THE DESIGN AND DEVELOPMENT OF A MAN-POWERED HYDROFOIL

by

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Abstract

Structures which support water vehicles can typically be classified as either surface-piercing displacement hulls, submerged streamlined bodies of revolution (torpedoes), or hydrofoils. Most contemporary human-powered vessels employ efficient displacement hulls, but faster water vehicles with less drag and greater agility can be developed with hydrofoils.

Hydrofoil stability is a problem and several wing configurations are commonly employed to render the craft more stable; however, as craft stability is improved drag increases.

A hydrofoil composed of three V-foils and driven by a pedal-powered propeller was developed and partially constructed in this project. The craft was designed to have a take-off speed of 2.7 m/sec. and a maximum speed of 4 m/sec. (9 mph).

Faster hydrofoils which can attain speeds up to 7 m/sec. (15.7 mph) are probably possible with a tandem submerged wing hydrofoil configuration, although it is more difficult to maintain craft stability with this design. It is recommended that a human-powered tandem submerged wing hydrofoil be developed.

Thesis Supervisor: Professor David Gordon Wilson

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I. Introduction

The design and construction of an energy-efficient, high-speed water vehicle is timely and especially important because it coincides with an age in which energy conservation as well as healthful exercise are primary public interests. A human-powered hydrofoil could be ideal for water recreation and sport, and may prove to be expedient for light duties which motor boats now perform. Driven by a pedal-powered propeller, the craft will run quietly and pollution-free, and should be potentially the fastest human-powered water-craft. Such a vehicle must incorporate the most efficient designs in all aspects of its configuration.

The speed and ease with which a water-craft travels through the water is dependent upon two constraints: 1) the available propulsion power, and 2) the drag of the vessel in the water (its resistance to forward motion). The effective design of a high-speed water-craft must maximize propulsion by the optimal use of available power. Equally important to the craft's design is an efficiently engineered hull, foil, or other vessel support structure which minimizes vessel drag, provides stability and seaworthiness, and enhances maneuverability.

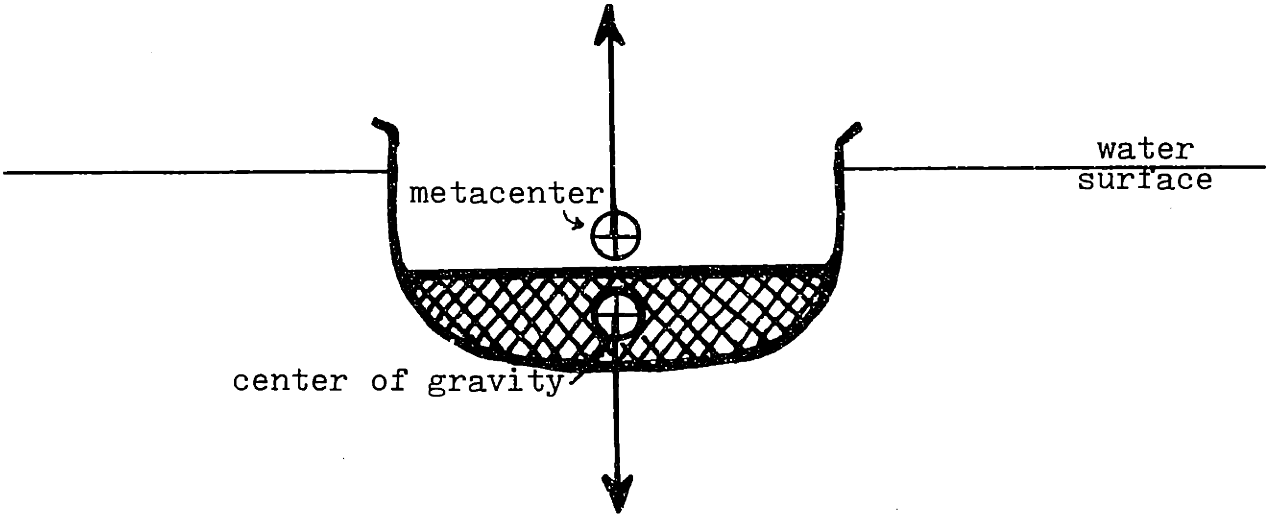
Hydrofoil configurations, equipped with pedal-powered propellers, optimize these constraints and seem to be superior to all other human-powered vessel designs for low drag and high maneuverability. Hydrofoil stability, however, often requires a relatively complex control system.

A. Available approaches and review of previous work

1. Structure and support. Vessels are supported in water by static displacement (buoyancy) or dynamic lift, and the supporting elements may be either submerged or surface-piercing. A direct result of vessel-supporting elements is drag, which is the sum of a number of components, including skin friction, pressure drag, parasitic drag, wave drag (the vessel's propensity to make waves), and possibly induced foil drag, each of which is of varying importance depending upon the type of ship support employed.

A second result of the vessel-supporting system is the stability, seaworthiness, and maneuverability of the ship. Stability in yielding water is a complex three-dimensional concern, and important to the basic stability of any water-going vessel is that the system's metacenter is above its center of gravity (Figure 1). Inherent instability is typical of vessels supported by submerged structures because this criterion is usually not met, and often unwieldy out-rigging supports are necessary which render the craft less efficient and less maneuverable than surface-piercing configurations. Many times, however, an active stabilizing system, similar to those used in bicycles, can be employed with submerged support vessels and it affords not only good stability, but excellent maneuverability.

a.) STABLE



b.) UNSTABLE

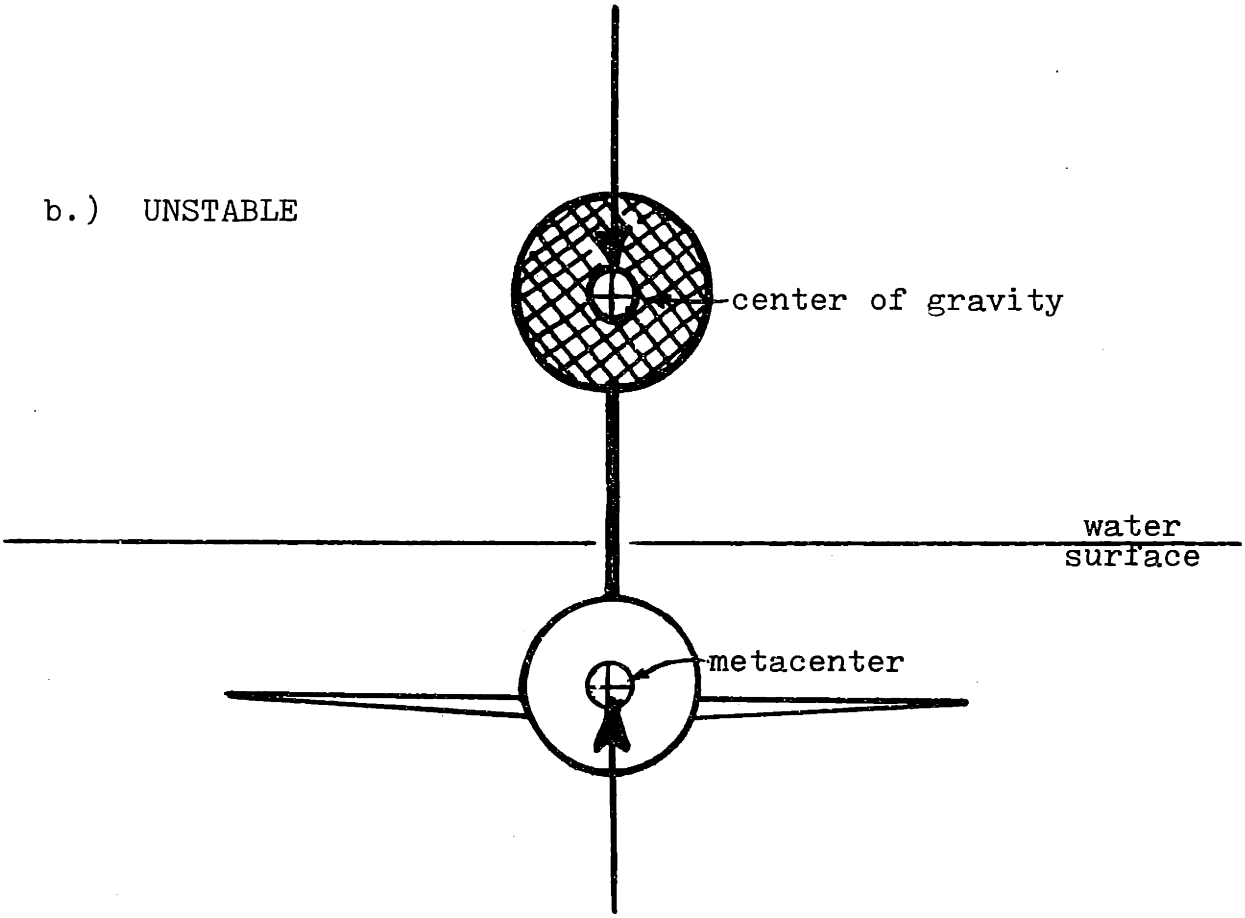


FIGURE 1. STABLE AND UNSTABLE VESSEL SUPPORT CONFIGURATIONS.

a. Shells. Shells are perhaps the most efficient form of familiar surface-piercing hulls which support vessels in the water by static displacement. The total drag as a function of velocity for a shell displacing 100 kg is compared to other similarly scaled vessel-support options in Figure 2. The main components of the significant shell drag are skin friction over its large wetted surface area and wave drag, a major problem of all surface-piercing configurations.

Shells are typified by length-to-beam ratios of 30 (extreme) and length-to-draught ratios of 108 (amidships) (Wellicome, 1964). These dimensions make the shell relatively unmaneuverable. When fully loaded, the shell system provides a relatively low center of gravity which enables the shell oars to render the craft stable.

Shells have proven to be the most popular vessel support structures for human-powered watercycles. A review of previous work done on pedal-powered water-craft is available in Bicycling Science (Whitt and Wilson, 1974).

b. Torpedoes. Torpedoes represent a submerged displacement system of vessel support and are superior to surface-piercing shells because they incur no wave drag if located three or more diameters below the water surface (Byquist, 1973; Hoerner, 1958). As with the shell, however, torpedo drag (Figure 2) is proportionate to the structure's displaced water volume raised to the 2/3 power. The major

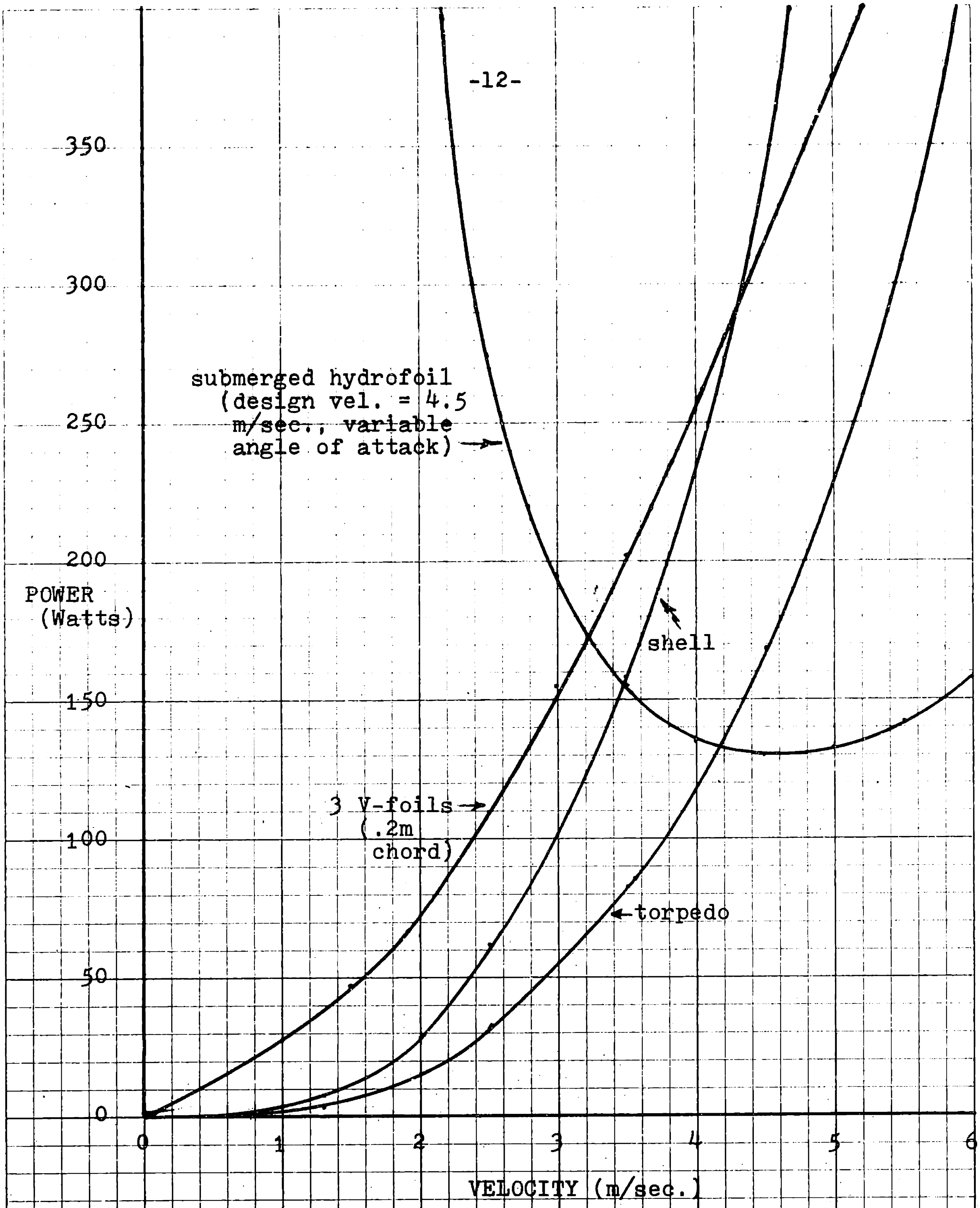


FIGURE 2. COMPARISON OF THE SPEED-VARYING POWER REQUIREMENTS FOR FOUR DIFFERENT VESSEL SUPPORT STRUCTURES.

Each structure supports 100 kg. (Note: the area of the three variable area V-foils extends to infinity at 0 m/sec. At 2.5 m/sec., wing span of each V-foil is 2.6 m.)

components of torpedo drag are skin friction and pressure drag, caused by flow separation towards the rear of the torpedo. This drag can be reduced if the propeller that drives the craft is located at the end point of the torpedo. This will induce flow which will energize the torpedo's boundary layer and should delay flow separation and reduce drag. Length-to-diameter ratios for torpedos can range from 5 to 10 for optimal performance (Pannell and Campbell, 1917; Pannell and Jones, 1919; Ower and Hutton, 1924; Ower and Hutton, 1931).

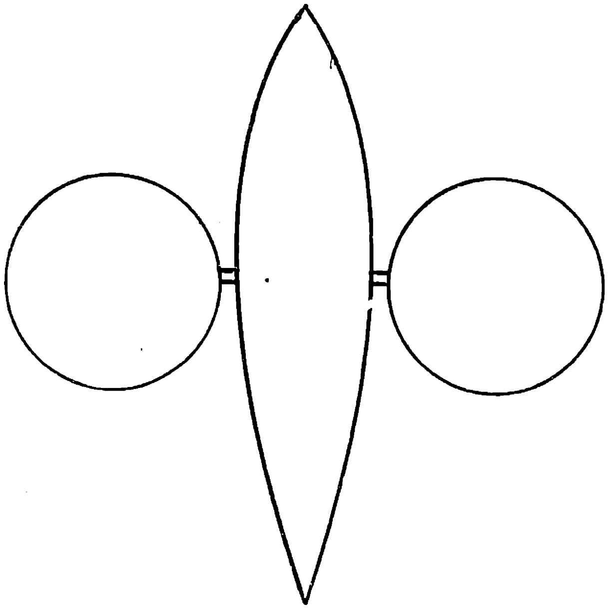
Unlke hull or shell design where the craft's displacement is negotiable and will naturally adjust to equal the load, torpedo displacement is fixed and represents a constant buoyancy force. This disadvantage requires the torpedo design to include lift or variable displacement devices in its configuration in order to accommodate various variable loads and forces confronted in the operation of the craft. Such forces arise from accelerations encountered in starting, stopping, turning, pitching, rolling, heaving, and wave crashing.

