EFFECTS OF CONTROL SYSTEMS ON OPTIMIZATION OF SHIP SIZE FOR NAVIGATION IN RESTRICTED WATERS OF THE GREAT LAKES

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SUMMARY

The study examined the question of how alteration of traditional channel clearances (i.e., three times ship width for one-way channels, and seven to eight times vessel beam for two-way traffic) would affect the economics of increasing the ship's dimensions. First there was a study of ship dimension optimization, holding draft constant, to meet Great Lakes depth constraints. It was found that the optimum-sized vessel is approximately 1,250' in length, 156' in width, and has a 27.2' draft (maximum allowable without dredging).

The second task was to estimate the costs required to modify channels and harbors to accommodate the optimally-sized ship.

It was estimated the dredging costs would be \$6-\$7 billion (1977 value) if the current channel/ship dimension relationships were maintained. This investment could be reduced to less than one billion dollars if the channel/ship dimensions were altered so that ships about 50 percent wider were permitted to operate in the same width channel. The savings (in excess of \$5.0 billion) would be available for investment in advanced ship control systems to maintain the original traffic safety factors. The exact amount of reinvestment into emplacing the control systems would be a function of the safety margin desired.

INTRODUCTION

The Great Lakes - St. Lawrence Seaway system is the world's largest body of fresh water. The system functions as a major trade route for the mid-continent of North America (Refs. 1, 2). Although a great deal of the system involves open-water navigation, the connecting waterways require transit through constricting channels and locks. These constraints, especially the locks, place a limitation on the number and size of vessels which can effectively use the system, thus establishing the capacity of the system.

Much of the traffic in the lakes carries dry bulk cargo: iron ore, coal, and rock (Refs. 1, 2, 6, 7, 8, 9). As with all bulk cargo, there is no practicable limit to the vessel size (under ideal conditions) if there is cargo available at the dock. Ship size would only be constrained by the dimensions of the waterways. The economic implications of this constraint become obvious when one considers the fact that any increase in ship size would be directly translatable into cheaper transportation costs per unit.

As a result of the economic benefits available from increasing ship size, there has been continuing interest in developing the waterways so that the largest possible vessels can be used (Refs. 1, 2, 3, 6, 7, 8, 9). Today, the upper limit in wetted-ship dimensions is 1,000' x 105' x 25.5' (Refs. 8, 9).

There have been several studies undertaken for examining the costs and benefits of increasing the waterway dimensions so that larger vessels can make transit (Refs. 1, 2, 3, 6, 7, 8, 9). One study (Ref. 9), for example, examined a series of alternatives that would increase ship size up to dimensions of 1,500' x 175' x 25.5' and 32'/36'. The estimated costs for widening and deepening the waterways for the larger vessels were staggering, easily exceeding $25 billion.

In all analyses to date, however, traditional navigation and vessel control systems have been assumed. The width of channel, for example, was assumed to be three times the vessel beam for one-way traffic and seven to eight times vessel beam for two-way traffic. These clearance dimensions have been found to be the practicable minimum, given the present methods of vessel control. But the question could be raised as to what extent improved vessel control might alter the channel dimensions requirement. It is plausible that with precision vessel positioning and with fine-tuned vessel steering and response controls the currently-used channel clearance standards could be reduced (Ref. 4). This study evaluates how reduced clearance and headway requirements affect the cost parameters for acquiring and maintaining channel dimensions. The data could be useful in ascertaining the optimum control-system/ship/channel-dimension relationships (Refs. 4, 5).

This study examined the question of how alteration of the traditional channel clearances would affect the economics of increasing the ship's dimensions. It had three specific objectives:

-- determine the costs associated with establishing and maintaining increased channel dimensions for restricted-passage transits in the Upper Great Lakes;

-- determine the benefits associated with making transits through restricted waters with vessels optimally sized for passage under different control system assumptions; and

-- relate the determined costs to the resulting benefits so that optimum instrument concepts may be determined.

First, an analysis was made of ship dimensions optimization. The discussion of this portion of the research is in the section on Ship Characteristics

Determination. The section on Costs for Developing and Maintaining Channels contains the presentation of the analyses concerning costs associated with channel modification to accommodate passage under different control system assumptions. That section also presents the results of the integration of costs with resulting benefits for different investment profiles.

And, finally, the last section contains the study conclusions and recommendations. The Appendices contain the supporting calculations.

SHIP CHARACTERISTICS DETERMINATION

The first step in the study was to determine the general characteristics of those new ship designs that would be logical contenders for use of the waterways if more elaborate control systems were emplaced. This chapter describes the analysis that was performed in making this determination.

There exists an almost infinite number of combinations of length, beam, draft, depth, horsepower, etc., that could be used in a new and large ship design. To aid in this preliminary design process, the University of Michigan's Extended Season Program (ESP), a computer ship design and operation model for the Great Lakes coal, iron ore, and taconite colliers, was used. This computer model has yielded accurate economic results for Great Lakes bulk carriers.[1] The measure of merit for the design of the large ship was the Required Freight Rate (RFR) criterion. Using the most recent building and operating cost information available, and by varying principal dimensions, the ESP model developed a preliminary ship design yielding an economic optimum for ships of this service.

1 It is pointed out, however, that the model has never been used to analyze the economics of ships in the size range under consideration, and no ships of these dimensions have ever been built for Great Lakes service. Hence, it has not been possible to validate the results of the model output against actual ships.

In making the analysis, consideration was given to the factors of:

- -- principal dimension
- -- cargo
- -- propulsion plant
- -- superstructure
- -- investment and financial criteria.

Ship Factors Considered

Principal Dimensions

In determining the new vessel, the principal dimensions must be consistent with the rules of sound naval architecture. Additionally, the dimensions must be compatible with the Great Lakes environment. In this context, draft of the vessel is the primary design-limiting dimension in the design process. The maximum draft presently operating in the Great Lakes is 25.5 feet. However, the maximum possible draft fluctuates with the rise and fall of the lakes' water level. Recent conditions, for example, have allowed safe drafts of 27.2 feet. It was decided to use the temporary draft level of 29.2 feet as the design criterion on the assumption that high lake levels will continue to occur in the future. The benefits from slight over-design for draft will offset the costs for the extra weight during those periods when lake level is such that lesser draft is required.

Except for draft, all other ship dimensions were allowed to vary during the optimization analyses. The parameters that were manipulated were length, beam, and block co-efficient (C_b).[2] The specific numbers were:

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2 Block coefficient is the percentage of a ship's sectional area that would fill a rectangle of the same beam and depth dimensions.

length: 1,000', 1,100', 1,200', 1,300', 1,400', 1,500'

beam: 105', 135', 150', 200'

block coefficients (C_b): 84, 86, 88, 90, 94, 96, 98.

Cargo

Bulk commodities would be the cargo that could effectively utilize the size of vessels under consideration. And of these, coal has the least density. With a density of 4-5 cubic feet per ton, coal would require a higher hold volumetric capacity for the same cargo deadweight. For that reason, the vessel designs were based on coal as the carried cargo. The vessel was also equipped with self-unloading equipment with an unloading rate of 10,000 long tons per hour.

Propulsion Plant

Because of the unique environment found in the Great Lakes, the propulsion plant must be capable of operating within a wide range of speeds typically encountered in both restricted waterways and open lakes, and in high maneuvering conditions. The ship will have controllable pitch propellers. In addition to the controllable-pitch propeller, the vessel shall be outfitted with a bow thruster to aid in maneuverability in restricted waters.

By comparison to the vessel size, large Great Lakes bulk carriers operate in a shallow draft condition. Because of the shallow draft operation, difficulties arise if the shaft horsepower is allowed to become too large. Such difficulties are seen in hydrodynamic and vibrational areas, and are a result of close propeller tip clearances, rake angle of the after-hull section, and propeller diameter restrictions coupled with the high applied horsepowers. All of the previously enumerated conditions are critical in shallow draft operations, even if propeller tunnels are used. Past experience on the Great Lakes under these conditions has indicated that a 10,000-horsepower per screw limit be observed to minimize the effects of shallow draft operation.

In order to observe these horsepower restrictions and still maintain the required speed for the ship, usually in the range of 12-14 knots, a twin screw operation is mandatory. With this type of required speed, a total shaft horsepower of 14,000 to 20,000 would be required. Twin screw configuration would allow 7,000 to 10,000 horsepower per screw, which would be within the allowable range.

Superstructure

The historical ship arrangement for Great Lakes vessels has typically been a fore and after superstructure. Newer vessels such as the thousand-footers have satisfactorily adopted the ocean going arrangement of an all-aft superstructure. Use of an all-aft superstructure saves both lightship weight and initial cost. Even though ship maneuvering in the Great Lakes is often in restricted channels, rivers, and locks, the all-aft superstructure has shown not to be detrimental to ship operations, and has been used in this evaluation.

Economic Criteria

Not only will the optimum vessel design depend on ship particulars, but it will also be affected by economic considerations. Such considerations include the owner's required rate-of-return-on-investment, ship life, and income tax rate.

With interest rates at unprecedented levels and long-term inflation generally predicted, a 15 percent after-tax rate-of-return-on-investment was selected as a reasonable investment criterion.

Ship life on the Great Lakes is much longer than on the oceans. Salt water is much harsher on steel ships and their components than is fresh water. The average vessel age of many Great Lakes fleets is over 50 years. As a result, a 35-year life expectancy seemed a reasonable and conservative vessel life factor to use in the calculations.

A corporate income tax-rate of 46 percent was used. This rate is approximately that currently applied today (1980) in the United States.

Optimum Design Selection

By using the University of Michigan computer program to optimize ship design parameters, the investigators were able to evaluate the economies of over 250 different design concepts. First, for each design, an estimate was developed for the delivered cost of the ship. Then operating costs were estimated over a variety of trade routes within the upper Great Lakes. Both the capital investment calculations and the annual operating cost calculations were performed on a specially structured computer program.[3] These calculations were then used as input into the required freight rate computations.

