Pressure Signatures of Great Lakes Bulk Carriers in Shallow Water and Restricted Channels

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ABSTRACT

One of the more noticeable environmental effects of larger Great Lakes vessels is the increased drawdown experienced when these vessels transit shallow water and restricted channels. This phenomenon, as observed from a fixed point on shore, consists of a marked fluctuation of the water surface elevation. The initial change of water level may be either up or down, depending on the lateral position of the ship in the channel, but the most striking feature is a relatively deep depression of the water surface adjacent to most of the ship's length.

The drawdown phenomenon can best be described in terms of the pressure signature of the vessel, which can be represented either as a spatial fluctuation of pressure along the ship's length or, as it would appear to an observer on the shore, a temporal fluctuation of the pressure at a fixed point during the transit. A simple hydrodynamic model of ship and channel has been used to estimate the amplitude, duration, and shape of the drawdown phenomenon for various existing and projected classes of Great Lakes ships, operating in channel cross-sections typical of the St. Marys River, subject to average current conditions and present speed limits.

The amplitude of the drawdown is strongly influenced by vessel beam and draft and by channel width and depth. Furthermore, vessel speed through the water is extremely important, as the drawdown amplitude varies essentially as the square of the speed. The duration of the drawdown depends primarily on vessel length and speed over the ground. These facts imply that speed limits have an influence on both amplitude and duration of drawdown. Finally, both the maximum drawdown and the shape of the disturbance depend on the ship's lateral position in the channel. The effect of the vessel's hull form, within the normal parameters for ships of this type, is extremely slight.

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I. INTRODUCTION

Great Lakes shipping is uniquely and intimately related to the geographic and environmental constraints of the lakes. In no other marine transportation setting do such large vessels spend such a significant proportion of their operating lives in restricted waters: maneuvering in narrow channels with difficult bends and currents, in shallow water, and often less than a ship length from a valuable and environmentally delicate shoreline. For this reason, each vessel transit represents a potentially damaging environmental influence on the shoreline and its users. And yet, Great Lakes shipping is also intimately connected with the economic well-being of the region, and the balance between economic and environmental concerns is an uneasy one. Due to the high volume of traffic on the principal connecting waterways of the Great Lakes system, the cumulative effect of vessel transit on the shoreline environment may become a critical issue in determining future policies for the development and use of these waterways, policies that will influence the design and operation of Great Lakes ships, the configuration of channel improvements, and the requirements for shoreline protection. Such policy decisions will be particularly important in view of the established trend toward larger vessels in the Great Lakes fleet.

The history of Great Lakes shipping has been marked by periodic increases in the maximum allowable vessel size, essentially determined by the constraining locks on the St. Marys Falls Canal, accompanied by a more or less steady growth in the average size of vessels as owners retire their older, less efficient ships and replace them with vessels built to the maximum allowable dimensions. Broadly speaking, the economies of scale achievable by larger ships are an influential factor in determining public policy, as manifested by the increased dimensions of locks, connecting channels, and harbor facilities. Once these public decisions are implemented, the larger maximum vessel size is reflected over the course of time by a shift in the size makeup of the fleet as a whole.

Prior to World War II, the typical Great Lakes bulk carrier was about 550 ft long, with a beam limited to 60 ft by the width of the old Davis and

Sabin Locks, and commonly only 54 or 56 ft in the older vessels. The demands of wartime steel production led to the construction of the MacArthur Lock, completed in 1943, and the larger of the two standard classes built during the war years had dimensions of 640 x 67 ft. For over two decades the MacArthur determined the size of the largest vessels on the Lakes, but it was only during the mid-1950's that vessels were actually built to the maximum permissible dimensions, 730 x 75 ft.

In 1968, with the opening of the new Poe Lock, a further increase in maximum vessel size brought the Great Lakes system essentially into its present form. The first vessels to take advantage of the new lock's dimensions were delivered in 1972. By 1980, the Great Lakes fleet included 11 ships of the largest size, approximately 1000 x 105 ft, with a typical operating draft of about 27.5 ft at present average midsummer lake levels. New vessels of this class will probably continue to be built at the rate of one or two per year. In this trend toward maximum-size vessels, the normal replacement of obsolescent tonnage in the traditional Great Lakes iron-ore trades is further augmented by the relatively new and growing demand for waterborne transport of western coal.

Recently, the Corps of Engineers approved the transit of vessels measuring up to 1100 x 105 ft through the Poe Lock. With the subsequent adoption of final load-line and scantling regulations for these longer vessels the advent of the 1100-footer is foreseeable, pending a decision by the U.S. Coast Gurad with respect to the safe navigation of an 1100-ft ship in the existing connecting channels. Ultimately, this approval seems likely.

For long-range economic planning, more radical increases in maximum vessel size have been projected. In a 1977 cost-benefit study performed by the Corps of Engineers (Ref. 1), hypothetical vessels ranging up to dimensions of 1500 x 175 ft, and operating at drafts up to 36 ft, were considered as possible candidates for the maximum-size class in a future Great Lakes fleet. From the estimated economic performance of these vessels of unprecedented size, it appears that the advantages of scale that have been the basis for past increases of vessel size continue well above the present limitation imposed by the Poe Lock. The results of this investigation were incorporated in the Corps of Engineers Revised Plan of Study for Great Lakes

Connecting Channels and Harbors (Ref. 2). As anticipated, the influence of increased permissible draft on vessel economics was particularly strong for the relatively shallow proportions typical of Great Lakes bulk carriers. However, it is evident that the massive initial cost and environmental impact of the required dredging of channels and harbors will place stringent constraints on this dimension.

In recent Sea Grant sponsored research, conducted concurrently with the work presented here, preliminary design and economic feasibility studies indicate that even with an operating draft constraint of 27.5 ft, minimum required freight rates are provided by a vessel of approximately 1250 x 150 ft (Ref. 3). On a typical Great Lakes route, from the head of the lakes to Burns Harbor or Cleveland, such a larger ship could provide an estimated transport cost saving of about 12% versus newbuilt vessels of the 1000 x 105 ft class, operating at the same draft. In view of this economic motivation, especially combined with a substantial improvement in fuel economy offered by the larger ship, an eventual increase in maximum vessel size should be regarded as a possibility, provided that the costs of the system improvements required to accommodate the larger vessels are not excessive, and that the environmental impacts of the vessels are judged acceptable.

Clearly, these last conditions are critical questions in planning for the future of Great Lakes marine transport. The system improvements required for a maximum size of 1250 x 150 ft would obviously include one or more new locks, the costs of which can be estimated on the basis of firm dimensions. However, the extent of channel improvement dredging required for the safe navigation of the longer, wider vessel is determined not merely by its over-all dimensions, but also by its maneuvering and control capabilities. These vessel characteristics, and the development of adaptive path-control systems to improve ship performance and safety in restricted waters, form the subject another concurrent Sea Grant funded project (Ref. 4). In view of the high costs and environmental sensitivity of dredging in many Great Lakes harbors and connecting channels, improvements in ship-control technology might be well applied to minimizing the amount of required dredging, thus yielding greater over-all benefits from the adoption of a larger maximum vessel size. In principle at least, the safe operation of larger vessels, aided by advanced adaptive path-control systems, might become feasible even within the existing channel dimensions, thereby limiting the required improvement dredging to the widening of certain critical areas, such as radical bends, turning basins, and passing areas. If this proves to be the case, total system-improvement costs and environmental impacts could be significantly reduced. With this possibility in mind, the direct environmental influences of larger vessels using the existing channels must be given careful consideration. This examination is the primary aim of the work reported here.

Regardless of possible future increases in the maximum size of Great Lakes vessels, however, the composition of the fleet will certainly shift toward a larger average vessel size over the coming years. The problems associated with this trend are many and complex. Among them, ship-safety and environmental concerns are paramount. Possible adverse environmental effects associated with the transit of larger vessels in confined waters have been noted in Ref. 2, specifically with regard to potential increases in the extent, frequency, and severity of shoreline erosion and damage to shore structures along the St. Marys, Detroit, and St. Clair Rivers.

Even in the existing fleet, differences have been noted between the visible shoreline effects of maximum-size vessels and those of smaller ships moving at the same speed and in the same position with respect to the shore. As the average size of vessels in the fleet increases, and the frequency of transits by large vessels becomes higher, the cumulative influence of these vessels on the shoreline environment will grow in importance. Furthermore, with the possibility of an eventual increase in maximum vessel size without a proportional increase in channel cross-section dimensions, as suggested by the findings of Refs. 1 and 3, the prediction of such effects should be an important element of the planning process.

The purpose of this work is to apply a theoretical hydrodynamic model, already validated by comparison with experimental results, to predict one of the key environmental effects of vessel transit in confined waters, namely, the behavior of the water surface elevation or pressure distribution around the ship. Specifically, the form of this pressure variation at a fixed point on the channel boundary during the passage of the vessel will be important in estimating some of the environmental influences of vessels of unprecedented size, most notably the forces on shore protective structures, and the resuspension and transport of sediments. The form of the hull-induced pressure signature is investigated for the simplified geometry of uniform motion along a straight, wall-sided channel, neglecting the local influence of propeller(s) and rudder(s). The results of sample numerical calculations are presented as functions of vessel and channel cross-section dimensions, current, ship speed, hull form characteristics, and vessel position with respect to the channel walls, using typical existing channel dimensions and speed limits for various reaches of the St. Marys River, and vessel dimensions up to 1250 x 150 ft.

II. LARGER GREAT LAKES VESSELS AND THE ENVIRONMENT

The environmental problems associated with increased maximum vessel size on the Great Lakes stem from two distinct sources:

1. Environmental disruption arising from the system improvements required to accommodate larger vessels: the construction of new locks and structures, loading and unloading facilities, and, most significantly, the dredging of connecting channels, harbor approaches, and turning basins.

2. Direct environmental effects of vessel operation attributable to increased vessel size.

The first of these categories is beyond the scope of this report, although any future decision with regard to increased maximum vessel size must hinge on the satisfactory resolution of these problems.

Focussing on the direct environmental effects of vessel operation, and with particular emphasis on the matter of ship size, it is important to make the following distinction: while a larger vessel can be expected to create larger environmental disturbances that a smaller one, it does not follow that the cumulative direct environmental impact of the Great Lakes fleet will be increased by a shift to larger vessels, whether this implies a larger maximum ship size or merely an increase in average ship size within the fleet. In fact the reverse may be true. Two main arguments may be cited to support this assertion.

First, the larger vessel carries a substantially greater payload, as shown in Table I. Thus, for a given annual cargo throughput, a fleet containing larger ships requires fewer vessels in operation, thereby reducing the frequency of vessel transit through environmentally sensitive areas. For this reason alone it is incorrect to measure the over-all environmental impact of the transport system in terms of the disturbances created by an individual ship. Rather, the trade off between larger unit disturbances and reduced transit frequency must be considered in detail. The precise nature of this analysis is undoubtedly quite complex, and beyond the expertise of the ship designer alone. However, the naval architecture of the situation may reveal certain basic information that will be useful in such a comprehensive

Table I. Historical Great Lakes bulk carrier cargo capacities.

Era	Vessel Size LOA (ft)	x Beam (ft)	Typical Midsummer Operating Draft	Approximate Payload (long tons)
1900	524	54	20.8	9,450
	550	56	21.4	10,800
1920	600	60	22.5	14,600
1940	620	60	25.5	16,700
1940	639	67	25.7	19,150
1950	730	75	27.5	24,400
1970	1000	105	27.5	62,100
?	1250	150	27.5	113,900

environmental analysis.

Second, and perhaps more compelling, it can be demonstrated that some of the important components of environmental stress per vessel transit do not increase proportionally with vessel size or cargo capacity. Several examples can be given:

1. Airborne emissions. This factor is essentially proportional to vessel horsepower, other things being equal. As presently envisioned, a vessel of 1250 x 150 ft would have a total installed horsepower of approximately 20,000 bhp, twin screw. The horsepower is limited by considerations of satisfactory propeller performance on the full, shallow-draft hull form typical of Great Lakes vessels. Existing 1000-ft ships are variously powered between 14,000 and 19,500 bhp, depending principally on the owner's operating philosophy and engine preference. Thus, the larger vessel should be able to produce approximately 20%-40% less airborne pollutants per ton of cargo delivered.

2. Thermal emissions. Hot water discharge is dominated by engine-cooling requirements for diesel-powered ships, and by condenser flow rates for steamships. In either case, the total thermal effluent is again essentially determined by installed horsepower, with similar savings in disturbance per ton of cargo.

3. Overboard discharge of waste and contaminated bilge and ballast water. Under present environmental regulations in force on the Great Lakes, zero discharge of these pollutants is required. Thus, the larger vessel should impose no additional environmental stress in this connection.

4. Toxic emission from hull anti-fouling coatings. This component is directly related to underwater surface area. In the loaded condition, at a draft of 27.5 ft, a vessel of 1250 x 150 ft will have approximately 60% more wetted surface than a typical 1000-footer. This represents a saving of about 11% in toxic emissions per ton of cargo delivered. A corresponding figure calculated on the basis of a typical ballast condition of 20 ft mean draft is about 9%. This estimated advantage is actually overconservative, since bottom shell plating, which accounts for nearly the entire increase in wetted surface, requires substantially less anti-fouling protection per

square foot than side shell plating nearer the waterline.

5. Exterior sound levels due to machinery. Again, this component of environmental impact is dictated by installed horsepower. It is quite possible, in addition, that a larger vessel could afford more extensive sound deadening characteristics, simply by virtue of its increased beam, depth, and internal volume.

6. Propeller-induced vibration. Propeller-induced low-frequency vibrations are conducted through both water and ground to influence shoreline structures and nearby dwellings. When operating in proximity to the shore, and in confined waters in general, any sizable vessel will be using a relatively small fraction of its available power, except during operations in ice. Nevertheless, due to the full stern form and heavily loaded propellers of Great Lakes bulk carriers, propeller-induced vibration may become troublesome even at reduced power settings. The problem is further aggravated in shallow water, where the small underkeel clearance usually results in highly disturbed flow into the propellers. Depending on the stern design of the larger vessel, this problem should not become significantly worse, since the increased beam would permit wider spacing of the propeller shafts, maintaining their relative location with respect to the vessel's sides. Of course, the larger vessel will require greater thrust at any given speed. This will increase the propeller loading and the level of propeller-induced vibration. The extent of this increase is not known, but it can be assumed that the larger ship will produce higher levels of vibration ashore. However, except during ice navigation, which represents a separate environmental issue outside the scope of this report, power settings in restricted waters are usually low enough to ensure relatively low levels of vibration transmitted to the shore, apart from momentary power applications required in maneuvering, acceleration, and backing. The over-all question of the environmental impact of propeller-induced vibration must be studied further, particularly in the context of winter navigation.

7. Disturbance of bottom sediments due to propeller and side-thruster wash. The intensity of propeller-related disturbance and scouring of bottom sediments is dependent on two principal factors: underkeel clearance and propeller loading. At a similar draft, the clearance of a larger vessel's

propellers will be approximately the same as that of existing 1000-ft ships, apart from a small difference due to the increased squat experienced by the larger ship at a given speed. (This factor will be mentioned in greater detail subsequently.) As indicated above, the propeller loading is higher for the larger ship. Thus, although the precise magnitude of the environmental difference is not known, it may be concluded that the bottom-sediment disturbance due to the transit of a larger vessel will be somewhat greater than that of a smaller ship, even during ice-free navigation. While further study of this effect is needed, it seems unlikely that the increase in environmental impact will be as great as the gain in cargo capacity.

During ice navigation, however, great increases in thrust are required at very low speeds, resulting in substantially more bottom disturbance by ships of all sizes. The problems of bottom scouring and increased water turbidity during winter operations on the St. Marys River have been noted by environmentalists (Ref. 5). There can be little doubt that vessels of increased size, with much higher thrust requirements in ice (several major components of ice resistance being proportional to vessel beam), will cause still greater concern.

Side thrusters are fitted on all existing vessels of the 1000-ft class, and many smaller ships as well. These maneuvering devices are useful only at very low speeds, such as in docking or undocking, and when swinging ship in a turning basin or channel. Because of their location near the bottom of the ship, their transverse orientation, and their relatively high power (up to 1500 bhp each, in current designs), the effect of thruster wash on shore structures and sediments can be noticeable. Projected bulk carriers of 1250 x 150 ft will in all likelihood be fitted with both bow and stern thrusters, as are some existing vessels. Due to the increased length, windage, and mass of the larger ships, an increase in thruster power may be desirable. However, the use of these devices will be limited to certain identifiable areas, many of which can be protected against wash damage. Therefore, it seems unlikely that a significant over-all increase in environmental impact will be attributable to these maneuvering aids.

8. Risks of environmental damage due to vessel hazards. For Great Lakes bulk carriers the principal types of vessel mishap involving risk to

the environment are grounding and collision, both of which entail the possible discharge of oil fuel. (The most common Great Lakes bulk cargoes, namely, iron ore, coal, and stone, are relatively innocuous if accidently released.) Clearly, both grounding and collision hazards are increased when operating in shallow, restricted waters while also maneuvering in heavy vessel traffic. This situation nearly always exists in the Great Lakes connecting channels. While this increased risk, of course, applies to ships of all sizes, the further influence of vessel size on these hazards is not easily determined, since several contradictory factors are at work. A larger vessel, due to its comparative unwieldiness and tighter geometric clearances, is theoretically under a greater risk of both grounding and collision. Furthermore, with a somewhat larger total bunker requirement the possible volume of fuel discharge is increased, although this can be alleviated by better subdivision and protection of fuel tankage permitted by larger dimensions.

