigational System Performance Requirements

The previous Section 3.1 dealt with the development and definition of one of the key requirements for a navigational guidance system; i.e, the accuracy of the positioning information made avilable to the ship's master. This section will deal with type and frequency of other information required and place this in the form of a guidance system performance specification.

The work discussed in Section 2.3 concerning the development of the rudder control law provided a background for developing the system performance requirements. It was found during this work that stable control of the study ships could not be effected by adjusting rudder angle on heading only, off-track position only, or on a combination of only these two variables. It was found, however, that stable control could be effected if only heading angle and rate of change of heading angle were used to command the rudder. Of course, the rudder angle must also be adjusted according to the off-track position error if the ship is to return to a desired track once it has been knocked off due to external disturbances. Introduction of the off-track position into the rudder control law, however, degrades the system stability and hence must be compensated for by increasing the heading and heading rate gains or by introducing cross track velocity gain.

Armed with this knowledge, an investigation was conducted to determine what feedback data rates on the variables used in the control law could be tolerated without loss of control of the ship. The maneuvering simulator was used for this investigation and a simulated voyage through the Pollys Gut reach (Reach No. 50) was selected because it is considered to be representative of the three "DYNAMIC" reaches. The investigation was carried out in two steps. In the first, the feedback interval was varied from 0.1 seconds to 180 seconds for all four variables in the rudder control law. Computations were handled as follows. As the ship passed through the reach, a rudder angle was computed based on the last update for all four variables. The rudder was then held at this value until a new rudder angle could be computed from the next update on the four variables. The results are shown in Table 3.10, Case 1. These results show the maximum excursions experienced during the run as a function of the data update rate interval. The 0.1 second update rate can be considered continuous for practical purposes and therefore forms a basis for comparison with the other update rates. It can be observed that update rates of up to 60 seconds could be tolerated without loss or significant degrading of control.

In the second step of the investigation, it was assumed that heading and heading rate data was continuously available and that only off-track position and cross track velocity information would be updated at various update rates. This assumption is based on the belief that all masters have this information currently available to them via the gyro compass repeater on the bridge. That is, as the ship swings in the water, the heading error and rate of change of headings are mentally "computed" and used by the master to formulate his rudder commands. The results are also shown in Table 3.10, Case 2. It will be noted that in this case update rates in the range of the study did

TABLE 3.10 MAXIMUM EXCURSIONS AT POLLYS GUT WITH DATA RATES ON CONTROL VARIABLES

DATA RATE	MAXIMUM EXCURSION CASE 1	 CASE 2
0.1 sec.	196.3 ft.	196.3 ft.
1	196.8	196.4
2	197.0	196.6
5	197.7	197.4
10	198.8	198.6
20	201.0	201.0
40	205.1	205.3
60	206.2	208.6
120	384.3	217.9
180	892.6	211.5

NOTES:

CASE 1 - Heading, Rate of Change of Heading, Off Track Position Cross Track Velocity are Updated at Indicated Data Rate

CASE 2 - Heading and Rate of Change of Heading are Updated Continuously
- Off Track Position and Cross Track Velocity are Updated at Indicated Data Rate

SHIP SPEED is 12 mph for all cases.

not produce any loss of control and the maximum excursion is only 11% greater than that with continuous updating of these two variables.

It thus appears from this investigaion that update rates of the four key control variables in the order of one minute could be tolerated without degrading the control over the ship. Selection of these update rates will therefore be deferred until the method of display is presented and discussed.