A second disadvantage of the torpedo is that the deeply submerged buoyancy, designed to escape wave drag, results in a metacenter located below the craft's center of gravity with long torque arms separating the two. The ensuing highly unstable configuration must be secured by countering the unstabilizing moments with additional properly placed displacement or lift devices, or they may be countered with an active control and stabilizing system similar to that of a bicycle.

Utilizing a front rudder to enable the vessel to turn into a fall in much the same way a bicycle's front wheel works, an active stability system would require extra buoyant rudder appendages and may not be effective because of the torpedo's resistance to quick and variable movements which would be required in such a design.

Additional lift or displacement elements which must be designed onto the torpedo increase the configuration's drag. For drag efficiency and to save weight, it is advantageous to generate the required stabilizing moments with small lift and buoyancy structures located at a distance from the vessel rather than by using large support structures adjacent to the craft (Figure 3). Extended over long torque arms, the small additional support devices will provide the same correcting moments as the close-by large ones, but they require less lift or buoyant force and will generate less drag in that they displace and disturb less water. These extended supports significantly inhibit the vessel's agility and make it unwieldly, limiting the usefulness of the craft.

It is also important in the design of a torpedo configuration to determine distribution of buoyancy between the torpedo and its additional support devices. If the a.) HIGH DRAG



b.) LOW DRAG

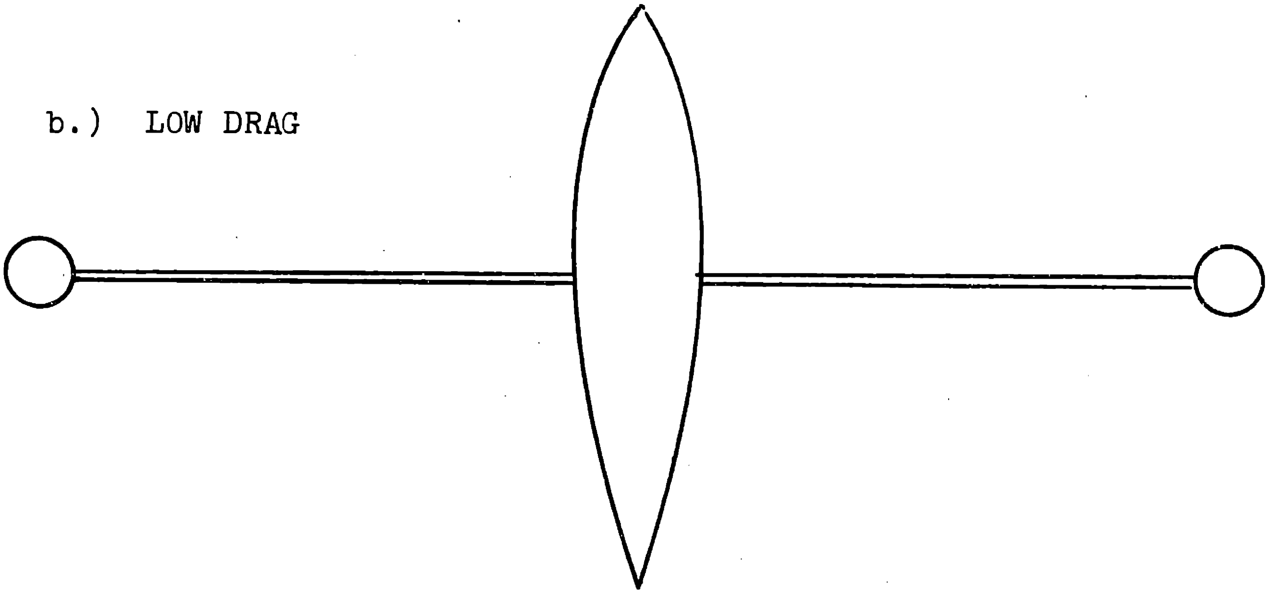


FIGURE 3. CONFIGURATIONS OF STABILIZING APPENDAGES FOR TORPEDOES. Both configurations provide the same stability.

torpedo supports almost all of the vessel and the extra structures provide only minimal lift buoyancy (a high 'buoyancy ratio') the torpedo craft will be more drag efficient but less stable. If a low buoyancy ratio formula is employed, where the supplementary devices incur greater support responsibility, the vessel will generate more drag but will be better behaved.

Figure 4 compares the power requirements as a function of speed for an assortment of various lifting surfaces and displacement structures. The devices are all sized to support 20 kg. The information on this graph can be used with the data of Figure 2 or other figures to determine the speed-varying power requirements of a desired configuration which combines various support structures and devices. Figure 5 shows the power required for a craft which combines a 0.08 m^3 displacement torpedo and two 0.01 m^3 verticle surface-piercing foils.

In practical application, the torpedo craft becomes a complex, although somewhat maneuverable vessel. Depending upon the variable displacement or lift devices used to stabilize the torpedoed craft, the losses incurred with these stabilizing appendages often outweigh the advantage of zero wave drag.

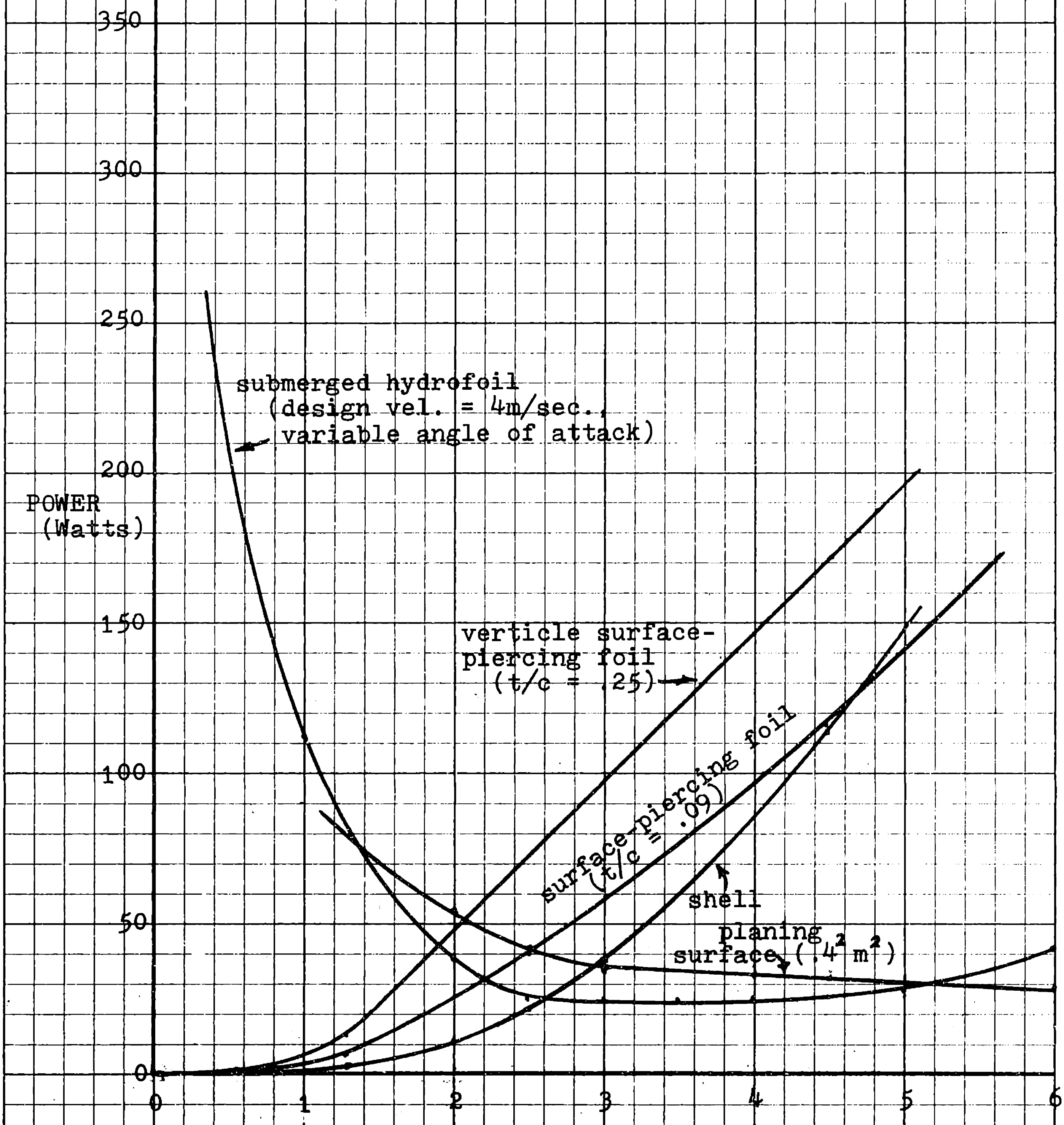


FIGURE 4. COMPARISON OF THE SPEED-VARYING POWER REQUIREMENTS FOR AN ASSORTMENT OF VARIOUS SUPPLEMENTARY SUPPORT STRUCTURES. Each structure supports 20 kg.

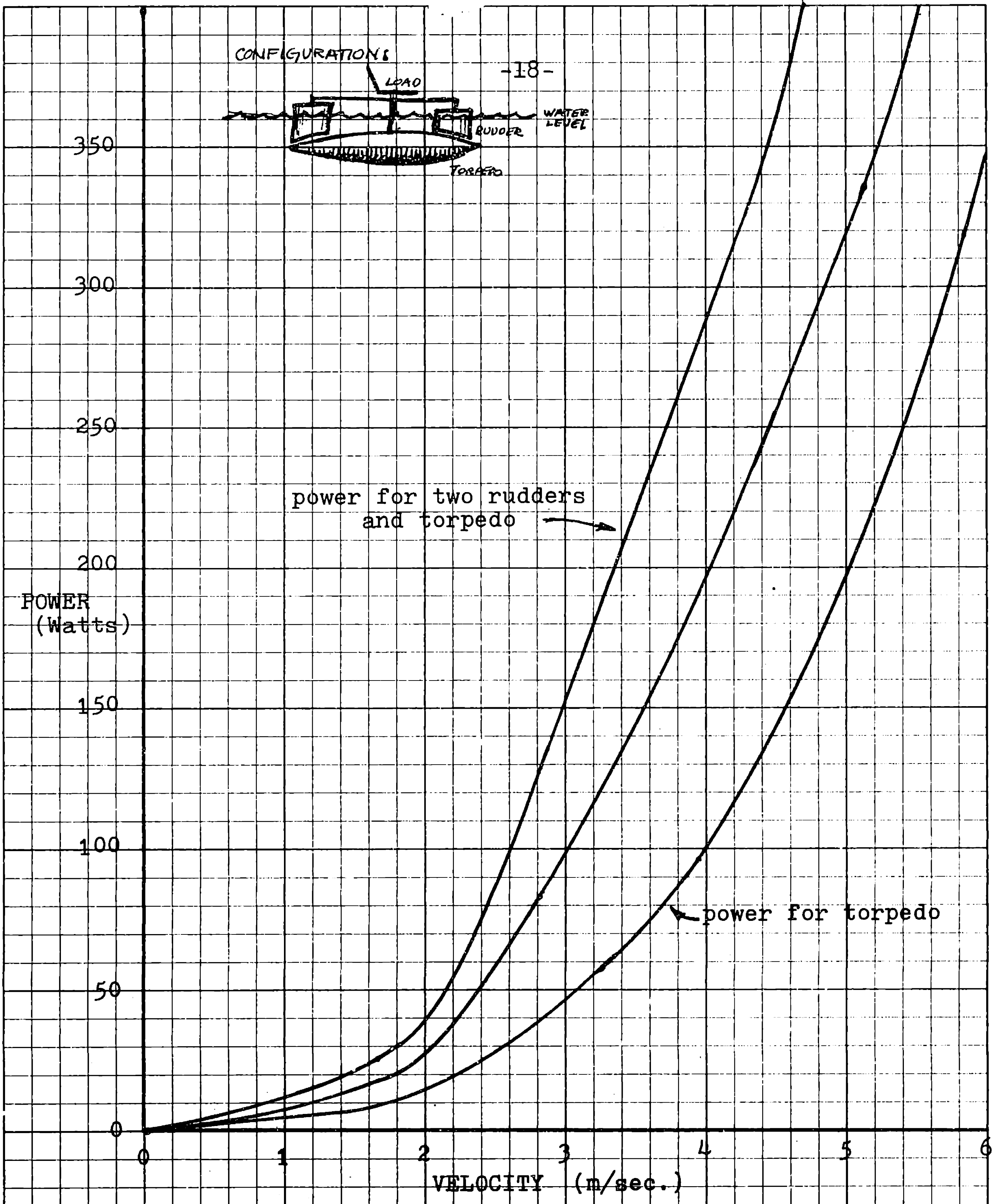


FIGURE 5. POWER VERSES VELOCITY FOR A CRAFT COMPOSED OF A TORPEDO AND TWO STABILIZING RUDDERS.

The torpedo supports 80 kg. and each rudder supports 10 kg. The craft would utilize an active bicycle-like stability system in addition.

c. Hydrofoils. Unlike the constant buoyancy force supplied by a submerged torpedo, hydrofoils are able to provide a changeable lifting force to support the craft as it incurs accelerations or load changes. The support force of a submerged lifting surface is a function of the vessel's velocity, the foil's surface area, and its angle of attack (which affects the wing's lift coefficient). The lifting forces necessary for the control and support of the craft may be generated at various cruise velocities by adjusting these latter two components.

To supply the necessary force for craft support at slow speeds, large wing areas and high angles of foil attack are required, each of which induces high drag forces. Small foil areas and low angles of attack, a combination resulting in low drag, are sufficient to generate the needed lift at high velocities. The use of hydrofoils is most effective, then, when employed with another support system, such as a shell, which would supply all of the buoyancy for the craft at zero velocity.

As vessel speed increases, the lifting force of the foils grows rapidly, causing the shell to rise off the water surface and serve no further function until the craft slowed again or "landed". The combination shell and foil configuration is ideal because it capitalizes upon the efficient operation of submerged wings designed for high speeds but avoids their forbiddingly high drag (when used to provide the total required lift) at low velocities.

Drag resulting from hydrofoils is the sum of four components: parasitic drag, profile drag, wave drag, and induced drag (Buermann, Leehey, and Stillwell, 1953). Parasitic drag, common also to other vessel-support structures, is due to shafts, struts, and guy wires breaking the water surface and creating spray and small waves. This factor can usually be neglected when compared to the other components.

Profile drag is a combination of the wing's skin friction and pressure drag. Measured by their drag coefficients, the planform shape of a submerged foil is about one-half as efficient as that of a shell or streamlined torpedo; however, the wetted surface areas of these buoyant displacement structures is ten times the required area for a foil providing an equal lift and the result is that the profile drag of the wing is much smaller than for its competitors.

Wave drag can be eliminated by positioning foils sufficiently far below the water surface, although often this is not practical in light of operating conditions. This drag component peaks at a low Froude number and becomes negligible as speed increases.