On the other hand there are a number of practical influences which tend to counter the assumed increase of risk. First, with larger but fewer ships in the fleet, and a consequent reduction in encounter frequency, the long-term incidence of collisions and groundings caused by evasive maneuvers can be reduced. Second, a larger investment in improved collision avoidance, navigation, and ship-control systems can be justified due to advantageous economic performance of the larger vessel. Third, with fewer vessels operating, traffic control in key areas becomes both easier and more effective. Finally, with a smaller fleetwide crew requirement, owners can afford to find the best available talent in selecting officers and crew. Put another way, larger and more comfortable ships attract better people. For these reasons the over-all effect of larger vessels on long-term environmental risk is likely to be favorable.

9. Changes in pressure, water level, and flow during vessel transit. This particularly visible environmental effect of vessel transit in restricted waters arises from the pressure field created by the moving hull. Even in deep water, a region of low pressure (which corresponds to a measurable depression of the water surface) is created around a vessel in motion. This effect increases roughly as the square of vessel speed, and also with decreased water depth. In a laterally confined channel the pressure field is

further exaggerated, resulting in greater "drawdown" of the water surface. With the change in water level the vessel itself is bodily lowered (squat), reducing underkeel clearance, and generally there is also a change in trim. Furthermore, if the vessel is asymmetrically located with respect to the channel a net horizontal force and yawing moment are imposed on the hull: the force tending to draw the vessel into the nearer bank, the moment tending to push the bow away from the bank while drawing the stern toward it. For this reason, a vessel moving along a restricted channel and closer to one side is forced to assume both a yaw and rudder angle in order to maintain its lateral position in the channel. This fact in turn causes a change in the observed pressure field.

The environmental effects of the pressure disturbance are numerous, although some are more readily apparent than others:

a. The time variation of pressure may cause excessive pore pressure gradients in bottom sediments. This in turn results in vertical flow through the sediment layer, with possible uplifting forces on individual particles and the creation of a quick condition or so-called explosive liquification. The ultimate environmental effects can include increased resuspension and transport of sediments, and the disruption of benthic biosystems.

b. In shallow water areas adjacent to the ship channel, or near the shoreline, the change in water level may approach or uncover the river bed. The local current velocity changes rapidly in both direction and magnitude as the waterline first recedes and then returns to its original level after the passage of the vessel. This drastic change in water level and velocity can result in various inconveniences for users of the shoreline, as well as loads on shore protection and other structures, and the disruption of sediments and benthic organisms.

c. Depending on channel-embankment slope and soil characteristics, local disturbances due to the changing pressure field can initiate mass soil movements or slides along the edges of the channel.

d. In tributary streams the change in pressure at the outlet can cause rapid and sizable changes in level and current. The flow in shallow streams may become supercritical, resulting in a characteristic hydraulic jump, or bore, reaching a significant distance upstream. This phenomenon can cause environmental damage and inconvenience.

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The results of numerical calculations of the pressure variations caused by existing and projected Great Lakes vessels operating in confined channels are presented in the following sections of this report. The influence of ship and channel dimensions, speed, current, and lateral position are of primary interest in this investigation. The key environmental results include not only the maximum water surface depression, but also the shape of the pressure distribution which, when properly transformed into the corresponding time history of pressure at a fixed point, gives some information on the maximum rate of pressure change. These results are primarily intended to be of use in further research into the actual mechanisms of environmental damage due to vessel-induced pressure variation, as listed above.

III. HYDRODYNAMIC MODEL, CHANNEL GEOMETRY, AND AREAS OF APPLICATION

The prediction of pressure distributions due to vessel transit in shallow, confined channels is based on slender-body theory and the method of matched asymptotic expansions, as presented by Beck (Ref. 6). That work, and the computer program developed in connection with it, were aimed at predicting the side force, yawing moment, squat, and trim on a vessel moving in a straight channel of rectangular cross section, at an arbitrary lateral position and yaw angle with respect to the channel walls. The numerical results presented in Ref. 6 were found to be in good agreement with experimental results. Although the method was intended primarily to predict forces acting on the ship, the nature of the numerical scheme is such that linearized pressures corresponding to the solution can be easily calculated for any point in the fluid or on the channel boundary.

The usual slender-body assumptions are particularly satisfactory for vessels of typical Great Lakes proportions, with length-beam ratios generally approaching 10, and length-draft ratios of at least 25, even at full load draft. The blunt ends typical of modern Great Lakes bulk carriers, usually in the form of a parabolic bow and immersed transom stern, are somewhat more troublesome. In particular, stern forms having nonzero sectional area at the trailing edge lead to numerical errors in the calculation of the pressure field, including anomalous nonzero pressures far upstream and downstream of the ship. For this reason, the sectional-area curves actually used in the calculations for transom-sterned ships are faired to zero, using a fictitious after terminal located a small distance behind the actual transom position. This modification introduces no substantial errors in the over-all pressure results. In any case, the far-field pressures predicted at the lateral position occupied by the ship itself (obviously not in the far field) are not reliable, and therefore are not presented here.

The assumption of shallow water in the channel is explicitly necessary in order to reduce the outer-region problem to two-dimensional flow in the horizontal plane, a simplification which facilitates the calculation of side force and yaw moment. In effect, this requirement is satisfied if the water depth and ship draft are approximately equal. With typical underkeel clearances of only a few feet in many Great Lakes channels this approximation should be acceptable.

Finally, the solution of Ref. 6 assumes subcritical flow in the channel, that is, a Froude number based on water depth of less than 1. This assumption is valid under all conditions of ship speed, current, and channel depth experienced in Great Lakes bulk carrier operations.

For a number of reasons that will be pointed out subsequently, the assumed channel cross section is rectangular, as in Ref. 6. While this geometry corresponds quite closely to several channel areas in the Great Lakes system, such as the Rock Cut and Little Rapids Cut on the St. Marys River, it is obviously not a completely convincing model of other environmentally sensitive reaches. Notable examples are Lake Nicolet and Munuscong Lake, also on the St. Marys, where the cross section more closely resembles a modification of the assumed geometry of Ref. 7 (see Fig. 1) insofar as the prediction of the gross pressure field surrounding the ship is concerned. The geometric situation is further complicated in narrower areas of the river, such as the middle Neebish, West Neebish, and Munuscong Channels, where the combination of a dredged ship channel with relatively nearby river banks leads conceptually to a combination of the geometries assumed in Refs. 6 and 7. In the neighborhoods of Johnson and Stribling Points, and in other places as well, the assumption of uniform linear motion (invoked in both Refs. 6 and 7) is patently violated, and the forces acting on a vessel negotiating a bend will also produce changes in the pressure field not predicted by a simple model.

In any case, a gross geometric model of the channel cross section which actually gives a fairly accurate prediction of both the forces on the ship and the pressure signature out in the channel will not necessarily provide the local details of the resulting flow in very shoal areas with sloping or irregular bottoms, that is, right at the shoreline itself. Most importantly, the character of the flow necessarily changes from subcritical to supercritical, with a resulting hydraulic jump. In fact, a linear hydrodynamic treatment as a whole breaks down at a natural, sloping beach. In very shallow water, furthermore, the viscous flow effects will not remain negligible, as is assumed.

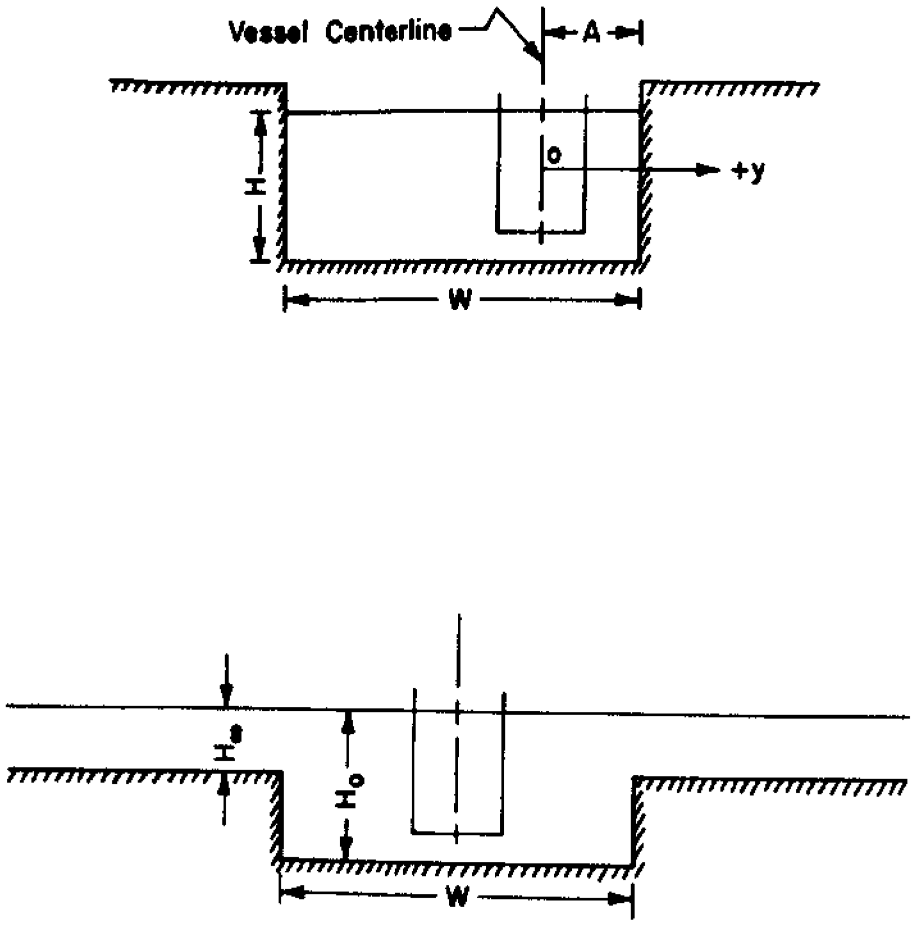


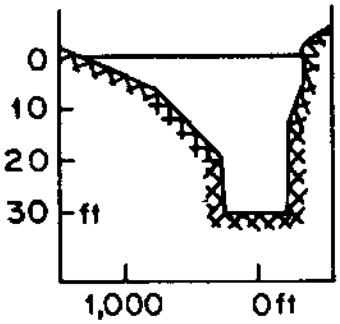
Figure 1. Comparison of model channel geometries. (Top) Assumed geometry of Ref. 1, adopted for this work. (Bottom) Dredged channel geometry of Ref. 7.

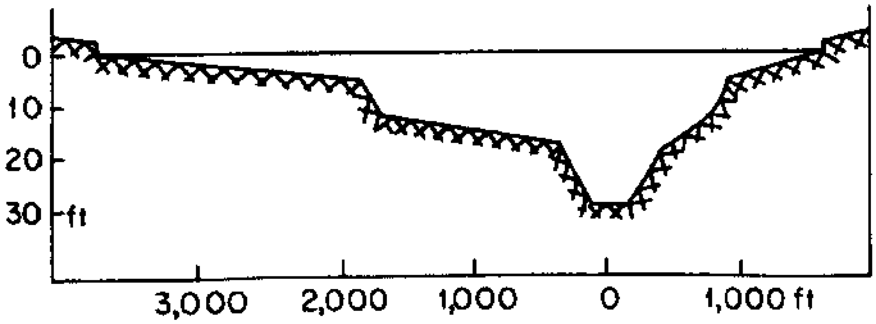
In this connection, it should be mentioned that the influence of river current on the pressure history experienced at a fixed point on the river bed is simply accounted for by considering speed through the water in calculating the steady pressure signature in the moving ship's frame of reference, and then using speed over the ground to transform this signature into the time history recorded by an observer at a fixed point. This treatment is strictly valid for a uniform current velocity, which will be the case for a hydraulically smooth, straight, rectangular-section channel, apart from the assumed negligible influences of the viscous boundary layer near the channel walls and bottom. In shallow areas outside the channel, where the effects of both viscosity and obstructed or transitional flow may become physically important, the assumption of a uniform free stream throughout the section is obviously invalid, although the current within the channel itself may remain essentially uniform. In any case, the assumption of a uniform free stream would be essential to simplify the method, regardless of the assumed cross-sectional geometry.

With these limitations in mind, the simpler rectangular channel of Ref. 6 was adopted here rather than the dredged channel of Ref. 7. The immediate practical advantage of this choice, namely, the ability to model vessel operations off the channel centerline, seemed more valuable in the context of this preliminary study than the influence of shallow-water areas of infinite lateral extent adjacent to the channel.

It should be kept in mind, then, that the predicted pressure curves are intended to be applied in their given form only within the limits of the assumed geometry. As shown in Fig. 2, this assumed geometry actually corresponds to two quite dissimilar cases:

1. Where the water depths inside and outside the channel are not greatly different, or alternatively, where the channel boundaries are close to the river banks. In either case the gross geometry can be approximated by a rectangular cross section of equal area without seriously compromising the accuracy of the calculated pressure field. Examples of such cross sections on the St. Marys River include De Tour Passage, Lime Island Channel, and parts of Middle Neebish Channel between Everens and Johnson Points. As mentioned above, cut canals such as the Rock Cut, Little Rapids Cut, and the approach





West Neebish Channel, on line bearing 270° from Winter Point Range Rear Light, looking downriver.

Figure 2. Typical cross-sections of channel-river combination on the St. Marys River. Approximate depths taken from NOAA Chart 14883.

channels to the Soo Locks, are quite similar to the model geometry.

2. Where the water depth directly adjacent to the ship channel is very shallow. In this case, the effective contribution of flow in the outer areas to the pressure field around the ship is slight, and the gross geometry can be approximated by the dredged channel section alone, simplified to a rectangular cross section, neglecting the shallow-water areas entirely. Of course, the calculated pressure distributions can then be applied only in the channel; the details of the resulting flows in the shallow areas can only be determined by a more complicated method accounting for the transition from subcritical to supercritical flow, viscous effects, etc. Examples of this type of section are portions of the West Neebish Channel above and below the Rock Cut, and the northern end of Lake Nicolet, just below the Little Rapids Cut.

For intermediate situations, where the outer areas are substantially shallower than the dredged channel, but neither shallow nor narrow enough o be neglected in the gross model geometry, the pressure field around the vessel should be expected to deviate from the predicted form using a rectangular section of equivalent total cross-sectional area. This interesting case may be more closely analogous to the assumed geometry of Ref. 7, but the influence of finite over-all width will require further study. This section type, exemplified in Fig. 3, is characteristic of most of Lake Nicolet. Obviously, gross asymmetry in the combined river-channel cross section, such as in the case of a dredged channel abutting the river bank or very shallow water on one side, with water of shallow but non-negligible depth and extent on the other side, will further complicate matters, as will the influence of river bends. These situations will require a still more refined geometric model.

However, in this first treatment, a relative comparison of the pressure fields created by vessels of various sizes, even in a highly simplified channel geometry, should provide at least an approximate quantitative insight into some of the environmental problems associated with the operation of Great Lakes ships of unprecedented dimensions within the existing channels. This first approximation is the primary goal of this work.

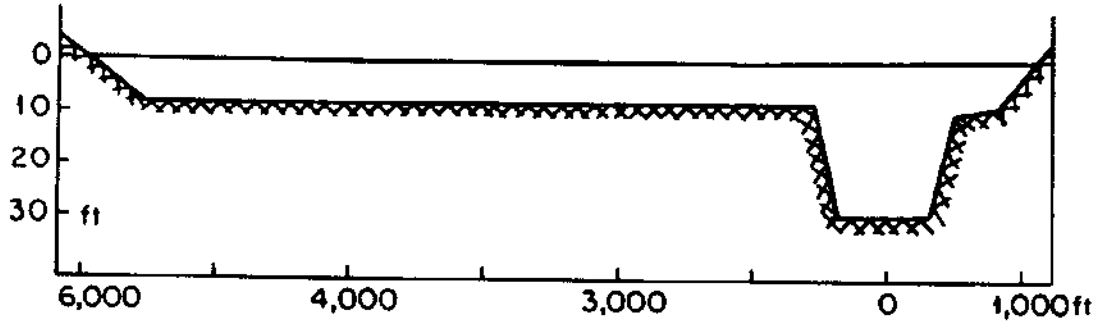


Figure 3. Typical section, Lake Nicolet, St. Marys River, north of Six-Mile Point. Note correspondance to hybrid of model geometries assumed in Refs. 6 and 7.

As mentioned in the introduction, the effects of propeller and rudder forces on the over-all pressure signature are not included in this analysis. It must be noted that the rudder plays an important role in determining the true equilibrium of forces and moments acting on the vessel when operating off the centerline of the channel, and thereby reduces the actual required yaw angle of the ship in steady state. This in turn influences the resulting pressure field created by the hull. In addition the rudder, acting in the accelerated flow of the propeller, generates its own concentrated pressure field in the vicinity of the stern. It is strongly recommended that this effect be considered in further research.

