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TECHNICAL AND ECONOMIC FEASIBILITY OF MULTIBARGE OPERATIONS IN OPEN WATER

Robert M. Scher

Prepared for
Dow Chemical USA
Midland, Michigan

THE DEPARTMENT OF NAVAL ARCHITECTURE AND MARINE ENGINEERING

THE UNIVERSITY OF MICHIGAN
COLLEGE OF ENGINEERING

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ABSTRACT

This report is the result of a preliminary study of the economic prospects and technical limitations of various multibarge systems potentially suitable for operation in unprotected waters. Particular emphasis has been placed on coastal, short-sea, and feeder applications of these systems, where a high degree of flexibility and intermodality is desirable.

The systems considered include well-known hardware, such as the LASH concept, a LASH-compatible feeder vessel (FLASH), as well as conjectural systems of various types. These include multibarge flotillas with articulated or flexible coupling devices, modular vessels, and rigid-frame barge integrators.

A qualitative discussion of generalized service patterns, terminal operations, cargoes, and cost-assignment decisions especially applicable to multibarge systems is included, together with specific technical information pertaining to each distinct type of system. An economic comparison and sensitivities to certain design parameters are presented for a sample complex route.

Finally, detailed synthesis models, including performance, towboat assignment, weights, and cost estimates are provided for three promising multibarge-feeder concepts: barge-carrying (LASH) vessel, float-on LASH feeder (FLASH), and multibarge flotilla.

ACKNOWLEDGEMENTS

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For much information, insight, and data, my thanks go to John Marriner, C. van Mook of Dravo, and Ed Shearer of Hillman Barge.

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I. INTRODUCTION

Multibarge operations have for many years been the dominant form of waterborne transport not only on the rivers and inland waterways, but within the larger ports and harbors, as well as in coastal movements in relatively protected waters. The economic virtues of multibarge systems are well known, and compelling. These advantages may be classified, although by no means exhaustively, under the following general considerations:

1. Fast turnaround, with consequent high levels of capital and labor productivity.

2. Flexibility in routing and service pattern.

3. Flexibility in schedule.

4. System reliability due to interchangeability of components, together with the possibility of economically maintaining units in reserve to protect service.

5. Efficient interfacing between transport subsystems, e.g., coastal and riverine, coastal and transocean, etc.

Note that low initial investment does not appear in the above listing. While low cost certainly applies to the traditional inland barge-tow combination, the concept of multibarge systems will be more broadly defined, for the purposes of this study, to include not only the familiar river-barge flotilla, but all marine transport systems involving multiple barge units, some of which are hardly characterized by a particularly low first cost. Barge-carrying vessels, for example, usually represent a large capital investment, and yet the economic advantages outlined above have proven sufficient to motivate investment in such systems.

While the advantages of multibarge operations have been extensively applied to river and inland transport, the role of multibarge systems in open-water shipping has not reached a comparable stature. In part, it is due to the fact that full exploitation of the multibarge system's economic advantages can only be realized under certain geographic and service-pattern constraints, most notably where a premium exists on an efficient interface between two otherwise disjoint subsystems. Largely, however, technological difficulties have presented the greatest obstacle to the successful implementation of open-water multibarge systems, regardless of the potential economic benefits that might be realized upon their solution.

Specifically, the aims of this pilot study can be summarized in terms of the following organization of tasks:

1. Compile engineering and economic information on the principal potential methods for operating multibarge systems in open water, for existing, projected, and speculative systems. This information is to include data on design arrangements, operating capabilities, technical problems, weights, and building and operating costs.

2. Generate rudimentary information on the potential areas of demand for multibarge transport in open water, not specifically in terms of an exact market analysis, but rather in terms of identifying the broad geographic areas and types of service to which a multibarge system would be most applicable.

3. Suggest and approach novel solutions to the technical problems of multibarge integration or linkage for open-water operation.

4. Develop preliminary techniques for predicting the comparative economics of alternative multibarge systems.

5. Illustrate the use of these techniques on a typical set of trade requirements.

Our over-all objective has not been to provide the definitive study of multibarge systems for offshore applications, nor have we even attempted to exhaust the engineering and economic issues involved. Rather, we have tried to make a significant start, identifying the key questions even when we cannot answer them to complete satisfaction. To the extent that this can be called a success, we feel that we have succeeded.

II. BACKGROUND OF THE STUDY

The underlying motivation for this work is well stated, from the point of view of a potential user of a multibarge transport capability, by Chomistek, (Ref. 1). While that work was directed specifically at the commercial environment of the Great Lakes region, many of the arguments can be applied with no less force to the conditions prevailing in coastwise and Gulf traffic, and to a certain extent, even in transoceanic service.

Central to Chomistek's thesis are a number of developments that are perhaps most striking in the context of Great Lakes shipping. Domestic commerce on the lakes is, as it has been for many decades, dominated by the movement of bulk cargo, not simply in terms of the types of commodities moved (iron ore, coal, grain, limestone), but just as importantly, in terms of the annual throughputs of these commodities. With this orientation, the trend towards increasing ship size has been natural and inevitable, in view of the economic advantages of scale. As replacement tonnage has shifted into the larger vessels, the obsolescence of smaller Great Lakes ships has become increasingly evident. With the eventual retirement of vessels of the smaller classes, the transport alternatives open to those firms dealing in other than large bulk shipments have been narrowed to the rail, highway, or barge modes.

In recent years, however, the same trends that resulted in the emphasis on increasing ship sizes have begun to operate within the barging industry. Basically, the multipurpose barge has grown in size in order to provide the most efficient service for those of its users who can appreciate the advantages of scale, namely, those who can fill the entire unit capacity with a single consignment. Once again, the shipper whose commodities normally move in smaller than shipload lots has been constrained to accept the diseconomies of ullage, or to rely more heavily on the alternative rail or highway modes.

Chomistek's conclusion is that there exists in the Great Lakes region a demand for waterborne transport of neo-bulk or non-bulk commodities characterized by relatively small consignment sizes. We accept as a premise Chomistek's statement that "The prime need is the capability to deliver small (1,000 to 2,000 ton) parcels (barges) economically to ports around the Lakes with routine and dispatch throughout the year."

The purpose of this study, then, is to investigate in a preliminary way the potential means by which this capability might be achieved. We will confine our efforts to those systems that, at least in concept, meet the following two criteria:

1. The system must offer an explicitly multibarge capability. We therefore exclude single-unit systems, whether integrated tug/barge or otherwise.

2. The system must offer open-water capability under all reasonable weather conditions. We therefore exclude "systems of opportunity," those concepts which can only be expected to operate safely in their normal configuration given the assurance of relatively placid weather, an assurance that exists solely on paper in any case.

It has been our intent to provide some general insights into the problems and potentials of multibarge systems as applied to open-water transport, not only on the Great Lakes, but in Gulf and coastal service as well. Nevertheless, for much of the specific engineering work, the lakes have provided a convenient reference frame, and hypothetical Great Lakes services have been used as the basis for the subsequent economic comparison.

In particular, the environment of the Great Lakes was an element of our thinking through the following three avenues:

1. The lakes provided a dimensional framework, not only in broad terms of geography, but also in terms of lock, dock, and channel restrictions. These constraints have, of course, played a part in the conceptual design process, but without a significant loss in the generality of our over-all method.

2. The Great Lakes offered an opportunity to study one of the crucial elements of the multibarge capability, namely, the ability to interface with another transport subsystem, the rivers and inland waterways.

3. The fresh-water environment has made certain assumptions regarding the life expectancy of flexible barge linkages more tenable than they might otherwise be.

Notwithstanding these factors, our method and, (by and large) our conclusions, will remain useful for coastal and Gulf services.

III. CATALOG OF POTENTIAL MULTIBARGE SYSTEMS: TECHNICAL ISSUES

From the outset, it was apparent that the technical possibilities for multibarge systems exceeded our abilities to name them all. Therefore, at an early stage, it became necessary to arrange some sort of classification scheme that would identify the salient features of the various systems. Figure 1 shows one possible arrangement of systems, organized on the basis of the following characteristics:

1. Are the barge units floating on their own displacement, or carried aboard a line-haul vessel that takes on added displacement as it is loaded? (A third possibility is a hybrid of the two concepts, with some of the units floating and some supported independent of their own buoyancy, or with the units carrying only a part of their own weight, while the remainder is supported by the vessel's displacement.)

2. If the barges float on their own buoyancy, how are they held together, and what sort of structure (if any) takes the over-all bending moments?

3. If the barges are carried aboard a line-haul vessel, how are they placed aboard?

4. If the barges are carried aboard a line-haul vessel, or integrated within a structural framework that constitutes in itself a vessel of sorts, is the vessel self-propelled or towed by an external power source?

5. Is the technology extant, proposed, or conjectural?

This hierarchy of characteristics is obviously not exhaustive, but it has been useful in categorizing the majority of possible multibarge systems. In the following description of some of these systems, we will be exploring some of the features of the various branches of Fig. 1.

A. The LASH System

A well-known example of the barge-carrying type of system, the LASH concept has already established its feasibility in ocean transport.

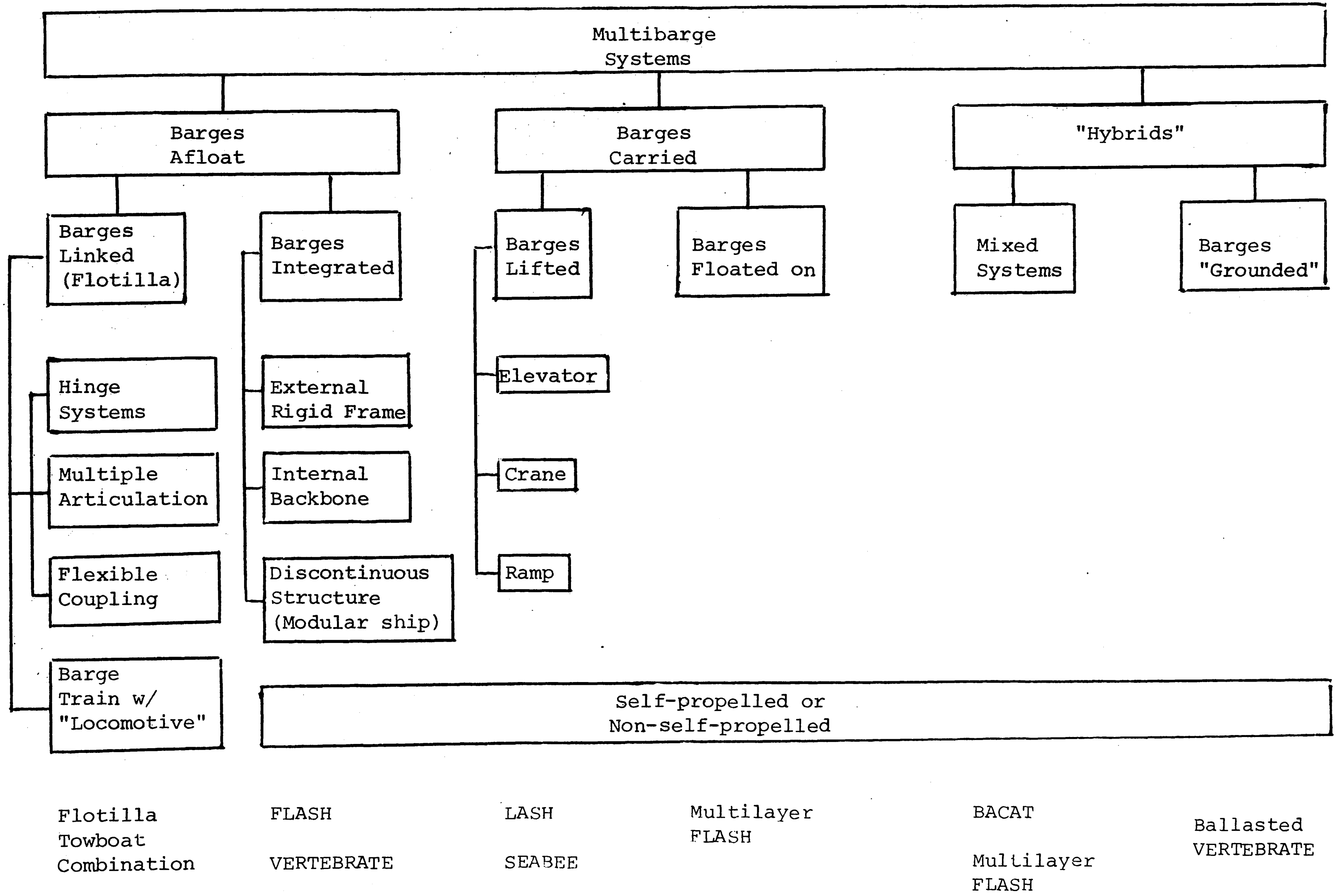


Fig. 1. A partial catalog of systems

Basically, a LASH system consists of a barge-carrying line-haul vessel, normally a self-propelled ship, and an arbitrarily large set of interchangeable box barges, the standard dimensions of which are as follows:

Length	61.5 ft
Beam	31.2 ft
Depth (typical)	13.0 ft
Maximum fresh-water draft	9.0 ft
Maximum displacement	480.0 lton
Empty weight	80.0 lton
Cargo deadweight	400.0 lton

The barges are normally loaded aboard the line-haul vessel by means of a gantry crane. (Apart from the size of the standard barge, and the use of an elevator in place of a crane system, there is little to differentiate the LASH from the SEABEE system in terms of their over-all economic characteristics.)

Among the advantages of the LASH (and SEABEE) concepts, particularly as a starting point for the study of generalized multibarge systems, are the following considerations:

1. They are existing systems, with known operational capabilities, design characteristics, and costs.

2. The barge units, particularly the LASH boxes, have attained widespread compatibility with other transport systems, a high degree of standardization, and hence, of interchangeability.

3. Specialized boxes for various types of cargo (e.g., palletized, containerized, bulk, liquid, or heavy-lift) present no special problems or added delays in loading the vessel.

4. The LASH vessel can load or unload in an open roadstead, and without the need for specialized docking facilities or shoreside equipment.

5. Since the line-haul vessel is normally self-propelled and shipform, sufficient ice-breaking capability for year-round operations on the Great Lakes is virtually assured, given sufficient power and structure.

However, many of the potential services in which a multibarge system might offer an attractive alternative are essentially feeder, or short-haul, services. For example, on the lakes, and in coastal trade in general, distances between terminals are often relatively short, and numerous stops are made on each round trip. Clearly, such services call for smaller vessels, lower service speeds and, importantly, reduced sensitivity of costs to port-time.

Thus, we arrive at the concept of a "dwarf LASH," a barge-carrying vessel adapted for the particular needs of coastal or short-sea trade. In Table I, the principal characteristics of our dwarf LASH, specifically intended for a hypothetical Great Lakes feeder or "milk-run" service, are compared with those of a typical ocean LASH vessel of one of the larger classes. A profile and midship section of the smaller vessel are shown in Fig. 2.

A number of alternative arrangements were studied, including one in which the barges were loaded with their *longer* dimension parallel to the vessel centerline, rather than athwartships, a rather undesirable departure from accepted LASH design practice, although with no insoluble technical problems. The sole reason for considering such an arrangement was the desire to maintain a suitable beam for upriver operations, and to allow transit through the smaller locks on the Great Lakes and seaway system. In any case, the final configuration was more or less conventional, with the exception of the machinery location and the narrowness of the side tanks.

It should be mentioned that if this constraint were removed, and a beam on the order of 90-95 ft adopted, the same capacity could be achieved on a shorter length, by stacking the barges higher, with a substantial saving in hull steel weight and cost. The problems of such a vessel, having a length-beam ratio of under 3.5, would be primarily in the field of resistance, and in particular, the horsepower penalty might outweigh construction cost savings over the life of the vessel. Nevertheless, the wider beam becomes more attractive for vessels of somewhat larger capacity, perhaps about 40-45 LASH units.

The critical operational difficulty of the dwarf LASH is the trim produced by hoisting a LASH barge, particularly with the vessel relatively lightly loaded. For a vessel of the approximate dimensions and form shown in Fig. 2, a trim angle of 1.5° would be about the maximum experienced, and this is not excessive. Nonetheless, when loading in shallow harbors, the after draft would have to be watched carefully as the last few barges were put aboard.

Apart from these considerations, the principal economic drawback of the dwarf LASH concept is tied up in one particular item of outfit: the gantry. The cost of a 500-ton-capacity crane is large, and quite independent of the size of the vessel, placing a relatively greater capital recovery burden on the smaller ship. Similarly, the crane's weight is a large item for a small ship.

Up to this point, we have been treating both LASH and SEABEE systems in one breath, as if they were entirely alike. In fact, the SEABEE barge is approximately twice the size of the LASH unit, displacing about 1000 lton fully loaded, and realizing an advantage of about 12% in tare weight per ton of payload. However, SEABEE is a less universal system, and the general argument regarding the weight and cost of barge-handling equipment apply even more stringently to the SEABEE elevator and guides than to the LASH crane. For these reasons, a dwarf SEABEE vessel was not explicitly studied, however the over-all economic results for the two systems should be fairly comparable.

Our next line of approach was to investigate alternative barge-handling methods, remaining within the LASH format. Our primary aim in this process was to free the small barge-carrying vessel of the heavy, capital intensive barge-lifting gear.

B. The FLASH System

The most obvious way to eliminate the need for a crane is simply not to lift the barges. The FLASH concept (float-on LASH), is already in use as a feeder for ocean-going LASH vessels. Basically, the FLASH vessel is little more than a floating dock, into which the LASH lighters

Table I. Comparison of principal characteristics of ocean and "dwarf" LASH vessels.

	Ocean	Dwarf
Length overall (ft)	893	480
Beam (ft)	100	75
Depth (ft)	60	36
Full load draft (ft)	40.7	22.5
Deadweight (lton)	46040	11700
Cargo deadweight (lton) (excluding tare)	35600	9600
Service speed (knot)	22	13
Shaft horsepower	32000	5400
Complement	34	27
Lighter capacity	89	24
Gantry capacity (lton)	510	510

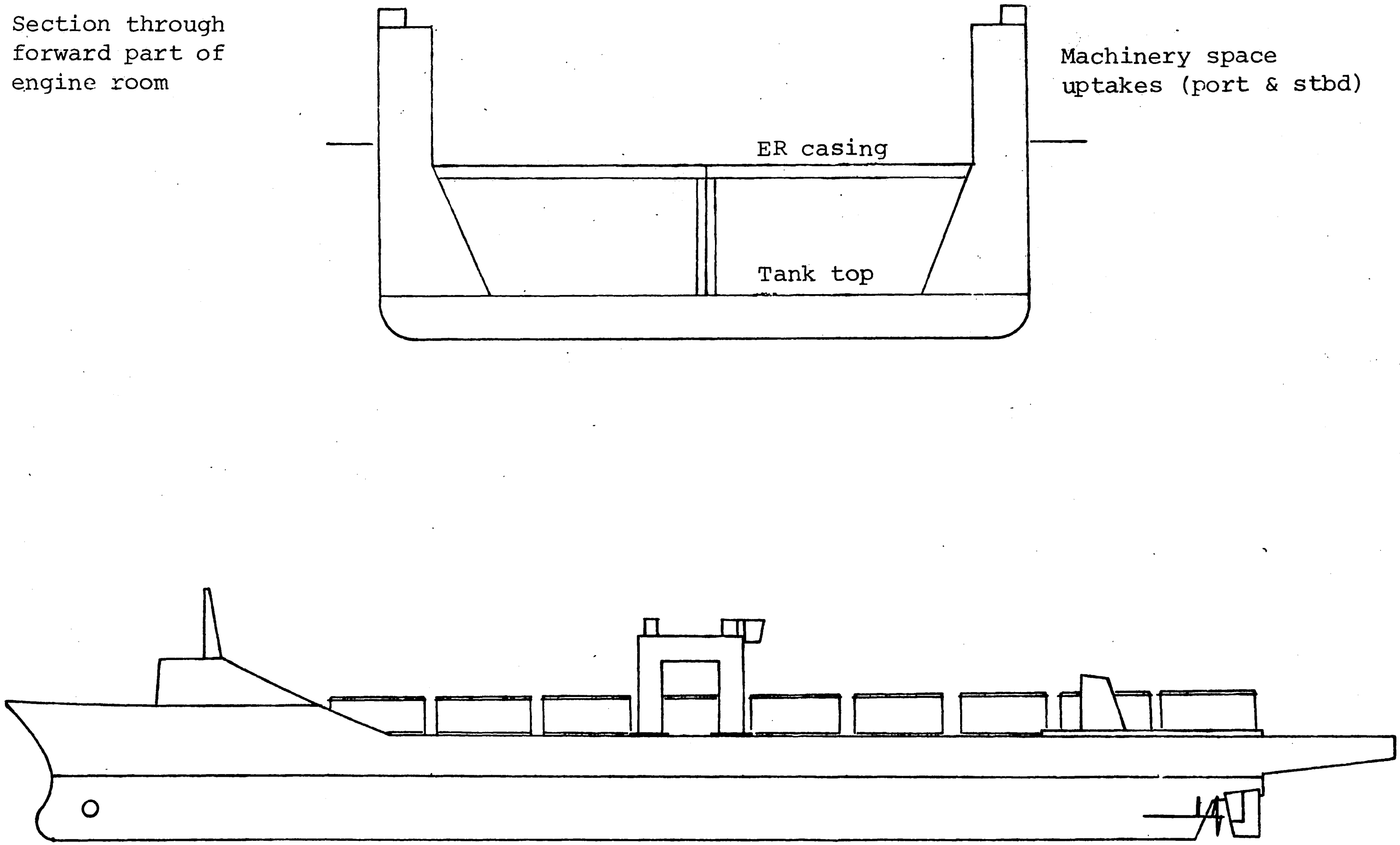


Fig. 2. Dwarf LASH vessel, 24 lighter capacity. Dimensions: 480 × 75 × 36/22.5 ft.
Twin screw 5400 shp, 13 knots.

are secured while still floating on their own buoyancy. The FLASH vessel thus remains at a constant displacement and draft whether in the loaded or empty condition. Variations in the draft of the individual lighters are accommodated entirely by adjustment of the securing gear, which may be as simple as tying the lighter in with lines, or may involve more sophisticated guides and locking mechanisms.

