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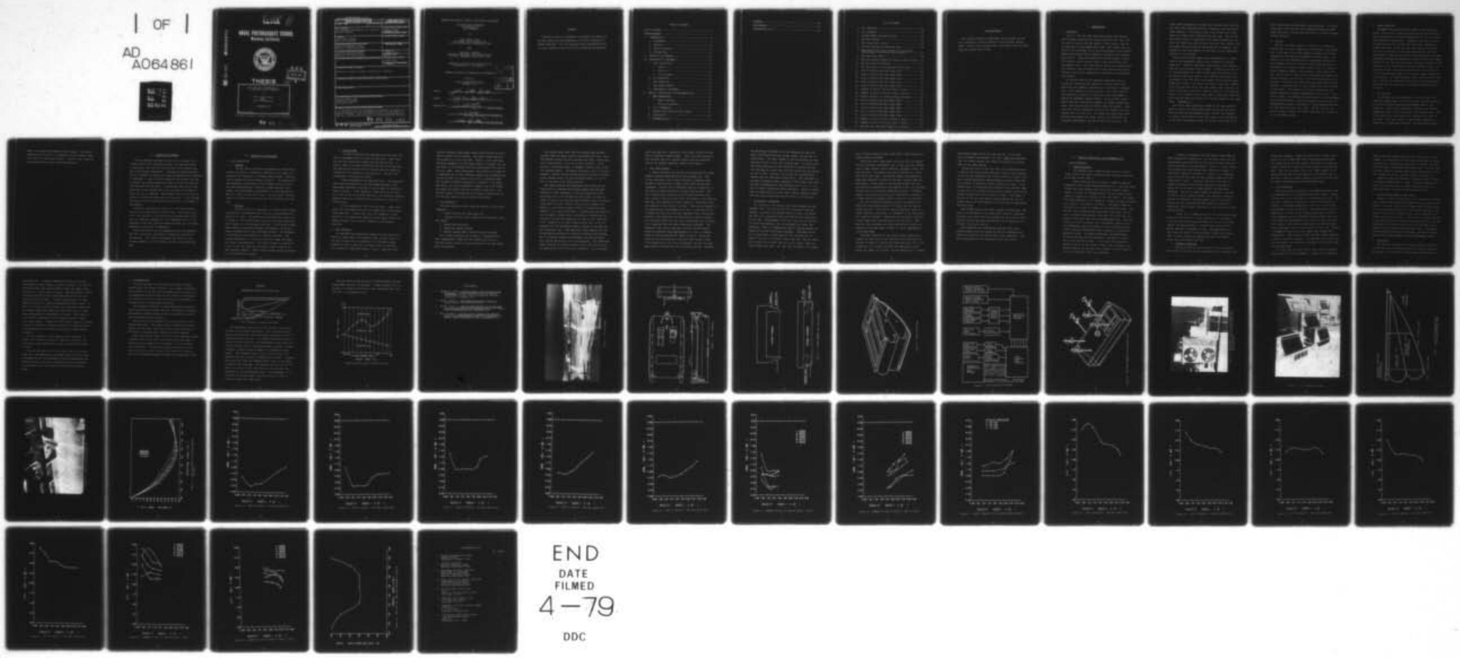

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NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

XR-3 BOW SEAL PERFORMANCE AS A FUNCTION OF SEAL GEOMETRY

by

John Arthur Fjelde
and
Carl Eric Gaenslen

December 1978

Thesis Advisor: D. M. Layton

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XR-3 Bow Seal Performance as a Function of Seal Geometry

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Submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE IN AERONAUTICAL ENGINEERING

from the

NAVAL POSTGRADUATE SCHOOL
December 1978

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ABSTRACT

A series of tests was conducted to determine the effects of bow seal shape upon the performance of the XR-3 captured air bubble testcraft. The lift and drag forces experienced by the bow seal, plotted versus velocity, are presented and analyzed.

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ACKNOWLEDGEMENT

The authors gratefully acknowledge the assistance and support provided by Professor Donald M. Layton and Mr. Michael Odell. Without their patient help, this project would not have seen the success that it did.

I. INTRODUCTION

A. BACKGROUND

The U. S. Navy has been sponsoring research and development programs concerning air cushion vehicles (ACV) since 1957 in order to realize the high speeds in naval vessels that are not feasible in displacement-type craft. The capabilities offered by ACV technology led to the establishment of the Surface Effect Ship Project Office (SESPO) to coordinate Navy development efforts. These ACV capabilities include speeds in excess of 100 knots, quick reaction times, lower construction costs and manning levels, very high payload capacities, enhanced open sea stability, and low drafts which allow shallow water operation and also provide susceptibility reductions to torpedo and mine threats.

Air Cushion Vehicles are generally subdivided into two categories, hovercraft and captured air bubble (CAB) craft. Hovercraft are completely encircled by a flexible air-trapping skirt, lift completely off the surface of the water, and are thus amphibious, capable of leaving the water environment to operate on reasonably smooth terrain. The hovercraft continuously vents air from the air chamber, or plenum, beneath the craft, thus necessitating relatively large lift engines. Hovercraft have been in commercial and naval use, notably with the Iranian Navy, for some time. The large lift engine and plenum pressure requirements put rather severe size limitations on hovercraft development, and thus on their tactical use. CAB craft, often rectangular in shape, have flexible seals fore and aft, while the longitudinal plenum boundaries are rigid structural sidewalls. The result is much like the hulls of a catamaran with rubber seals connecting the hull ends. Most of the CAB craft's weight is supported by the plenum overpressure, but since the craft lifts only partially from the water surface, the continuous venting problem of the hovercraft is removed. Lift engines are thus much smaller in CAB craft, but the amphibious capability is sacrificed.

Due to their smaller power plant requirements, U. S. Navy research and development efforts have stressed CAB vehicles since 1960. SESPO has sponsored, among others, craft ranging from one to one hundred tons in weight. Contracts have been let for the development of a 3000 ton prototype CAB vessel, to be delivered in the early 1980's. This two-foot draft craft will be powered by four FT9 water jets capable of over 200,000 horsepower total thrust. The vessel will have six lift fans capable of 60,000 cubic feet of air flow per second, have a velocity in excess of 90 knots, and have a range in excess of 2,500 nautical miles. As an example of this type craft's rough water abilities, the 3,000 ton craft will attain 50 to 60 knot speeds in sea state three. (Reference 1)

One of the craft sponsored by SESPO is the three ton XR-3. Built in 1965 by the David Taylor Model Basin, now the Naval Ships Research and Development Center, the XR-3 was operated by various test activities until 1970, when it was transferred to the Naval Postgraduate School for further investigations in basic and advanced surface effect ship technology. In the ensuing years, the craft has been operated continuously under SESPO work orders, and has been the subject of several student research projects.

B. THE XR-3

The XR-3 testcraft (figures 1,2, and 3) is a three ton vehicle with a 24 foot length and a 12 foot beam. The plenum area is enclosed by two rigid sidewalls running fore and aft, connected by bow and stern inflatable, flexible seals. Propulsion is by two extended drive 55 horsepower Chrysler outboard engines, while air pressure to the plenum and seals is provided by five single cylinder, single cycle, air cooled internal combustion engines, each driving a single stage axial fan. Two of the five fans directly pressurize the plenum, two others pressurize the bow seal, and the fifth pressurizes the aft seal. The three "seal fans" have adjustable bypass valves attached to allow portions of their output flow to be diverted to the plenum. The aerostatic lift force generated by the plenum overpressure supports approximately 80 per cent of the craft's weight, the remainder being provided by the displacement lift of the twin hulls. Electrical power for the data and instrumentation systems is provided by a stern mounted 1500 watt, 110 volt auxiliary power unit (APU). The XR-3 has two one-person cockpits, however all control functions are carried out in the starboard cockpit.

C. THESIS OBJECTIVE

Throughout the entire velocity regime of the CAB craft, various lift and drag forces are acting on the vessel's seals. Many investigations have been conducted on the XR-3 to further understanding of these forces. Reference 2 details the relationship between XR-3 velocity and total drag. Reference 3 studied the forces on the bow seal in particular, and noted the lack of constancy in seal shape and position over this speed regime. This thesis deals with the optimization of craft performance through the mechanical variation of bow seal shape. Studies of seal lift and drag forces, and their relation to seal shape can lead to operation in the most economical mode. Optimization of the lift and drag forces over the velocity profile, by varying seal shape, will result in higher ranges and/or velocities. On future CAB craft, both larger and more complex, the task of monitoring craft velocity and appropriately adjusting the seal shape may be relegated to microprocessor circuitry.

D. THE BOW SEAL

The original bow and stern seals of the XR-3 were semi-rigid and unadjustable. In 1972 new seals, designed and built by the Naval Ships Research and Development Center, were installed. These seals, essentially identical, are made of rubberized fabric riveted and glued to an aluminum frame. The frame, made of two inch angle stock, measures 120 inches by 46 inches. The fabric forms two tear shaped compartments separated by a perforated membrane. The perforations permit equal air pressures and enhance water drainage. The curved bottom face of the seal is stiffened by twelve equally spaced four inch by 48 inch steel springs. Figures 3 and 4 show the seal installations and the construction details.

II. NATURE OF THE PROBLEM

Both air pressure and water forces act on the seals of a surface effect ship, creating resultant lift and drag forces. An aerostatic force acts on the rear face of the forward seal due to the plenum overpressure. Although the plenum pressures are not constant, an analysis of their distributions was reported in reference 4. Due to the aft raking of the bow seal from top to bottom, the plenum overpressure tends to force the seal forward and down into the water. A hydrostatic force acts on the front face of the forward seal and is related to the depth to which the seal is immersed. Hydrodynamic forces arise from the motion of the craft through and over the water. A more thorough discussion of the forces acting on the bow seal is included in the Appendix.

Load cells, described in Section III, are used to obtain total lift and drag forces on the bow seal. The output observed by the load cell is the force actually experienced by the seal, an algebraic combination of the component forces. With knowledge of the seal shape and immersion depth, the individual components of force may be separated.

Since these forces are all dependent on the seal geometry, they may be partially controlled by mechanical variation of the geometry. This thesis investigates the effects of the variable geometry on lift and drag, and thus on seal performance.

III. DESCRIPTION OF EQUIPMENT

A. DATA ACQUISITION

1. General

The XR-3 has an extensive instrumentation system which consists of sensors, transducers, amplifiers, and signal conditioners all feeding to a 14 channel tape recorder. This system is sketched in block diagram in figure 5. The sensors will simultaneously record thrust, lift and drag on the bow seal, seal and plenum pressures, velocity, rudder position, wave height, and displacement, displacement rate, and acceleration about all three of the craft's axes. For this thesis the parameters of interest were velocity, and lift and drag on the bow seal.

2. Velocity

The XR-3 velocity is measured by a Potter velocity meter installed on a bow-mounted strut, and run in undisturbed water ahead of the craft. The probe and its installation can be seen in figure 1. The velocity meter consists of a small magnetized free turbine in a flow-through axial duct. The rotating turbine wheel induces a sinusoidal voltage, the frequency of which is directly proportional to the testcraft velocity. The frequency is converted to two voltages by a velocity converter. One voltage conversion is to a zero to five volt range, and feeds the cockpit instrumentation. The other voltage is converted to a zero to one volt range and then fed as input to one of the tape recorder channels. Both of these voltage ranges correspond to a 40 knot velocity regime.

3. Lift and Drag

In order to measure lift and drag on the bow seal, the seal is suspended solely by a set of load cells. These cells are the only connections between the seal and the hull. A plastic sheet is inserted between the aft end of the seal and the underside of the wet deck to prevent escape of plenum air through the void occupied by the load cells. The load cell installation is pictured in figure 6.

Drag is measured by two drag load cells. The load cells sense drag individually but are then summed through a 3440J operational amplifier to provide a "sum of drag" on the seal as shown in figure 5. This summation of drag value is inverted due to the action of the 3440J amplifier, and therefore indicates negative values for a rearward force and positive values for a forward force.

Lift is measured by four lift load cells. These cells sense lift individually and are also summed thru a 3440J operational amplifier. Unlike drag, this lift summation is then applied to a 741 operational amplifier which again inverts the signal and makes lift a positive quantity in the upwards direction.

B. DATA RECORDING

The amplified and conditioned signals from the sensors are input to a Pemco model 120-B magnetic tape recorder (Figure 7). The tape recorder has the capability of recording fourteen channels of data in addition to an edge track for recording voice narrative during data taking. Power is supplied to the recorder through a Pemco power supply which provides 26 volts direct current to the recorder. The input voltage range for the recorder is ±1.414 volts RMS. However, since other data reduction equipment will not handle negative voltages, all signal inputs to the recorder have been conditioned for a zero to one volt range. While taking data, the recorder is located in a compartment aft of the starboard cockpit and is remotely controlled by means of a panel on the pilot's instrument panel. The recorder is normally operated at a speed of 1 7/8 inches per minute, but can be operated at speeds of up to 60 inches per minute for higher sensitivity needs as they arise. The recorder weighs 100 pounds and can be easily removed from the XR-3 for post operation data reduction activities.

C. DATA REDUCTION

The data reduction system (figure 8) consists of five major components:

1. Signal selector and conditioner unit
2. Analog to Digital (A/D) converter and calculator interface module
3. Monroe 1880 calculator
4. Monroe PL4 digital plotter
5. Hewlett Packard model 7100B strip chart recorder

All of these components are housed in a Champion motor home, appropriately named the "XR-3 Mobile Data Facility." The mobile home interior has been modified for the data equipment installation.

Raw analog signal data from the fourteen tape recorder channels feed the signal selector and conditioner unit. Here the operator chooses the path the data will take. Analog data can be sent directly to the strip chart recorders. Alternatively, the analog signal is changed to digital form in the A/D converter module. The Monroe calculator, with its various programs, controls further manipulation of the data to provide either tabular output via the calculator printer, or an X-Y plot of the data on the digital plotter.

The signal selector and conditioner unit allows the operator ease in selecting and routing signals from the tape recorder to other components of the data reduction system. The analog data is fed through low pass filters in order to reduce as much of the spurious high frequency noise as possible. Since some of the XR-3 sensor circuits do not contain zero adjusts, a zero offset voltage circuit is included for each channel in the signal conditioner. Variable gain resistors are also included to permit exact calibration of outputs and the scaling of the one volt outputs to as high as five volts full scale. Normally up to eight signals can be sent to the A/D converter and the multiplexer module, located in the same signal conditioner case. Once digitized, these signals are sent to the Monroe calculator for control of plotting and printing. The A/D converter module was inoperable and awaiting repair parts during the period of this investigation. The conditioned output can also be routed in analog form to any of nine ports for application to the strip chart recorders. Any two output ports can feed into a particular strip chart recorder for display as continuous analog output. This strip chart system is very reliable and gives accurate results and was therefore used as the primary reduction system in this thesis.

D. SEAL SHAPE CONTROL

A control mechanism was devised for varying the seal shape without requiring modification to the existing seal. This system consisted of steel cables attached to downstop rings located at two positions on each of the twelve spring steel stiffeners. The two sets of downstop rings are located 30 inches and six inches forward of the seal trailing edge. The set of twelve cables attached to the forward downstop rings were routed to the top of the seal, over pulleys, aft along the seal top, and attached with cable clamps to a transverse steel rod running the full width of the seal. This rod was mounted to the aluminum seal frame members so as not to allow any forces to bypass the load cells and thus compromise their indications. Gearing on the transverse rod facilitated its manual turning, with the cable taken up by the turns translating into a raising of the downstop rings and their associated stiffeners. The diameter of the rod was such that ten full rod revolutions raised the downstop rings approximately 0.5 inch. A counter geared to the rod measured the number of turns. During the course of the investigation it was seen that lacking a means to hold down the aft end of the stiffeners, the seal trailing edge position followed that of the forward downstop. Therefore the adjustments afforded by the aft downstop and cable set merely duplicated positions already tested, and were not of significance. The cable lengths of the aft downstop set were adjusted to give a level seal trailing edge. The cables from the forward downstop set were adjusted to position the seal trailing edge two inches above the keel bottom and the counter was set to 0000. Figures 9 and 10 show the downstop/cable assembly and the rod/counter installation. Seal positions investigated included counter readings of 0000, 9990, 9980, 9970, and 9950 corresponding to seal positions of 0, 0.5, 1.0, 1.5, and 2.5 inches respectively above reference. Figure 11 charts the seal shape for each of the above counter readings as measured with seals pressurized and the craft out of the water.

E. EXPERIMENTAL PROCEDURES

All testing for this project took place between July and November 1978. The site for the XR-3 testing was Lake San Antonio, a reservoir in southern Monterey County, California. The lake is a large fresh water lake and has calm water most of the time. Disadvantages of the test site are its location 110 miles from Monterey, and its extremely hot summer temperatures. These hot temperatures require cooling systems for several of the XR-3 electronics packages. Advantages of the site include ample storage space for the testcraft and its support vehicles, an excellent twelve lane boat ramp for launch and recovery of the craft, and its 16 mile length, ideal for long straight data runs. All test runs are made in the company of an 18 foot outboard driven "chase boat," which serves as a safety observer platform.