Early analyses indicated that the optimum ship length would be from 1,000 to 1,300 feet long; the optimum beam would be at a ratio of about one-eighth of the length; the optimum horsepower would be in the 7,000 to 20,000 horsepower range; and the block coefficient (C_b) would be in the .88 to .94 range. A series of required freight rates on a coal service between Duluth and Buffalo for five typical configurations is shown in Table 1. As seen, the major design parameters all fall in the ranges just enumerated.

3 A sub-program of the University of Michigan Department of Naval Architecture and Marine Engineering Extended Season Program.

TABLE 1. Required freight rates for selection of coal colliers in Duluth/ Buffalo service.

Vessel Specifications	Required Freight Rate ($/ton) 7,000 Shp	14,000 Shp	20,000 Shp
1,000 ft x 105 ft x 56 ft x .94 C_b	$6.69	$6.49	$6.59
1,100 ft x 137.5 ft x 61.5 ft x .91 C_b	6.34	6.01	5.99
1,200 ft x 150 ft x 67 ft x .89 C_b	6.37	5.98	5.92
1,250 ft x 156 ft x 69.5 ft x .89 C_b	6.41	5.97	5.89
1,300 ft x 162.5 ft x 72.5 ft x .89 C_b	6.47	6.00	5.91

Source: Calculated.

It should be noted that the first ship in Table 1 (the 1,000 ft x 105 ft x 56 ft) is capable of operating in the Great Lakes today. There would need to be channel and/or harbor modifications to accommodate any of the remaining four.

After iterating through the cases, an optimum ship design was selected, and is identified in Table 2. Also in the table, for comparison, is the largest ship (called "parent") capable of operating in the upper Great Lakes today.

Table 3 compares the optimum ship against the existing parent for a variety of transits in the Great Lakes. As seen, the reduction in unit transportation costs ranges from less than two percent to over ten percent. The most likely transits for the coal carriers (from the port of Duluth) average about ten percent savings.

In examining Table 2 and Table 3 it should be remembered that the costs only considered investment and operation of the ships. Channel preparation and maintenance costs are not considered in these calculations.

The data clearly indicated that there is an optimum ship size for upper Great Lakes service. And while it is not readily apparent in the data, the optimum point is strongly influenced by the draft limitation. (In ocean

TABLE 2. Comparison of optimum ship design with largest ship presently capable of operating in upper Great Lakes.

Item		Parent	Optimum
Length	ft	1,000	1,250
Beam	ft	105	156
Depth	ft	56	69.5
Draft	ft	27.2	27.2
Displacement	tons	74,781	131,492
Deadweight	tons	60,169	105,290
Speed	mph	16.51	14.69
Engine		Diesel	Diesel
SHP		20,000	20,000
Unload Rate	LT/hr	10,000	10,000
Cargo	FT^3/ton	45	45
Crew		26	26
Cb		.94	.89
L/D		17.86	17.99
L/B		9.52	8.01
B/D		1.875	2.245
B/T		3.860	5.735
V/L		.453	.361
CN		58,800	135,525
Steel Weight	tons	11,796	22,796
Outfit Weight	tons	791	1,016
Mach. Weight	tons	894	894
Light Ship	tons	14,612	26,201
Investment	$	50.53M	75.12M
Ship Life	years	35	35
Interest	%	15	15
Tax	%	46	46
Fuel Intr 15	$/ton	189	189
Steel HSS	$/ton	460	460

Source: Calculated

service, where operators have no draft limitation, the economic optimum-sized-ship is essentially infinite, or at least significantly greater than found in the Great Lakes.)

Finally, the analyses also clearly indicated that freight rate reductions are possible if ship size can be increased beyond the presently existing maximum

TABLE 3. Required freight rates for two ships in coal service in upper Great Lakes ($/ton of coal).

Route	RFR Parent	RFR Optimum	Reduction In RFR %
Duluth to Buffalo*	$6.589	$5.894	10.55%
Duluth to Ashtabula*	5.985	5.894	10.18
Duluth to Burns Harbor*	5.610	5.070	9.63
Duluth to Detroit	5.012	4.550	9.22
Toledo to Buffalo	2.209	2.170	1.77
Toledo to Burns Harbor	4.811	4.388	8.79
Escanaba to Ashtabula	4.159	3.829	7.93
Escanaba to Burns Harbor	2.308	2.255	2.30
Escanaba to Buffalo	4.762	4.345	8.74

* Assume Soo Locks are able to allow transit of optimum ship.

size. It now remains to be determined whether this benefit potential would be more than offset by costs associated with either increasing channel size or by emplacing control systems that would permit larger ships to safely operate in the current channels. The next section will examine the capital costs and operating costs associated with developing and maintaining channels to accommodate the larger ships.

COSTS FOR DEVELOPING AND MAINTAINING CHANNELS

While the Great Lakes have a large number of ports, only a small number are involved in most of the cargo movement. The first task in investigating the development and maintenance of channels was to decide upon which ports should be included in the analysis. The second task was to develop costs for enlarging and maintaining the channels. In conjunction with this activity, cost analyses were developed on the basis of emplacing an advanced control system (i.e., only deepening the channel to accommodate ships of the dimensions under consideration; widening the channel was omitted). The final activity was to compare the different costs, and their assumptions, and to isolate those costs that would be eliminated with the use of advanced control systems.

Port Selection

There was first an extensive screening of all ports in the upper Great Lakes that are capable of handling any ship that can transit the Welland Canal (730' x 76' x 26'). The ports were then categorized according to annual cargo tonnage, and availability of Corps of Engineer Lake Survey charts. The final selection included:

Harbors	Commodities
Duluth-Superior, MN and WI	Iron ore, coal, general cargo
Two Harbors, MN	Iron ore
Presque Isle, MI	Iron ore
Calumet, IL	Iron ore, general cargo
Indiana, IA	Iron ore
Gary, IA	Iron ore
Burns Waterway, IA	Iron ore, general cargo
Detroit, MI	Iron ore, coal, general cargo
Toledo, OH	Iron ore, coal, general cargo
Sandusky, OH	Coal
Lorain, OH	Iron ore, coal
Cleveland, OH	Iron ore, coal, general cargo
Ashtabula, OH	Iron ore, coal
Conneaut, OH	Iron ore, coal
Buffalo, NY	Iron coal, coal, general cargo

Channels
St. Marys River
Straits of Mackinac
St. Clair River
Detroit River
Toledo Harbor to Detroit River
Pelee Passage

Fortunately, the Corps of Engineers, Chicago District, recently (1977) performed extensive analyses on the same ports. The investigation, therefore, concentrated on extending the Corps' effort to specific questions raised in this study.

In their analysis, the Corps of Engineers examined project maps, dredging surveys, Lake Survey Center charts, and harbor modifications. Information was also obtained from the Corps' Rivers and Harbors Port Series, Greenwood's Guide to Great Lakes Shipping, and the Great Lakes Pilot.

The Corps' analyses "assumed that generally: (1) a no-passing channel should be three times the beam of the vessel, (2) a two-way channel should be 7.6 times vessel width, and (3) turning basins should be 1.5 times vessel length."[4]

The Corps of Engineers next prepared detailed estimates of costs that would occur in sizing the channels to accommodate vessels of different sizes. Appendix A contains a description of the procedures that were followed in making these estimates.

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4 "Methodology for Cost Estimating," undated memorandum, Corps of Engineers, Chicago District. The memo cites the following documents as the basis for dimensions: Engineering Manual EM111021607 (2 August 1965) Tidal Hydraulics, Page 13, and the Gross Isthmus Canal Study, Panama, Appendix 6, Navigation in Confined Channels, Page F-2.

As noted, the improvements were calculated on the basis of increasing a channel dimension to accommodate a ship of a particular size using a ratio of channel width to ship beam as one reference point, and a ratio of turning basin diameter to ship length as a second reference point. Ship depth was a third factor in establishing the channel size. Appendix B presents the costs that resulted from the analyses for several vessel sizes, each with a variety of drafts. Also included are the projected operating and maintenance costs for keeping the channels at the prescribed dimensions after the initial expansion has been completed.

Table 4 is a presentation of calculations derived from the Corps of Engineers costs. It shows the differences in costs (1977 dollars) that would occur in expanding the ports and channel facilities to accommodate various sizes of vessels under two different sets of assumptions:

1) expanding the channel clearances per the traditional ratio; 3 times ship beam for one-way traffic; 7.6 times ship beam for two-way traffic; 1 1/2 times ship length for turning basin diameter.

2) not altering the channel widths, but dredging to meet turning-basin requirements as per 1.5 times ship's length. This option would be considered typical of the expense required to accommodate larger vessels if they were also equipped with advanced control systems.

Table 4 shows the cost estimates for channel preparation for different sizes of ships under the two sets of assumptions described above. (The details for the federal capital cost are shown in Appendix C.) The data show quite clearly that significant increases occur as ship's beam expands, especially when the traditional allowances for ship beam/channel width are followed.
Of particular interest is the difference in capital costs between the two

TABLE 4. Capital costs required to modify channels and ports to accommodate larger ships in upper Great Lakes (thousands of 1977 dollars).

