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Bethesda, Maryland 20084-5000

WAVESTRIDER HULLFORM EVALUATION

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The WAVESTRIDER concept was proposed by Ketron, Incorporated as an over-the-horizon transporter of Marine Corps tracked amphibians. DTRC was tasked to evaluate the concept. From analyses, model tests, and at-sea trials, the conclusion of the Navy's evaluation is that the WAVESTRIDER concept is basically flawed.

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ABSTRACT

The WAVESTRIDER concept was proposed by Ketron, Incorporated as an over-the-horizon transporter of Marine Corps tracked amphibians. DTRC was tasked to evaluate the concept. From analyses, model tests, and at-sea trials, the conclusion of the Navy's evaluation is that the WAVESTRIDER concept is basically flawed.

ADMINISTRATIVE INFORMATION

The work described herein was performed by a number of Navy and Navy-contracted activities under the technical supervision of the Systems Programs Division, Code 123, of the David Taylor Research Center (DTRC). The DTRC codes that participated include: the Surface Effect Ship Support Office (SESSO), Code 1232; the Surface Ship Design Division, Code 1222; the Special Ship and Oceans Systems Dynamic Branch, Code 1562; and the Marine Corps Program Office, Code 124. Other Navy activities that participated include: the NAVSEA Combat Systems Engineering Station, Norfolk, Code 63, the Marine Corps Research, Development and Acquisition Command, Code AW; and the Naval Sea Systems Command, PMS 300 and 310. The Navy contracted activities include: Ketron, Incorporated; Kinetics, Group; MAR, Incorporated; and Dr. Dale Calkins of the University of Washington in Seattle.

The work was funded by the Office of Naval Technology (ONT-211) as a part of the Surface Ship Technology Program Element (PE 0602121N) and the Marine Corps Research, Development and Acquisition Command (MCRDAC AW) as a part of the Marine Corps Surface Mobility Technology Program (PE 0602131M).

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EXECUTIVE SUMMARY

The WAVESTRIDER concept was proposed by Ketron, Incorporated as an over-the-horizon transporter of Marine Corps' tracked amphibian vehicles. The David Taylor Research Center (DTRC) was requested by the Office of Naval Technology (ONT-211) to assess the validity of the WAVESTRIDER technology, the maturity of the WAVESTRIDER design process and the compatibility of the WAVESTRIDER concept with amphibious assault assets and practices. Close liaison was maintained with the Marine Corps Research, Development and Acquisition Command, Warfare Technology Directorate (MCRDAC AW) with respect to Marine Corps equipment and mission needs.

The WAVESTRIDER concept was invented by Mr. Peter R. Payne. At the time of the initiation of this evaluation, Mr. Payne was an employee of KAI, a subsidiary of Ketron, Inc. On 11 May 1988 the Navy entered into a contract with Ketron Inc. for the evaluation of the WAVESTRIDER concept. The contracted effort was divided into discrete tasks as follows:

Task I:	Concept Development and Risk Analysis
Task II:	At-Sea Trials of two WAVESTRIDERs
Task III:	Model Tests of two WAVESTRIDER Models
Task IV:	Program Analysis and Summary

The results of Tasks I, II, III and IV were intended to provide ONT and MCRDAC with essential data to make an informed decision as to whether to support a follow-on Task V, Feasibility-Level Design.

In Task I, concepts were developed by both Ketron and the Navy. The Navy concept, developed by the Surface Ship Division at DTRC, was used as a reality check on the work done by Ketron. The results of the comparison were provided to Ketron for their comments. Task II involved the testing of two existing WAVESTRIDERs, a 24-foot craft built in 1985 for the SpecWar community and a 60-foot yacht, built for a commercial customer in Florida. The 24-foot craft was initially tested by the NAVSEA Combat Systems Engineering Station (NAVSEACOMBATSYSENGSTA) in Norfolk until it was damaged in high seas (sea state 2-3). It was then moved to DTRC's Surface Effect Ship Support Office (SESSO) located at the NAS, Patuxent River. There it was repaired and modifications suggested by the inventor were made. The craft was then tested again. In general, the craft never performed as predicted by its inventor.

ONT 211 and DTRC 123 visited the 60-foot WAVESTRIDER yacht for what was to be a demonstration ride prior to initiation of formal testing, however, on the day of the demonstration, the yacht's engines failed, and it has not yet run.

The outcome of the Navy's evaluation process is summarized as follows:

(a) Ketron consistently under predicted drag by 100% or more. Examination of Ketron's performance prediction model reveals an incomplete, simplistic and, at times, trivial treatment of a very complex phenomenon.

(b) Ketron's concept development of a WAVESTRIDER configured as a 96-foot AAVP Transporter appears to have several severe deficiencies.

- The speed performance predictions for the 96-foot Transporter are based on methodology used in the performance predictions for the 24-foot and 60-foot WAVESTRIDERs. These predictions have been shown to be grossly optimistic.
- Referenced against a concept development by the Navy, using standard Navy practice, the Ketron structural weight is *approximately 30% lower*. This is unrealistic for a craft that is claimed to go 60 knots vs. the Navy's projected speed of 40 knots.
- The proposed configuration, to meet Ketron's design speed, will likely entail power levels that cannot be met by any existing gas turbine engines that will physically fit within the craft.

(c) Operational aspects of the WAVESTRIDER concept in a Transporter configuration have not been satisfactorily resolved.

- The craft is extremely sensitive to changes in center of gravity. This will complicate cargo spotting and tiedown requirements.
- The WAVESTRIDER configuration appears extremely "*vulnerable*" with overhanging appendages (foils, Arneson props, and wings). Damage to any of these would likely incapacitate the entire craft.

The conclusion of the Navy's evaluation is that the WAVESTRIDER won't work. The WAVESTRIDER concept is basically flawed. The claims made by Peter Payne, and Ketron, the company that employed him, were greatly exaggerated and were not confirmed by prototypes or model tests. From analysis, model tests, and at-sea trials, it is clear that the WAVESTRIDER will not make the predicted speed (>70 knots) or the required speed (>40 knots), and that significant improvements are unlikely. Furthermore, again based on analysis, model tests and at-sea trials, <u>and</u> in spite of claims to the contrary, the ride quality of the WAVESTRIDER will be unacceptable for the anticipated mission. In addition, the WAVESTRIDER hullform is not considered suitable for use as an AAVP Transporter because it is not conducive to wide payload variations (as would be experienced in actual operations) and it is not compatible with well deck restrictions.

1. OVERALL WAVESTRIDER EVALUATION PROGRAM

1.1 Objective

The use of the WAVESTRIDER concept had been proposed as the hullform for a high-speed ship to transport Marine Corps' AAV-P7A1 tracked amphibian vehicles from an over-the-horizon amphibious ship to an off-shore line of debarkation during an amphibious assault.

The purpose of this program was to analyze the WAVESTRIDER concept, to evaluate its feasibility, and to determine if it has sufficient promise to justify proceeding into the next stage of design/development.

1.2 Genesis of WAVESTRIDER Concept

The WAVESTRIDER concept goes back to original GAYLE BOAT launched in 1967. The GAYLE BOAT, and a related derivative, SEAKNIFE, were patented by Mr. Payne in 1973 (U.S. Patent No. 3,763,810 granted 9 October 1973, "High Speed Boat With Planing Hull" and the "High Speed Boat" U.S. Patent No. 3,709,179 granted 9 January 1973).

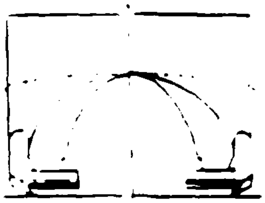
The WAVESTRIDER concept involves a hullform that consists of two SEAKNIFE-like hulls connected together as a catamaran. WAVESTRIDER utilizes a combination of planing hull and hydrofoil/planing plate dynamic lift to reduce both resistance and motions at high speeds (**Figure 1**). Mr. Peter R. Payne, is the inventor of WAVESTRIDER (Patent Application Serial Number 029,054 filing date 23 March 1987, "Planing Catamaran"). At the time of the initiation of this evaluation, Mr. Payne was an employee of KAI, a wholly owned subsidiary of Ketron, Inc.

Although the GAYLE BOAT and the SEAKNIFE were reported to be smooth riding at speed in a seaway, the extremely high beam loading of the narrow hulls resulted in excessive hump drag. Also, since they were intentionally soft in pitch (as well as heave), it took only relatively small center of gravity shifts or a change in heading relative to the wind to cause excessive changes in trim angle which had to be compensated for with craft levelers mounted on the hull transoms. These levelers could only serve to trim the bow down, not up.

In 1982, a new craft, the WAVESTRIDER, **Figure 1**, was designed and built for the United States Navy SpecWar community. Unlike the GAYLE BOAT and SEAKNIFE, this 24-foot WAVESTRIDER had a step in each hull about three-quarters of the way aft. Immediately forward of this step, a wing or "planing plate" bridged one hull to the other. Fixed canards were located towards the bow of the boat. These additions to the basic hull were intended to completely eliminate the problem of high hump drag and permit a wide range of longitudinal center of gravity locations once the boat was planing. There was, however, a downside to the "improvements" over SEAKNIFE. The longitudinal center of buoyancy was now much more restricted before the boat would get on plane. If it were so far forward such that the canard would be at a negative angle of attack, then the craft would not get on plane at all.

Essentially, this craft was intended for mainly people transportation, and those being "fit young men" according to Mr. Payne. It was not intended to give a very soft ride, only soft enough to avoid physical injury such as the lower leg fractures which

TWIN HULL (CATAMARAN-LIKE) CRAFT



SUPERCRITICAL PLANING TWO-STEPPED HULL & HYDROFOIL/PLANING PLATES

TWO PARTIAL PLANING PLATES (FORWARD)
SINGLE FULL-SPAN PLANING HYDROFOIL (AFT)

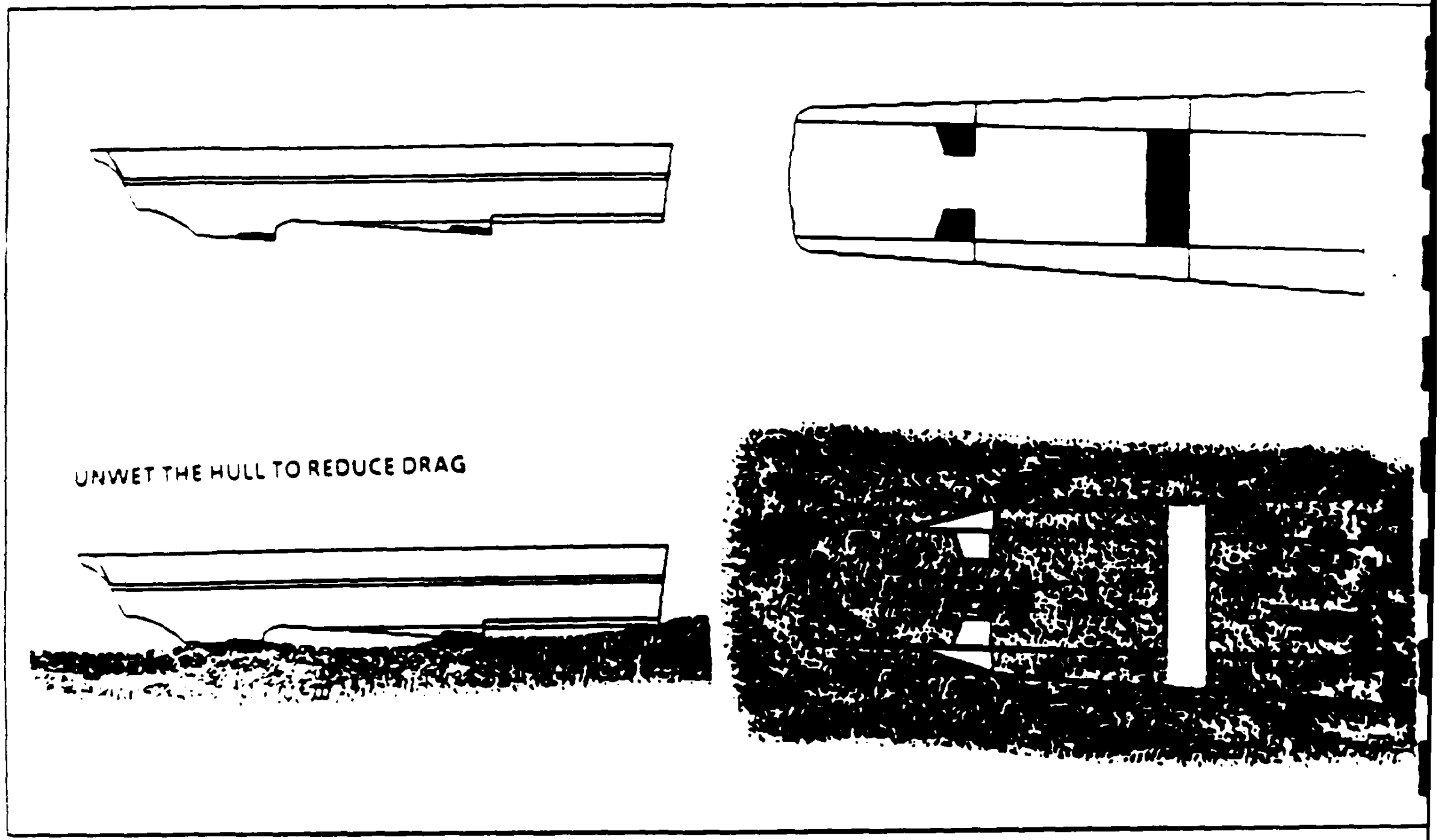


FIGURE 1 - WAVESTRIDER CONCEPT

were then occurring with existing equipment, and just soft enough to avoid extreme discomfort.

As a result of Mr. Payne's experience with this boat, he came to believe that all-moving canards which could be trimmed to be almost awash when carrying their load would have many advantages. In particular:

- Much lower vertical accelerations; and
- Elimination of the narrow longitudinal center of gravity range needed to get on plane because the canards can also be trimmed to large bow-up angles.

In proposing the use of WAVESTRIDER as an AAVP Transporter, Mr. Payne and Ketron claimed that the WAVESTRIDER would provide markedly reduced drag, such that speeds much in excess of 40 knots would be possible. In this regard, it was stated that the 24-foot WAVESTRIDER that had already been built had already achieved speeds in excess of 60 knots. The WAVESTRIDER concept of operations was also said to work independently of speed or sea state or heading. It was also claimed that the WAVESTRIDER would provide good seakeeping in rough seas on all headings. Mr. Payne cited his many papers, experiments, the GAYLE BOAT, the SEAKNIFE, the 24-foot WAVESTRIDER, and the 60-foot yacht as evidence of more than twenty years of his personal R&D on advanced hull forms. It was this extensive background that was said to have led to what what he termed "a successful and innovative" WAVESTRIDER hullform.

1.3 Evaluation Approach

On 11 May 1988 ONT signed sole source contract (*N00014-88-C-0367*) with Ketron, Inc. for the evaluation of the WAVESTRIDER concept. Five major tasks were planned. These are outlined in **Figure 2**.

Task I was titled *Concept Development and Risk Analysis*. It involved the generation of a (nominal 95-foot) WAVESTRIDER to transport four to six AAV-P7A1s. Two concept development efforts were undertaken, one by Ketron, and the other, a parallel "reality check" by the Navy. The results of the independent Navy "reality check" was provided to Ketron, in parallel with their effort. In addition to the concept development, Task I was also to generate a Risk Analysis that identified areas of risk. A preliminary Verification Plan to address these risk areas was also to be developed under Task I.

The desired characteristics for the WAVESTRIDER AAV-P7A1 Transporter titled *Exploratory Requirements and Standards,* were developed and included as a Tab in the contract. They are attached as Appendix C.

Task II involved *At-Sea Trials* of two WAVESTRIDERs. The first was to be a 60-foot WAVESTRIDER yacht that was being built in Florida for a commercial customer. (**Figure 3**). This vessel was to be chartered by Ketron for dedicated Navy trials. It was planned that Navy personnel would also monitor the Builder's and Owner's Trials, as feasible.