Before each day's operations, the voice track was annotated with pertinent information such as date, data run numbers, pilot's name, weather, water condition, equipment status, and seal position. The sensors were then calibrated on a level area of the boat ramp. Calibration signals were applied on applicable channels to obtain a null and a voltage range for each sensor. Known loads of zero and 200 pounds (zero and 200 millivolts respectively) were applied to the lift and drag sensors and a zero-velocity signal was recorded. Following launch, the calibration process was completed by running at a 20 knot velocity calibration point, which was also recorded.

With the systems functioning, the XR-3 was brought to a speed just over primary hump (9 1/2 knots) and the tape annotated as such. The craft was then accelerated, while on a steady heading in calm water, in increments of two knots until full speed was reached. Conditions were allowed to stabilize at each speed before accelerating to the next mark. Where possible, this procedure was then reversed with velocity decreasing to the hump speed in order to verify repeatability of the data taken.

Following completion of the above velocity profile procedure, the seal position was adjusted to the next point of interest by manually rotating the transverse steel rod in the plenum until the counter indicated the appropriate value. During the summer this process involved sending over a swimmer who surfaced under the XR-3 to turn the rod. As the test series extended into November, the water temperature dictated that, for safety reasons, the craft be recovered on the boat ramp for the shape changes.

During the course of the test runs it was deemed necessary to measure the trailing edge position of the bow seal relative to the wet deck throughout the velocity profile in order to obtain a better qualitative understanding of the seal shape and the variation in aerostatic forces acting on the seal. To accomplish this, a nylon cord was attached to the lower aft edge of the seal at its centerline, and routed through a hole in the wetdeck straight up to the co-pilot's cockpit. The change in position of the aft seal edge at various speeds was then recorded directly by the movement of the cord from an appropriate reference point.

Even though the data was taken on many different days, the results are considered to be taken under identical conditions. The winds were always calm and although the water and air temperature varied, they were considered to be of negligible importance to the test results.

Data reduction was accomplished using the strip chart recorder output trace of a given run and eye integrating the results to eliminate the various small noise components. This noise suppressed data was then hand plotted for analysis.

IV. RESULTS, CONCLUSIONS, AND RECOMMENDATIONS

A. DRAG PERFORMANCE

1. Shape Variations

The appendix gives a general description of the different forces which make up measured drag, hereafter referred to as drag in this thesis.

Drag on the bow seal is actually a negative quantity producing a force in the forward direction (i.e., one that tends to push the craft forward) over the entire velocity regime tested. The plot of recorded drag for the seal shape of 0000, figure 12, begins at a velocity of ten knots and is -235 pounds. This drag decreases to -275 pounds at 13 knots and then increases to a value of -195 pounds at 26 knots. The general shape of the curve is a result of changes in the hydrostatic drag. Once the XR-3 has accelerated past the primary hump speed, the bow seal is actually hydroplaning, with much less of the seal immersed in the water than in a non-hydroplaning mode. Since the velocity is still relatively low, hydrodynamic effects do not yet predominate, and the decrease in drag is primarily hydrostatic since less hydrostatic drag is present to counter the aerostatic force. As velocity increases, the hydrodynamic forces become more and more effective, continuing to cancel more of the aerostatic force. If the craft were capable of speeds in excess of its present 26 knot limit, eventually the measured drag on the bow seal would become a positive value as all of the aerostatic force was countered.

Figures 13 through 16 show the drag at seal shapes of 9990 through 9950 respectively. All of these curves have the same general characteristics as the curve for shape 0000, and can be explained in the same manner. There is a clear distinction between the drag patterns above and below 17 knots, as observed in figures 12 through 16. Figure 17 is a composite plot of the bow seal drag for the different shapes for velocities below 17 knots. The plots show that as the seal is raised to position 9980 the drag continues to increase in value, but as the seal is raised further, the drag again decreases. The initial drag increase is because as the seal is raised, the bow settles further into the water causing the effects of hydrostatic and hydrodynamic drag to be greater. Raising the seal past position 9980 causes the effects of hydrostatic drag to begin a decrease in value due to the hydroplaning effect.

Figure 18 is a composite plot of the various seal shape drags for velocities of 17 knots and above. As in figure 17 it can be seen that the drag increases as the seal is raised, however the drag continues to increase until position 9970 before starting to decrease in value. The explanation for this result is similar to the less-than-17-knot case, except that it takes a higher seal position to make the planing effect felt and decrease the drag.

2. Pressure Variations

During one data collection session it was discovered that several lift fans were not operating at full potential due to fan belt slippage. Figure 19 shows a plot of drag versus velocity at seal shape 9980 with a varying plenum pressure. This figure points out very clearly that there is a large increase in drag for a relatively small decrease in plenum pressure. Since the aerostatic force is a simple product of the plenum pressure and the area upon which the pressure acts, a decrease in pressure greatly reduces the ability of that force to counter the hydrostatic and hydrodynamic drags.

B. LIFT PERFORMANCE

Lift on the seal is positive in an upwards direction, and acts perpendicular to the plane of the water surface. Figure 20 shows the lift on the seal at a seal position of 0000. The lift has a tendency to decrease in value as the velocity increases. The primary generation of lift is a result of the displacement of water by the seal. Additional minor lift is generated as a result of the planing action and is the vertical component of the hydrodynamic force acting on the seal. Even though the hydrodynamic force, and thus lift, increases with velocity, the planing action results in much less water being displaced, and thus the decrease in total lift. Figures 21 through 24 are plots of seal shapes 9980 through 9950 respectively. These plots all show the same typical decrease in lift as velocity increases. The decrease in all cases can be attributed to the reduction in buoyant lift resulting from the planing action.

As is the case with drag, the 17 knot velocity separates the behaviors of lift performance. Figure 25 is a composite plot of the seal shape lift forces over the ten to 17 knot regime. As can be seen, the lift tends to decrease in value as the seal is raised until shape 9950 is reached. The 9950 and 0000 shape lifts approach the same values. Once the seal has been lifted far enough a much larger surface area of the seal touches the water, allowing a greater buoyant lift.

Figure 26 shows the same type of response above 17 knots as figure 25 showed below 17 knots. The only exception to this is that as the seal is raised to position 9950 it actually has more lift than it does at position 0000.

C. DYNAMIC FORCE EFFECT ON SEAL SHAPE

Figure 27 shows a typical plot of the variation in the bow seal trailing edge height with respect to a zero velocity reference. It can be seen from this figure that the seal raises to six inches above reference at the high and low ends of the velocity profile, but settles to only three inches above reference in the mid velocities. The bow wave is being swallowed at the lower velocities, causing the additional heave, and the turbulence of the water flow past the trailing edge at the higher velocities brings about the same effect. Throughout the mid velocity portion of the profile, the flow is smooth and the rise in seal height is due to hydrodynamic forces.

D. CONCLUSIONS

The collected data shows very clearly that the shape of the bow seal does, as expected, effect the drag on the seal. Also noted is the fact that the drag-shape relationship is a non-linear one. A shape of maximum drag exists, with drag decreasing for shape changes in either direction. For the XR-3 bow seal tested, seal position 9980 yielded the highest drag in the 10 to 17 knot velocity sector. Drag decreased in either direction with the greater improvement seen as the seal was lowered to position 0000. A general drag minimum, for each shape, was noted at a speed of approximately twelve knots. In the 17 to 26 knot velocity sector, seal shape 9970 experienced the highest drag, while shape 9990 became the best, or least drag configuration at approximately 23 knots. Thus, there is a seal shape of minimum drag for a desired velocity range. This shape, however, changes with the velocity range of interest. It was also noted that plenum pressure was an important factor in drag experienced, with drag decreasing as plenum pressure increased.

The lift response to seal shape was also nonlinear in nature, with least lift noted for shape 9970, and most lift occurring at shape 0000, below 17 knots, and shape 9950 above 17 knots.

Since the bow seal lift is but a small part of the total craft lift, and inasmuch as a decrease in bow seal lift would be absorbed by the lift generated by plenum overpressure and sidewall buoyancy, the most consideration should be given to the reduction of bow seal drag when choosing an operating shape.

E. RECOMMENDATIONS

The trailing edge of the bow seal was noted to change position over the velocity profile. This change is related to the stiffness of the seal and the dynamic forces acting on it. An examination should be made into the effects of increasing the stiffness of the seal, and in particular some method of prohibiting the trailing edge from rising.

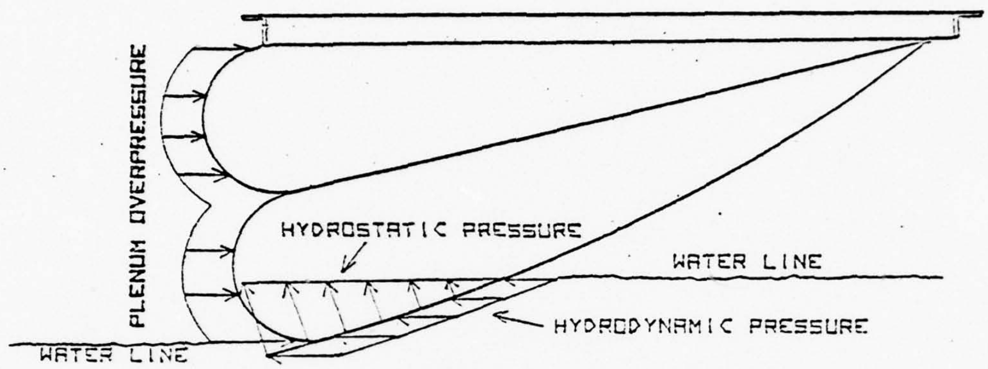
The incidental discovery of the plenum pressure effect on seal forces should be further studied. The effects of greater differentials between plenum and bow seal pressures on both lift and drag should be examined.

Both of the above techniques will have an impact on the hydroplaning angle. This angle greatly influences the hydrodynamic lift and drag, especially at the higher velocities. The effects of planing angle should be further examined.

Future captured air bubble craft utilizing inflatable spring stiffened seals of the type tested should have some means of varying the seal geometry while underway, so as to optimize craft efficiency. The exact seal shapes selected will vary from seal to seal, craft to craft, and velocity to velocity, and must be determined through testing on the applicable craft.

APPENDIX

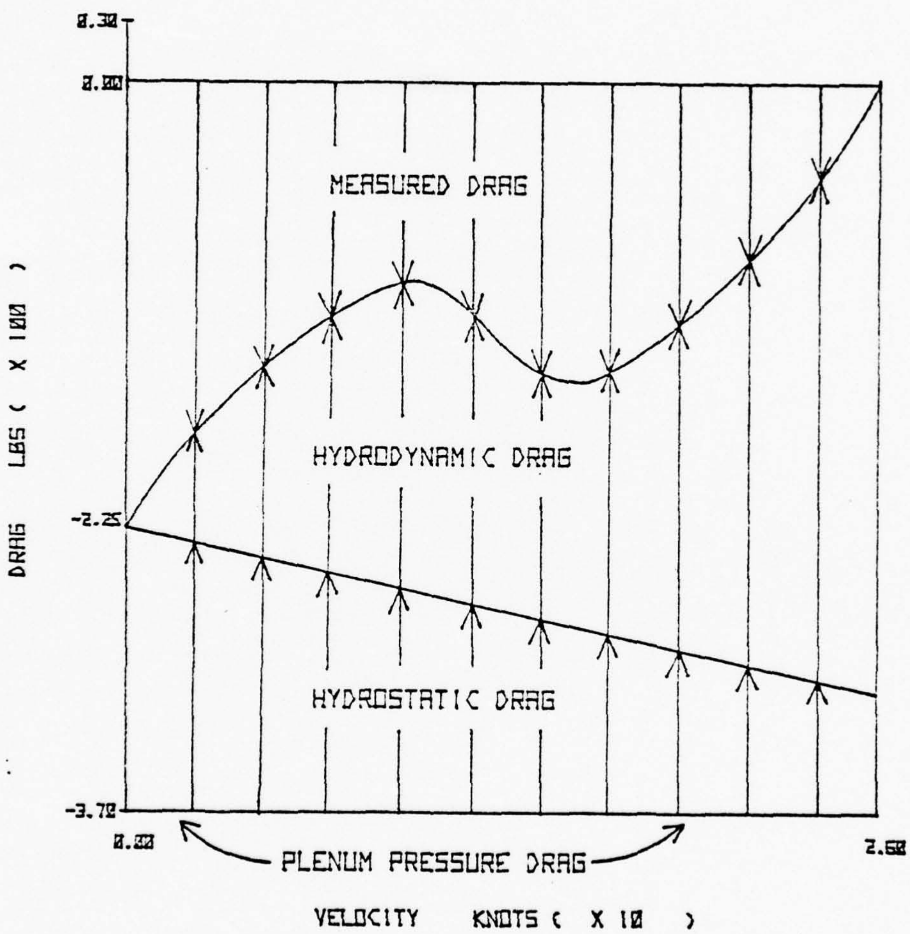
PREDOMINANT FORCES ON THE BOW SEAL



Major Pressures Acting on Bow Seal

The predominant drag force on the bow seal is the force created by the plenum overpressure. This overpressure acts against the hydrostatic and hydrodynamic pressures on the immersed portion of the seal. The plenum overpressure force is larger than the hydrostatic and hydrodynamic forces until the velocity becomes greater than approximately 28 knots, thereby producing a negative drag throughout the examined velocity regime. The predominant drag forces on the bow seal will depend on how far the seal is immersed in the water. A typical drag curve for a bow seal immersed eight inches in the water is shown on the next page. The decrease in drag noted at 9.5 knots is a result of the "swallowing" of the bow wave, the beginning of the hydroplaning action. This phenomenon is referred to as "primary hump," and the velocity at which it occurs is called the "hump speed."

The lift force on the bow seal is caused primarily by the displacement of water, or buoyancy. A small negative lift, or suction, is created by the flow of water around the seal, however this is a negligible force.



Typical Bow Seal Drag vs Velocity Curve

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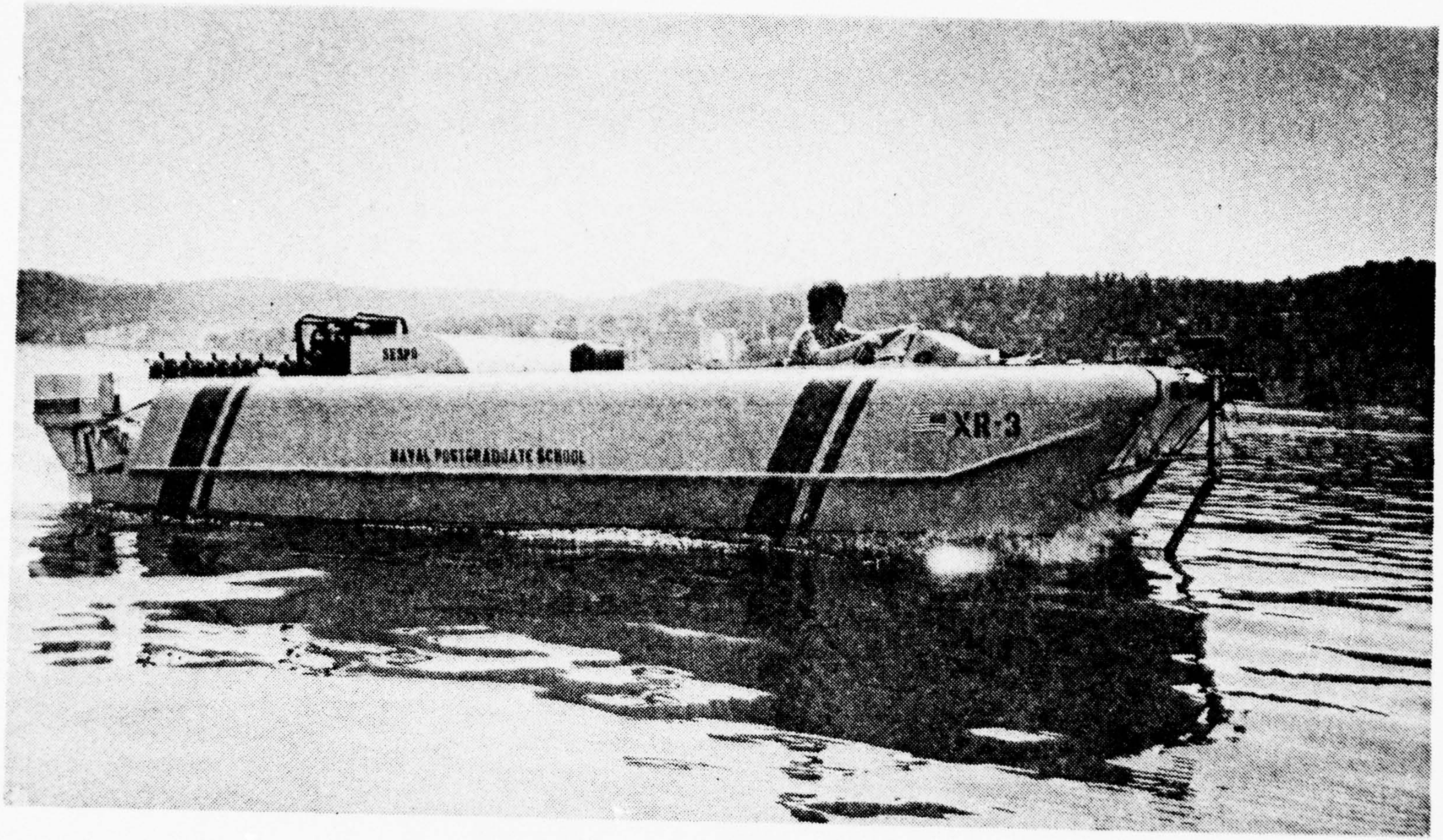