Several members of the ARCTEC staff have handled ships in water similar to the study section of the St. Lawrence River under simulated low visibility conditions and have trained in ship maneuvering simulators. These staff members were therefore used to assist with the preparation of the display requirements. A sketch of the recommended display for use by the ship's operator is shown in Figure 3.4.* The display can be oriented such that north is always up or the direction of travel is always up. The operator's ship is shown in full so as to be distinguished from other ships shown in outline. The length and beam of the ships are shown to scale and a heading cursor equal to two ship lengths shows the heading of the ship. The channel centerline is marked by a solid line and the channel boundaries by dotted lines. Numerically displayed in the upper left corner is the distance of the operator's ship off-track (OFF: 15 FT R), the speed of the ship over the ground and the course being made good (SPD: 6.2 MPH, 004°), the next turn point distance (NTPD: 2.1 MI), the next turn point time (NTPT: 1 HR 20 M 30 S), and the scale of the graphic display (SCALE: 1 IN - 1,000 FT).

The position and orientation of the ship is updated periodically. The last two positions and orientations of the ship are also displayed except these images are shown in medium and low brightness to contrast them against the current image which is shown bright. By displaying current and past images of the ship and the true dimensions of the ship and channel boundaries, the operator should be provided with sufficient information on heading error, rate and direction of change of heading, position error and cross channel speed and direction, to maintain control over his ship and safely navigate it through the Seaway under conditions of low visibility. The ships move across the screen in this display. The operator may select any of five scales ranging from a very large coverage (1 in = 1,600 ft) to a very small coverage (1 in = 200 ft). When the operator's ship reaches the end of the screen, the display automatically shifts to a new display. The operator may also perform such a shift manually at any time.

It is important to point out that the workability of this display is a matter of opinion. It is our opinion that a prudent master could be trained to use such a display for successful navigation of his ship under low visibility conditions. However, this would have to be demonstrated and acceptance by the various pilots and masters of vessels operating in the Seaway would depend on verification of the workability of the display and its reliability. Most pilots and masters are taught not to trust electronic equipment because it is subject to errors and breakage. Consequently, the reliability of the displayed information is of utmost importance to its acceptability by these operators.

The rate at which the position and orientation of the ship is updated must be consistent with the data processor speed and the needs of the master.

*Figure 3.4 also appears as Figure A-1.