The obvious advantage of the FLASH concept is simplicity. Shallow draft and low first cost are also important to a vessel whose chief role is as a feeder to a larger, deeper draft, and more expensive vessel. Existing FLASH carriers have been designed with capacities ranging between 8 and 15 LASH units. Without exception, these vessels have been non-self-propelled, undecked barges, open at the stern for entrance to the "dock."

In expanding the FLASH concept from a feeder vessel into a surrogate for the dwarf LASH, we encounter a dimensional constraint at once. Even allowing for no space between lighters (unlikely, to say the least) a FLASH vessel with a capacity of 24 lighters would require a length of 750 ft, *plus* the length of a suitable bow. Apart from being a rather inefficient and uneconomical length for a vessel with a total payload of under 10 000 lton, such a giant FLASH runs afoul of several of our dock and lock constraints on the lakes.

A somewhat smaller FLASH vessel, designed to Great Lakes constraints and intended for much the same service as the dwarf LASH, is shown in Fig. 3. The vessel is non-self-propelled, and indeed, given the conventional arrangement of the lighters with their longer dimension athwartships, it is difficult to see where an engine room might be worked in without fairly intense problems of one sort or another.

For example, machinery spaces in the sides of the vessel would require engines suitable for a rather unconventional engine-room layout less than 7 ft wide, no trivial problem when diesel engines of about 2000 shp are in question. Machinery could be placed topside, above the lighters, but only with grave questions of stability, since the vessel is a floating dock with limited waterplane area and inertia. Or machinery space might be incorporated into a deep double-bottom compartment, or in the bow, or even in the stern, with access to the dock through the sides of the vessel, somehow,

'FLASH'

FLOAT-ON LASH INTEGRATOR AND TOWBOAT

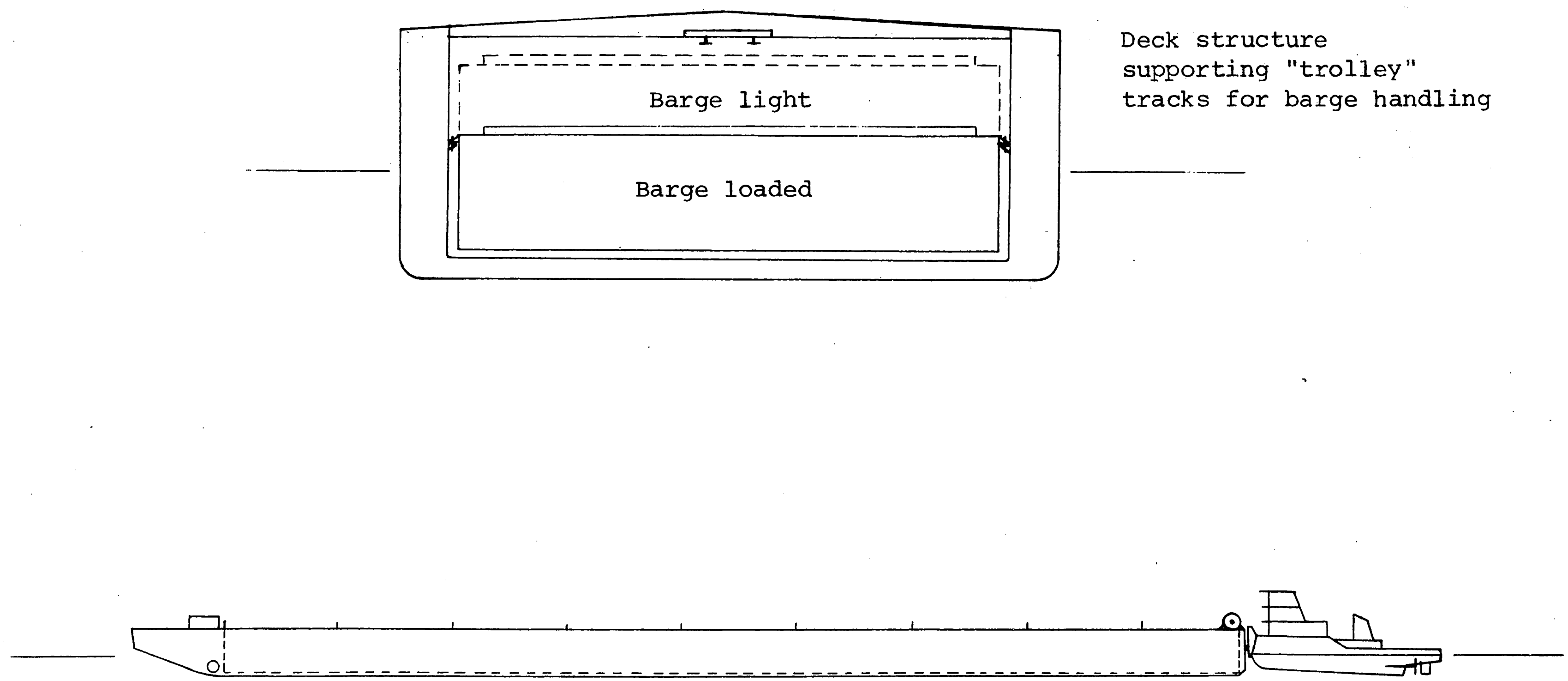


Fig. 3. FLASH vessel, 18 lighter capacity, and towboat. FLASH dimensions: 615 × 75 × 28/12 ft. Towboat: 4200 shp, 12 kt service speed.

etc. Even with suitable location for the machinery space, similar problems surround the propeller, and the maintenance of zero trim would be critical for float-on loading or unloading operations, requiring fine control in ballasting. Given these problems, it seems that by far the simplest solution is to put the engines in a towboat and have done with it.

Aside from the matter of propulsion, the FLASH vessel raises an interesting problem in structures. Torsional rigidity is a major problem in many vessels with large deck openings, such as containerships and barge carriers. In this respect, the FLASH vessel is even more seriously compromised by its lack of transverse bulkheads. In our design, we have assumed that the vessel is decked over, and that sufficient torsional strength can be obtained through web frames, in combination with the box girders formed by the side tanks.

The general problem of the forces acting on a lighter inside a FLASH vessel operating in waves is obviously quite complex, and outside the scope of this study, important as it might prove to the operational feasibility of the system. Similarly, the effect of the slack water within the dock on the roll behavior of the system has not been investigated. It is not impossible that the water in the dock might act as a flume-type stabilizer (or destabilizer). It has been assumed that the rather small clearances between the barges and the sides of the dock, and between the barges themselves, would reduce the virtual length of the U-tube, resulting in a shortened period of oscillation. Together with the long rolling period anticipated for a vessel of this type, with the metacentric height substantially reduced by free surface, it appears that the enclosed water will not have much effect on roll damping. However, a careful check of this assumption is called for.

In any case, the positioning system for the lighters is assumed to consist of fixed horizontal rails on the inner plating of the dock, with vertically adjustable brackets at the corners of the lighters, to compensate for draft and trim of the individual barge. Longitudinal motion within the dock is accomplished by towing the barges from an overhead trolley, running along the underside of the deck.

One of the principal operating difficulties of the FLASH vessel, as depicted in Fig. 3, is that the loading and unloading sequences cannot be made independent of each other, nor can loading and unloading operations proceed simultaneously. It is a single-string pattern, "first in, last out." In theory, a hinged bow opening could resolve this difficulty, permitting a simple "one-push" operation, with a new string of barges replacing the offloaded string in a continuous manner. However, the engineering problems involved in such a bow design have not been examined in detail, beyond assuring ourselves that it *could* be done for a price.

Apart from loading operations, the FLASH vessel of Fig. 3 depends to a great extend on a practical coupling between the unpowered carrier and the towboat. Since we will be returning to this matter at some length in our subsequent discussion of barge-flotilla operations, we will not dwell on it here.

With the FLASH system, we have retained some of the principal advantages of the LASH concept: standardization, fast turnaround, and ice-breaking capability. At the same time, the LASH vessel's gantry crane has been replaced, in effect, by the float-in guides and rails, with a substantial saving in first cost.

The fundamental constraint on the FLASH system is vessel capacity. For the Great Lakes dimensional limitations we have chosen, a capacity of 18 LASH lighters seems to be close to the maximum. To increase the capacity without increasing the over-all dimensions, additional layers of barges must be carried. An approach to this problem was made in the form of a two-tiered FLASH vessel. Basically, the operating concept is that the upper layer of barges is floated aboard with the vessel ballasted down to receive them. The ballast is then pumped out, and the lower tier of lighters is floated on. A number of arrangements were postulated for this scheme, but all run into the same geometric problem: enormous reserve buoyancy is needed to lift the upper layer of barges completely out of the water and high enough to float the lower layer underneath them. This reserve buoyancy in turn requires enormous amounts of ballast to sink it low enough to receive the top layer. The volume may be found in side tanks only if the lighters are placed with their longer dimension on the vessel centerline; if the barges are placed athwartships, suitable buoyancy is available only in a pathologically deep double bottom. An example of the former arrangement is shown in a self-propelled configuration in Fig. 4. The peculiar shape of the topsides is necessary to reduce the ballasting requirement.

In any case, we are left with no doubts about the multilayer FLASH concept. The technical difficulties, delays, and costs of depressing and elevating the vessel through the flooding and discharging of ballast tanks are quite simply horrendous. The pumping system costs alone are discouraging enough, even without the geometric absurdity required for such an extreme draft change. The loading sequence is constrained even more stringently than in the case of the simple FLASH, and the loading arrangements must now be made to resist the effects of periodic submergence. Without a doubt, the multilayer FLASH defeats the original aim, which was to *simplify* the barge-handling problem of the LASH system. No more need be said.

To return to the more promising system, the single-layer FLASH is felt to offer a promising alternative to the conventional LASH vessel, assuming that the technical problems mentioned above can be worked out. We next turn our attention to barge systems outside the LASH format.

C. Modular Vessel and Rigid-Frame Flotilla Systems

Figure 5 shows an artist's conception of a modular tanker. The modules are simply floated together to form a ship. The underlying problem in this scheme is the absence of continuous longitudinal structure in the form of deck and bottom flanges for the hull girder. Structural connections between the tank modules would have to take most of the stresses due to hull bending moments, even if a rigid centerline backbone were provided. The difficulty of securing structural integrity, particularly when the lower connections would have to be made submerged, cannot be denied. In addition, variation of the individual module drafts is unacceptable, and would have to be corrected by ballasting each unit to a common draft.

An offshoot of the modular-vessel concept is shown in Fig. 6. This is the so-called VERTEBRATE, in effect, a barge flotilla with a rigid frame.

TWO-TIER 'FLASH'

A FLOAT-ON LASH SHIP

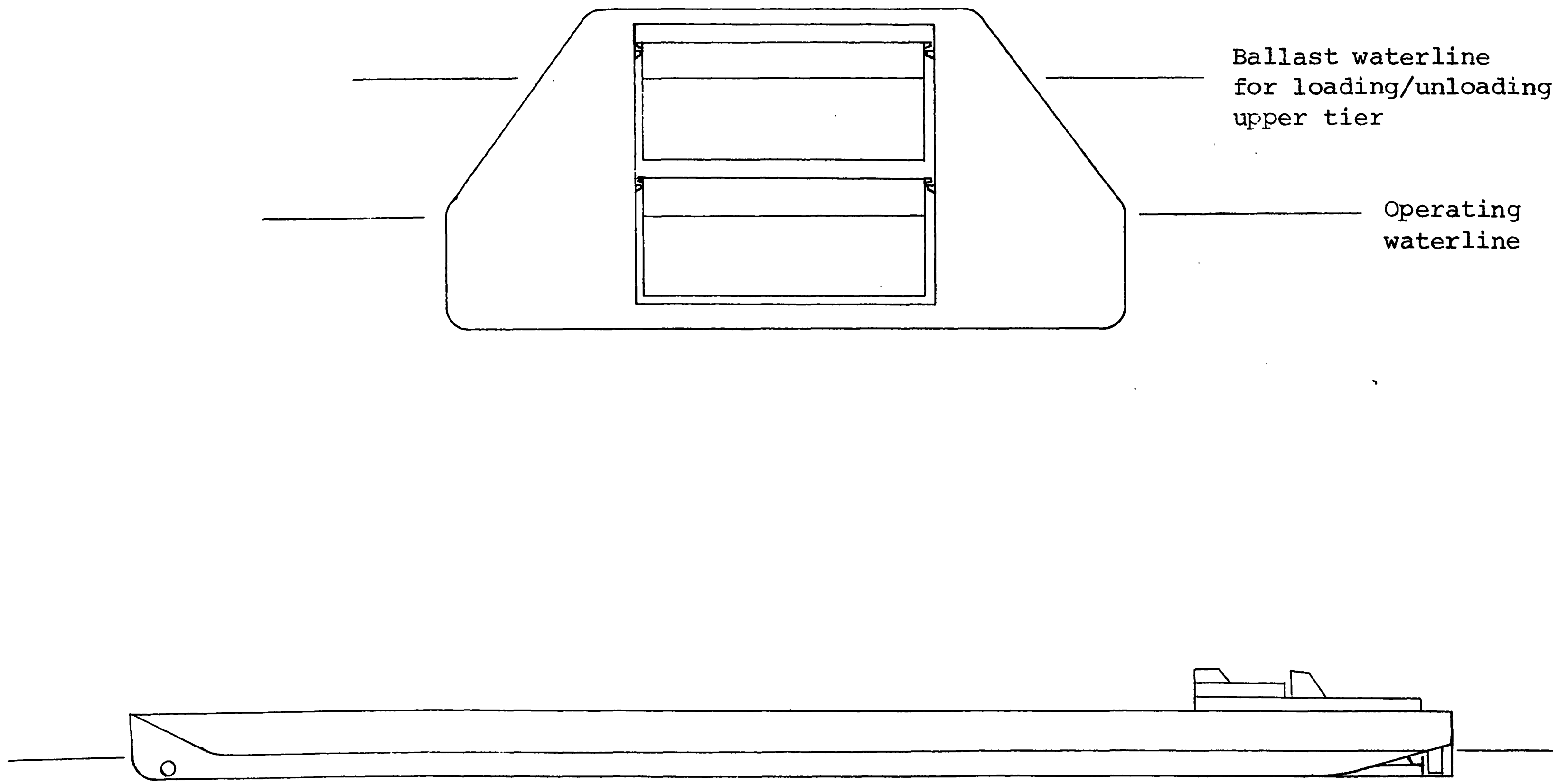


Fig. 4. Two-tier FLASH vessel, self-propelled. Dimensions: 730 × 75 × 35.5/12.5 ft. Lighter capacity 22. Twin-screw, 5800 shp, service speed 13 knot.

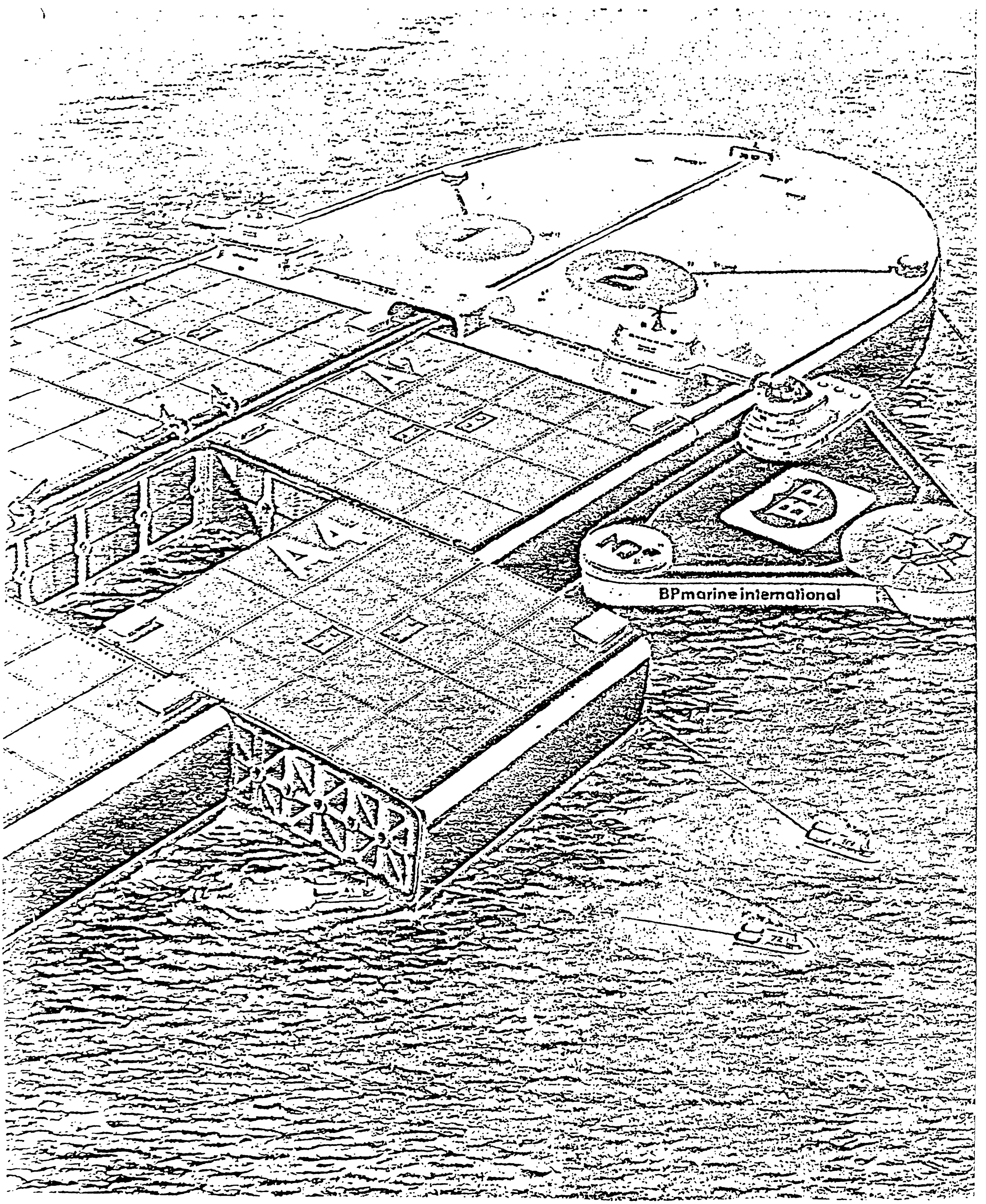


Fig. 5. Artist's conception of a modular ship, in this case, a large tanker.