	Vessel Size:	1,100' x 105'		1,100' x 130'	
		Enlarge Channels and Harbors	Emplace Control System	Enlarge Channels and Harbors	Emplace Control System
(1)	Federal capital cost (includes dredging, bridges, tunnels, breakwaters, locks, relocations)	197.3	114.5	2,400.6	204.6
(2)	Aids to navigation (1%)	2.0	1.1	14.0	2.0
(3)	Real estate (2%)	3.9	2.3	48.0	4.1
(4)	Total	203.2	117.9	2,472.6	210.7
(5)	Contingency (20% of line 4)	40.6	23.6	494.5	42.1
(6)	Total federal capital cost	243.8	141.5	2,967.1	252.8
(7)	Engineering & design (5% of line 6)	12.2	7.1	148.4	12.6
(8)	Supervision & administration (6% of lines 6 & 7)	15.4	8.9	186.9	15.9
(9)	Total federal first cost	271.4	157.5	3,302.4	281.3
(10)	Non-federal first cost (2% of federal first cost)	5.4	3.2	66.0	5.6
(11)	Total first cost	276.8	160.7	3,368.4	286.9
(12)	Interest prior to beginning accrual of benefit stream (6 5/8% for 5 years) (.33125)	91.9	53.2	1,115.8	95.0
(13)	Total investment costs (1977 dollars)	369.4	213.9	4,484.2	381.9

Source: Calculated from data developed by Corps of Engineers

(continued).

TABLE 4. (Continued).

Vessel Size:		1,200' x 130'		1,300' x 130'	
		Enlarge Channels and Harbors	Emplace Control System	Enlarge Channels and Harbors	Emplace Control System
(1)	Federal capital cost (includes dredging, bridges, tunnels, breakwaters, locks, relocations)	2,578.9	353.3	2,621.9	385.9
(2)	Aids to navigation (1%)	25.7	3.5	26.2	3.9
(3)	Real estate (2%)	51.4	7.1	52.4	7.7
(4)	Total	2,645.0	363.9	2,700.5	387.5
(5)	Contingency (20% of line 4)	529.0	72.8	540.1	79.5
(6)	Total federal capital cost	3,174.0	436.7	3,240.6	477.0
(7)	Engineering & design (5% of line 6)	158.7	21.8	162.0	23.9
(8)	Supervision & administration (6% of lines 6 & 7)	200.0	27.5	204.2	30.1
(9)	Total federal first cost	3,532.7	486.0	3,606.8	500.9
(10)	Non-federal first cost (2% of federal first cost)	70.7	9.7	72.1	10.0
(11)	Total first cost	3,603.4	495.7	3,378.9	510.9
(12)	Interest prior to beginning accrual of benefit stream (6 5/8% for 5 years) (.33125)	1,193.6	164.2	1,218.6	169.2
(13)	Total investment costs (1977 dollars)	4,794.0	695.9	4,897.5	680.1

Source: Calculated from data developed by Corps of Engineers

(continued).

TABLE 4. (Continued).

Vessel Size:	1,100' x 175'		1,200' x 175'	
	Enlarge Channels and Harbors	Emplace Control System	Enlarge Channels and Harbors	Emplace Control System
(1) Federal capital cost (includes dredging, bridges, tunnels, breakwaters, locks, relocations)	3,151.0	204.8	3,648.8	377.7
(2) Aids to navigation (1%)	31.5	2.0	36.5	3.8
(3) Real estate (2%)	63.0	4.1	73.0	7.6
(4) Total	3,245.5	210.9	3,758.3	389.1
(5) Contingency (20% of line 5)	649.1	42.2	751.7	77.8
(6) Total federal capital cost	3,984.6	253.11	4,510.0	466.9
(7) Engineering & design (5% of line 6)	194.7	12.7	225.5	23.3
(8) Supervision & administration (6% of lines 6 & 7)	245.4	15.9	284.1	29.4
(9) Total federal first cost	4,334.7	281.7	5,019.6	519.6
(10) Non-federal first cost (2% of federal first cost)	86.7	5.6	100.4	10.4
(11) Total first cost	4,421.4	287.3	5,120.0	530.0
(12) Interest prior to beginning accrual of benefit stream (6 5/8% for 5 years) (CRF of .33125)	1,464.6	95.2	169.6	175.6
(13) Total investment costs (1977 dollars)	5,886.0	382.5	6,816.0	705.6

Source: Calculated from data developed by Corps of Engineers

(continued).

TABLE 4. (Continued).

Vessel Size:

		a.	
(1)	Federal capital cost (includes dredging, bridges, tunnels, breakwaters, locks, relocations)	3,664.[illegible]	415.3
(2)	Aids to navigation (1%)	36.6	4.2
(3)	Real estate (2%)	73.3	8.3
(4)	Total	3,774.8	427.8
(5)	Contingency (20% of line 4)	755.0	85.6
(6)	Total federal capital cost	4,529.8	513.4
(7)	Engineering & design (5% of line 6)	226.5	25.7
(8)	Supervision & administration (6% of lines 6 & 7)	285.4	32.3
(9)	Total federal first cost	5,041.7	571.4
(10)	Non-federal first cost (2% of federal first cost)	100.8	11.4
(11)	Total first cost	5,142.5	582.8
(12)	Interest prior to beginning accrual of benefit stream (6 5/8% for 5 years) (CRF of .33125)	1,703.5	193.1
(13)	Total investment costs (1977 dollars)	6,846.0	775.9

Source: Calculated from data developed by Corps of Engineers approaches. These differences have been plotted in Figure 1. The range is caused by costs associated with increasing the length (with the beam remaining constant), the lower estimate being the cost for 1,100-foot ships. The upper range is for 1,300-foot ships.

As seen in Table 4, the (1977 dollar) cost for enlarging channels and increasing turning basin diameter to accommodate 1,100-ft x 105-ft ships would be $370 million if the traditional channel/ship relationships are followed. If the channels and ports were to be expanded only to meet the length requirements, and the locks were to be increased only to meet minimum pass-through requirements, the cost would only be $215 million (1977 dollars). Theoretically, then, the difference in the two costs ($155 million) is the amount that could be spent to emplace control systems that would provide the same margin of safety, and still not exceed the costs for the traditional system.

It is possible, by interpolation, to estimate the cost for improving channels and ports to accommodate the optimum design described in the preceding chapter, a ship with dimensions of 1,250 ft (length) by 156 ft (width). The cost (1977 dollars) would be approximately $5.99 billion if channel and port enlargement is based on the traditional ship/channel width relationships. The cost (1977 dollars) would be about $720 million if channel improvements were confined to only those improvements necessary to complement an advanced control system, i.e., turning basins and locks. If a control system could be emplaced that would provide the same traffic flow attributes as a conventional channel system for $5.2 billion ($5.99 - .72 billion) or less, then it would make economic sense to choose that alternative.

Finally, Figure 2 shows the difference in capital costs between the two systems (i.e., conventional channel clearance and a control system-oriented

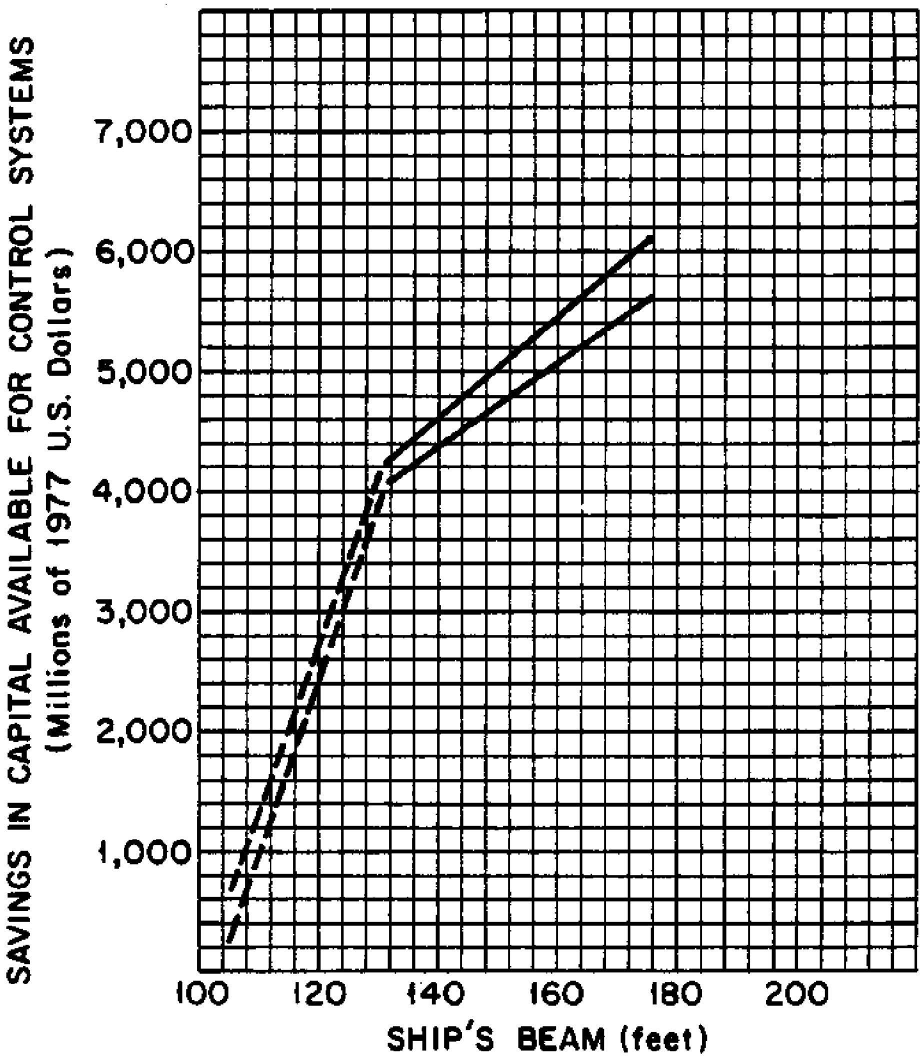

FIG. 1. Differences in capital costs between two systems for accommodating larger ships in upper Great Lakes channels and ports.
Source: Table 4.