Induced drag is a resistance force unique to lifting surfaces and is the result of the actual wing lift being non-perpendicular to the direction of vehicle travel (Figure 6). Induced drag is proportional to the angle of foil attack and is inversely related to the aspect ratio (length/chord) of the wing. This is the major reason why fixed-area, variable-angle-of-attack hydrofoils become less power intensive as velocity

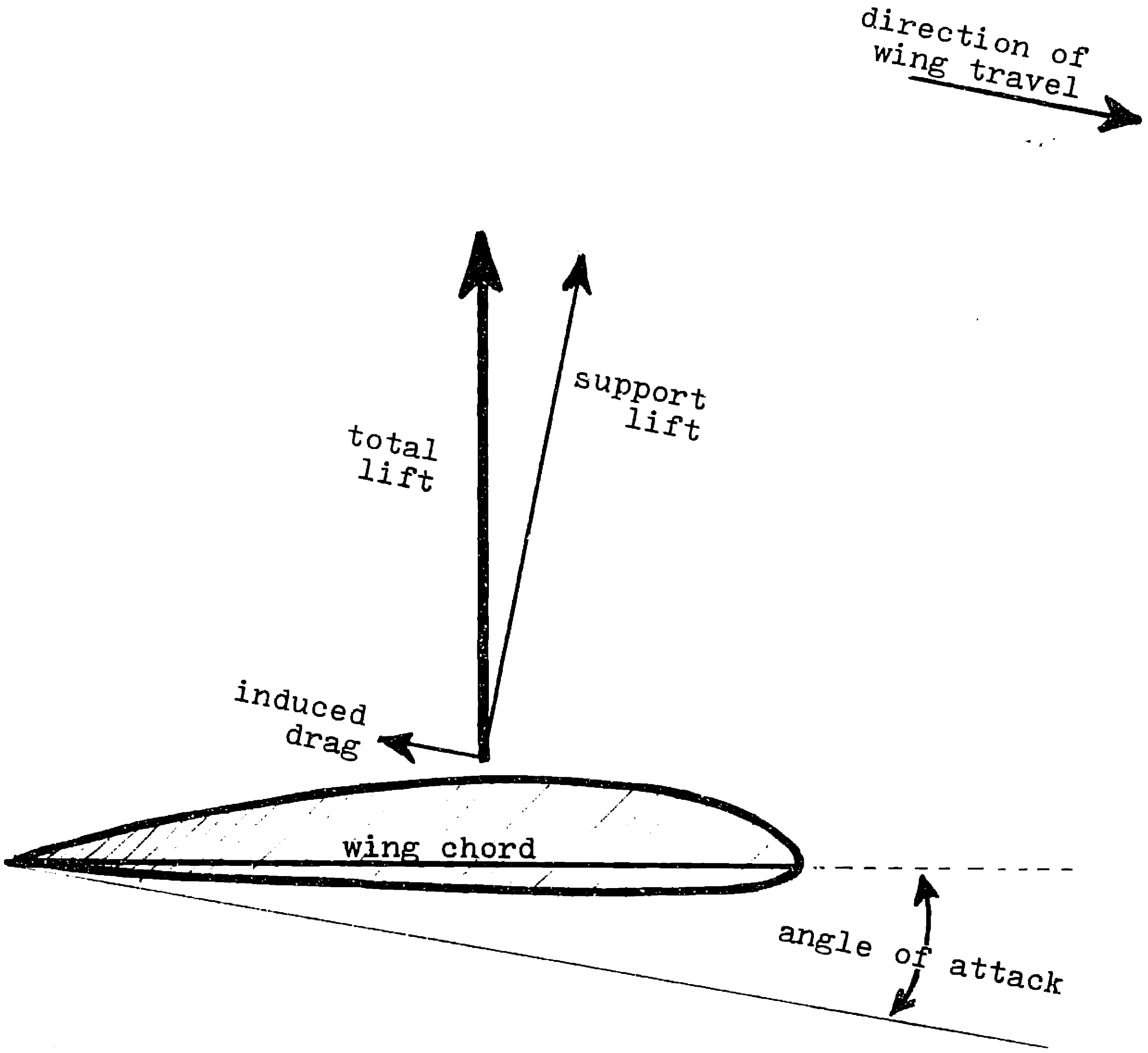


FIGURE 6. INDUCED DRAG OF A WING.

increases: angles of foil attack required to maintain constant lift grow smaller as speeds get larger, and the drag force decreases correspondingly (Figure 2).

The stability problems of hydrofoils are similar to those of the torpedo because the metacenters of these craft, on the level of the submerged lifting surfaces, is well below the vessel's center of gravity. Various foil configurations which address the stability requirements of hydrofoil craft are "tandem submerged foils, surface-piercing ladder foils, surface-piercing V-foils, and submerged after foil plus surface skids" (Buermann, Leehey, and Stillwell, 1953, pp.243-244). (Figure 7).

Self-stabilization is evident in the ladder and V-foils configurations. As the vehicle is loaded disproportionately to one side, more lifting foil area is submerged, providing additional stabilizing lift. Constant support lift is naturally maintained when velocity changes by varying submerged foil area with the craft rising or falling slightly.

Because total wing area is divided between so many wings, aspect ratios for these craft are low which results in high induced drag. This problem is aggravated as V-foils rise out of the water with increased speed because their aspect ratios grow even smaller. Induced drag will further increase with growing speed if, in order to maintain equilibrium at various speeds, the natural foil-area variation is substituted for angle-of-attack control and the angle of foil attack cannot be lessened.

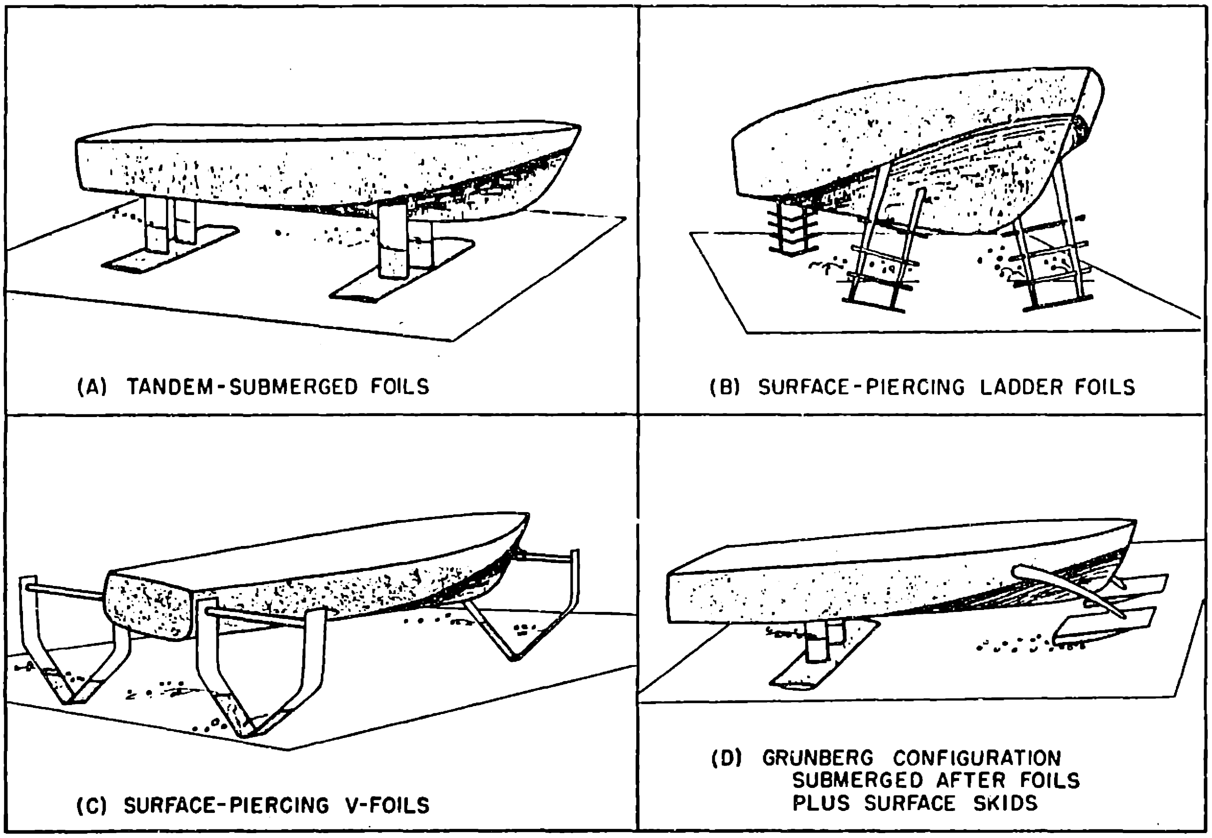


FIG. 1.—TYPICAL HYDROFOIL CONFIGURATIONS

From Buermann, Leehey, and Stillwell, 1953, p. 244. Used with permission.

FIGURE 7. FOUR KINDS OF HYDROFOIL CONFIGURATIONS.

Further unnecessary drag is characteristic of V-foils in that they have excess submerged area which contributes only to the craft's drag and not to its lift. Only the wing area projected onto the water surface (Figure 8) contributes to the lift. For a right-angled V-foil, 30 percent of the submerged foil area generates drag with no contribution to lift.

Tandem submerged foils may have the advantages of large aspect ratios, variable angle of attack, and small wing areas, but control and stability of these craft is a very complex problem.

The respective power requirements for a fixed angle-of-attack V-foil configuration and a tandem submerged foil design, each providing 980 newtons of lift (supporting 100 kg), are compared as a function of velocity in Figure 2. Although the control and stability system for the submerged foil is very complex, its advantages in terms of reduced drag and increased speed are obvious. These advantages are primarily due to: 1) the large aspect ratio (which also lends stability) available with a submerged foil configuration, and 2) the ability of the fixed-area submerged foil to decrease its angle of attack with increasing speed. The submerged foil has no parasitic drag because it does not pierce the water surface, and wave drag is reduced since the wings have a lower mean submergence than the V-foils. Further, the submerged wings are flat and do not have the excess foil area and the resulting excess drag of the V-foils.

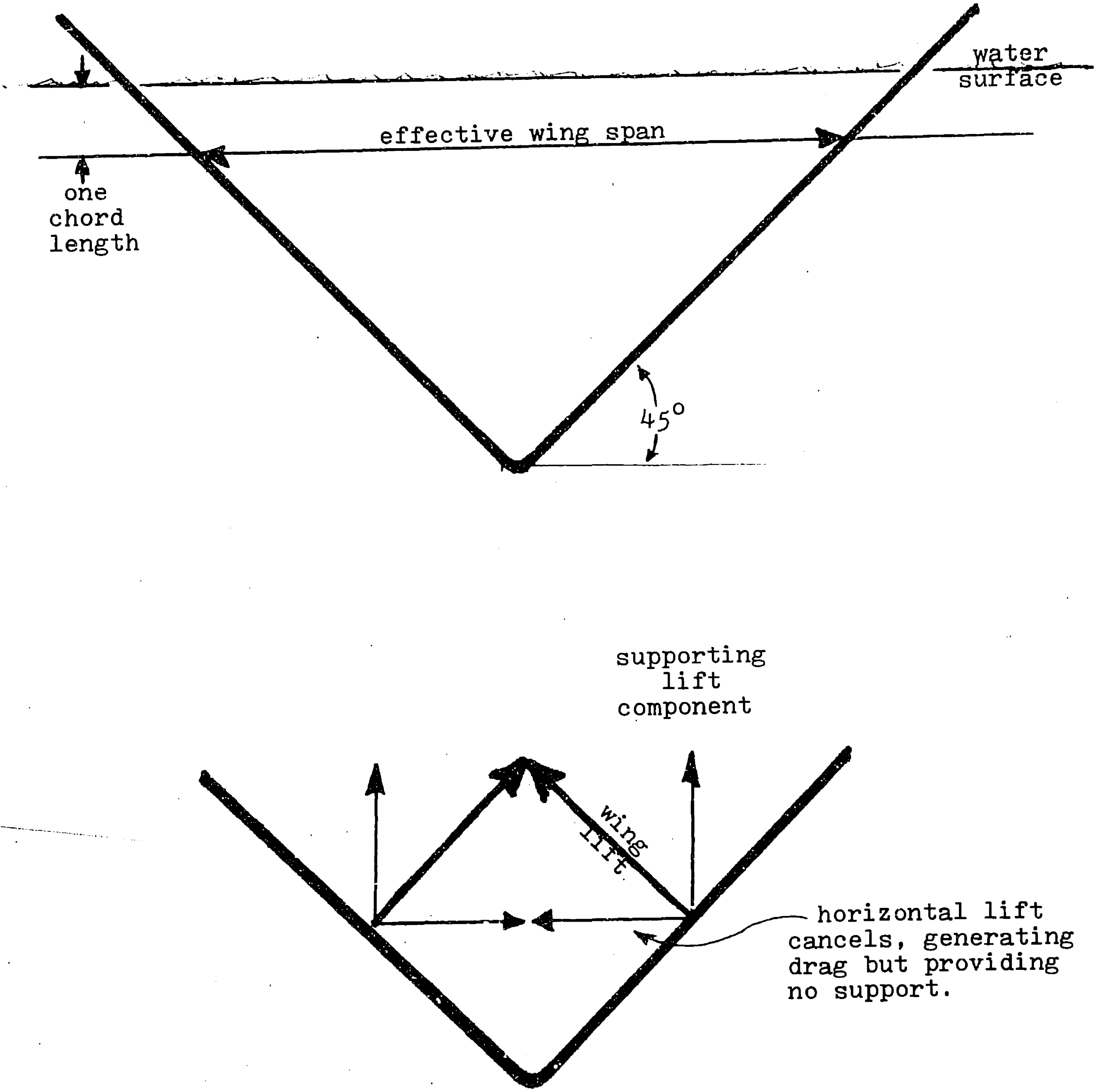


FIGURE 8. V-FOIL GEOMETRY AND LIFT COMPONENTS.

An excellent review of contemporary commercial hydrofoil vessels can be found in Jane's Surface Skimmers: Hovercraft and Hydrofoils 1978 (McLeavy, editor, 1978).

In general, those vessels which least disturb the water surface generate the lowest drag and are able to attain the highest speeds. Relative to this, there is also an overall connection between stability and drag, such that the most stable configuration produces the greatest drag.

From Figure 2 comparisons are easy. The loaded shell system has relatively high drag, high stability (with oars or in pairs), and low maneuverability. Torpedoes are characterized by medium drag, low stability, and are presumably moderately maneuverable. Hydrofoils may range between medium and low stability, moderate and high maneuverability and potentially have very low drag.

2. Propulsion. It is essential to the operation of any vessel that it overcome the resistive forces opposing its supporting structure in order to propel itself through the water. Power must be utilized effectively and efficiently with minimal losses from source to delivery in order to attain maximum speed. This is more and more important as the power available becomes smaller and more limited as with human-powered machines.

The power available for propelling a human-powered craft through the water is limited to the maximum power output of a single human being. With the efficient use of proper muscles in pedaling or forced rowing motions, this output can exceed 373 watts (0.5hp) for a limited duration (Whitt and Wilson, 1974).

To utilize this power source, oars, paddle wheels, and propellers are options.

Although they have a low propulsion efficiency, paddle wheels are convenient because they rotate in the same plane as leg pedaling, thereby facilitating a simple transmission. They are difficult for use on hydrofoils in that a complex system would have to be developed to insure their continued contact with the water as the craft rose and fell.

Rowing enables a low system center of gravity to be used which increases stability and is therefore advantageous over pedaling. Oar work is a discontinuous method of power delivery, however, and massive body parts must wastefully accelerate and deaccelerate for each stroke. Rowing suffers the same delivery problem as the paddle wheel.

Pedallers should be located above the pedals for comfort and efficiency in power delivery. This consideration requires a pedal-powered propeller system to have a relatively high, unstable center of gravity (the pedaller).

The configuration would also necessitate a transmission which could twist the rotary pedaling motion 90° to the plane of the propeller. By using a drive shaft, however, propellers can deliver power continuously regardless of the hydrofoil's operating position. Most important, the propeller is the most efficient propulsion device of the three alternatives.

"According to the <u>Dictionary of Applied Physics</u> (Glazebrook, 1922), screw propellers, paddle wheels, and oars can all be designed and used to give an applied power efficiency of up to about 70 percent," but "screw propellers have been able to exceed paddle wheels in efficiency by a considerable margin...the figure of 70 percent for all three devices must be considered to be a rough approximation, because an optimized screw propeller can perform at a much higher figure." (Whitt and Wilson, 1974, p. 206).

B. Present Approach

The approach of this project placed importance on design simplicity and ease of construction. Sacrificing speed, a somewhat stable support structure was decided upon at the cost of drag efficiency in order to avoid complicated control and stability requirements.

A three-point V-foil configuration was chosen because the design would attain high speeds and yet require a stability system within our available resources. Propulsion would be provided by a pedal-powered propeller.