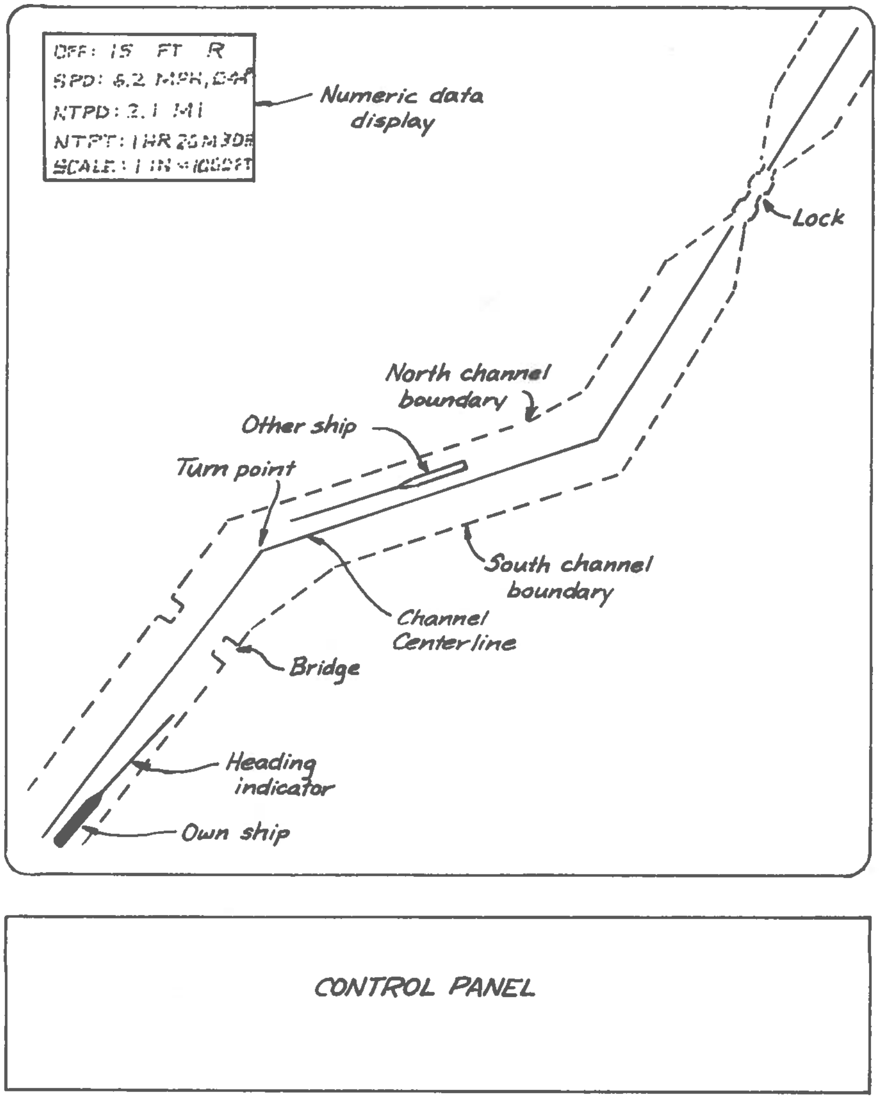

Figure 3.4 Sketch of Recommended Display for Operation

The master will have three images of the ship to use in estimating the rate of change of heading and off-track position. Thus an update rate of x seconds will require 3x seconds before the master can estimate these variables. The update rate should be as small as possible but still provide time for fade out of past images. An update rate of 5 seconds appears reasonable considering both processor speed and image fade out time.

Whether or not the other ships should be displayed is important to discuss. In our opinion, no prudent master would ever navigate his ship under low visibility conditions without precise knowledge of oncoming ships. However a master probably would navigate under these conditions provided he was assured that he would not meet ships coming in the opposite direction and that no ships were allowed to overtake another ship.

To test the effect of not displaying other ship information on the increase in capacity, the Capacity Computer Program was modified such that when the navigation guidance system was required to be used, only one way navigation was allowed. A run was then made assuming a 0-foot accurate system. Table 3.11 compares these results with the runs in which no guidance system is available and a 0-foot accurate guidence system which displays other ships. It can be seen that the percent improvement in all year capacity is decreased from 29.8% to 22.6% when only the own ship is displayed.

Appendix A contains the Navigation Guidance System Performance Specifications prepared during this study. The document is self explanatory and will not be repeated in this section. However, it should be pointed out that in this document we envisioned a display unit and associated processor that would be portable by one man. This was based on the belief that these units might be expensive and therefore would be taken aboard the ships at one end of the Seaway and removed at the other. Since this study did not look at the costs or benefits of employing a navigation guidance system, this may not be the best approach. Indeed, as was pointed out in Section 3.1, such decisions might best be made on the basis of cost/benefit analyses conducted along the lines suggested in that section to make a final decision on system accuracy. Such an analysis could also be applied to help with the decision on whether or not other ship information should be displayed.

This concludes the section on results and this report. The Appendices provide the computer programs used to generate the results used in this report. These programs can readily be used or converted to produce additional data not required by the scope of work for this study.

APPENDIX A

NAVIGATION GUIDANCE SYSTEM PERFORMANCE SPECIFICATION

APPENDIX A

NAVIGATION GUIDANCE SYSTEM
PERFORMANCE SPECIFICATION

FOR THE

SAINT LAWRENCE SEAWAY

BETWEEN

LAKE ONTARIO AND MONTREAL, QUEBEC

I. INTRODUCTION

The purpose of this document is to describe the requirements of a guidance system which will enable ship movement on the St. Lawrence Seaway (between Lake Ontario and Montreal, Quebec) during periods of low visibility and at night when floating, lighted aids to navigation have been removed from the Seaway. The requirements are based on a detailed study of all factors which affect ship movement in, and the ship processing capacity of, the Seaway.