IV. RESULTS

Three vessels were considered in the sample calculations presented here. They are, respectively, a typical 730-footer of early 1960's vintage, an existing 1000-footer typical of mid-1970's new construction, and a projected bulk carrier of 1250 x 150 ft. Ship particulars are listed in Table II, and sectional-area curves, bow and stern profiles, and waterline offsets (all required input for the hydrodynamic program) are shown in Fig. 4 for the full-load condition. Corresponding approximate data for the ballast condition were derived from these curves, with typical forward and after drafts assumed, and the resulting sectional-area curves are shown in Fig. 5.

A brief explanation of the terminology used in the presentation of results is given here. To simplify the dependency of the pressure variation on speed it is most convenient to express the results in terms of the nondimensional linearized pressure, p*, defined as

$$p^* = p/\tfrac{1}{2}\rho V^2 \ ,$$

where p is the actual pressure, ρ the density of water, and V the speed of the ship through the water, in any consistent units. It is this nondimensional form that is used in all subsequent results. To convert the nondimensional pressure to an equivalent change in water-surface elevation, the following relationship may be used:

$$h = \tfrac{1}{2}p^* V^2/g \ ,$$

where g is the acceleration of gravity.

The coordinate system is as follows: the origin is located at the midships station on the vessel centerline. The coordinate x lies along the direction of vessel motion (assumed parallel to the channel) positive aft. The coordinate y is perpendicular to the direction of motion, positive to starboard. The vessel yaw angle is indicated by θ, relative to the negative x direction. The channel width is denoted by W, water depth by H, and the distance to the starboard wall (assumed to be the near wall in the following results) by A. The ship length is L.

Table II. Ship particulars.

Length over-all (ft)	730.0	1000.0	1250.0
Length waterline (ft)	712.0	1000.0	1250.0
Beam (ft)	75.0	105.0	150.0
Midsummer Operating Draft (ft)	26.5	27.5	27.5
Depth (ft)	39.0	56.0	62.5
Length of entry (ft)	142.0	121.0	175.0
Length of parallel midbody (ft)	392.0	744.0	940.0
Length of run (ft)	178.0	135.0	135.0
Ballast drafts (for'd/aft) (ft)	20/25	22/27	22/27
Block coefficient at operating draft	0.864	0.942	0.947
Displacement at operating draft (long tons)	33,960	75,560	135,640
Installed horsepower	9,000	14,000	20,000
Service speed (mph)	16.8	15.0	14.4

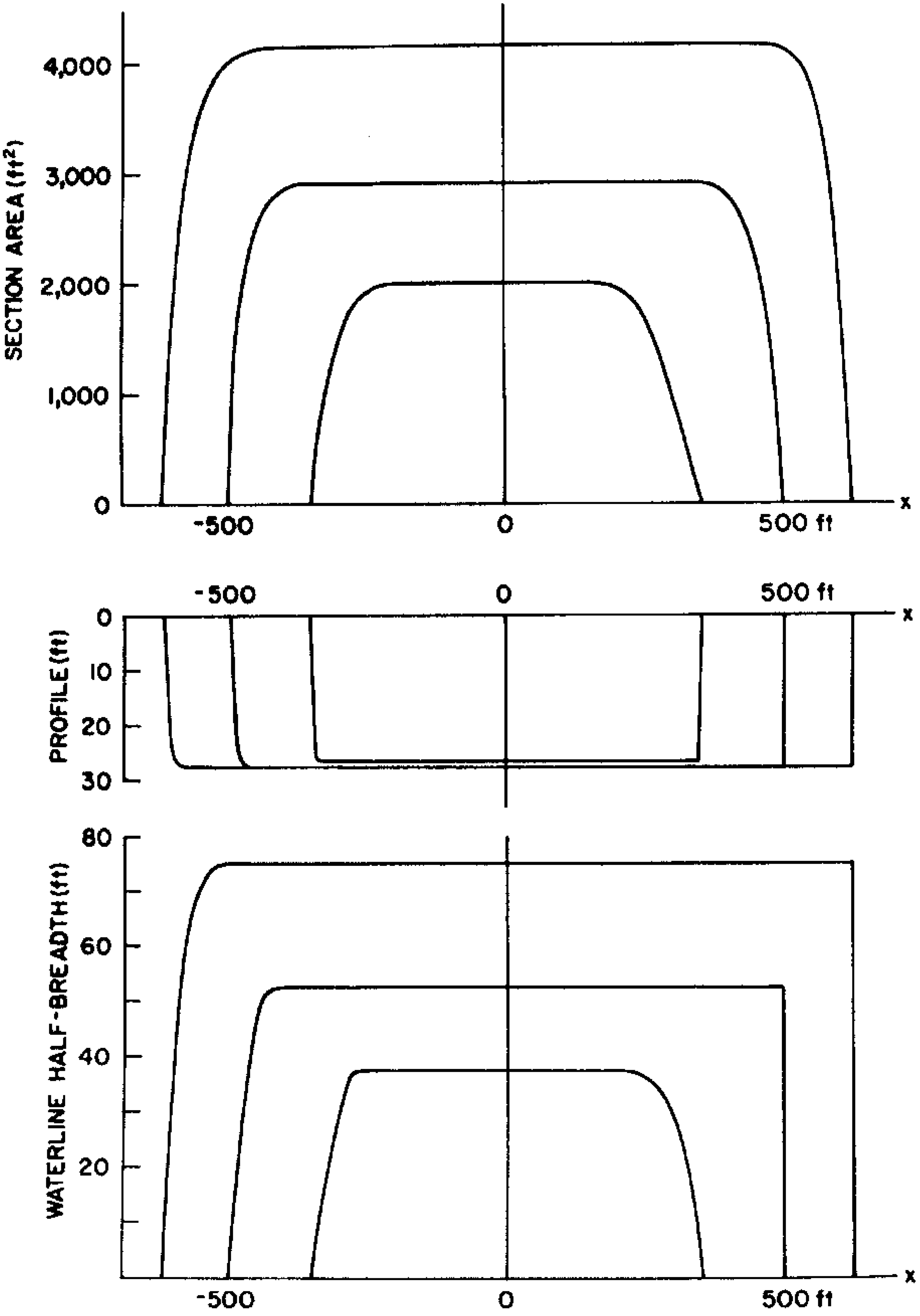


Figure 4. Sectional-area curves, underwater profiles, and waterline half-breadths for three ships.

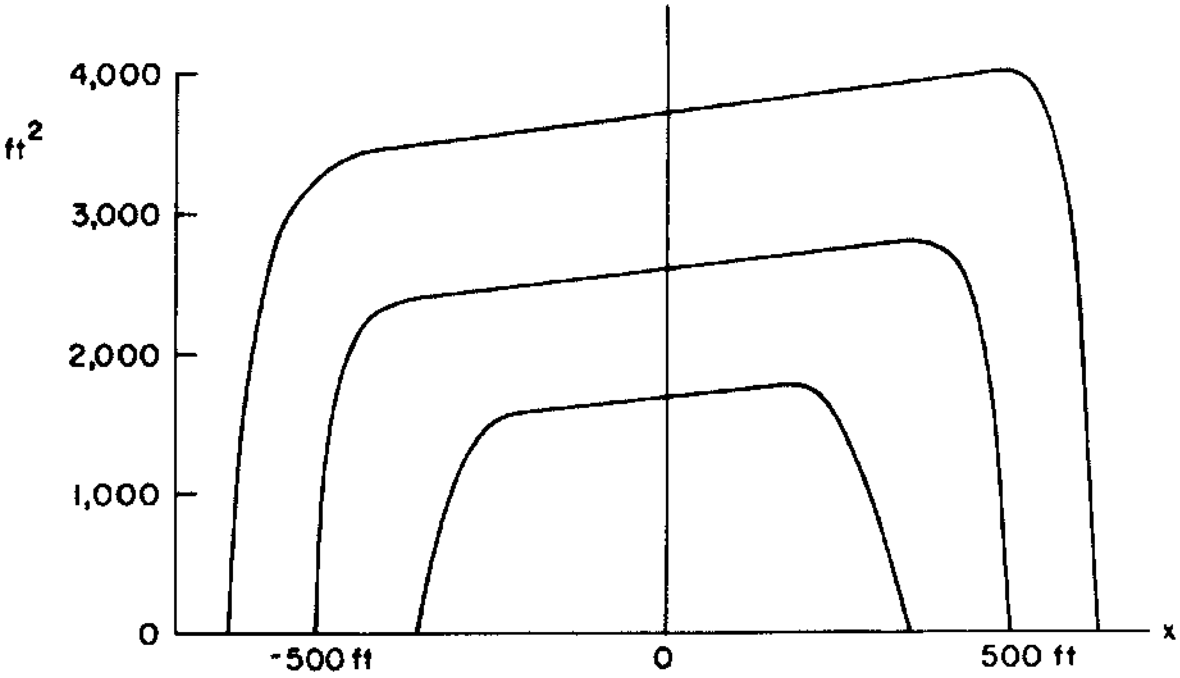


Figure 5. Sectional-area curves of three ships in ballast condition.

Pressure Signatures in Laterally Unbounded Shallow Water

Before considering vessels in narrow channels it may be of interest to observe the predicted pressure patterns created by vessels moving in laterally unrestricted but shallow water. This case, of course, represents the limiting behavior of the pressure signature in channels is the width is allowed to increase. Figure 6, a three-page figure composed of a separate plot for each of the three vessels, shows several longitudinal contours of the pressure signature at various distances (y) from the centerline. In this case, all three vessels are in the full load condition and moving at the same speed, 10 mph.

The differences in magnitude between the three signatures are quite large, although not quite proportional to midship section area. The general form of the pressure variation is consistent: a slow rise in pressure ahead of the bow, followed by a rapid fall toward amidships. The signatures of all three vessels are quite symmetrical fore and aft (of course, this analysis neglects the influence of the propeller, which would tend to destroy this symmetry).

In laterally unbounded water the pressure disturbance extends a number of ship lengths both ahead and astern, with no particular sharp boundaries. Furthermore, the longitudinal contours of the pressure signature quickly decrease in magnitude as the distance from centerline increases. These features, together with the pressure rise ahead and astern of the ship, are characteristics that are lost in tightly confined channels, except in the case of supercritical flow, which we will not consider here.

It should be noted that the double-humped behavior seen for the two larger ships just forward and aft of amidships is spurious. These peaks quickly die out with increasing distance from the ship. As mentioned previously, the linear hydrodynamic model used here will not give reliable results in the immediate vicinity of the ship, and the problem is exaggerated when the station spacings submitted in data are too large. In any case, this behavior is also lost in constricted channels, as will be seen.

The influence of ship speed on the form of the signature is shown in Fig. 7, for the case of the 1000 x 105 ft vessel. The behavior of the signature with speed is complex, in that at various locations with respect to the

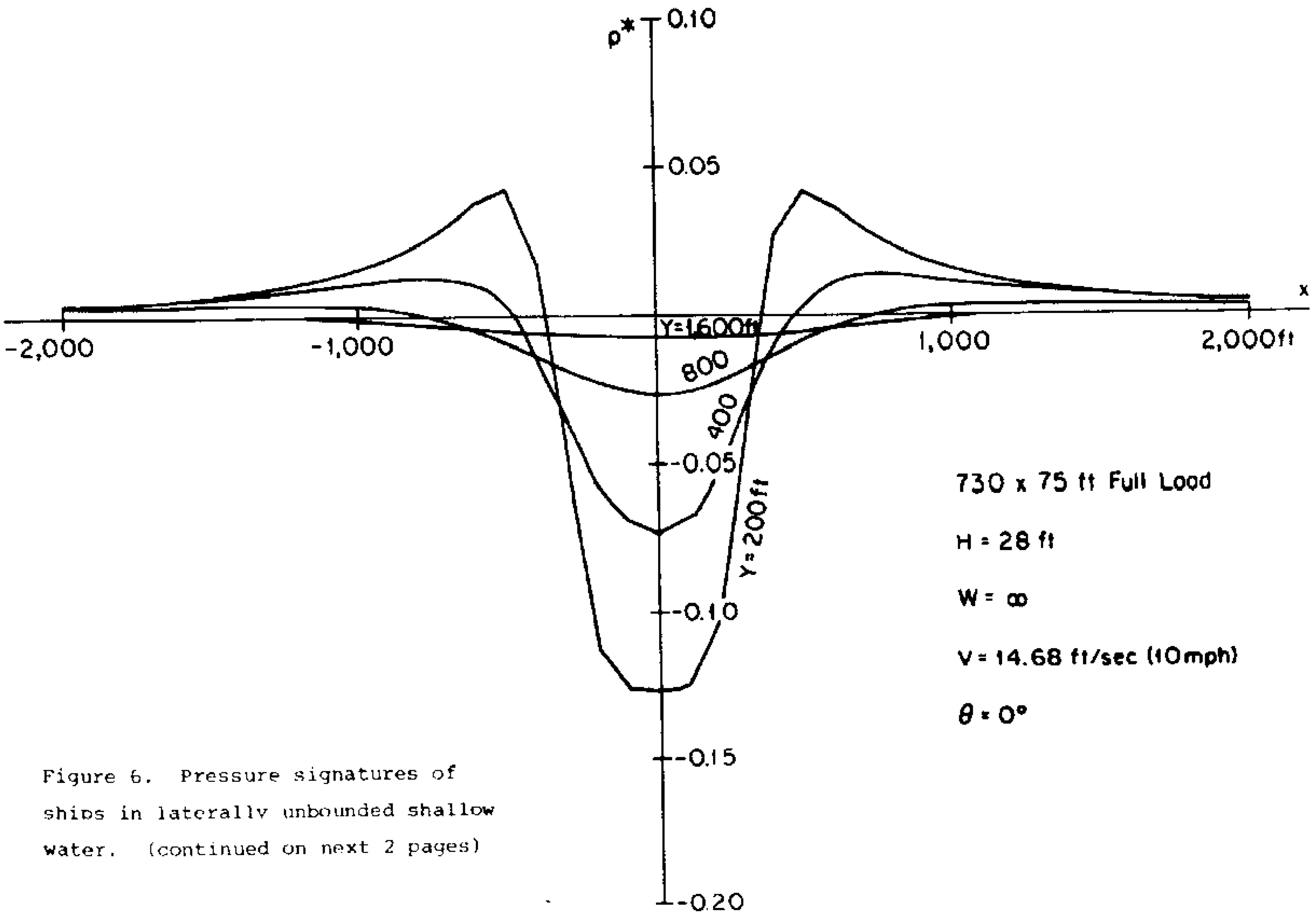


Figure 6. Pressure signatures of ships in laterally unbounded shallow water. (continued on next 2 pages)

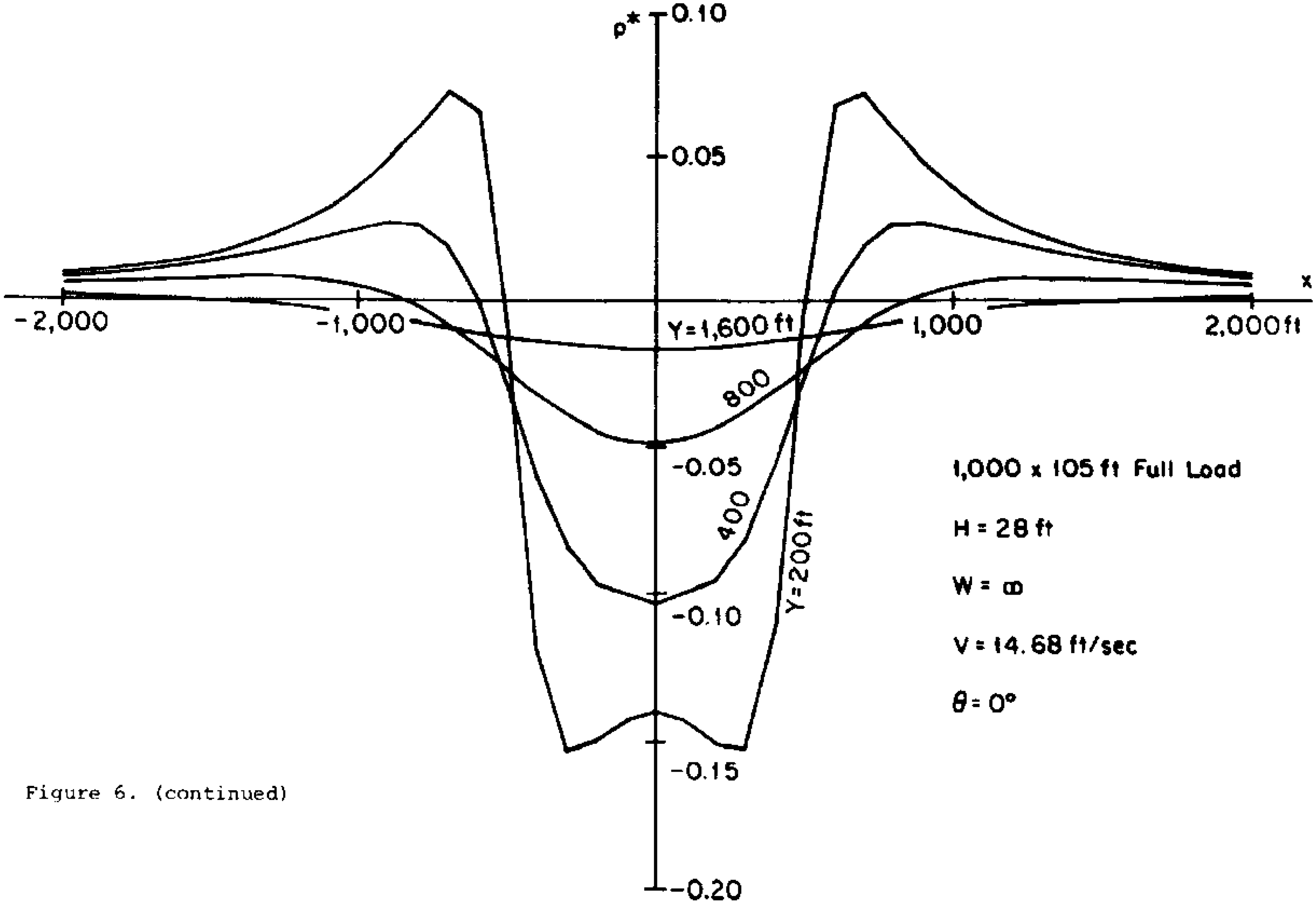


Figure 6. (continued)