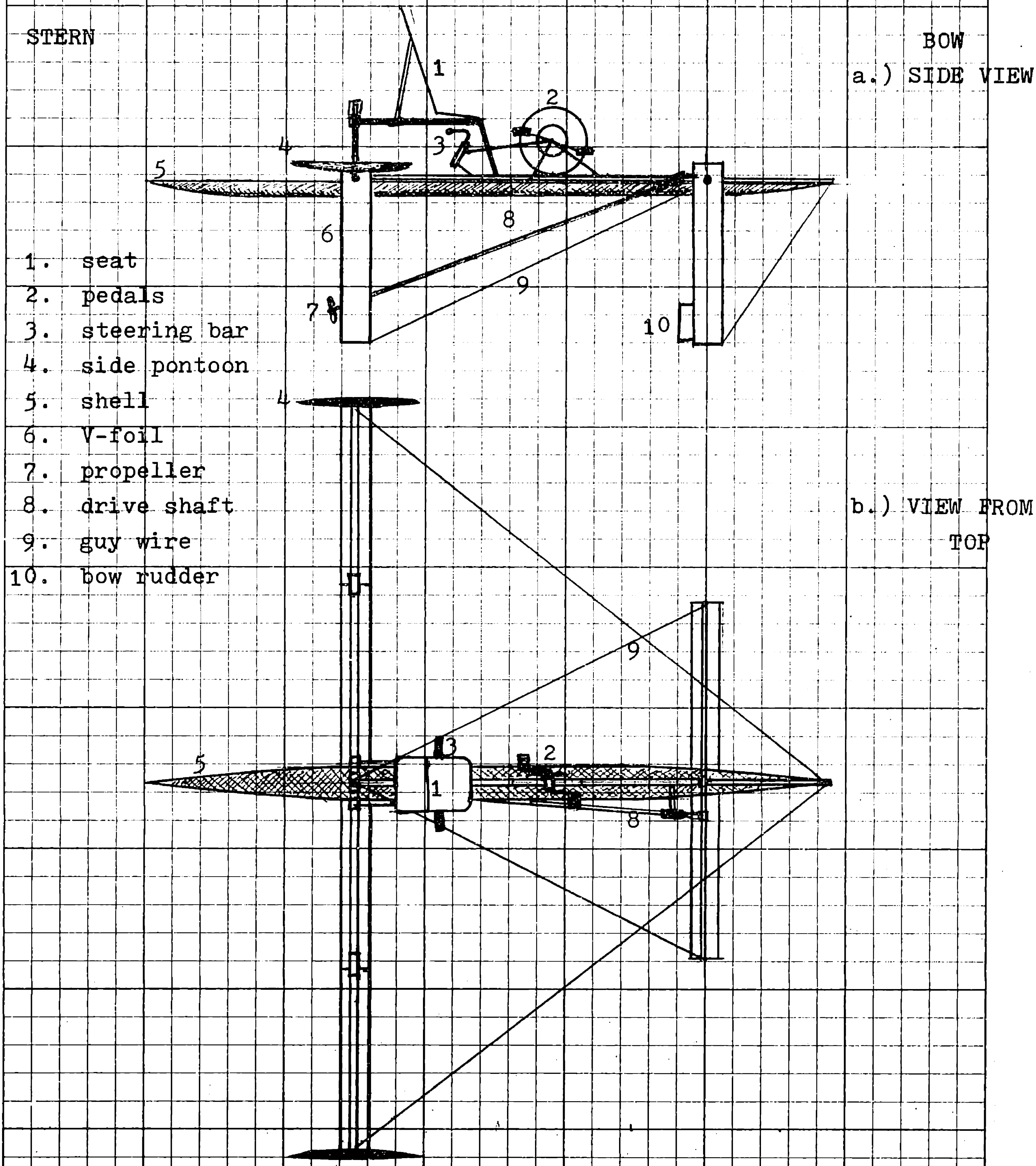
II. Design

The design of the hydrofoil attempted to optimize the craft's speed, stability and maneuverability within imposed constraints. The power available for propulsion was constrained to 373 watts (0.5 hp). To reduce required lift and resulting drag, the combined weight of the vessel and operator must be minimized and, for design purposes, was limited to 100 kg. This proved to be a very accurate estimation. Size was restricted as much as possible to render the hydrofoil more useful and maneuverable. Ease and speed of practical construction were important considerations.

A. Configuration

The designed hydrofoil is illustrated in Figure 9. The configuration is composed of three V-foils centered on a light weight shell which provides craft support at low velocities. Outriggers are located at the outer tips of the rear V-foils in order to lend stability to the vessel at slow speeds before take-off. The three-point foil configuration maintains stability after take-off and permits maneuverability. Steering is accomplished by turning the front bow rudder.

The seat and pedal arrangement is designed for comfort and efficient power delivery and, to aid stability, is located as low as possible. Because the major load of the system is the operator, the seat is situated at the center of lift. The propeller is positioned between the two stern



1. seat
2. pedals
3. steering bar
4. side pontoon
5. shell
6. V-foil
7. propeller
8. drive shaft
9. guy wire
10. bow rudder

FIGURE 9. THE DESIGNED HYDROFOIL OF THIS PROJECT.

V-foils and is powered by a surface-piercing drive shaft which connects to the pedals by a twisting drive belt.

B. Wings

1. V-foils. Right-angled V-foils were chosen for the hydrofoil's lifting surfaces chiefly because of their self-stabilizing action. V-foils require no surface-piercing parasitic support struts inasmuch as the wings proceed directly out of the water and avoid submerged-end effects. Although fixed-angle-of-attack V-foils cannot lessen their attack angle to decrease induced drag, neither can they increase their angle of attack to increase their induced drag, which is required with fixed-area foils in order to maintain lift. V-foils "have proved to be one of the lowest-drag configurations and should be considered wherever speed and simplicity are important." (Buermann, Leehey, and Stillwell, 1953, p. 256)

Relatively high parasitic drag is generated by the six large wing sections piercing the surface. Support struts would be much smaller and incur less drag. A second disadvantage of V-foils is that the required wing surface area is divided between three sections and therefore the resulting foil aspect ratios are low. This increases the induced drag. The most important drawback of the right-angled V-foils is that only 70 percent of the submerged area produces lift useful for vessel support. The remaining wing area generates useless horizontal lift and drag forces (Figure 8).

For simplicity, the V-foil angle of attack for our hydrofoil was designed to be unchangeable. The angle of attack could be corrected slightly for trim by adjusting guy wires, but constant lift would be maintained at various speeds by variable area alone. An angle-of-attack and lift coefficient which would be optimal over a range of speeds was determined as follows in the next section.

2. Cross-section shapes of wings. The drag and lift characteristics of a wing are determined by its planform area and its cross-section shape. Profile drag is directly related to the projected form and area of the foil in the water stream and it changes with the angle of wing attack. Induced and wave drags are dependent upon the wing area and upon the lift coefficient of the foil which is a result of the wing's cross-section shape and its angle of attack.

The lift provided by a wing is a product of the wing area, relative dynamic pressure, and its lift coefficient. In hydrofoil application, constant lift, regardless of speed, must be maintained to support the craft and this lift can be developed by a variety of lift coefficient and wing area combinations. This variety of combinations will also result in a range of various consequent drags. It is advantageous to determine the wing-area/lift-coefficient combination which produces the required lift and generates the least drag.

Figures 10 and 11 illustrate the variation in total drag as the area and lift coefficient of three V-foil wings are

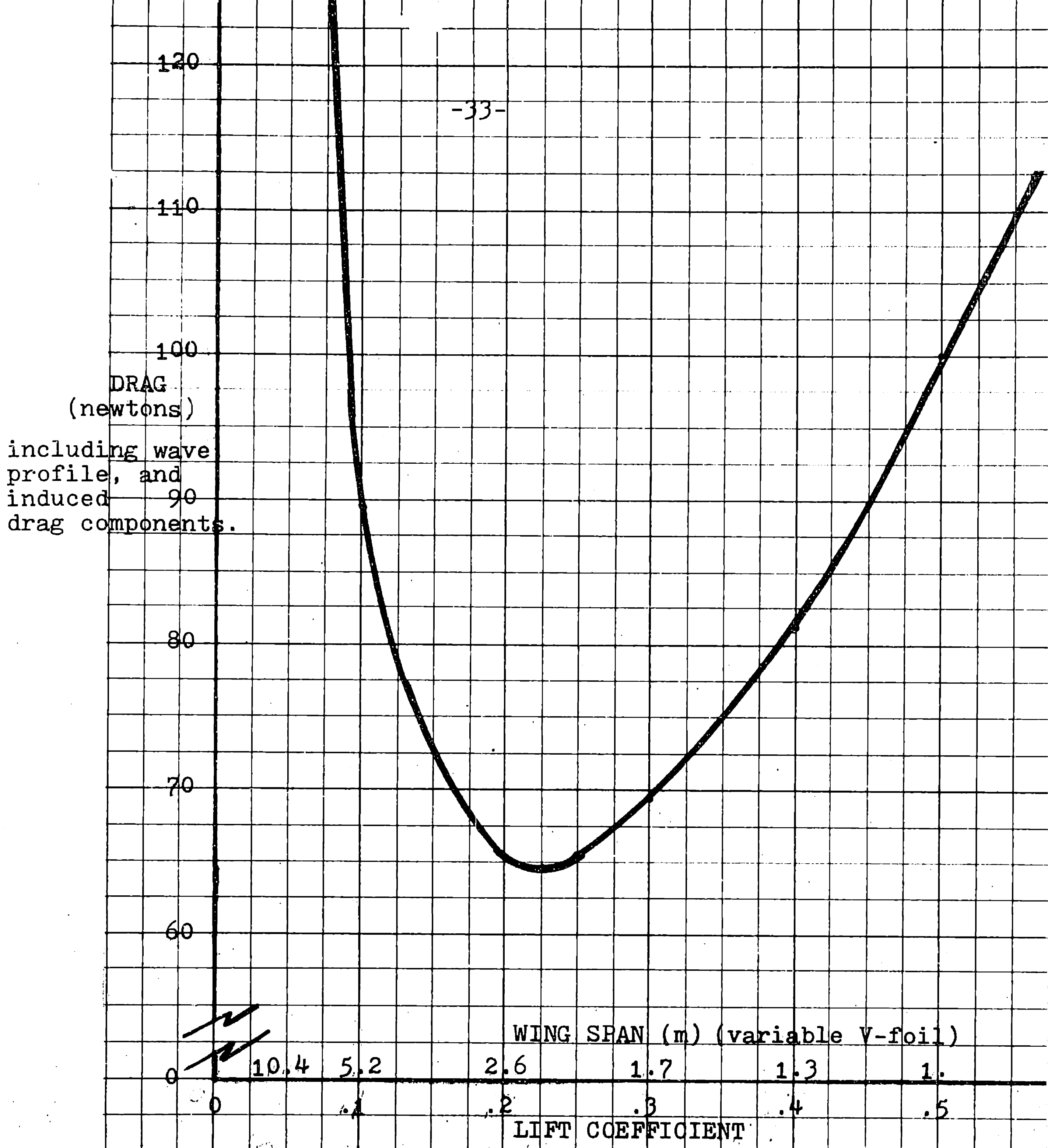


FIGURE 10. VARIATION IN THE TOTAL DRAG OF A WING PROVIDING CONSTANT LIFT WITH DIFFERENT AREA/LIFT COEFFICIENT COMBINATIONS.

Wing presented here is a V-foil with an average profile drag coefficient of .0058. Velocity is constant at 2.5 m/sec. Wing provides a constant lift of 327 newtons. Drag totals are for three wings (resulting in 980 newtons of constant lift).

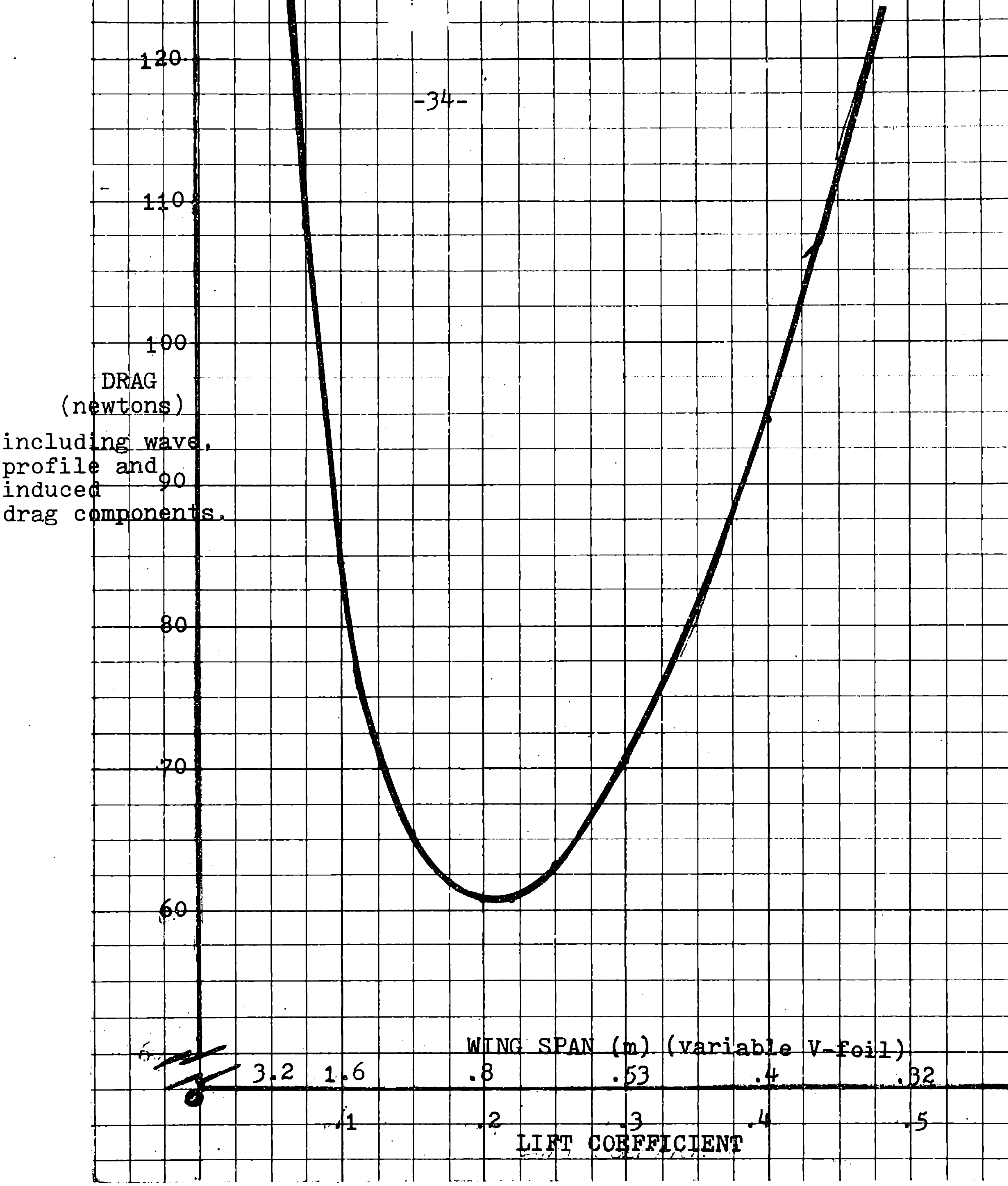


FIGURE 11. VARIATION IN THE TOTAL DRAG OF A WING PROVIDING CONSTANT LIFT WITH DIFFERENT AREA/LIFT COEFFICIENT COMBINATIONS.

Wing presented here is a V-foil with an average profile drag coefficient of .0058. Velocity is constant at 4.5 m/sec. Wing provides a constant lift of 327 newtons. Drag totals are for three wings (resulting in 980 newtons of constant lift).

modulated to maintain the constant lift of 980 newtons (100 kg x 9.8 m/sec^2). From these graphs, the best wing dimensions for a given design velocity can be determined. Choosing a design lift coefficient of about 0.21, the required wing area for optimal operation at any speed will be naturally employed by a variable-area V-foil vessel. Buermann et al. (1953) and Hoerner (1958) corroborate optimal operational lift coefficients of 0.2 to 0.3.

With the establishment of an ideal lift coefficient, a wing section can be found which will yield that lift coefficient at a minimal profile drag. It is also important that the profile drag remain low over a range of angles of attack. The NACA 66-209 wing section was found to best meet these criteria for a required 0.2 lift coefficient (Abbott and Von Doenhoff, 1959). (Figure 12).

3. Wing-area distribution. The planform dimensions of the wing were carefully determined to insure high aspect ratios and low drag. All three V-foils were designed with identical dimensions to facilitate construction.

Short wing chords make for large aspect ratios which are characteristic of low drag, but flow transition as well as actual construction must also be considered in the design. Turbulent flow of the water across the wing surface is essential to low profile drag (Abbott and Von Doenhoff, 1959; Hoerner, 1958). Transition from laminar to turbulent flow over foils is complete at a Reynolds number of about 5x10^5,

FIGURE 12. ACTUAL SIZE AND CROSS SECTION SHAPE OF V-FOIL WING, THE NACA 66-209.

Re = 5×10^5 at 3m/sec.

according to Hoerner. For a median operating speed of 3 m/sec. in 60° F water, a chord of 0.2 m is required to insure turbulent flow. This dimension is compatible with construction requirements.

V-foil vessels are customarily not operated at speeds which require less than one-half of their foil area to be submerged, since their stability is impaired. The maximum speed of these craft, therefore, should be approached just as the foils rise to one-half submergence (Buermann, Leehey, and Stillwell, 1953).