Figure 1. XR-3 TESTCRAFT

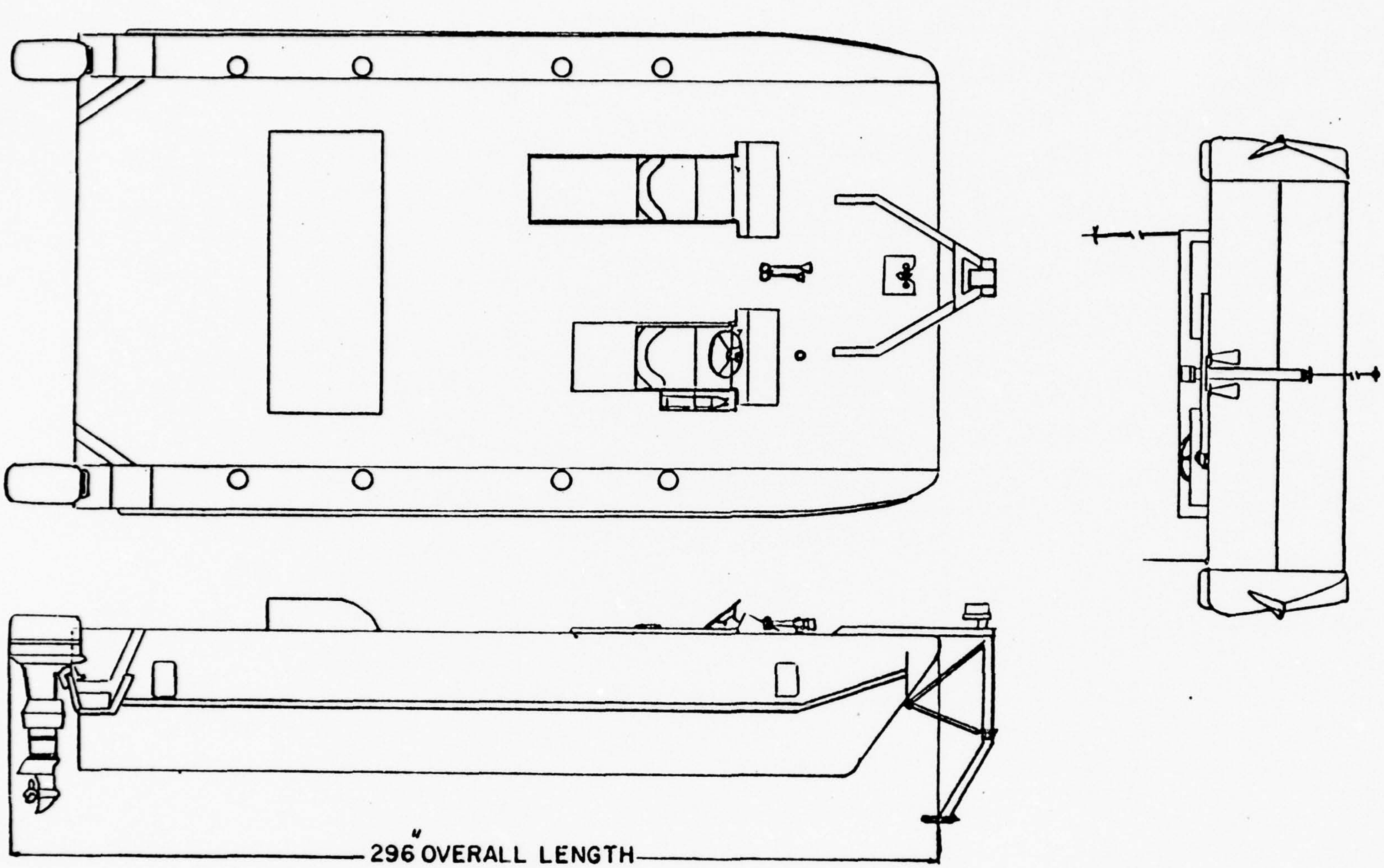

Figure 2. XR-3 SCHEMATIC

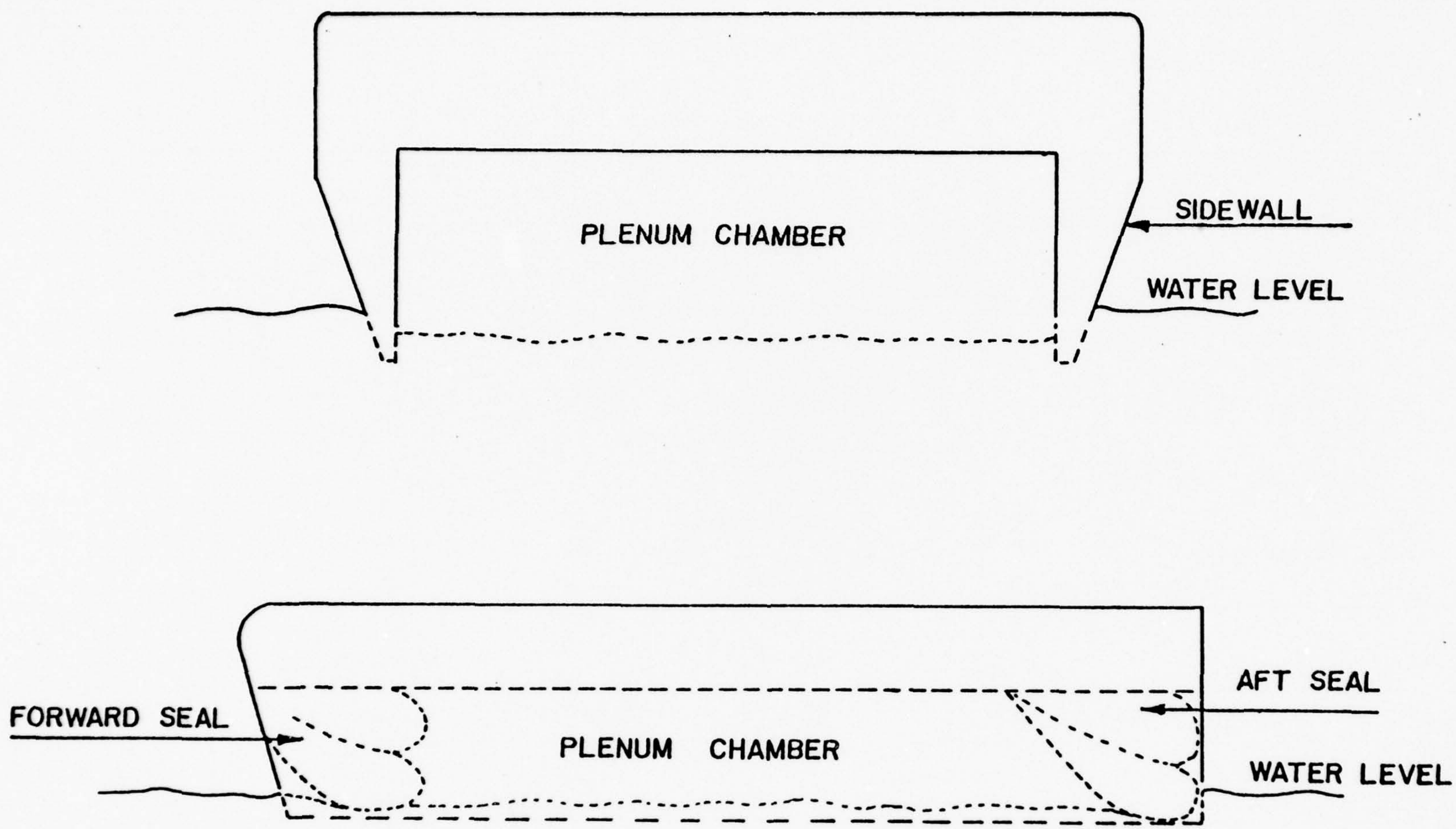

Figure 3. PLENUM CHAMBER AND SEAL OUTLINES

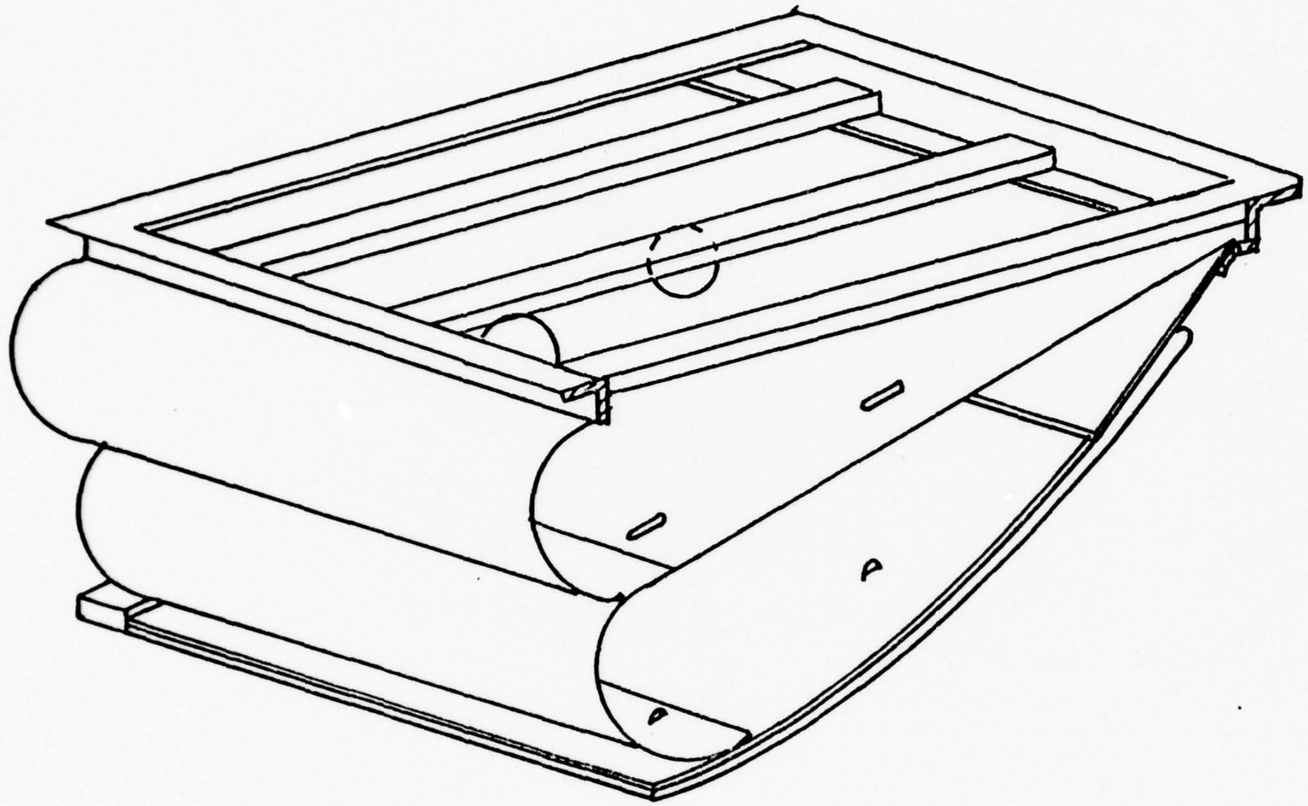

Figure 4. BOW SEAL SECTION

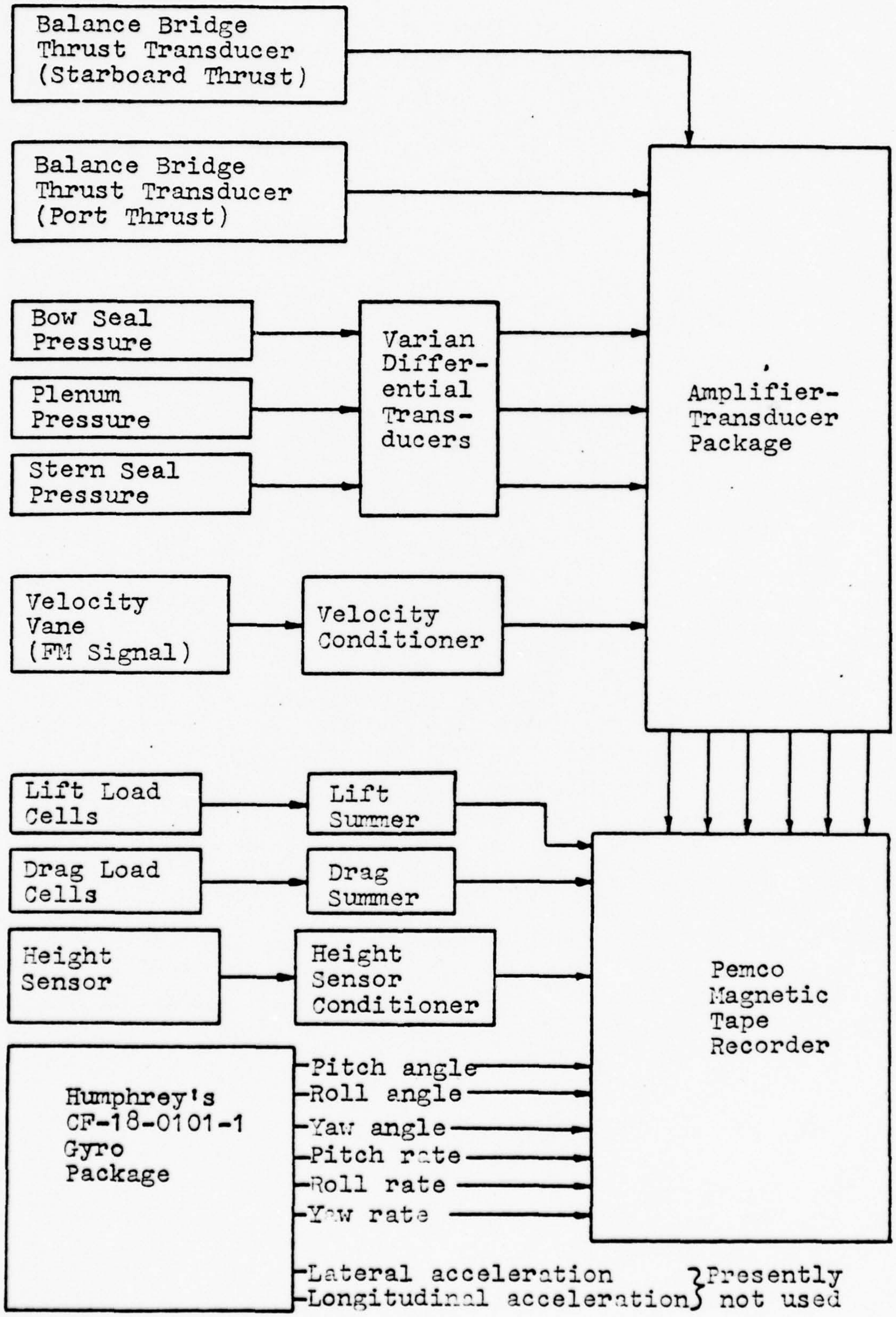

Figure 5. DATA ACQUISITION SYSTEM

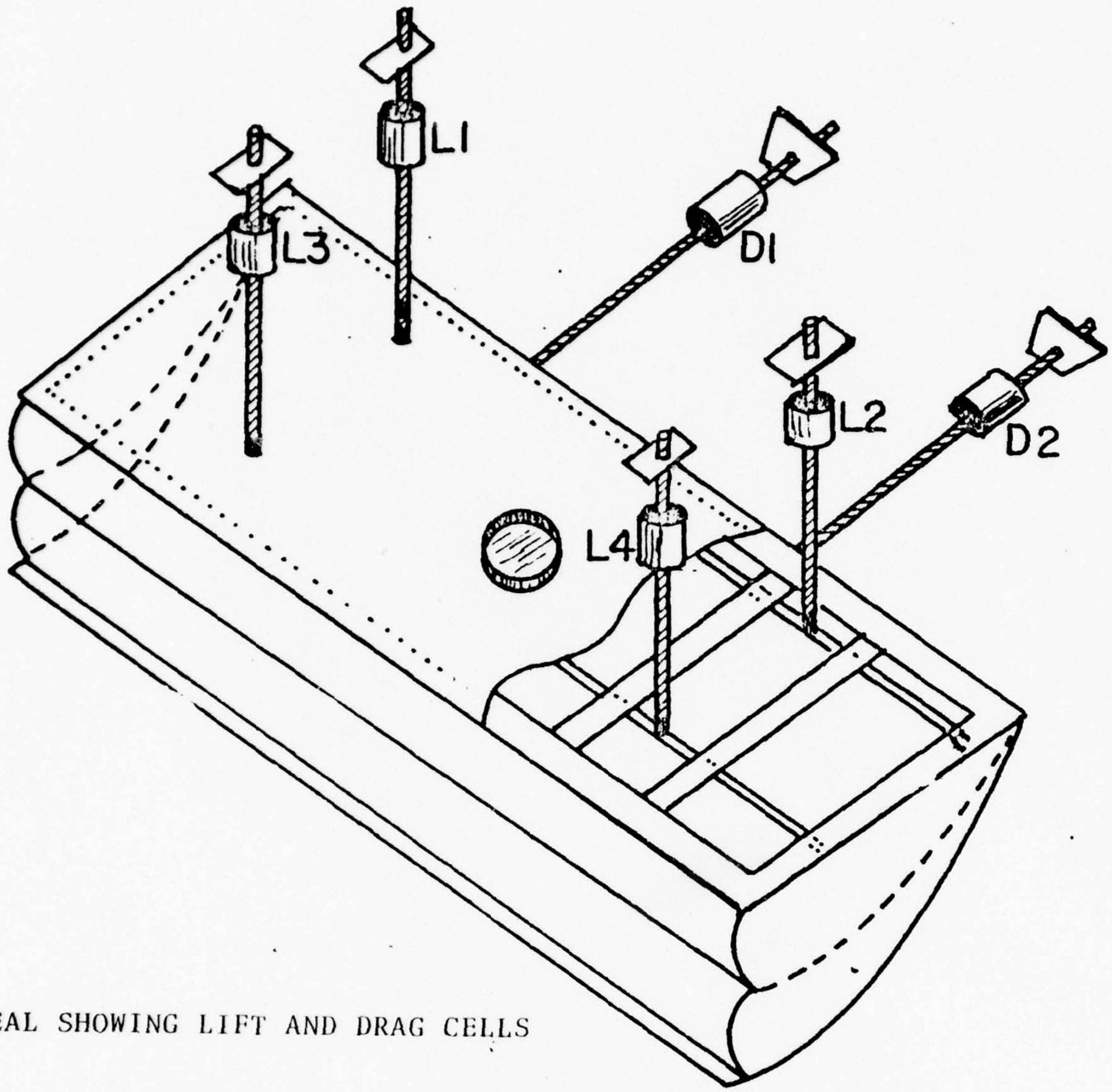

Figure 6. BOW SEAL SHOWING LIFT AND DRAG CELLS