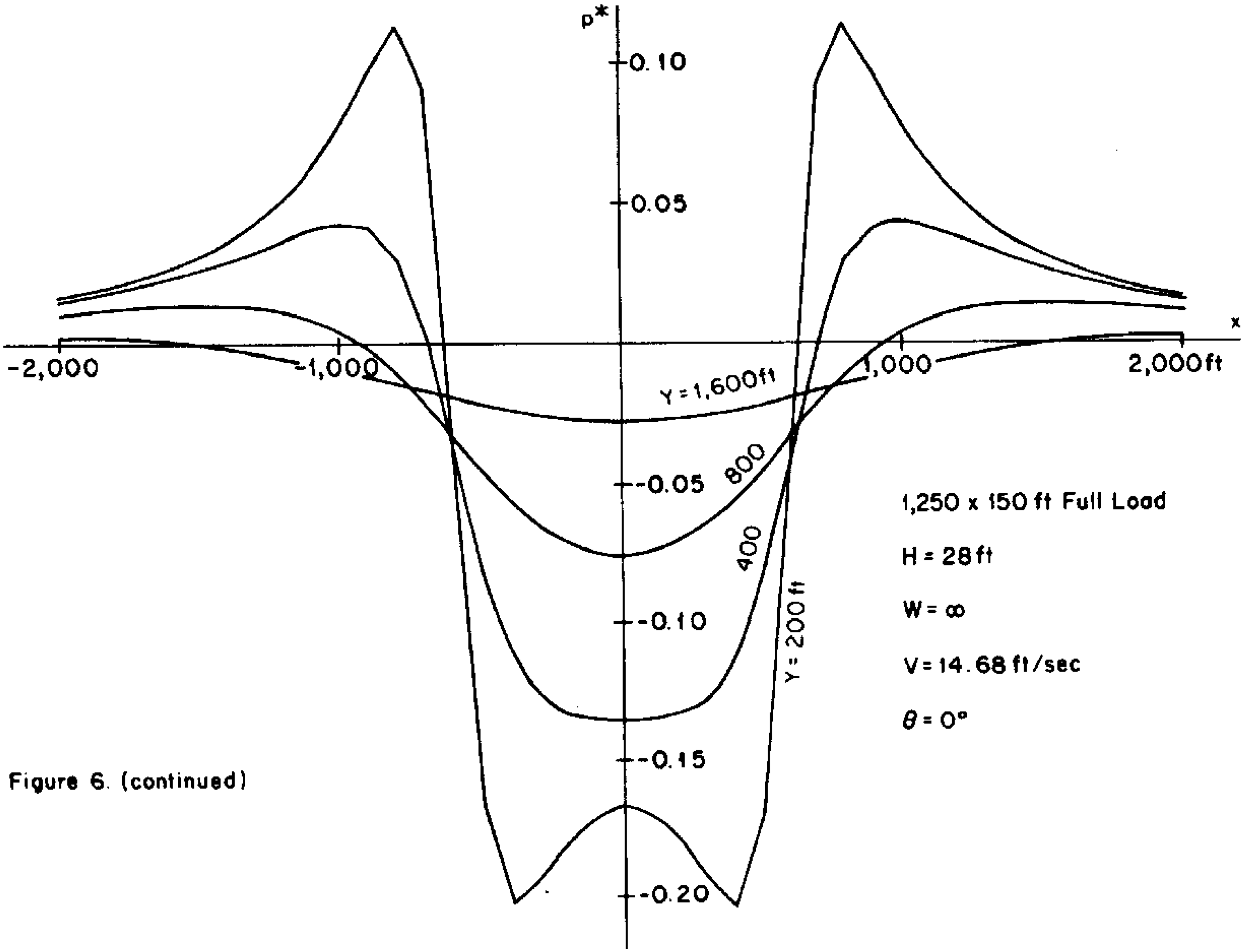


Figure 6. (continued)

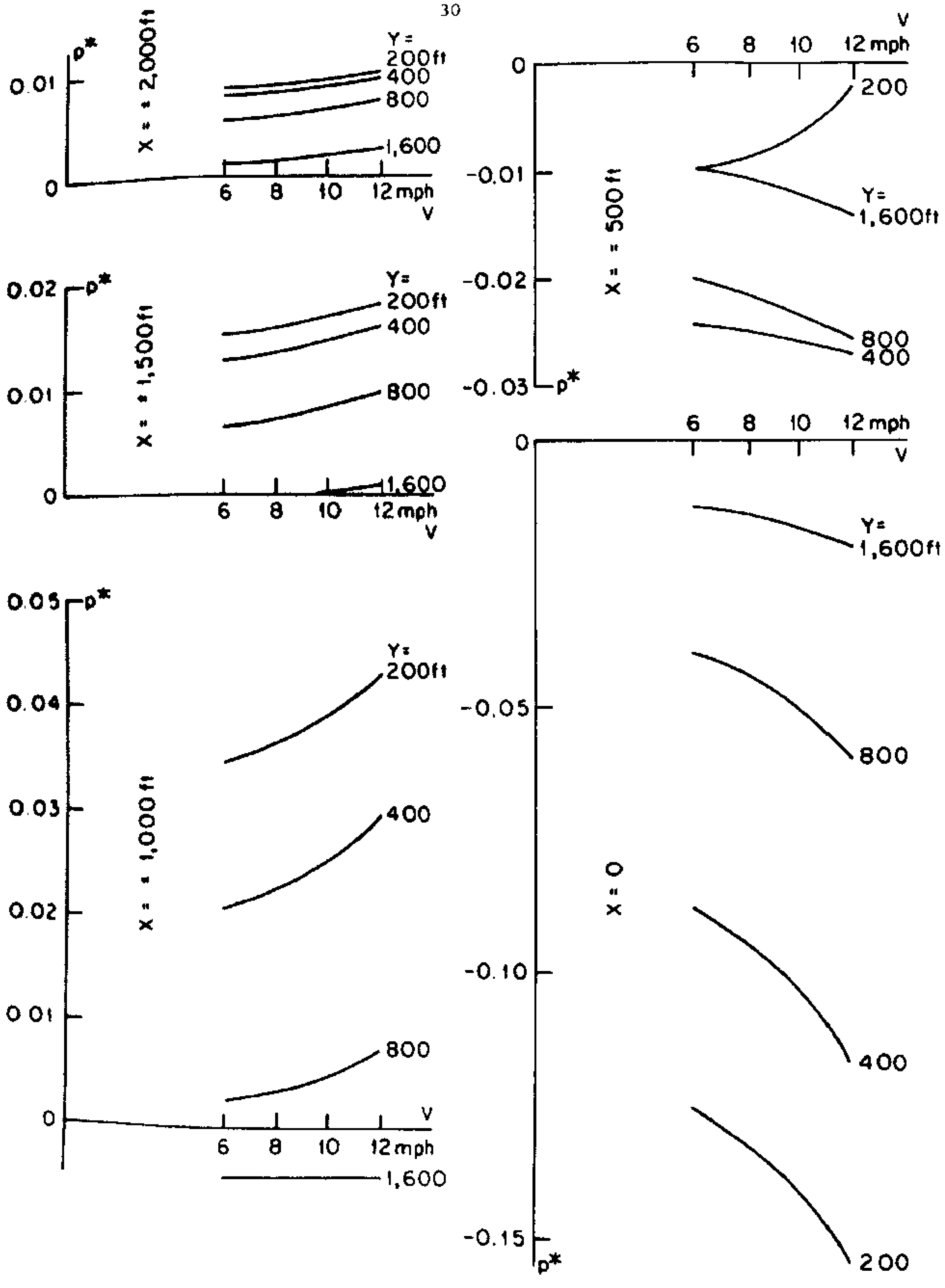


Figure 7. Sample variation of pressure signature shape with vessel speed, 1000 x 105 ft, laterally unbounded shallow water, $\theta = 0°$.

ship the behavior of the pressure as a function of speed may not be uniform, even in direction. For example, at x = 1500 ft, y = 1600 ft, a shallow trough changes into a crest. In the vicinity of the ends of the vessel, in this case at x = 500 ft, the behavior at various values of y is contradictory. For this reason, the detailed behavior of the shape of the signature with speed will not be considered in depth here.

On the other hand, it is apparent that the magnitude of the signature, in terms of its maximum pressures, increases somewhat faster than V^2, since the dimensionless values plotted in Fig. 7 already contain a V^2 dependency. This general behavior applies to both the amidships trough and the crests ahead and astern of the vessel, as shown by the plots for x = 0, and larger values of x, respectively. This behavior with respect to speed is quite similar for the other two ships.

The effect of yaw is shown in Fig. 8, again for the 1000-ft vessel. In order to show the asymmetry of the pressure signature the figure consists of transverse contours at a number of locations, rather than the longitudinal contours as in Fig. 6. It should be noted that this figure corresponds to a rather large yaw angle of 2°, chosen to accentuate the asymmetry of the situation. This yaw angle generates a calculated side force of almost 1 million lb, which is unlikely to be encountered during steady state running on a straight course. The salient feature of the signature, of course, is that the pressure on one side is greatly reduced (the suction side), while that on the other is increased. This pressure change due to circulation is then super-imposed on the pattern due to the sectional area curve of the ship. Yawed signatures for the other vessels are generally similar in form.

Finally, for comparison, the pressure signature of the 1000-ft vessel in the ballast condition is shown in Fig. 9. The difference between this signature and the corresponding full load pressure distribution in Fig. 6 is rather subtle, considering the gross change in sectional-area curve. In fact the principal difference is confined to the amidships portion of the curve, where the distribution of sectional area is matched by a shift in the centroid of the pressure curve. Again, the double-humped behavior at y = 200 ft is spurious, and quickly disappears with increasing distance. The bow pressure rise is somewhat smaller than in deep load, but the after extremity

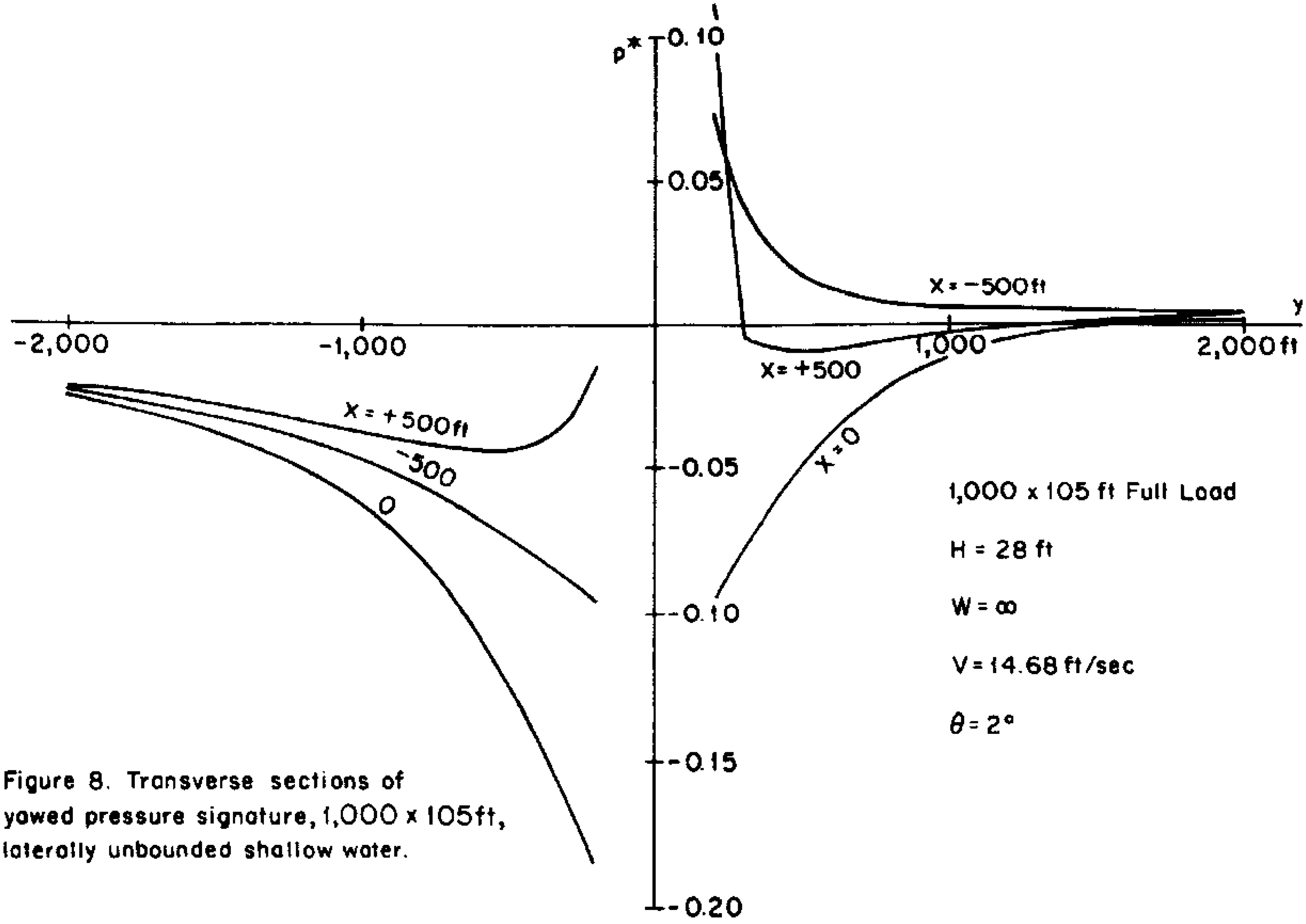


Figure 8. Transverse sections of yawed pressure signature, 1,000 x 105ft, laterally unbounded shallow water.

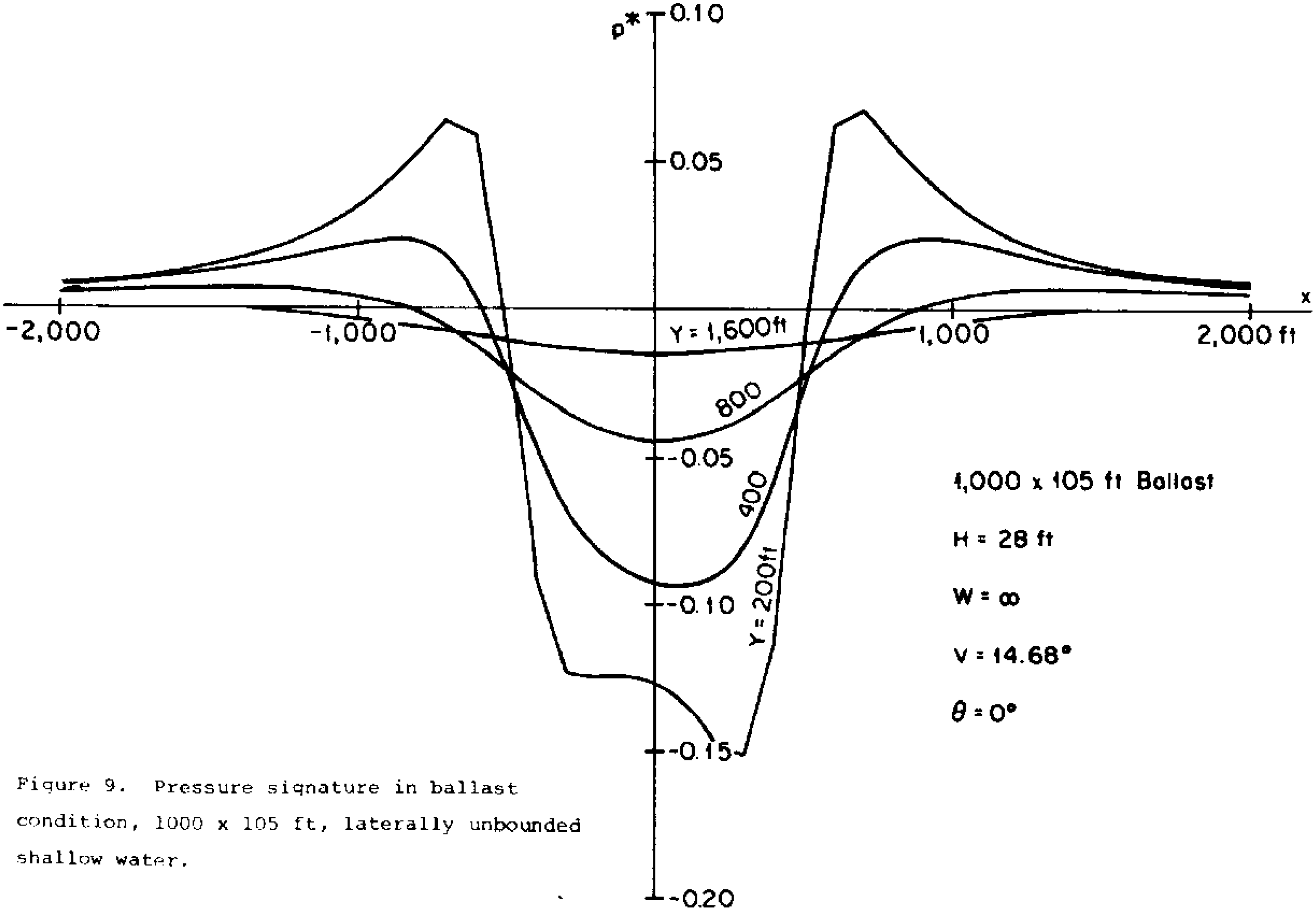


Figure 9. Pressure signature in ballast condition, 1000 x 105 ft, laterally unbounded shallow water.

of the signature is almost identical to deep load. This, it appears, is a result of the large assumed after draft in the ballast condition. The fore and aft asymmetry in the pressure contours decays rapidly with lateral distance.