'VERTEBRATE'

A RIGID-FRAME BARGE FLOTILLA OR MODULAR SHIP

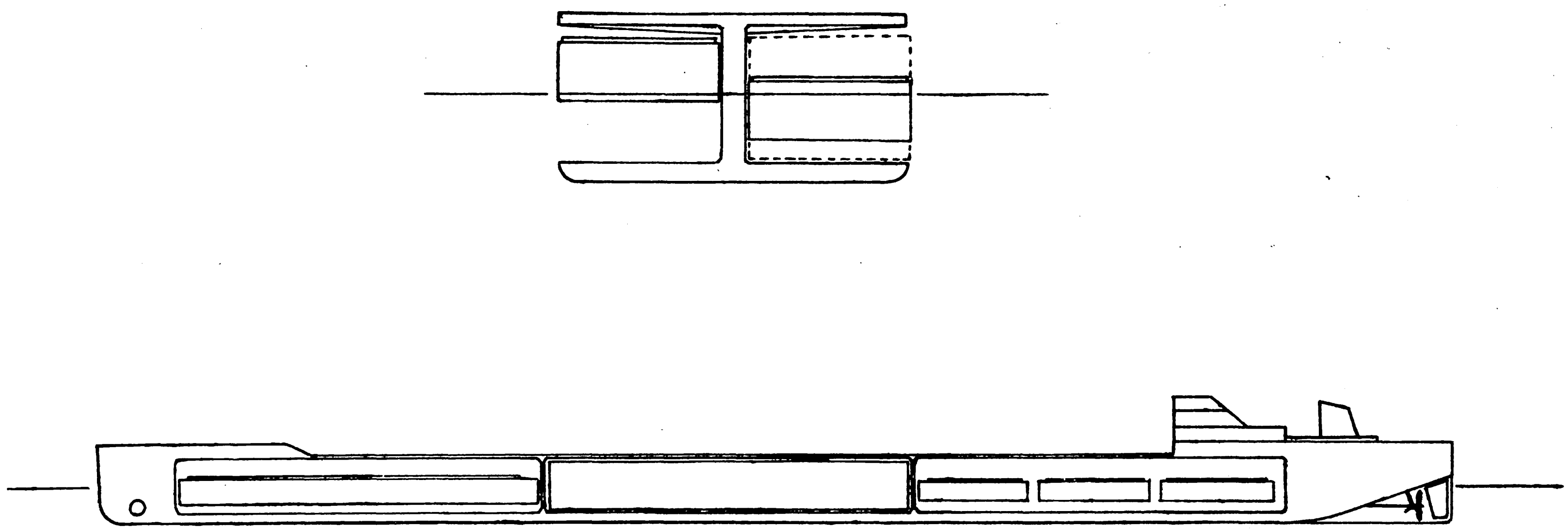


Fig. 6. VERTEBRATE. Overall dimensions: 730 × 75 × 36/19 ft. Twin-screw, 6000 shp, 13 knot service speed. Standard module: 195 × 35 × 28/15 ft, approximate deadweight 2400 lton each. Also shown: standard jumbo river unit (forward), 3 × LASH (aft).

The over-all concept is based on a rearrangement of the conventional ship hull girder, moving the side plating inward towards the centerline, resulting in a section that corresponds to a wide-flange beam instead of a box girder. Deck and bottom structures take the hull bending loads, and the barges or hull modules are locked into place between them.

The structural compromise is now in torsion, even though suitable transverse bulkheads can be installed. The distance between these bulkheads is determined by the length of the barge units, and this must be sufficiently short to obtain torsional strength. (It is assumed that the barges are isolated from over-all hull girder loads, and that the locking mechanisms serve only to hold the modules in place on the structure. Even with this assumption, the mechanisms will have to take the wave loadings on each module, no mean trick from the engineering standpoint.

As in the FLASH system, the displacement of the "backbone" vessel is independent of the barges. If suitable clearances are provided in the vertical direction, adjustment for individual barge draft can be provided in the locking mechanisms alone. These clearances, however, result in a very irregular underwater hull form, and would undoubtably entail a significant increase in resistance. If the modules are sized to fill the available space in the structure, then they will have to be ballasted to a common draft.

In the configuration of Fig. 6, the modules correspond to the length and breadth of a standard river barge, namely, 195 × 35 ft, and in fact, they could actually be river barges. The loading sequence of the units is now arbitrary, however, the performance of the system with one or more units not in place is seriously compromised from the hydrodynamic point of view.

It should be mentioned that the barge units are unprotected from wave action, and must be given suitable scantlings and hatch covers, even though they are theoretically isolated from over-all hull bending moments. The economic importance of this fact will be explored in some detail subsequently.

It seems clear that the modular-vessel concept is hemmed in by a number of problems: structural integrity, transverse stability in the empty condition, locking-mechanism loads, draft compatibility, and resistance. It is a matter of pure speculation at this point whether these technical difficulties can be solved in an economically viable way, but it is our opinion that the odds are not good.

D. The BACAT System and Derivatives

The proposed BACAT (barge-carrying catamaran) system is a hybrid of mixed barge-lifting *and* float-on capability. The vessel shown in Fig. 7 combines an elevator to upper-deck stowage with an enclosed dock for float-on barges. The sizes of the units may be identical or mixed. In any case, the BACAT vessel shares many of the characteristics of the LASH/SEABEE concepts, principally with regard to the expense, weight, and complexity of the barge-handling equipment. While the BACAT may be competitive as an ocean-going line-haul vessel, large, fast, and rarely in port, the concept suffers from shrinkage whether of the route or the vessel itself.

If the barge-lifting capability is omitted for the smaller version engaged in feeder or short-haul service, we are left with a floating dock, analogous to the FLASH concept apart from the size of the barge units. The same problems and potentials are anticipated, in general, regardless of the size chosen for the barge units. In fact, the choice of unit size is largely a matter of balancing the requirements of average consignment volume, system flexibility, operational restrictions, and the tare weight advantage realized by larger units.

Of particular interest is the concept of mixed barge sizes, operating within the float-on-vessel system. A certain degree of generalization in barge-securing gear would be required, but the difficulties could be minimized by offering barge units sized as integral multiples of the basic unit, sharing one common principal dimension (probably length). By adjusting the mix of barge sizes within the service fleet, the operator would be able to tune his service to the specific needs of shippers whose commodities require different consignment sizes.

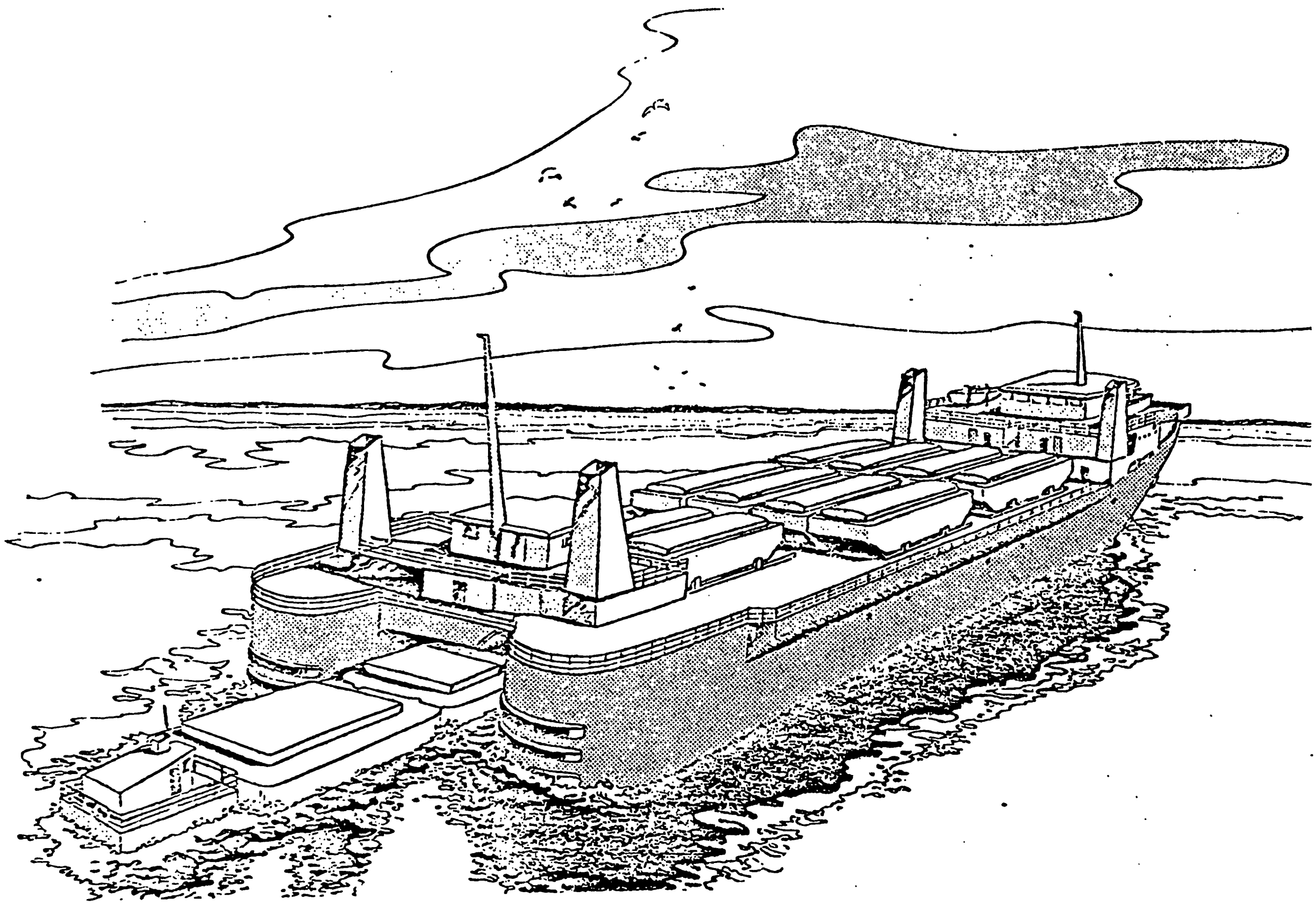


Fig. 7. A mixed barge carrier, BACAT. Smaller lighters are carried stacked on deck, while larger barge units are integrated between the twin hulls in the after part of the vessel.

As in the FLASH system, the generalized float-on vessel would probably be non-self-propelled, decked, and loaded from one or both ends. Barge-securing arrangements could be simple and relatively labor-intensive, or more sophisticated and capital intensive, although hardly to the same extent as in a vessel with barge-lifting gear.

E. Barge Flotillas with Coupling Devices

The barge flotilla/towboat combination is, of course, the dominant multibarge system for river and inland waterway traffic. It is a multibarge system reduced to its basic elements, barges and propulsion, eliminating the need for a supporting or integrating structure.

In flat water, with no substantial wave loadings or vertical bending moments either on the barges or the flotilla as a whole, the linkage between barges is completely noncritical, and in fact a cable or hawser lashing is more than adequate. The barges are usually in contact with each other, and the largest stresses on the connections are usually due to transverse bending moments, particularly for long, narrow flotillas.

The simplicity and adaptability of the river flotilla are the keys to the concept's success. The hawser connection is not limited in any way by variations in barge draft, and it can even be applied to barges of any size mixed within the same flotilla. Standardization of river-barge dimensions has been wholly a matter of convenience in the fleeting operation, allowing a certain degree of geometric regularity in the flotilla. The principal dimensions of two common river barges are as follows:

	Old Standard	"Jumbo"
Length	175 ft	195 ft
Beam	26 ft	35 ft
Depth	11 ft	12 ft
Normal river draft	9 ft	9 ft
Empty weight	179 lton	246 lton
Full load displacement	982 lton	1585 lton

The weights apply to open hopper barges, that is, without hatch covers of any sort.

In recent years, the so-called jumbo has become the most common barge unit for inland commerce, particularly on the great rivers. Neither of these barges are suitable, as described, for open-water service. Leaving aside, for the moment, the matter of economical draft, the following characteristics of the river barges are inadequate for open-water operations:

1. The hull structures are not designed for wave bending loads or local wave impact.

2. Watertight hatch covers would be required for any reasonable weather conditions that might be encountered in open-water service.

3. In the case of salt-water operations, protective hull coatings and cathodic protection would be needed.

4. The hawser connection is obviously incapable of holding the flotilla together in anything but unusually calm conditions.

While all these considerations entail added costs, which we will discuss subsequently, the only factor involving significant technical innovation is the last one. The development of a practical, reliable, and economical barge linkage is the key to any offshore capability for a multibarge flotilla.

A detailed discussion of the relative motions and forces involved in a multibarge flotilla operating in waves would be outside the scope of this report. A great deal of experimental data, theory, and design methodology is available in Refs. 2-4. However, a few general conclusions regarding the technical problems of linkage devices can be offered:

1. For most linkage configurations, maximum stresses are encountered in bow or quartering areas, and with a wavelength of approximately two barge lengths.

2. The principal source of longitudinal forces in the linkage members is the lateral bending moment acting on the flotilla. This moment is very closely proportional to flotilla length, and is at a maximum in bow and quartering waves. The longitudinal forces can be minimized by keeping the flotilla short and broad.

3. Vertical forces in the linkage members are the result of relative pitch, heave and roll forces. The beam of the flotilla has little or no effect on the magnitude of vertical forces.

4. Transverse forces due to relative sway are of about the same order of magnitude as the vertical forces, and much smaller than the longitudinal forces.

5. By allowing added degrees of freedom to the linkage, vertical and transverse forces can be reduced to manageable levels. Without freedom in relative yaw, however, the longitudinal forces are quite high, usually on the order of 10%-50% of the individual barge weights at the critical wavelength and heading angle. (We have considered a standard wave height of $1.1L^{1/2}$, and a wavelength of twice the barge length.)

6. The strongest influence on linkage forces is flotilla length/beam.

7. For a given total flotilla displacement, linkage forces decrease as the barge size decreases and the number of barges increases, however, there is no effect on the lateral bending moment if the draft is held constant.

8. Rigidity in yaw is required for directional stability and control of the flotilla. Therefore, the linkage, regardless of what form it assumes, must take the longitudinal loading due to transverse bending moment.

Figure 8 shows the three major classifications of linkage: single-hinge, multiple articulation, and flexible coupling. Many variations of each type have been proposed, but certain similarities exist between all the variations of a given class.

Single-hinge systems normally permit free motion in relative pitch only, and thus, the vertical and transverse reactions are particularly high in bow or quartering seas.

Multiple articulated devices permit relative pitch and at least one additional degree of freedom, usually heave and roll. The loads are somewhat less in the vertical plane, but since relative motion is usually

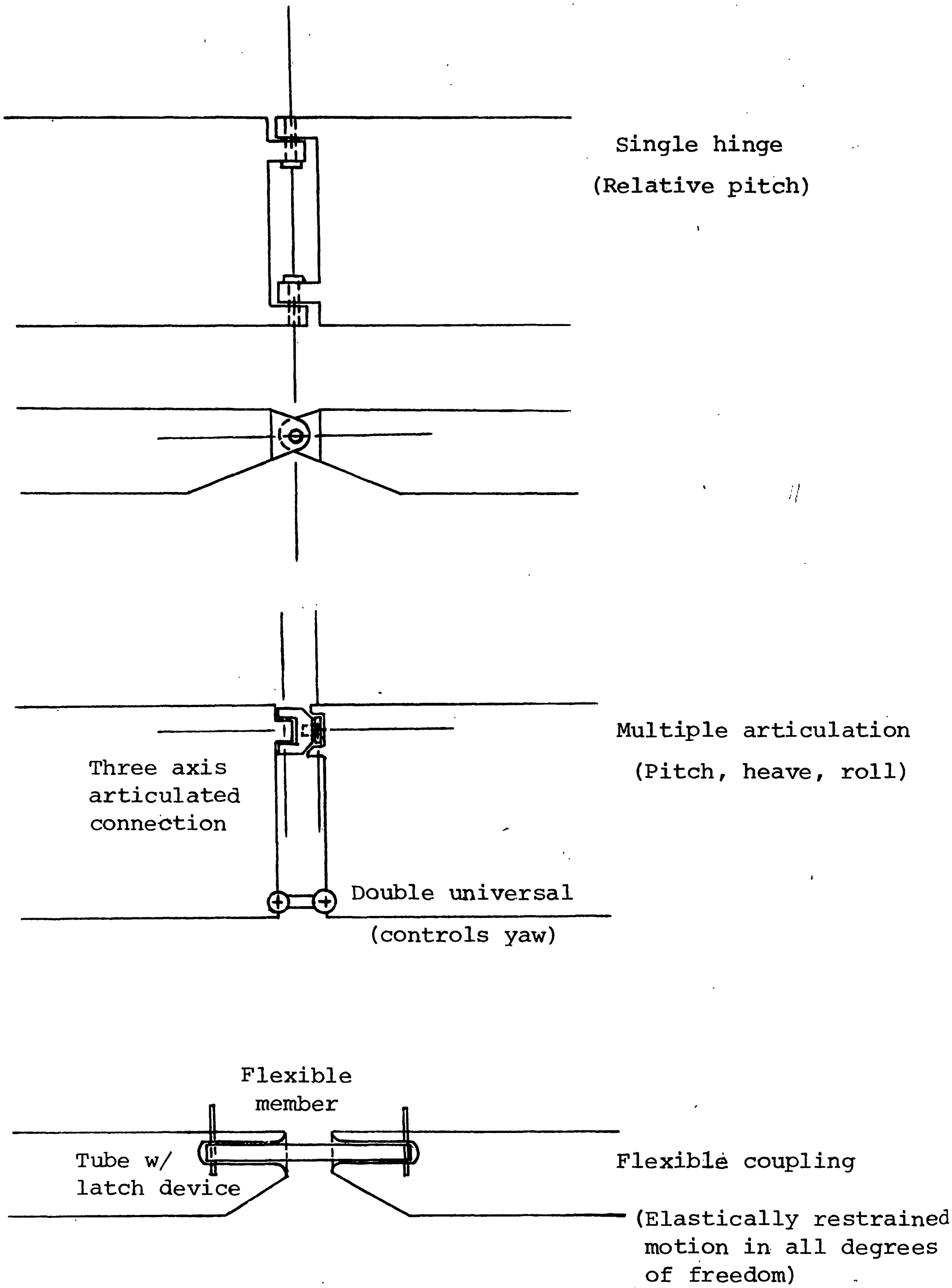


Fig. 8. Generic types of barge linkage (schematic).

prevented in the horizontal plane, (zero surge, sway, and yaw), longitudinal and transverse forces are approximately the same as for a single hinge device. A practical advantage of the multiple-articulated linkage is that its relative motion capability in heave also permits the linkage of two barges at very dissimilar drafts, while a single transverse hinge point would have to be aligned prior to coupling.

Flexible couplings permit elastic relative motion in all degrees of freedom except surge and yaw. Vertical and transverse loads are reduced to a minimum due to this freedom, and the couplings, in effect, act as energy absorbers. For this reason, however, there are materials problems other than simple strength. Principally, the coupling units generate internal heat which must be removed. For fairly small units, radiation is enough, but for larger couplings, where the ratio of cooling surface to heat-producing volume is insufficient for heat transfer, temperature may become a problem unless internal cooling systems are incorporated.

Vertical and transverse forces in a typical flexible coupling are approximately 5%-10% of the values for a single-hinge system, but the critical longitudinal forces are about the same.

In general, the results of sample calculations show that multiple-articulated systems and flexible couplings represent the most feasible multibarge linkage systems in terms of the manageability of forces. The most stringent limitation on the system is the magnitude of the lateral bending moment, which is closely governed by the flotilla length and beam. Also, the calculated forces include no allowance for shock loadings due to slack in the linkage, a matter which deserves considerable further study.