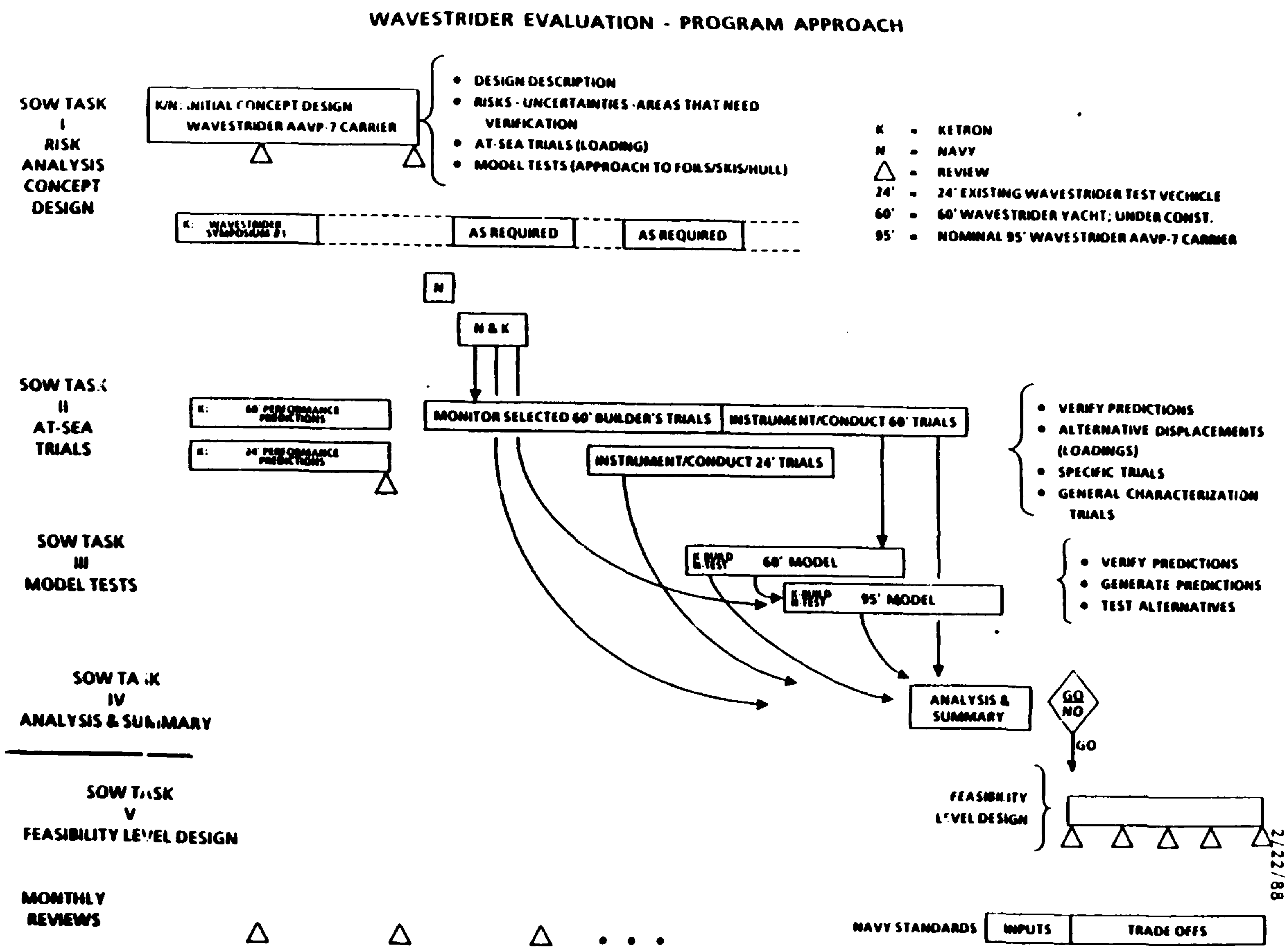


FIGURE 2 - WAVESTRIDER EVALUATION - PROGRAM APPROACH

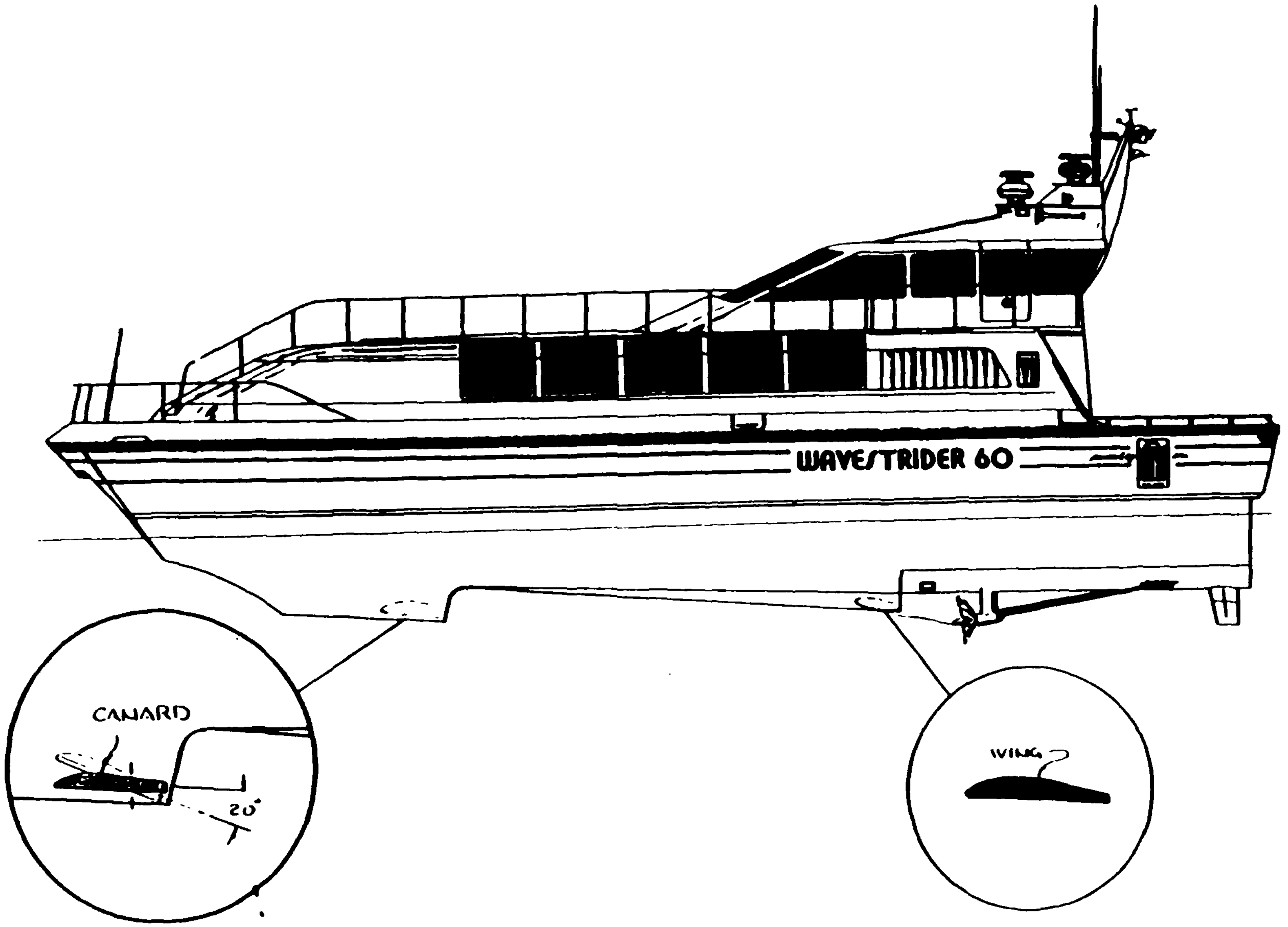


FIGURE 3 - THE 60-FOOT WAVESTRIDER DESIGN FOR THE VIRTUE BOAT COMPANY

The second WAVESTRIDER to be tested was a 24-foot boat designed by Mr. Payne (**Figure 4**). It was to be tested in the Cheasapeake Bay or the Norfolk, VA area.

Prior to commencing any at-sea trials, Ketron was required to provide performance predictions for the craft. The purpose of these at-sea trials was to verify the predictability of the performance characteristics of WAVESTRIDERs. Therefore, the most important result of these trials was to be a determination of the correlation between predicted performance and actual performance.

Task III was titled *Model Tests* and was to involve the design and construction of towing tank test models of two WAVESTRIDERs. The models were to be delivered to the Navy and tested by the Navy at the DTRC facility (or at a facility chosen by DTRC).

The tests of this model were intended to verify the analytical prediction capability for WAVESTRIDER performance and to assess the utility of a model of this size in realistically predicting the performance of a full-scale WAVESTRIDER. This task was to validate the use of prediction calculations and/or model tests as a design tool for this type of hullform.

The second WAVESTRIDER model to be evaluated was one of the design of the (nominal 95-foot) WAVESTRIDER AAV-P7A1 Transporter that was to be developed.

As will be seen, this task was never initiated because the 60-foot yacht, the basis of the first model, has yet to successfully operate.

Task IV was titled *Program Analysis and Summary* and involved the overall analysis and summary of all the Navy and Ketron efforts associated with the WAVESTRIDER evaluation.

Task V was to be a follow-on *Feasibility-Level Design*. It was to be initiated in the event of a favorable Navy-Marine Corps Review. It was not undertaken.

2. BASIC PRINCIPLES OF WAVESTRIDER CONCEPT

2.1 Description

The WAVESTRIDER is claimed to be a planing craft. At design speed the weight of the vehicle is supported by three planing surfaces (two canards and one main foil). (**Figure 1**).

Figure 5a depicts the essential generic elements of any planing phenomenon. Planing lift is generated when a planing surface imparts a downward momentum to the free surface of the water. This action is manifested as a downward depression of the water surface behind the planing plate. The planing surface is generally the bottom of a planing hull, but, in theory, it can be any surface including, on the WAVESTRIDER hullform, the forward canard, the after foil, or a portion of the slender side hulls. This is depicted in **Figure 1** as the <u>unshaded</u> portions of the lower right sketch.

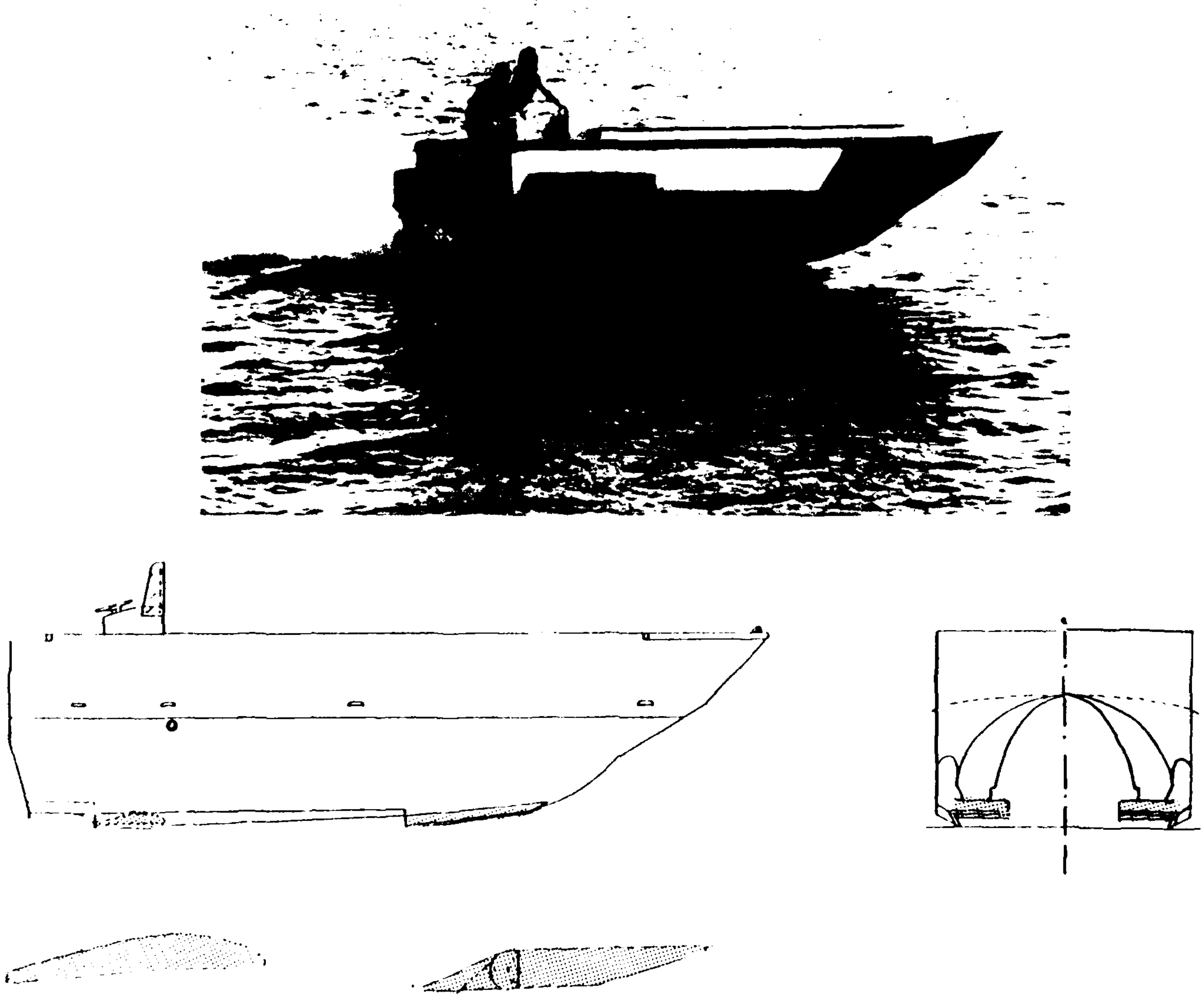


FIGURE 4 - 24-FOOT WAVESTRIDER

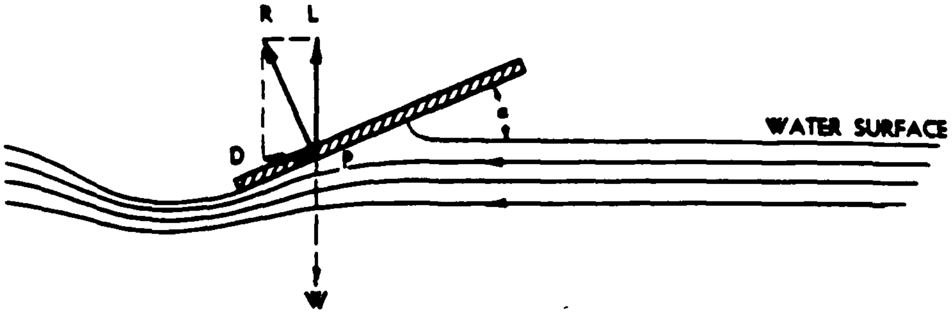


FIGURE 5a - ESSENTIAL PLANING GEOMETRY

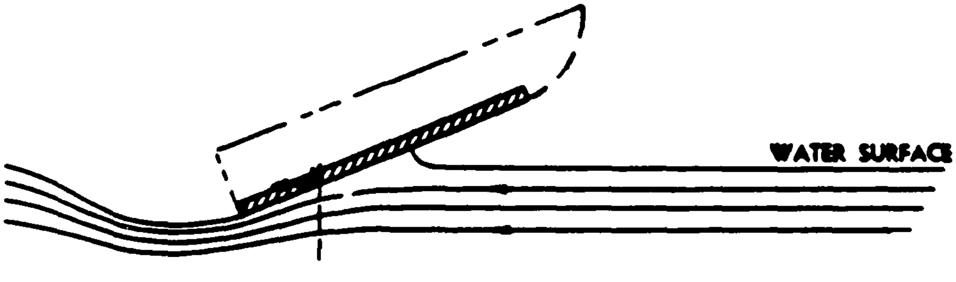


FIGURE 5b - PLANING HULL

FIGURE 5 - PLANING HULL PHENOMENON

Planing theory in calm water is relatively well understood and has been extensively documented. References 1 through 7 are some of the more comprehensive treatments of the planing phenomenon. Unfortunately, calm water in the real world is a rarity, and a practical planing craft must operate over irregular water surfaces. These irregularities (waves and wakes) cause the actual planing or lifting surface (wetted area) to experience drastic excursions (**Figure 5c**). Even in relatively small waves, the lifting area of a typical planing craft may change by several hundred percent. This results in the very drastic slamming and impact loads that are usually characteristic of planing hulls. Furthermore, planing theory in a sea state is not well understood, nor is it sufficiently well developed to allow confident design procedures. The effect of sea state is generally treated by empirical corrections of calm water performance predictions.

Returning to the specific WAVESTRIDER hullform (**Figure 1**), its salient hydrodynamic features include two catamaran type hulls with a bridging foil-like cross structure. Each hull can be viewed as primarily a triangular or wedge in configuration, with a step in the bottom about 2/3 aft from the bow. The space between the hulls and under the cross structure describes a converging tunnel. Each bow is fitted with a "canard" planing plate. At the step of the wedge hulls, and spanning the space between the hulls, the WAVESTRIDER is fitted with the main planing surface (often referred to as the "wing"). At design speed, it is intended that the two "canards" and the "wing" support the total weight of the craft.

Mr. Payne and Ketron claim (13)* that what makes the WAVESTRIDER different from other planing craft is that the maximum planing or lifting area is limited to that of the chord or area of the "canards" and the "wing". As a result, they claim that the lift force excursions are controlled, thereby limiting slamming and vertical accelerations. It is further argued (12) that the wake (the depressed free surface) behind the bow canards causes the wedge sidehulls to unwet and thereby eliminate the parasitic friction drag of the sidehulls. **Figures 6 and 7** illustrate the proposed unwetting phenomenon. The final claim for the hydrodynamics of the WAVESTRIDER focuses on the constructive interaction between the bow canards and the main lifting wing. It is argued (18) that the canards shape the wake such that the surface exhibits a favorable inflow to the main planing surface (wing). This characteristic is also portrayed in **Figure 1**.

2.2 General Evaluation

The preceding claims for the WAVESTRIDER appear to be largely based on high speed, theoretical, calm water characteristics and behavior. In a real world sea state, there appear to be two modes of operation. The first can best be described as "skipping". For small wave heights (not exceeding the forward vertical projection of the planing surface), the wetted area (active lifting surface) may exhibit excursions that range from full chord to zero values. The second mode of "in-sea state" operation is the "penetration" mode. Here the wave height exceeds the forward vertical projection of the planing surface. The lifting surface now punches into the wave until the full chord is wetted and then continues on to penetrate the wave.

Figure 8 depicts the mechanics of the "penetration" phenomenon. Once the lifting surface penetrates the wave its lifting area reaches its maximum value and hence the lift is limited. By contrast, in a conventional planing hull (**Figure 9**), the lifting area would continue to increase drastically, giving rise to very high vertical accelerations.

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*Note: Numbers in parenthesis refer to the reference number in Attachment B.

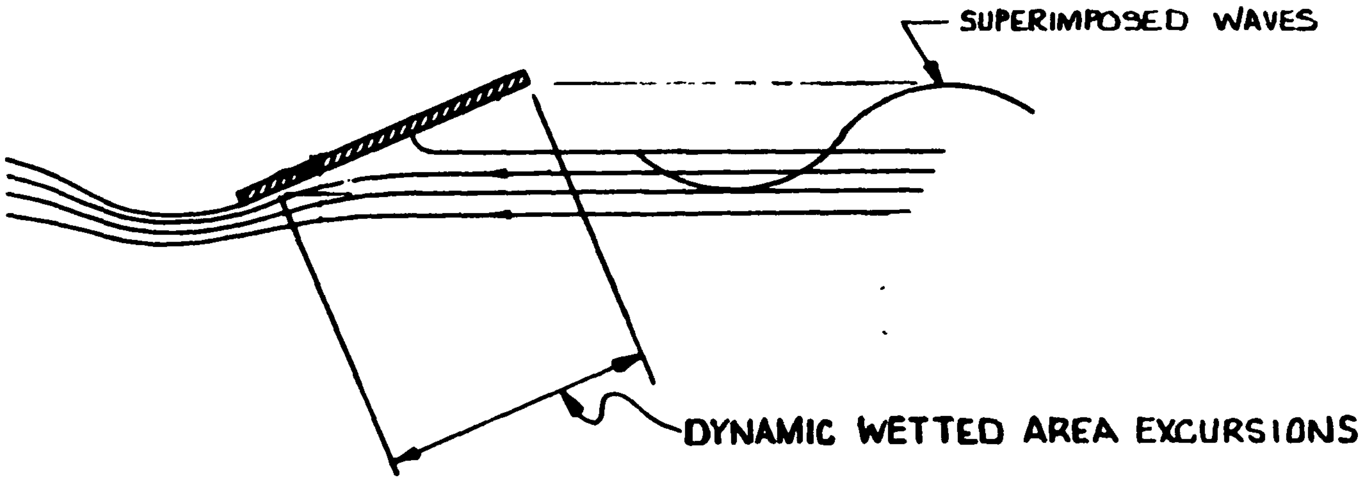


FIGURE 5c - SEA STATE PLANING

FIGURE 5 - PLANING HULL PHENOMENON

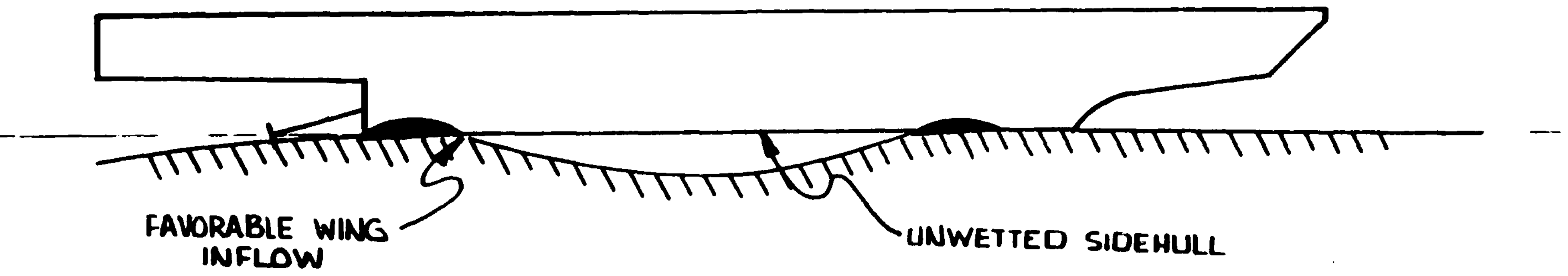


FIGURE 6 - BASIC PRINCIPAL IN "ON-DESIGN" OPERATION
(Schematic Only)