Before turning to pressure signatures in laterally restricted waters a final note on the magnitude of the effect in horizontally unbounded shallow water should be offered. The effect is very small; at the assumed speed of 10 mph, even for the vessel of 1250 x 150 ft, the bow and stern crests correspond to water-surface elevations of less than 3 inches, only 200 ft out from the centerline. The amidships depression is only 8 inches deep at the same lateral location. As will be seen, the pressure signature becomes far more significant as an environmental factor in narrow channels.

Pressure Signatures in Shallow, Restricted Channels

The channel sections investigated for this report included widths of 300, 600, and 900 ft, at various water depths, loosely corresponding to a number of areas on the St. Marys River. Vessel speed limits in the various reaches of the river were used to set appropriate vessel speeds for sample calculations, in conjunction with typical values of current. These speed limits and currents are given in Tables III and IV, respectively.

For the purposes of emphasis, the following results, Figs. 10-19, are presented for a channel width of 300 ft. This situation corresponds explicitly to the Rock Cut area, but it is presented rather as a lower practical limit of application, corresponding to the upper limit of laterally unbounded shallow water. It may be noted that the 300-ft dredged channel width, approximately 3 times the maximum allowable vessel beam, is a currently accepted standard for Great Lakes channels intended for 1-way traffic only, as in the West Neebish Channel. At present, this channel is used only for downbound vessels, almost without exception fully loaded, during the normal navigation season.

Figure 10 shows a comparison of the three vessels, fully loaded, on the

Table III. St. Marys River vessel speed limits. Speeds in statute mph, over the ground. From <u>Great Lakes Pilot</u> April 1980.

Reach	Speed Limit
De Tour Reef Lt to Sweets Pt Lt	17
Round Island Lt to Pt Aux Frenes Passing Range Front Lt	14
Munuscong Channel Lighted Buoy "8" to Munuscong Channel Buoy "14"	12
Munuscong Channel Buoy "14" to Sailors Encampment Channel Buoy "26"	9
Sailors Encampment Channel Buoy "26" to Lake Nicolet Lighted Buoy "62"	10
Lake Nicolet Lighted Buoy "62" to Lake Nicolet Lighted Buoy "80"	12
Lake Nicolet Lighted Buoy "80" to West Neebish Channel Lt "10"	10
Lake Nicolet Lighted Buoy "80" to Six-Mile Pt Range Rear Lt	10
Six-Mile Pt Range Rear Lt to Lower End St. Marys Falls Canal	(upbound) 8 (downbound) 10
Upper End St. Marys Falls Canal to Pt Aux Pins Main Lt	12

Table IV. St. Marys River channel currents (mph). From Great Lakes Pilot April 1980.

Channel	Current		
	Usual	Low	High
Rock Cut	2.0	1.25	3.5
Middle Neebish Channel (Course 6)	1.5	1.0	3.0
Little Rapids Cut	1.5	1.0	3.0

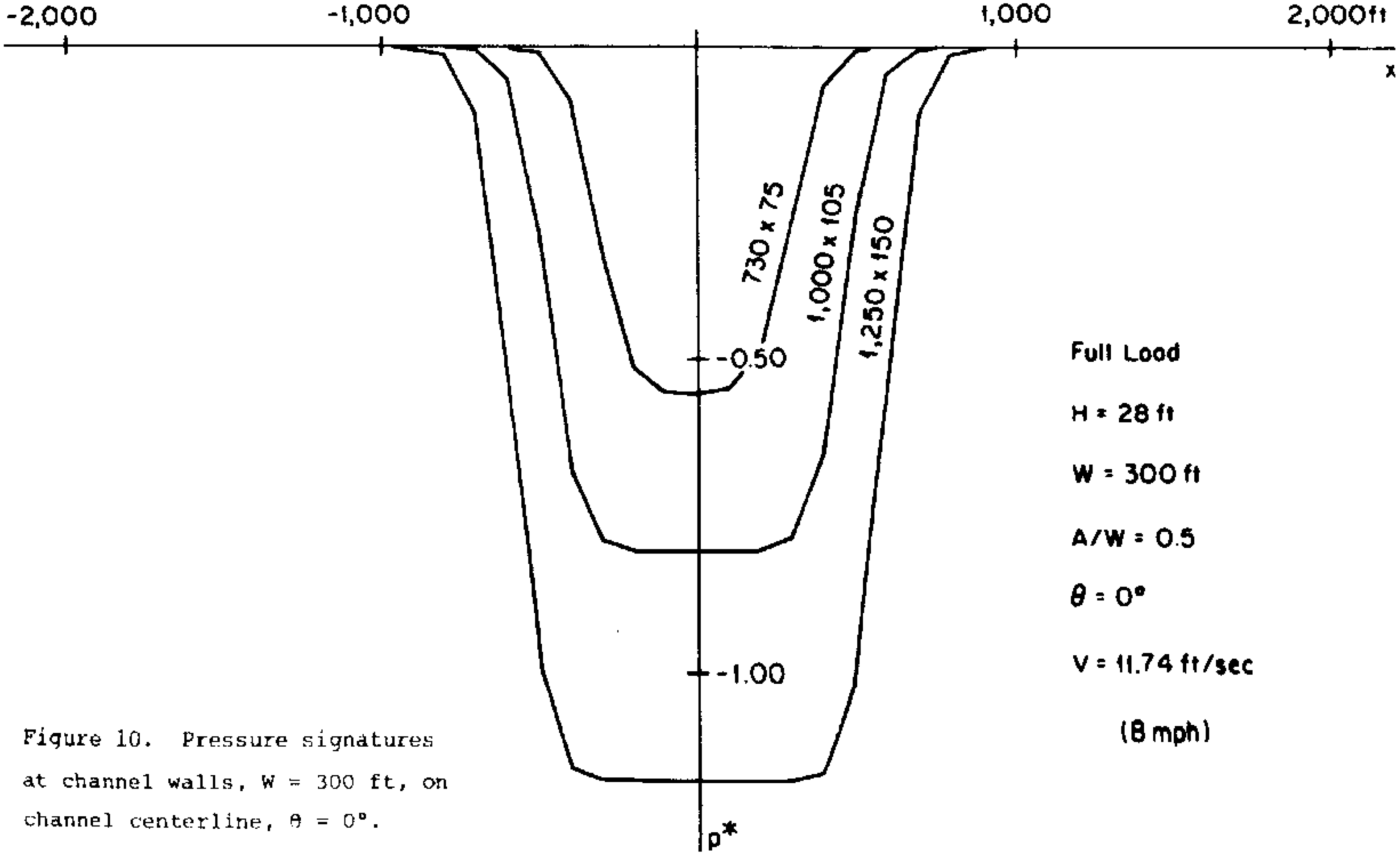


Figure 10. Pressure signatures at channel walls, W = 300 ft, on channel centerline, θ = 0°.

channel centerline, at a speed of 8 mph. This speed through the water corresponds to a speed over the ground (SOG) of 10 mph, with a current of 2 mph.

As opposed to the situation in laterally unbounded water, the pressure signature in the narrow channel varies extremely little in the y direction. In fact, apart from the expected irregularities at the location of the ship centerline, the pressure signature takes the form of a trough extending almost unchanged from the vessel's side to the the channel wall. For this reason, the results in the narrow channel will be plotted only at the wall positions.

It is clear from an inspection of Fig. 10 that the upstream and downstream extensions of the signature are far more closely limited than in laterally unbounded water, returning to values near zero within one ship length or so from the bow and stern. More importantly, however, the magnitude of the pressure change is far larger in the narrow channel. In fact, at the assumed speed of 8 mph, the maximum surface elevation change corresponding to a dimensionless pressure of -1.159 (in the trough caused by the 1250 x 150 ft ship) is almost 2.5 ft. Notice also that the rises in pressure in advance of the bow and aft of the stern have vanished in the case of unyawed vessels on the channel centerline, and that the double-humped amidships feature found in unbounded shallow water close to the ship have also disappeared.

The signature effects of increased and decreased vessel speed through the water, corresponding in a practical sense to lower and higher current velocities at the same SOG, are shown for the case of the 1000-ft vessel in Fig. 11. It will be noticed that the pressure signature changes very little at the ends, but the amidships dimensionless pressure changes somewhat with speed, indicating that the actual drawdown increases in magnitude rather faster than the square of the speed, as was already found in unbounded shallow water. In Fig. 12, the maximum dimensionless pressure, p^*_{max}, is shown for the three fully loaded vessels as a function of ship speed. In Fig. 13, to show the true magnitudes of the maximum water level variations, these values of p^*_{max} are converted to corresponding maximum drawdown, h_{max}. This figure shows the effectiveness of vessel speed limits in controlling the maximum depth of the pressure signature in narrow channels. In passing, note that the

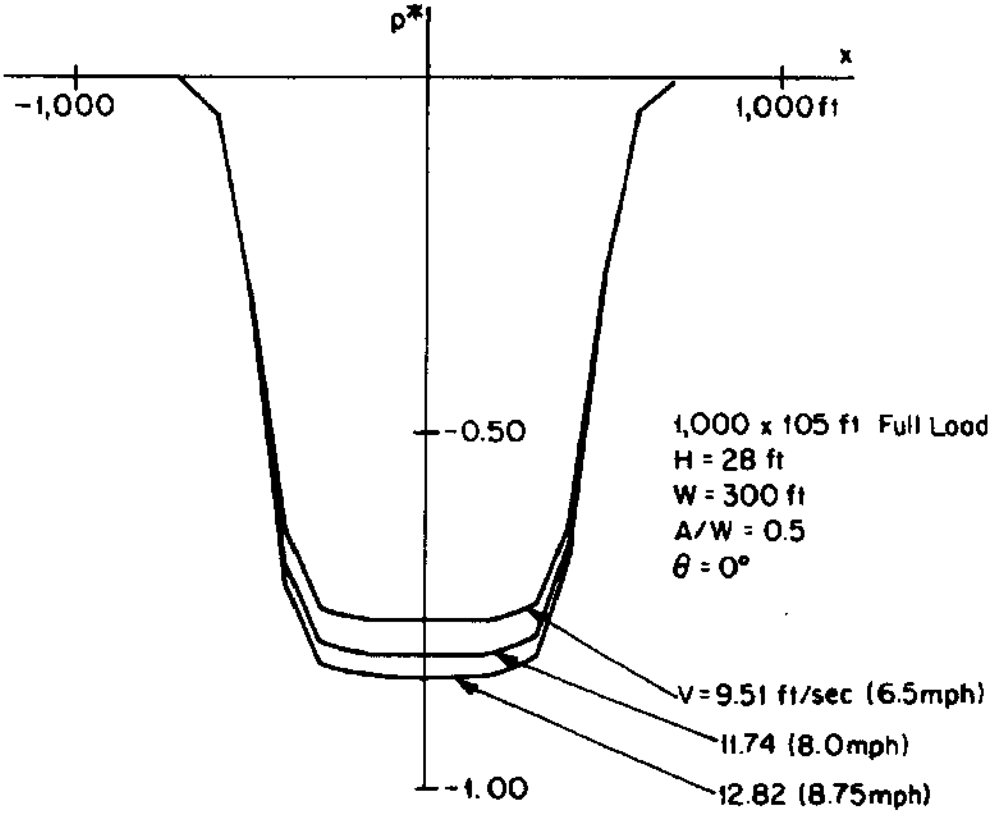


Figure 11. Influence of vessel speed on wall pressure signature, 1000 x 105 ft, W = 300 ft, θ = 0°.

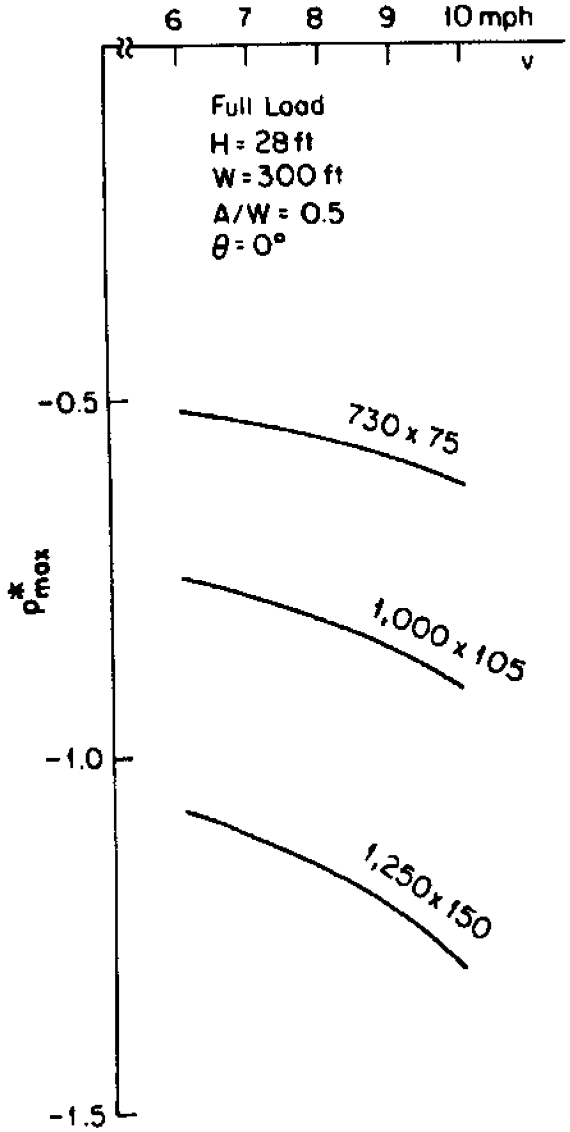


Figure 12. Influence of speed on maximum dimensionless pressure drop, W = 300 ft, θ = 0°.

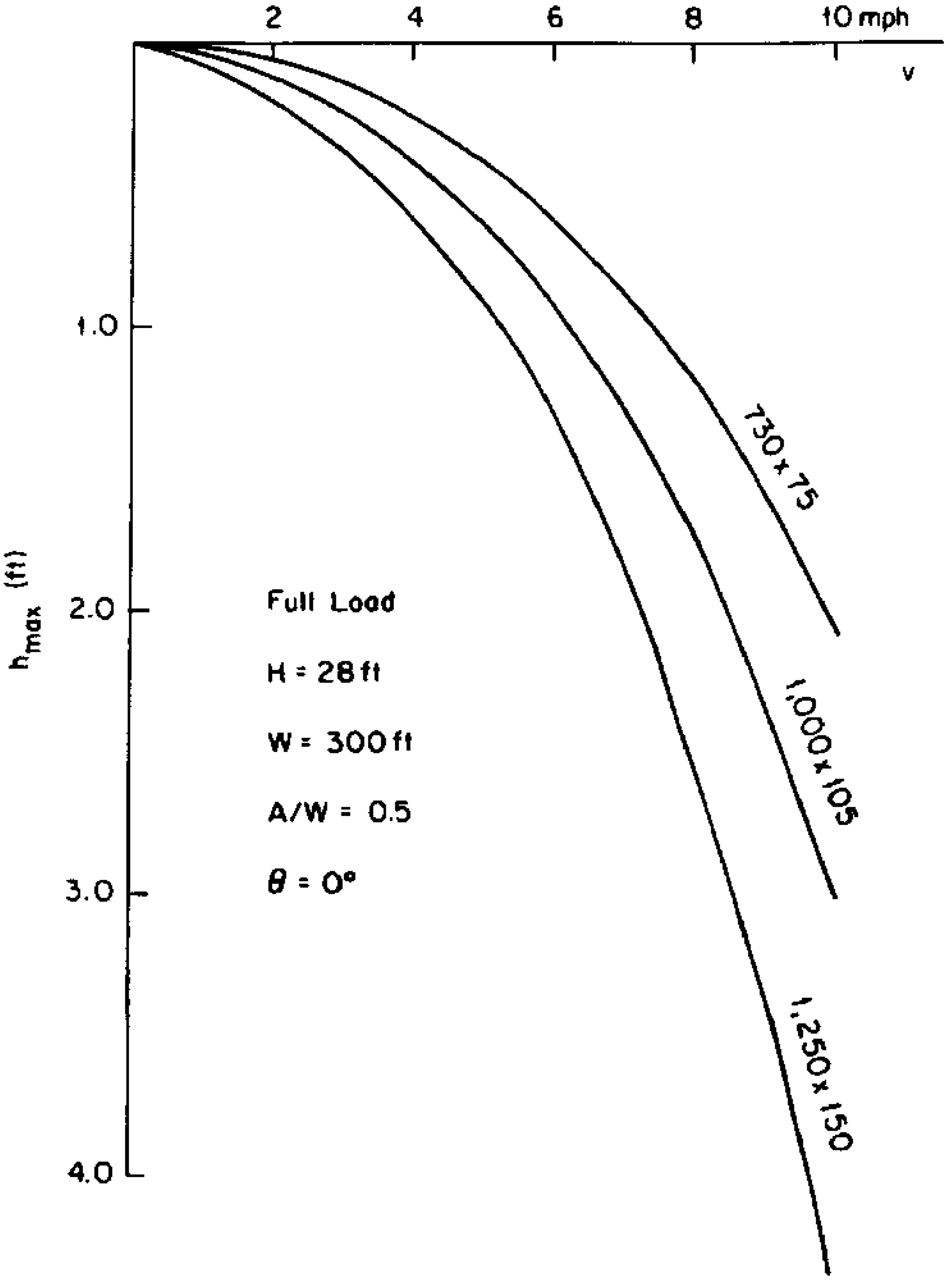


Figure 13. Maximum water-surface depression versus vessel size and speed, W = 300 ft, θ = 0°.

largest vessel produces the same maximum pressure change at a speed of 5.8 mph as the smallest ship does at 8 mph. Thus, speed limits distinguishing between vessels of various size classes are a valuable tool in controlling shore related effects due to maximum drawdown. However, it should be remembered that with a reduced speed through the water the larger vessel will spend a longer period actually passing a given point on the shore. With a 2 mph current, for example, the small ship at SOG = 10 mph and the largest ship at SOG = 7.8 mph take 50 and 110 seconds, respectively, to travel their own length. In some areas, though not necessarily in the rather well-protected cut canals, the trade off between maximum drawdown versus duration of drawdown may not be obvious, in terms of over-all environmental impact.