A design speed of 4.5 m/sec. was chosen for the maximum velocity of our hydrocycle because calculations (Figure 2) indicated that with this configuration power requirements would be forbidding at speeds much above that. To provide the necessary constant lift at this speed, an 0.8 m projected wing span was required for each of the three V-foils which were designed with an 0.2 m chord and an 0.2 lift coefficient. This dimension constrained a maximum projected wing span of 1.6 m and would provide enough lift for take-off at about 3.2 m/sec. Partially for structural purposes, the foils were constructed almost 35 percent longer than required and could provide a 2.5m projected wing span such that take-off would be accomplished at about 2.7 m/sec. The effective projected wing span for V-foils is measured at a submergence of one wing chord because surface effects interfere with the wing's operation in this shallow region (Buermann, Leehey, and Stillwell, 1953). (Figure 8)

C. Transmission and propulsion

The transmission system was designed for maximum propulsion efficiency. The configuration allows effective power delivery by the human being and transfers the power to the water with minimal losses.

A reclining pedaling position was chosen because it provides a low center of gravity and improves vessel stability. The recumbent configuration generates less wind resistance than conventional positions (Whitt and Wilson, 1974) and enables the handlebars to be situated beneath the seat and thereby eliminates a major source of accident injuries. This is especially important in a potentially unstable water vehicle. The pedaling position dimensions were designed by Dr. David Gordon Wilson, Mechanical Engineering Department, Massachusetts Institute of Technology (Wilson, 1978). The seat is adjustable to allow for effective use by different size people.

A two-bladed propeller was designed to operate at a maximum efficiency of 82 percent with a desired power delivery of 373 watts (0.5 hp) at 10 knots (5 m/sec.) (Troost, 1951). The propeller was designed with a pitch of 0.20 m and a 0.17 m diameter. This optimal propeller diameter corroborates data given by George L. West, Jr., in Mark's Standard Handbook for Mechanical Engineers (Baumeister, 1967). The propeller's torque was investigated and found to have a negligible effect upon the craft's operation.

Power is transferred to the propeller drive shaft from the pedals with toothed (or cogged) belts. These manipulable belts were chosen for their ability to operate through a 90° twist, enabling the plane of rotation to be turned 90°. This was essential in order to transfer power from the plane of pedal rotation to that of the propeller.

To attain the high propeller speed of rotation from the pedaling rpm, the toothed belt had to be geared at the proper ratio. Whitt and Wilson report that about 50 rpm is the optimal pedaling speed for power requirements below 159 watts (0.2 hp). For power needs beyond this, however, higher speeds are required (Whitt and Wilson, 1974). A pedaling rpm of about 70 was decided upon.

The pedaling speed must be increased by more than 28 times to provide the necessary propeller rpm. This was easily arranged with commercially available toothed-belt gears, although several gear sets were required. The gears could be located conveniently along the frame, and the propeller drive shaft was designed to run down a point between the V-foils which would remain submerged even at full speed operation (Figure 9). Near the frame, the drive shaft was unsymmetrically positioned off to one side but aimed diagonally at the centrally located propeller. This was to facilitate the jettison of the crew shell, if desired, after take off. Flow-directing shrouds encompassed the propeller in order to correct its altered alignment.

D. Control and stability

1. Low speed. Stability for the hydrofoil craft at low speeds was provided by the centrally located shell and the two outriggers. The 0.005 m^3 displacement outriggers supply roll stability through 1 m waves. Yawing and pitching disturbances are tamed by the shell which displaces about 0.1 m^3 of water. Side sway and heave of the vessel are significantly inhibited by the extensive submerged foil area. As speed increases, the buoyancy and stability maintained by the shell decreases until finally there is no contribution at take-off.

Because drag-efficient shells are nine or ten meters long, they can substantially inhibit the maneuverability of the hydrofoil. A light-weight, surface-piercing displacing vessel which is much shorter and wider than the shell, although incurring four to five times more drag, would decrease the vessel's overall size and greatly increase its agility. Such a high-drag device would be easily tolerable within the hydrofoil's power limitations (Figure 13).

A more efficient but less convenient option to eliminate the cumbersome shell is to jettison the shell after take-off. If this approach were implemented, it would reduce the hydrofoil's overall weight and required lift and would hence reduce drag. Disposing of the shell would render the craft highly maneuverable, but would require additional displacement buoyancy, located at convenience, to support the vessel when it slowed or landed. In order to take off again, the

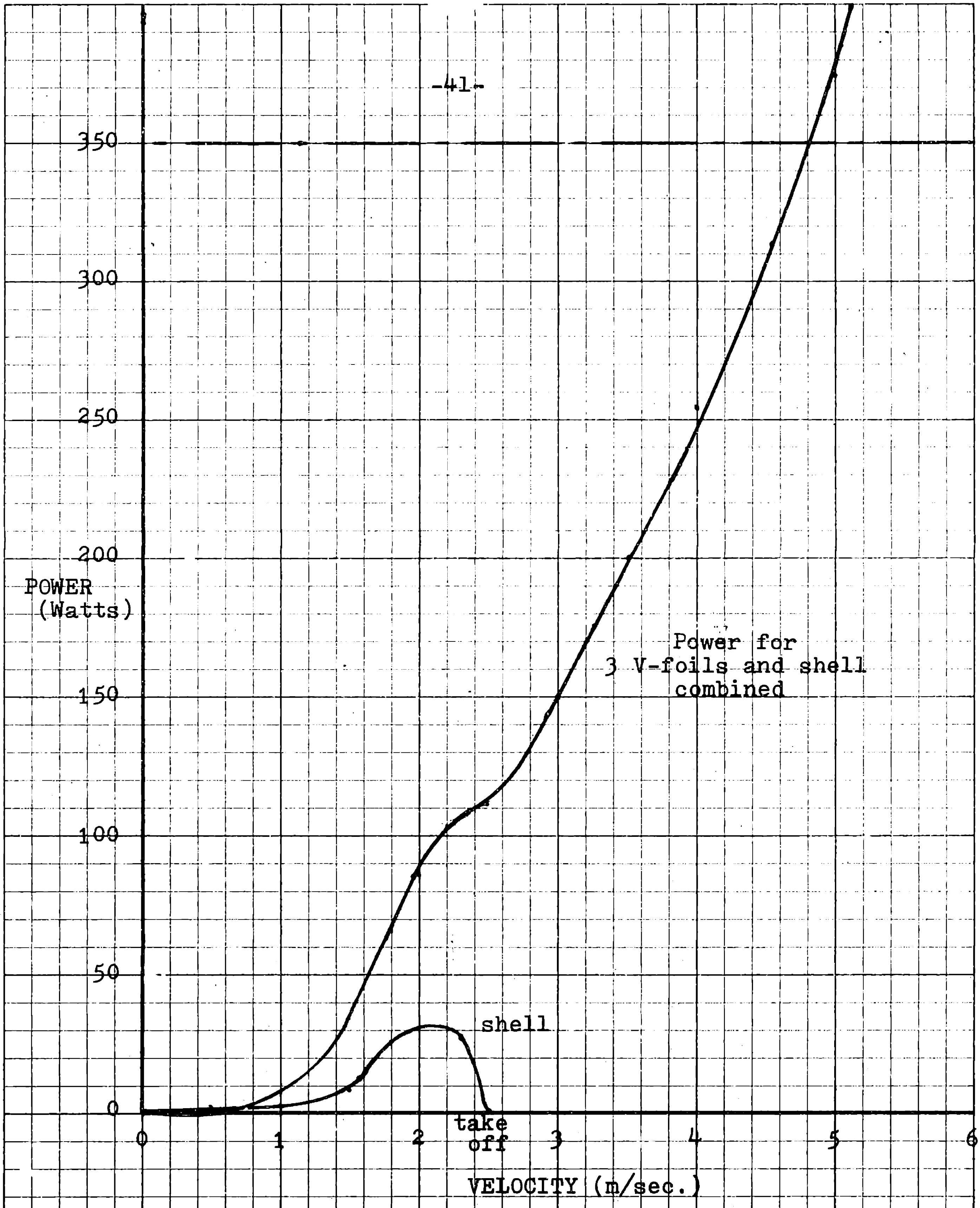


FIGURE 13. SPEED-VARYING POWER REQUIREMENTS FOR THE DESIGNED HUMAN-POWERED HYDROFOIL.

Peripheral drag of guy wires, rudder, and drive shaft excluded.

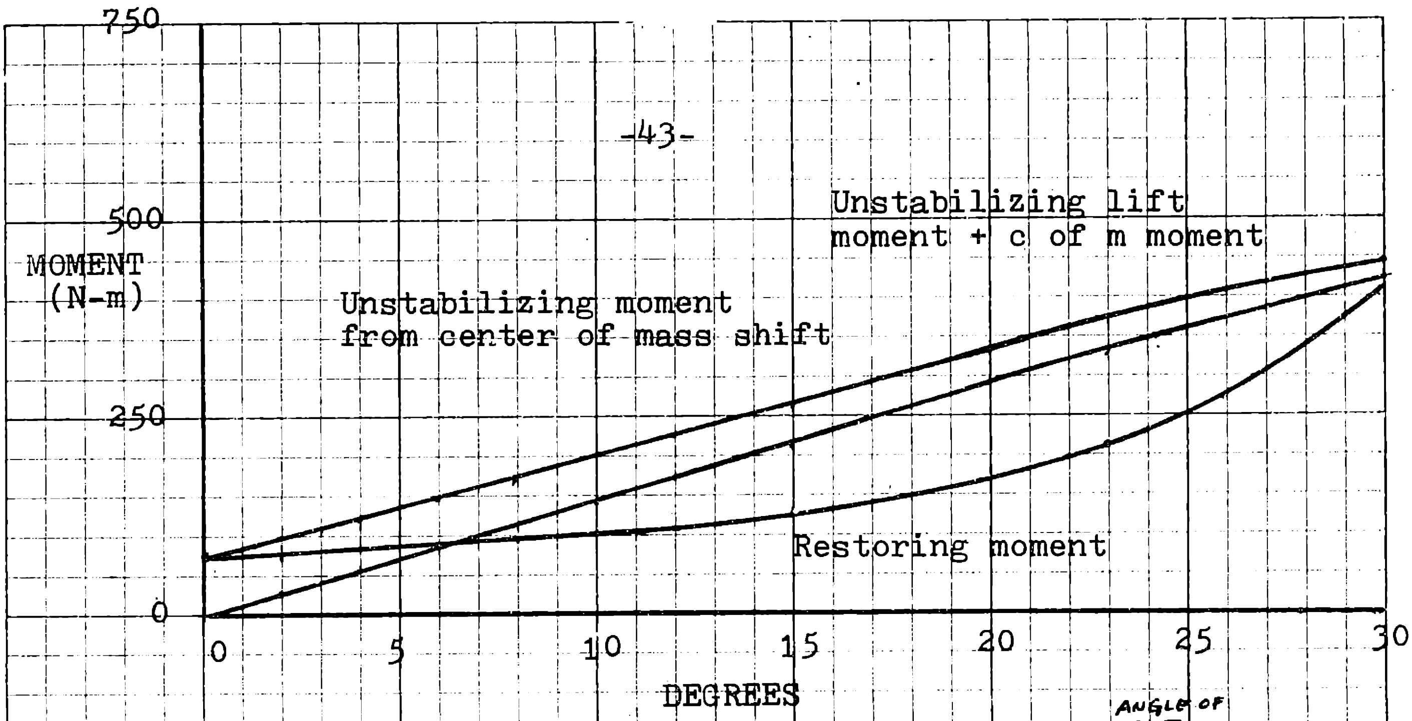
hydrofoil would have to be remounted on the shell.

The design of the hydrofoil presented in this project allows for the implementation of any of these options.

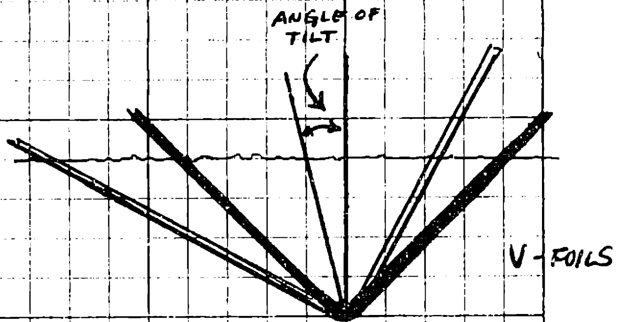
2. Rolling and steering. As described earlier, V-foils enhance stability after take-off because the foils are stabilizing members as well as lifting surfaces. The extra restoring lift generated when the craft heels to one side is not, however, enough to provide stability. Figures 14 and 15 compare the unstabilizing moments to the restoring moment for the bow and stern V-foils at 3 and 4 m/sec. The unstabilizing moment created by the displacement of the center of gravity overpowers the restoring moment at tilt angles up until somewhere between $15^{o}$and 30^{o} at which point the craft is seriously careened but the moments finally balance.

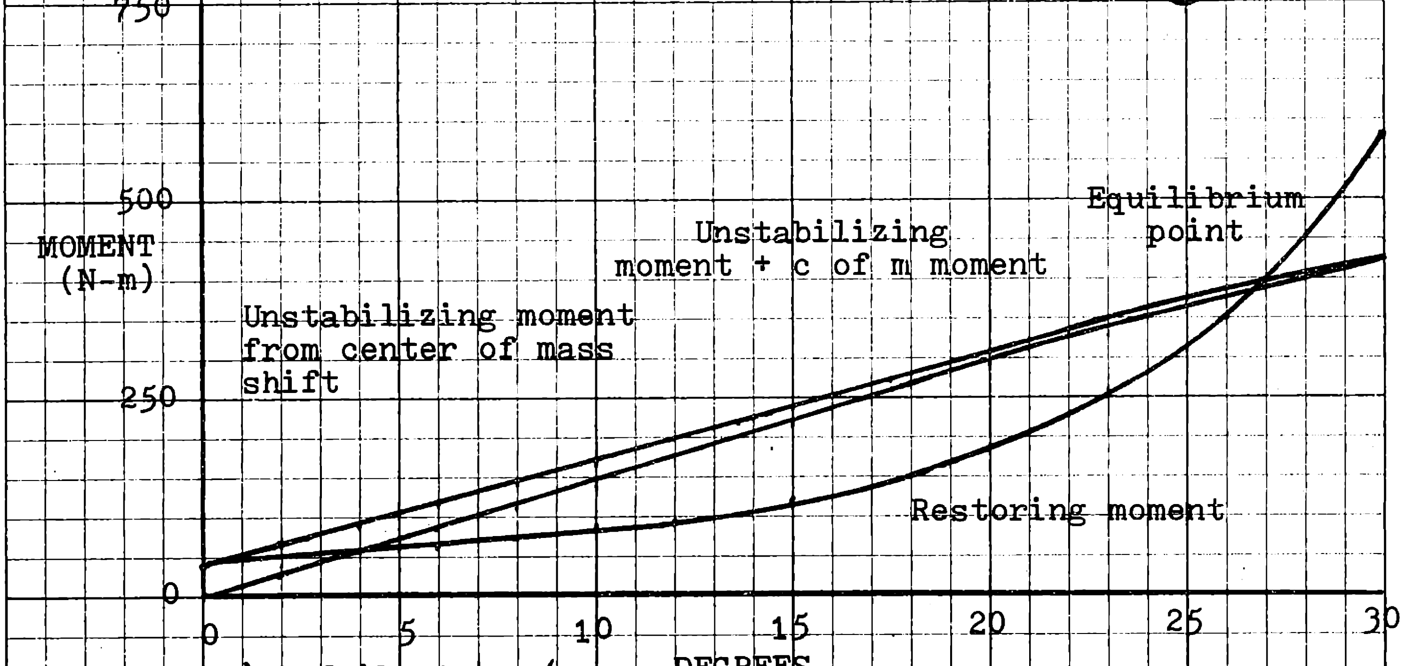
A number of alternatives would resolve this problem: 1) eliminate disturbances which would displace the center of gravity, 2) reduce the mass of the load, 3) lower the center of gravity considerably, reducing its torque arm, 4) employ a V-foil which would introduce more restoring lift area at a faster rate, or 5) use, in addition to the V-foils, an active stabilizing system.

Figure 16 compares the restoring and unstabilizing moments of a 30^{o} V-foil. This foil submerges more restoring lift area faster than the 45^{o} V-foil, and although this wing results in a balance of moments at a reduced heel angle, the problem of initial instability still remains.



a.) Single V-foil at 3 m/sec.





b.) V-foil at 4 m/sec.

FIGURE 14. COMPARISON OF UNSTABILIZING MOMENTS AND RESTORING MOMENTS FOR SINGLE 45° V-FOIL.

Degrees is angle of tilt from vertical. Moments for constant velocity of 4 m/sec.