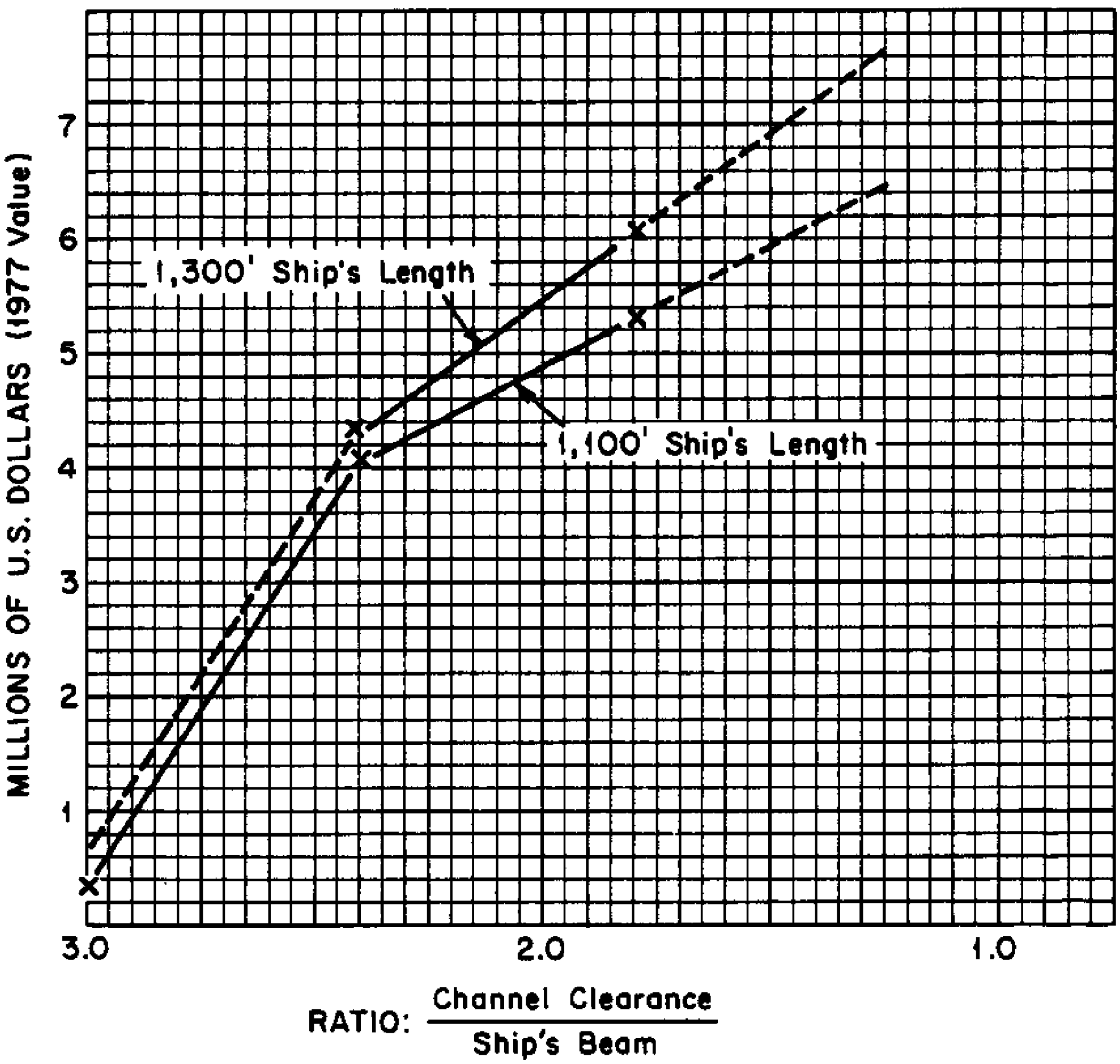

FIG. 2. Capital available for installation of advanced control systems as the relationship between ship's beam and channel clearance is reduced (for ships with length of 1,100 to 1,300 feet).

clearance) as functions of the ratio between ship beam and one-way channel clearance distance. (The ratio for the conventional system is 3:1.) As seen, the more the ratio of channel dimension to ship's beam can be reduced, the greater the fund availability for control system emplacement.

CONCLUSIONS AND RECOMMENDATIONS

There were two major conclusions of the study. First, the optimum size bulk carrier for upper Great Lakes services was determined to be 1,250 ft by 156 ft, assuming a maximum draft constraint of 27.2 feet. The shallow draft is the major factor in forcing the length and width limitations. Vessels of the optimum size would produce a savings in excess of 10 percent on the longest transits (Duluth to Buffalo) when compared with the largest (and most efficient) ships in service today.

There would be major capital investments required to modify the water system so that the larger vessels could be accommodated. It is estimated that an initial investment of $6 billion (1977 value) would be required to complete the channel and turning basin expansions, and lock enlargements. On the basis of current traffic flows, and assuming a 50-year capital investment write-off period, all bulk cargo would be confronted with a surcharge of $1-2 per ton.[5]

The second conclusion of the study was that it is possible to save up to $5.0 billion (1977 value) in channel, turning basin, and lock improvement costs by emplacing advanced concept ship maneuvering control systems. The exact amount of savings would be a function of a control system's ability to precisely regulate the movement of the vessel. The greater the control, the less clearance is required between ship and channel bank.

5 Based on annual total tonnage of about 120,000,000 tons.

It was beyond the scope of the study to investigate the economics of emplacing advanced concept control systems only within specific channel networks, (e.g., St. Marys River). Such analysis would be logical next steps in further analyses. The analyses would be compared with research which is presently underway on the effectiveness and adaptability to a specific channel location of various control systems.

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1. Great Lakes Winter Navigation - Technical and Economic Analyses. Department of Naval Architecture & Marine Engineering, The University of Michigan, 5 Volumes.

   Volume I: Methods of Evaluation, by H. Nowacki et al., Report No. 151, 1973.

   Volume II: Computer Program - Documentation and User Instructions, by Steve Callis et al., Report No. 152, 1974.

   Volume III: Parametric Studies, by H. Nowacki, Report No. 153, 1974.

   Annex: Methods of Evaluation and Computer Program, by Peter Swift et al., Report No. 156, 1975.

2. Transport Analysis - Great Lakes and Seaway. Department of Naval Architecture & Marine Engineering, The University of Michigan, 5 Volumes.

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5. Maneuverability in Restricted Waters, by Masataka Fujino, Report No. 184, Department of Naval Architecture & Marine Engineering, The University of Michigan, 1976.

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8. Plan of Study for Great Lakes Connecting Channels and Harbors Study, U.S. Army Corps of Engineers, Detroit, Michigan, 1978.

9. Feasibility Study for Additional Locks and Other Navigation Improvements, St. Lawrence Seaway - Plan of Study, U.S. Army Corps of Engineers, Buffalo, New York, 1978.

APPENDIX A

DESCRIPTION OF PROCEDURES USED BY THE CORPS OF ENGINEERS IN DETERMINING COSTS OF CHANNEL IMPROVEMENTS TO ACCOMMODATE LARGER VESSELS

PLANS AND COST ESTIMATES

Channels: The work to establish channel cost estimates consisted of the development of criteria to size the channels relative to the considered vessel sizes. This was followed by the development of a computer program to efficiently translate the criteria into channel dimensions for the 79 reaches, both up and down bound conditions, times 28 vessel's cases for a total of 4,424 distinct solutions. Next came a plan layout of these cases, the estimation of dredging quantities of rock and other material for the cases from cross sectioning the 79 reaches, and finally applying cost figures which include the disposal price to obtain the dredging estimate first costs.

The criteria established are based upon current literature and practice. References for this are:

1. Interoceanic Canal studies, Appendix 6, Navigation in Confined Channels. Corps of Engineers 1970.
2. Journal of the Waterways, Harbors, and Coastal Engineering Division, American Society of Civil Engineers. Volume 97, August 1971, containing water depths required for ship navigation (R.G. Waugh), and vessel controllability in restricted waters (E.W. Edrin), Volume 99, February 1973, containing design of ship channels and maneuvering areas (C.K. Kray).
3. EM 1100-2-1607, 2 August 1965, Corps of Engineers.
4. Squat Study - St. Lawrence ship channel, L. Simard, March 1969.
5. Report No. 3, Committee on Tidal Hydraulics, Corps of Engineers, May 1965.

In addition, discussions were had with the University of Michigan Naval Architecture and Marine Engineering Department to confirm the approach and criteria.

Squat criteria are based upon the empirical equation

$$S = \frac{V,^2}{2g} \quad 1.01 \quad \frac{A_1}{A_w} \quad ^{2} - 0.84$$

from the St. Lawrence study.

$V,$ = Ship velocity relative to water

A_1 = Cross sectional area of channel

A_w = Channel cross section area - vessel cross section area

g = 32.2 ft/sec^2

In addition, the channel type, either confined or open, is recognized through a modification to the effective width of the channel. This recognizes that squat appears to be less in channels cut in wider shallow bodies of water as opposed to channels immediately bounded by banks or placed in narrow rivers where the ship channel constitutes a significant portion of the river.

Required channel widths are a function of the controllability of the vessels using the channel. It is a function of the vessel distance from the bank, passing or no passing conditions, vessel velocity relative to the water, channel shape, and amount of water under the vessel keel. Channel width appears to be a trade-off with channel depth. The wider a channel, the less can be the depth of water under the keel to maintain the same degree of controllability. This situation of controllability is discussed more fully in the reference documents. The mathematical procedures outlined in the Interoceanic Canal studies were utilized in the computer model of this study. This was done through curve fitting techniques that reduce the family of curves graphed on the next two pages to equation form for efficient computer programming.