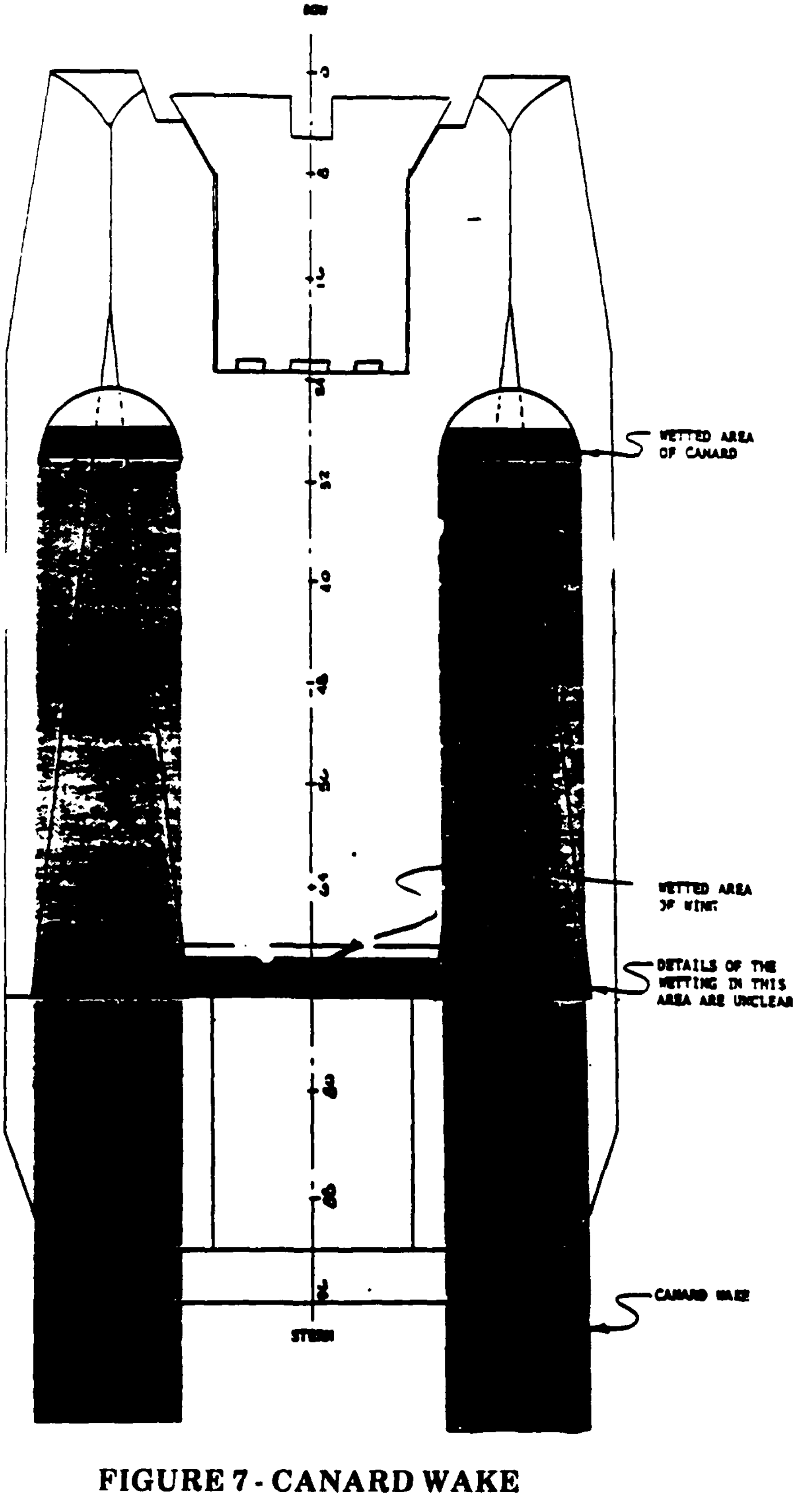


FIGURE 7 - CANARD WAKE

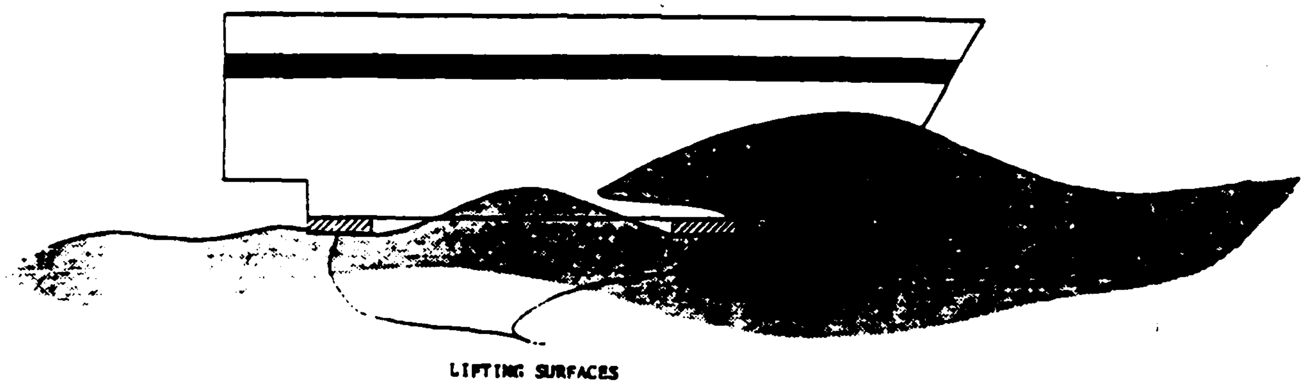


FIGURE 8 - "PENETRATING" MODE OPERATION

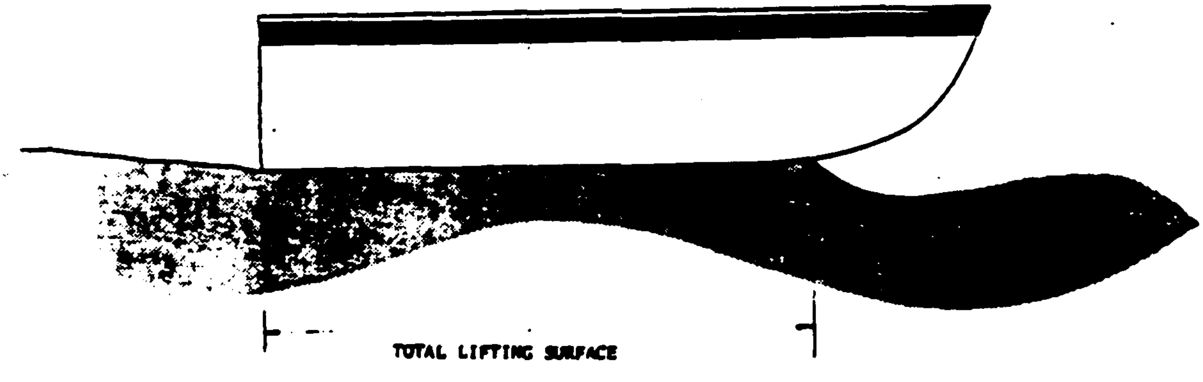


FIGURE 9 - CONVENTIONAL HULL SLAMMING

3. WAVESTRIDER HARDWARE STATUS

The WAVESTRIDER vehicle status can be considered as being bracketed by three vehicles: two real and one paper design (although there were others). The smallest WAVESTRIDER is the 24-foot craft (**Figure** 4). It has been built and tested. The next vehicle size up is a private 60-foot yacht that has been fabricated but not yet tested. The last and largest WAVESTRIDER (**Figure 10**) is the 96-foot Transporter concept developed under this program to transport from four to six tracked amphibians.

The overall strategy of this evaluation was to sequentially develop performance predictions for each of the three WAVESTRIDER configurations. These predictions would then, also sequentially, be checked against the measured performance of the 24-foot craft and the 60-foot yacht. The goal was to assess the maturity of the WAVESTRIDER design methodology. If predictions for existing vehicles accurately represented experimental results, then there would be confidence in the predictions made for the concept development of the 96-foot Navy Transporter.

This section focuses on the physical characteristics of the three WAVESTRIDER vehicles and identifies their similarities and their differences. The discussion concludes with a comparison of the WAVESTRIDER craft and contrasts them against other high performance marine vehicles.

3.1 Existing Vessels

3.1.1 24-Foot Craft

The general arrangement of the 24-foot craft was presented in **Figure** 4. The 24-foot WAVESTRIDER is the most developed of the three craft. Ketron claimed that they had done considerable computer modeling and computer optimization of the 24-foot design. The 24-foot WAVESTRIDER has been independently tested by the Navy at the NAVSEA Combat Systems Engineering Station (Norfolk) and by DTRC's Surface Effect Ship Support Office (SESSO) located at the Naval Air Station, Patuxent River, MD. Thus, for the 24-foot craft, there exists an extensive database for comparing the performance predictions that were developed by Ketron to the actual operating test data. Further, the data comes from two independent sources. The predicted speeds of 55 knots have not been realized. In the Navy at-sea trials the test craft achieved a maximum speed of only 38 knots.

3.1.2 60-Foot Yacht

The 60-foot WAVESTRIDER yacht was designed for a private customer. Projected speeds were in excess of 50 knots. **Figure 3** provides a side view of the yacht. The key technical specifications are shown in **Figure 11**. The configuration of the 60-foot yacht is significantly different from that of the 24-foot craft. Perhaps the key difference is in the increased size of the sidehulls. The 60-foot sidehulls are rather substantial blunt wedges, whereas the 24-foot craft had very fine catamaran hulls. The other unique departure for the 60-foot yacht is the forward facing propeller (tractor) arrangement. It is argued that these propellers will operate as surface running ventilated propellers in the wake of the hull step. It is expected by Mr. Payne that the step will provide surface control to allow precise adjustment of the operating propeller disk immersion. The 60-foot WAVESTRIDER yacht has been built and launched. To date the yacht has not exceeded a speed of 13 knots.

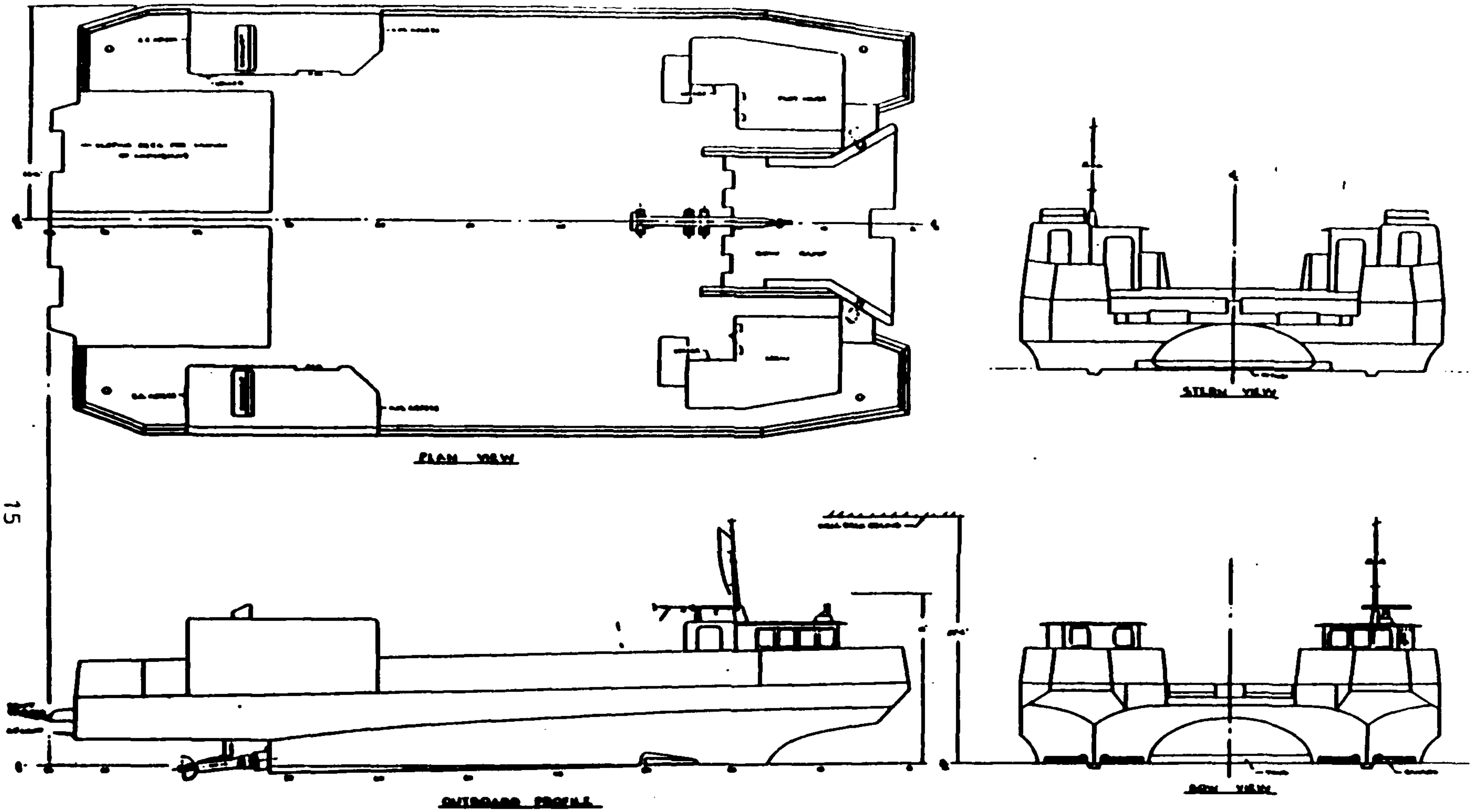


FIGURE 10 - 96-FOOT TRANSPORTER

Length Over All	60 feet, 2 inches
Beam	23 feet, 6 inches
Draft	
Light Ship	
(With Propeller)	4 feet, 3 inches
Heavy Ship (55,000 Pounds)	
(With Propeller)	5 feet, 3 inches
Displacement	
Light Ship	36,414 pounds
Heavy Ship	
Including cargo and crew	55,000 pounds
Fuel Capacity	1,373 U.S. gallons
Passenger/Cargo	
(Tanks Full)	13,559 pounds
Powering	Two, 500 horsepower diesel (Isotto Frashini ID38SS 6V)
Gearing	
Marine Drive (IRM 320-PL)	1.5:1 reduction
V-Drive (ZF V-160/250M)	1.45:1 reduction
Total Reduction	2.18 reduction
Propeller	Surfacing-piercing
Diameter	30 inches
Pitch	37.2 inches
Number of Blades	4
Blade Area Ratio	40 percent
Center of Gravity (Light Condition)	
Horizontal	30.41 feet (Aft of Station 0)
Vertical	6.33 feet (Above Baseline)
Calm Water Range	
(With Standard Tanks)	2,680 nautical miles
Deckspace	1,200 square feet

FIGURE 11 - TECHNICAL SPECIFICATIONS FOR THE 60-FOOT WAVESTRIDER YACHT ENTERPRISE

3.2 Possible Future Vessels

3.2.1 96-Foot AAVP Transporter

The 96-foot AAVP Transporter WAVESTRIDER configuration is depicted in **Figure 10**. This was developed as a paper concept under this evaluation program. In general, the 96-foot Transporter more closely resembles the geometry of the 60-foot yacht than the 24-foot craft. The key difference appears to be in the fineness of the sidehulls. The sidehulls of the 96-foot WAVESTRIDER are very wide and shallow compared to those of the 60-foot yacht. Propulsion is to be provided by gas turbine driven Arneson-mounted surface ventilated propellers. These propellers are located under the bustle or stern overhang.

3.3 Comparisons

There are similarities and differences among the three WAVESTRIDER vehicles. To provide an overall perspective, they have been plotted on the classic Karmann-Gabrelli (VK-G) transport efficiency graph (**Figure 12**). The data points are based on "claimed" performance and are calculated for a common speed of 60 miles per hour. It is evident from the figure that the projected "transport efficiency" of the WAVESTRIDER is comparable to that of hydrofoils.

For the only WAVESTRIDER for which performance was actually measured (the 24-foot craft), the specific resistance, P/WV, is considerably worse than predicted.

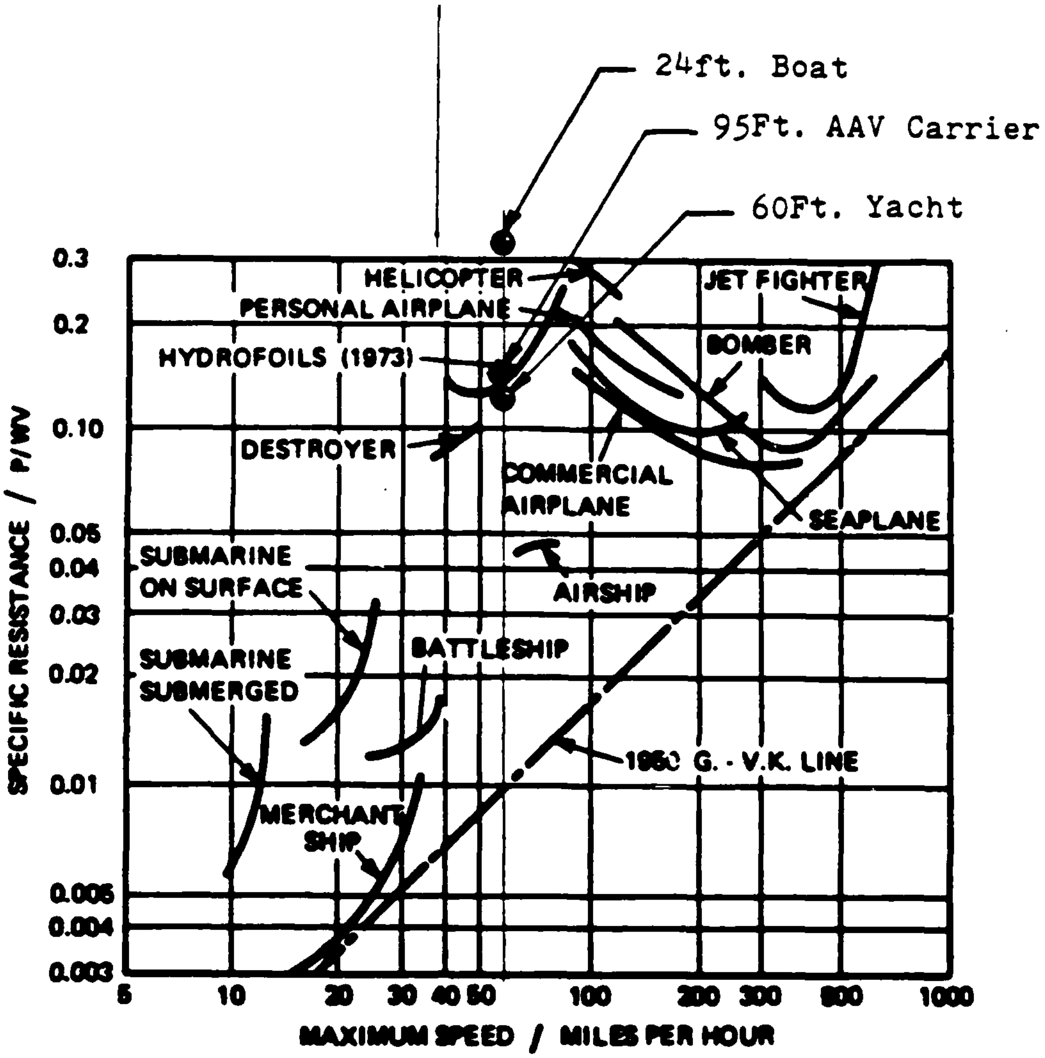
Figure 13 is a side-by-side comparison of the salient features of the three concepts. A number of key points are in order:

(a) The predicted loading per square-foot on the planing surfaces (canards & wing) exceeds 4000 psf for the 96-foot Transporter. The tested 24-foot craft has a lift load of approximately 300 psf. The significance in this is that this lift is achieved only by the lower planing surface. As a comparison, the Boeing "Jet Foil" lifting surfaces are high aspect ratio, fully submerged foils. Approximately 60% of the lift comes from the upper surface. The total foil loading is approximately 1100 psf. This is a very efficient lifting system. If the projected lift loading is used to calculate an equivalent lift coefficient, then the 96-foot craft would have to operate with a lift coefficient exceeding 0.5. The lift per square-foot generated by the 96-foot WAVESTRIDER configuration has to be four times higher than the best existing hydrofoil designs.

(b) **Figure 13** also identifies three important geometric parameters: the sidehull taper ratio, or the fineness of the sidehulls; the interhull convergence ratio, or the tunnel taper; and the tunnel height ratio. It is clear that:

- The 24-foot craft has very fine sidehulls and hence one would expect relatively low hull drag. The 60-foot and 96-foot WAVESTRIDERs have increasingly blunt sidehulls.

NOTE: (1) Common Speed Of 60 mph.
(2) Ordinate is "Power per Ton Knot"
(The lower the number the higher
the efficiency of the vehicle)



24ft. Boat

95Ft. AAV Carrier

60Ft. Yacht

Specific Resistance of Single Vehicles

FIGURE 12 - PERFORMANCE CHARACTERISTICS COMPARISON

	24 ft.	60 ft.	95 ft.	Units
Disp.	4500	50,000	490,000	lbs
Fwd. Area	2.5	4	24	ft-sq
Aft. Area	12	20	160	ft-sq
Lift Fwd. (1)	360	2500	4080	psf
Lift Aft. (1)	300	2000	2450	psf
Cl @ 40 m.w.	.065	.433	.530	-
Taper Ratio (2)	12	7.5	4.8	-
Convergence Ratio (3)	1.5	1.5	1.66	-
Height Ratio (4)	0.5	0.2	0.142	-

Note: (1) The foil loadings are based on an 80/20 load split between the main and bow surfaces.

(2) Hull "Taper Ratio" is the nominal hull length divided by the nominal beam at the step.

(3) Tunnel "Convergence Ratio" is the nominal tunnel width at the bow divided by the width at the step.

(4) Tunnel "Height Ratio" is the nominal tunnel height at the bow divided by the overall craft beam at the step.

FIGURE 13 - WAVESTRIDER VEHICLE COMPARISONS

- The convergence of the space between the sidehulls (the tunnel) is very pronounced for the 96-foot design.
- The tunnel height is much smaller for the 96-foot WAVESTRIDER than for the 24-foot craft. In fact the 96-foot WAVESTRIDER Transporter, when fully loaded, has a tunnel top (the underside of the cross-structure) that is below the free water surface.

The trends toward a more squat and blunted geometry are a source of concern. It is not clear, nor has Ketron established, what the impact of these kinds of configurational changes will be on the total drag of the vehicle.

4. PERFORMANCE PREDICTIONS

One of the key elements of the process of Navy's evaluation of the WAVESTRIDER concept was the comparison between Ketron's performance predictions and actual measured performance of the 24-foot craft and the 60-foot yacht. The WAVESTRIDER proponents (Mr. Payne and Ketron) were tasked, under contract, to generate drag-speed curves for the three WAVESTRIDER vehicles (24-, 60-, and 96-feet). These were to address calm water conditions as well as sea states 1 through 3. Predictions also were to be made of the dynamics (accelerations) of the three WAVESTRIDER configurations as well.