The influences of yaw and lateral position in the channel are shown separately (an artifice) in Figs. 14 and 15, respectively. Again, the yaw angle in Fig. 14 is arbitrarily selected as 2°. With the vessel on the channel centerline the distinction between the pressure signatures on the low-pressure wall ($y = -150$ ft) and the high-pressure walls is large. In addition, a small pressure rise occurs forward of the bow on the pressure side; no such feature occurs on the suction side at the channel wall. The shape of the pressure signatures nearer amidships are characteristic of the yawed situation. From the point of view of environmental stress, it appears that the low-pressure side has been particularly adversely affected; the maximum drawdown is 40% greater than in the case of zero yaw, although the maximum rate of change is approximately the same as before. By contrast, the high-pressure side has almost the same maximum drawdown as with zero yaw, but the over-all rate is slower in reaching this maximum. However, the case of yaw alone is not realistic; the calculated side force due to this yaw angle is 1.39×10^{6} lb, versus only 9.42×10^{5} lb in the laterally unbounded case of Fig. 8. Either way, there is nothing to balance this force, so the condition must either be transient or in a turn.

In the equally artificial circumstance of Fig. 15, again it is the low-pressure wall (in this case the near wall) that receives the larger environmental stress. And again, the far-wall signature is not very much changed from the centerline situation. Two small pressure rises appear in thenear-wall signature, but these are almost insignificant.

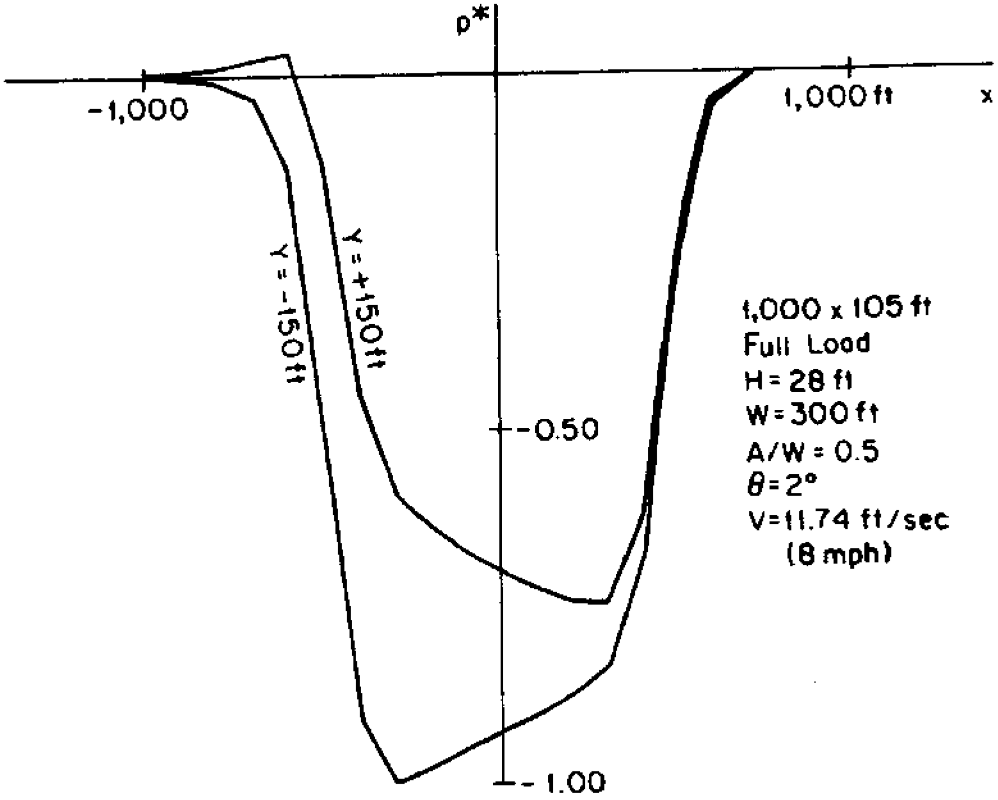


Figure 14. Yawed pressure signatures at walls, 1000 x 105 ft, W = 300 ft, A/W = 0.5. Note side force in negative y direction.

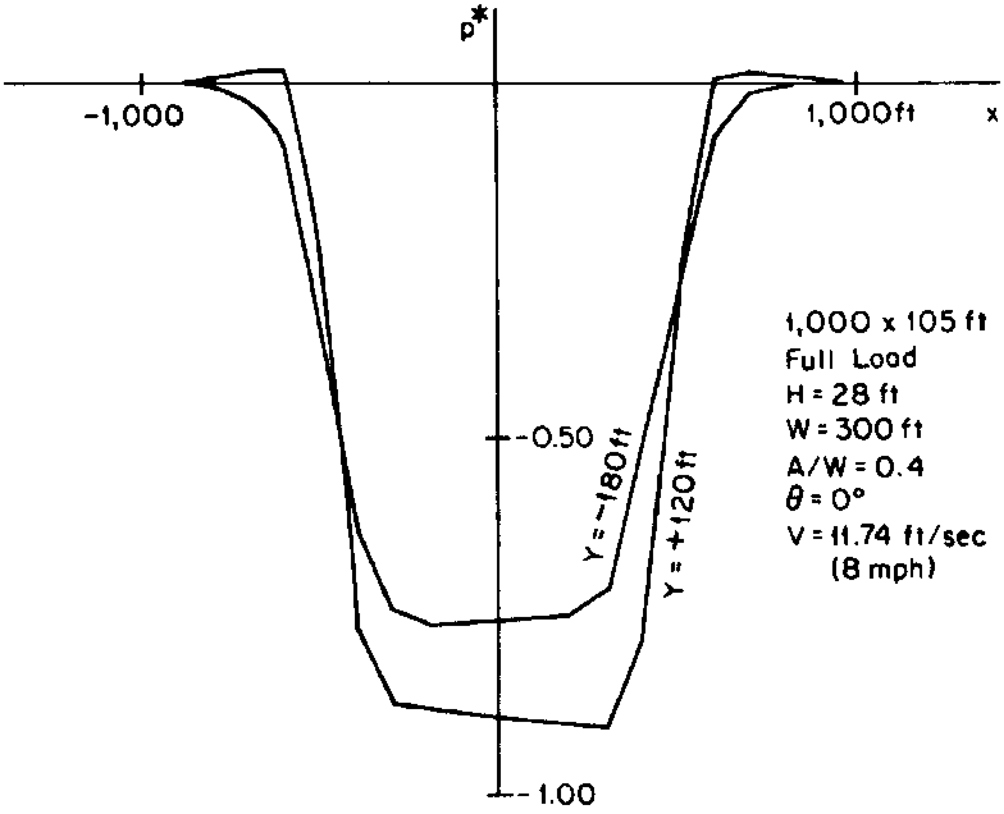


Figure 15. Influence of channel position with zero yaw on near and far-wall pressure signatures, 1000 x 105 ft, $\dot{W}$ = 300 ft, A/W = 0.4.

Figure 16 shows an approximate equilibrium position (of course, neglecting rudder adn propeller forces) at $A/W = 0.4$ and $\theta = 0.80^{\circ}$. Both near and far-wall maximum pressure changes are somewhat altered from the extreme cases of Figs. 14 and 15, but it is the comparison with the centerline unyawed case of Fig. 10 that is most interesting. The near-wall maximum drawdown is about 9% greater than in Fig. 10, although the far-wall maximum is about the same, occurring at a station somewhat farther forward. The pressure rises forward and aft are still present, with the bow wave slightly accentuated.

The fore-and-aft asymmetries of the signatures created by the ship operating off the channel centerline will have important effects on the time histories of pressure at the walls. In particular, the near wall appears to undergo a more rapid pressure drop and rise, as well as a slightly deeper maximum pressure change. This conclusion, however, may be somewhat influenced by the inclusion of rudder/propeller effects. These influences are substantially increased with vessel size at a given location within the cross section. In fact, as the vessel side approaches the channel wall, critical flow may result. The hydrodynamic model used here explicitly assumes subcritical flow, and as a result the pressure signatures become erratic at very small wall clearances.

In any case, in such a narrow, 1-way channel the vessel will normally remain on or near the channel centerline. The effects of ship size on pressure signatures, taking into account more typical departures from the centerline, will be presented in connection with a channel of 600-ft width, where meeting and passing situations can arise and vessel operation off the centerline is to be expected.

The effect of channel depth is shown in Fig. 17 for the 1000-ft ship, on the centerline, in the full load condition. Pressure signatures are drawn for $H = 28$, 30, and 32 ft. Again, as in the case of speed variation, the major effect is a change in the maximum drawdown, with very little influence on the signature in the ends. To a good approximation, the maximum drawdown varies as the ratio of cross-sectional areas, as expected from simpler hydraulic approximations. An off centerline, yawed, equilibrium condition corresponding to $A/W = 0.4$, $\theta = 1.2^{\circ}$, is shown in Fig. 18 at $H = 30$ ft,

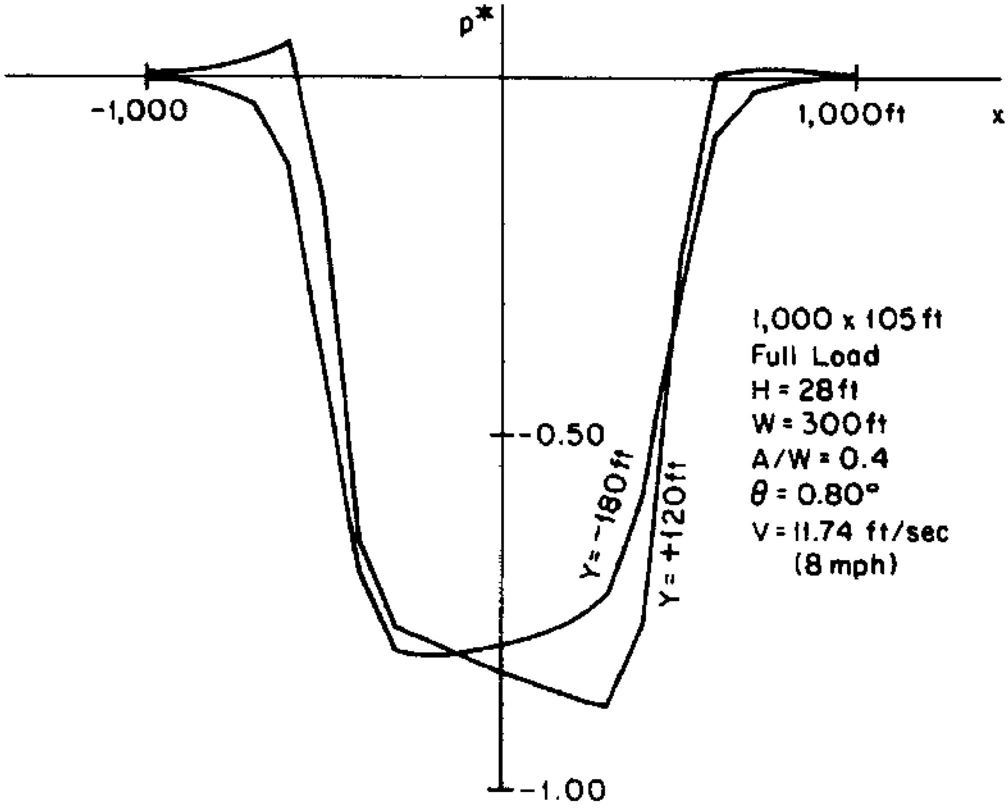


Figure 16. Near and far-wall pressure signatures at approximate equilibrium yaw angle, 1000 x 105 ft, W = 300 ft, A/W = 0.4, θ = 0.80°.

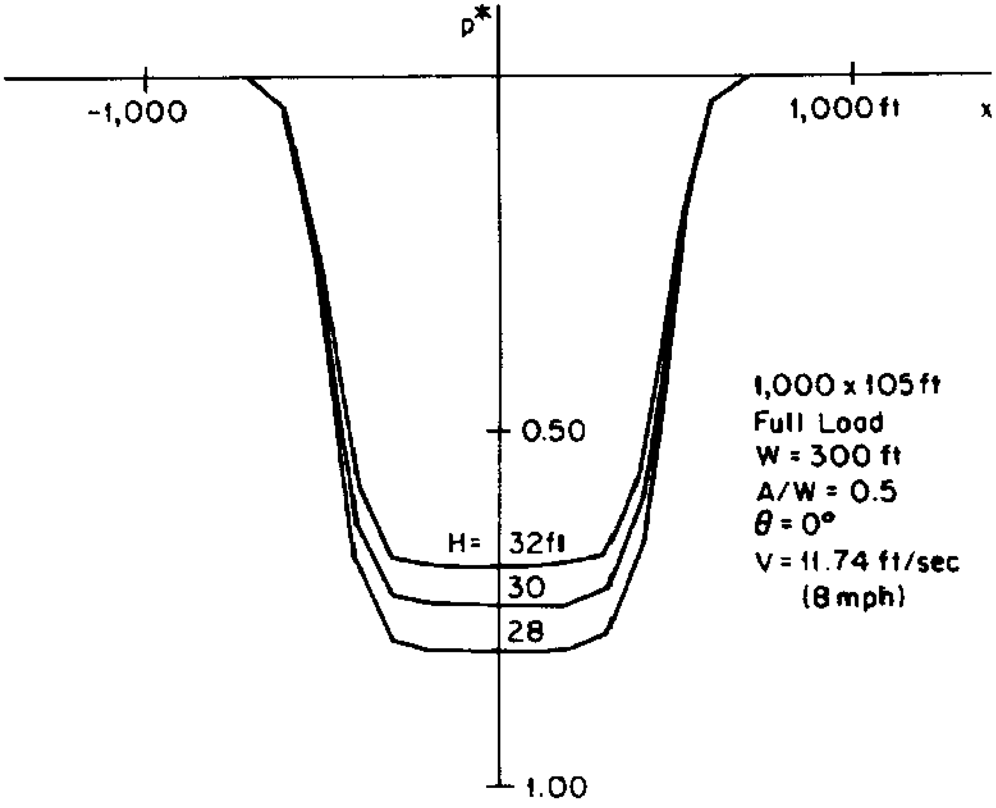


Figure 17. Influence of channel depth on pressure signature at wall, 1000 x 105 ft, $W = 300$ ft, $A/W = 0.5$, $\theta = 0°$.