Figure 9 shows a hypothetical Great Lakes multibarge combination, consisting of six jumbo-sized units (195 × 35 × 12.5 ft depth), operating at a river draft of 9 ft. By comparison with the river barge, the open-water unit loses about 120 lton deadweight, due to the increased steel weight required for strength, as well as the addition of watertight hatch covers. These weights apply to hopper barges; a complete analysis of weights and costs for various types and sizes of barge unit will be found in Appendix C.

BARGE TOW WITH FLEXIBLE COUPLINGS

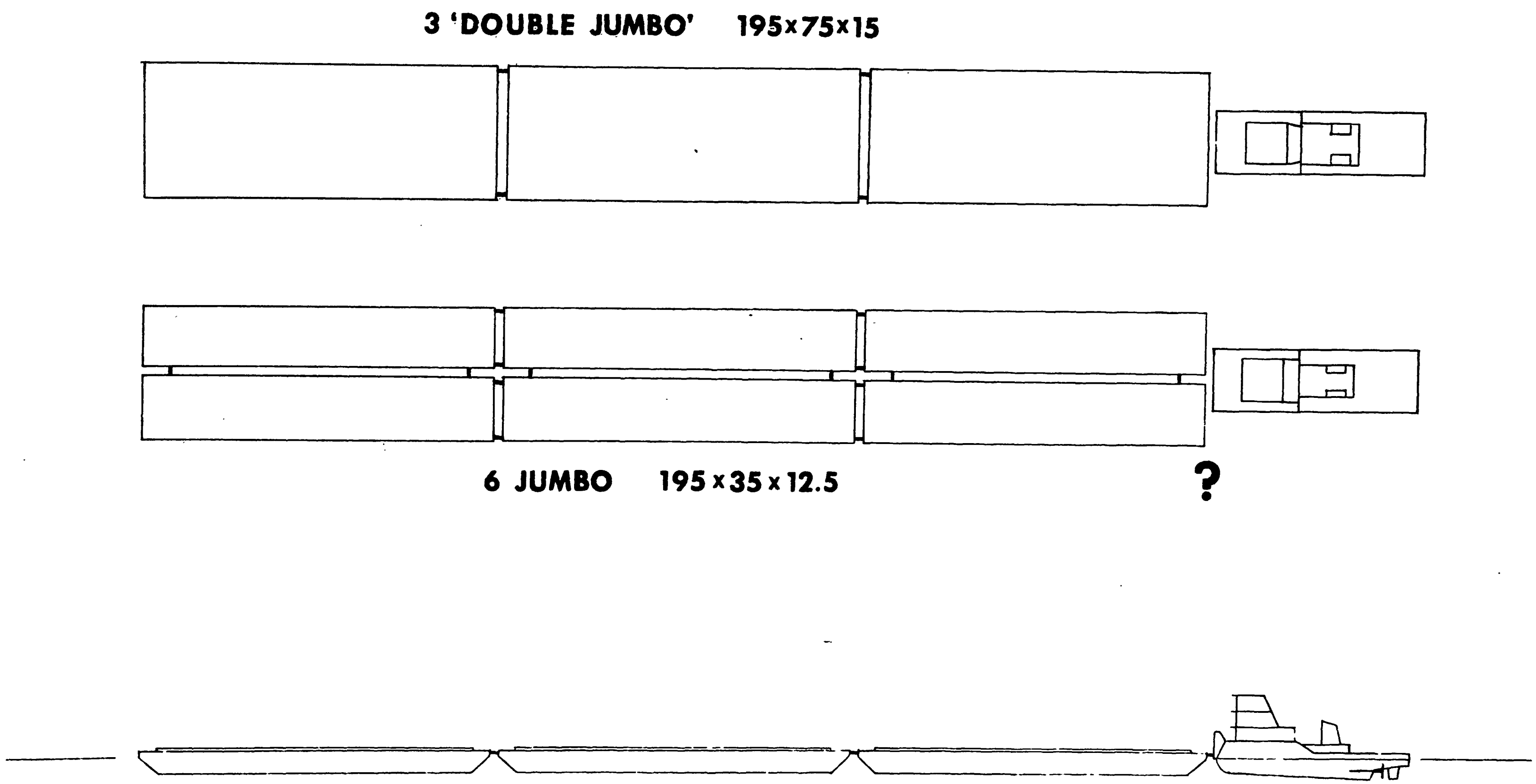


Fig. 9. Barge flotilla/towboat combination with flexible couplings. With double jumbo units operating at a draft of 9 ft, a 6500 shp towboat would give 25% power margin on a 12 knot service speed; a 3300 shp boat, 10 knots.

As an alternative unit, the "double jumbo" is also shown in Fig. 9, sharing the same length and depth, but with a beam of 70 ft. The virtue of this unit, apart from the advantage of reduced tare weight, is in the simplification of the fleeting operation and the reduction of the required number of couplers. In fact, the absence of transverse couplers greatly simplifies the structural and relative motion uncertainties involved.

The river draft of the flotilla is based on a desire to secure a rapid and efficient interface with the river system, and to eliminate the need for transshipment. The economic implications of this interchange of barges for lake-river operations will be dealt with subsequently.

In any case, the operation of barge flotillas in ice is open to grave doubts. Not only is the straight raked bow of the flotilla an inefficient ice-breaking form, but the accumulation of ice between barges raises serious questions regarding the working of the linkage mechanism, whatever its form. Of course, for winter operations, it would be possible to couple an ice-breaking bow section onto the flotilla, but the economics of this scheme would have to be considered carefully. In addition, it might prove that even with such a bow, the accumulation of broken ice between the barges would still take place, and the associated problems of freezing in the linkage mechanisms themselves would remain unresolved.

F. Towboats for Open-Water Multibarge Service

Apart from the obvious advantages of a coupling system that would allow push towing under all weather conditions and on all headings, there is little to say regarding required technical innovation in towboats. The preferability of push towing is based on considerations of both resistance and control, and applies as much to multibarge operations as to single-barge towing.

Currently, typical notch-barge operations in the Gulf require hawser towing approximately 25% of the time at sea. This relatively high figure reflects the fact that once the tug is forced to leave the notch it is quite difficult to get back in while at sea. If this were not so, it is estimated that the fraction of sea time spent on the wire could be reduced to about 10%. In the conceptual design of our systems, we have assumed that the towboat will have to be suitable for the remote wire tow if severe sea conditions require it.

Regardless of the exact fraction of time in use, a tow-rope capability requires fairly ship-like proportions for the tug, since it will have to operate in waves unprotected by the tow, and of course depending on its own resources for stability and seaworthiness. The tug will also need adequate displacement to stand up to the tow, a length suitable for this displacement, and of course, the requisite towing equipment in addition to the push-tow linkage.

If a linkage existed that would positively relieve the towboat of the necessity for a tow-rope capability, a marked change in proportions and equipment would be possible. In particular, a trend towards very short, beamy vessels might be anticipated, for the following reasons:

1. Extremely stubby proportions would yield weight and cost savings on the towboat itself. (Length/beam ratios in neighborhood of 1.5, or even square, would not be out of the question.)

2. A shorter towboat would allow greater barge length and payload under a given total length limitation.

3. For a given barge length, the shorter towboat would reduce over-all lateral bending moment, while the wider beam would allow smaller linkage forces at the flotilla-towboat connection.

4. As an adjunct to the fleeting operation, the towboat would be more maneuverable at minimum length.

In this study, we have not assumed a 100% operating envelope for the linkage system, and accordingly, our towboats are of fairly standard tug proportions. Figure 10 shows a comparison of two equivalently powered multibarge towboats, river service and open-water. Both vessels are intended for push towing multibarge combinations; the differences between them arise solely from the operating environment. The principal divergences in design are in hull depth and draft, reserve buoyancy and stability, propeller and rudder arrangement, and scantlings. The open-water towboat is also fitted with a towing winch, for the reasons outlined above.

2 800-SHP TOWBOATS

INLAND	GREAT LAKES — OFFSHORE
110 x 34 x 10.5 FT	110 x 35 x 15 FT
DRAFT 9	DRAFT 12
Δ_{FL} 604 LTON	Δ_{FL} 855 LTON

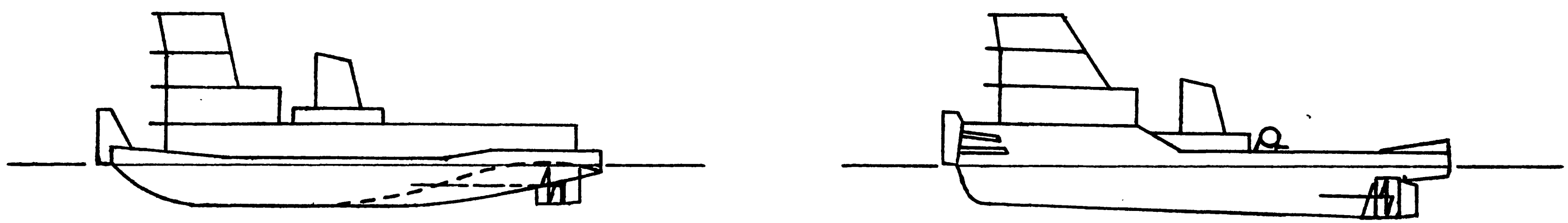


Fig. 10. Comparison of inland and offshore multibarge towboats, 2800 shp.

The assumed dimensions of our series of open-water multibarge towboats are given in Fig. 11, as functions of installed shaft horsepower. While it is realized that wide variation in these parameters occurs in practice, it is felt that the curves of Fig. 11 represent a fairly reliable basis for assessing the economics of multibarge operations in open water. We have chosen a conservative viewpoint, and our towboats are slightly on the large side for their capability.

Complete details of the towboat dimensions, weight and cost models used in this study are given in Appendix D.

G. Barge Trains

So far, we have discussed schemes in which the barge combination is rigid in yaw, and we have concentrated on the structural problems arising from this rigidity. As a final speculative concept, consider a train of barges coupled in much the same way as a conventional railroad train, that is, free in *all* modes with the possible exception of surge. If this combination were pushed from astern, the result would be inevitable and catastrophic: you can't push a string. However, by pulling the string, either remotely with a conventional wire towrope, or close-coupled with a "locomotive" tug on the head end, we can succeed in exchanging a structural problem for a control problem.

The basic technical problem of a completely supple barge train is the matter of keeping it in line and keeping it from generating slack that would impose large loads when it came taut. Figure 12 shows a barge train combination with a head-end and rear-end power unit, each having side thruster capability. It is assumed that the stern unit is remote controlled, and normally unmanned, while the forward unit is the main power source and central control station. As already noted, the problem has been removed from the field of structure, and placed in the field of control. Similarly, the costs of the control systems, while uncertain, would have to be large.

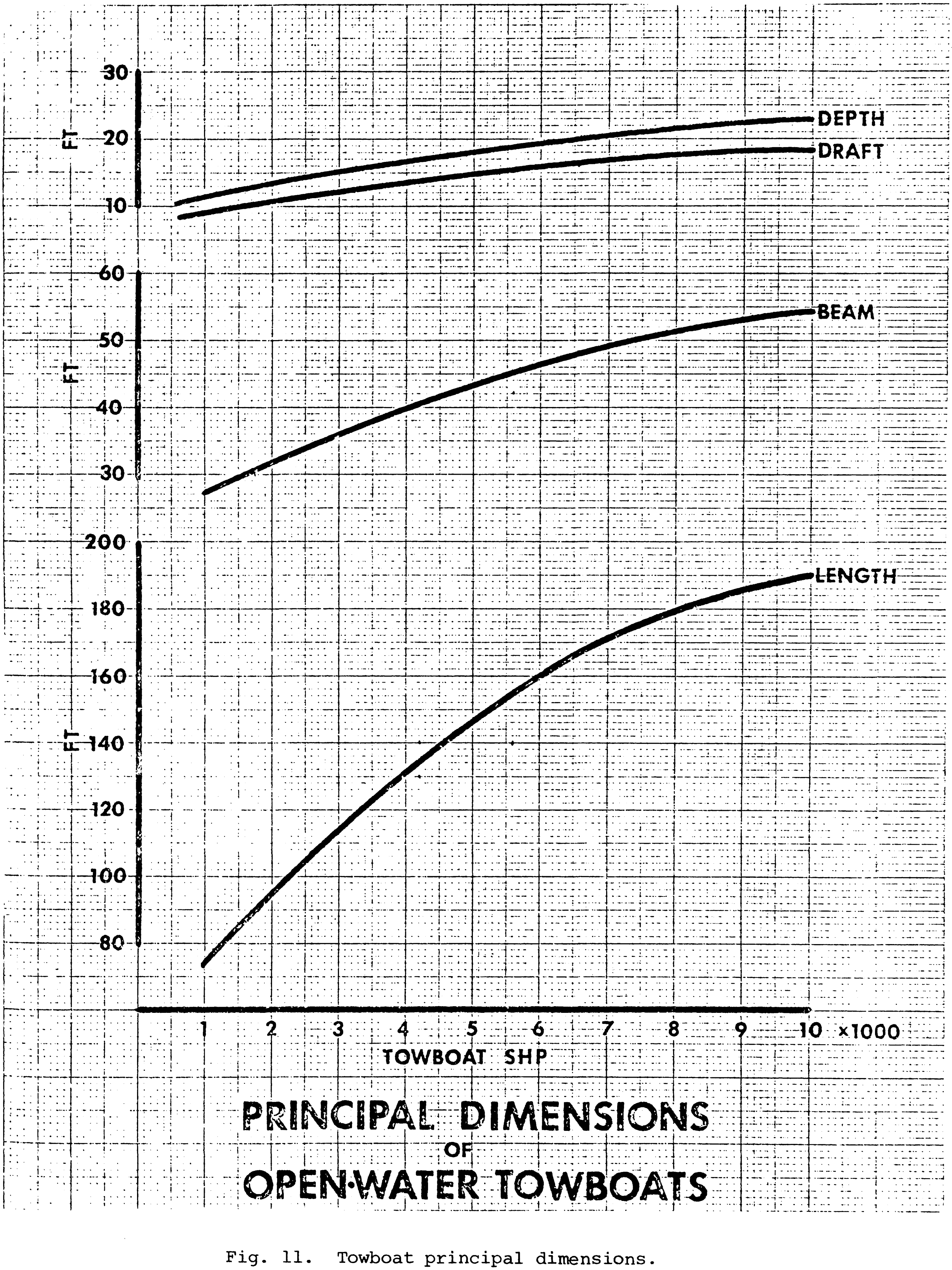


Fig. 11. Towboat principal dimensions.

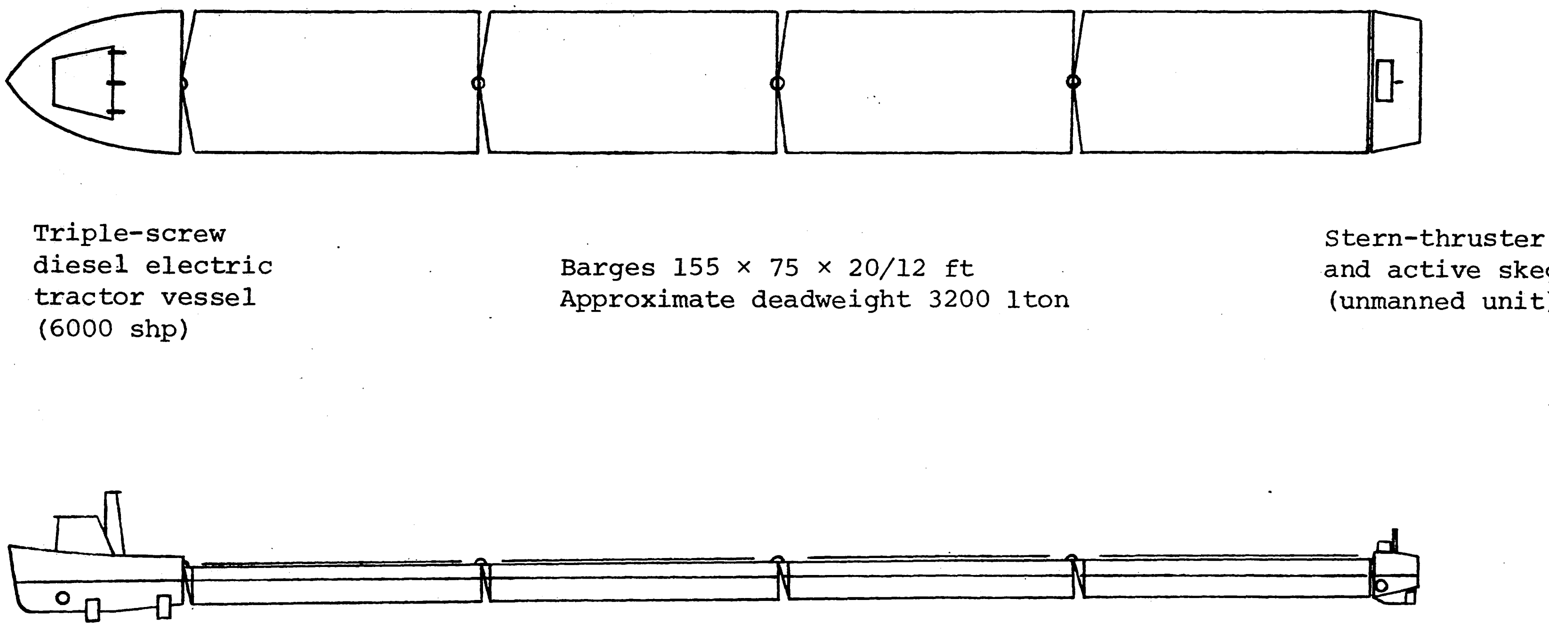


Fig. 12. A "barge-train" with tractor tug and stern-thruster/rudder slave unit. Relative motion between barges is essentially free in all modes, and there are no vertical or lateral bending moments on the train as a whole, regardless of length.

IV. SERVICE PATTERNS FOR MULTIBARGE SYSTEMS

Before turning to the comparative economics of the various multibarge systems, it seems advisable to set the scene with a brief description of the types of service in which a multibarge operation might be expected to excel. We have already identified, in very general terms, the virtues of a multibarge capability, but to specify the service patterns that are most suitable for such a system we must again approach the question: what does a multibarge system offer that cannot be had with a fleet of small vessels or single-unit tug-barge combinations?

A. Generalized Service Patterns

Figure 13 shows, in schematic form, generalized service patterns that are commonly seen in transport systems. The nodes represent not only geographic locations, but in the case of scheduled services, specified times. Additionally, each node also represents a series of cargo-handling (or barge-handling) operations.

The simplest service pattern consists of a shuttle run between two points. If the terminals are true endpoints of the entire transport system, that is, not assembly points from other branches of the system, then there is no particular need for a multibarge capability. In actuality, the requirements of such a simple system are best met by a single vessel, whether a ship or a tug-barge combination.

As the complexity of the system increases, the requirements for flexibility become important. The radial pattern is basically a set of shuttles served consecutively, as for a single commodity source and several destinations. Depending on the nature of the shipments, and the regularity of schedule on each of the links, a multibarge capability may be attractive, if only to eliminate the problem of overcapacity on the slack link. In general, however, the radial service pattern resolves itself into a series of shuttle round trips, and the need for a multibarge system's flexibility is problematic.

Triangular service patterns often arise from the needs of a particular industry, or out of a peculiar set of geographic requirements.