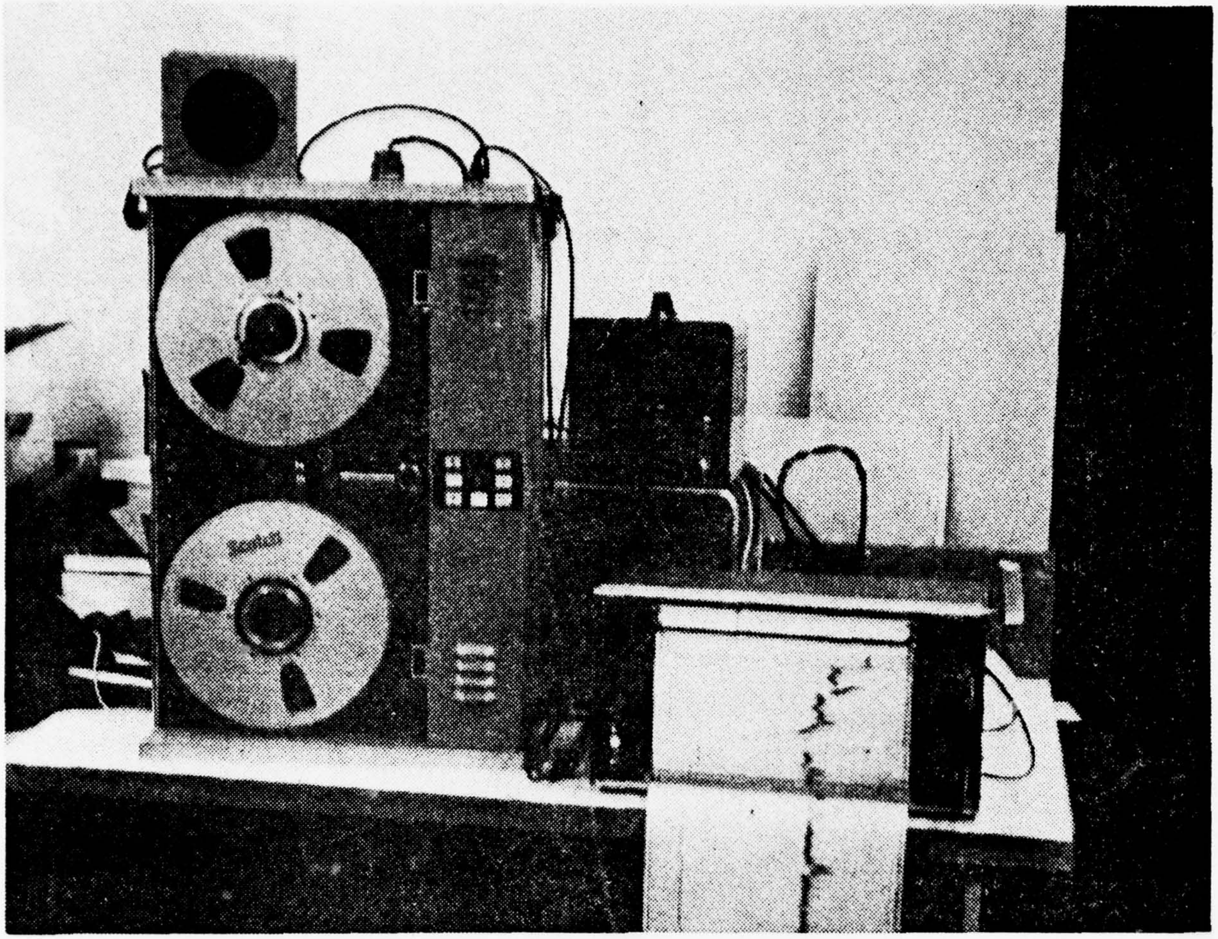

Figure 7. PEMCO MODEL 120-B TAPE RECORDER AND THE HEWLETT PACKARD MODEL 7100B STRIP CHART RECORDER

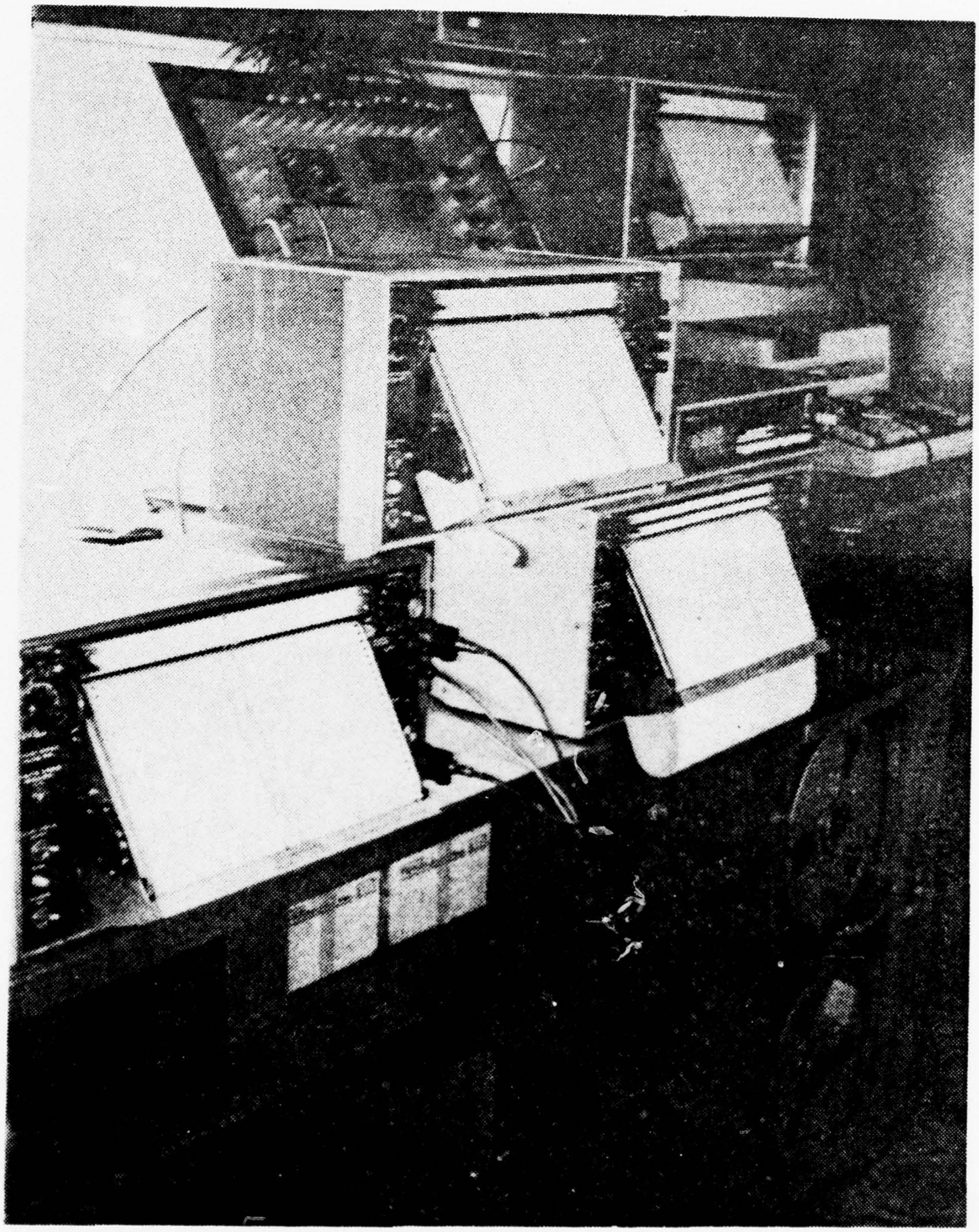

Figure 8. DATA REDUCTION SYSTEM

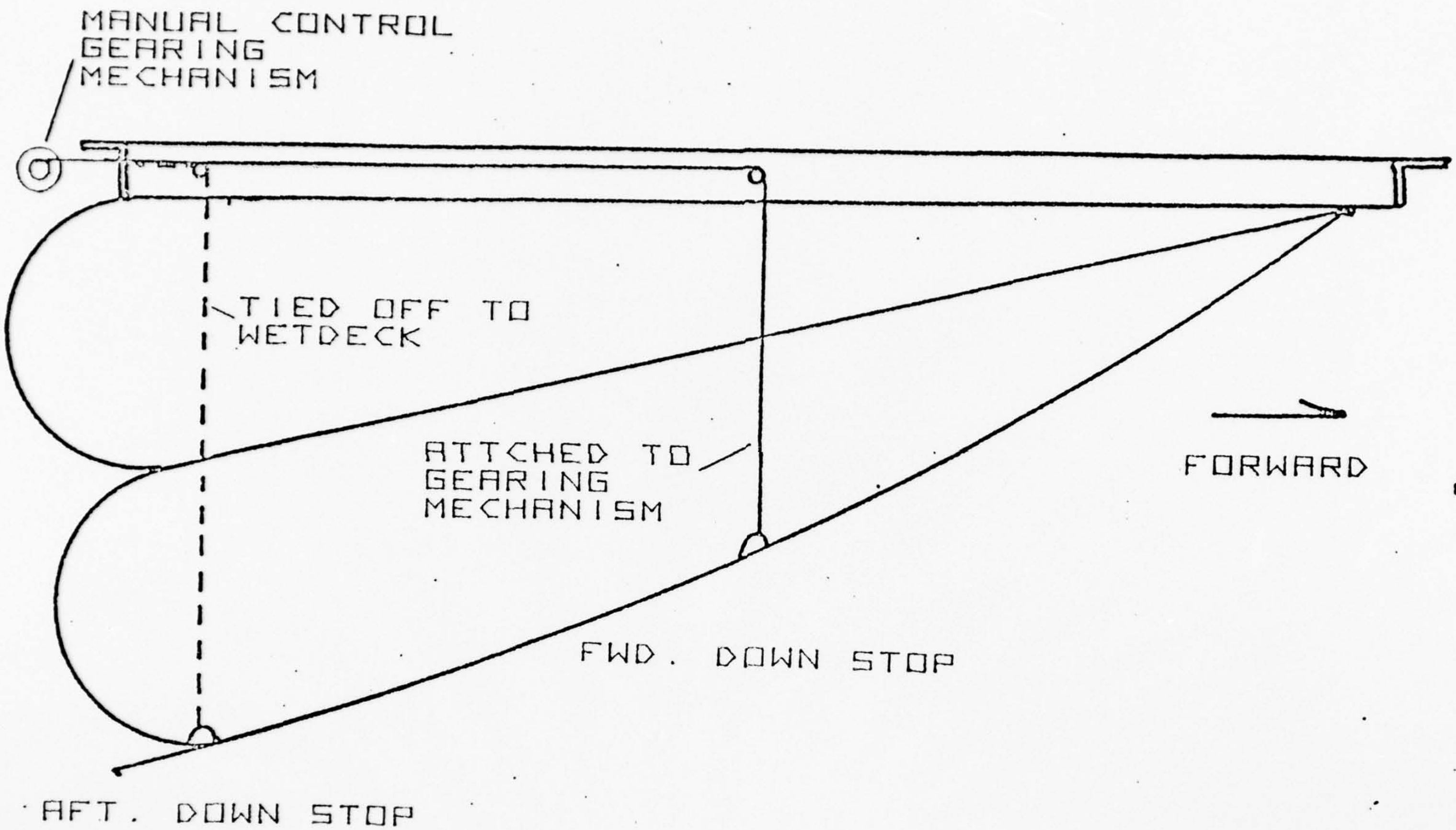

Figure 9. BOW SEAL SHOWING RIGGING OF POSITION CONTROL CABLE

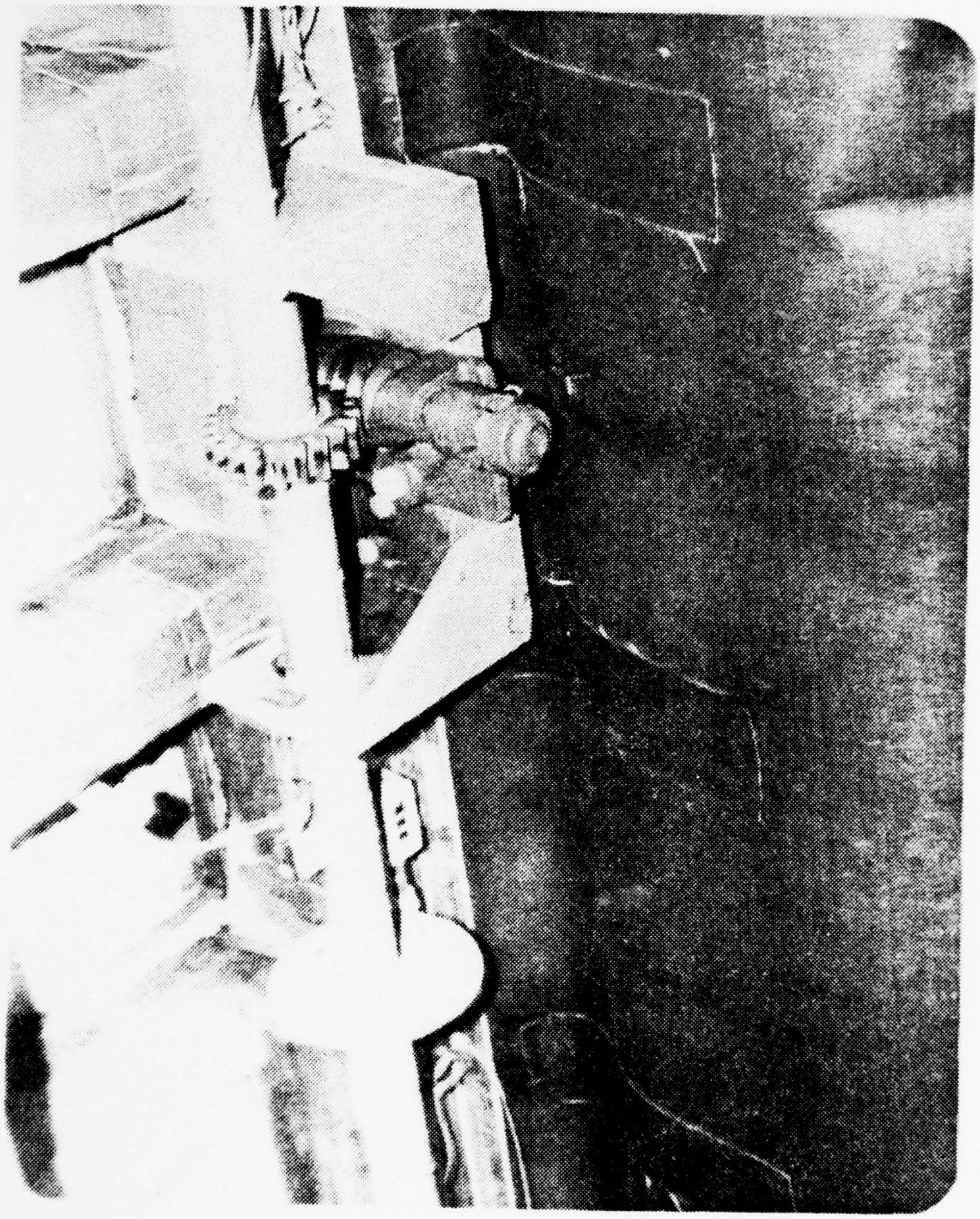

Figure 10. BOW SEAL CONTROL MECHANISM