The resulting equations are:

First graph upper portion

$$Ratio_x = (240.12\ F_\gamma\ ^{.362})^2 - Ratio_y - 37.18)^2 - 55.8$$

First graph lower portion

$$Ratio_x = (93.92\ F_\nabla\ ^{.1079})\ /Ratio_y\ ^{12.7226}$$

Second graph

$$Ratio_y = (115.99\ R\ ^{2.0371})\ (F_\nabla)^{4.351}$$

F being a Froude Number

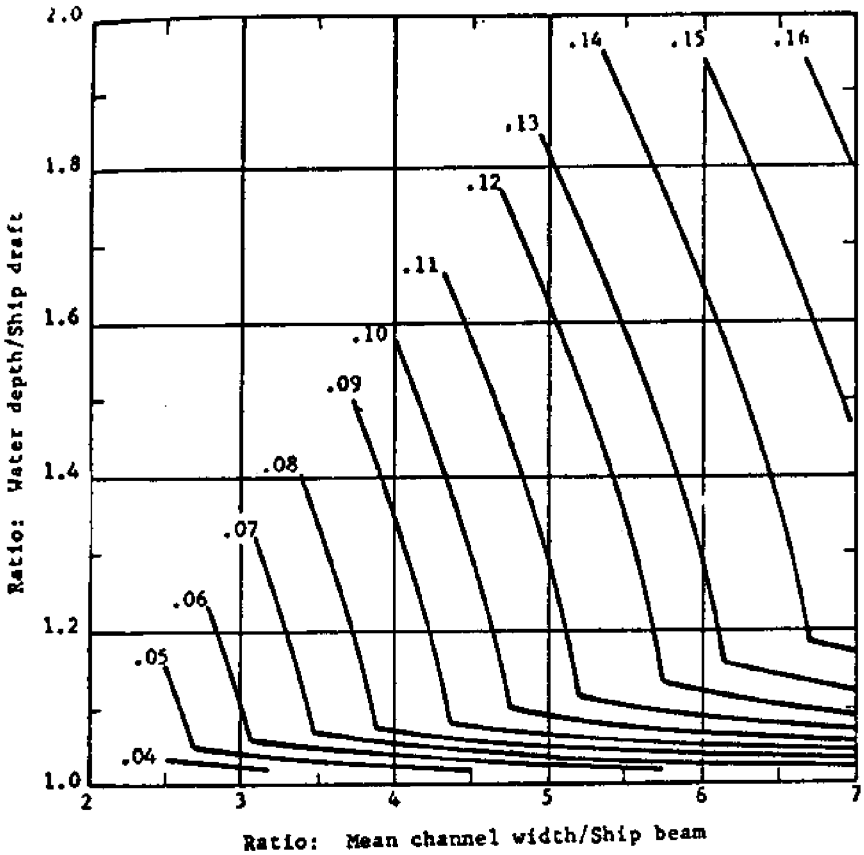
R being (ship cross section) / (channel cross section)

These graphs are shown as exhibits on the following pages.

The limits of 3 times vessel beam for one way traffic and 7.6 times vessel beam for two way traffic were utilized as lower and upper bounds, respectively to constrain the empirical equation of the computer model.

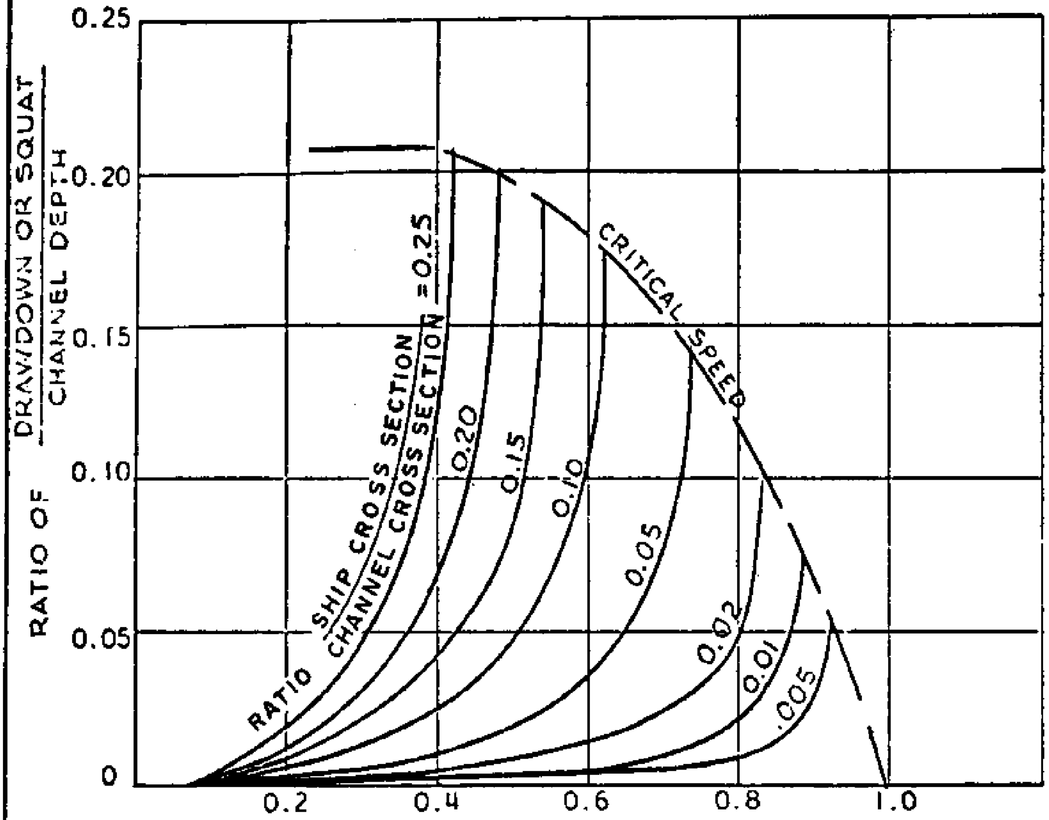
Trim and bottom clearance are handled in the model by the addition of a 2-foot clearance to the calculated squat regardless of bottom material type.

Harbors: Two types of work had to be performed at each of the harbors investigated. First, entrance and inner harbor criteria had to be estimated, plans prepared, and cost estimates made. Second, similar work had to be accomplished to provide for berthing spots and turning basins. Work was essentially confined to the non-river sections of the harbors, as inspection indicated facility improvements necessary to allow the transiting of the rivers would for the most part be exceedingly non-economical.



Legend
.07 Contour of indicated Froude number along which ship navigability is approximately constant. The nearly horizontal part of the contour represents conditions at which the ship just clears the channel bottom.

CHANNEL DESIGN CURVES



$$\text{FROUDE NUMBER} = \frac{\text{SHIP SPEED RELATIVE TO WATER IN FT./SEC.}}{\sqrt{32.2 \times \text{CHANNEL DEPTH}}}$$

DIMENSIONLESS SQUAT IN RESTRICTED CHANNELS*

*Committee on Tidal Hydraulics — Corps. of Engineers — Report No. 3 page X-8.

Harbor entrance criteria considered vessel roll, pitch, heave, squat, and trim. Vessel roll response was estimated from charts on pp. 434-437 in Section 2, Ocean Navigation, Report of Proceedings XXIInd Congress of Permanent International Association of Navigation Congresses, 1969; extrapolation from the charts was necessary. Pitch-heave response was estimated according to (pitch + heave - amplitude) at bow = 0.2x (wave height as recommended by E.O. Tuck (University of Michigan). Dr. Tuck's recommendation was based on extrapolation of charts in the paper, Beck, R., and Tuck, E., Computation of Shallow Water Ship Motions, Proc. Ninth Symposium on Naval Hydrodynamics, 1970. Waves used in the roll, pitch, and heave calculations were 10-year recurrence summer (July-August-September) waves for Lakes Erie, Huron, and Michigan from WES TR H-76-1, Reports, 1, 3, and 4, Design Wave Information for the Great Lakes by D. Resio and C. Vincent. For Lake Superior, as Report 5 of TR H-76-1 has not yet been published, it was arbitrarily assumed that the summertime climates of the Lake Superior ports would resemble that of Milwaukee. Squat was computed from an equation on page F-11 of Annex V, Appendix B, of the Study of Engineering Feasibility of a sea-level Panama Canal. An additional 2-foot clearance was allowed, regardless of whether the lake bed was rocky or soft material. Recommended harbor entrance widths vary from three times the vessel beam (20 June 1977 letter from President, Lakes Carriers' Association, to Division Engineer, NC) to 7.6 times the vessel beam. (CERC special report #2, Small Craft Harbors: Design, Construction and Operation.)

Width of harbor entrance should be as follows:

Beam	No Passing Width (3x Beam)	Width (5x Beam)	Passing Width (7.6x Beam)
105 ft	315 ft	525 ft	798 ft
130	390	650	988
175	- 525	875	1330

Squats were calculated for vessel speeds of 5 mph and 10 mph, except where existing channels are so narrow that squat would exceed 6 to 8 feet. Also calculated were channel widths for which 1 ft and 2 ft squat would be experienced at those two speeds. Outer harbors protected by permeable breakwater were assumed to be infinitely-wide channels due to the permeable walls; consequently, zero squat was predicted for such areas. The 1,300 and 1,500-foot vessels were found to have very small roll and pitch-heave responses to summertime storm waves.