This section is structured in three parts. The first provides an overview of the formulation of the resistance equations that were presented by Ketron. The second outlines the key elements of Ketron's solution methodology for calculating the resistance from the equations. The third part focuses on Ketron's dynamics model of the WAVESTRIDER.

4.1 Resistance Model

The resistance or drag model used by Ketron was developed and presented in references 16, 17, and 18 for the 24-, 60-, and 96-foot craft, respectively. With minor variation, the same equations were used in each case. The dominant drag (resistance) sources are identified as follows:

- Aerodynamic drag
- Hull wetted skin friction drag
- Various step drags
- Canard drag
- Wing drag
- Various appendage drags (rudder, propeller hub, etc.)

There are four points to be made regarding the drag formulation as was used in calculating the resistance of the craft.

- The total drag is the algebraic summation of a series of stand-alone hydrodynamic components. The resistance model does not include synergistic interactions between the various craft components.

- The model employs steady state or time averaged constants. The real phenomenon is very dynamic and clearly time dependent.
- The resistance model allows motions only in pitch and heave. It does not include roll and surge.
- The resistance model neglects wetting and spray drag. In the 60-foot yacht, the model neglects the propeller support strut drag (which is in the propeller race), and the 60- and 96-foot resistance models do not consider the impact of the propeller rooster tail on the underside of the bustle.

The WAVESTRIDER resistance formulation was based on calm water conditions. Resistance in sea states is estimated by applying a fixed percentage correction factor (~10% per sea state). **Figures 14** and **15**, taken from performance predictions for the 24-foot craft dated 10/6/88 and 11/4/88, respectively, show the interdependencies between weight, canard trim angle, and sea state.

It is interesting to note that cross-plotting is not possible. Point A of **Figure 14c**, ratio corrected for weight and canard trim, is not consistent with the curves presented in **Figure 15**.

For the 60-foot yacht predictions, similar irrationalities and inconsistencies are evident. **Figures 16** through **19** were developed as cross plots of a number of different predictions that were generated by Ketron. They are included here to highlight some of the more obvious points:

- <u>Figure 16</u>: It appears that the drag converges at high speed.
- <u>Figure 17</u>: In sea state 3, light ship (48,000 lbs) has a higher drag than medium weight (54,000 lbs).
- <u>Figures 18 and 19</u>: Considerable confusion exists as to the predicted drag value at hump speed.

Figure 20 suggests a very significant dependency of drag on CG (center of gravity) location and on canard trim angle. **Figure 21**, on the other hand (for the same conditions of calm water and 54,000 lbs), implies an approximate drag variation of 5% with canard variation from 2 to 8 degrees. Thus, it may be concluded that the CG is the dominant variable.

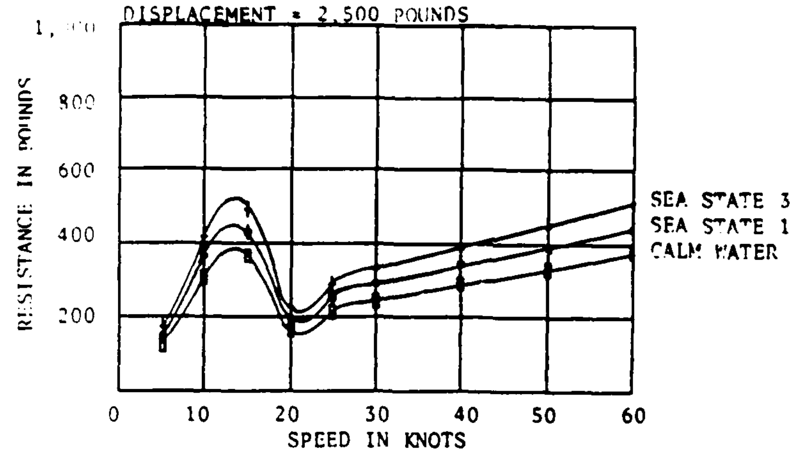


FIGURE 14a - CANARD TRAILING EDGE ANGLE AT 7°

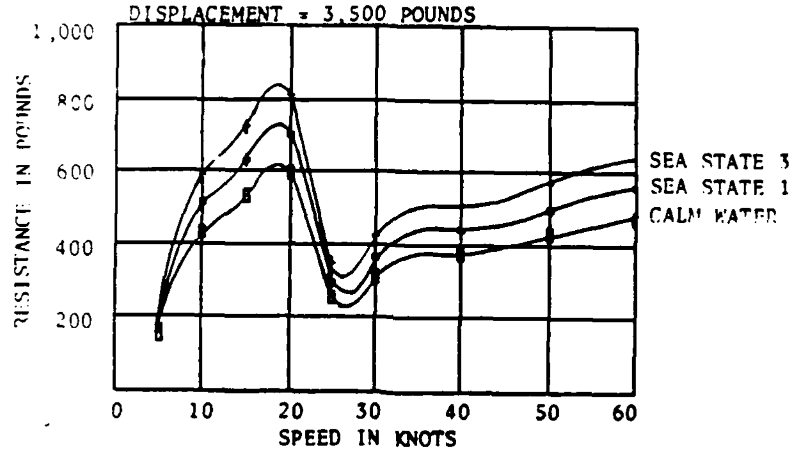


FIGURE 14b - CANARD TRAILING EDGE ANGLE AT 7°

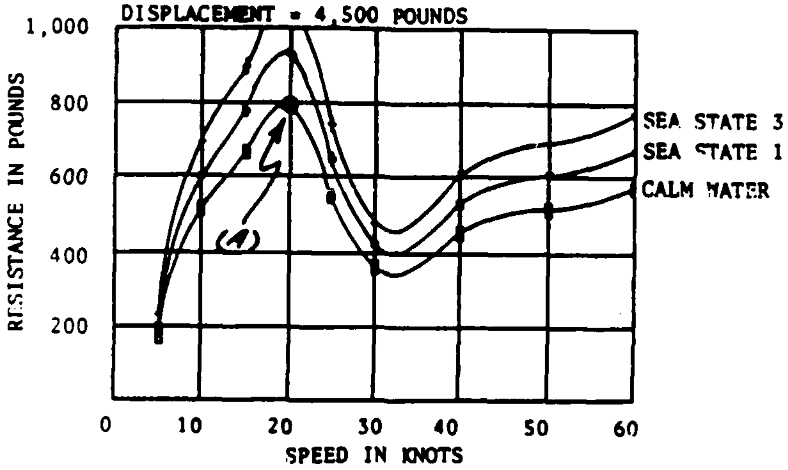
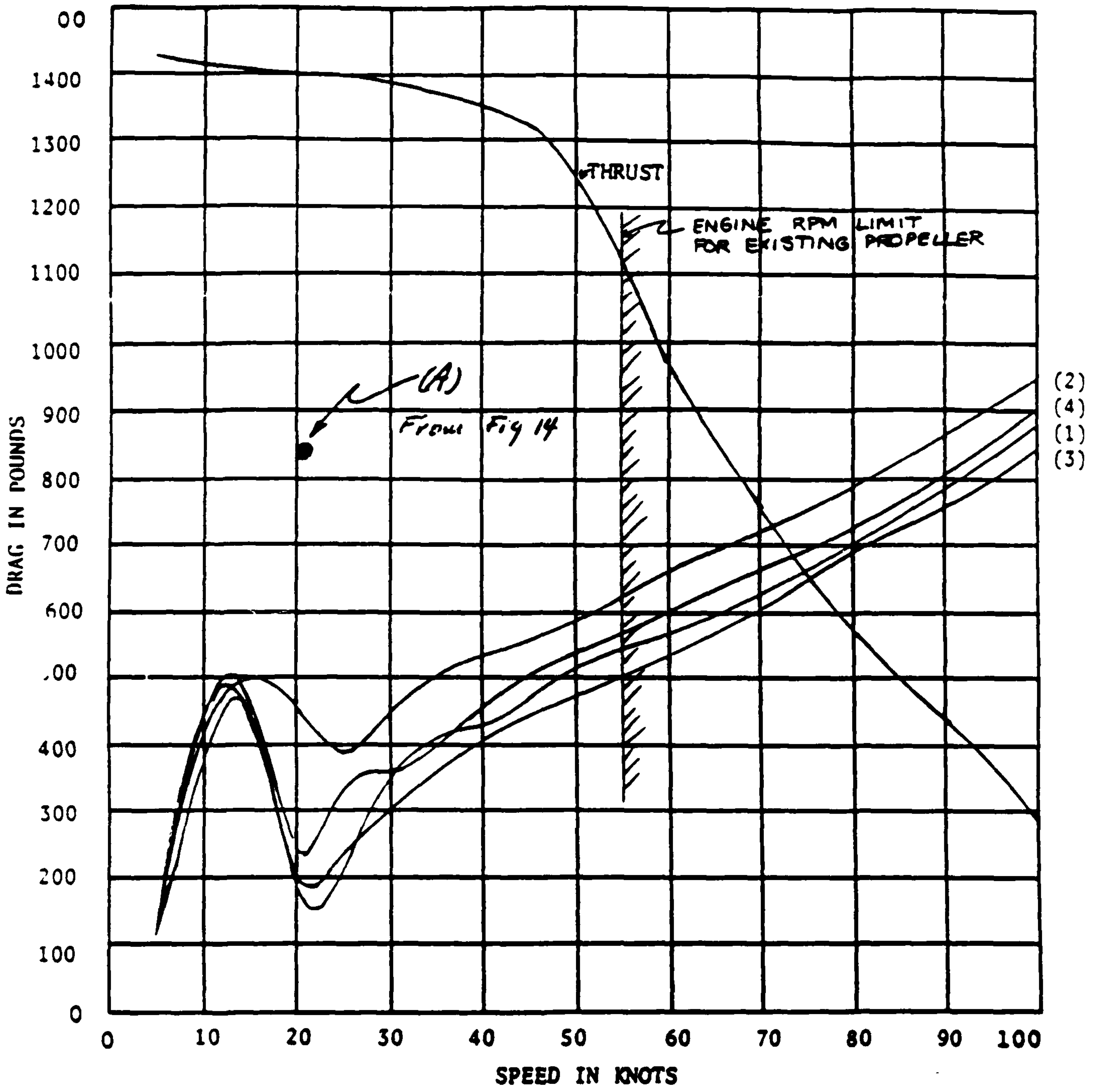


FIGURE 14c - CANARD TRAILING EDGE ANGLE AT 7°

FIGURE 14 - 24-FOOT DRAG PREDICTIONS WITH DIFFERENT DISPLACEMENTS



(1) LCG = 16 FEET, CANARD CAMBER = 0°

(2) LCG = 16 FEET, CANARD CAMBER = 3°

(3) LCG = 18 FEET, CANARD CAMBER = 0°

(4) LCG = 18 FEET, CANARD CAMBER = 3°

FIGURE 15 - 24-FOOT THRUST AND RESISTANCE CURVES, WEIGHT = 4,200 POUNDS, CALM WATER

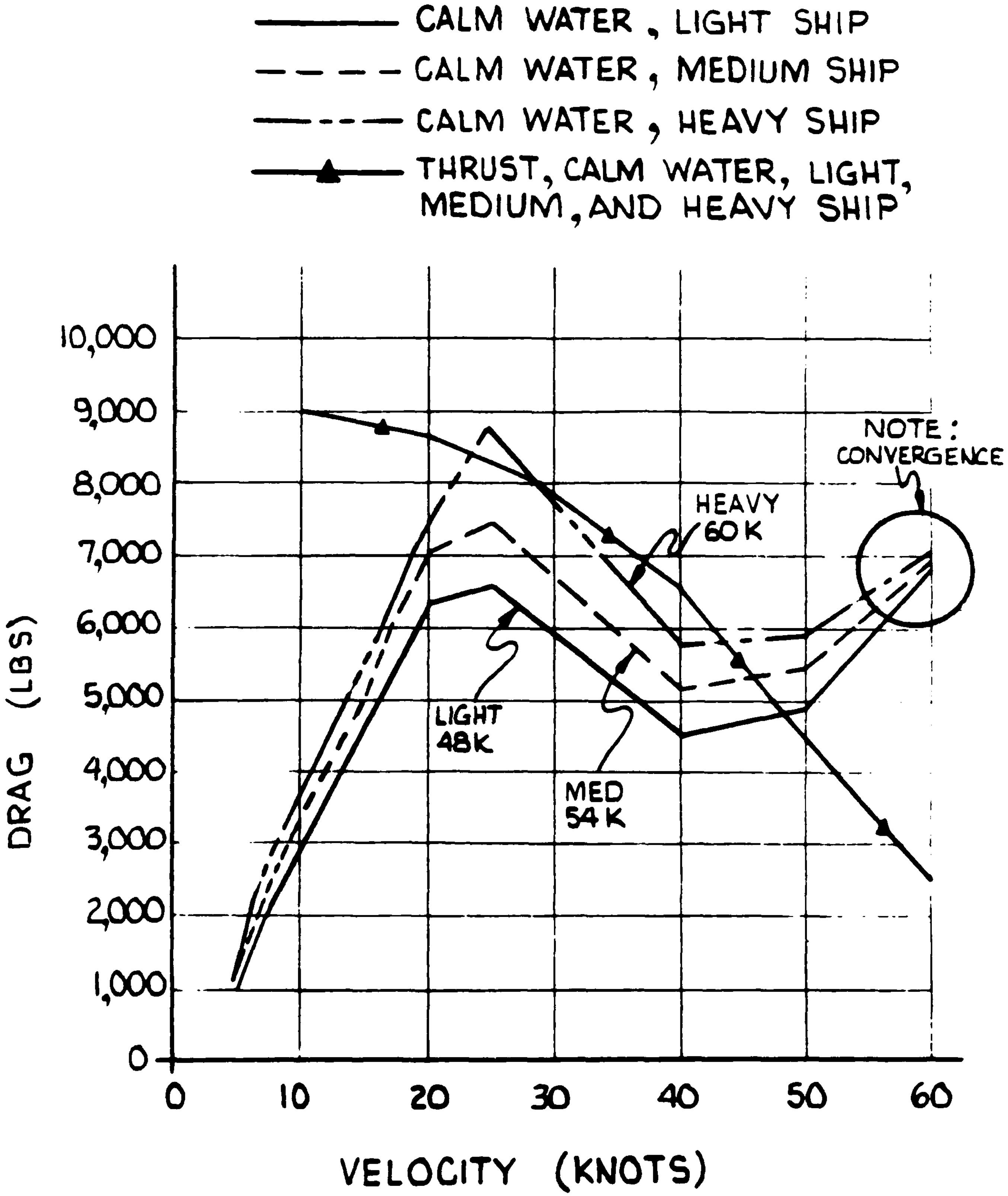


FIGURE 16 - 60-FOOT WAVESTRIDER

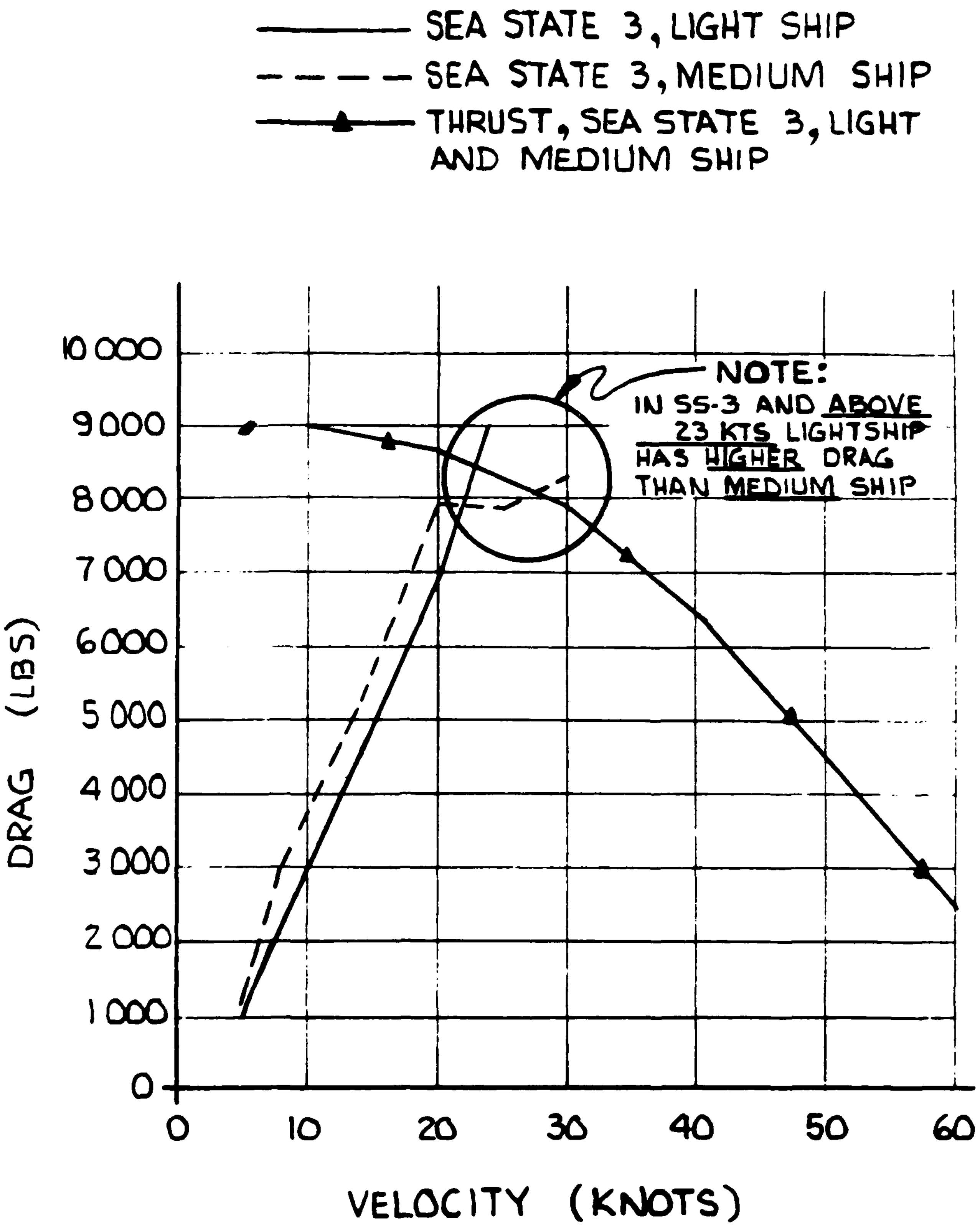


FIGURE 17 - 60-FOOT WAVESTRIDER (SS3)