The document does not explain how to achieve the requirements; however the guidance system envisioned in this specification would consist of the following:

- A radio location system capable of providing position fixes to each ship within the Seaway
- A shipboard receiver compatible with the above system
- A data processing display system capable of providing to a ship operator such information as is necessary for the safe navigation of the ship through the Seaway
- A radio communication system capable of transmitting the ship position to the appropriate Seaway station and capable of receiving the position of other ships from the Seaway station.

II. OVERVIEW OF SYSTEM

A sketch of the display required for use by the operator of a ship is shown in Figure A-1.[*] A hypothetical picture is shown and the various data displayed is identified for discussion purposes. The graphic display can be oriented such that north is always up or the direction of travel is always up. The operator's ship is shown in full so as to be distinguished from other ships shown in outline. The length and beam of the ships are shown to scale and a heading cursor equal to two ship lengths shows the heading of the ship. The channel centerline is marked by a solid line and the channel boundaries by dotted lines. Numerically displayed in the upper left corner is the distance of the operator's ship off-track (OFF: 15 FT R), the speed of the ship over the ground and the course being made good (SPD: 6.2 MPH, 004°), the next turn point distance (NTPD: 2.1 MI), the next turn point time (NTPT: 1 HR 20 M 30 S), and the scale of the graphic display (SCALE: 1 IN = 1,000 FT).

The position and orientation of the ship is updated every 5 seconds. The last two positions and orientations of the ship are also displayed except these images are shown in medium and low brightness to contrast them against the current image which is shown bright. By displaying current and past images of the ship and the true dimensions of the ships and channel boundaries the operator is provided with sufficient information (heading error, rate of change of heading, position error and cross channel ship velocity) to safely guide his ship through the Seaway.

The ships move across the screen. The operator may select any of five scales for the display ranging from a very large coverage (1 in = 2,000 ft) to a very small coverage (1 in = 200 ft). When the operator's ship moves to within 15 percent of the end of the screen, the display automatically shifts to a new display. The operator may also perform such a shift manually at any time.

[*] Figure A-1 also appears in the text as Figure 3.4.