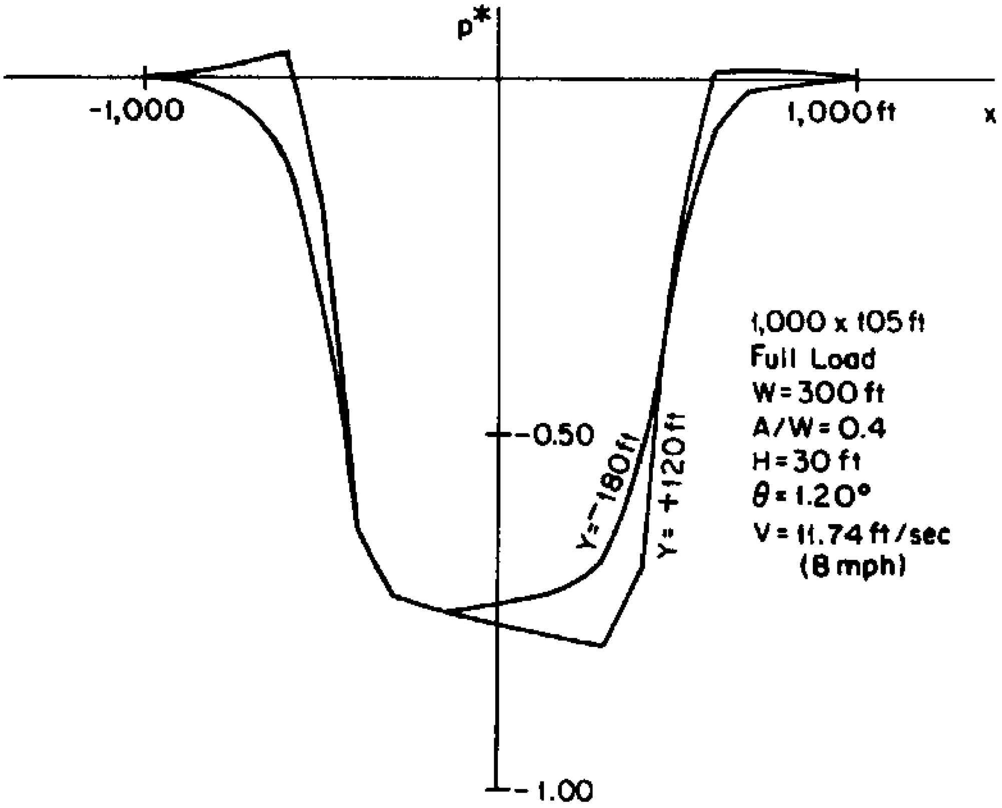


Figure 18. Pressure signatures at near and far-walls, approximate equilibrium yaw angle, H = 30 ft. Compare with Fig. 16.

for comparison with Fig. 16. The increased required yaw angle is noteworthy, versus the identical situation at-28 ft depth, but the pressure maxima on both walls are not as drastically increased from the centerline condition as in the case of the shallower water. In the practical world of the Great Lakes, however, the assumption that increased water depth will lead to greater underbottom clearance is false. For economic reasons, any additional water depth that becomes available due to changes in stage is very soon filled with ships. Most newbuilt Great Lakes vessels are designed for maximum load drafts substantially in excess of their normal operating draft, to be able to take advantage of this fact.

Although the 300-ft wide channel areas are presently used only for downbound, fully loaded ships, a pressure signature of the 1000-ft vessel in the ballst condition is shown for purposes of comparison in Fig. 19. Note that the speed through the water has been left at 8 mph, corresponding to the original assumptions of a downbound course at 10 mph SOG before a 2-mph average current. Upbound, the equivalent SOG is a rather slow 6 mph, but this seems more reasonable than 12 mph through the water at the existing SOG limit. The magnitude of the signature at such a speed can be inferred from the speed behavior shown in Figs. 11, 12, and 13. The calculation is of limited practical significance, however, since the vessel in ballast trims further by the stern and squats into the bottom very hard.

The effect of channel width is graphically indicated by a comparison of Fig. 20, which presents the 730-ft ship in the full load condition, on the centerline of a 600-ft wide channel, with the comparable curve from Fig. 10, with W = 300 ft. Notice, however, that a speed difference exists here, 8 mph in Fig. 10 versus 9.5 mph in Fig. 20. Converting both figures to absolute drawdown height, the narrow-channel case represents 39% greater maximum drawdown, even at the lower speed.

Values of the maximum dimensionless pressure, p^*_{max}, at the channel walls, with a uniform ship speed of 9 mph, with the vessel on the channel centerline, are shown as a function of channel width in Fig. 21. Constructed in this way, these curves should, of course, tend to zero in the limit of increasing channel width. This misses the point, however. As the situation more nearly approaches that of unbounded shallow water, the change of pressure

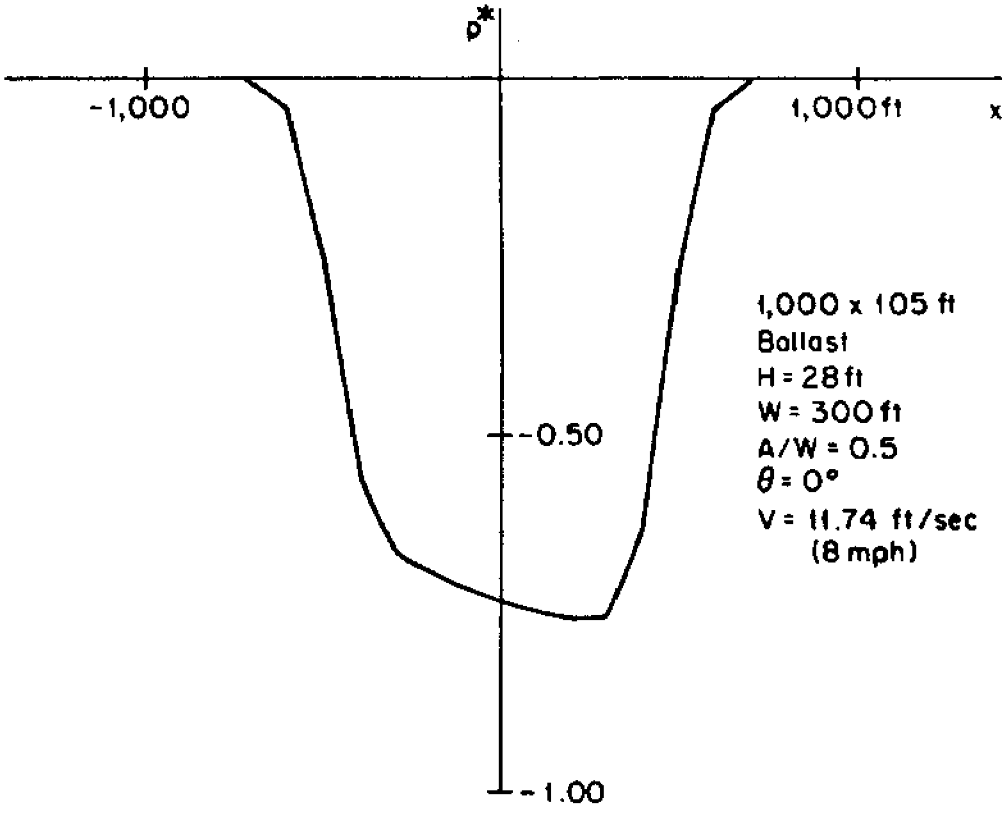


Figure 19. Wall pressure signature in ballast condition, 1000 x 105 ft, W = 300 ft, A/W = 0.5, θ = 0°.

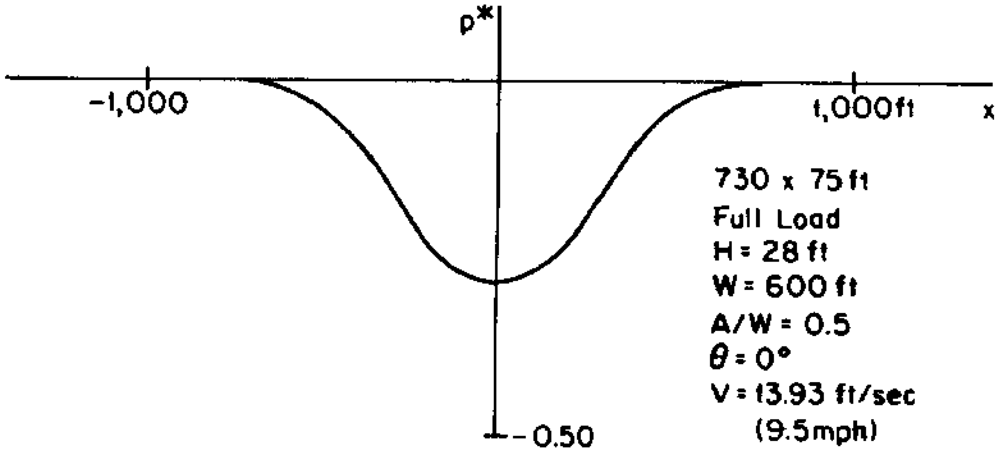


Figure 20. Pressure signature at walls, 730 x 75 ft, W = 600 ft, A/W = 0.50. Compare with Fig. 10.

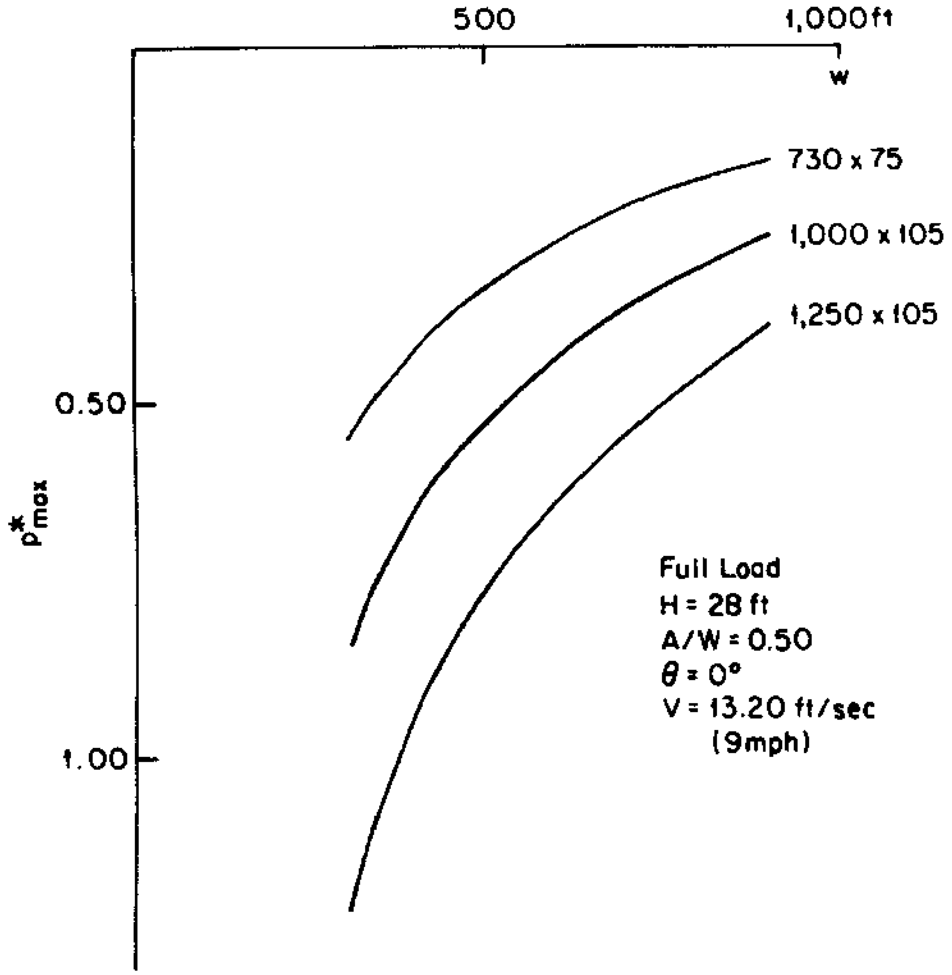


Figure 21. Effect of channel width on maximum dimensionless pressure change at walls.

in the y direction, which was almost zero in narrow channels, must become non-negligible. Thus, it is no longer true that the maximum pressure value can be approximated by its value at the channel wall. A detailed map, of the type presented in connection with laterally unbounded water, Fig. 6, becomes necessary. In any case, near the ship, the pressure signature rapidly tends to the case for unbounded water.

For vessels operating off the channel centerline, as in meeting or passing situations, the practical distinction between downbound fully loaded and upbound in ballast is made for the remainder of these sample calculations. Vessels are assumed to operate at equilibrium yaw angles for A/W = 0.25, which is rather closer to the channel bank than would usually be the case in steady-state operations. Typical SOG limits of 10 mph downbound and 8 mph upbound are applied, together with a 1.5-mph current, giving 8.5 mph and 9.5 mph through the water, down and up, respectively. Using these values, downbound full load and upbound ballast pressure signatures at the walls are shown in Figs. 22 and 23, respectively, for all three ships. For clarity, near and far-wall pressure signatures are compared separately in each plot. It may be noted that by comparison with the signature of Fig. 16, the 1000-ft vessel has a less drastic dimensionless curve in the wider channel at the near wall. However, both the near and far-wall signatures are starting to reach out ahead and astern of the vessel, as in unbounded shallow water, while the far wall signature in particular has lost the asymmetry and steep profiles that were still present in the 300-ft wide channel at the far wall. In fact, the far-wall signature is starting to show some y-dependency, but this is not drawn here.

For convenience in comparisons among the various parts of Fig. 22 and 23, scales of drawdown are placed at the left side of each figure. Note that the scales are different for Figs. 22 and 23, reflecting the different speed through the water upbound and downbound.

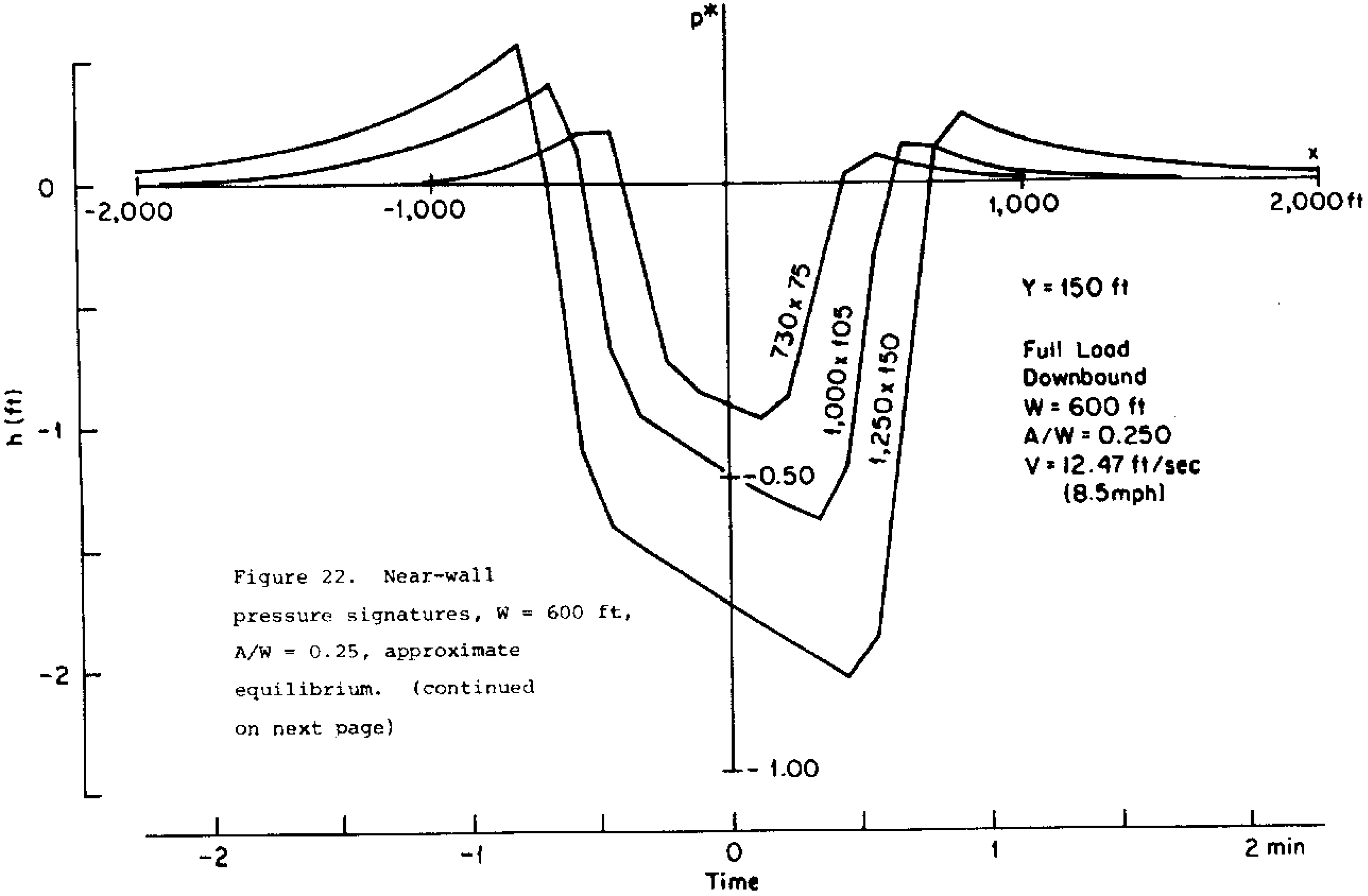


Figure 22. Near-wall pressure signatures, W = 600 ft, A/W = 0.25, approximate equilibrium. (continued on next page)