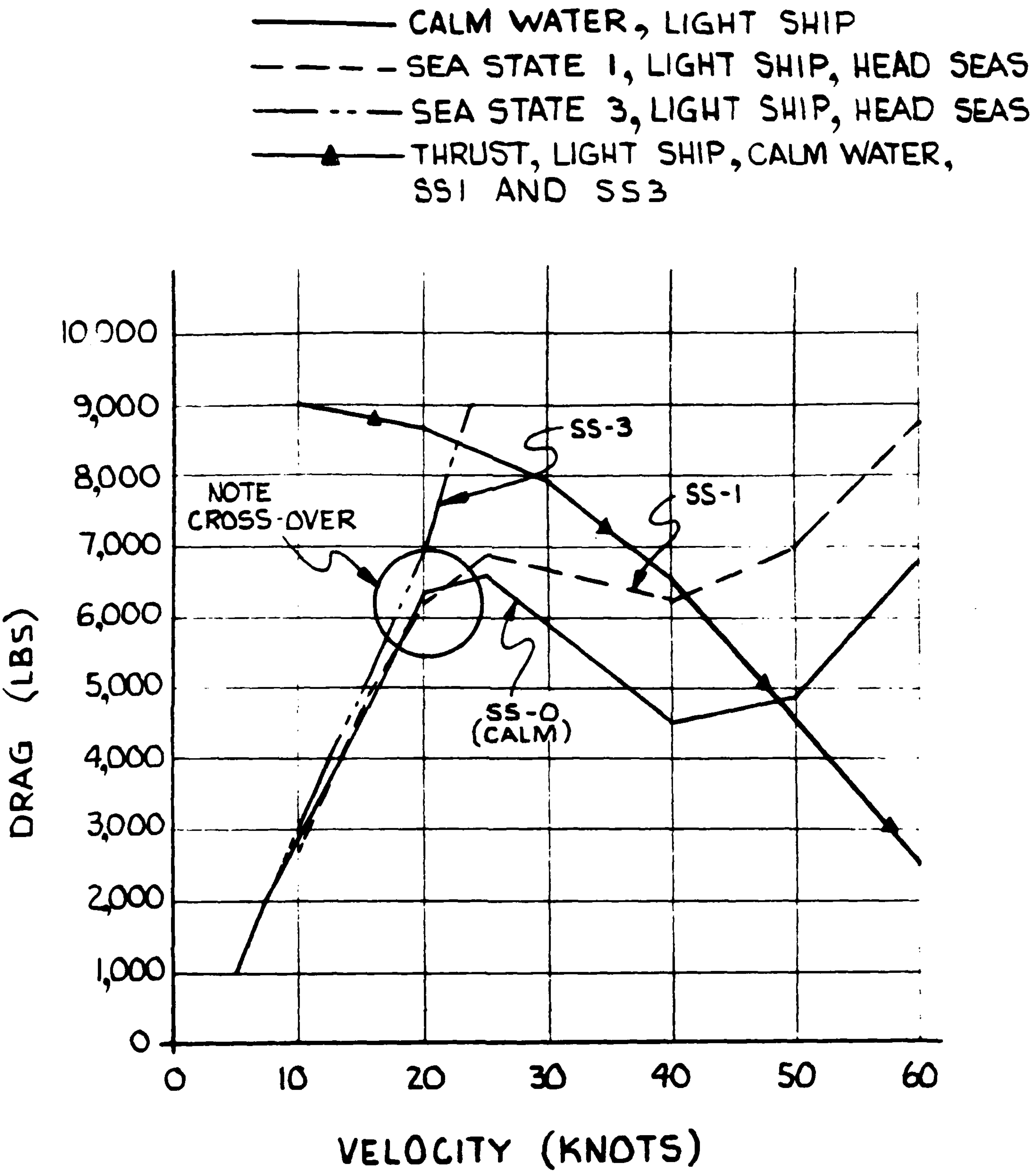


FIGURE 18 - 60-FOOT WAVESTRIDER LIGHT CONDITION (48 K LBS)

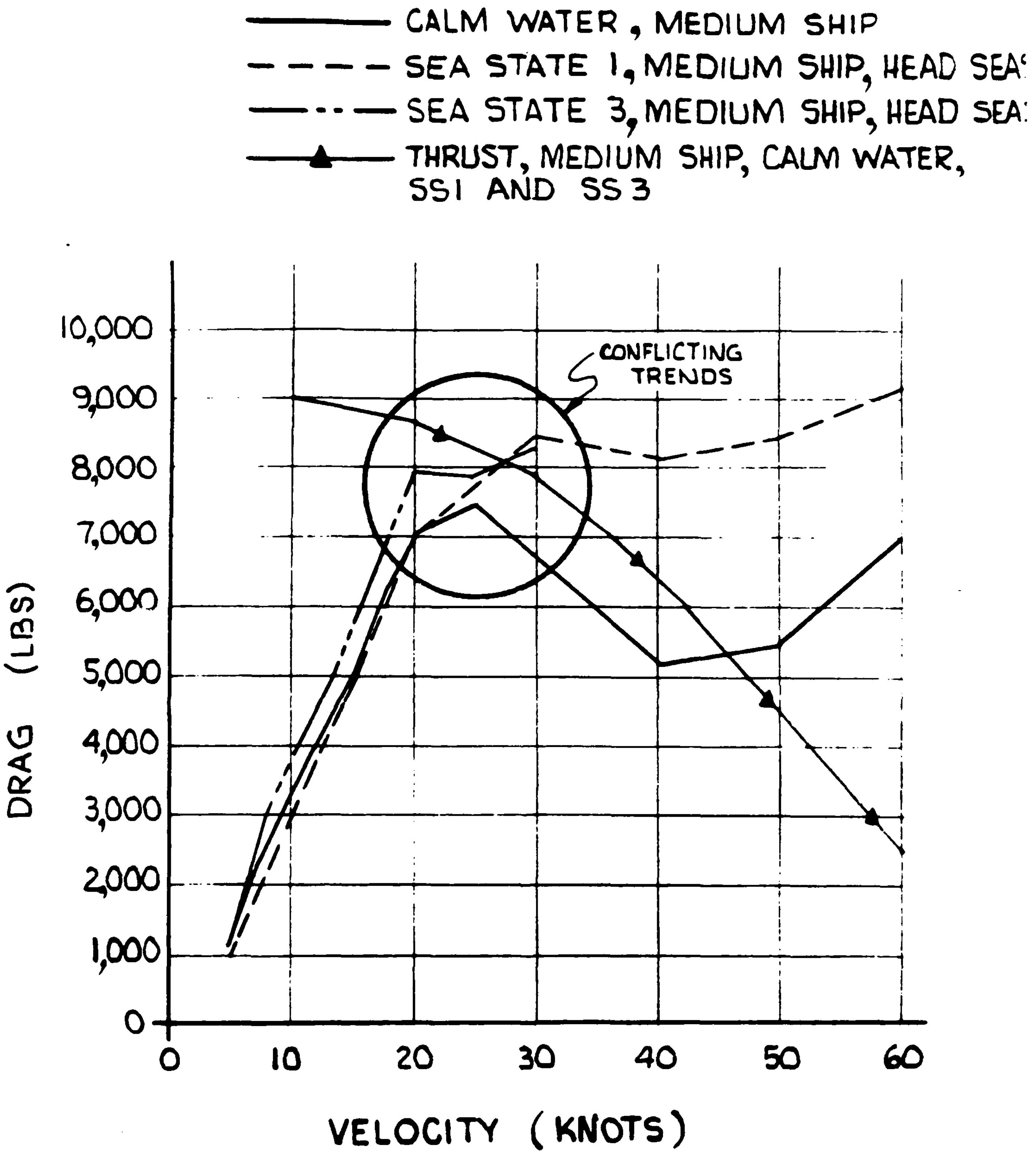


FIGURE 19 - 60-FOOT WAVESTRIDER MEDIUM SHIP PERFORMANCE

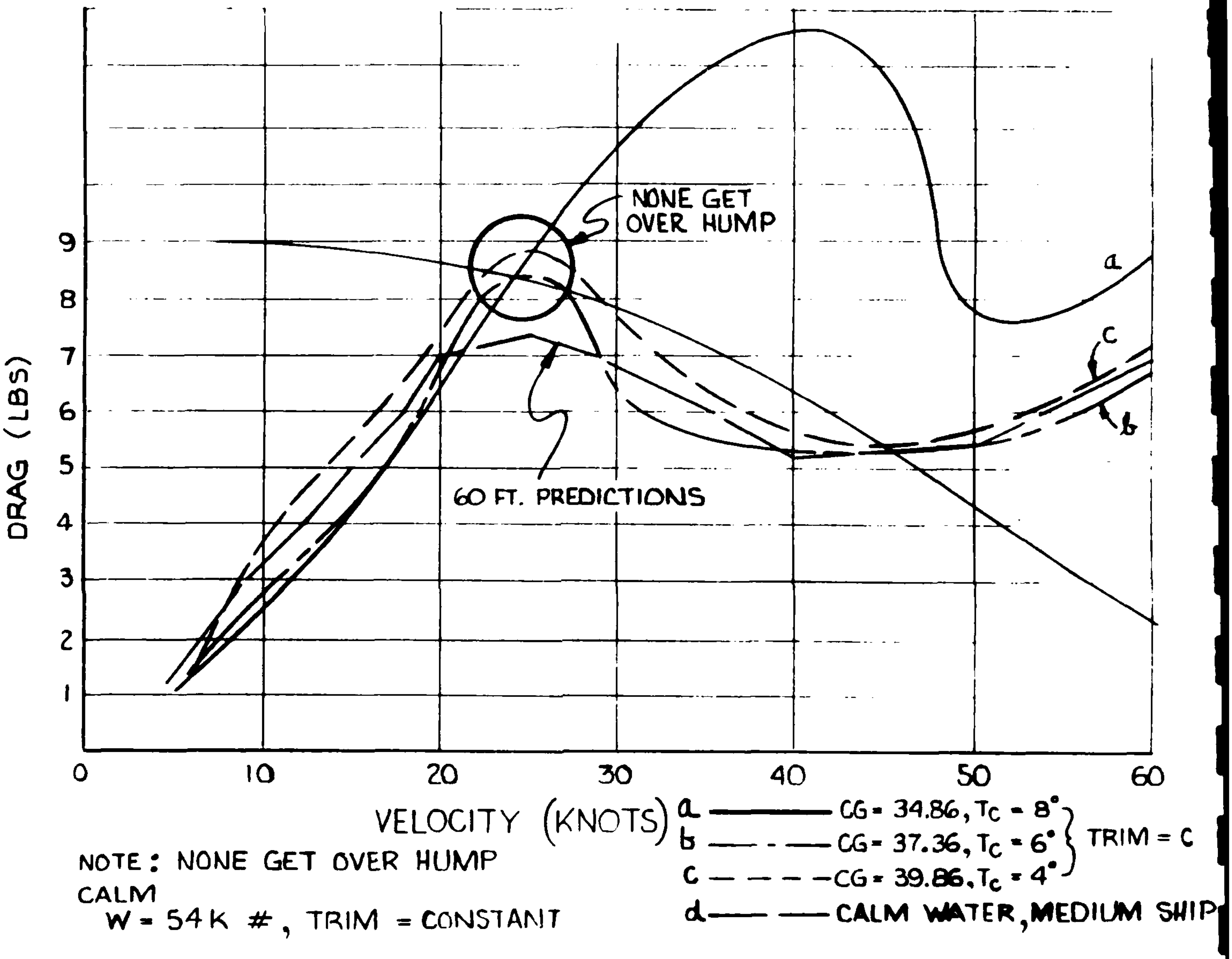


FIGURE 20 - 60-FOOT WAVESTRIDER CG SENSITIVITY

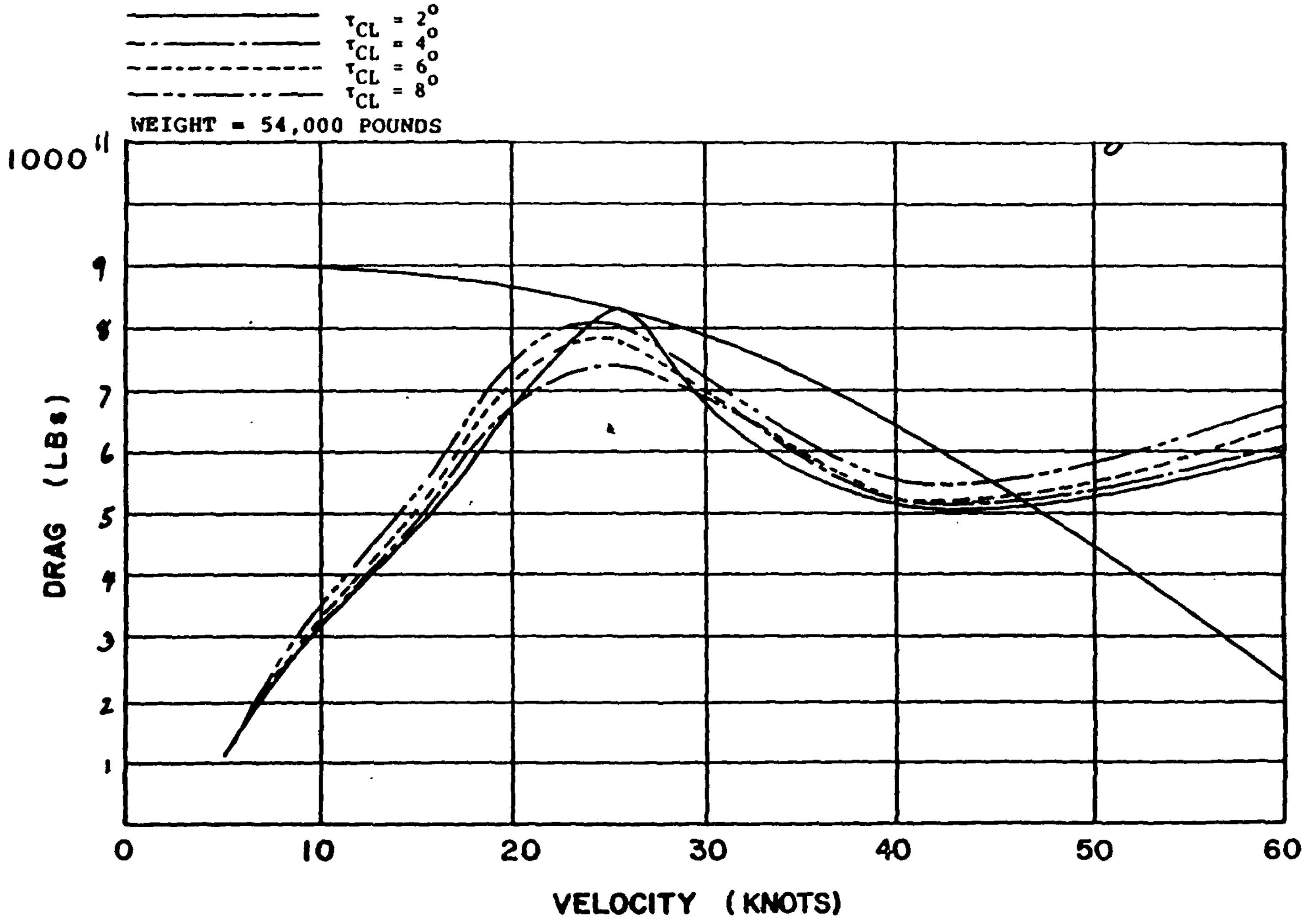


FIGURE 21 - 60-FOOT WAVESTRIDER DRAG VERSUS VELOCITY FOR VARIOUS CANARD ANGLES, MEDIUM WEIGHT SHIP

Performance predictions for the 96-foot WAVESTRIDER configuration (dated 11/4/88) also demonstrate a wide range of drag values and quite diverse trends. **Figure 22** represents 96-foot sample drag curves for calm water but varying CG and varying planing surface sizes and angles. The characteristics of the 96-foot WAVESTRIDER and its performance are summarized in **Figure 23** (which was taken from Ketron's Design Summary). Note that drag information from **Figure 22** and the projected speed from **Figure 23** yield an L/D ~10.0. Back calculation from these conditions (~84 knots; calm water), yields a thrust horsepower of ~13,000 hp. This power, when corrected for overall propulsion efficiency (assumed at 60%), suggests an installed engine power of ~22,000 hp. Ketron's design, however, provides for only 12,000 installed engine horsepower.

4.2 Equation Solution Methodology

The drag equations for the WAVESTRIDER concept can be solved in a closed form. Ketron, however, has chosen to perform the computations using a so-called "time domain" model. Reference 15 provides a brief description of the "time domain" methodology. The name "time domain" may lead one to conclude that the solution methodology is a dynamic one which includes time dependent phenomena (such as lift on planing surfaces in other than steady speed and calm water).

The classic "time domain" methodology is simply an iterative solution technique that calculates a series of <u>steady</u> conditions until the hypothesized results converge. It is not a dynamic technique. What is needed is a truly <u>time-dependent</u> formulation of the lift and drag, not only of the planing surfaces, but of the hulls as well -- all operating in a realistic sea state. Ketron did not do this.

4.3 *Dynamics of the* WAVESTRIDER Concept

This section addresses the predictions for the motions (displacement, velocity, and acceleration) of WAVESTRIDER vehicles in general. Ketron's documentation is replete with much discussion about ride quality, human comfort, and craft dynamics. Substantive mathematical treatment is extremely deficient. Reference is made to a "greatly simplified dynamic model" (Reference 18). In reality the "dynamic model" that Ketron formulated consists of a simplistic mass, spring, damper system. The initial formulation by Ketron (Reference 15) considers only heave. Pitch and surge are normally considered crucial to stability of a vehicle such as this, and these have <u>not</u> been included.

Ketron does <u>imply</u> (27) that pitch, in addition to heave, is modeled. However, the pitch and heave equations are presented in their uncoupled form and solutions or results are not provided. Furthermore, only planing lift forces are considered; drag forces as well as buoyancy forces are omitted. In addition, damping coefficients for the various force terms are missing.

From the documentation of the dynamics model provided by Ketron, the following conclusions can be reached:

- The proposed motions model is trivial.
- The model has insufficient degrees of freedom.
- The model neglects key force inputs.

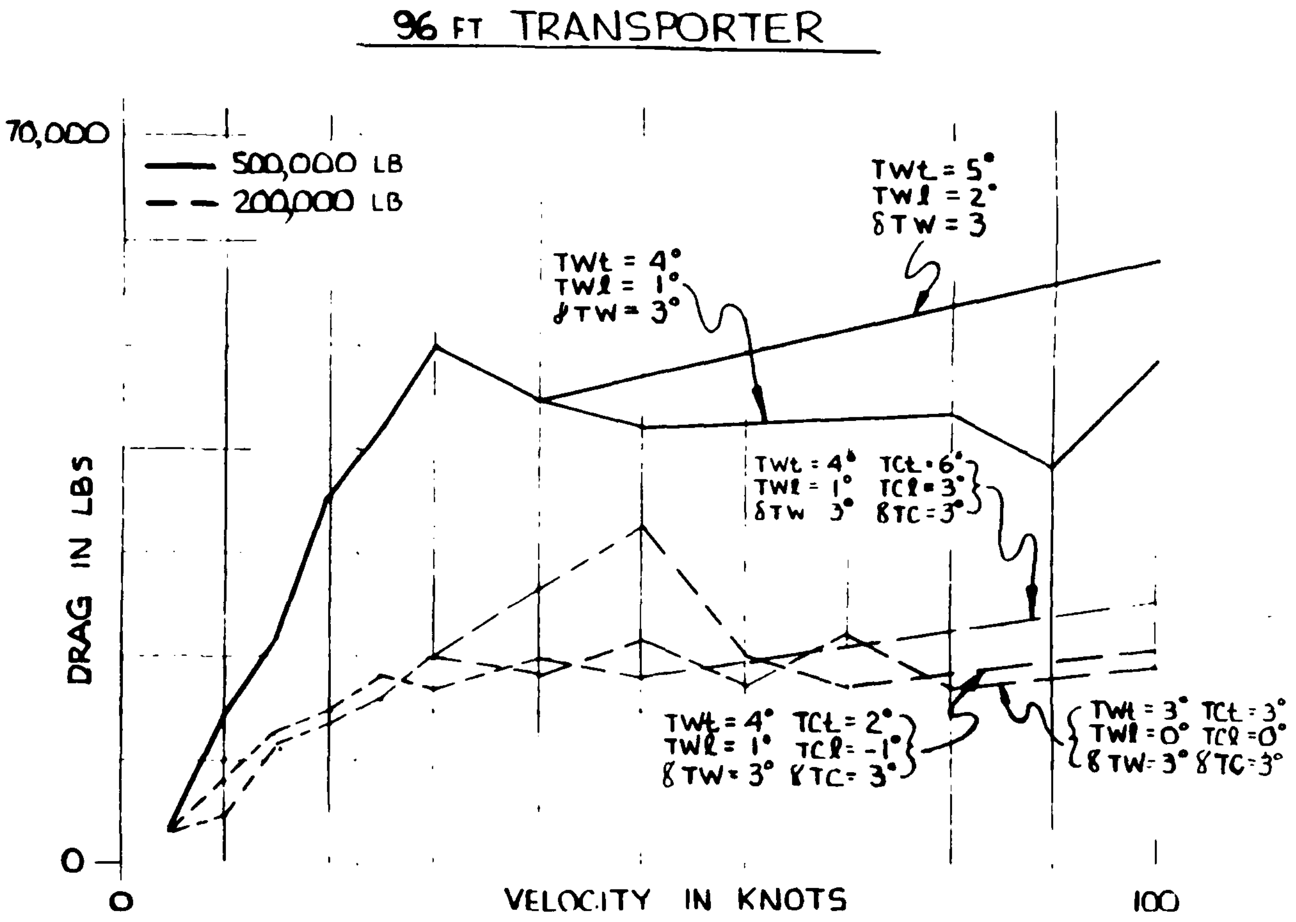


FIGURE 22 - VARIABILITY OF DRAG WITH WEIGHT & TRIM

Beam	47 feet
Light Ship Weight	200,000 pounds
Heavy Ship Weight	500,000 pounds
Maximum Speed, Light Ship	
Sea state 0	101 knots
Sea state 2	99 knots
Sea state 3	97 knots
Maximum Speed, Full Load	
Sea state 0	84 knots
Sea state 2	81 knots
Sea state 3	74 knots
Operational Range	400 nautical miles (plus 10 percent reserve)
Loitering Time	One hour additional
Structural Material	Aluminum Alloy 5086
Propulsion Power System	Twin Allison Gas Turbines 571-K, 6,000 horsepower each at 100°F
Drive System	Twin Arneson ASD-18 driving surface-piercing propellers
Auxiliary Power Drive for Loitering	Twin North American Tractor Jet, 150 horsepower, jet pump units
Fuel Capacity	5,620 Gallons DFM
Crew	Five

FIGURE 23 - CHARACTERISTICS 96-FOOT WAVESTRIDER

5. AT-SEA TRIALS

In Task II of the WAVESTRIDER Evaluation, the Navy performed a series of experimental at-sea trials. These were designed to evaluate and compare Ketron's prediction methodology with actual measured values and to discover and quantify operating phenomena that might not be evidenced in Ketron's analysis.