APPENDIX B

CORPS OF ENGINEERS

SUMMARY OF COSTS ASSOCIATED

WITH INCREASING CHANNEL CLEARANCES

FOR LARGER GREAT LAKES VESSELS

(All figures in 1977 dollars)

SUMMARY OF FEDERAL CONSTRUCTION CAPITAL COSTS

Vessel Size: 940' x 105'

($000)

	DRAFT			
Location	25.5'	28.0'	32.0'	36.0'
Duluth Harbor	---	38,000	58,500	78,500
Superior Harbor	---	---	---	---
Two Harbors	N/A	N/A	N/A	N/A
Presque Isle Harbor	N/A	N/A	N/A	N/A
Milwaukee Harbor	6,100	10,800	18,300	25,800
Calumet Harbor	---	54,087	122,443	187,834
Indiana Harbor	---	---	---	---
Gary Harbor	---	---	---	---
Burns Harbor	1,200	3,380	6,830	10,500
Detroit Harbor	---	1,607	3,513	4,520
Toledo Harbor	131,850	164,480	245,930	584,780
Sandusky Harbor	---	---	---	---
Lorrain Harbor	---	---	---	---
Cleveland Harbor	450	4,152	12,065	20,650
Ashtabula Harbor	---	---	---	---
Conneaut Harbor	---	---	---	---
Buffalo Harbor	---	---	---	---
Total Harbors	139,600	276,506	467,581	912,584
St. Marys River	57,763	537,529	1,015,234	1,350,711
Straits of Mackinac	---	3,739	25,078	52,830
St. Clair River	---	577,463	1,090,984	1,525,528
Detroit River	---	712,036	5,273,515	9,201,230
Toledo Harbor to Detroit River	---	48,232	86,816	125,400
Pelee Passage	---	49,680	174,645	607,815
Total Channels	57,763	1,928,679	1,746,453	13,776,098
Total	197,363	2,205,185	2,214,034	4,688,682

SUMMARY OF FEDERAL CONSTRUCTION CAPITAL COSTS

Vessel Size: 940' x 105'

($000) (Operating & Maintenance)

	DRAFT			
Location	25.5'	28.0'	32.0'	36.0'
Duluth Harbor	---	20	30	40
Superior Harbor	---	---	---	---
Two Harbors	N/A	N/A	N/A	N/A
Presque Isle Harbor	N/A	N/A	N/A	N/A
Milwaukee Harbor	0	19	25	31
Calumet Harbor	4	6	8	10
Indiana Harbor	---	---	---	---
Gary Harbor	---	---	---	---
Burns Harbor	---	---	---	---
Detroit Harbor	20	33	36	39
Toledo Harbor	183	201	221	240
Sandusky Harbor	---	---	---	---
Lorrain Harbor	---	---	---	---
Cleveland Harbor	10	10	13	16
Ashtabula Harbor	---	---	---	---
Conneaut Harbor	---	---	---	---
Buffalo Harbor	---	---	---	---
Total Harbors	217	289	333	376
St. Marys River	---	85	94	103
Straits of Mackinac	---	---	---	---
St. Clair River	---	144	304	342
Detroit River	---	93	197	221
Toledo Harbor to Detroit River	---	100	110	121
Pelee Passage	---	86	185	492
Total Channels	---	508	890	1,279
Total	217	797	1,223	1,655

SUMMARY OF FEDERAL CONSTRUCTION CAPITAL COSTS

Vessel Size: 1,100' x 105'

($000)

Location	DRAFT 25.5'	28.0'	32.0'	36.0'
Duluth Harbor	0	84,700	122,500	No Plan
Superior Harbor	0	10,738	17,305	"
Two Harbors	0	6,100	13,700	"
Presque Isle Harbor	0	1,580	6,450	"
Milwaukee Harbor	0	0	0	"
Calumet Harbor	0	63,294	143,285	"
Indiana Harbor	0	40,900	97,500	"
Gary Harbor	0	9,980	23,400	"
Burns Harbor	0	1,800	3,750	"
Detroit Harbor	75,440	104,330	163,330	"
Toledo Harbor	0	128,480	209,030	"
Sandusky Harbor	80,930	118,306	183,069	"
Lorrain Harbor	8,630	15,376	26,858	"
Cleveland Harbor	9,530	13,682	27,895	"
Ashtabula Harbor	2,700	6,380	13,661	"
Conneaut Harbor	2,330	3,980	13,503	"
Buffalo Harbor	20,930	37,378	93,289	"
Total Harbors	200,490	647,004	1,158,525	
St. Marys River	67,595	548,348	1,026,908	"
Straits of Mackinac	0	3,739	25,078	"
St. Clair River	0	577,463	1,090,984	
Detroit River	0	712,036	5,273,515	
Toledo Harbor to Detroit River	0	48,232	86,816	
Pelee Passage	0	49,680	174,645	
Total Channels	67,595	1,939,498	7,677,946	
Total	268,085	2,586,502	8,836,471	

September 1977 Costs

SUMMARY OF FEDERAL CONSTRUCTION CAPITAL COSTS

Vessel Size: 1,100' x 105'

($000) (Operating & Maintenance)

	DRAFT			
Location	25.5'	28.0'	32.0'	36.0'
Duluth Harbor	0	49	59	No Plan
Superior Harbor	---	---	---	---
Two Harbors	---	---	---	---
Presque Isle Harbor	---	---	---	---
Milwaukee Harbor	---	---	---	---
Calumet Harbor	0	6	8	---
Indiana Harbor	0	4	6	---
Gary Harbor	---	---	---	---
Burns Harbor	---	---	---	---
Detroit Harbor	20	33	36	---
Toledo Harbor	183	201	221	---
Sandusky Harbor	10	34	41	---
Lorrain Harbor	0	8	20	---
Cleveland Harbor	10	10	13	---
Ashtabula Harbor	10	14	30	---
Conneaut Harbor	0	0	10	---
Buffalo Harbor	48	53	58	---
Total Harbors	281	412	502	
St. Marys River	0	85	94	
Straits of Mackinac	0	0	0	
St. Clair River	0	144	304	
Detroit River	0	93	197	
Toledo Harbor to Detroit River	0	100	110	
Pelee Passage	0	86	185	
Total Channels	0	508	890	
Total	281	920	1,392	

SUMMARY OF FEDERAL CONSTRUCTION CAPITAL COSTS

Vessel Size: 1,200' x 130'

($000)

	DRAFT			
Location	25.5'	28.0'	32.0'	36.0'
Duluth Harbor	75,180	95,810	134,550	173,190
Superior Harbor	9,167	13,059	21,024	32,863
Two Harbors	4,000	7,000	16,300	29,900
Presque Isle Harbor	790	1,510	6,980	15,830
Milwaukee Harbor	---	---	---	---
Calumet Harbor	18,068	85,488	193,528	296,881
Indiana Harbor	10,140	25,020	64,040	140,840
Gary Harbor	5,800	9,200	21,900	49,800
Burns Harbor	6,000	1,910	3,900	6,150
Detroit Harbor	9,250	13,610	20,800	27,530
Toledo Harbor	125,360	158,700	250,540	589,500
Sandusky Harbor	92,550	134,270	206,665	352,621
Lorrain Harbor	13,840	22,783	37,943	67,813
Cleveland Harbor	9,790	14,681	29,324	45,160
Ashtabula Harbor	3,560	7,880	16,950	37,288
Conneaut Harbor	3,280	5,580	15,387	28,790
Buffalo Harbor	23,400	37,848	94,573	187,648
Total Harbors	410,125	634,349	1,134,404	2,081,804
St. Marys River	870,419	1,140,322	1,797,967	2,421,371
Straits of Mackinac	---	3,739	25,078	52,830
St. Clair River	573,600	718,336	1,163,143	1,628,938
Detroit River	658,622	873,193	5,661,509	9,886,057
Toledo Harbor to Detroit River	39,416	59,720	107,496	155,272
Pelee Passage	15,660	49,860	174,645	607,815
Total Channels	2,142,057	2,845,170	8,929,838	14,752,283
Total	2,552,182	3,479,519	10,064,242	16,834,087

SUMMARY OF FEDERAL CONSTRUCTION CAPITAL COSTS

Vessel Size: 1,200' x 130'

($000) (Operating & Maintenance)

	DRAFT			
Location	25.5'	28.0'	32.0'	36.0'
Duluth Harbor	55	65	78	94
Superior Harbor	---	---	---	---
Two Harbors	---	---	---	---
Presque Isle Harbor	---	---	---	---
Milwaukee Harbor	---	---	---	---
Calumet Harbor	4	6	8	10
Indiana Harbor	2	4	6	8
Gary Harbor	---	---	---	---
Burns Harbor	---	---	---	---
Detroit Harbor	25	41	45	49
Toledo Harbor	842	926	1,018	1,120
Sandusky Harbor	30	44	53	64
Lorrain Harbor	4	12	22	40
Cleveland Harbor	14	16	30	50
Ashtabula Harbor	12	14	40	60
Conneaut Harbor	10	12	15	30
Buffalo Harbor	59	66	73	80
Total Harbors	1,057	1,156	1,388	1,605
St. Marys River	266	293	322	354
Straits of Mackinac	---	---	---	---
St. Clair River	337	396	435	478
Detroit River	218	256	282	309
Toledo Harbor to Detroit River	421	463	509	560
Pelee Passage	37	86	185	492
Total Channels	1,279	1,494	1,733	2,193
Total	2,336	2,650	3,121	3,798

SUMMARY OF FEDERAL CONSTRUCTION CAPITAL COSTS

Vessel Size: 1,300' x 130'

($000)