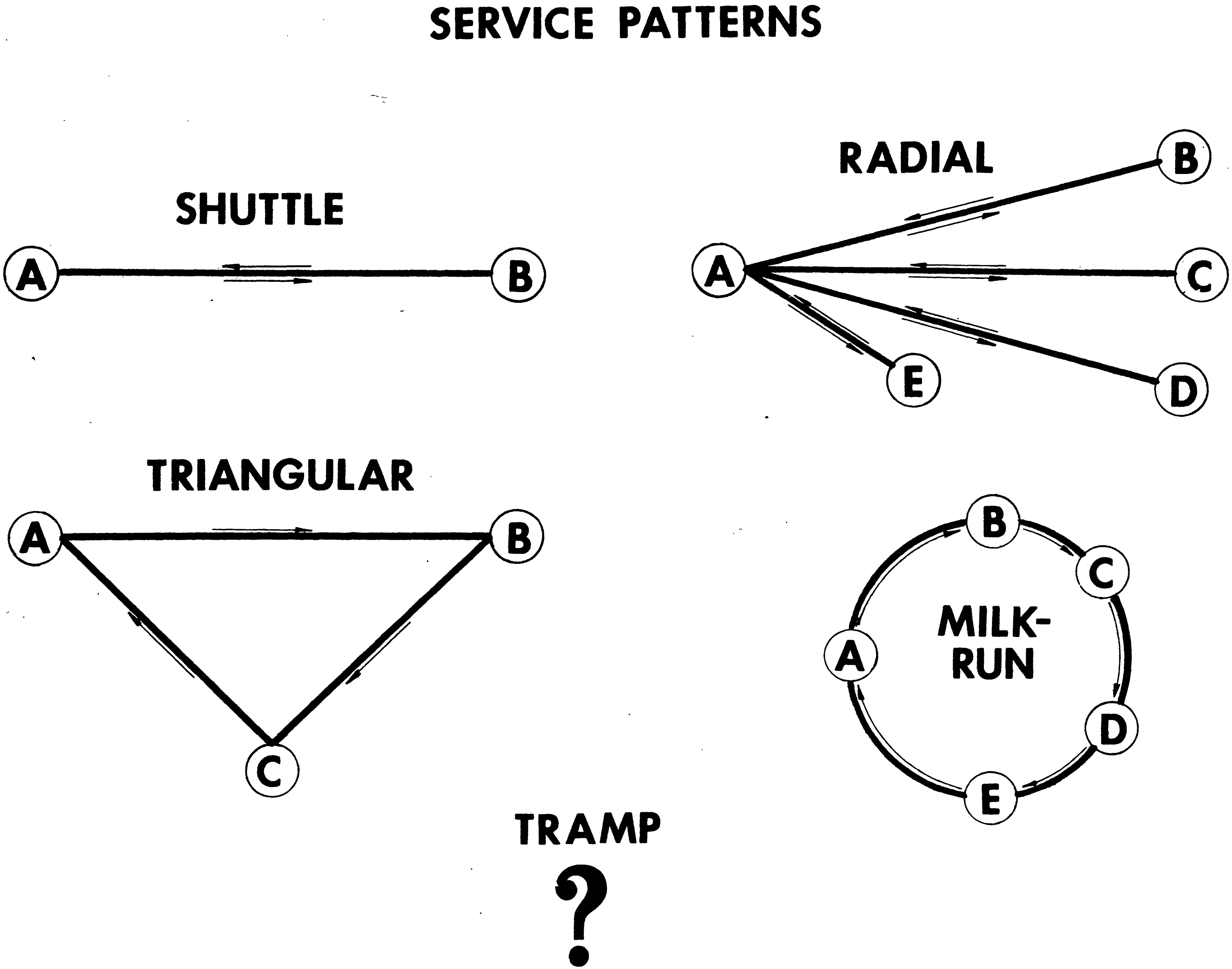


Fig. 13. Generalized service patterns.

The classic example of the former consists of a coal mine, a coking plant, and a steel mill's blast furnace, while the latter is usually cited in histories of eighteenth-century Atlantic commerce. In any case, assuming that one vessel is suitable for the transport of all the cargoes involved, there is again no compelling reason to invoke a multi-barge capability.

A generalization of the triangular service pattern to include an arbitrary number of nodes results in the "milk-run" pattern. The transport system may involve a single origin, with multiple destinations and several kinds of cargo (a "classical milk-run"), or any combination of origins and destinations along the route, with any number of different commodities. In fact, any or all the nodes may be both sources and sinks for some commodity on a regular or irregular basis.

The point is, the more complex the system becomes, both in route and schedule, the greater degree of flexibility is required in the transport hardware. In addition, with a dissimilarity in cargoes there is a greater emphasis on parcel shipments of various sizes, with specialized containers or barges to accommodate them. Finally, with an increased number of stops per trip, a drop-off or swapping capability becomes vital to ensure fast turnaround. (We will return to the matter of barge swapping in the next section.)

Of course, most transport systems involve a combination of basic service patterns. For example, a typical LASH-based service might consist of a shuttle operation (for the line-haul vessel) with radial services at each end, gathering the LASH lighters from a number of sources for marshalling at the terminal, and distributing them among various final destinations. Similarly, a milk-run service might have one or more "spurs" attached to various nodes.

Such systems are characterized by at least one node with more than two links attached to it, where cargo is transported *through* the node, rather than originating or terminating at it. In an intermodal transport system, such a node may represent a transshipment operation, but for the purposes of multibarge application, it is more interesting to consider the node as a potential for *avoiding* transshipment. In particular, the interface between two marine transport subsystems having dissimilar operating conditions and restrictions is the ideal province for multibarge systems.

In summary, the following considerations tend to favor the application of a multibarge system:

1. Complexity of routing and scheduling requirements.
2. Mixed regular and irregular movements.
3. Non-uniform consignment sizes.
4. An assortment of different (perhaps incompatible) cargoes.
5. An interface where transshipment can be avoided feasibly and desirably.

The final service pattern of Fig. 13, tramp service, is characterized by its freedom from any formal pattern, in either route or schedule. In fact, flexibility is the only thing a tramp service has to sell. For this reason alone, a multibarge tramping operation might be economically viable in certain areas where the demand for irregular service is dominant. However, these areas are usually quite localized, and rarely involve significant open-water operations. In addition, the risk involved in supporting even a well-established tramp service is usually great enough to discourage new building specifically for that service. We will return to the more unstructured uses of a multibarge capability for open-water traffic when we discuss the matter of barge ownership.

B. Terminal Operations

For a conventional ship, there are only two basic operations that take place at the terminal: loading or unloading. The delay involved may vary, but not the intent of the operation.

For single-unit tug-barge combinations, a third option is available. The tug may stay around for loading or unloading, in which case it is little more than the engine room of a conventional ship, or it may swap barges and leave. The advantages of a barge-swapping capability are clear:

1. Labor productivity is increased, as is the capital productivity of the tug.

2. Maintenance scheduling of the barge and tug are independent.
3. Reserve or rented power is available to protect service.

However, the principal disadvantage of the system is the requirement for increased investment in barges. The "ideal" barge-swapping arrangement consists of three barges and a single tug. At any given moment, there is one barge at each terminal (in a shuttle service) either loading, unloading, or waiting for the tug, while the third unit is in transit with the tug. (The possibility that the tug might have to wait for a barge is unthinkable, since the entire purpose of the triple-barge arrangement is to keep the tug busy all the time.)

Whether the net economic benefit of a barge-swapping capability outweighs the extra capital cost of the barges is problematic, and the answer depends very heavily on the extent and economic impact of port delay. In general, though, the delays must be quite long, the tug expensive (high-powered), and the barges cheap, if triple-barging is to be an attractive system. In any case, we must distinguish between systems offering true multibarge capability and those that merely involve the ability to swap. Deliberately, we will not discuss the advantages, capital, operating, or statutory, of tug-barges over conventional ships; that battle should be left for another day.

For multibarge combinations, the possible permutations for terminal barge-handling are greatly expanded, as shown in Fig. 14. In fact, the ability to rearrange a multibarge flotilla is probably the key factor that distinguishes the flotilla concept from the other, carrier-oriented, schemes. Of course, barges unloaded from a carrying vessel can be fleeted up for river or inland waterway transits, but the open-water system itself functions as a ship, restricted to the two fundamental operations, loading or unloading.

The economic value of this in-terminal flexibility of the flotilla concept can only be evaluated in terms of delay reduction, the costs of transshipment saved, and so on. For example, a flotilla arriving at a system interface (say Chicago) might be split up, with one part destined to lock out of the lakes at Lockport, while the remainder continues around the southern end of the lake to Gary. Handling of the flotilla through the locks might be a matter of the open-water towboat pushing the barges in, uncoupling, and backing out. The barges are then locked through alone, and a river towboat picks them up at the top. (Here, again, the linkage device is a crucial part of the system, since any delays in coupling or uncoupling tie up the lock as well as the vessels.)

Barge-handling operations are also independent of shoreside facilities. The fleeting, splitting, or individual barge pickups can be conducted at the pier, in the harbor, or outside if weather conditions permit. It is quite possible to cut out or pick up a barge with the flotilla under way at reduced speed, a common practice on the inland waterways.

It can fairly be said that the flotilla concept is oriented around the terminal operations rather than the linehaul. For this reason, in attempting to identify those areas or services where a multibarge towing capability might be economically attractive, it can be assumed that the more numerous pickups and deliveries are, the better the system looks by comparison with other marine systems.

C. Cargoes

The multibarge concept is predicated on its ability to handle different cargoes within the same flotilla or carrying vessel. However, certain general kinds of commodities will be more amenable to multibarge transport than others, and the principal determinant will be consignment size.

In particular, large bulk shipments, such as iron ore, limestone, coal, and grain, will normally move in the largest vessels suitable for the route. If the transport system involves a river link, there is a possibility that the advantages of avoiding transshipment might outweigh the obvious disadvantage of operating at river draft in the deep-water part of the system. In general, however, the deep-water leg would have to be very short by comparison with the river leg in order to make up the difference, since the sensitivity of the economic performance to operating draft is quite strong, as we will demonstrate subsequently.

On the other hand, finished goods of high value and correspondingly high inventory costs, while the consignment sizes are generally small and variable, usually must be moved at a higher speed than the multibarge

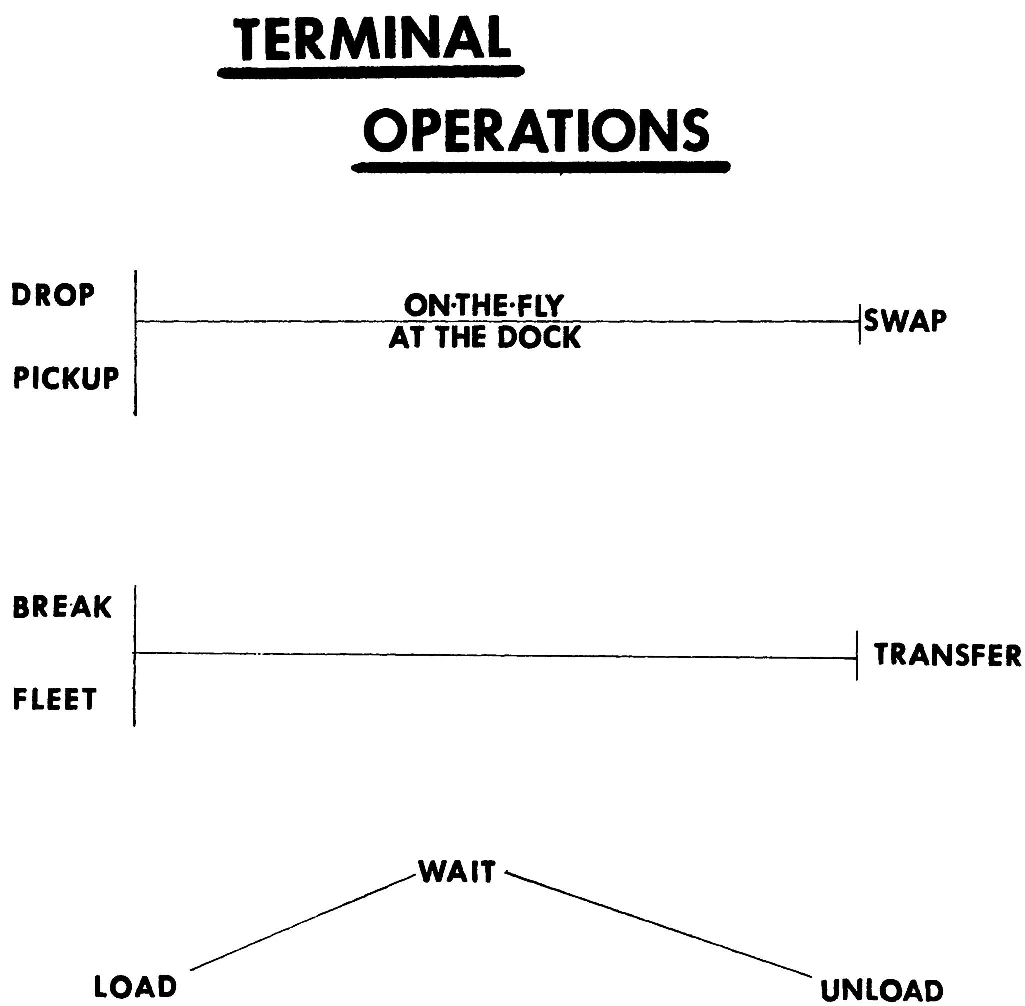


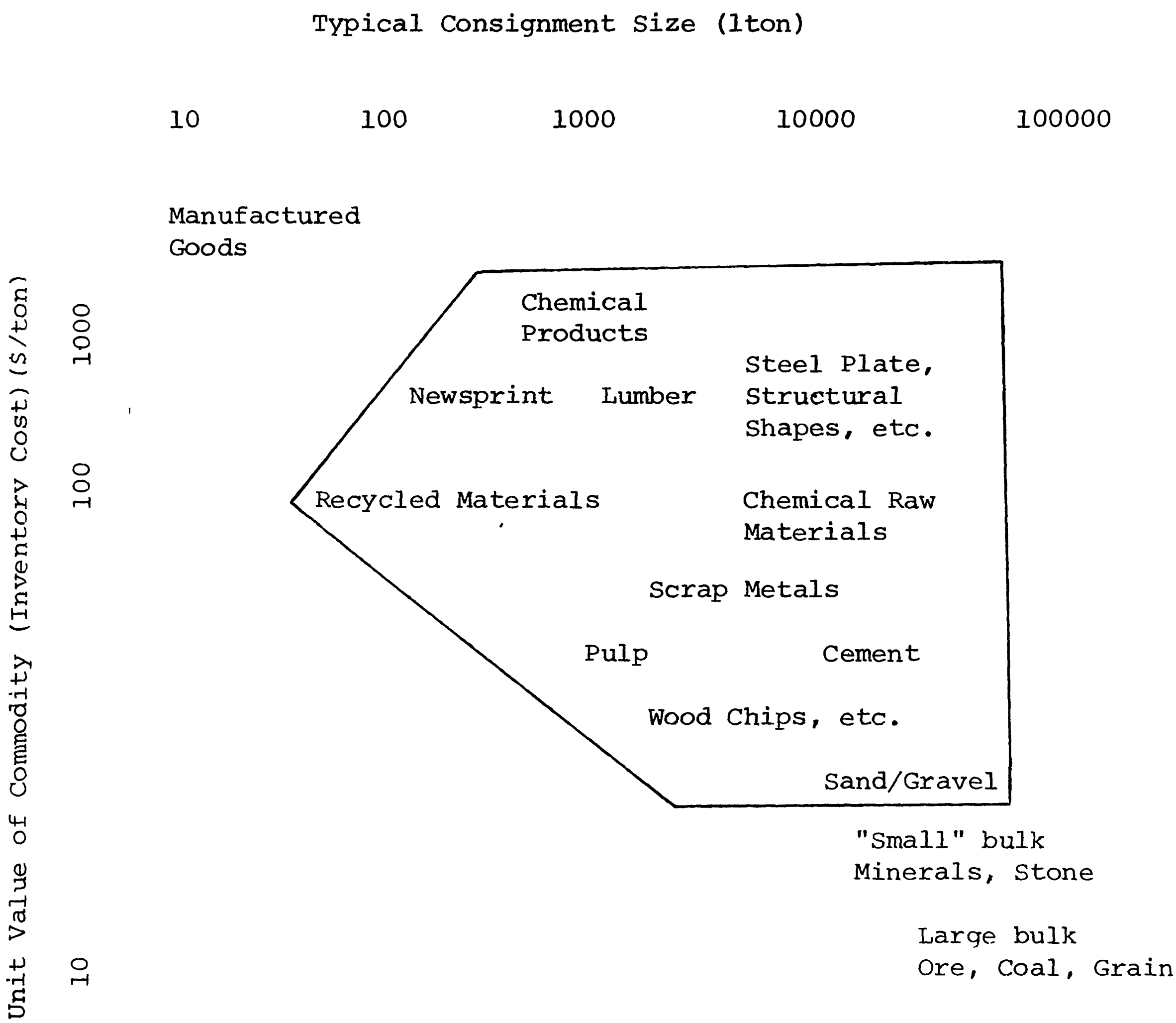
Fig. 14. Operations at a flotilla terminal.

system can offer, particularly if it is employed in a "milk-run" type service with many stops along the route. We do not reject the concept of containerized cargo aboard decked or specialized container barges, however, the requirements for speed in transit and flexibility in routing are somewhat conflicting.

Somewhere between the two extremes of large-shipment, low-value bulk cargo and small-shipment, high-value finished products, that is, somewhere between a bulk carrier and a containership, we must try to find the commodity movements that could benefit from multibarge capability, given suitable geographic service patterns and port arrangements. A partial listing of possible generic cargoes, arranged in terms of typical consignment size, is shown in Table II. While a detailed market survey would be necessary in order to pinpoint the need for a multibarge service, it is also beyond the scope of this pilot study. However, the content of Table II is felt to be a reasonable suggestion for places to look.

In summary, the potential cargoes for a multibarge system are hemmed in by the requirements for large deadweight (that is, maximum draft) on one side, and high speed (that is, containerization and direct non-stop service) on the other. It is a difficult position, but not a hopeless one. One potential arrangement could be called a "tag-along" operation, in which smaller barges, loaded with typical cargoes of finished or semifinished goods, are coupled alongside a larger, single-unit tug-barge combination, a bulk carrier. The small units could be at river draft, if required, while there would be no such constraint on the bulk carrier, which serves, in effect, as the backbone structure of a rigid-frame flotilla. The bulk-carrier would have to be suitably equipped and strengthened for its secondary role, and of course, the schedule and geography of the bulk-cargo movement would have to be compatible with the tag-along traffic, a rather special case. In addition, beam constraints would almost certainly preclude lock transits and many port operations while the tag-alongs were attached.

Table II. Potential cargoes for multibarge applications



D. Barge Ownership

A number of options are available to both the consumer and vendor of a multibarge service. For general purpose barging on a short-term or one-trip basis, it would be necessary to have a pool of barges, hoppers for the most part, probably owned by the operator of the service. For specialized cargoes requiring either nonstandard barges or non-standard routing, there are undeniable advantages to barge ownership by the shipper of the commodity.

Among these advantages are:

1. Detailed control over barge specification, design, and costs.
2. Assured availability of specialized barges.
3. Better control over costs of barge ownership.

Of course, the problems associated with barge ownership cannot be overlooked: maintenance and repair costs may be greater on a per-unit basis for the smaller, captive barge fleet; towing arrangements may be complicated by the extra paperwork involved, standardization of barges and linkage systems would require careful study and cooperation, and some overhead costs would be duplicated. Then, too, the total investment required for a given transport capacity (in terms of barge units), depends on the round trip time, which will be under the control of the operator, through his choice of flotilla size and power assignment.

V. ECONOMIC COMPARISONS

Economic comparisons of systems whose chief attribute is flexibility, rather than the ability to deliver goods from a single fixed source to a single fixed destination, are necessarily more involved with the exact costs of the service to each user, rather than with a single value of a measure of merit. In addition, there is the matter of how attractive the service might be to a potential operator, as well as to the consumers.

In the sample economic comparisons that follow, we will consider the transport costs from a number of viewpoints:

1. The costs of barge ownership to an individual user of the service.
2. The costs of towing.
3. Average required freight rates for certain hypothetical routes.
4. Generalized freight rates per ton-mile, for the purpose of rough comparison between multibarge services and other competitive modes.

We will also examine a few of the sensitivities of the economic measure of merit to design and operational variables: speed, barge draft, delay assumptions, etc.

A. Selection of a Sample Route

In order to give some form to the economic comparisons, we have chosen a hypothetical scheduled milk-run service, operating between ports on Lakes Huron and Michigan. While the exact schedules vary due to the performance differences between the various alternatives, we have chosen the size of the various units in such a way that annual transport capacity is nearly identical between alternatives.