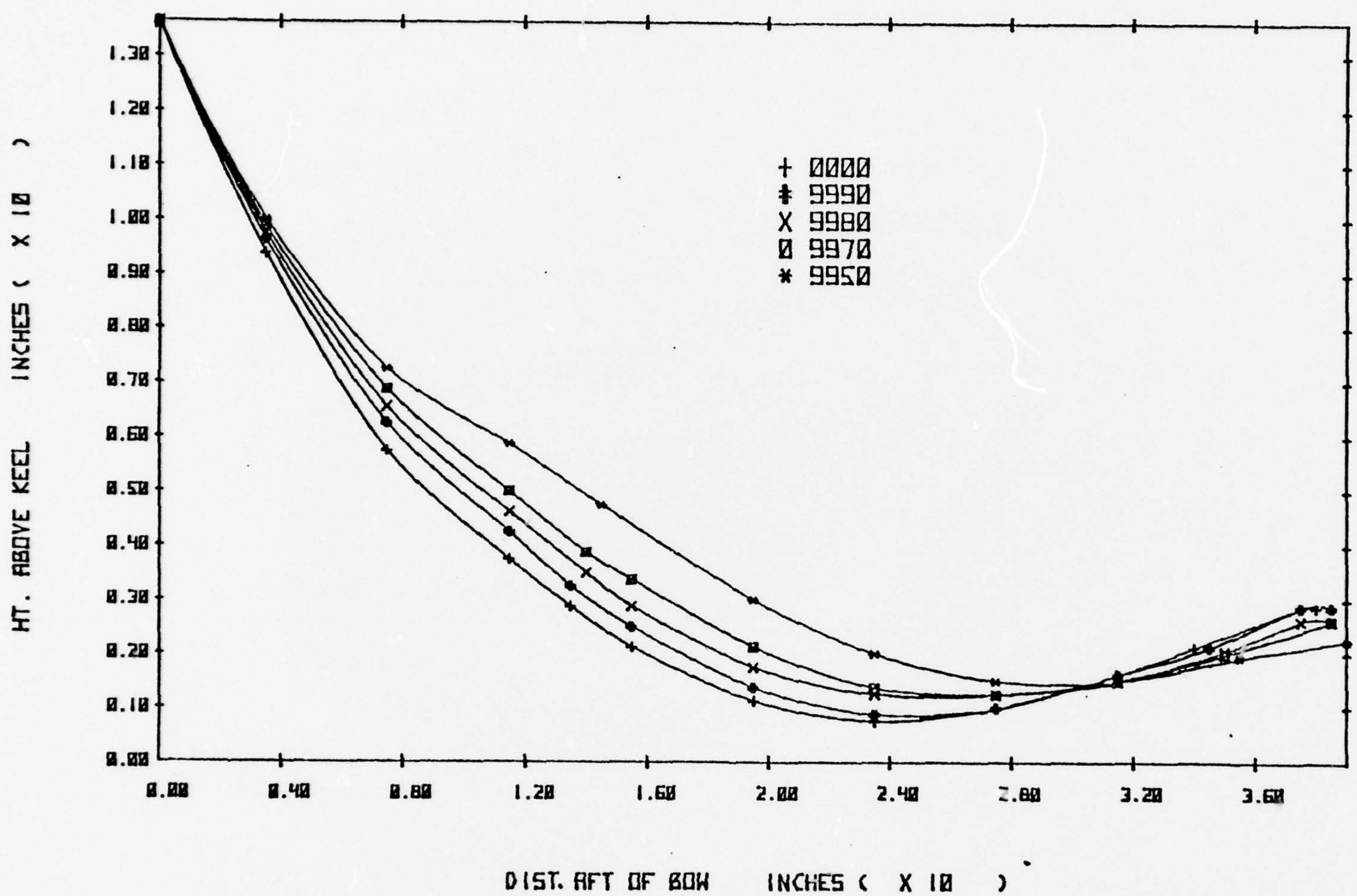

Figure 11. BOW SEAL SHAPES AT VARYING CONTROL POSITIONS

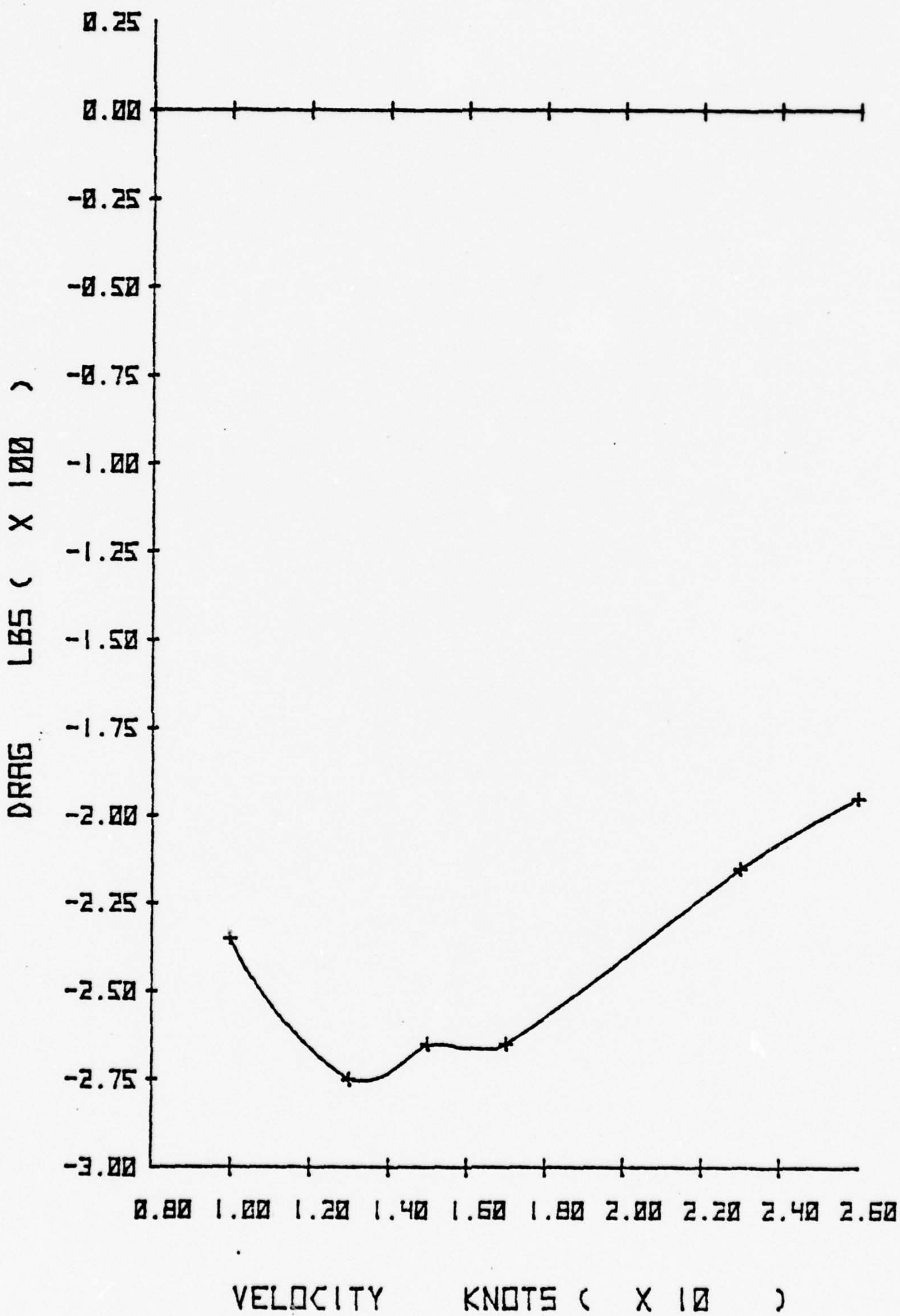

Figure 12. DRAG VS VELOCITY - BOW SEAL SHAPE 0000

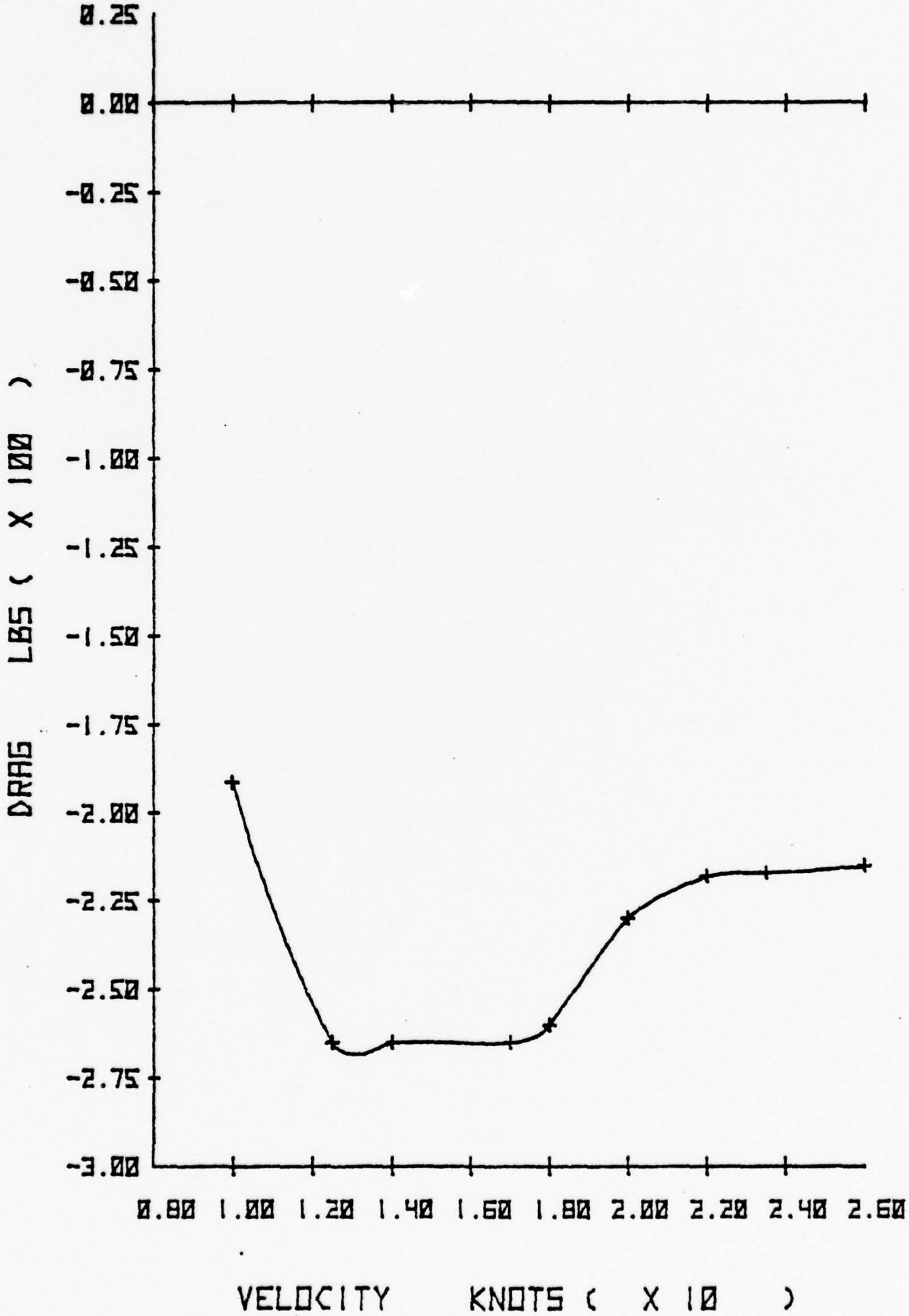

Figure 13. DRAG VS VELOCITY - BOW SEAL SHAPE 9990

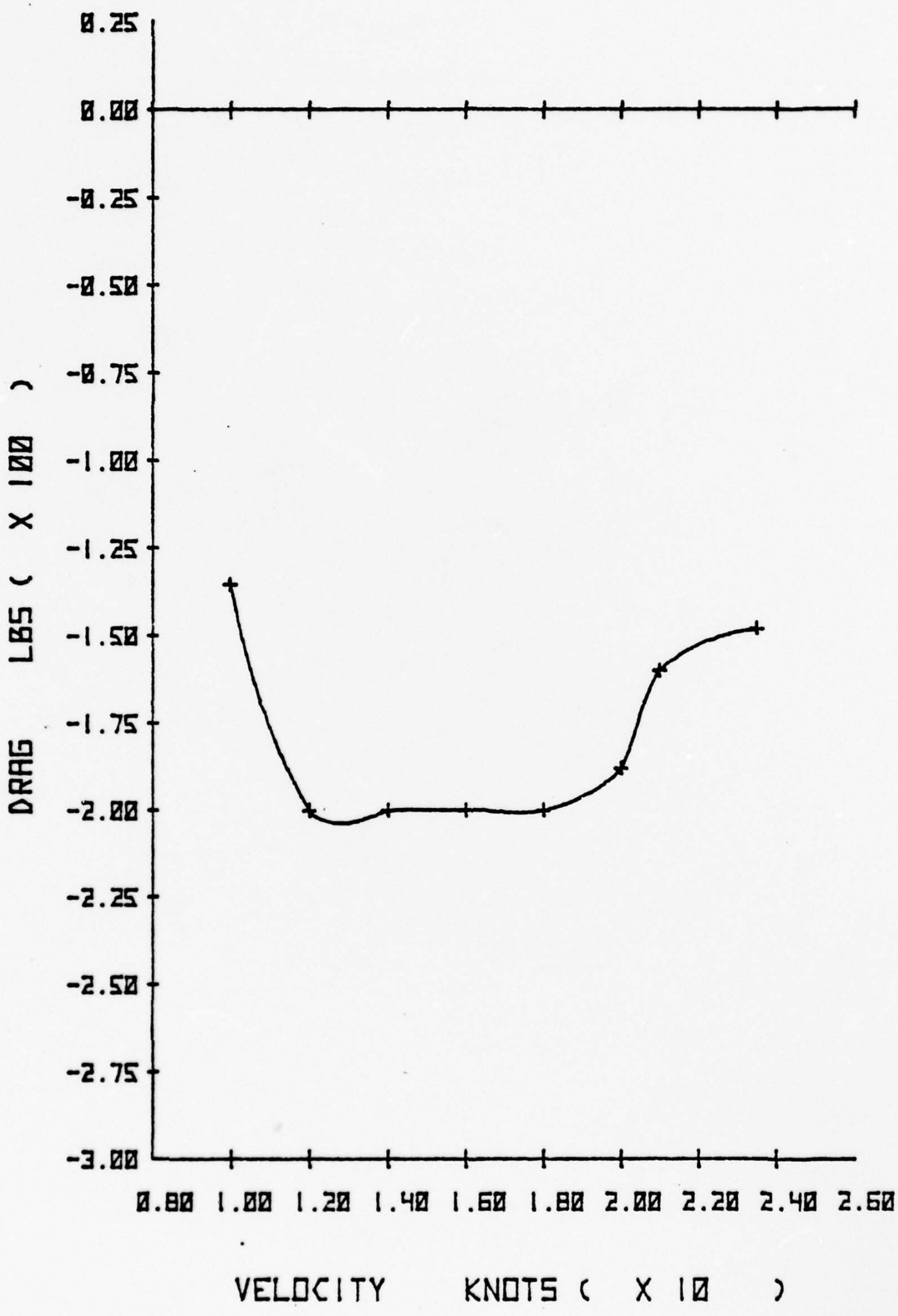

Figure 14. DRAG VS VELOCITY - BOW SEAL SHAPE 9980

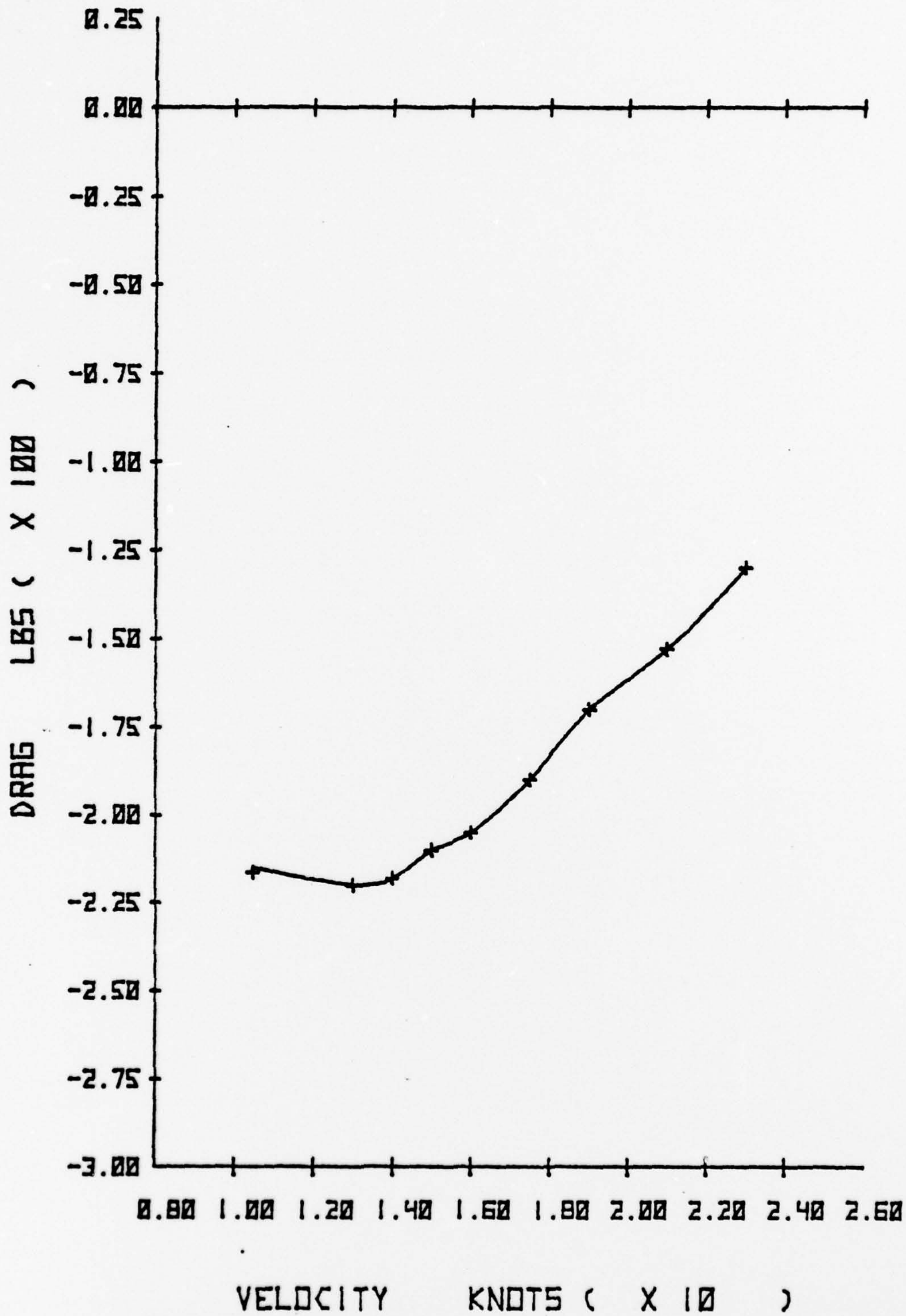