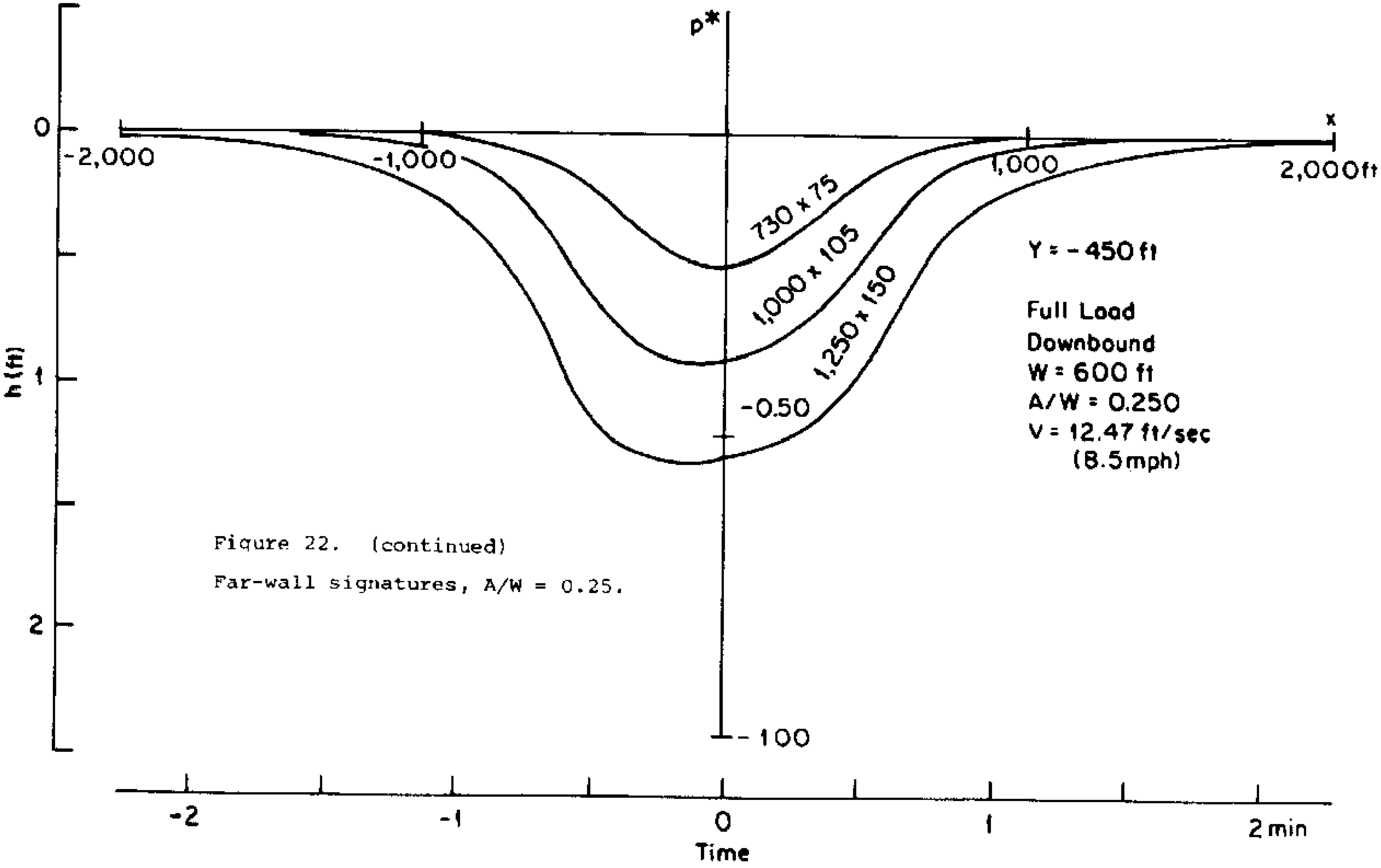


Figure 22. (continued)

Far-wall signatures, A/W = 0.25.

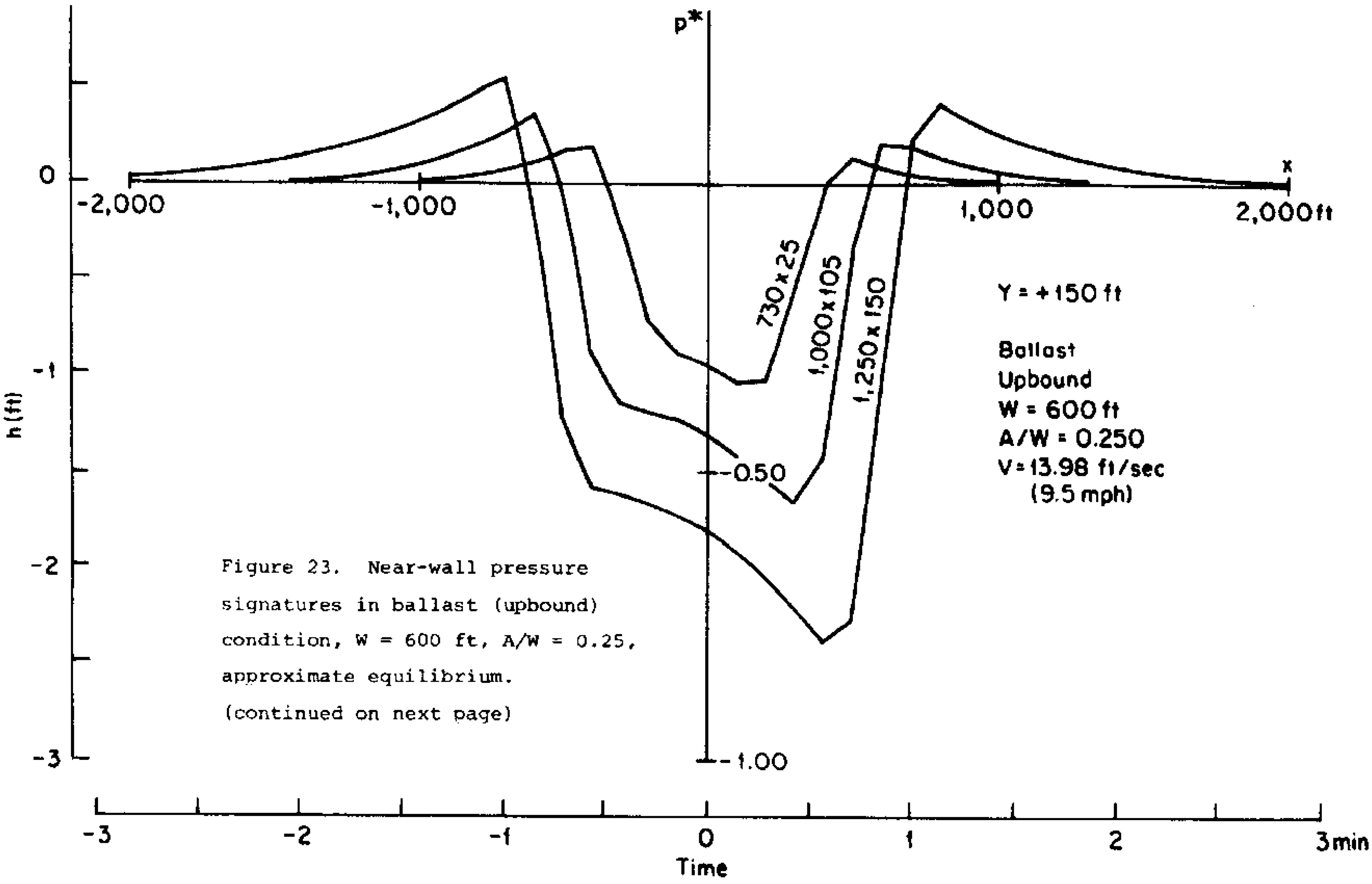


Figure 23. Near-wall pressure signatures in ballast (upbound) condition, W = 600 ft, A/W = 0.25, approximate equilibrium.

(continued on next page)

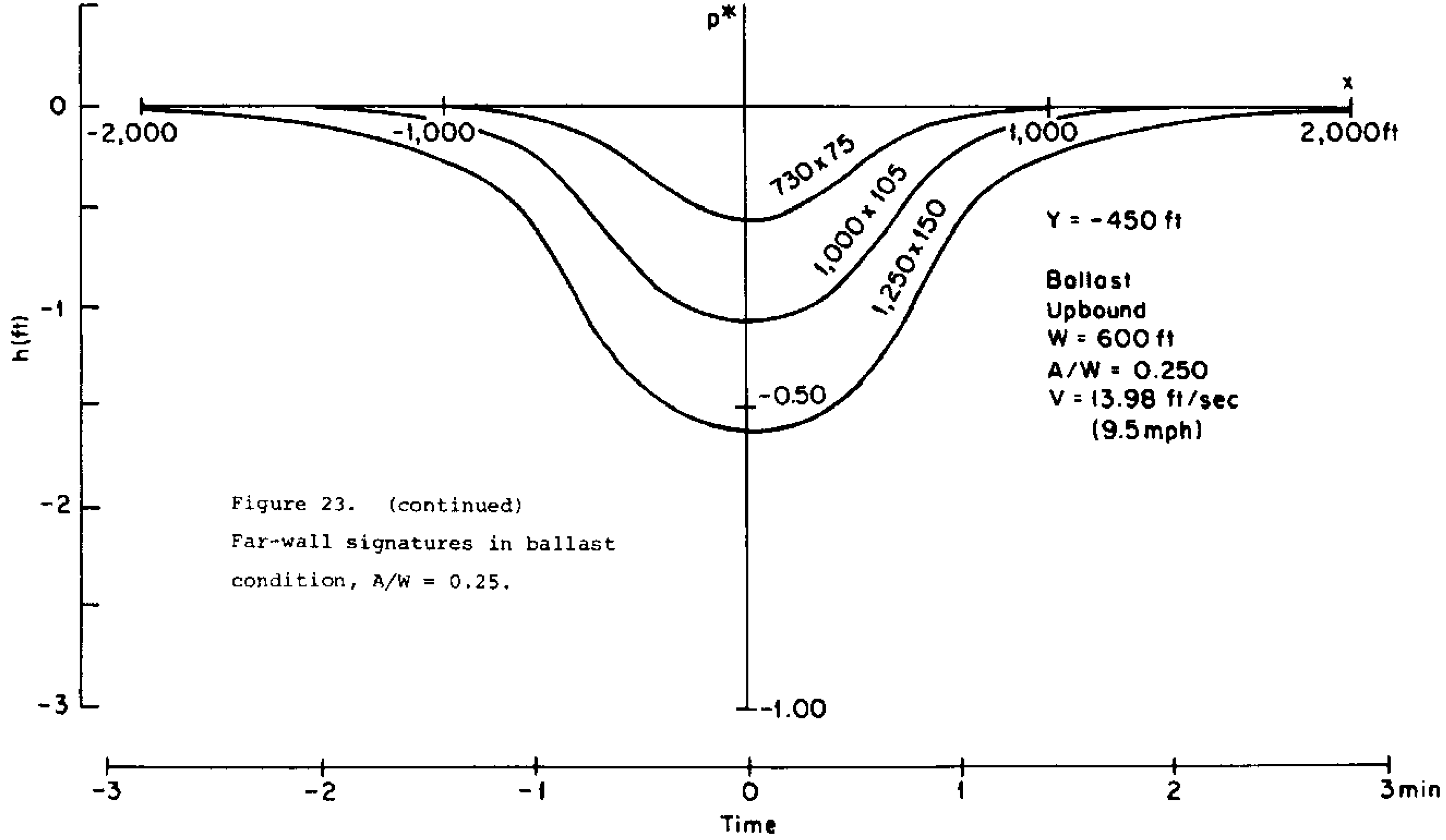


Figure 23. (continued)
Far-wall signatures in ballast
condition, A/W = 0.25.

Time Records Derived from Pressure Signatures

As discussed previously, in determining the effect of pressure variation on sediment disturbance and other environmental processes, the rate of pressure change may be as important as the maximum drawdown depth. For such purposes the time history of pressure variation at a fixed point must be derived from the pressure signature in the ship's frame of reference.

Such a transformation requires nothing more than the insertion of an appropriate time scale into any of the signature plots. This time scale must be determined by reference to the speed over the ground. These scales (in minutes) are placed at the bottom of Figs. 22 and 23, and they may be added to any of the signature plots in this paper, provided that the speed over the ground is known.

While the time scale is based on SOG, it is obvious that the dimensionalization of the pressure signature must still use speed through the water. This leads to a few simple but interesting considerations. For example, consider a downbound vessel operating at a constant speed limit (SOG). With an increase in current velocity the ship speed through the water is decreased, reducing the magnitude of the signature by a factor of at least V^2. Since SOG is constant, the time scale of the effect is unchanged, and thus not only the magnitude but the rate of pressure change are decreased. Naturally, the reverse is true of an upbound vessel at constant SOG.

On the other hand, for a vessel moving at constant speed through the water, the pressure signature remains constant. Thus an increase in current velocity will cause a more abrupt pressure change at a fixed point for a downbound ship, and a more gradual pressure change for an upbound, but with a consequently prolonged period of drawdown.

The relative importance of maximum pressure change, maximum and average rate of change, and drawdown duration depend on the particular environmental effect under consideration. For example, the uncovering of the river bed depends almost solely on the maximum pressure signature. The resuspension and transport of bottom sediments may depend on both absolute levels and rates of change, the details known only to specialists in pore pressure gradients and soil phenomena, and not necessarily to ship designers. Finally, the resulting flow and levels in tributary streams may depend to a great extent on maximum drawdown and duration. Other examples of such correspondance can probably be drawn as well.

V. CONCLUSIONS

Of the various environmental stresses that may be imposed by larger Great Lakes vessels operating in restricted waters, one of the most visible is the change in water-surface elevation and the resulting flow due to the ship's pressure signature. This effect, in turn, is closely related to the choice of vessel dimensions and, to a lesser extent, hull form characteristics. In addition, the influences of vessel speed through the water and over the ground can have a large effect on the depth and maximum rate of pressure change experienced at the shore or in bottom sediments. For these reasons, methods for estimating the pressure signatures of projected vessels, including ships of unprecedented size, should be of value in formulating policy for channel improvements, vessel speed limits, and other operating constraints.

A simple hydraulic approach is sufficient to give approximate values of the maximum pressure variation around a ship in a restricted channel, treating the vessel as a channel obstruction. However, such an approach needs considerable reworking to account for the pressure effects due to side forces and moments on the vessel, the effects of Froude number (speed) below the critical speed, and the shape of the pressure signature at the ends. In particular, the simplest methods give a strict speed-squared dependency for the signature. In order to model the influences of speed, yaw angle, and lateral position a slender-body approach was adopted, following the procedures of Ref. 6. A simple rectangular-section channel was considered, which, in spite of its limitations, should give some quantitative information on the relative magnitudes and shapes of pressure signatures for differenr vessels operating in channels of various cross-sectional areas. The major drawback of the assumed geometry is that it does not consider the flow in shallow areas outside the channel insofar as any contribution to the pressure field around the ship is concerned.

In a narrow channel, at a given speed, the magnitude of maximum drawdown is proportional to vessel cross section, as predicted by simple hydraulic considerations. As channel width increase, however, the maximum drawdown very gradually assumes a more complicated dependency on vessel sectional area, as well as on the lateral position with respect to the ship.

The rates of pressure variation, that is, the slopes of the pressure signatures near the ends, seem to be relatively insensitive to maximum sectional area, apparently depending more strongly on bow and stern shapes, and on the length of parallel midbody.

In all cases, the maximum drawdown increases considerably faster than the speed squared. Again, the shape and slopes of the pressure signature at the ends are not substantially affected. However, this effect of speed (through the water) on the signature must be distinguished from the purely kinematic effect of speed over the ground on the apparent rate of pressure change experienced at a fixed point.

For a yawed vessel operating off the channel centerline, the near-wall signature is increased substantially, depending on the distance to the wall. In the specific case of a 600-ft wide channel, a conventional sized vessel operating at the quarter-width position produced a 40% deeper maximum drawdown than when operating on the centerline at the same speed. Maximum signature slopes are also increased on the near-wall side. On the other hand, far-wall signatures are rapidly attentuated by increasing distance, provided the channel is not extremely narrow over-all.

In terms of time histories of pressure at a fixed point, the influences of the speed limit and current are pronounced. It appears that with existing speed limits and average currents, upbound ships in ballast, at a relatively high speed through the water and low SOG, can produce pressure changes as large or larger than downbound, fully loaded ships, which are operating at a higher SOG and a lower speed through the water. In short, the influence of speed on pressure signature depth is strong enough to dominate the change in sectional area between full load and ballast conditions. At the same time, however, the upbound vessel takes somewhat longer to pass a given point, so the rate of pressure change is reduced, albeit with a longer duration of the effect.

In summary, the pressure signatures, time rate of change of pressure, and duration of any given pressure level can be calculated for vessels in restricted waters as functions of vessel and channel dimensions, hull form characteristics, speed, and yaw/lateral position. With regard to a projected vessel of 1250 x 150 ft, the following conclusions can be drawn with respect to the environmental stresses associated with the pressure disturbance in confined waters:

1. A maximum pressure change or surface drawdown approximately 43% larger than that caused by an existing 1000-footer at the same speed through the water.

2. Maximum rates of pressure change essentially similar to existing ships of the larger classes.

3. Duration of maximum drawdown effect approximately 25% longer than existing maximum-size vessels at the same speed over the ground.

4. Greater effects of lateral position. At a given distance from the channel centerline, the near-wall pressure signature will be much deeper than for smaller ships at the same speed and location. This effect increases continuously as distance from the centerline increases. For this reason, more accurate path control for larger ships may be justified not only by consideration of ship safety, but by environmental concerns as well.

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