There were three separate but commonly focused trials efforts:

- Performance trials of the 24-foot craft by the NAVSEA Combat Systems Engineering Station, Norfolk.
- Modification and follow-on performance trials on the 24-foot craft by SESSO.
- Independent Navy contracted exploratory and phenomenon oriented small scale model tests.

5.1 24-Foot Craft Trials at Norfolk

The 24-foot craft, although Navy property, was in Ketron's custody at the time the WAVESTRIDER Evaluation Program was initiated. It had not been operated for some time. Ketron's initial attempts at getting the craft operational were only partially successful. In September of 1988 the 24-foot craft was moved to the NAVSEA Combat Systems Engineering Station located in Norfolk, VA. There the craft and engines were refurbished and placed back in operational status. **Figure 24** summarizes the key results of testing conducted by NAVSEACOMBATSYSENGSTA. For both 4200 lb and 5100 lb displacement, the measured drag was more than 100% greater than the drag predicted by Ketron. The details of the Norfolk at-sea trials (and tribulations) are presented in Reference 33.

The trials results obtained at Norfolk were transmitted to Ketron on 13 January 1989 at a meeting held in Norfolk at NAVSEACOMBATSYSENGSTA offices. In response, on 17 March, Ketron provided an explanation for the apparent discrepancies (Reference 28). The salient points of Ketron's explanation for the differences between measured and predicted drag can be summarized as follows:

- A number of surfaces were found to be "very rough", (Reference 28), and Ketron's model assumed "smooth" surfaces.
- The wing had considerable negative camber while Ketron's prediction model assumed a flat wing.
- Increased drag due to wing-hull juncture and possible missing fairings were not included in Ketron's mathematical prediction model.
- The assumption in the 24-foot predictions, that "the forward hull...was shielded (unwet) by canard wakes, was found incorrect."

As shown on **Figure 25**, Ketron indicated that at about 30 knots, about half the drag differences could be explained by the first two items (skin

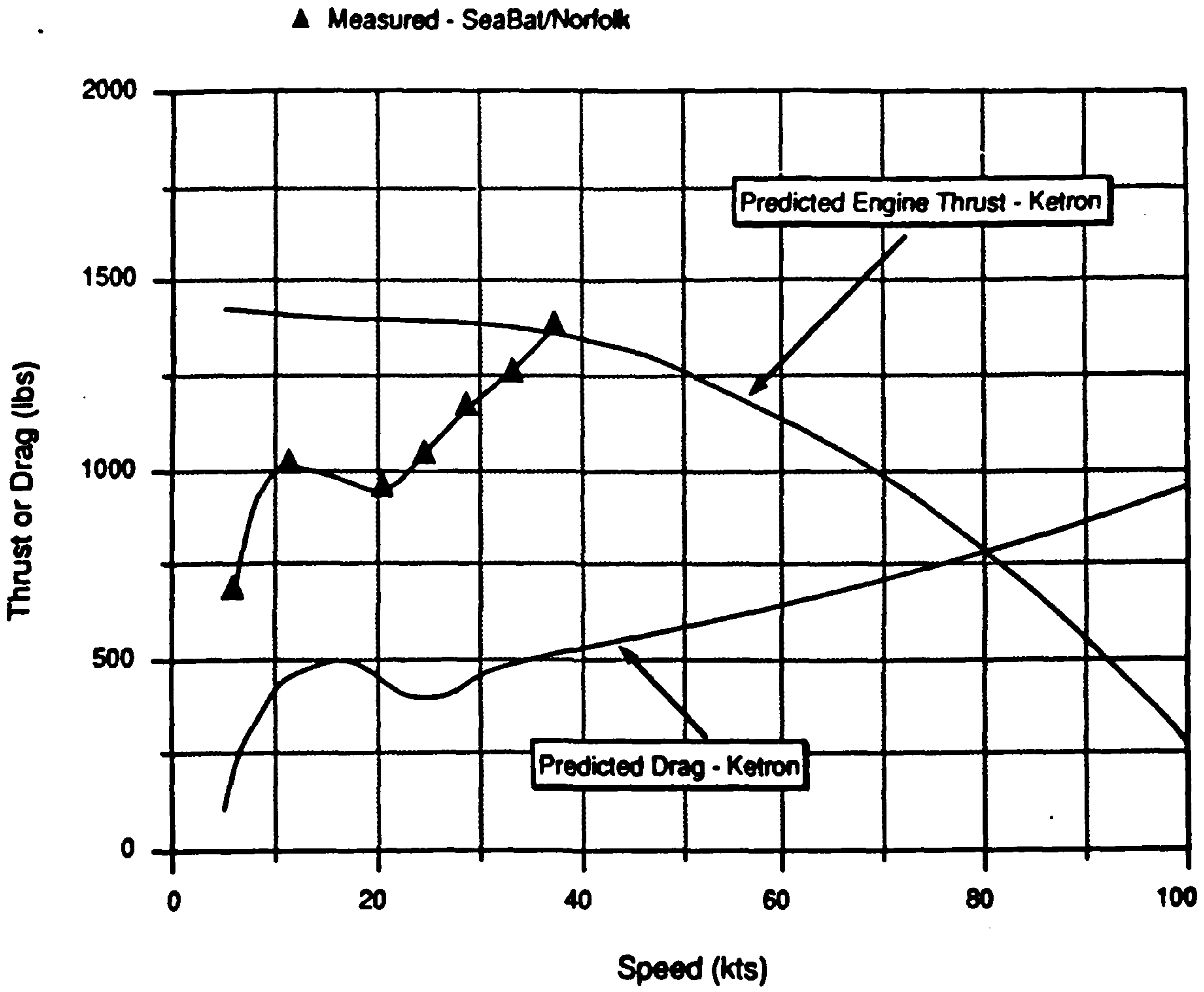


FIGURE 24 - 24-FOOT WAVESTRIDER, CALM WATER PERFORMANCE, 4200 LBS DISPLACEMENT

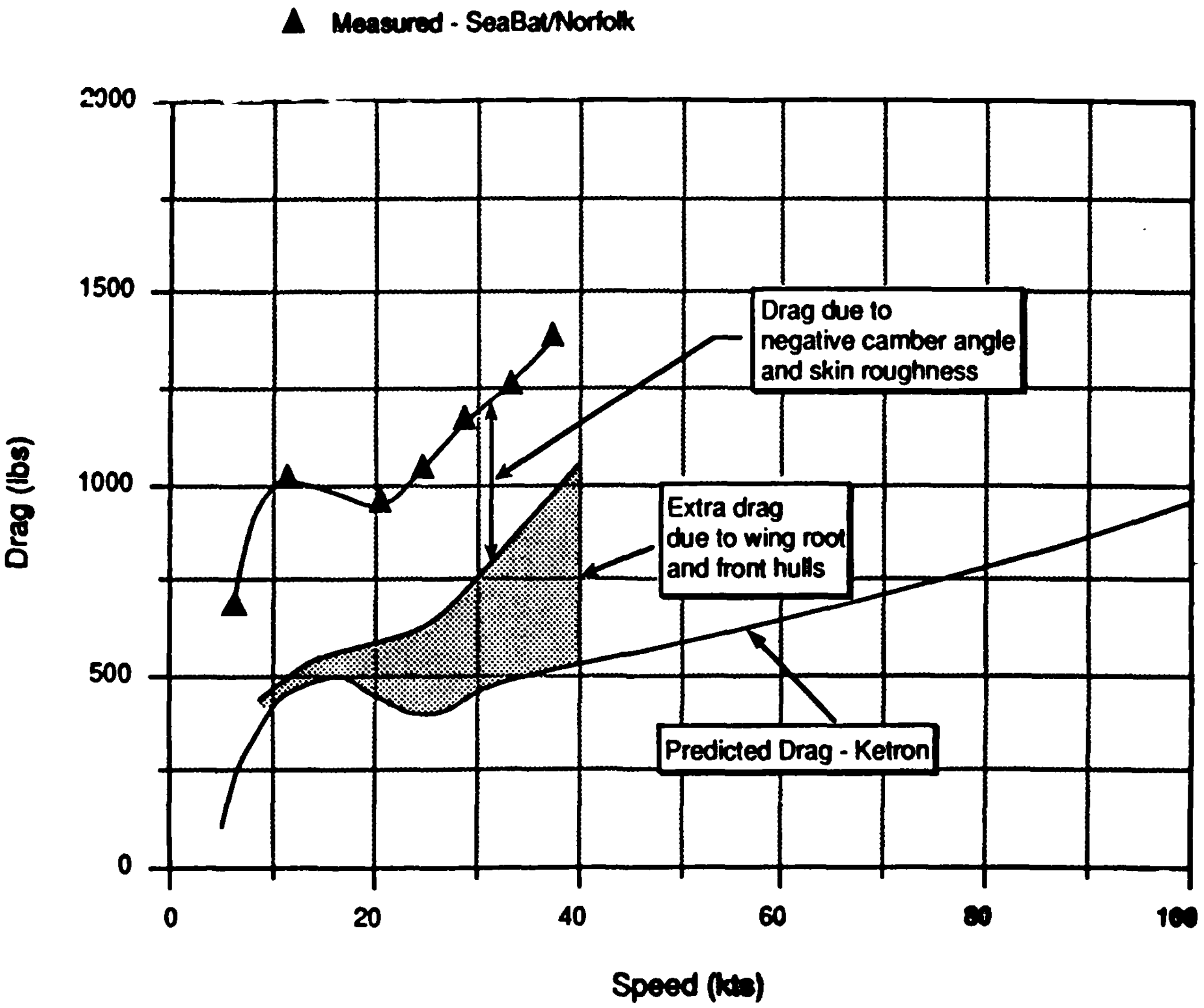


FIGURE 25 - KETRON "EXPLANATION" OF DIFFERENCES BETWEEN PREDICTED AND MEASURED DRAG

roughness and wing camber), and the other half by the last two (wing root and front hull interferences).

It is interesting to note that even at low speed (i.e. 5 knots) the measured drag is seven times the predicted value.

5.2 24-Foot Craft Trials at SESSO

In January of 1989, during NAVSEACOMBATSYSENGSTA's first attempt at high sea state operations, the 24-foot craft experienced severe damage (**Figure 26**). In April the craft was moved to DTRC's Surface Effect Ship Support Office located at the Naval Air Station, Patuxent River, MD. There repairs were made to the damaged structure (**Figure 27**). SESSO, together with NAVSEACOMBATSYSENGSTA and Yamaha contracted help, again refurbished the craft's engines.

Then, SESSO incrementally made modifications to the craft to correct three of the four "deficiencies" identified by Ketron. (**Figures 23** through **31**).

At each repair increment, at-sea trials were rerun and a new drag relationship plotted. The results are shown in **Figure 32**.

It is clear that the discrepancy in drag between the original predicted values and the measured test results at Norfolk are not due to the items identified by Ketron. In general, the corrections proposed by Ketron, when implemented, had no effect on the measured drag. In one case, when the bottom curvature of the main lifting surface was faired in, the measured drag actually increased by about 15%.

5.3 60-Foot Yacht Trials

The 60-foot WAVESTRIDER yacht, Enterprise, was a private-venture construction project. The physical details and key dimensions of the yacht are presented in **Figures 3** and **10**. This yacht is of particular interest to the Navy in that its characteristics more closely resemble the proposed 96-foot WAVESTRIDER Transporter. Unlike the 24-foot craft, which has relatively slender sidehulls and is very lightly loaded, the 60-foot yacht and the 96-foot Transporter have significantly beamier sidehulls and a more pronounced tunnel convergence. Also, the tunnel height for the 60 and 96-foot configurations is significantly smaller than that for the 24-foot craft. (Refer to **Figure 13** for actual ratios.)

After Ketron suffered much financial and technical tribulation, and associated delay, the 60-foot yacht was launched and was to be tested in the Spring and Summer of 1989. The 60-foot yacht, as built, turned out to be approximately 15% over design weight. As part of the Navy contract, Ketron was tasked to develop drag predictions for the 60-foot yacht. Ketron states that the same methodology that was used to predict the 24-foot craft performance was also used to predict the speed-drag curves for the 60-foot yacht. **Figure 33** is a typical representation of the results.

Ketron's original drag predictions for the 60-foot yacht were not useful because the yacht was so far above its design weight. As a result, Ketron had to generate revised predictions. **Figure 34** is one such prediction provided by Ketron. Plotted on it is the only measured performance of the 60-foot yacht. Maximum speeds achieved