Figure 15. DRAG VS VELOCITY - BOW SEAL SHAPE 9970

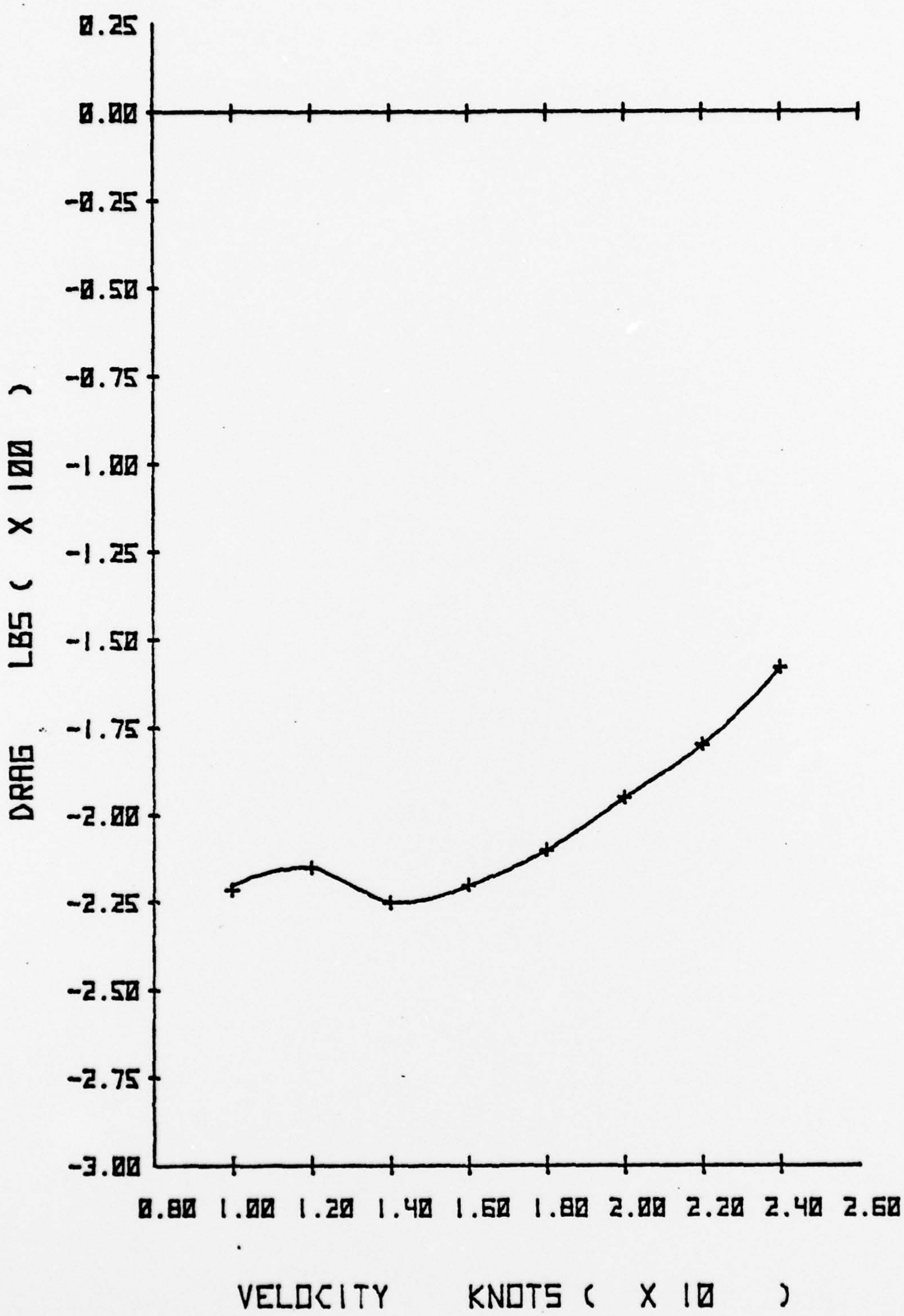

Figure 16. DRAG VS VELOCITY - BOW SEAL SHAPE 9950

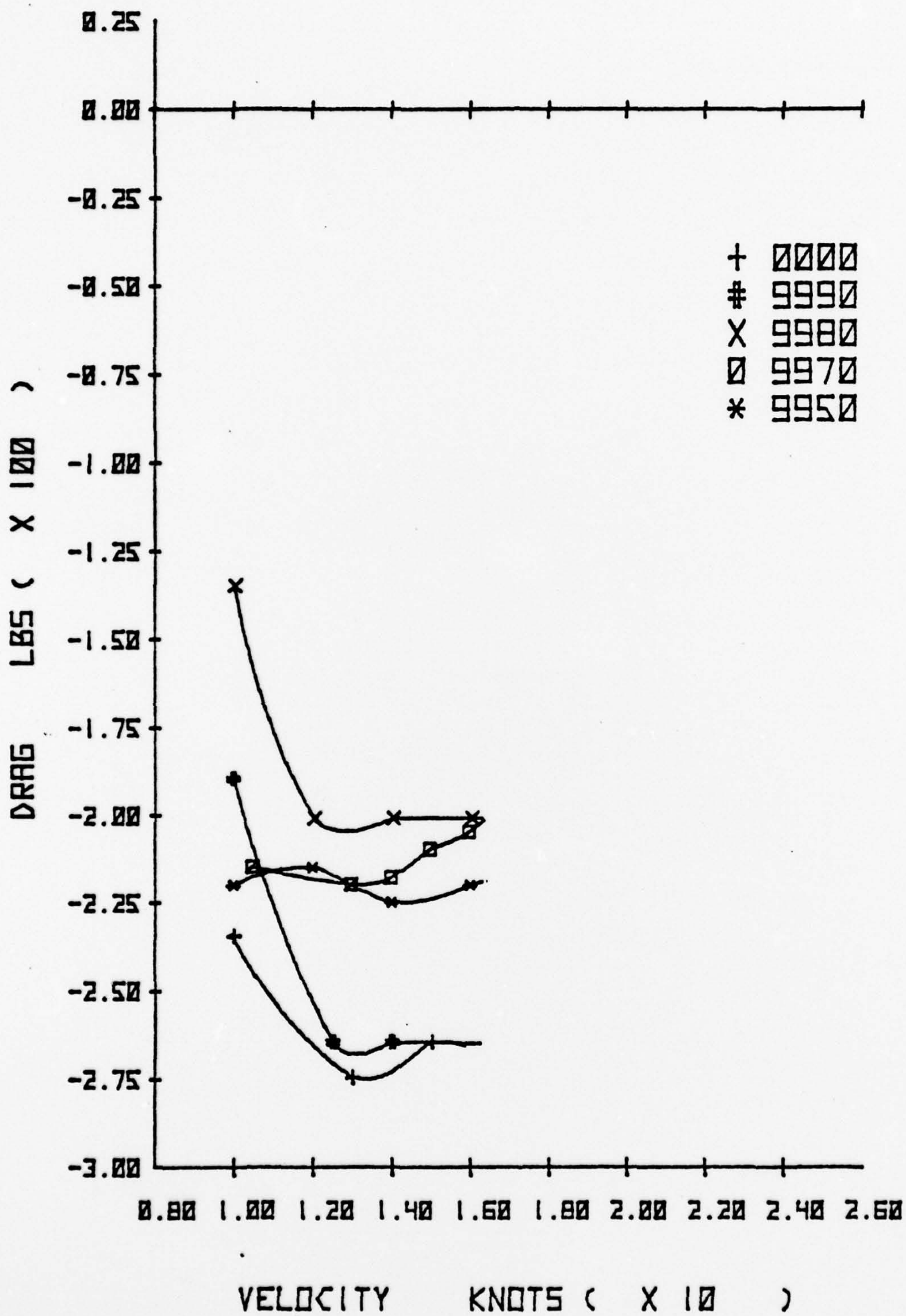

Figure 17. SUMMARY OF DRAG VS VELOCITY BELOW 17 KNOTS

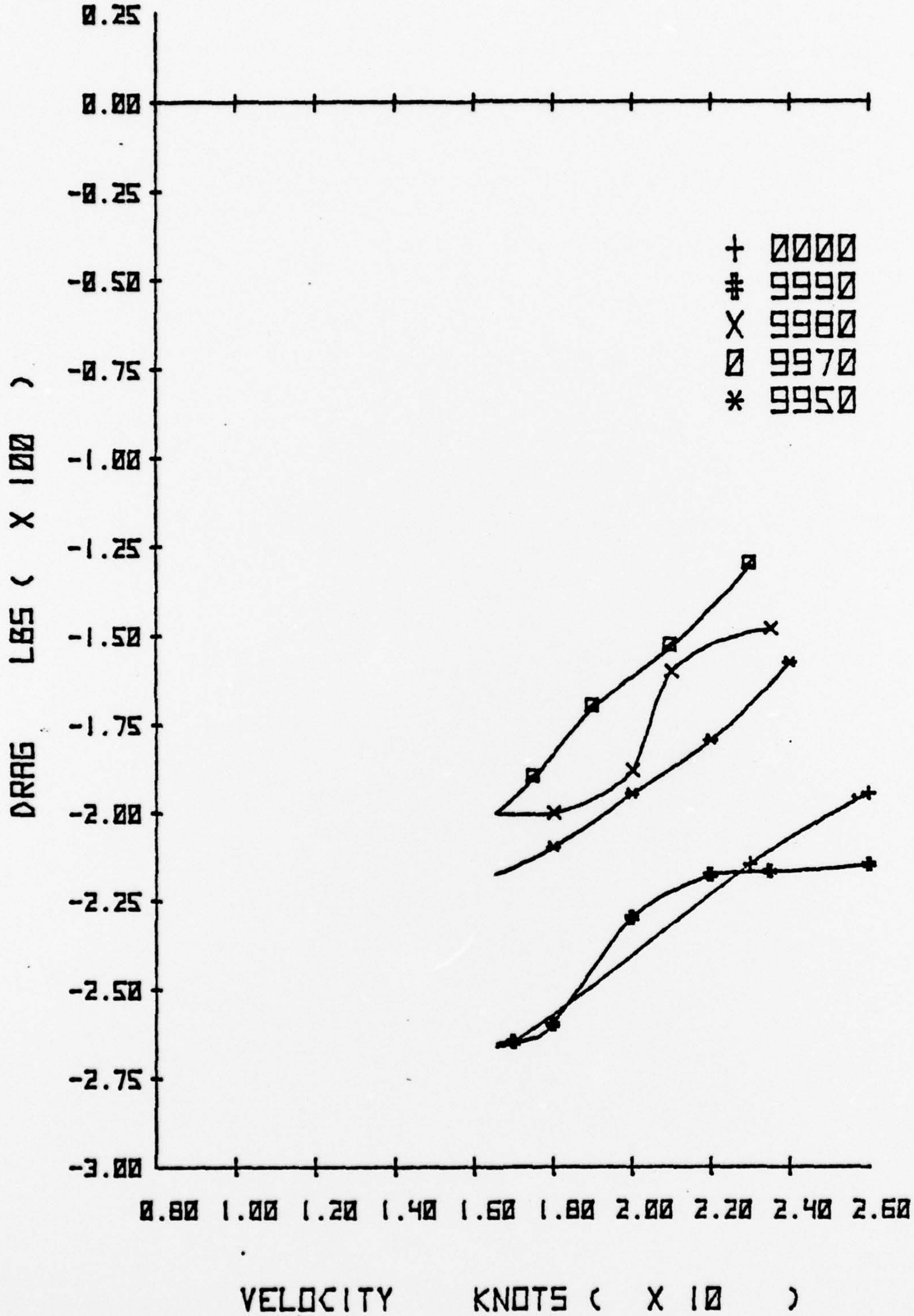

Figure 18. SUMMARY OF DRAG VS VELOCITY ABOVE 17 KNOTS

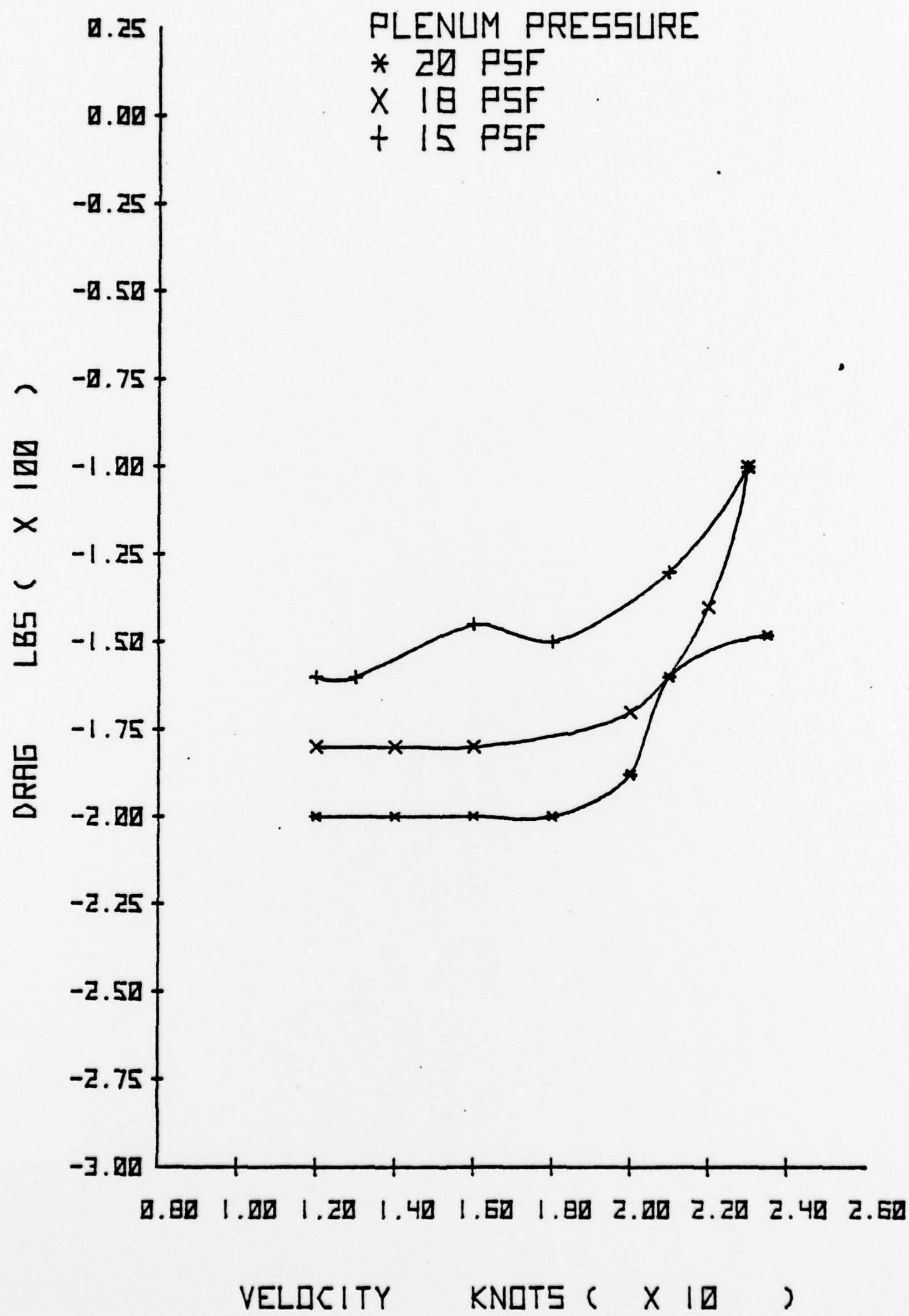

Figure 19. DRAG VS VELOCITY FOR VARYING PLENUM PRESSURES