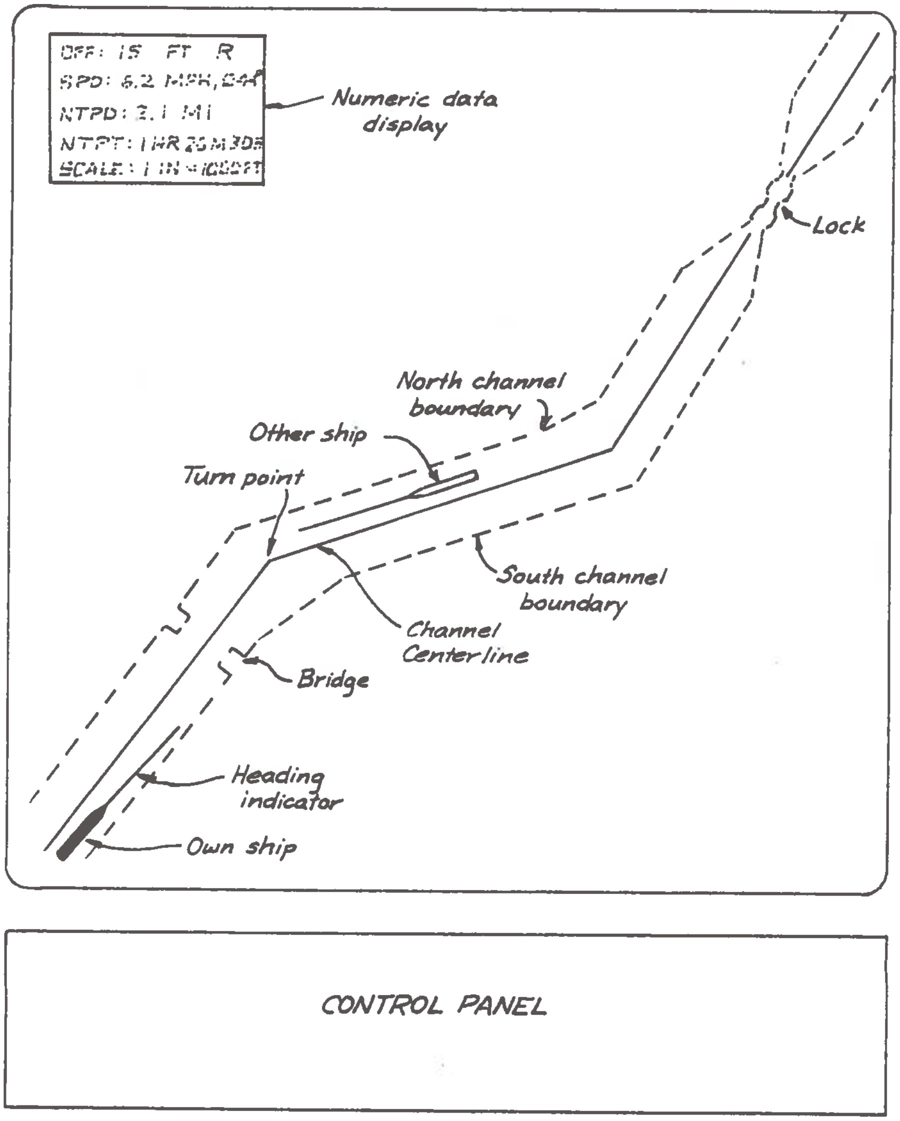

Figure A-1. *Sketch of Recommended Display for Operation*

III. VARIABLE TO BE MEASURED

The guidance system must be capable of measuring the variables listed in Table 1 over the specified range, within the accuracy and at the rates given.

TABLE A-1. VARIABLES TO BE MEASURED

Variable	Units[3]	Range[3]	Accuracy[1]	Measurement[4] Rate
Receiver Latitude	deg-min-sec	44°00'-45°35'N	± 100 ft[2]	5 s
Receiver Longitude	deg-min-sec	73°30'-76°30'W	± 100 ft[2]	5 s
Ship Heading	deg	0°-360°	± 0.50°[2]	5 s
Time	day-hr-min-sec	0-365 day	± 1.0 s	5 s

Notes:

1. These bounds must include 100 percent of all measurements.
2. Although the accuracy of these variables may fall within the limits specified, successive readings displayed must be repeatable within ± 1 ft in the case of receiver latitude and longitude, and ±0.05° in the case of ship's heading. This may be accomplished by filters provided the true movements of the ship are not masked.
3. Any similar coordinate system may be employed.
4. Period beteeen measurements shall not exceed this time interval.

IV. VARIABLES TO BE READ AS INPUT

These variables are divided into two groups according to who is responsible for their preparation and input into the guidance system. The variables to be stored in the system by the manufacturer are listed in Table 2. The variables to be stored in the system by the ship's operator are listed in Table 3.

TABLE 2. SEAWAY VARIABLES TO BE STORED IN UNIT

- Course intersection points for entire Seaway
- South channel boundary intersection points for entire Seaway
- North channel boundary intersection points for entire Seaway
- Location of fixed aids to navigation and prominent landmarks which normally are detected by shipboard radar

Note: This information is available from the Seaway Navigational Charts.

TABLE 3. VARIABLES TO BE STORED IN UNIT BY USER

- Ship's beam
- Ship's length
- Distance between receiver antenna and ship's midpoint
- Distance between receiver antenna and ship's centerline

V. VARIABLES TO BE DISPLAYED

The variables to be displayed aboard the operator's ship are given in Table 4 along with the method of display, units, range, accuracy and rates.