The route selected for a test case is shown in Fig. 15. The total annual cargo flows are prespecified as follows:

Total round-trip distance:
1335 stat mile

cargo-flow distances:

Bay City - Escanaba	335	stat mile
Milwaukee	486	
Chicago	573	
Alpena - Escanaba	245	
Escanaba - Ludington	136	
Chicago - Milwaukee	78	
Chicago - Escanaba	285	
Chicago - Alpena	483	

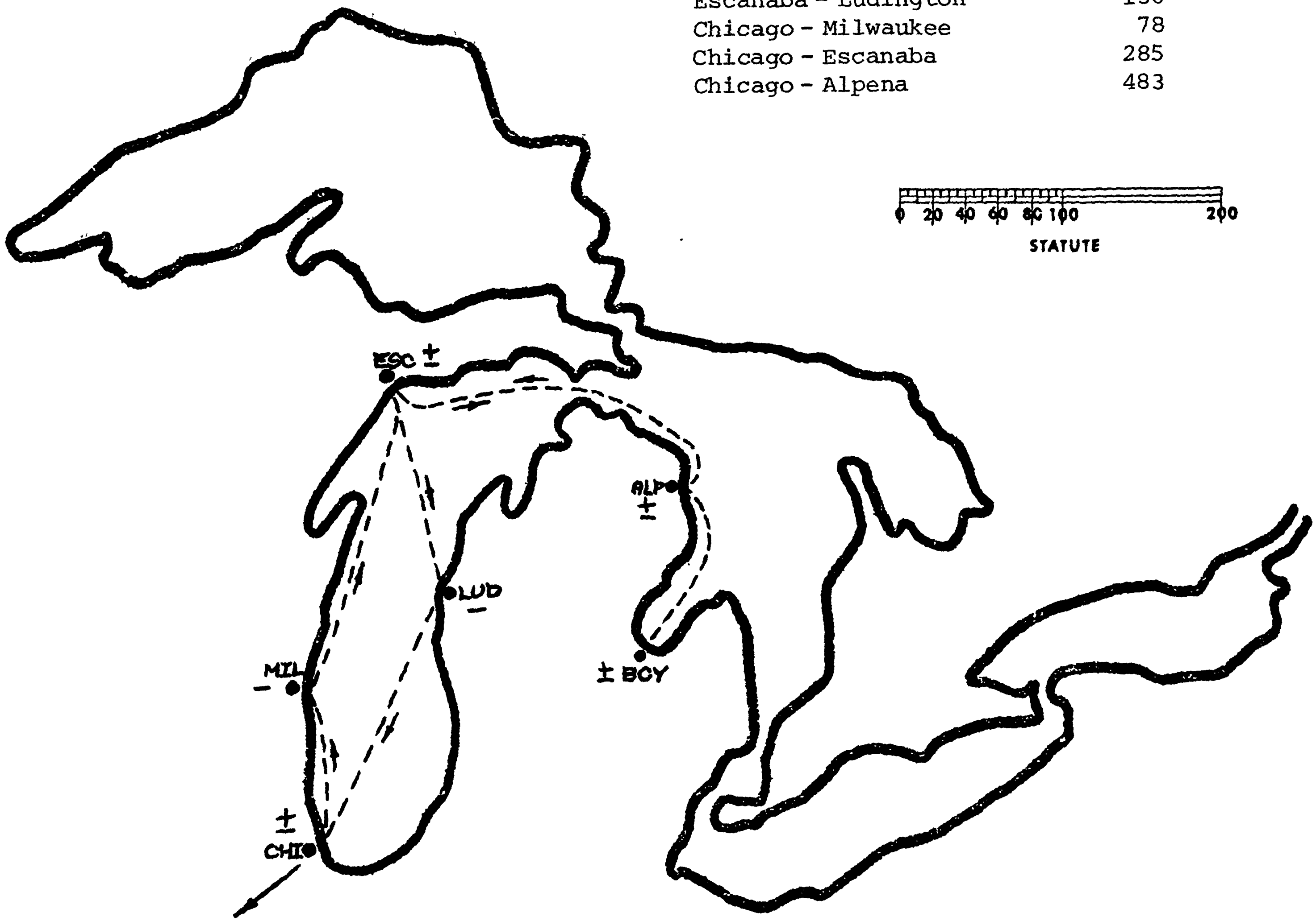


Fig 15. Sample route. Plus indicates source, minus indicates sink.

Bay City - Escanaba	tanker	25 000 lton
Bay City - Milwaukee	tanker	50 000
Bay City - Chicago	tanker	75 000
Alpena - Escanaba	hopper	25 000
Escanaba - Alpena	hopper	50 000
Escanaba - Ludington	hopper	50 000
Chicago - Bay City	tanker	100 000
Chicago - Milwaukee	hopper	100 000
Chicago - Escanaba	hopper	100 000
Chicago - Alpena	hopper	25 000
Total annual cargo		600 000 lton

As a first attempt, we assume that the costs of all elements of the transport system will be assigned to the cargo flows, in other words, no partial assignment of "outside" assistance will be made. The exact itinerary of the service, and specific details of the operation, will vary from alternative to alternative, as we shall see. We have also assumed that an allowable deviation from the nominal annual cargo flow is plus or minus 10%, on each flow.

Note that the above service is purely hypothetical. It is perhaps more complicated than an actual multibarge service would ideally be, and the individual cargo flows are relatively small. However, this is a demonstration of the capabilities of a system that is designed to serve complex networks and schedules, and it is not felt that this route and service is amenable to a single unit transport system, whether barge or ship, or even a fleet of small, independent vessels. In this sense, it is the kind of service that a multibarge operation is best fitted to serve.

B. Multibarge Alternatives

The principal characteristics of the multibarge alternatives designed for the sample route are given in Table III. The following constraints have been placed on the vessels or flotillas, uniformly:

Table III. Principal characteristics of multibarge alternatives developed for sample route service. Round trip distance sailed: 1335 stat mile. Annual cargo tonnage: 600 000 lton. Annual cargo ton-miles, based on nominal cargo flows and short-line distances port to port: 206.5 million.

	LASH	FLASH	FLOTILLA	VERTEBRATE	TWO-TIER FLASH
Length overall	415	730	730	730	610
LBP	365	715	720	725	605
Beam	75	75	75	75	75
Depth	31	28	12.5	30	33
Full load draft	22.5	12.5	9	13	12.5
Displacement	12 810	14 720[a]	9 720[a]	17 700	14 200[a]
Cargo deadweight	7 200	7 200	7 260	7 260	7 200
Installed shp	2 700	4 200[b]	6 500[b]	4 800	4 200[b]
Service speed (kt)	12	12	12	12	12
Daily fuel	8.4	13.0	20.3	14.9	13.0
Complement	25	18	16	20	20
Barge capacity	18 LASH	18 LASH	6 Jumbo	6 Jumbo	18 LASH

[a]Vessel non-self-propelled. Displacement does not include towboat.

[b]Towboat shaft horsepower.

1. Maximum operating draft in lake service (river draft) of 22.5 ft.
2. Maximum length for river and port operations of 730 ft over-all.
3. Maximum length for lake operations of 1000 ft over-all.
4. Maximum over-all beam of 105 ft.

C. Capital Costs

A comparison of the alternatives on the basis of initial investment cost is shown in Table IV, itemized under the general headings of barge units and towboat or carrying vessel.

D. Barge Ownership and Operating Costs: Required Freight Rate

A comparison of barge ownership costs to the individual owners under the various alternatives is given in Table V. Table VI shows a comparison of operating costs.

Values of required freight rate for each link of the assumed service are calculated on the basis of total barge ownership cost plus total operating cost, the sum divided by the individual cargo flow.

An "average" required freight rate is derived from total annual costs and the nominal annual cargo ton-mileage, corrected for differences in annual capacity between the alternatives. The relationship of each individual user's freight rate to the average value will depend not only on the individual ton-mileage of his shipments, but on the geography of the entire round-trip operation. The exact assignment of costs will have to reflect the delays incurred by each user due to the system's servicing all the others. Obviously, if the vessel or flotilla must travel other than the direct distance between the terminals of a given link, in order to make intermediate stops, all costs are increased. The precise method for assigning these costs from one user to another, based on some measure of inventory cost, perhaps, will not be approached in this study.

E. Simple Sensitivities

The principal sensitivities for LASH and FLASH systems are those that directly relate to round trip time, namely, service speed and added

Table IV. Capital costs of multibarge alternatives developed for sample route service.

LASH vessel 415 × 75 × 31/22.5 ft, 2700 shp	$ 12.6 M
24 LASH hoppers	1.3
24 LASH tankers	3.0
Total	$ 16.9 M
FLASH carrier 615 × 75 × 28/12.5 ft	9.3
Towboat 4200 shp 110 × 50 × 17.5/12/5 ft	4.0
24 FLASH hoppers	1.4
24 FLASH tankers	3.1
Total	$ 17.8 M
FLOTILLA Towboat 6500 shp 130 × 60 × 20/15	5.4
8 Jumbo hoppers	3.5
7 Jumbo tankers	4.0
Total	$ 12.9 M
VERTEBRATE vessel 730 × 75 × 30/13 ft, 4 800 shp	13.8
15 Jumbo barges as above	7.5
Total	$ 21.3 M
TWO-TIER FLASH carrier 610 × 75 × 33/12.5 ft	12.2
Towboat 4200 shp	4.0
48 FLASH barges as above	4.5
Total	$ 20.7 M

Table V. Annual total barge ownership costs under various multibarge alternatives, based on 350 day operating season

System	Barge type	Deadweight river draft 9 ft	Average unit price in series of 10 units	Annual M&R cost plus insurance	Total annual cost per deadweight ton
LASH	Hopper	400 lton	$ 55000	$ 1320	$ 27.91
	Tanker	398	125000	3000	63.76
	Heavy lift	360	78000	1870	43.98
FLASH	Hopper	400	$ 60000	$ 1440	$ 30.45
	Tanker	398	130000	3120	66.31
FLOTILLA Jumbo w/ couplings	Hopper	1210	$ 454400	$ 10900	$ 57.89
	Tanker	1175	553700	13300	95.66
	Deckhouse	1195	426800	10200	72.50
FLOTILLA Double jumbo w/ couplings	Hopper	2828	$ 806600	$ 19400	$ 57.89
	Tanker	2776	1000500	24000	73.16
	Deckhouse	2811	768500	18400	55.50

Table VI. Total annual costs and average freight rates per ton-mile, based on nominal cargo flows and short-line distances, (1000 $).

	LASH	FLASH	FLOTILLA	FLOTILLA	VERTEBRATE
Operating season	350	350	275	350	350
Sea days/RT	4.03	4.03	4.03	4.03	4.03
Port days/RT	1.26	1.12	0.66	0.66	0.66
Avg. delay/RT	0.22	0.21	0.28	0.35	0.21
RT/year	63.52	65.30	55.33	69.44	71.43
Annual crew cost	591	454	341	434	494
Annual insurance	221	246	110	214	277
Annual M & R	203	264	91	171	282
Annual fuel	333	496	628	800	594
Annual lube oil	12	18	22	28	21
Annual layup	0	0	75	0	0
Annual overhead	64	57	11	11	85
In-port towing	150	150	83	106	106
Wharfage	150	150	118	150	150
Annual operating	1724	1835	1479	1914	2009
Annual capital	2205	2344	967	1092	2415
Barge costs	877	926	1525	1750	1525
Total Annual Cost	4806	5105	3971	4756	5949
Average RFR/ton-mile	$0.0233	0.0241	0.0221	0.0211	0.0257

delay. This is so because there is no way to alter the barge itself.

Sensitivities of the "average" RFR, which we will call *transport cost* from now on, are shown in Figs. 16 and 17.

For multibarge flotillas, the additional variable of barge draft is also a most important factor. Even for limited cargo flows, where increase of vessel deadweight is not necessarily desirable, an increase of draft at constant deadweight reductions, with a saving in barge weight and cost, and a significant reduction in required horsepower. Sensitivities to speed, delay, and barge draft are shown in Figs. 18-20.

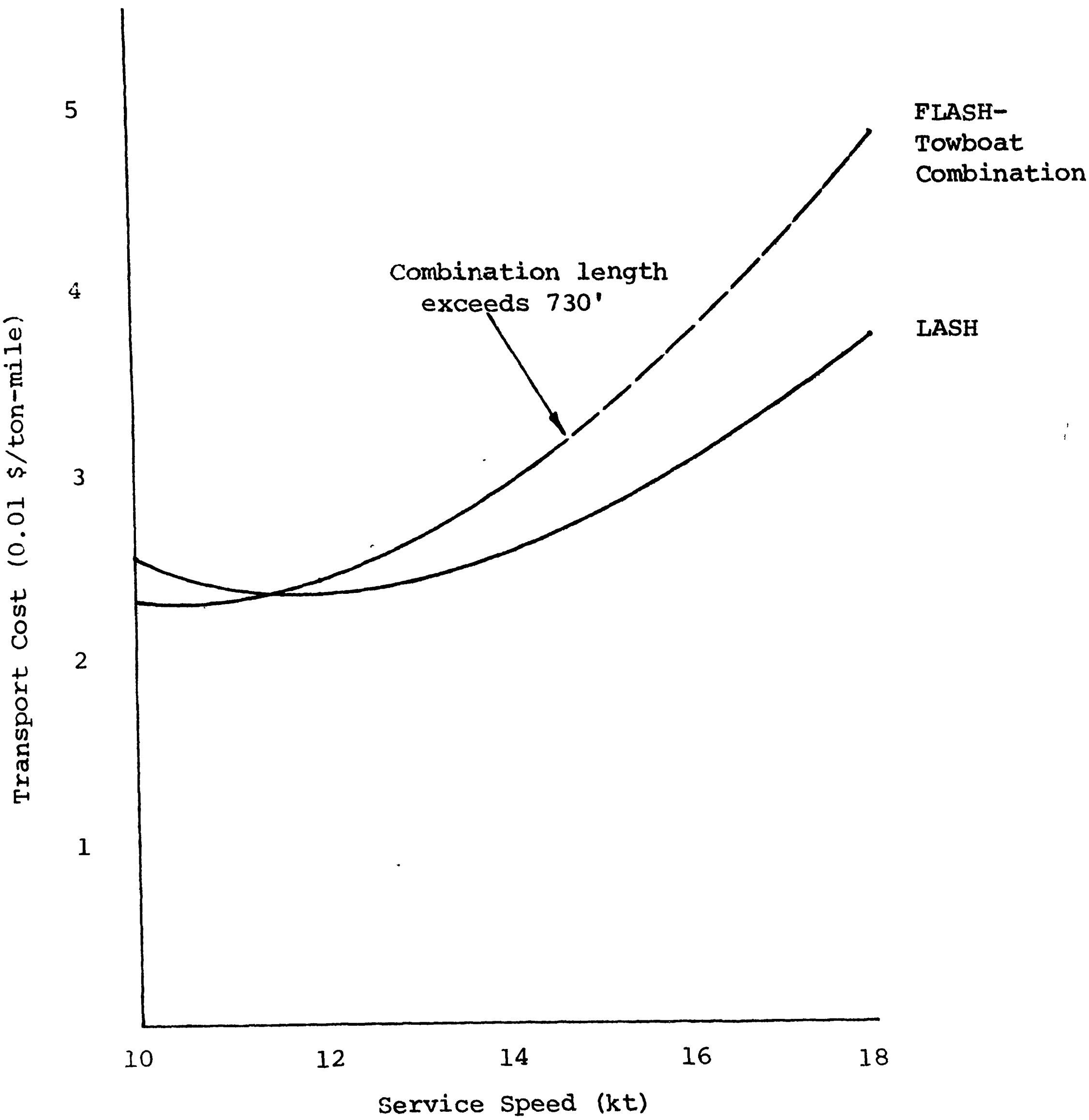


Fig. 16. LASH and FLASH average RFR, (transport cost per ton-mile), vs design service speed. Vessel capacity: 18 LASH lighters.

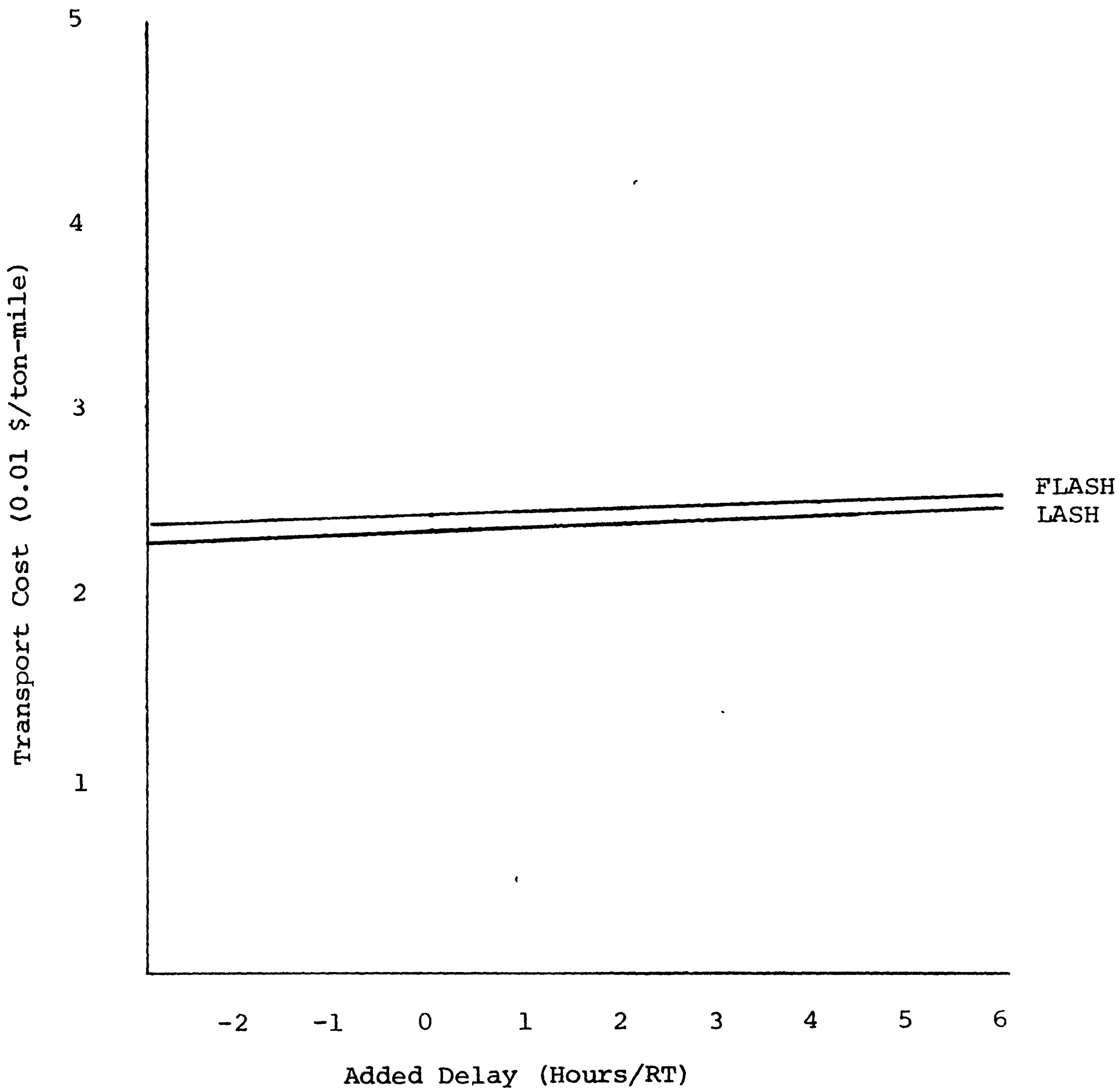


Fig. 17 LASH and FLASH transport cost per ton-mile vs additional (weather) delay. Service speed: 12 kt.