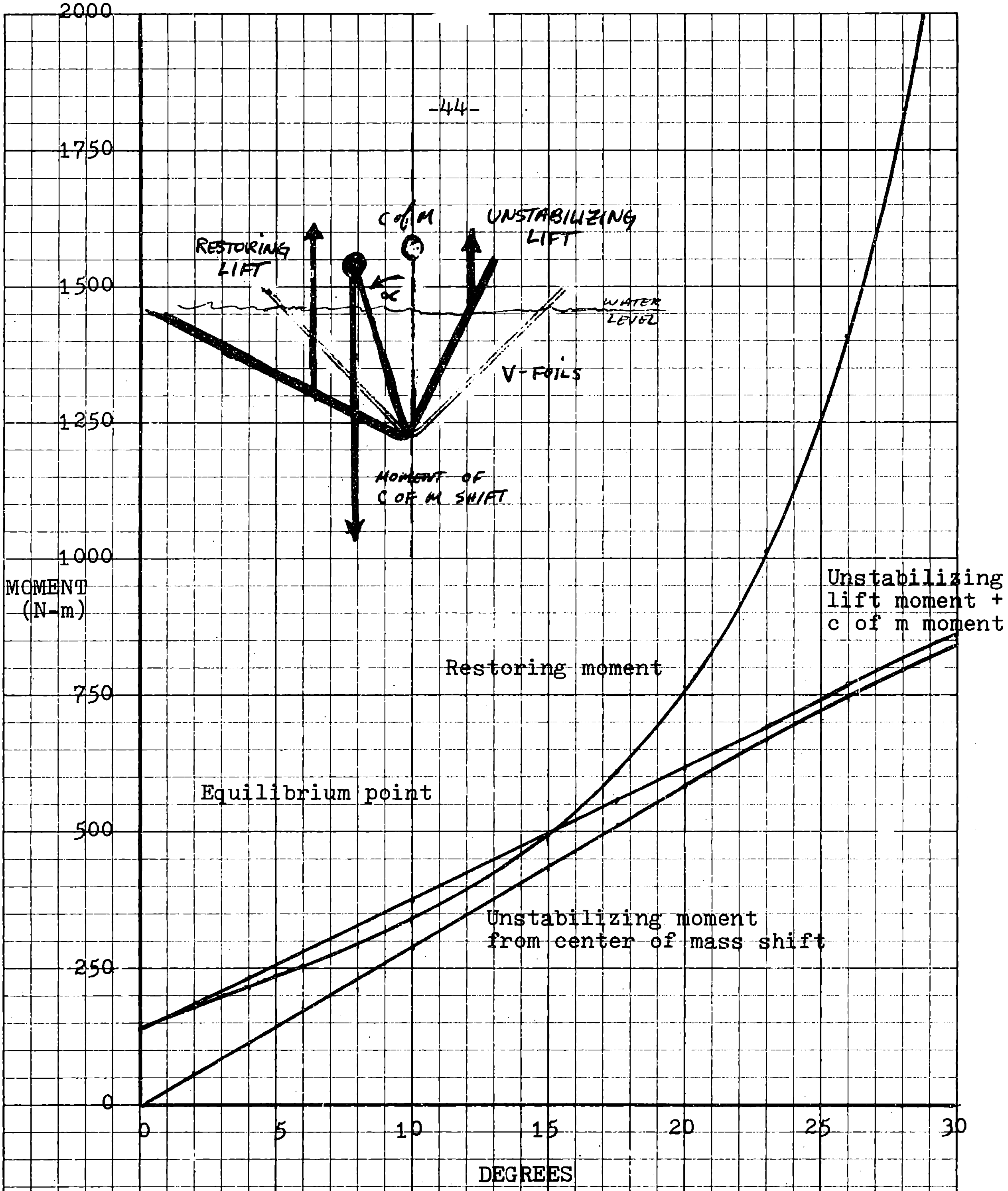


FIGURE 15. COMPARISON OF UNSTABILIZING MOMENTS AND RESTORING MOMENTS FOR TWO SIDE-BY-SIDE 45° V-FOILS. Degrees is angle of tilt from vertical.

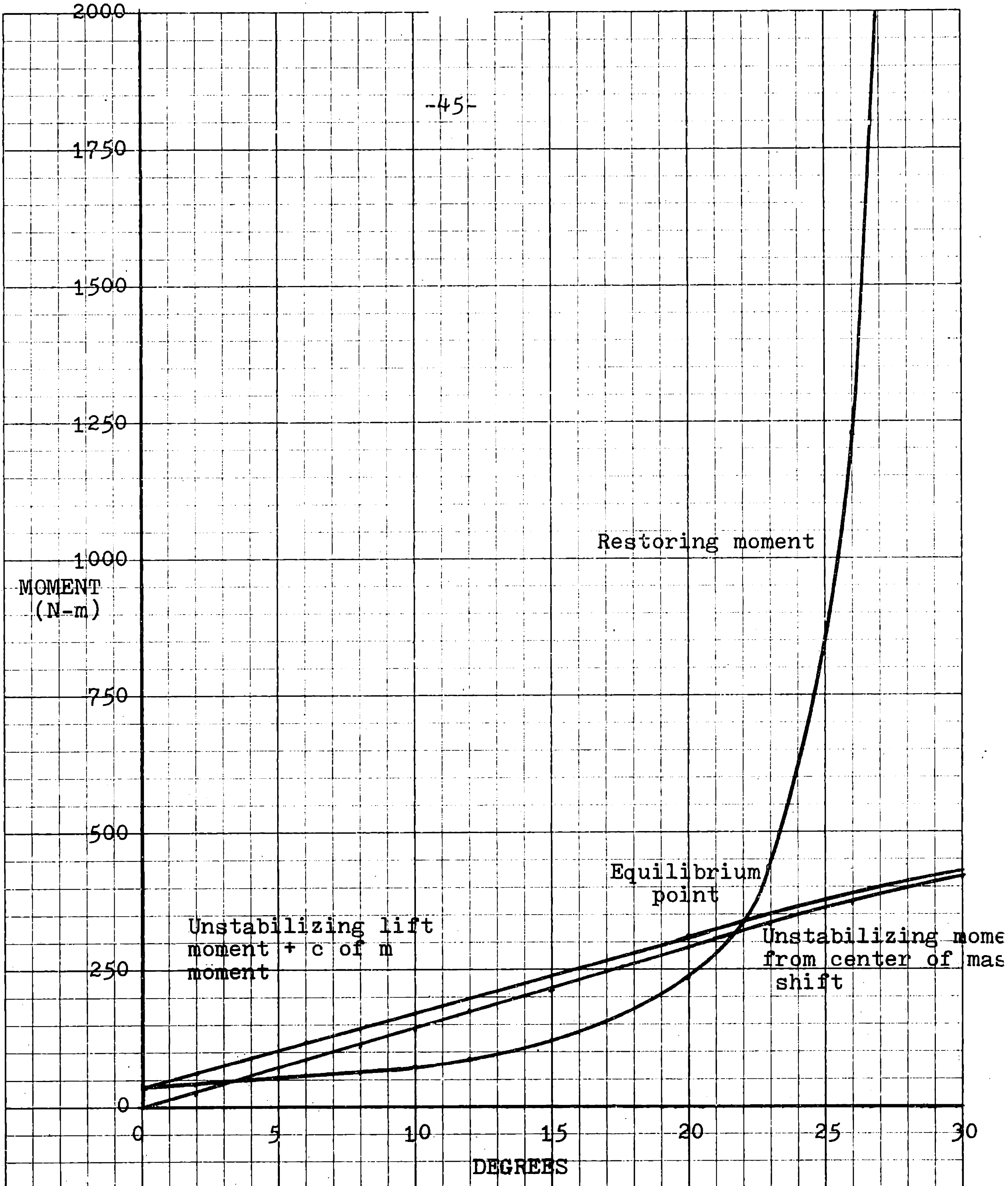


FIGURE 16. COMPARISON OF UNSTABILIZING MOMENTS AND RESTORING MOMENTS FOR SINGLE 30° V-FOIL.

Degrees is angle of tilt from verticle. Moments for constant velocity of 4 m/sec.

An active stabilizing system had to be employed. Actively shifting the center of gravity by leaning would be very effective and more than adequate if the configuration resembled a conventional bicycle. The recumbent position, with the handle bars situated below the seat, limits leaning and weight shift to such an extent that this is not a viable option.

Another active stability system could incorporate ailerons located on the V-foils. This approach would violate the simplicity of the craft by adding an extra control function into the operation.

The hydrofoil was planned with a steering arrangement which would actively balance and stabilize the craft. Almost identical in application to the front wheel of a bicycle (Whitt and Wilson,1974), the vessel utilizes a bow rudder located in the apex of the front V-foil. This rudder enables the craft to turn into a fall. Steering the craft in the proper curve will generate a moment due to angular acceleration, and this moment should exactly balance the net unstabilizing moment at different combinations of turning radius, vessel speed, and heel angle. This steering arrangement has the added capability of correcting the vessel's yaw as well as its roll.

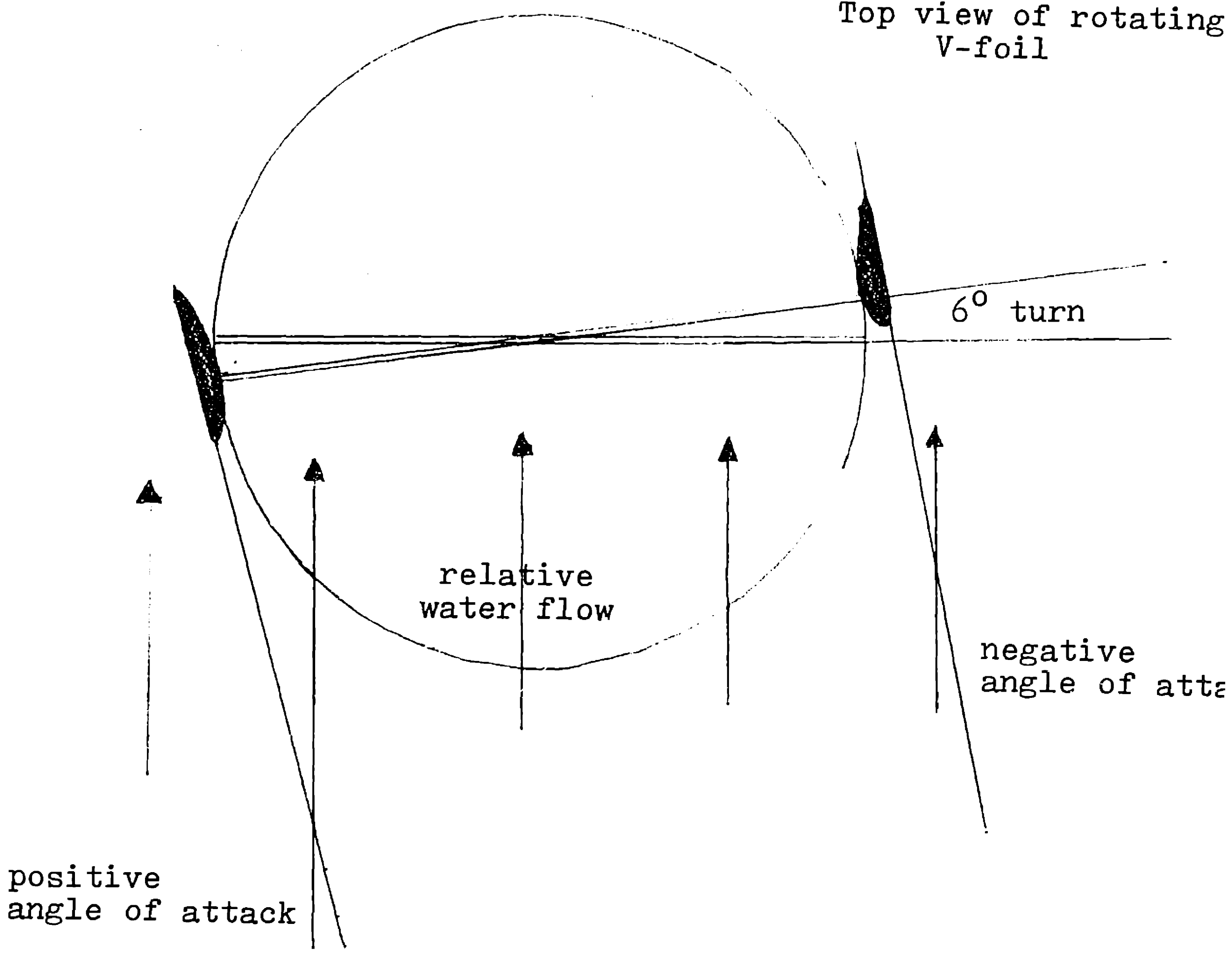
The hydrofoil was designed with a somewhat long distance between the bow and the stern foils in order to accommodate the long shell and to decrease the craft's propensity to pitch. Locating the foils closer together, however, would greatly increase the steering responsiveness and enhance the roll stability system in much the same way as wheelbase affects bicycle stability (Whitt and Wilson, 1974).

Steering the vessel by rotating the bow V-foil is not possible from a stability standpoint. In pivoting the front V-foil for a turn, the angle of attack of each wing section is altered in such a way that one side experiences an enlarged positive lift coefficient and the other side a negative lift coefficient (Figure 17). The result is a very large unbalancing moment which cannot be countered. The angular acceleration moment caused by the induced turn is large enough to counter less than 5 percent of this unstabilizing couple.

In steering with the bow rudder, this same problem may be encountered to a lesser degree, since the relative angle of water flow across the wings is altered when the craft turns. Also, it is possible with the bow rudder and fixed bow foil that much drag will be incurred in attempting to sweep the V-foil broadside through the water for a required stabilizing turn. This increased drag would slow the hydrofoil and intensify the balancing problem.

3. <u>Pitching</u>. The wide 'wing base' of the craft insures the vessel's stability against pitching. As in the case of rolling, the V-foils automatically generate restoring lift forces to counter an unstable pitch or heave disturbance. An exceptionally large pitch would bring the bow or stern of the shell into contact with the water and the instability

Top view of rotating
V-foil



Front view of V-foil
showing lift-generate
forces.

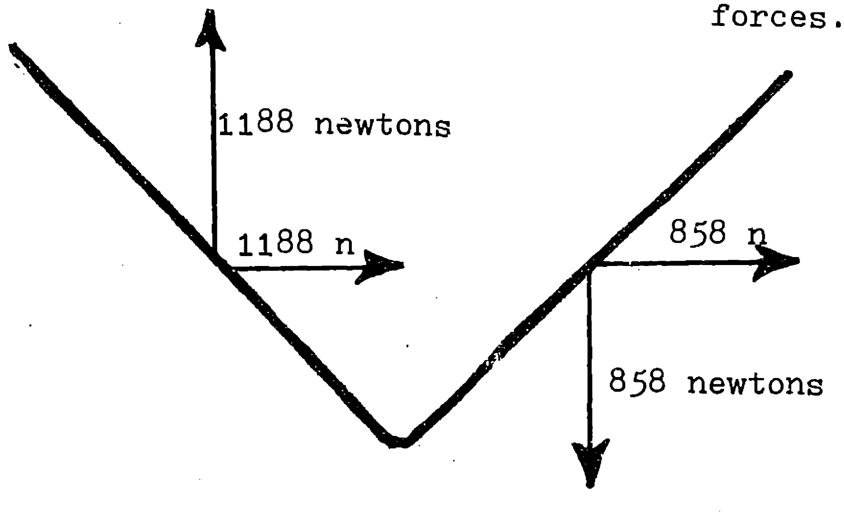


FIGURE 17. THE UNSTABILIZING, LIFT-GENERATED FORCES EXPERIENCED IN TURNING THE BOW V-FOIL.

Velocity to produce these forces is 3.5 m/sec. Foil is rotated 6°. As can be seen, the vertical forces combine to generate an overpowering moment.

would be thus rectified. With pitching of this magnitude, the foils would probably stall and the craft would land onto its buoyant support.

Small to medium size waves are not expected to disturb the craft as they would a conventional hull vessel because the thin wings will slice through these protuberances.

The V-foils have a fixed angle of attack and a change in speed must be balanced by a change in submerged area in order to maintain the same constant lift. The vessel may be trimmed before operation by adjusting the bow or stern V-foil apex guy wires. This will slightly increase or decrease the angle-of-attack of the respective foil, resulting in an increased or decreased lift force to correct the ship's trim. Alternatively, the seat may be adjusted forwards or backwards to change the center of gravity and establish trim.

E. Drag

The total drag of the proposed hydrofoil configuration is diagramed in Figure 13. This drag represents the total drag of three V-foils and the shell and does not include any peripheral water drag associated with guy wires, the propeller shaft, shrouding, or the rudder. This drag total also neglects wind resistance.