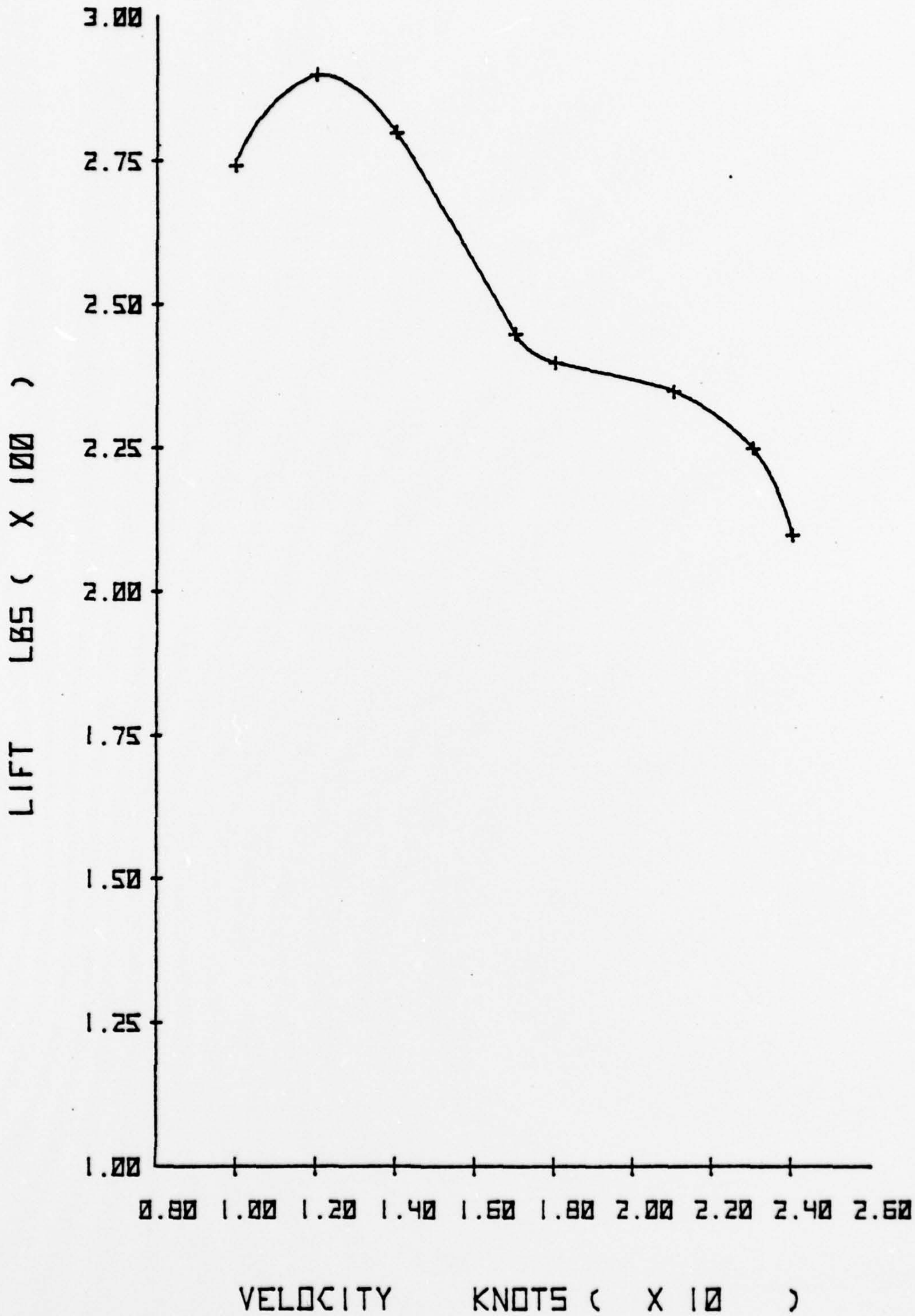

Figure 20. LIFT VS VELOCITY - BOW SEAL SHAPE 0000

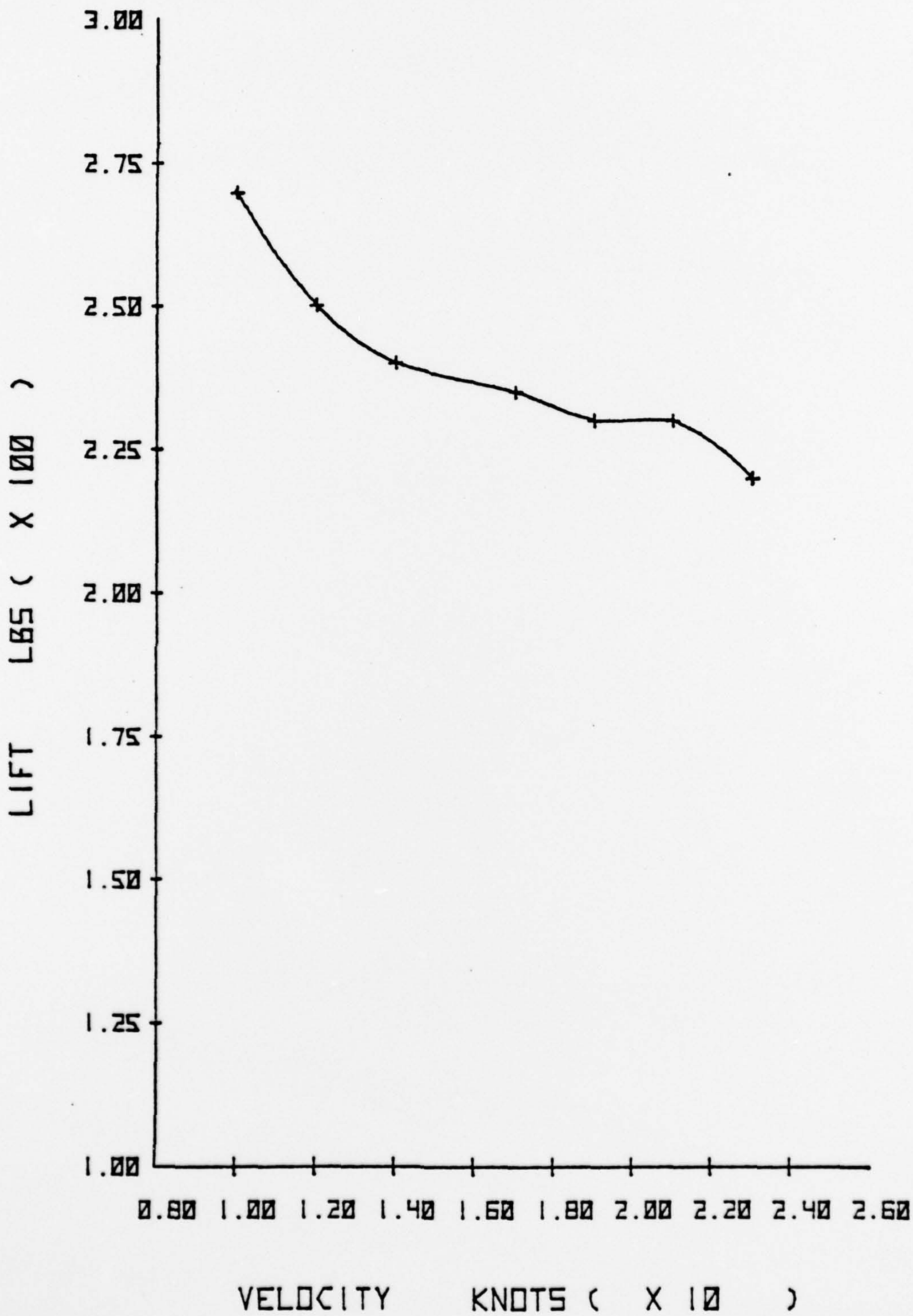

Figure 21. LIFT VS VELOCITY - BOW SEAL SHAPE 9990

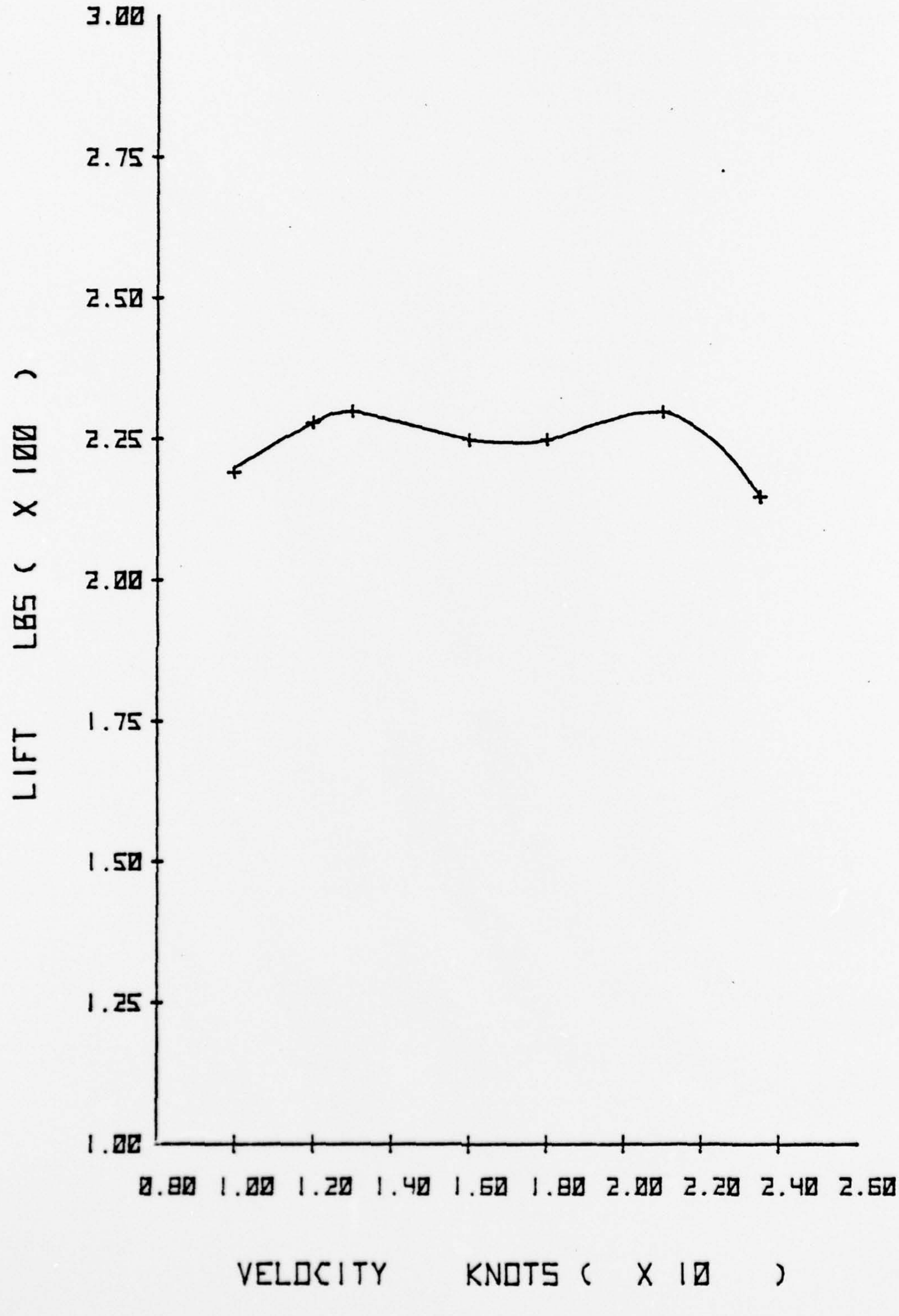

Figure 22. LIFT VS VELOCITY - BOW SEAL SHAPE 9980

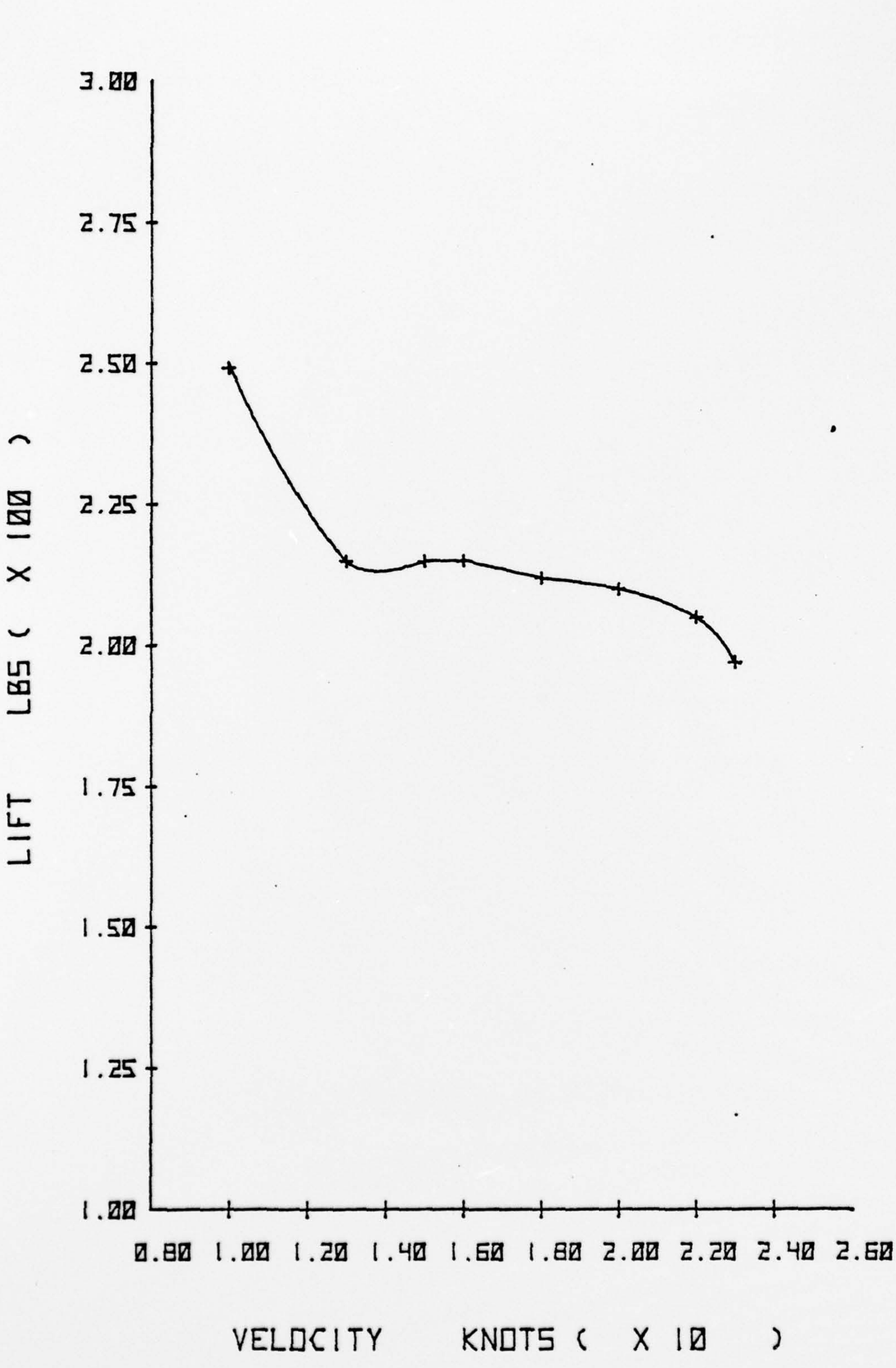

Figure 23. LIFT VS VELOCITY - BOW SEAL SHAPE 9970

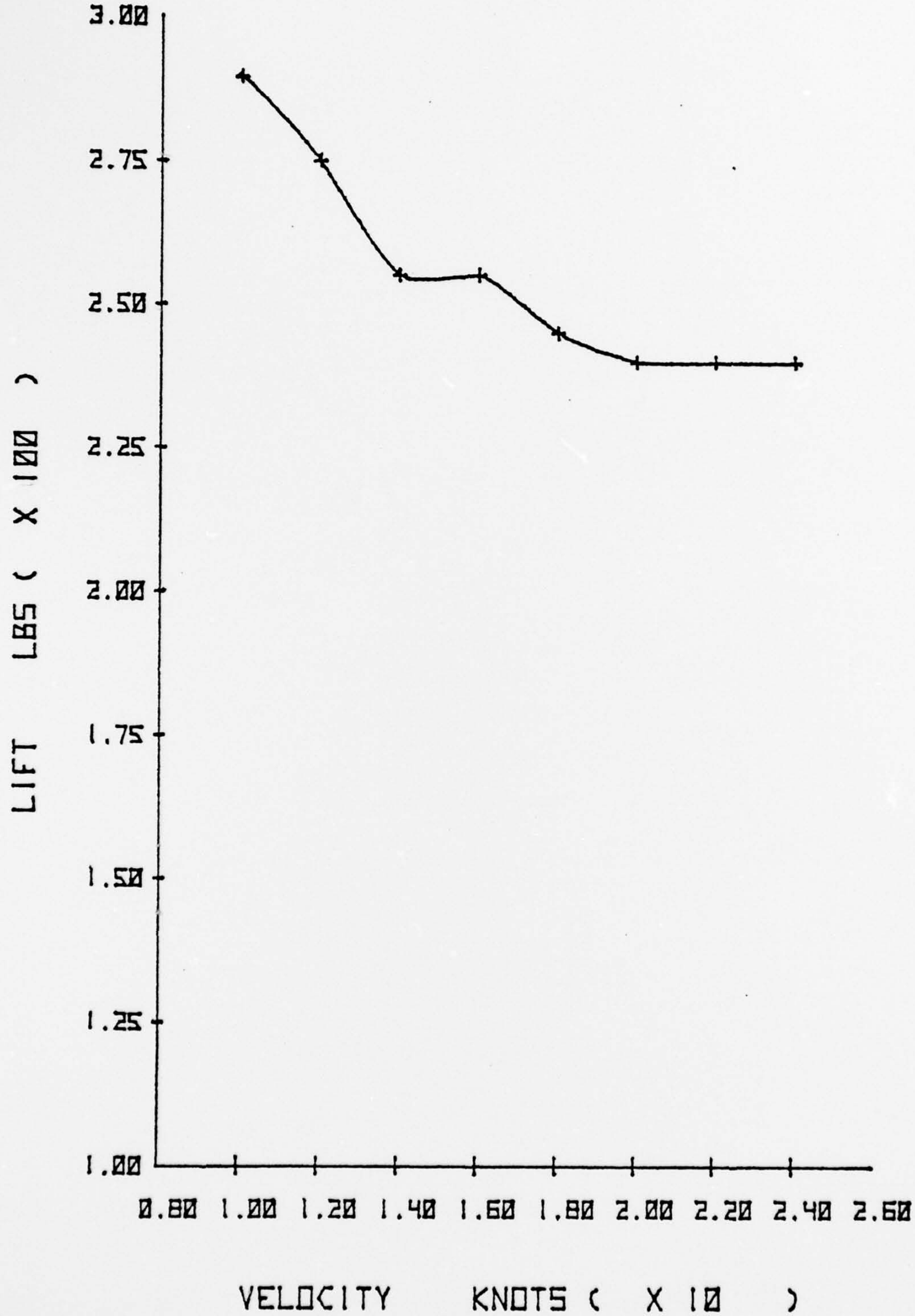