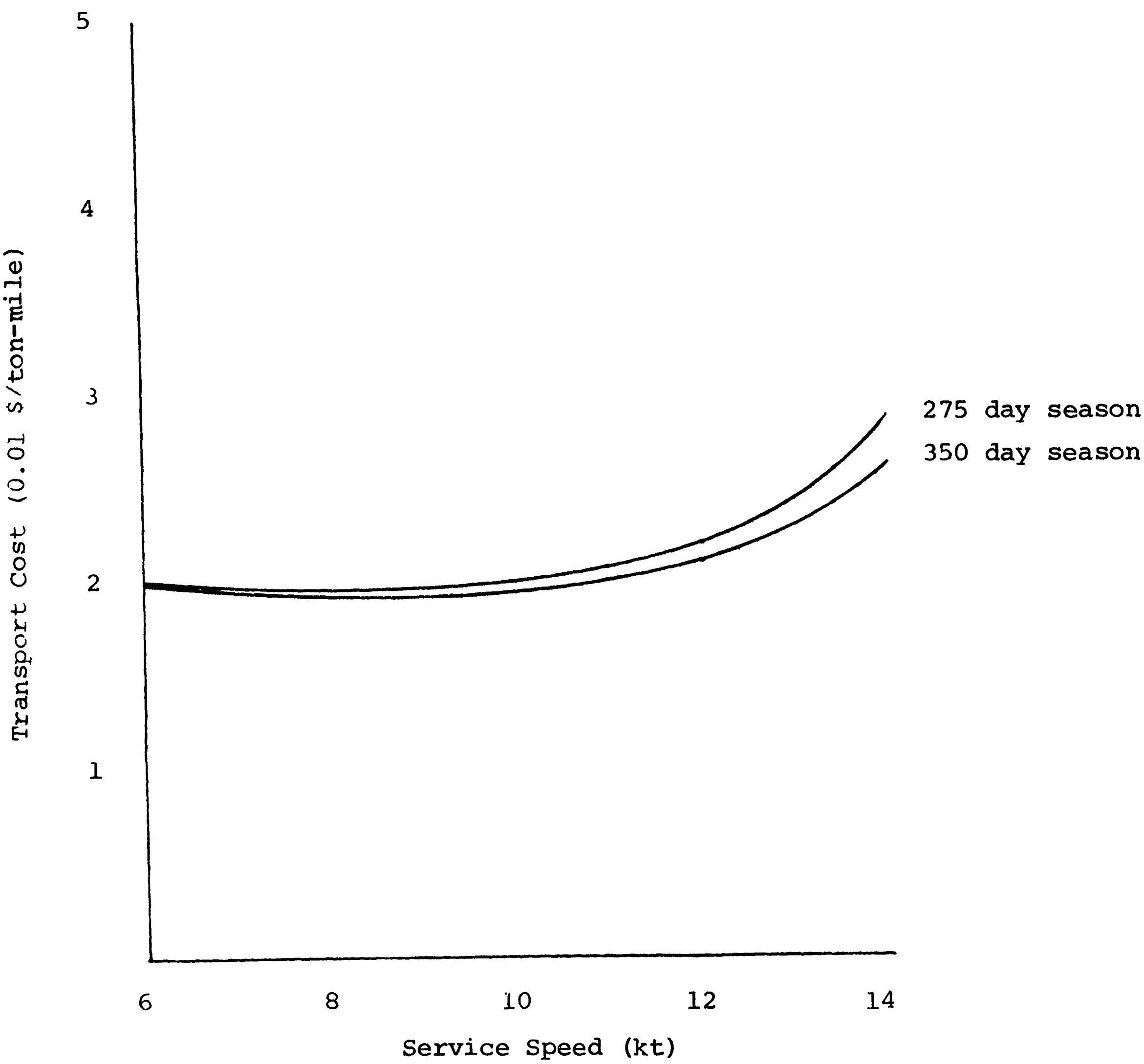


Fig. 18. Transport cost for six-jumbo FLOTILLA vs design speed.

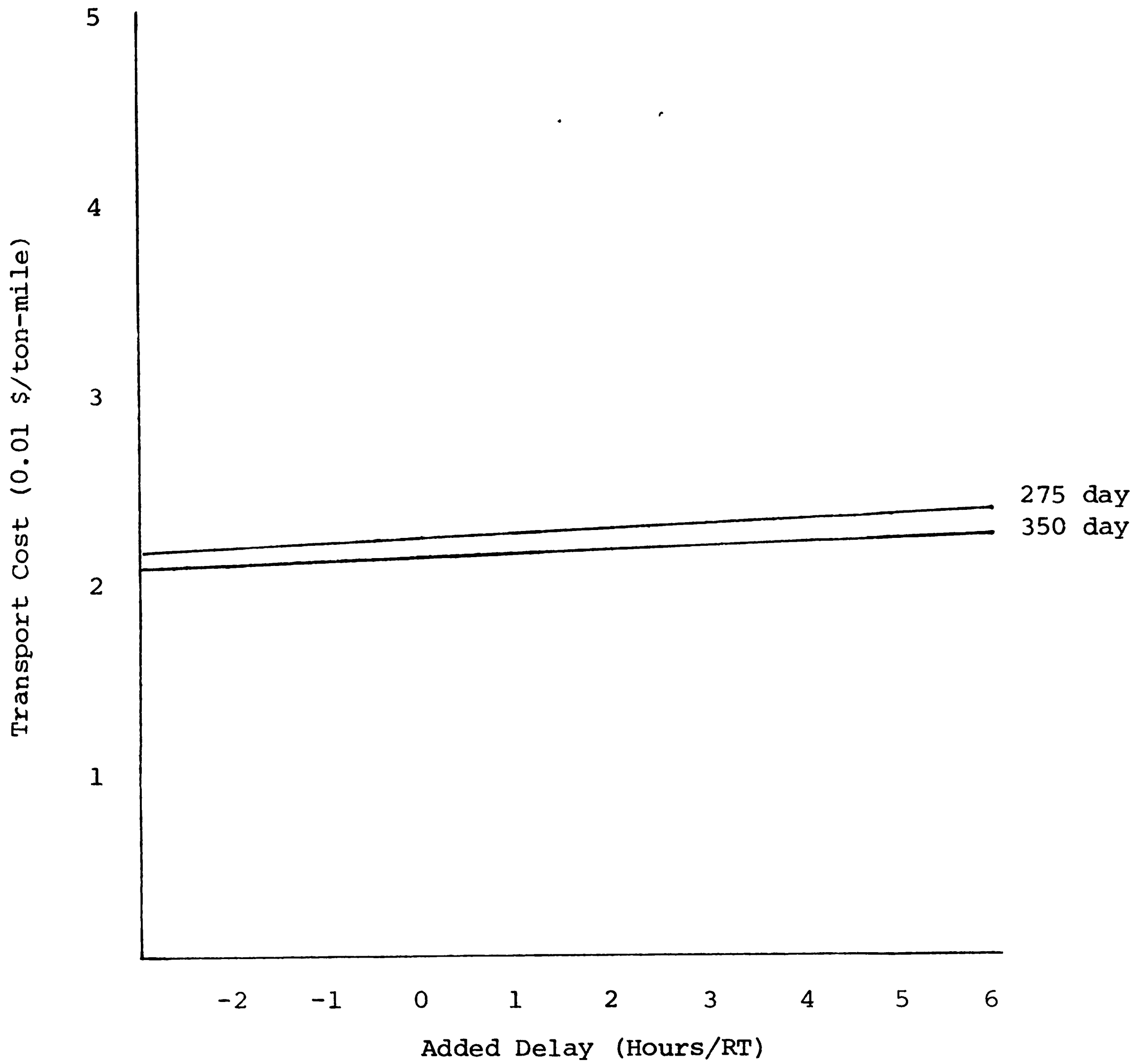


Fig. 19. FLOTILLA transport cost vs additional weather delay.
Service speed: 12 kt.

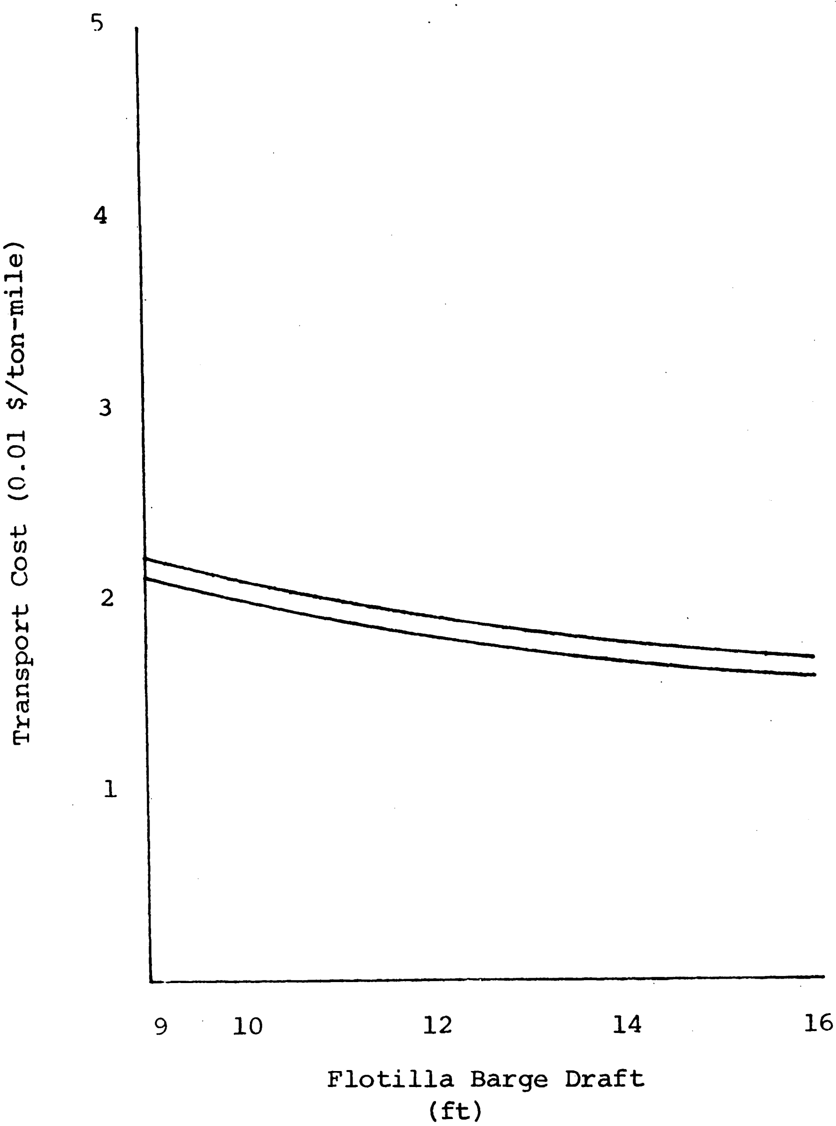


Fig. 20. Sensitivity of transport cost to flotilla draft, at constant speed and annual throughput. Barge proportions were altered with length and beam as inverse square root of draft.

VI. GENERAL CONCLUSIONS AND SUGGESTIONS FOR FURTHER STUDY

The following general conclusions are offered:

1. The technical feasibility of multibarge operations in open-water has been proven for barge-carrying vessels. For flotilla operations, technical feasibility depends on the efficiency of the linkage device.

2. The principal attribute of multibarge systems is flexibility, in terms of route and schedule, and it is on this basis that any potential service must be marketed.

3. The economic competitiveness of multibarge services is favored by complex transport networks, numerous, closely spaced ports of call, and the potential for avoiding transshipment.

4. Presently, the multibarge alternatives that seem to offer the best economic performance are, in order, flotilla/towboat combinations, dwarf LASH vessels, and FLASH/towboat combinations.

5. Presently, the multibarge systems that offer the most credible technical feasibility are, in order, dwarf LASH vessels, FLASH/towboat combinations, and multibarge flotilla/towboat combinations.

6. The economics of flotilla systems serving a combination of open-water, and river ports, is favored by a minimization of the capital cost difference between river and open-water hardware. Due to the relatively high cost item represented by watertight hatch covers, it seems that the cost difference is more favorable to barges not requiring such covers, namely tank barges.

7. The details of operating-cost assignment are extremely complex, resembling railroad rather than standard marine practices.

8. Standardization of barge size is necessary. However, the choice of dimensions will be a compromise, at best. The possibility of mixed barge sizes, using a standard "lowest common denominator", is one possible solution for this problem, although the choice of the unit size, even given this approach, is not obvious, and will reflect a distribution of consignment sizes.

9. The so-called "tag-along" alternative, in which small barges are coupled to a larger-bulk-carrying vessel, is promising. However, the exact details of the system must depend on a fortuitous coincidence of bulk and nonbulk cargo flows, both in geography and, to a lesser extent, schedule.

10. Multibarge systems of any description are not consistent with services dealing in large-volume bulk shipments only. The marketing of such a system depends on the need for transporting smaller consignments of diverse goods.

11. Finished and semi-finished products seem to constitute the general type of cargo that would best be served by a multibarge capability, insofar as open-water applications are concerned.

12. Long-haul (e.g., transoceanic) services for multibarge combinations in flotilla form are not considered as promising as short-haul services, for the following reason: long-haul shipments of finished and semi-finished goods tend to favor higher speeds, hence relatively fine-formed, specialized ships, while low-value, large-bulk commodities favor larger unit sizes, also specialized ships.

13. Multibarge capability is enhanced in economic value if it is a part of a large, interlocking fleet. Only a large fleet can support the redundant components necessary if reserve units are to be maintained in order to protect the reliability of the service.

14. A mixed type of barge-ownership pattern will probably be necessary, with specialized barges owned by their users, while a general pool of standard barges, mainly hoppers, would be owned either by the towing company or a user's consortium.

15. While a detailed economic analysis of tramp operations was considered beyond the scope of this study, it appears that this form of transport constitutes one of the most promising applications for an open-water multibarge capability, on general grounds.

Further study is required along the following lines:

1. Detailed market analysis will be necessary in order to identify specific potential users of a multibarge service, the distribution of consignment sizes, and the areas which would be most efficiently served.

2. Optimization studies of service speed, barge dimensions, and standard drafts should be conducted.

3. The general problems of multibarge dynamics in waves must be given far more rigorous treatment than was possible in this pilot study. The analysis will yield valuable results not only for barge and linkage design for flotillas, but also for the motions and loads imposed on barges integrated within surrounding structures.

4. Detailed optimization studies of routing and scheduling of multibarge operations for a number of applicable areas would be necessary.

5. The problems of winter navigation for multibarge flotillas should be given a more explicit treatment than was accorded to them here.

6. Finally, the ultimate question will revolve around the vendor of the service. The exact nature of the arrangement will depend on specific circumstances, of course, and many details of cost assignment, barge pooling, and individual ownership of barges and towboats will have to be worked out. Whether the multibarge service will be offered by the towing firm, or by a shipper's consortium, will be a matter for study.

APPENDIX A: BARGE-CARRYING VESSEL (LASH) SYNTHESIS MODEL

The elements of this model are adapted from Ref. 5. All weights are given in long tons (lton), and costs in January 1976 US$.

1. Dimensional Restrictions

	Length	Beam	Draft
St. Lawrence Seaway	730	75	25.75
Great Lakes (Poe Lock)	1000	105	26.85
Great Lakes (standard)	730	75	26.85
Great Lakes (typical river service)	650	68	22.50
Des Plaines River, Lockport locks	600	105	9.00

2. Weights

a. Steel weight $W_s = 0.00083\ L^{1.76}B^{0.71}D^{0.37}$, L, B, D are length overall, beam, and depth, respectively.

b. Outfit weight $W_o = 1.04(LBD)^{0.425}$, includes normal items of ship's outfit, but not specialized cargo-handling gear.

c. Barge-handling weight $W_{bh} = 400 + 30\ Z + 12\ N$, where Z is the number of tiers in the highest stack, and N is the total lighter capacity.

d. Machinery weight $W_m = C_m(\text{shp}/1000)^{0.57}$, where shp is the total shaft horsepower installed, and C_m is the machinery weight coefficient, as follows:

Single-screw medium-speed geared diesel	$C_m = 180$
Single-screw steam turbine	200
Twin-screw medium speed geared diesel	202
Twin-screw steam turbine	267

Bow-thruster weight was assumed to be 70 ton, regardless of capability.

3. Speed and Powering Estimate

In order to facilitate the application of the model, we present a relatively simple, self-contained method for approximating shaft horsepower at an early stage of the design process. The following expression is based on Watson (T.R.I.N.A. Vol. 102), with a correction for beam/draft ratio due to Silverleaf and Dawson, as cited in Ref. 5.

$$shp = k(DIS)^{0.667} V^{3} \frac{(CLB)}{(CLT)} (CBT) \quad ,$$

where k = 1.0 for single-screw ships, k = 1.08 for twin-screw ships;

DIS = displacement in long tons;

V = service speed in knots;

$CLB = 36 - 0.0045\ L + 360(C_B + 0.5V/\sqrt{L} - 1)^2 - 10.8\ C_B$;

$CLT = 15000 - 183\ V\sqrt{L/T}$;

$CBT = 0.962 + 0.000541(10^{0.67B/T})$;

and L, B, T, C_B are length between perpendiculars, beam, draft, and block coefficient, respectively.

A service margin on the shaft horsepower resulting from this method is appropriate at 15% for Great Lakes service, 25% for ocean service.

4. Ship-Building Costs

a. Hull structure material acquisition cost was based on a unit price for steel of $314/ton, 10% scrap allowance, and 15% for additional steel in castings and forgings, etc. Thus, steel cost is given by $\$_s = 397\ W_s$.

b. Outfit and barge-handling equipment acquisition costs were placed at an average of $2800/ton, $\$_{obh} = 2800\ (W_o + W_{bh})$

c. Machinery costs, installed, were as follows:

$\$_m = 10900\ (shp)^{0.62}$ for medium-speed geared diesel plants, and

$\$_m = 42200\ (shp)^{0.50}$ for steam-turbine installations.

In either case, shp is the total installed shaft horsepower, including service margin.

d. Hull structure man-hours were related to steel weight as:

$$MH_s = 1140\ W_s^{0.71} .$$

Total outfit and barge-handling equipment installation man-hours were calculated on the total of the item weights, as:

$$MH_{obh} = 329\ (W_o + W_{bh})^{0.90}$$

The unit price of shipyard labor, including benefits and overhead, was placed at $12.50/man-hour.

e. The installed price of a bow thruster was a flat $380 000.

The installed price of electronics and automatic control systems was a flat $300 000.

f. A shipyard profit of 5% on the total of material and labor costs was assumed.

5. Operating Costs

a. Ship's complement. An approximation of crew size, assuming a level of automation consistent with current practice, was made as follows:

Deck department $CREW_d = 9 + 2\ N^{0.4}$, where N is the lighter capacity.

Engineering $CREW_e = 7$, for all steam-turbine plants;

$CREW_e = 4 + 3.32\ \log_{10}(shp/2500)$, for medium-speed diesel.

Steward's $CREW_s = 0.17\ (CREW_d + CREW_e)$.

b. Crew costs. Total annual crew costs, including wages with normal overtime, benefits, subsistence, stores and supplies, were evaluated as:

$$\$_{crew} = 45000\ (CREW)^{0.8} (OSD/350) ,$$

where CREW is the total complement, and OSD is the length of the operating season in days.

c. Insurance costs. Total annual insurance, including damage and loss, liability, and protection-indemnity, was estimated from the following:

$$\$_{ins} = [0.014\ (PRICE) + 1600\ (CREW)](OSD/350) \quad ,$$

where PRICE is the total ship cost from part 4, above.

d. Maintenance and repair costs. Annual M&R costs were itemized under three groups: hull, barge-handling equipment, and machinery. The approximations were as follows:

Annual hull M&R $\$_{hmr} = 12.5\ (LBD)^{0.685}\ (OSD/350) \quad ,$

where L, B, D, are length over-all, beam, and depth, respectively.

Annual barge-handling M&R $\$_{bhmr} = 5200\ N^{0.5}\ (OSD/350) \quad ,$

where N is the lighter capacity.

Annual machinery M&R $\$_{mmr} = 107\ (shp)^{0.667}\ (OSD/350)$, for steam turbines;

$\$_{mmr} = 3.3\ (shp) + 77\ (shp)^{0.667}$, for diesels.

e. Fuel costs. The daily fuel consumption under way was related to installed shp as follows:

$DFC = 0.0039\ (shp)$ for steam turbines;

$DFC = 0.0031\ (shp)$ for medium-speed diesels,

where DFC is the daily consumption in long tons per day.

An in-port fuel-consumption rate of 5 ton/day was assumed.