Combining an overall transmission efficiency of 95 percent with the 80 percent efficiency of the propeller, an overall power delivery efficiency of 76 percent results for the hydrofoil This limits the craft's maximum propulsion power output to 285 watts for an input of 373 watts (0.5 hp). This available power, along with the extra peripheral drag, constrains the hydrofoil's speed to 4 m/sec. at best (Figure 13). In reality, the additional skin friction and pressure drag of imperfectly constructed wings and inefficiency due to misalignment of the V-foils would further lower this maximum attainable speed.

It is evident from Figure 13 that a less cumbersome and less drag-efficient shell could be used initially for take-off, as suggested earlier in this paper on page 40 under the subheadings "Control and stability. 1. Low speed," since there is room for additional power consumption at these low velocities. This would enhance the hydrofoil's agility after take-off.

Figure 18 compares the contributions of induced, profile, wave, and parasitic components of the total drag for the three V-foils as a function of velocity. The graph portrays the drag of the three V-foils as they maintain a constant total lift of 980 newtons which requires more submerged V-foil area as the velocity decreases. For speeds below 2.5 m/sec, the area required to maintain the lift is excessive, making the V-foils impractical in this application, and these points are plotted on the graph only for theoretical comparison. (At 0.2 m/sec. the V-foil projected wing span is 408.3 m !)

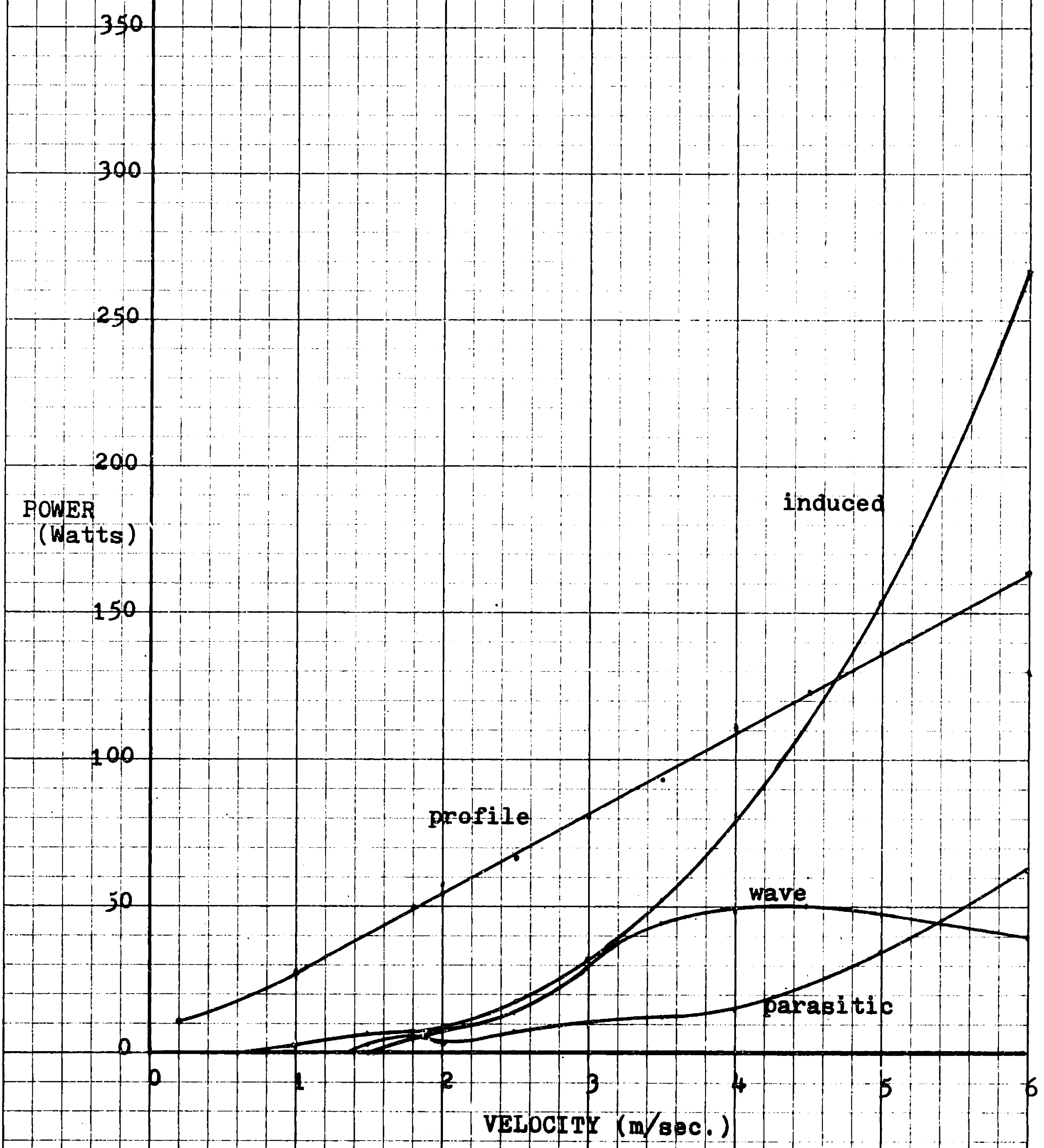


FIGURE 18. CONTRIBUTIONS OF INDUCED, WAVE, PROFILE, AND PARASITIC DRAG COMPONENTS TO THE TOTAL POWER REQUIRED BY THE HYDROFOIL. A constant lift of 980 newtons is maintained by the variable-area V-foils. Speeds below 2.5 m/sec. are impractical, since the wing area increases substantially. (At .2 m/sec., V-foil projected wing span is 408 m for a .2 m chord!)

Of the four drag components, the induced drag is the most negotiable. The induced drag may be cut or increased by as much as an order of magnitude by adjusting the wing geometry or by altering the wing area/lift coefficient combination. For example, it is obvious from Figure 18 that the induced drag is the most important drag component of the V-foils at high speed. If the same submerged foil area is maintained with a 0.2 m chord, altering the V-foil geometry to double the effective foil aspect ratios would cut the induced drag (and induced power requirement) in half. This effect alone would considerably extend the maximum velocity of the craft, and make operation at lower speed easier.

Wave drag decreases at high velocities where the system's Froude number finally becomes large. Wave drag can further be reduced by decreasing the angle of foil attack and by designing a deeper mean submergence for the foils.

Profile drag is not negotiable. Parasitic drag could be eliminated by the use of submerged foils which would not pierce the water surface. As explained earlier, the overall drag of the hydrofoil could be reduced by 30 percent if flat foils were used instead of the V-shaped wings.

Ground effect, ceiling effect, wing end effects, and tandem-wing wave-drag-cancellation are drag considerations which were not included in the power graphs.

V-foil wings pierce the water surface and therefore have no submerged end effects. Submerged wing end effects are not always inefficient but can often be beneficial if the wing tips are properly designed (Hoerner, 1958).

On a hydrofoil, if a stern wing is positioned in tandem behind an identical bow, the power consumed in the wave drag of the first submerged foil can be recovered at a speed determined by the distance separating the two foils (Hoerner, 1958; Buermann, Leehey, and Stillwell, 1953). If the bow and stern wings of our hydrofoil were identical, the wave drag of the bow foil would be cancelled at a speed of 2. m/sec, based on the 2.5 m separation of the foils.

A "ground effect" is noticeable in shallow water and it can affect wave drag appreciably. In shallow water, wave drag is negated if the foils cruise above a certain critical speed determined by the depth of [illegible] water (Hoerner, 1958). Figure 19 plots for different water depths the critical speed of a hydrofoil above which the craft must travel in order to avoid wave drag.

Operating below the water surface, a foil will give rise to a downwash flow commencing at a distance behind the foil determined by the wing span. This "ceiling effect" increases the induced drag of tandem foils if they are located far enough behind the first foil to experience this phenomenon (Hoerner, 1958). The "wing base" of the hydrofoil presented in this project is small enough to avoid this negative effect.

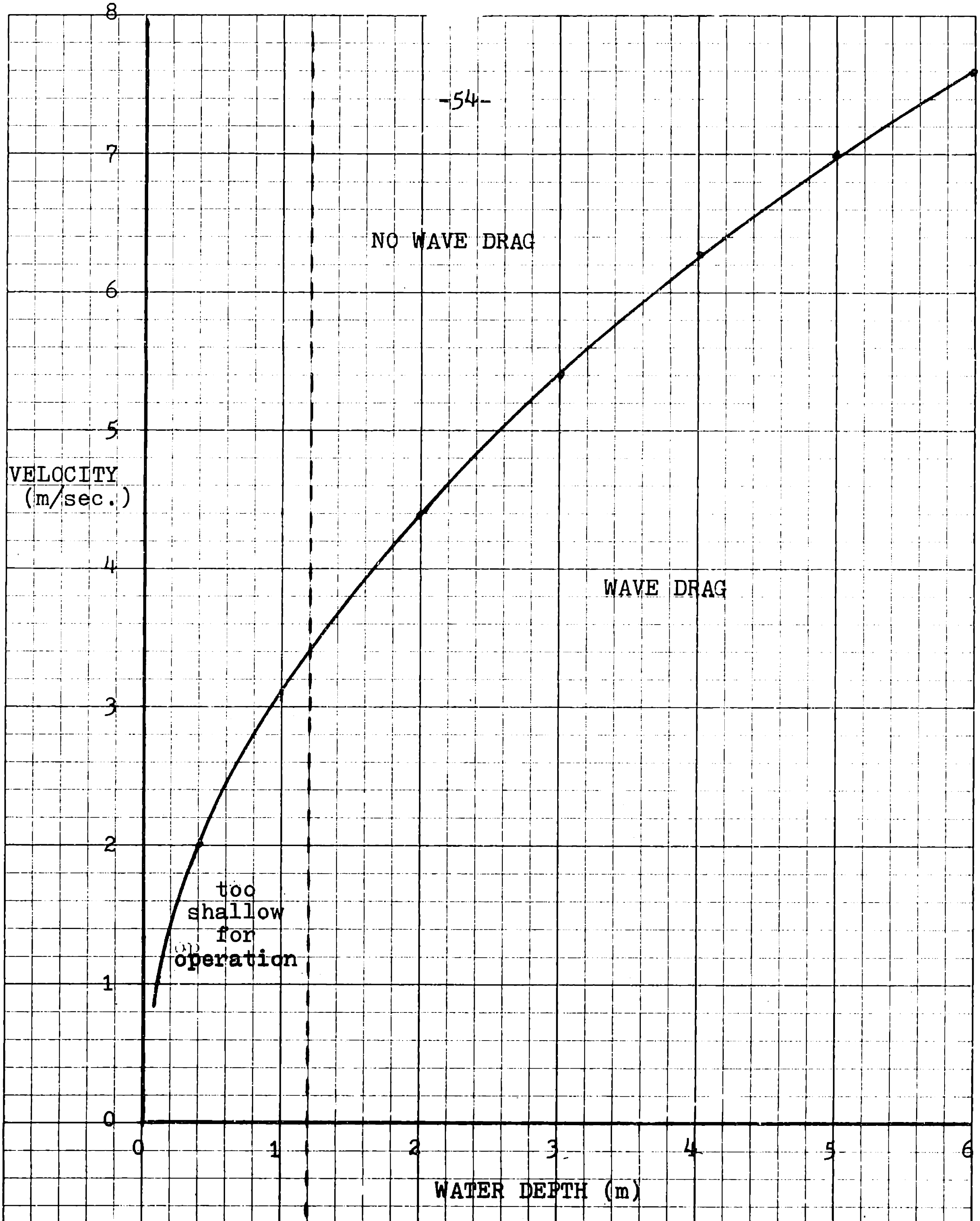


FIGURE 19. THE CRITICAL VELOCITIES ABOVE WHICH VESSELS MUST OPERATE IN ORDER TO AVOID WAVE DRAG IN SHALLOW WATER.

The design of this hydrofoil attempted to provide a high speed and easily stabilized craft while maintaining simplicity and ease of construction. The process of design uncovered many advantageous alternatives as well as unexpected problems which could not be included or considered in the final design and construction because of time limitations.

III. Construction

The weight and strength of materials were important construction considerations. It was desirable to make the craft as light-weight and as small as possible. Vessel construction was oriented towards making the craft modular so that the three V-foils could be individually removed to facilitate storage, transportation, and repairs or alterations.

A. Wings

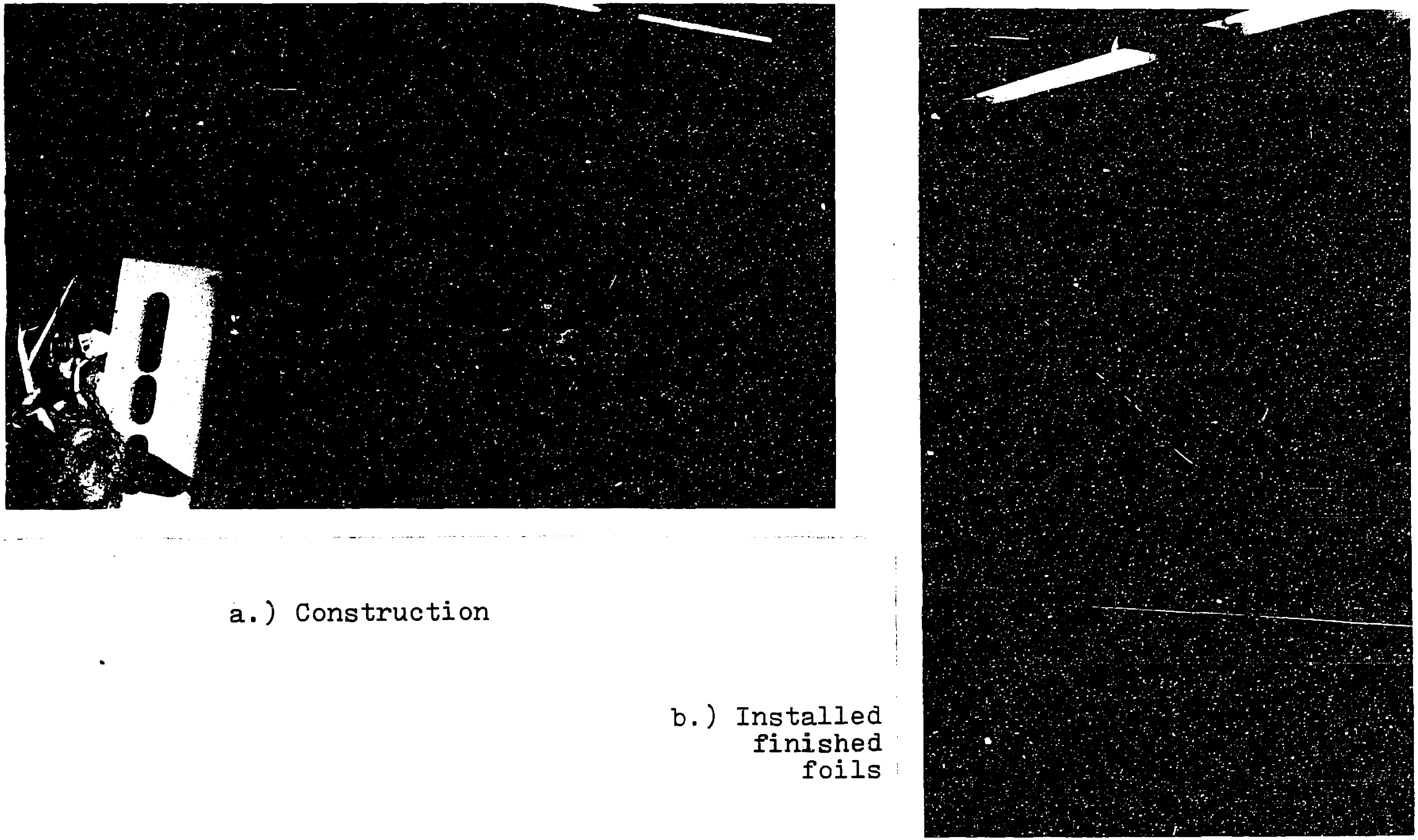
The V-foils were constructed in two sections, each part making up one side of the V. Each wing section was 0.2 m wide and 1.8 m long, and made of fiberglass with polyester resin.