	DRAFT			
Location	25.5'	28.0'	32.0'	36.0'
Duluth Harbor	81,480	106,430	146,500	186,590
Superior Harbor	9,931	14,148	22,776	35,602
Two Harbors	4,800	8,100	19,000	31,900
Presque Isle Harbor	900	1,430	7,500	17,100
Milwaukee Harbor	---	---	---	---
Calumet Harbor	19,574	92,612	209,656	321,730
Indiana Harbor	10,990	27,110	69,380	152,580
Gary Harbor	5,630	8,480	20,550	49,280
Burns Harbor	6,750	2,000	4,050	6,380
Detroit Harbor	9,750	14,340	21,910	29,030
Toledo Harbor	152,480	188,930	292,050	666,380
Sandusky Harbor	104,180	149,870	228,565	383,001
Lorrain Harbor	19,050	30,023	48,403	84,463
Cleveland Harbor	10,050	15,581	30,334	46,280
Ashtabula Harbor	4,430	9,380	20,070	39,988
Conneaut Harbor	4,130	7,200	17,147	31,170
Buffalo Harbor	23,810	32,298	95,663	195,718
Total Harbors	467,935	713,932	1,253,554	2,277,192
St. Marys River	871,237	1,147,916	1,803,611	2,423,075
Straits of Mackinac	---	3,738	25,077	52,830
St. Clair River	573,600	718,336	1,163,143	1,628,938
Detroit River	653,923	868,034	5,531,793	9,834,419
Toledo Harbor to Detroit River	39,416	59,720	107,496	155,272
Pelee Passage	15,660	49,680	174,645	607,815
Total Channels	2,153,836	2,847,424	8,805,765	14,702,349
Total	2,621,771	3,561,356	10,059,319	16,979,541

SUMMARY OF FEDERAL CONSTRUCTION CAPITAL COSTS

Vessel Size: 1,300' x 130'

($000) (Operating & Maintenance)

	DRAFT			
Location	25.5'	28.0'	32.0'	36.0'
Duluth Harbor	65	74	89	107
Superior Harbor	0	0	0	0
Two Harbors	0	0	0	0
Presque Isle Harbor	0	0	0	0
Milwaukee Harbor	0	0	0	0
Calumet Harbor	4	6	8	10
Indiana Harbor	2	4	6	8
Gary Harbor	---	---	---	---
Burns Harbor	---	---	---	---
Detroit Harbor	30	49	54	59
Toledo Harbor	842	926	1,018	1,120
Sandusky Harbor	38	48	58	69
Lorrain Harbor	6	12	26	45
Cleveland Harbor	14	16	30	50
Ashtabula Harbor	12	18	40	75
Conneaut Harbor	10	12	15	30
Buffalo Harbor	59	66	73	80
Total Harbors	1,082	1,231	1,417	1,653
St. Marys River	266	293	322	354
Straits of Mackinac	---	---	---	---
St. Clair River	337	396	435	478
Detroit River	218	256	282	309
Toledo Harbor to Detroit River	421	463	509	560
Pelee Passage	37	86	185	492
Total Channels	1,279	1,494	1,733	2,193
Total	2,361	2,725	3,150	3,846

SUMMARY OF FEDERAL CONSTRUCTION CAPITAL COSTS

Vessel Size: 1,300' x 175'

($000)

Location	DRAFT 25.5'	28.0'	32.0'	36.0'
Duluth Harbor	85,580	110,530	150,600	190,690
Superior Harbor	14,197	18,838	27,582	40,397
Two Harbors	4,000	8,100	19,000	31,900
Presque Isle Harbor	900	1,430	7,500	17,100
Milwaukee Harbor	---	---	---	---
Calumet Harbor	26,350	124,670	282,230	433,099
Indiana Harbor	14,800	36,500	93,400	205,400
Gary Harbor	5,630	8,480	20,550	49,280
Burns Harbor	6,750	2,000	4,050	6,380
Detroit Harbor	11,560	15,990	23,230	30,010
Toledo Harbor	152,480	188,930	292,050	666,380
Sandusky Harbor	104,180	150,523	231,617	397,884
Lorrain Harbor	19,050	30,344	49,533	88,914
Cleveland Harbor	10,052	15,753	31,057	47,872
Ashtabula Harbor	4,430	9,380	20,396	42,740
Conneaut Harbor	4,130	7,200	17,371	33,059
Buffalo Harbor	24,524	39,457	100,452	215,304
Total Harbors	489,413	768,095	1,370,618	2,496,409
St. Marys River	1,375,085	1,666,822	2,430,540	3,187,753
Straits of Mackinac	---	3,739	25,078	54,076
St. Clair River	876,488	1,050,919	1,678,655	2,247,890
Detroit River	854,882	1,088,695	5,965,971	10,311,588
Toledo Harbor to Detroit River	53,056	80,384	144,696	209,008
Pelee Passage	15,660	49,680	174,645	607,815
Total Channels	3,175,171	3,940,239	10,419,585	16,618,130
Total	3,664,584	4,708,334	11,720,203	19,114,539

SUMMARY OF FEDERAL CONSTRUCTION CAPITAL COSTS

Vessel Size: 1,300' x 175'

($000) (Operating & Maintenance)

	DRAFT			
Location	25.5'	28.0'	32.0'	36.0'
Duluth Harbor	80	98	118	142
Superior Harbor	---	---	---	---
Two Harbors	---	---	---	---
Presque Isle Harbor	---	---	---	---
Milwaukee Harbor	---	---	---	---
Calumet Harbor	4	6	8	10
Indiana Harbor	2	4	6	8
Gary Harbor	0	0	0	0
Burns Harbor	---	---	---	---
Detroit Harbor	40	65	72	79
Toledo Harbor	1,432	1,575	1,733	1,906
Sandusky Harbor	42	52	62	74
Lorrain Harbor	8	15	30	50
Cleveland Harbor	18	20	40	80
Ashtabula Harbor	14	24	55	85
Conneaut Harbor	13	14	20	35
Buffalo Harbor	80	89	98	107
Total Harbors	1,733	1,962	2,242	2,576
St. Marys River	750	825	908	998
Straits of Mackinac	---	---	---	---
St. Clair River	731	803	822	970
Detroit River	473	519	570	627
Toledo Harbor to Detroit River	716	787	866	953
Pelee Passage	37	86	185	492
Total Channels	2,707	3,020	3,351	4,040
Total	4,440	4,982	5,593	6,616

APPENDIX C

DETAILS OF COMPARISON OF FEDERAL CONSTRUCTION COSTS

FOR DIFFERENT METHODS OF INCREASING VESSEL SIZE

IN UPPER GREAT LAKES SERVICE

(Based on Costs Shown in Appendix B)

(All figures are in thousands of 1977 value dollars)

COMPARISON OF FEDERAL CONSTRUCTION COSTS
FOR DIFFERENT METHODS OF INCREASING VESSEL SIZE IN UPPER GREAT LAKES SERVICE
VESSEL SIZE: 1,100' x 105'

Location	Enlarge Channels & Harbors	Emplace Control System	Comment
Duluth Harbor	---		
Superior Harbor	---		
Two Harbors	---		
Presque Isle Harbor	---		
Milwaukee Harbor	---		
Calumet Harbor	---		
Indiana Harbor	---		
Gary Harbor	---		
Burns Harbor	---		
Detroit Harbor	75.4	---	All dredging from widening channels
Toledo Harbor	---	---	------
Sandusky Harbor	80.9	80.9	Dredging for turning basin only
Lorrain Harbor	8.6	8.6	Dredging for turning basin only
Cleveland Harbor	9.5	9.5	Remove breakwater
Ashtabula Harbor	2.7	2.7	Dredge turning basin
Conneaut Harbor	2.3	2.3	Dredge turning basin
Buffalo Harbor	20.9	10.5	Widen channel (50%); dredge turning basin (50%)
St. Marys River	57.8	57.8	New locks
Straits of Mackinac			
St. Clair River			
Detroit River			
Toledo Harbor to Detroit River			
Pelee Passage			
Total	197.3	114.5	

COMPARISON OF FEDERAL CONSTRUCTION COSTS
FOR DIFFERENT METHODS OF INCREASING VESSEL SIZE IN UPPER GREAT LAKES SERVICE
VESSEL SIZE: 1,100' x 130'

Location	Enlarge Channels & Harbors	Emplace Control System	Comment
Duluth Harbor	---	---	
Superior Harbor	---	---	
Two Harbors	---	---	
Presque Isle Harbor	---	---	
Milwaukee Harbor	---	---	
Calumet Harbor	---	---	
Indiana Harbor	---	---	
Gary Harbor	---	---	
Burns Harbor	6.0	6.0	Deepening of channel
Detroit Harbor	9.3	---	Widen channel
Toledo Harbor	98.3	---	Widening channel to 1,330' (Cost based on 1,200' x 130' less 1,800' x 130' - 1,200' x 130')
Sandusky Harbor	83.8	80.9	Dredging for turning basin only; widening channel
Lorrain Harbor	8.6	8.6	Dredging for turning basin only
Cleveland Harbor	9.5	9.5	Remove breakwater
Ashtabula Harbor	2.7	2.7	Dredge turning basin
Conneaut Harbor	2.3	2.3	Dredge turning basin
Buffalo Harbor	23.4	13.7	Widen channel (50%); Dredge turning basin (50%)
St. Marys River	869.4	80.9	$77.8M for locks; 2.1M for bridge mod; deduct $1.0 for dredge saving between 1,200' and 1,100'
Straits of Mackinac	---	---	
St. Clair River	573.6	---	All costs associated with widening channel
Detroit River	658.6	---	All costs associated with widening channel
Toledo Harbor to Detroit River	39.4	---	All costs associated with widening channel
Pelee Passage	15.7		All costs associated with widening channel
Total	2,400.6	204.6	

COMPARISON OF FEDERAL CONSTRUCTION COSTS
FOR DIFFERENT METHODS OF INCREASING VESSEL SIZE IN UPPER GREAT LAKES SERVICE
VESSEL SIZE: 1,100' x 175'