Figure 24. LIFT VS VELOCITY - BOW SEAL SHAPE 9950

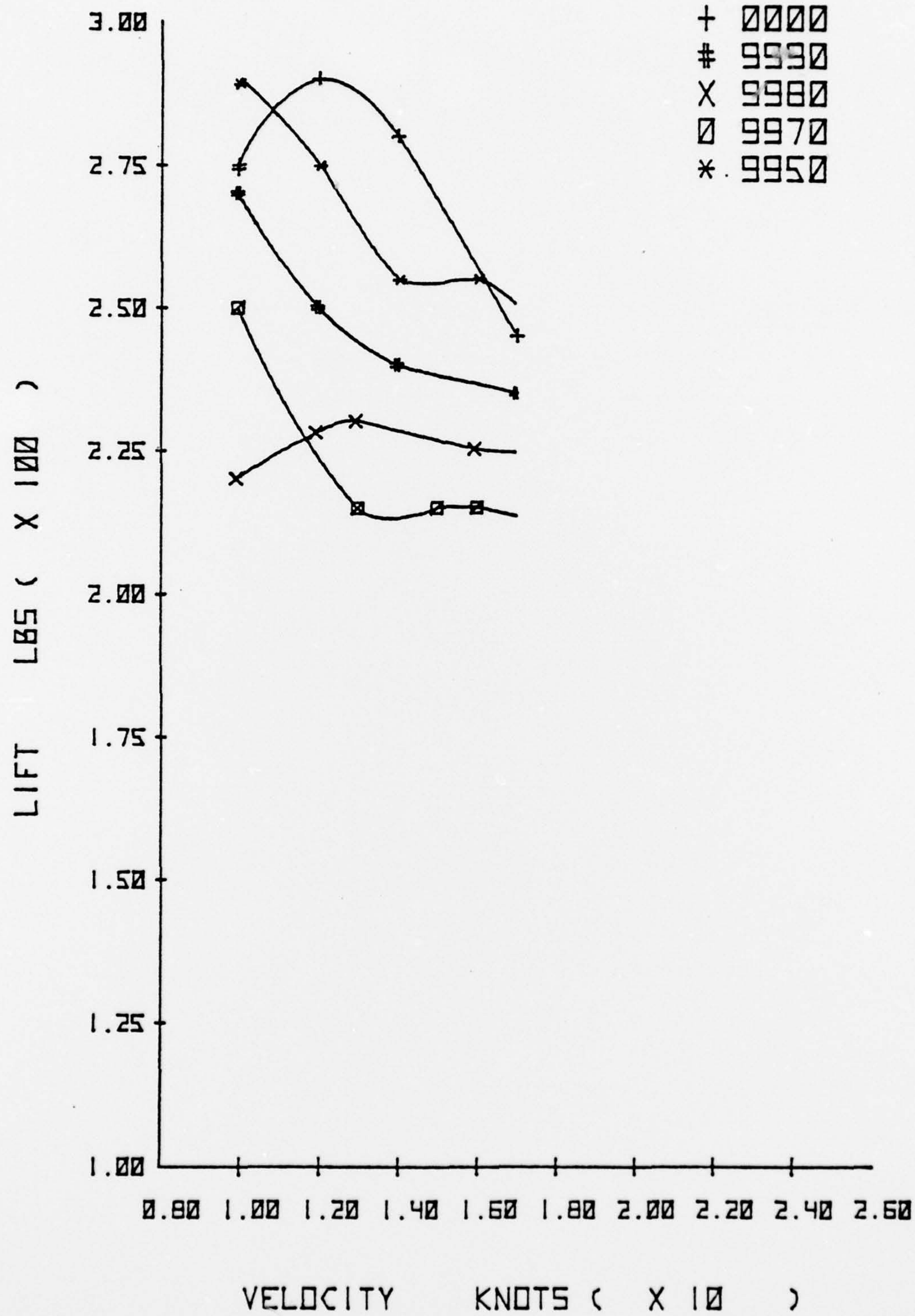

Figure 25. SUMMARY OF LIFT VS VELOCITY BELOW 17 KNOTS

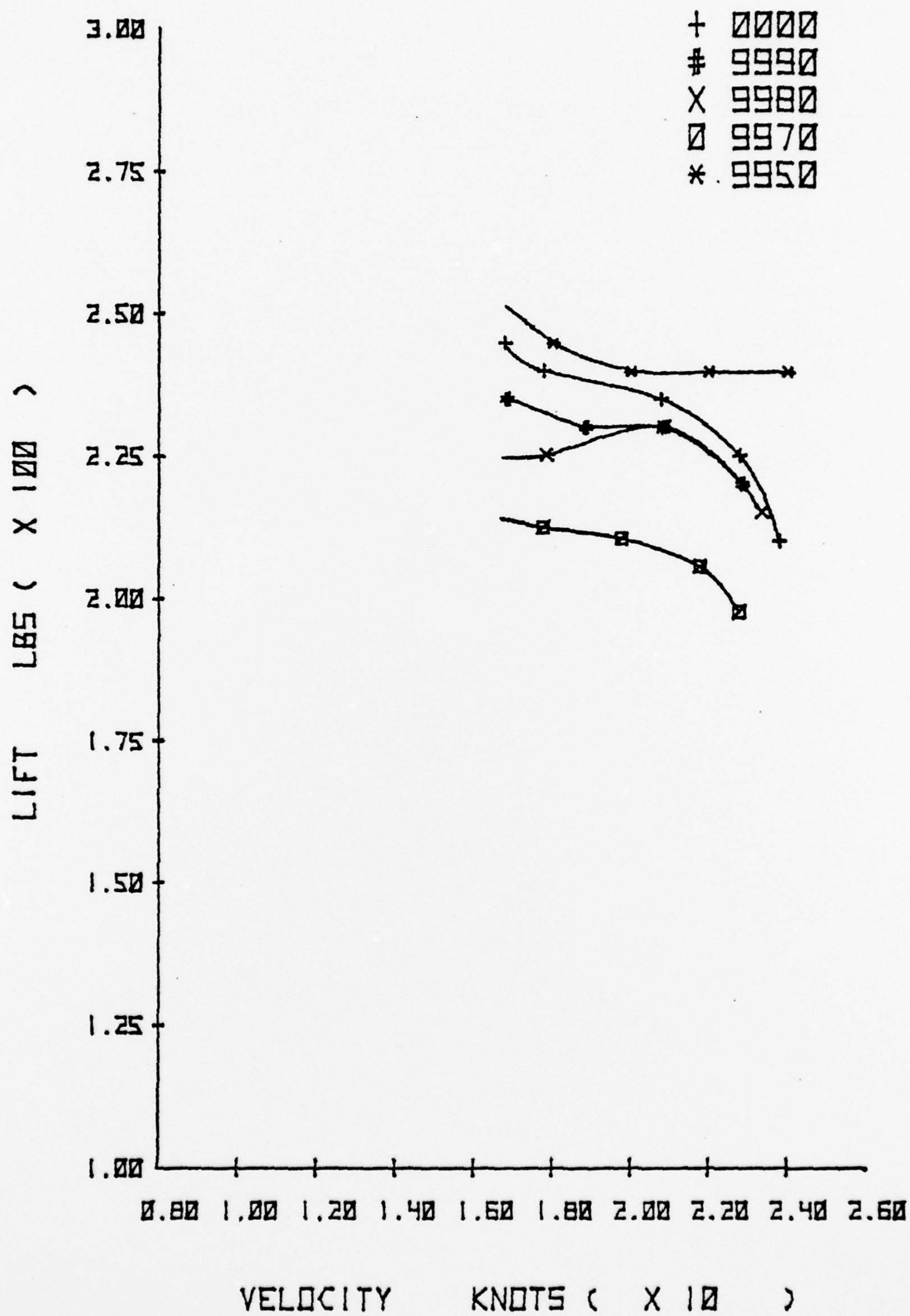

Figure 26. SUMMARY OF LIFT VS VELOCITY ABOVE 17 KNOTS

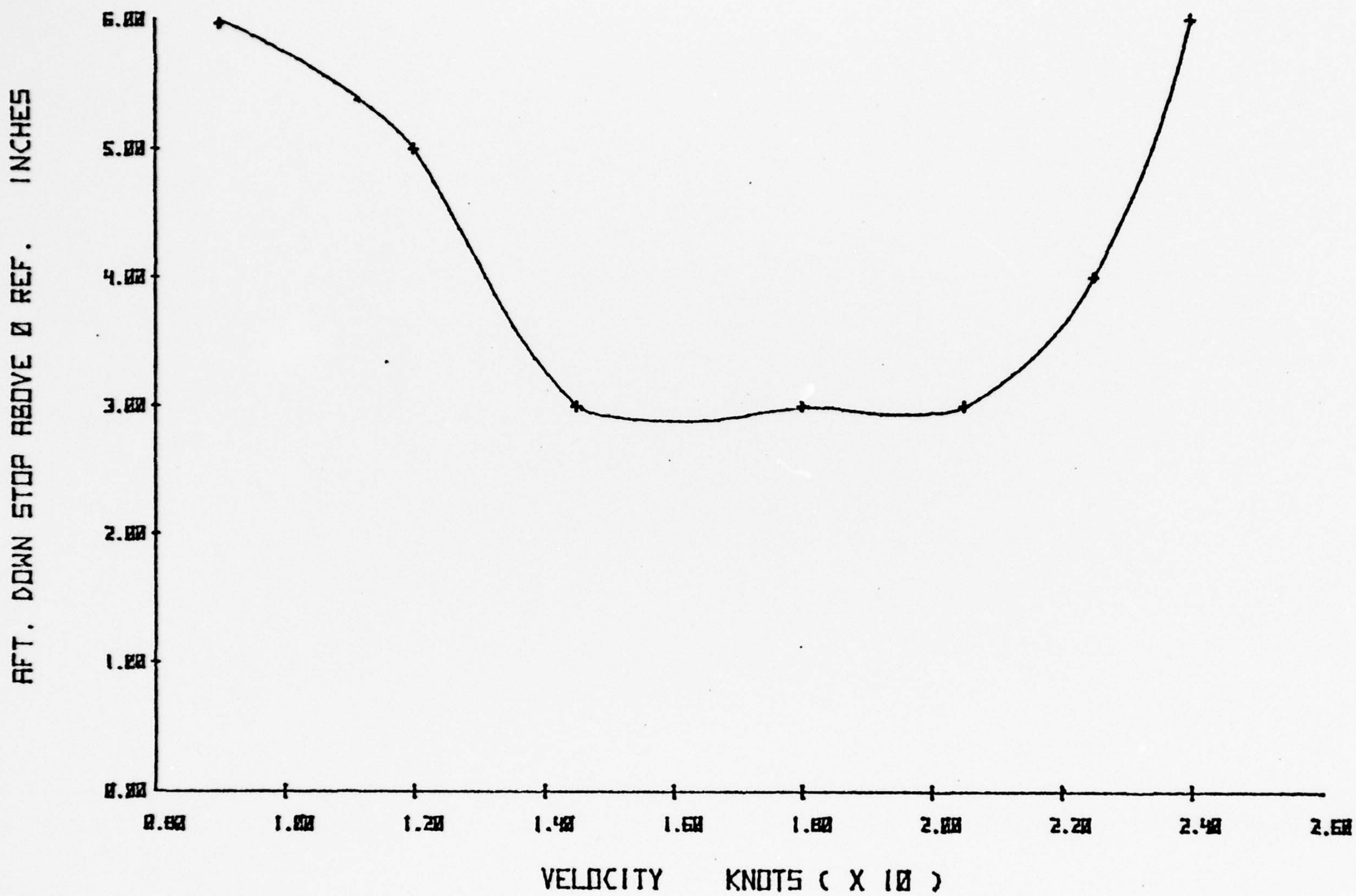

Figure 27. BOW SEAL AFT. DOWN STOP POSITION VS VELOCITY

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