The shipboard unit provided by the manufacturer shall be of such size and weight as to be portable by one man. Each ship using the Seaway shall be required to install the necessary receiver/transmitter antenna and shall provide a location next to the ship's radar for housing the unit. At this location will be a ship's service electrical supply outlet identical to that provided to the radar set and a jack for the receiver/transmitter antenna.

The visual display shall be as shown in Figure 1 and as additionally specified in Tables 4 & 5. Below the display shall be a console which provides for at least the functions listed in Table 6.

TABLE 4. VARIABLES TO BE DISPLAYED

Variable	How Displayed	Units	Range	Absolute Accuracy	UPDATE RATE[1]
Distance off course track	CRT & Numeric	ft	± 3000	± 100 ft	5 s
Ship heading	CRT	-	-	-	5 s
Desired course	CRT	-	-	-	-
Ship speed	CRT & Numeric	mph	0-20	± 0.1 mph	5 s
Next turn distance	CRT & Numeric	ft	0-25	± 100 ft	5 s
Next turn time	CRT & Numeric	hr-min-sec	0-10 hrs	± 1 sec	5 s
South channel boundary	CRT	-	-	-	-
North channel boundary	CRT	-	-	-	-
Ship length	CRT	-	-	-	-
Ship beam	CRT	-	-	-	-

Notes: 1. Period between data displays shall not exceed this time interval .

TABLE 5. CRT DISPLAY SPECIFICATIONS

Screen size:	24" diagonal, square or rectangular
Scales:	1" = 200', 1" = 400', 1" = 800', 1" = 1,600'
Ships:	Length and beam to scale with bow pointed
Heading indicators:	Projecting 2 shiplengths ahead of bow and always .01" thick
Channel centerline:	Solid line always .01" thick
Channel boundaries:	Dotted line always .01" thick

Notes: Ship and ship heading indicator's last and next to last display shall persist at a medium and low intensity while current display is presented at bright intensity.

Just before ship moves to within 15% of the end of the display, the image shall automatically reset and reposition ship at left or right edge of display as appropriate. This operation shall not exceed the 5 second data update rate.

TABLE 6. REQUIRED CONSOLE FUNCTIONS

- Power on/off
- Screen brightness control
- Screen focus control
- Manual image reset
- Slot to accept card containing ships ID number, beam, length, distance of antenna from midpoint of ship, and distance of antenna off ship's centerline. Unit is not to display any images until this card has been inserted.
- Power failure alert
- Equipment failure alert
- Keyboard for manual input of user data

APPENDIX D

REPORT OF NEW TECHNOLOGY

APPENDIX D - REPORT OF NEW TECHNOLOGY

COMPUTER PROGRAMS USED TO DETERMINE NAVIGATIONAL GUIDANCE SYSTEM PERFORMANCE SPECIFICATION

The purpose of this study was to develop and define navigational guidance system performance requirements which will allow improvement in the capacity of the Saint Lawrence Seaway.* "Navigational guidance system performance requirements" means the type, accuracy, and frequency of information which must be made available to a ship's master in order to facilitate the safe passage of his ship through the Seaway. "Capacity" means the number of ships which could be processed through the Seaway in a given period of time under the assumption that ships are always available for processing at both Montreal and Lake Ontario.

A ship maneuvering simulation model and a Seaway capacity model were developed to determine the navigational guidance system performance specification which would allow improvement in the Capacity of the St. Lawrence Seaway. Computer programs--AWCAP and MANVER--of the above models were also developed.

Program AWCAP (All Weather Capacity) determines the Capacity of the Seaway for several historic weather years as a function of the accuracy of the navigational guidance system. Program MANVER, the ship maneuvering simulation model, computes the ship maneuvering room requirements and determines the type and rate of information required by the ship's master.

Detailed descriptions of programs AWCAP and MANVER are contained in Appendices B and C, respectively.

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* The Saint Lawrence Seaway as used herein is that section of the Saint Lawrence River from Montreal, Quebec, to Lake Ontario.

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