To form the foils, the actual size and shape of each half of the wing's cross section was carved from wood .0065 m (1/4 in) thick. The wood sections were then dragged broadside through freshly mixed plaster resting in tubs 1.9 m long, 0.30 m wide, and 0.03 m deep (6 ft x 1 ft x 1.5 in). As the plaster set, the cross-section shape of each half of the wing was molded into the plaster. Each plaster mold, representing the top or bottom half of the wing, was then coated with mold-release wax and paint. The next step entailed soaking woven fiber glass in the polyester resin which was combined with a hardening agent and layed in the coated plaster molds. The wing cross-section cavity was packed with matted fiberglass and polyester resin mixture. When fully hardened the wing halves were attached together and one section of the V-foil was formed (Figure 20). The section's edges were trimmed and the wing surfaces were finally sanded with griddle bricks, recoated with polyester, and then sanded again.

The completed wing sections weighed an average of 4 kg (9 lbs) each (8 kg or 18 lbs per V-foil), and could support at least a dynamic loading of 115 newtons at the section center. The sections provided about 9.8 newtons of buoyant lifting force each when statistically submerged in water. Had the sections been fabricated from wood, they would weigh about 8 kg (18 lbs) each (16 kg or 36 lbs per V-foil).

B. Frame

The frame consists of the V-foil support arms and braces, the seat and pedal supports and the drive shaft. For most of this construction, 6061 T6 aluminum tubing of 0.254 m (1 in) outside diameter and about 0.0254 m (0.1 in) thickness was used. Standard ten-speed bicycle frames, pedals, cranks, and bearings were used to accommodate the steering and pedaling systems (Figure 21). Electrical conduit T-connectors and copper plumbing T's were used to connect the tubing at joints. Polyester-fiberglass lashings were also considered for mating tubing. Oxyacetylene welding was determined to be undesirable because it alters the metal's temper, rendering the aluminum softer, weaker, and

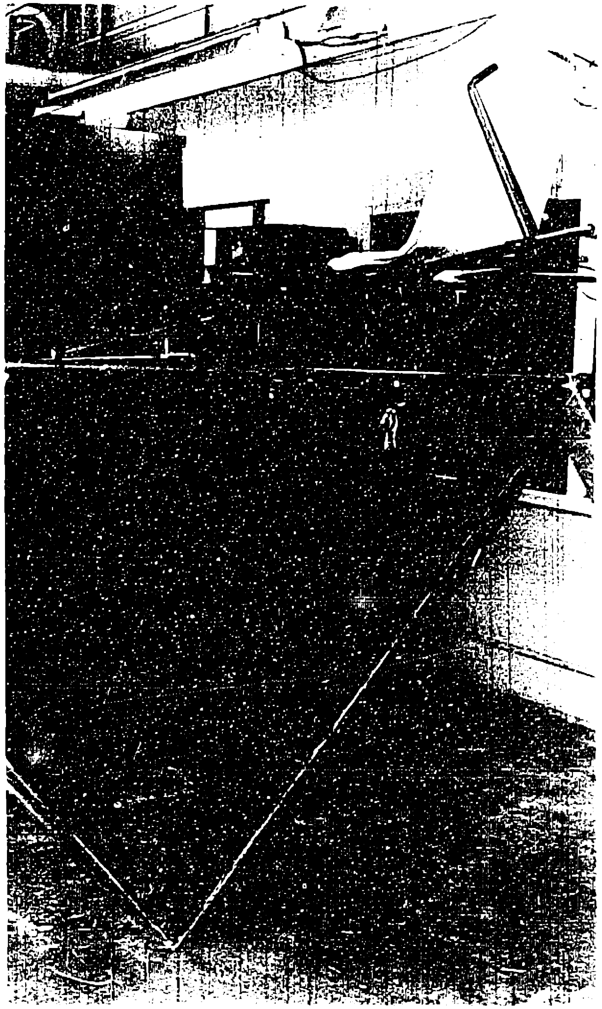


a.) Construction

b.) Installed
finished
foils

FIGURE 20. FIBERGLASS WING CONSTRUCTION.
Note plaster molds.

[illegible]



[illegible] Installed
finished
[illegible]

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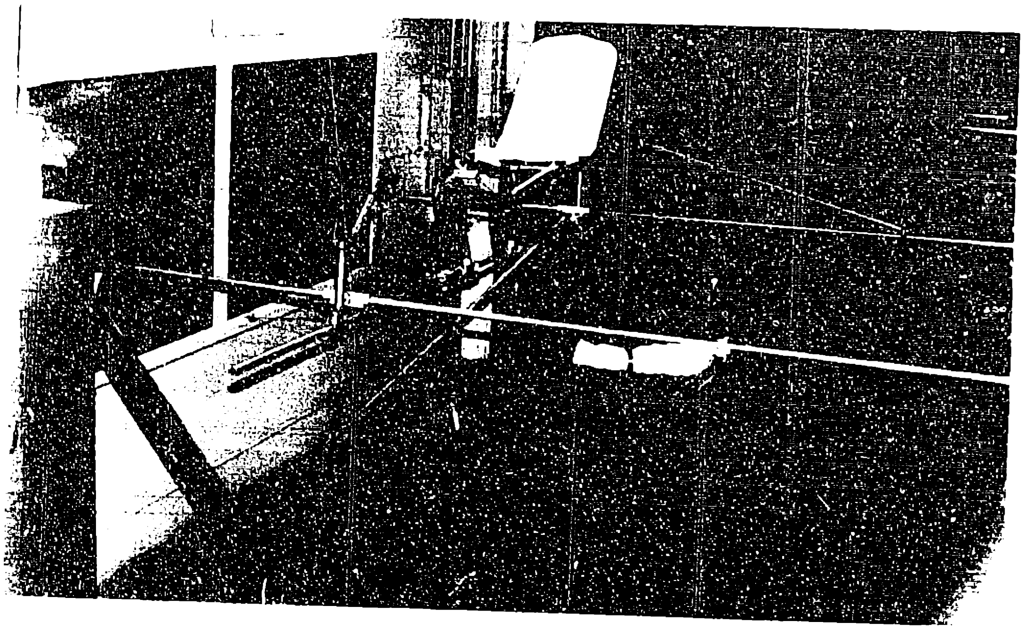
a.) Front view.

b.) Side view

FIGURE 21. PARTIALLY CONSTRUCTED HYDROFOIL.
Note aluminum tubing, bicycle frame (inverted), and 'T' joints.



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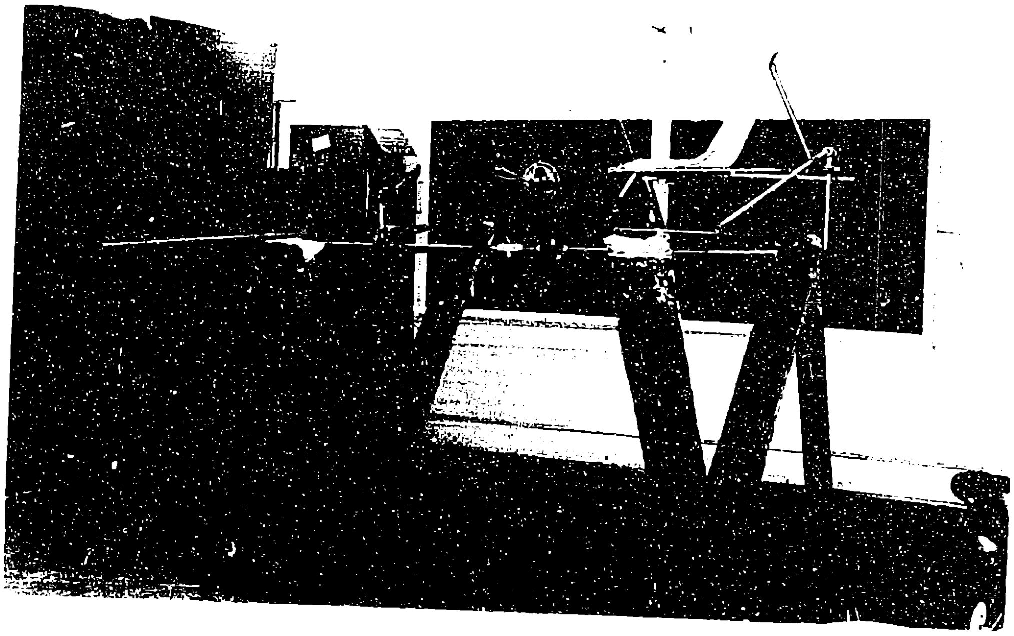

[illegible]

[illegible]

fatigue resistant.

Wherever possible, structural forces and operational loads were routed in tension rather than compression. This enabled light-weight guy wires to provide much of the strength and regidity of the craft and saved on heavy and expensive tubing. Guy wire connections were also easier and cheaper than tubing joints, and facilitated assembly, disassembly, storage, transport, and alteration.

The dimensions of the craft, as displayed, are 5.2 m wide, 3 m long (without shell), and 2.7 m from top to bottom.

C. Future work

A considerable amount of additional work must be accomplished on the hydrofoil. The wing sections remain to be attached to form V-foils. This connection must be done with care so that the proper angles-of-attack result on the completed V-foils. The foils must be attached to the frame and the guy wires installed.

The hydrofoil's bow rudder and bearings must be constructed and installed and the steering system should be completed.

Fixtures must be constructed to hold the shell to the underside of the hydrofoil's frame.

The transmission and propulsion arrangement, including the drive belts, gears, shaft, and propeller should probably be constructed only after the hydrofoil has been test-towed in a body of water and proved stable, controllable, and seaworthy. In such a test, actual power requirements for the craft could be empirically found, and the overall feasability of this human-powered vessel could then be determined.

IV. Conclusions

In the review of the various vessel support structures, it seems that those structures which least disturb the water surface are the most drag efficient and are able to attain the highest speeds. Stability in vessel support is to be achieved only with increased drag and at the cost of speed.

Hydrofoils will support a moving vessel in water, but are unstable in and of themselves and require a complicated control and stability system. Submerged foils are best when used with a buoyant support structure. In this capacity, the wings may be designed for minimum drag at high speeds because they do not have to be operational at low speeds where the displacement structure supports the craft. Hydrofoil craft can be highly maneuverable and potentially have very low drag resulting in the ability to attain high speeds.

Different hydrofoil configurations (Figure 7) yield dissimilar stability characteristics and drag efficiencies. V-foils and ladder foils have relatively high stability because their wing geometries generate restoring forces in response to an unstabilizing disturbance. Tandem submerged foils facilitate large wing aspect ratios, do not pierce the water surface, and their geometry enables the most effective use of wing area to generate supporting lift. The submerged foils are consequently more drag efficient, but they also require a more complex control system than the other two configurations.

For low drag and high speed, tandem-submerged hydrofoils seem to be the best. The approach to this project, however, did not strictly follow a high speed formula, but placed great emphasis on ease and speed of construction and simply achieved stability. Shortness of time limited further development of a more efficient hydrofoil.

A human-powered hydrofoil utilizing three 45° V-foils has been designed and partially constructed in this project. The foils were variable-area, fixed angle-of-attack wings which provided take off at 2.7 m/sec. At speeds below this, the vessel was supported on a low-drag one-man shell. The hydrofoil's stability was enhanced with an active balancing system, similar to that used on a bicycle, which was provided by a bow rudder. The craft was driven by a pedal-powered propeller and was expected to attain speeds of 4 m/sec.

The success of this project lies in 1) the practical experience gained in working with foils, 2) the collection of useful references, and most importantly 3) the formulation of the basic concepts and data relating to human-powered water-craft and hydrofoils. The project uncovered advantageous alternatives as well as unexpected problems and limitations associated with human-powered water travel and hydrofoil application.

It is concluded that hydrofoils are perhaps the best way for attaining high speed and high maneuverability in a human-powered water vehicle.

It appears that the most efficient and fastest water craft could be developed with the fully submerged tandem foil configuration. Any continued effort should be expended towards this end, and towards solving the stability problems associated with this low drag design.

V. Recommendations

The completion of the project's V-foil water-craft is dependent upon the unfinished work outlined on page 60 of this paper under the heading, "III. Construction, C. Future work." It is suggested that if work were to continue on this craft, only construction necessary to render the hydrofoil seaworthy and able to be test towed should be accomplished. A test tow of the craft would yield information regarding its stability, control, structural strength, and power requirements, and the feasibility of continuing work on the V-foil design could be determined.

It is recommended, however, that work on the V-foil design cease and that further effort to be expended on high-speed, maneuverable, man-powered water vehicles should be focused on the tandem submerged hydrofoil configuration (Figure 7). The advantages of this design in terms of low drag and high speed have been present through out this report and are graphically illustrated in Figure 2 and Figure 22. The superior drag efficiency of the tandem submerged foil configuration more than outweighs its complex stability problems for those designers who are seriously interested in developing a low-drag high-speed water vehicle.

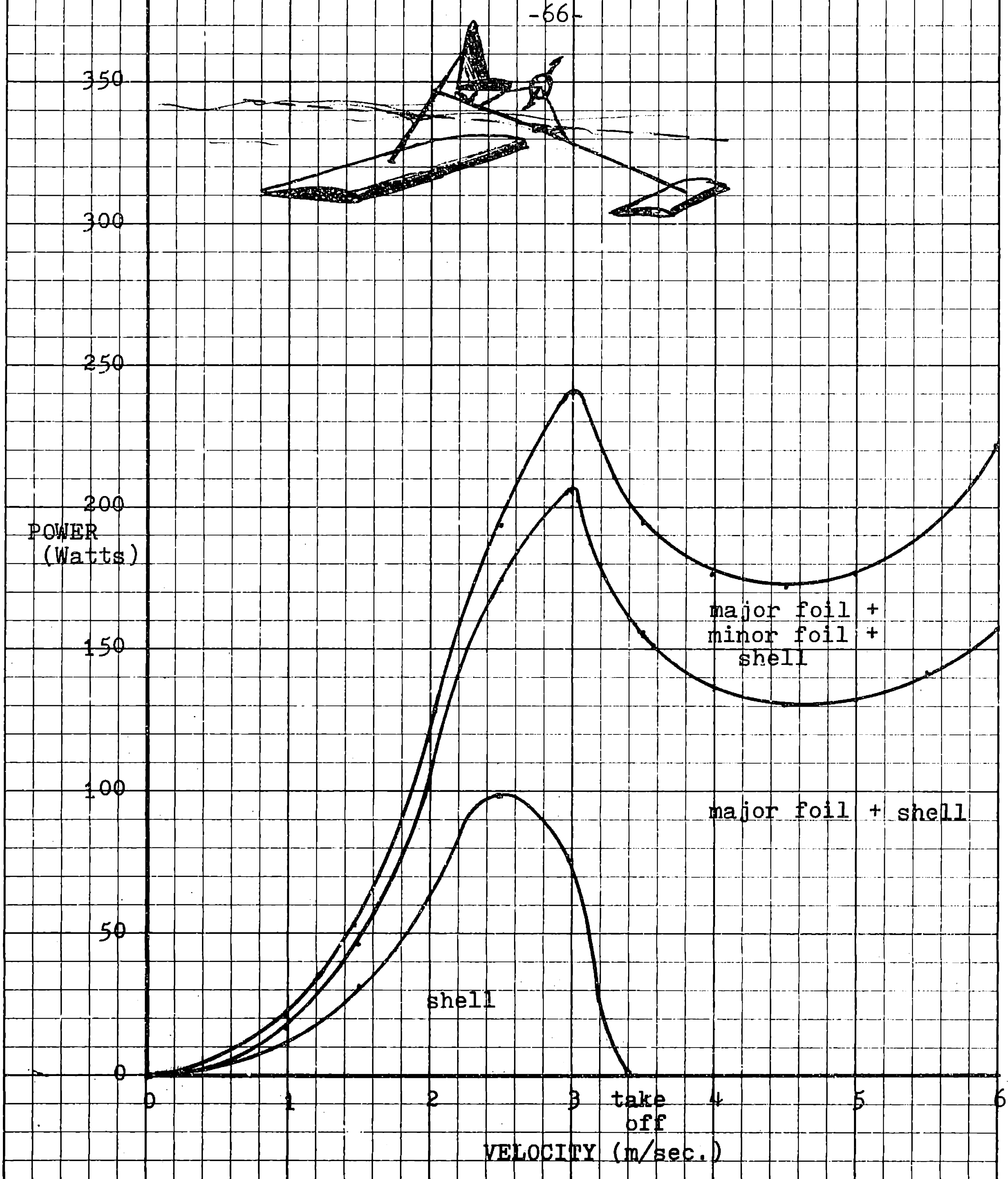

FIGURE 22. THE SPEED-VARYING POWER REQUIREMENTS FOR A TANDEM SUBMERGED WING HYDROFOIL (variable angle of attack).

The major foil of this conservatively designed vessel supports 80% of the 980 newton load. The minor wing supports 20% after take-off. Wing chords are .2 m and the wing span of the major foil is 1.8 m.

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