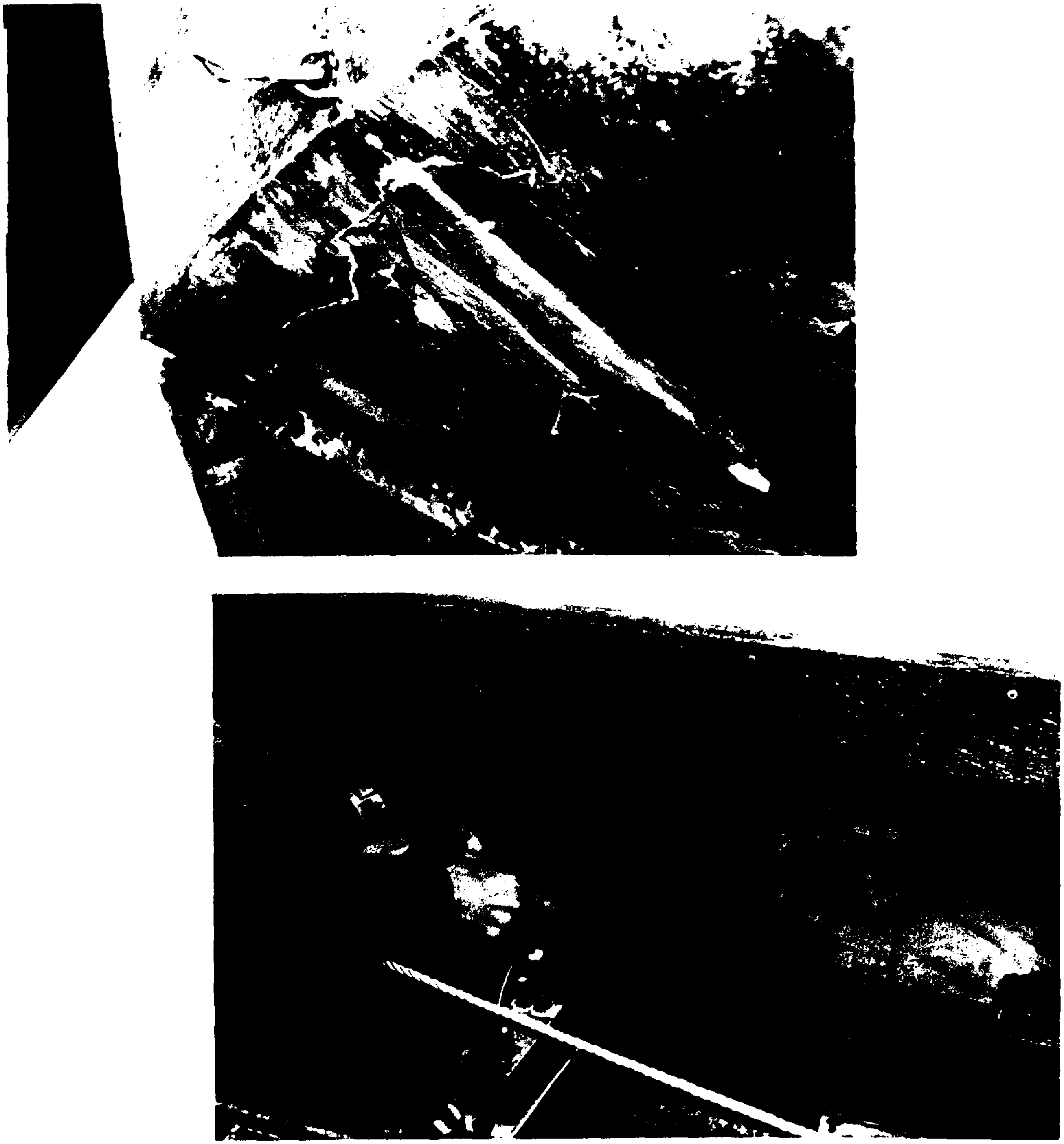


FIGURE 26 - HIGH SEA STATE DAMAGE TO 24-FOOT WAVESTRIDER

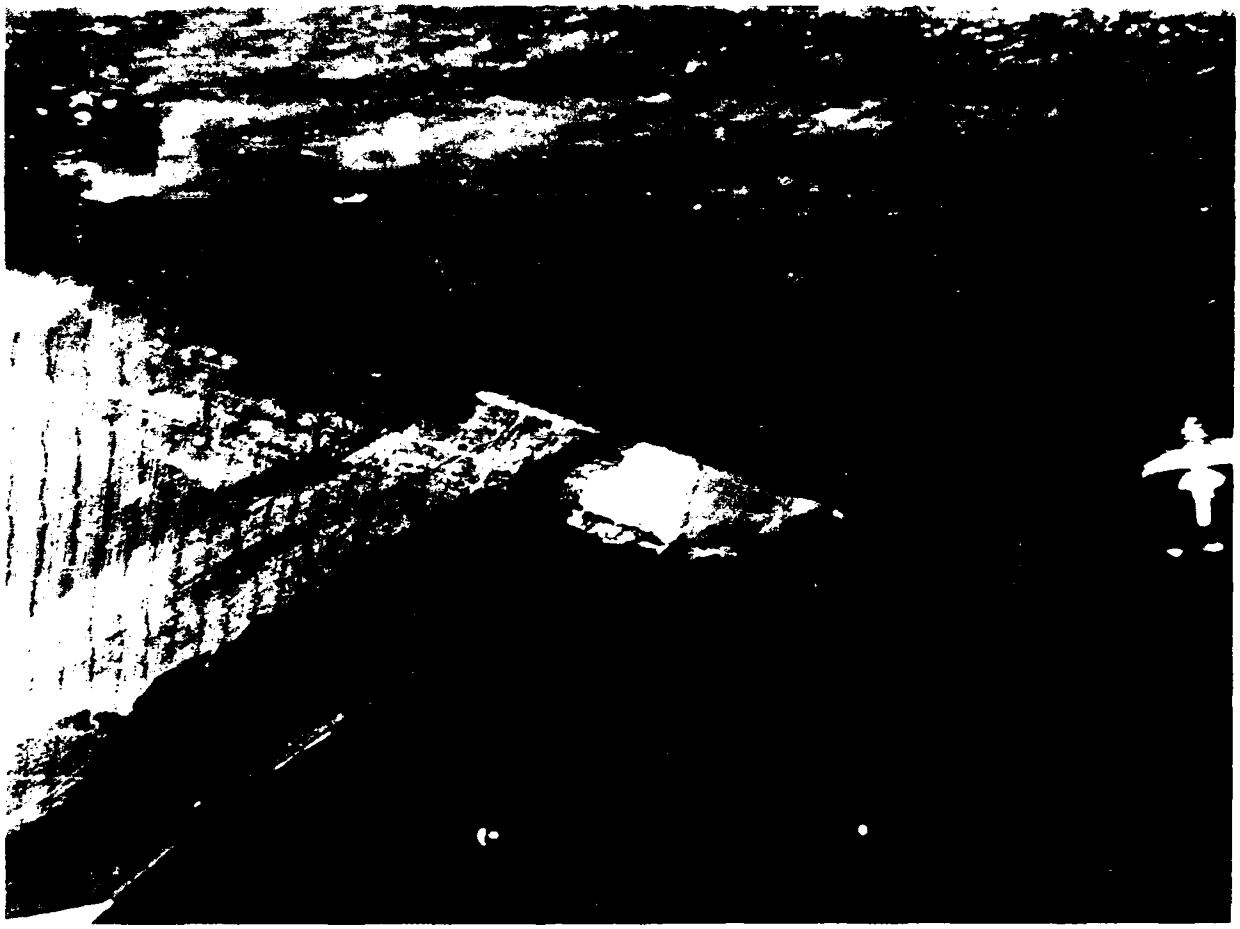


FIGURE 27 - REPAIRS TO 24-FOOT WAVESTRIDER HULL

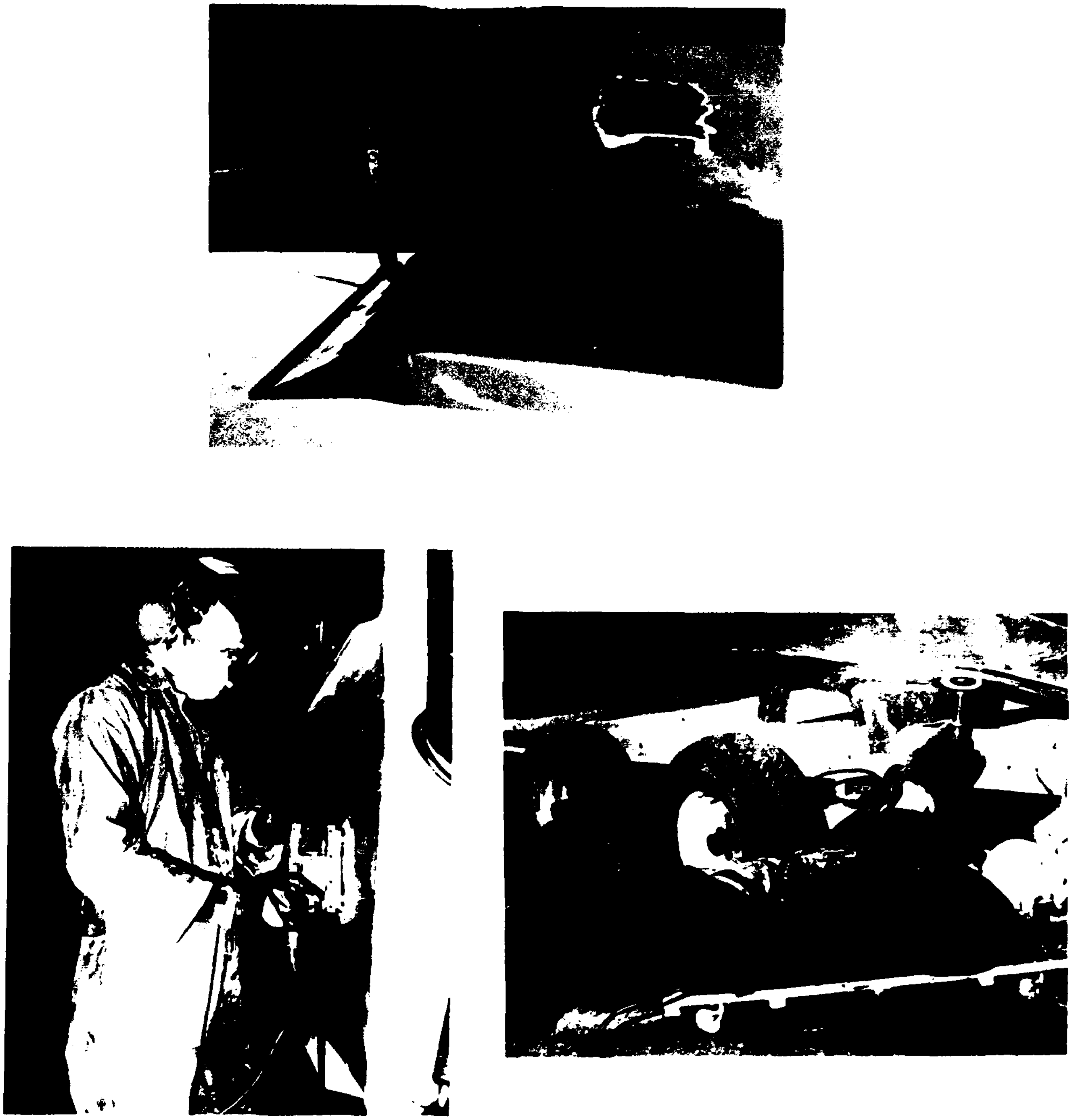
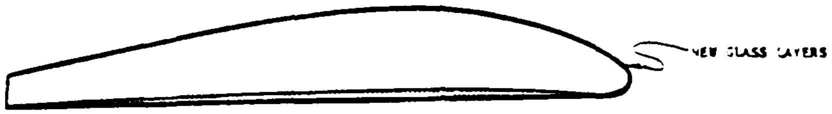


FIGURE 28 - SMOOTH THE HULL TO REDUCE SKIN ROUGHNESS

Eliminate wing bottom camber by screeding-in filler and covering with glass to approximate original wing configuration. This should result in a major drag reduction.