Unit fuel prices were assumed to be \$97/ton for bunker C, and \$125/ton for diesel.

f. Lubricating oil costs. Annual lubricating oil costs were assumed to be negligible for steam-turbine plants. For medium-speed diesels, the annual cost was given by

$$\$_{lube} = 4.35\ (shp)\ (OSD/350) \quad .$$

g. Other costs. The total cost for winter layup, including the laying up operation, winter watch costs, and spring refit, was estimated at a flat $100 000. Annual overhead was approximated by $\$_{over}$ = 0.005 (PRICE) (OSD/350).

h. Port fees. In the absence of good data, it was considered best to neglect port fees, especially for vessels in short-haul or milk-run services. In any case, it is probable that port fees, together with such items as in-port towing, barge wharfage, and cargo handling, would be assigned to the individual lighter operations, rather than to the carrying vessel.

6 Capital Recovery Costs

Annual capital recovery cost is given by

$$Y = (CRF)\ (PRICE) \quad ,$$

where PRICE is the total ship cost and CRF is the capital recovery factor for the specified interest rate and economic life. The usual assumptions are 10% return after 48% corporate income tax, while the economic life of Great Lakes vessels is usually placed at 35 years. (For ocean operations, a life of 20 years is typical.) Thus, for the purposes of this model, we assume

CRF = 0.175 for Great Lakes service;

CRF = 0.179 for ocean service.

It is likely that an emerging technology would only attract capital at a higher than usual interest rate, however, the amount of this risk penalty is problematic, and we have not attempted to evaluate it.

7. Ship Operations

a. Loading and unloading delays. Each barge handling operation, regardless of sequence or direction, was assumed to incur an average delay as follows:

$$\text{Time per lift (hour)} = 0.25 + 0.002\ N \quad ,$$

where N is the total lighter capacity.

b. River transit, port, and locking delays. River transit at reduced speed is neglected as a source of delay for the services under consideration. It is assumed that lighters would be marshalled in the open roadstead, or near the river mouth. A uniform port delay of 1.5 hour per call was assumed, allowing for channel operations and turning, but not barge-handling. A locking delay of 0.5 hour per transit is appropriate for Great Lakes operations.

c. Fueling delays. It was assumed that fueling would be performed once per round trip. The associated delay time was

$$\text{Fueling time (hour)} = 2 + 0.02\ (\text{DFC})(\text{RTD}),$$

where DFC is the daily fuel consumption, tons, and RTD is the scheduled round-trip time, days.

d. Miscellaneous, weather, and ice delays. For the Great Lakes, seasonal average delay times were related to round-trip distance and service speed, using the following approximations:

Summer	1 Jul - 30 Sep	Add delay per RT =	0.015 (RTD)
Autumn	1 Oct - 31 Dec		0.030 (RTD)
Winter	1 Jan - 31 Mar		0.090 (RTD)
Spring	1 Apr - 30 Jun		0.030 (RTD),

where the added delay is in days, and RTD is the nominal sea time per round trip, that is, round trip distance divided by service speed.

The winter delay figure is based on average winter severity, with ice-conditions typical of Lake Michigan or Lake Huron.

e. Operating deadweight. The approximation used for operating deadweight was as follows:

$$\text{Op Dwt} = 1.25\ (\text{DFC})(\text{RTD}) + 1.5\ (\text{CREW}) \quad .$$

8. Lighter Assignment and Costs

a. Lighter assignment. In the absence of specific data, it is assumed that a typical LASH system includes a number of lighters equal to 2.5N, where N is the LASH ship's capacity.

b. Lighter acquisition costs. The standard LASH box barge with weathertight hatch cover has already been described in Section III A. The following weights and costs are assumed for the purposes of the model.

Type	Empty Weight	Payload	Price
Dry-cargo (standard box)	80 lton	400 lton	$ 55 000
Double-skin tank (Amercoat)	82 lton	398 lton	125 000
Heavy-lift box	120 lton	360 lton	78 000

c. Lighter operating costs. The following costs are assigned to the individual lighters:

i. Annual maintenance = 0.01 (Barge Price).

ii. Annual insurance = 0.014 (Barge Price).

iii. In-port towing. A towing fee of $\$20\,d\sqrt{n}$ is charged for each in-port towing operation, where d is the distance from the drop-off to the dock, and n is the number of lighters towed.

iv. Barge wharfage and miscellaneous costs were estimated at $15 per barge per day, in port only.

d. Lighter capital recovery costs. An economic life of 20 years was assumed, resulting in a capital recovery factor of 0.179 under standard assumptions.

APPENDIX B: FLOAT-ON LASH (FLASH) SYNTHESIS MODEL

The following model applies to non-self-propelled float-on barge-carrying units, as described in Section III B. All elements of the LASH model (Appendix A) apply, except for those explicitly given below.

1. Ship Weights

a. Steel weight $W_s = 0.0052\, L^{1.25}\, B^{0.85}\, D^{0.55}$.

b. Outfit weight $W_o = 0.3\, (LB)^{0.5}$, including normal items of outfit, deck castings and forgings, rig, etc.

c. Barge-handling equipment weight $W_{bh} = 25 + 18\, N$, where N is the lighter capacity.

d. Coupling and towing equipment weight $W_{ct} = 0.0048\, (W_s + W_o + 480\, N)$

2. Ship-Building Costs

The cost relationships of Appendix A hold, with the following exceptions:

a. Outfit, barge-handling and towing gear acquisition costs were placed at

$$\$_{obh} = 3500\, (W_o + W_{bh} + W_{ct})$$

b. Hull structure man-hours were estimated as

$$MH_s = 975\, W_s^{0.71} .$$

c. Total outfit, barge-handling, and towing gear installation man-hours were given by

$$MH_{obh} = 320\, (W_o + W_{bh} + W_{ct})^{0.90} .$$

3. Operating Costs

a. Assignment of crew costs. A crew of four men is assigned to the FLASH vessel, for barge-handling operations. The costs associated with the additional crew members are assigned to the towboat, Appendix D.

b. Insurance costs. Total annual insurance was estimated as

$$\$_{ins} = 0.014 (\mathrm{PRICE}) (\mathrm{OSD}/350).$$

c. Maintenance and repair costs. Annual hull M&R costs were approximated by

$$\$_{hmr} = 12(LBD)^{0.68}(OSD/350) \quad .$$

Annual barge-handling equipment and towing gear M&R costs were estimated as follows:

$$\$_{bhmr} = 1500\ N^{0.667}(OSD/350) \quad .$$

4. Capital Recovery Costs

Capital recovery factors were assumed to be identical with those of Appendix A.

5. Resistance Formulation, Speed, and Powering

The following resistance and propulsion estimating procedure is adapted from Ref. 6.

a. Effective horsepower of barge alone. As a first step, the barge ehp is evaluated as

$$ehp_b = \frac{(DIS/Kd)^{2.54}(V/Kv)^{3.55}}{B^{1.86}\ T^{2.49}} \ (1.30) \quad ,$$

where DIS is the barge displacement (remember to *include* the water inside the "dock"), V is the service speed in knots, B and T the beam and draft, respectively, and Kd, Kv are coefficients defined as follows:

$$KD = 16.0 + 0.137\ C_B L \quad ; \qquad Kv = 1.015 - 0.158\ V/\sqrt{L} \quad ,$$

where C_B is the barge block coefficient, and L is the length between perpendiculars.

b. Effective horsepower augment due to towboat. The towboat, pushing in a nearly close-coupled position, is treated as an appendage of the barge. The effective horsepower augment is approximated by applying the above formulation once again, using the displacement and dimensions of the towboat alone, the towboat block coefficient, and for speed, substituting the quantity $V(1 - w)$, where w is the barge wake coefficient, given by

$$w = 0.727 - 1.86\ C_B + 1.75\ C_B^2 \quad .$$

c. Total effective horsepower. To a reasonable degree of accuracy, the total ehp of the barge-towboat combination is given by

$$ehp_t = 1.10\ (ehp_b + ehp_a) \quad ,$$

where ehp_a is the effective horsepower augment due to towboat, and the factor of 1.10 accounts for appendages, including added resistance due to the gap between the barge and tug.

d. Propulsive coefficient and shaft horsepower. The propulsive coefficient is estimated from the following relation:

$$PC = 0.60(1 - 0.6\ w)/(1 - w) \quad ,$$

and shp is then given by

$$shp = ehp_t/PC \quad .$$

A service margin of 20%-25% is applied for weather and fouling.

During operations, weather conditions may require a hawser tow, resulting in an additional towrope effective horsepower of 15%-30% of ehp_t. An arbitrary reduction in service speed of 15% was assumed during wire tow operations.

6. Delay Assumptions

a. Loading and unloading. Each barge-handling operation is assumed to require an average delay per barge of

$$\text{Delay per barge (hour)} = 0.012\ N \quad ,$$

where N is the lighter capacity.

b. River transit, port, and locking delays are as stated in Appendix A.

c. Miscellaneous, weather, and ice-related delays are assumed to average approximately as the allowances given in Appendix A, however, a more detailed analysis would be necessary in order to investigate the effects of hull form, horsepower, and linkage device effectiveness on weather and ice delay times.

7. Towboat Costs and Operations

The synthesis model for offshore push towboats fitted with linkage devices is contained in Appendix D.

8. Lighter Operations

All factors relating to the operations of individual lighters are as outlined in Appendix A. An added cost item of $5000 is attached to each lighter for the adjustable locking equipment necessary to compensate for lighter drafts, since the draft of the carrying vessel is assumed fixed.

9. Hinged "bow visor" for double-ended loading/unloading. The initial cost of a bow visor, including actuating gear, seals, etc., is assumed to be a flat $250 000. Annual maintenance costs associated with the hinged bow are placed at $5000. It is further assumed that the ice-breaking capabilities of the vessel are unaffected by the addition, and that loading and unloading delay times are reduced by 45% from the values given in Section 6, above.

APPENDIX C: MULTIBARGE FLOTILLA SYNTHESIS MODEL

The elements of this model are based on a combination of data available for river-service units and conventional offshore barges.

1. Barge Weights

a. Steel weight = $W_s = k_s F_f L^{1.25} B^{0.85} D^{0.55}$,

where L, B, D, are the barge length over-all, beam, and draft, respectively, k_s is a steel-weight coefficient based on the type of barge, and F_f is a factor for required increase of steel weight to compensate for lateral bending moment in excessively long (or narrow) flotillas, defined as follows:

$$F_f = 1, \text{ for } L_f/B_f \leq 8 \quad ; \quad \text{otherwise,}$$

$$F_f = 0.287 \; (L_f/B_f)^{0.6} \quad ,$$

where L_f and B_f are the over-all length and breadth of the flotillas, including the towboat.

Values of the steel-weight coefficient k_s are as follows:

Hopper barge	k_s = 0.0049
Double-skin tanker	0.0056
Covered deckhouse barge	0.0060 .

b. Outfit and hatch covers. The total weight of outfit items and watertight hatch covers are given as follows:

Outfit weight $W_o = 0.15(LB)^{0.5}$;

Hatch covers W_{hc} = 0.0085 LB for lift-off covers,

= 0.01 LB for rolling covers,

Tank barge hull engineering $W_{the} = 0.0053 \; (LBD)^{0.08}$.

c. Coupling and towing equipment weight was estimated as

$$W_{ct} = 0.0015 \; (L_f/B_f)(DIS_b) \quad ,$$

where DIS_b is the individual barge full-load displacement.

2. Barge Building Costs

a. Structural steel material acquisition, assuming a total allowance of 8%, was $\$_s = 339\ W_s$.

b. Outfit, hull engineering, and coupling equipment cost was estimated as

$$\$_{ohect} = 3000(W_o + W_{he} + W_{ct}) \quad .$$

c. The installed price of watertight hatch covers was estimated as

$\$_{hc} = 1600\ W_{hc}$ for lift-off covers,

$= 1950\ W_{hc}$ for rolling covers.

d. Structural steel man-hours $MH_s = 197\ W_s^{0.78}$.

e. Outfit, hull engineering, and coupling equipment installation man-hours

$$MH_{ohect} = 110(W_o + W_{he} + W_{ct})^{0.90} \quad .$$

f. The unit price of barge yard labor, including overhead, was $11/man-hour.

3. Operating Costs

a. Assignment of crew costs. A crew of N/3 men, where N is the number of barges in the flotilla, is assigned to barge-handling operations. The costs associated with these crew members, however, are assigned to the towboat, Appendix D.

b. Insurance costs. Total annual insurance on each barge was estimated as a flat percentage of barge price, prorated for length of operating season, as

$\$_{ins} = 0.014(PRICE_b)(OSD/350)$, where $PRICE_b$ was the barge price, and OSD the length of the operating season, in days.

c. Maintenance and repair costs. Total barge M&R costs were set at

$$\$_{mr} = 0.01(PRICE_b)(OSD/350) \quad .$$

4. Annual Capital Recovery Cost

The life of barge units was assumed to be 20 years, whether in salt or fresh water. The corresponding capital recovery factor of 0.179 was used.

5. Speed and Powering of Multibarge Flotillas

The following resistance and propulsion formulation is adapted from Ref. 6.

a. Effective horsepower of flotilla without towboat. Flotilla ehp is evaluated from the following:

$$ehp_f = \frac{(DIS_f/Kd)^{2.54}\,(V/Kv)^{3.55}}{B^{1.86}\,T_e^{\,2.49}} ,$$

where DIS_f is the total flotilla displacement, V the speed in knots, B the over-all breadth of the flotilla, T_e the so-called effective draft as defined by

$$T_e = T\,e^{-0.105\,N} ,$$

where T is the flotilla draft and N the number of barges in the flotilla. The coefficients Kd and Kv are defined as

$$Kd = 16.0 + 0.137\,L_f \; ; \qquad Kv = 1.015 - 0.158V/\sqrt{L_f} ,$$

where L_f is the length of the flotilla.

b. The effective horsepower augment due to the towboat in its pushing position is evaluated from the formula of Appendix B, Section 5a, utilizing the towboat's displacement, dimensions, and block coefficient, and a speed of V(1 - w), where w is the flotilla wake coefficient, estimated as 0.49 for a typical flotilla with extremely high block coefficient.

c. Total effective horsepower is approximated by the sum of flotilla and towboat ehp, with a 5% addition for appendages.

d. Propulsive coefficient and shaft horsepower. The propulsive coefficient is estimated as

$$PC = 0.52 + 0.0075\, T_t \quad ,$$

where T_t is the towboat maximum draft. Shaft horsepower is then defined as

$$shp = ehp/PC \quad .$$

A service margin of 25% is added for weather, fouling and towrope resistance.

6 Operations

a. Each barge handling operation, whether a drop or pickup, is assumed to require a delay of 0.25 hour. Likewise, splitting the flotilla is also assumed to require 0.25 hour.

b. River transit and associated delays are set at an average of 1.5 hour per call.

c. Miscellaneous and weather related delays are assumed to be given by

Added delay per RT = 0.06(RTD), where

RTD is the nominal sea time per round trip.

d. Winter operations of multibarge flotillas. As mentioned previously, the difficulties of ice operation of multibarge combinations are considered very stringent. In fact, the provision of an ice-breaking bow unit would probably be effective, but expensive. For this reason, we have assumed that the operating season for multibarge combinations would normally be 275 days. As a rough estimate, however, the cost of an icebreaking bow for a flotilla of 75 ft breadth was placed at $650 000, excluding bow thruster. No cargo carrying capacity was taken into account, and the length of the unit was placed at a minimum of 85 ft. Thus, we were able to postulate that flotilla operations could continue through the winter months with a delay factor of 12%.

Estimated annual maintenance and repair for the barge units, other than the bow, were taken at 30% greater than the formulation given above shows, for year round operation. The maintenance and repair cost for the bow itself was placed arbitrarily at 2% of its total cost.

APPENDIX D: MULTIBARGE TOWBOAT SYNTHESIS MODEL

1. Assumptions and Preliminary Estimate of Principal Dimensions

The assumptions underlying the choice of towboat proportions are treated in Section III.F, above. Figure 11 shows the principal dimensions assumed, as functions of installed shaft horse power. The following additional assumptions were made:

a. All towboats were twin-screw, medium-speed diesel powered.

b. Both linkage and hawser towing capabilities were required.

c. Propeller arrangements were assumed to include a standard type nozzle.

d. Rudder arrangements were as standard for sea-going vessels, that is, no flanking rudders were fitted.

2. Weights

The multibarge towing vessels under consideration in this model are rather novel in form and application, representing a hybrid of ocean-going tug and river towboat. For this reason, it was found that most existing weight-estimating relationships do not give results consistent with more detailed weight-per-foot calculations. The following relationships were generated from our own preliminary data, and should be regarded as unverified.

a. Steel weight $W_s = 0.0195(LBD)^{0.85}$, where L, B, D are length over-all, beam, and depth, respectively.

b. Outfit, hull engineering, coupling and towing equipment weight. These weight items were estimated from the relation

$$W_o = 0.011(LBD)^{0.825} \quad .$$

c. Machinery weight $W_m = 200(shp/1000)^{0.5}$,

where shp is the total installed shaft horsepower.

3. Towboat Building Costs

a. Structural steel material acquisition cost, assuming a 10% total margin on \$314/ton unit price, was given by

$$\$_s = 345\ W_s \quad .$$

b. Outfit, hull engineering, coupling and towing gear acquisition was placed at $\$_o = 2800\ W_o$.

c. Machinery cost, installed, was estimated as

$$\$_m = 10500\ (SHP)^{0.62}$$

d. Structural steel man-hours were approximated from

$$MH_s = 1060\ W_s^{0.71} \quad .$$

e. Outfit installation man-hours were set at

$$MH_o = 280\ W_o$$

f. The unit price of shipyard labor, including benefits and overhead, was assumed to be \$11.75/man-hour.

g. A shipyard profit of 5% was assumed.

h. The installed cost of all electronic and automation equipment was a flat \$300 000.

4. Operating Costs

a. Ship's complement. The towboat crew is assumed to consist of the following departments: tug deck personnel, machinery plant crew, barge-assigned crew members, and steward's department. The size of each component is estimated as follows:

i.	Tug deck personnel	$CREW_d = 6$
ii.	Engineering	$CREW_e = 4 + 3.32\ \log_{10}(SHP/2500)$
iii.	Barge	$CREW_b$ as obtained from Appendices B or C
iv.	Steward	$CREW_s = 0.17(CREW_d + CREW_e + CREW_b)$.

b. Crew costs $\$_{crew} = 45000\ CREW^{0.8}(OSD/350)$.

c. Insurance costs were estimated as follows:

$$\$_{ins} = (0.02\ (PRICE) + 1800\ (CREW))\ (OSD/350) \quad .$$

d. Annual maintenance and repair cost, for hull and machinery, was estimated as follows:

$$\$_{hmr} = 15\ (LBD)^{0.7} \quad ;$$

$$\$_{mmr} = 3.5\ (shp) + 80\ (shp)^{0.667} \quad .$$

e. Fuel costs were determined as in Appendix A5.e.

f. Lubricating oil costs were estimated as in Appendix A5.f.

g. Layup cost, including all sources, was estimated at a flat $75000. Annual overhead was set at $\$_{over} = 0.0025\ (PRICE)\ (OSD/350)$.

6. Annual Capital Recovery Cost

A capital recovery factor of 0.179 was assumed, corresponding to an economic life of 20 years.

7. Ship Operations

All delays, with the exception of fueling operations, are covered in the synthesis models dealing with the tow, Appendices B and C.

The fueling delay per round trip, in hours, is estimated as

$$\text{Fueling time} = 2 + 0.02\ (DFC)\ (RTD) \quad ,$$

where DFC is the daily fuel consumption in tons, and RTD is the scheduled round trip time in days.

Operating deadweight was estimated as

$$\text{Op Dwt} = 1.25\ (DFC)\ (RTD) + 1.5\ (CREW) \quad .$$

APPENDIX E: MULTIPLE UNIT COST REDUCTION FACTORS

The average cost of identical units, built as a series, decreases as the number of standard units built increases. For the purposes of this study, we have used the following relationship:

$$AVGPRICE = PRICE/N^{b} \quad ,$$

where AVGPRICE is the average unit price of the series, PRICE is the total initial cost of the first unit, N is the number of identical units produced, and b is a coefficient derived statistically for a given type of vessel.

For flotilla barges, Appendix C, the value of b is assumed to be 0.10, while for towboats, Appendix D, the value is placed at 0.09.