Location	Enlarge Channels & Harbors	Emplace Control System	Comment
Duluth Harbor	4.1	4.1	Bridge improvements
Superior Harbor	---	---	
Two Harbors	---	---	
Presque Isle Harbor	---	---	
Milwaukee Harbor	---	---	
Calumet Harbor	---	---	
Indiana Harbor	---	---	
Gary Harbor	---	---	
Burns Harbor	---	---	Widen channel
Detroit Harbor	11.6	---	Widen approach and entrance channels to 1,380' (cost based on 1,500' x 175'-4 times Δ 1,300' x 130' 1,200' x 130')
Toledo Harbor	119.1	---	
Sandusky Harbor	83.8	80.9	Dredging for turning basin; widening channel
Lorrain Harbor	19.1	9.5	Remove breakwater; widen approach channels
Cleveland Harbor	10.1	2.7	Dredge turning basin; widen approach channels
Ashtabula Harbor	4.4	2.7	Dredge turning basin; widen approach channel
Conneaut Harbor	4.1	2.3	Dredge turning basin; widen approach channel
Buffalo Harbor	24.5	13.7	Dredge turning basin; widen channel
St. Marys River	1,374.1	93.0	91.9 for locks; 2.1 for bridge, deduct $1.0 for dredge saving between 1,200' and 1,100'
Straits of Mackinac	---	---	
St. Clair River	876.5	---	All costs associated with channel
Detroit River	554.9	---	All costs associated with channel
Toledo Harbor to Detroit River	53.1	---	All costs associated with channel
Pelee Passage	15.7		All costs associated with channel
Total	3,151.0	204.8	

COMPARISON OF FEDERAL CONSTRUCTION COSTS
FOR DIFFERENT METHODS OF INCREASING VESSEL SIZE IN UPPER GREAT LAKES SERVICE
VESSEL SIZE: 1,300' x 130'

Location	Enlarge Channels & Harbors	Emplace Control System	Comment
Duluth Harbor	81.5	81.5	Dredging for turning basin only
Superior Harbor	9.9	9.9	Dredging for turning basin only
Two Harbors	4.8	4.8	New breakwater and dredging for turning basin
Presque Isle Harbor	.9	.9	Dredging for turning basin only
Milwaukee Harbor	---	---	------
Calumet Harbor	19.6	19.6	Dredging to provide docking space; deepen entire channel
Indiana Harbor	11.0	11.0	New breakwaters; new turning basin
Gary Harbor	5.6	5.6	Dredging for turning basin only
Burns Harbor	6.8	6.8	Dredging for turning basin; deepen entire channel
Detroit Harbor	9.8	2.9	Channel is widened (70%); turning basin expanded (30%)
Toledo Harbor	152.5	15.3	Channels widened (90%); turning basin expanded (10%)
Sandusky Harbor	104.2	83.4	Channels widened (20%); turning basin expanded and dikes removed (80%)
Lorrain Harbor	19.1	19.1	Change breakwater and dredge turning basin
Cleveland Harbor	10.1	10.1	Change breakwater and dredge turning basin
Ashtabula Harbor	4.4	4.4	Dredging for turning basin only
Conneaut Harbor	4.1	4.1	Dredging for turning basin only
Buffalo Harbor	23.8	23.8	Dredging for turning basin; deepen entire channel
St. Marys River	871.2	82.7	2.0 Mil for dredging from 1,100' to 1,300'; 78.6 Mil for locks; 2.1 Mil for bridge
Straits of Mackinac	---	---	
St. Clair River	573.6	---	All costs associated with widening channel
Detroit River	653.9	---	All costs associated with widening channel
Toledo Harbor to Detroit River	39.4	---	All costs associated with widening channel
Pelee Passage	15.7		All costs associated with widening channel
Total	2,621.9	385.9	

COMPARISON OF FEDERAL CONSTRUCTION COSTS
FOR DIFFERENT METHODS OF INCREASING VESSEL SIZE IN UPPER GREAT LAKES SERVICE
VESSEL SIZE: 1,300' x 175'

Location	Enlarge Channels & Harbors	Emplace Control System	Comment
Duluth Harbor	85.6	85.6	Dredging for turning basin; improve bridge
Superior Harbor	14.2	9.9	Dredging for turning basin only
Two Harbors	4.8	4.8	Dredging for turning basin only
Presque Isle Harbor	.9	.9	Dredging for turning basin only
Milwaukee Harbor	---	---	
Calumet Harbor	26.4	26.4	Dredging for turning basin only; deepen entire channel
Indiana Harbor	14.8	14.8	Additional backwaters; new turning basin
Gary Harbor	5.6	5.6	Dredging for turning basin only
Burns Harbor	6.8	6.8	Dredging for turning basin only
Detroit Harbor	11.6	2.9	Channel is widened; turning basin expanded
Toledo Harbor	152.5	15.3	Channel is widened; turning basin expanded
Sandusky Harbor	104.2	83.4	Channel is widened; turning basin expanded and dikes removed
Lorrain Harbor	19.1	19.1	Replace breakwaters; widen channels (same as 1,300' x 130')
Cleveland Harbor	10.1	10.1	Enlarge turning basin; widen channel (same as 1,300' x 130')
Ashtabula Harbor	4.4	4.4	Enlarge turning basin; widen channel (same as 1,300' x 130')
Conneaut Harbor	4.1	4.1	Enlarge turning basin; widen channel (same as 1,300' x 130')
Buffalo Harbor	24.5	24.5	Enlarge turning basin; widen channel (same as 1,300' x 130')
St. Marys River	1,375.1	96.7	2.0 Mil for dredging from 1,100' to 1,300'; 91.9 Mil for locks; 2.8 Mil for bridges
Straits of Mackinac	---	---	
St. Clair River	876.5	---	All costs associated with widening channel
Detroit River	854.9	---	All costs associated with widening channel
Toledo Harbor to Detroit River	53.1	---	All costs associated with widening channel
Pelee Passage	15.7		All costs associated with widening channel
Total	3,664.9	415.3	

COMPARISON OF FEDERAL CONSTRUCTION COSTS
FOR DIFFERENT METHODS OF INCREASING VESSEL SIZE IN UPPER GREAT LAKES SERVICE
VESSEL SIZE: 1,200' x 130'

Location	Enlarge Channels & Harbors	Emplace Control System	Comment
Duluth Harbor	75.2	75.2	Dredging for new turning basin only
Superior Harbor	9.2	9.2	Dredging for new turning basin only
Two Harbors	4.0	4.0	New breakwater and dredging for turning basin
Presque Isle Harbor	.8	.8	Dredging for turning basin only
Milwaukee Harbor	---	---	
Calumet Harbor	18.1	18.1	Dredging to provide docking space; deepen entire channel
Indiana Harbor	10.1	10.1	Additional breakwaters; new turning basin
Gary Harbor	5.6	5.6	Dredging for turning basin only
Burns Harbor	6.0	6.0	Dredging for turning basin; deepen entire channel
Detroit Harbor	9.3	2.8	Channel widened (70%); turning basin expanded (30%)
Toledo Harbor	125.4	12.6	Channel widened (90%); turning basin expanded (10%)
Sandusky Harbor	92.6	74.1	Channel widened (20%); turning basin expanded, dikes removed (80%)
Lorrain Harbor	13.8	13.8	Change breakwater and dredge turning basin
Cleveland Harbor	9.8	9.8	Change breakwater and dredge turning basin
Ashtabula Harbor	3.6	3.6	Dredging for turning basin only
Conneaut Harbor	3.3	3.3	Dredging for turning basin only
Buffalo Harbor	23.4	23.4	Dredging for turning basin; deepen entire channel
St. Marys River	870.4	80.9	1.0 Mil for dredging to 1,200'
Straits of Mackinac	---	---	
St. Clair River	573.6	---	All costs associated with widening channel
Detroit River	658.6	---	All costs associated with widening channel
Toledo Harbor to Detroit River	39.4	---	All costs associated with widening channel
Pelee Passage	15.7		All costs associated with widening channel
Total	2,567.9	353.3	

COMPARISON OF FEDERAL CONSTRUCTION COSTS
FOR DIFFERENT METHODS OF INCREASING VESSEL SIZE IN UPPER GREAT LAKES SERVICE
VESSEL SIZE: 1,200' x 175'

Location	Enlarge Channels & Harbors	Emplace Control System	Comment
Duluth Harbor	85.6	85.6	Dredging for turning basin; improve bridge
Superior Harbor	14.2	9.2	Dredging for turning basin only
Two Harbors	4.0	4.0	Dredging for turning basin only
Presque Isle Harbor	.8	.8	Dredging for turning basin only
Milwaukee Harbor	---	---	
Calumet Harbor	18.1	18.1	Dredging for turning basin; deepen entire channel
Indiana Harbor	10.1	10.1	Additional breakwaters; new turning basin
Gary Harbor	5.6	5.6	Dredging for turning basin only
Burns Harbor	6.0	6.0	Dredging for turning basin only
Detroit Harbor	11.6	2.8	Channel is widened (1,300' x 175' estimate); turning basin expanded
Toledo Harbor	152.4	12.6	Channel is widened (1,300' x 175' estimate); turning basin expanded
Sandusky Harbor	104.2	74.1	Channel is widened (1,300' x 174' estimate); turning basin expanded, and dikes removed
Lorrain Harbor	19.1	13.8	Replace breakwater; widen channels
Cleveland Harbor	10.1	9.8	Enlarge turning basin; widen channels to approach
Ashtabula Harbor	4.4	3.6	Enlarge turning basin; widen channels to approach
Conneaut Harbor	4.1	3.3	Enlarge turning basin; widen channels to approach
Buffalo Harbor	24.5	23.4	Enlarge turning basin; widen channels to approach
St. Marys River	1,374.2	94.9	1.0 Mil for dredging to 1,200'; 91.1 Mil for locks; 2.8 Mil for bridge
Straits of Mackinac	---	---	
St. Clair River	876.5	---	All costs associated with widening channel
Detroit River	854.5	---	All costs associated with widening channel
Toledo Harbor to Detroit River	53.1	---	All costs associated with widening channel
Pelee Passage	15.7		All costs associated with widening channel
Total	3,648.8	377.7	