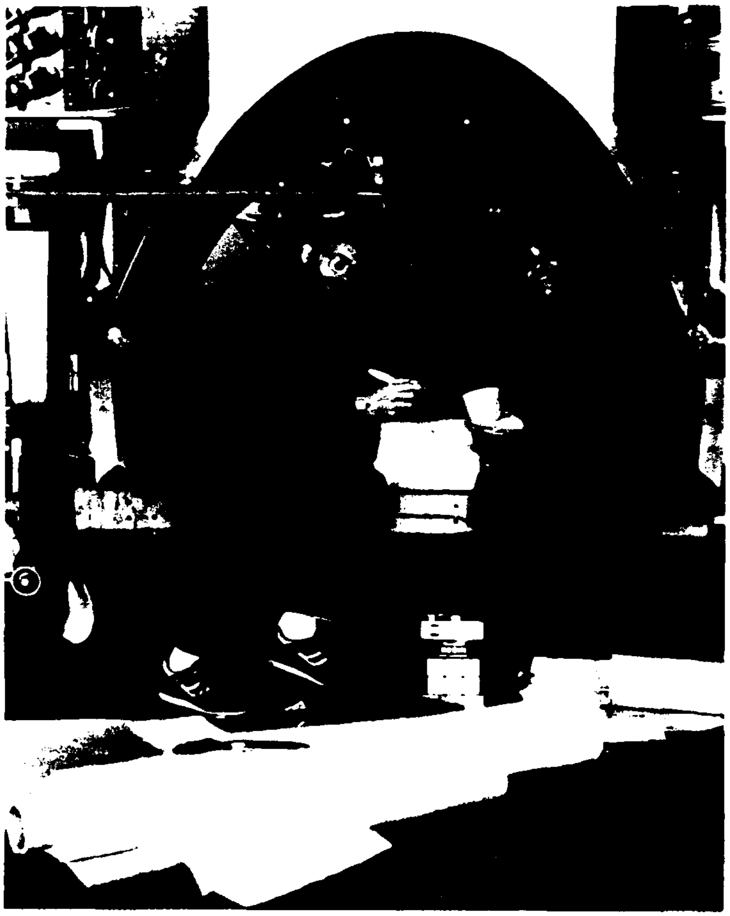


FIGURE 29 - FLATTEN FOIL SURFACE TO ELIMINATE NEGATIVE CAMBER ANGLE

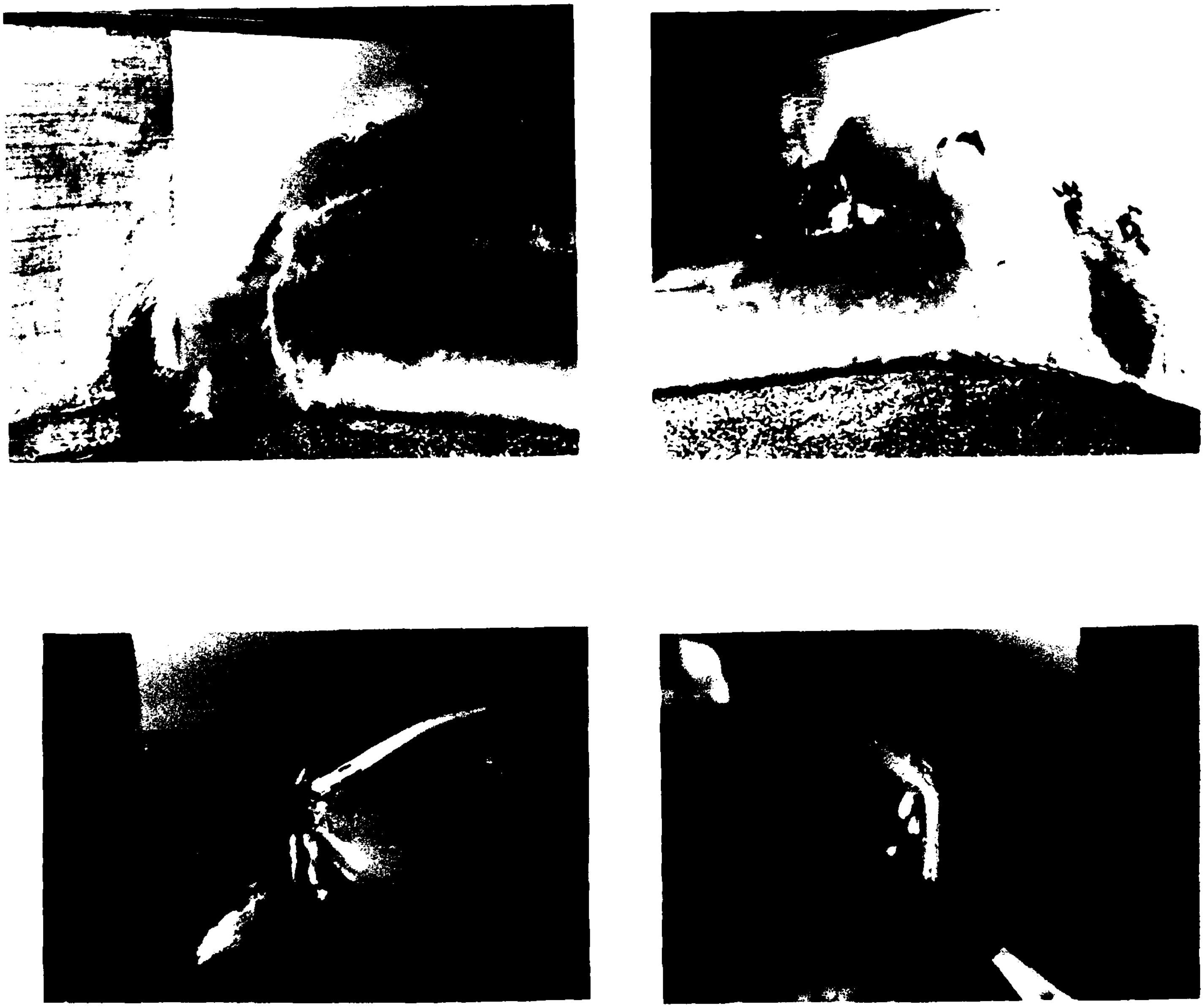


FIGURE 30 - REPLACE FOIL FAIRING AT WING-HULL ROOT JUNCTURE

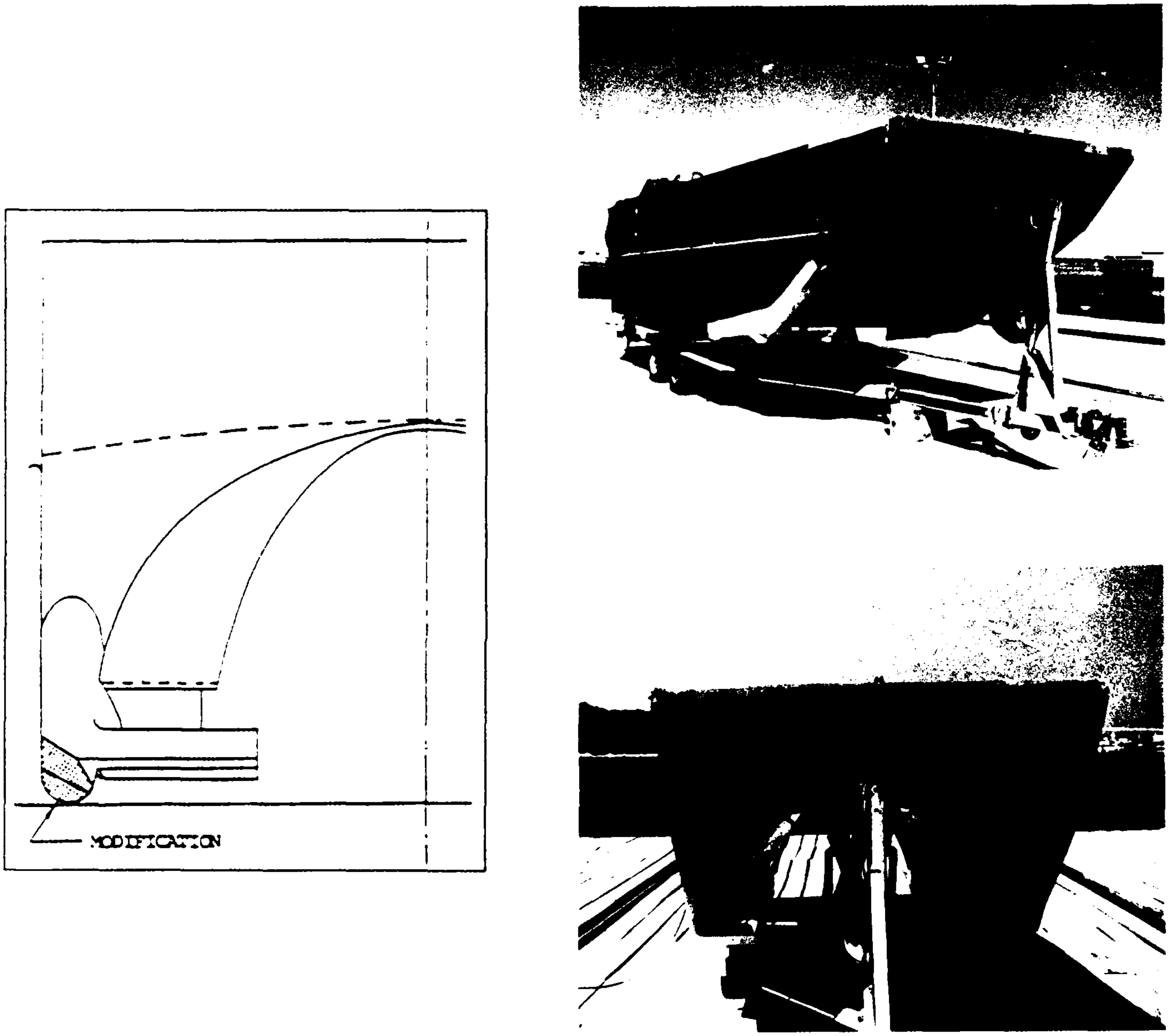


FIGURE 31 - MODIFY BOW TO REDUCE FRONT HULL DRAG

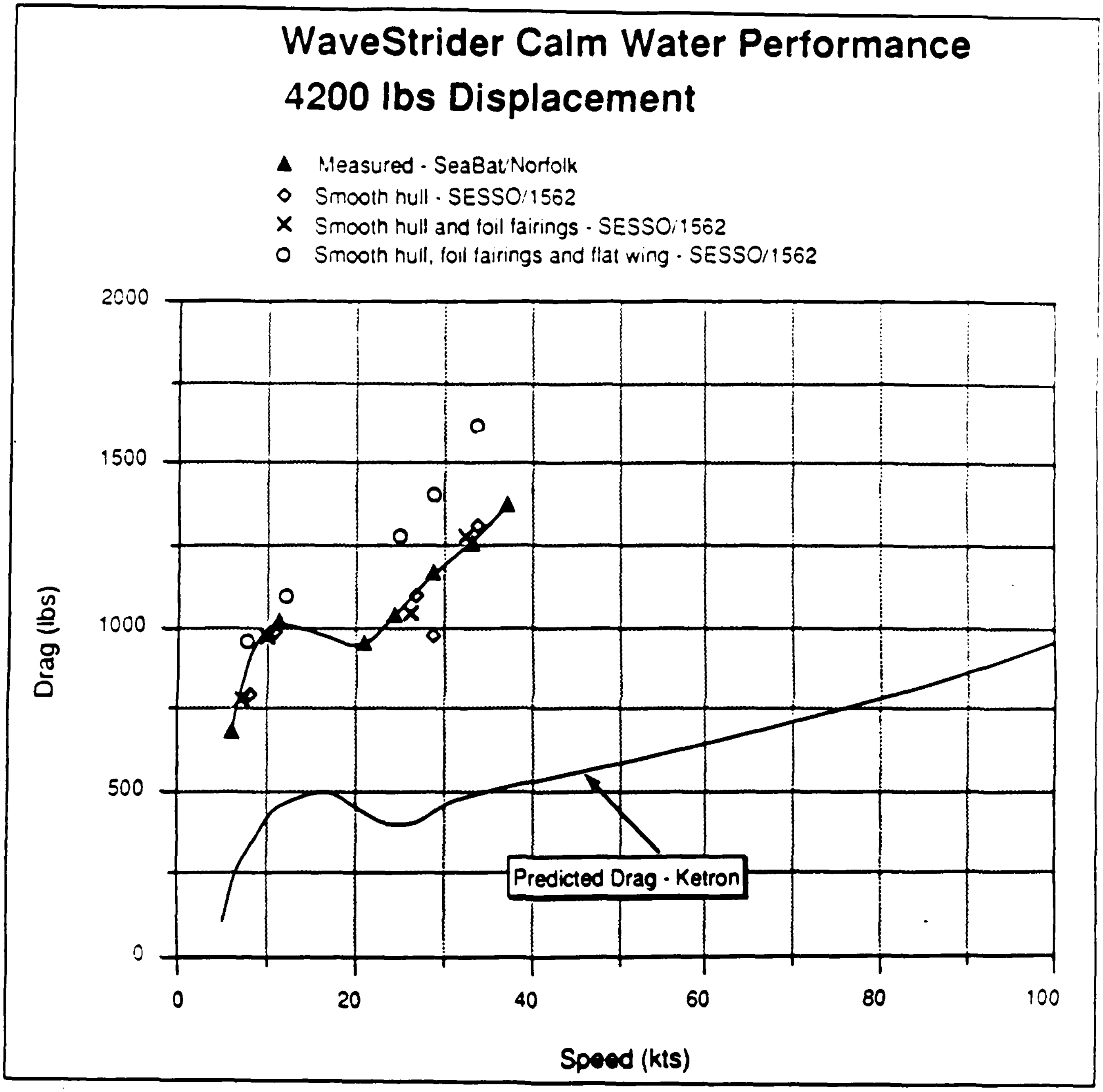


FIGURE 32 - RESULTS OF SESSO REPAIRS/TRIALS

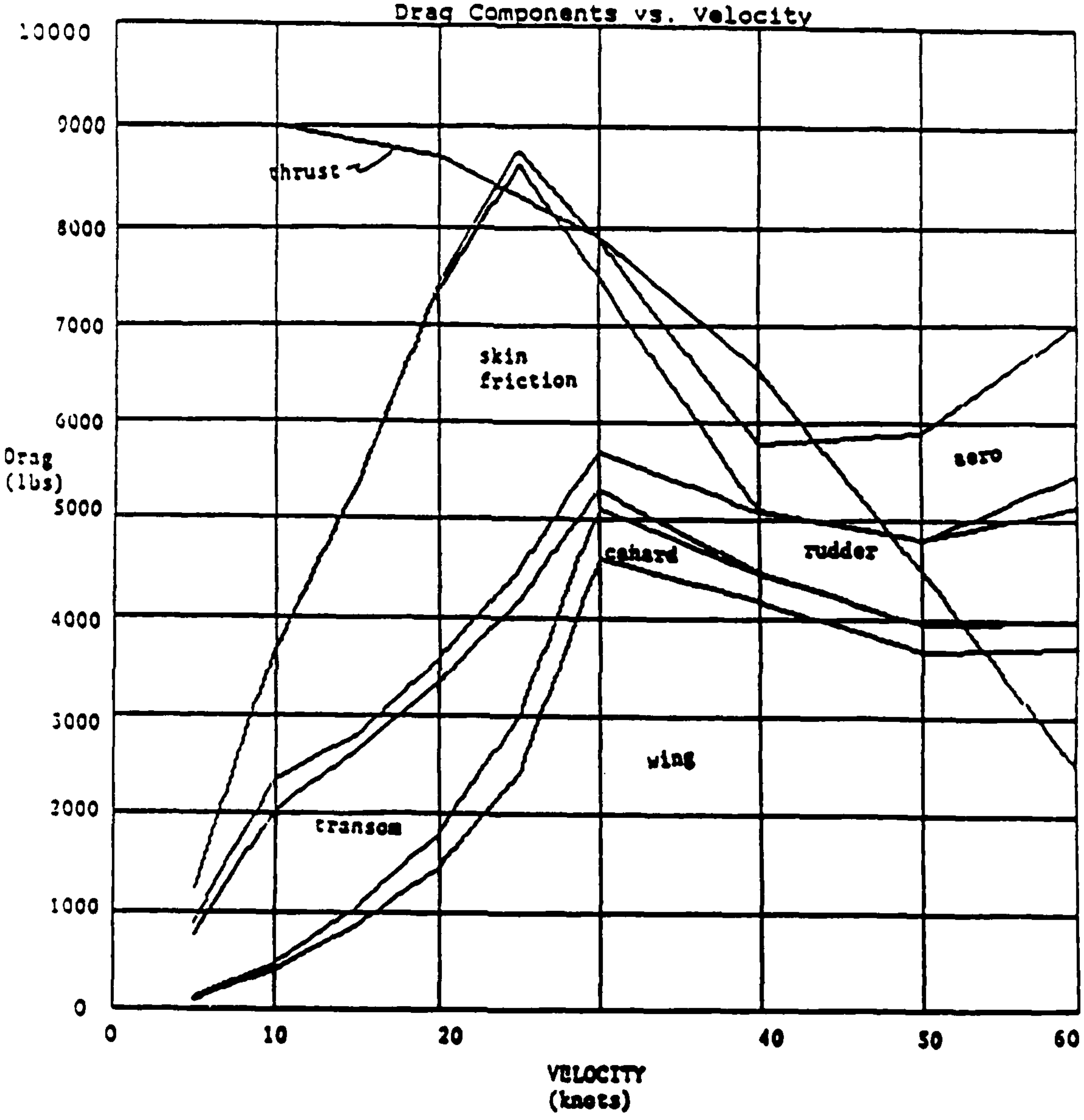
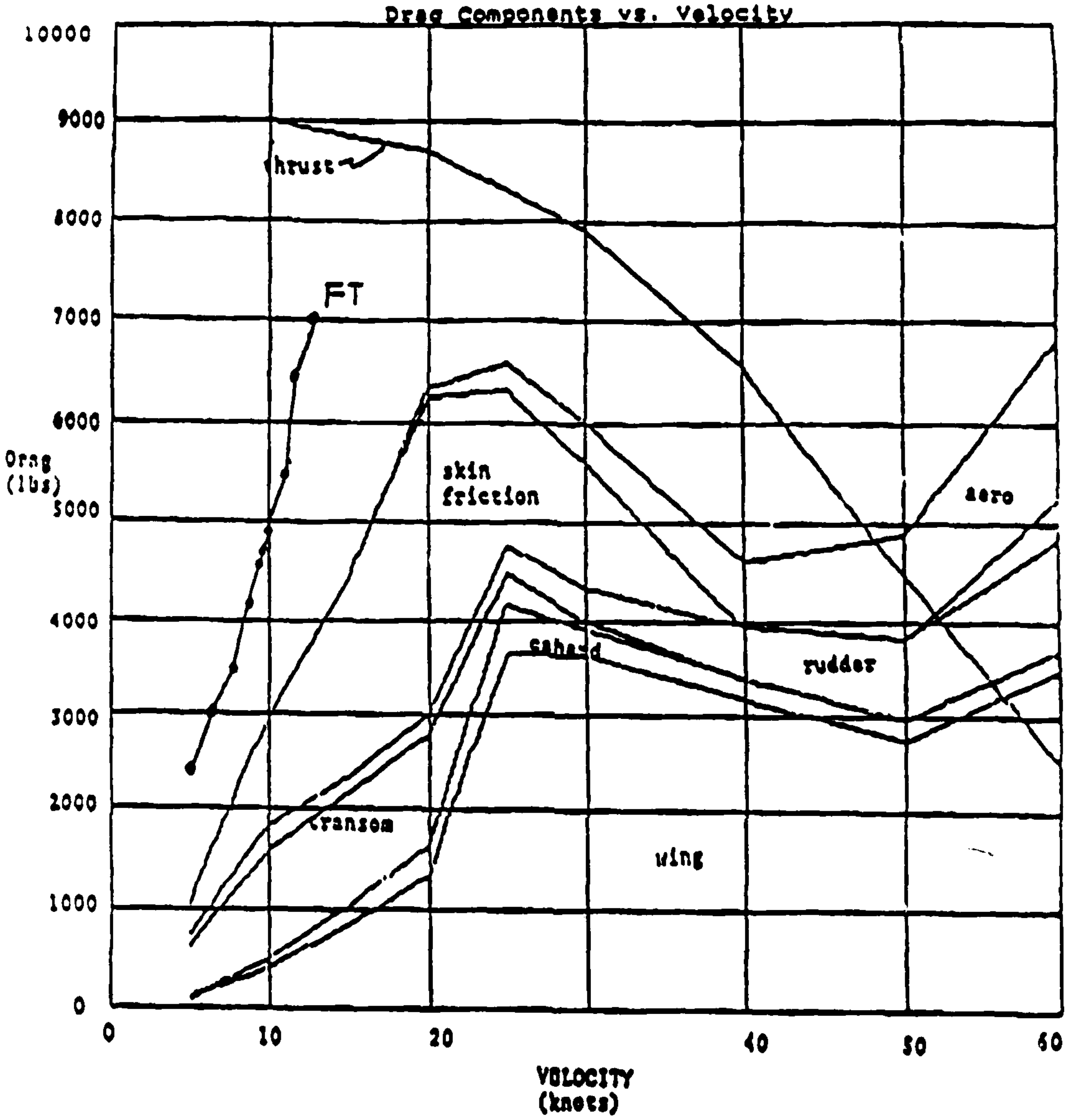


FIGURE 33 - 60-FOOT PERFORMANCE PREDICTION-TYPICAL



60-Foot WAVESTRIDER, Enterprise, predictions.

Displacement = 48,000 pounds (light ship). $C_f = 0.0045$

Calm water.

Canard angle = 2°.

•—• SEA TRIALS, 5/23/89, sandbags, 800 pounds, in bow.

FIGURE 34 - 60-FOOT YACHT TRIALS RESULTS

during the tests did not exceed 13 knots. In all cases the measured drag exceed the predicted values. As an example:

- At 5 knots measured drag exceeded predicted by 150%.
- At 10 knots measured drag exceeded predicted by 66%.
- At 13 knots measured drag exceeded predicted by 84%.

The yacht never went faster than 13 knots, at that point its engines were at full throttle (FT on the graph in **Figure 34**). While it is clear that the propellers were not generating their predicted thrust, it is also clear that the measured drag was significantly higher than predicted.

These are the only data that were ever obtained on the 60-foot yacht Enterprise.

On 25 May, Jim Gagorik from ONT and Jeff Benson from DTRC went to Fort Lauderdale to observe some Builder's Trials and prepare for the Navy At-Sea Trials. The boat engine failed during a pre-demonstration run, and its operation was never able to be observed by Government representatives, although some limited videotape was shown. The 60-foot yacht has never been "on plane".

6. EXPLORATORY MODEL TESTS

A central element of Ketron's WAVESTRIDER concept is the hydrodynamic performance of a number of planing surfaces and their adjacent hull structures. Ketron appears to treat the planing surfaces and the two main hulls of the craft as stand-alone, independent elements of the vessel. Ketron's performance predictions and their formulation of resistance equations for the WAVESTRIDER, do not consider the hydrodynamic interaction among these components.

From observations of trials on the 24-foot WAVESTRIDER it became clear that even with the slender sidehulls of the craft, the wash in the tunnel zone was pronounced. Also, from observation of other craft, such as the PHM and other planing hulls in general, it is clear that the bow surface entry flowfield results in significant displacement of water and generation of spray sheets. Thus, under some conditions the convergent tunnel zone between the two WAVESTRIDER hulls can be expected to dominate drag production (e.g., when the hulls are partially submerged, as during take-off; and in a sea state when the hulls and bow planing plates "punch" through a wave face). This phenomenon was not included in Ketron's prediction of drag.

Another key issue in Ketron's performance estimates focuses on the coefficients (such as Cl, Cd, etc.) used in the performance prediction formulas. The values used are based on "steady state" equations. (As used here, "steady state" means that the coefficients do not change with time.) This may be valid for a planing surface operating on a glass smooth water surface and held in a fixed attitude. The WAVESTRIDER, however, operates under conditions where the planing surfaces either "skip" on the surface or penetrate ("punch through") the wave face. It is likely that under these conditions, values of the lift and drag coefficients will be significantly different from "steady state" values.

To address these two questions (hull interactions and dynamic planing behavior) two exploratory model tests were conducted. The first was devoted to the qualitative assessment of the importance of the interhull tunnel flow. The second test focused on the "dynamic" time-dependent behavior of a planing plate. The goal of these exploratory model tests was not to obtain absolute measurements, but rather, to gain an insight into the significance and relative importance of the sea state variables.

3.1 Hull Interaction Tests

A breadboard model of the 96-foot WAVESTRIDER hulls was fabricated and assembled. The overall length was two feet. The model approximately matched the overall shape and dimensions of Ketron's 96-foot design. **Figure 35** is a diagram of the model. The two wedge hulls were connected by a plexiglass bridging structure.

The WAVESTRIDER hull model was mounted in a test fixture on a towing tank carriage at BC Research Ocean Engineering Center. The model's pitch and heave were fixed.

The model was positioned such that the hull baseline was at the calm water free surface. An approximately 1.75" high sinusoidal wave was generated and the model operated at various speeds. This condition roughly approximates WAVESTRIDER flight at mid-wave depth. The model was then repositioned such that the hull baselines were 2" below the calm water free surface. Waves of 1.75" were again generated and the model operated at increasing speed.This latter attitude corresponds to the WAVESTRIDER flight with planing plates at the wave trough.

During each run, a videotape recording was made and speed and drag values were recorded in real time.

The results of this exploratory model test are summarized in **Figure 36**. Plotted is the drag of the model against the model speed in meters/second. Also shown on the abscissa is the corresponding speed (ft/sec) of the 96-foot WAVESTRIDER. 40 knots full scale is identified on the graph.

For the "mid-wave height" baseline data, as would be expected, there is a clear trend of increasing drag. Examination of the video record reveals that the convergent tunnel cross- section between the hulls serves to trap and focus incoming waves. This traps water in the tunnel. The net result is that the two-hull system of the WAVESTRIDER traps and moves more water than would a single hull.

A more significant effect occurs when the model is operated in a submerged attitude corresponding to the waterline of the fully loaded 96-foot WAVESTRIDER. The drag increases two to three fold. Again, the video recording attests to the importance of the hydrodynamic interplay in the interhull convergent tunnel. Clearly, in this attitude the tunnel acts as a trap and results in significant drag; a drag component that was not included in Ketron's prediction.

From these exploratory tests on the WAVESTRIDER hull geometry, it can be concluded that the hull hydrodynamic interaction <u>is important</u> in drag predictions and <u>cannot</u> be ignored.

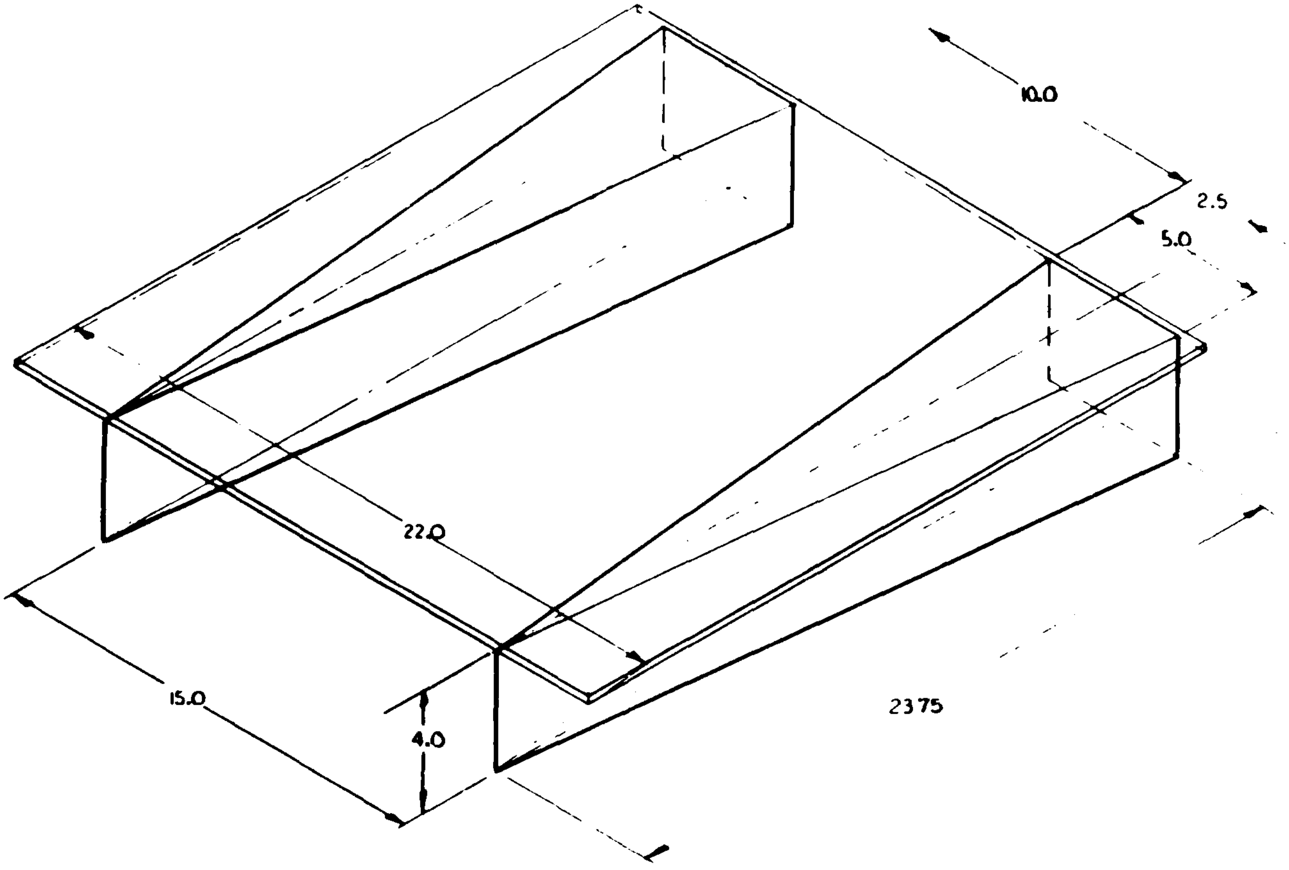


FIGURE 35 - DETAILS OF MODEL WAVESTRIDER HULL CONFIGURATION

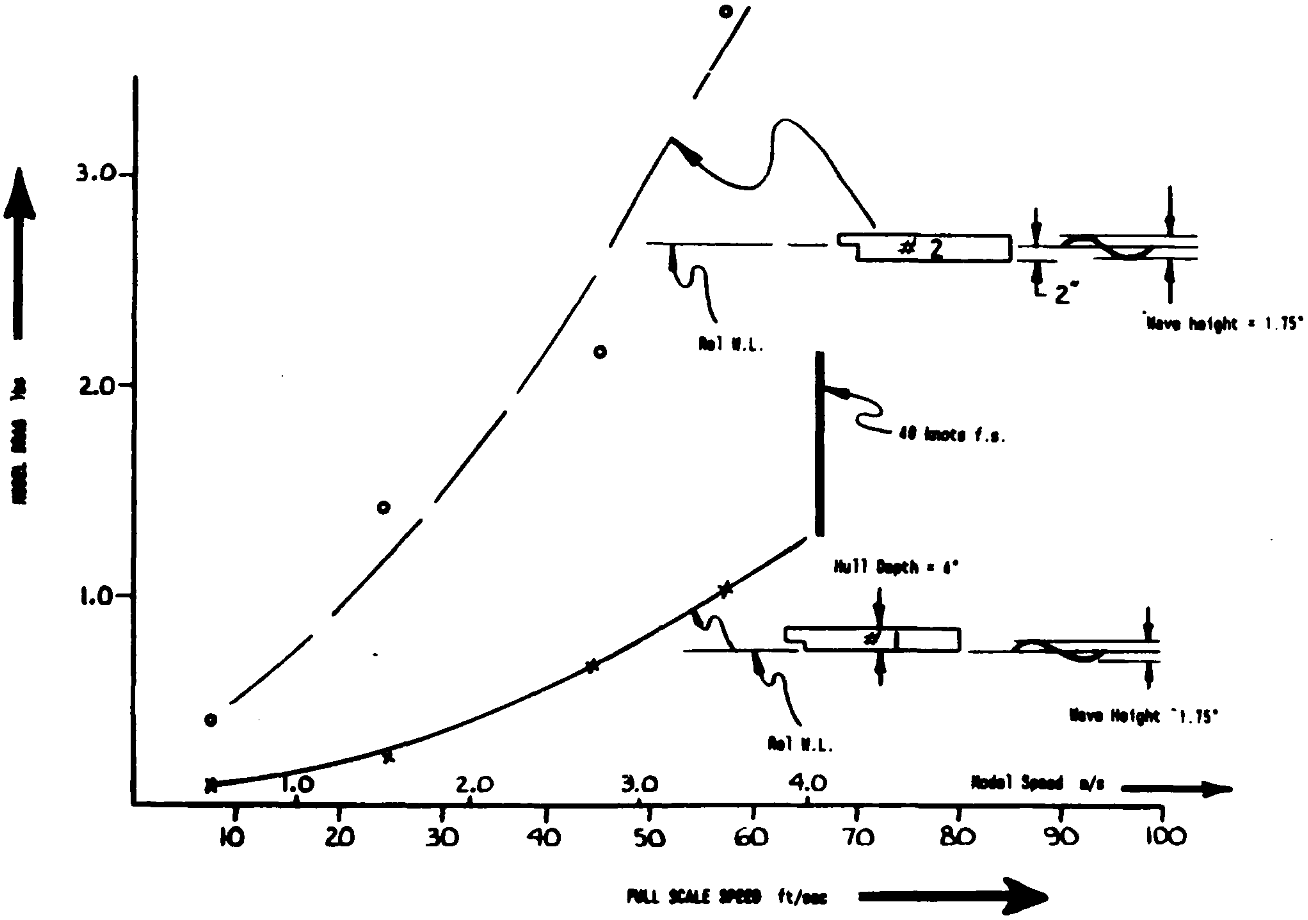


FIGURE 36 - TUNNEL DRAG HYDRODYNAMICS

6.2 Planing Plate Performance

A simple flat plate (1/16" thick x 8" beam x 2-1/2" chord) was tested in planing mode under calm water, nominal 1/2" and nominal 2" wave conditions. The starting conditions are depicted in **Figure 37**. The plate was set at a nominal 6 degrees of trim and operated at 1, 2, 3, and 4 meters/sec. The lift and drag were recorded. A video recording was made of the wake and flow field around the planing plate.

The following are the results of the twelve runs that were conducted:

Run #	Speed (m/s)	Lift (lbs)	Drag (lbs)	Lift/Drag Rates
Calm Water - No Waves				
1	0.5	.03	.01	3.0
2	1	.22	.05	4.4
3	2	1.55	.38	4.1
4	4	7.35	1.81	4.1
Wave Heights ~0.5" at 1.6 Hz				
5	1	.21	.527	.39
6	2	.86	.73	1.18
7	3	1.88	.97	1.94
8	4	3.34	1.22	2.74
Wave Height ~2" at 1.6 Hz				
9	1	.199	.545	.37
10	2	.87	.75	1.16
11	3	1.73	1.07	1.62
12	4	2.74	1.23	2.23

The wake of a planing surface in calm water was observed to be speed-dependent. It follows that the claimed WAVESTRIDER "constructive" wake interaction between the bow canard planing surfaces and the main aft planing surface is valid at one speed only. For the 96-foot WAVESTRIDER Transporter, this constructive interaction appears at relatively low speeds (when the wake wave is ~5 canard chord lengths). In fact, the canard wake may be detrimental to the wing hydrodynamics (**Figure 38**). The situation is further complicated by the three-dimensionality of the finite beam of the real planing plate. The wake produced by the flow at the tips significantly complicates the picture. As the planing plate loading is increased (lb/ft) and as the beam (or span) is decreased, the tip driven flow phenomenon appears to dominate the wake.

The planing plate behavior in waves, where the wave height is approximately equal to the projected height of the planing surface, is depicted in **Figure 39a**. In these sea conditions, the planing surface experiences the most severe excursions in the forces that are generated. The behavior in 2" waves appears to be different (**Figure 39b**). The 2" waves present the planing plate with a significantly increased slope of the wave face. Thus, the leading edge of the plate enters the wave profile first. This appears to somewhat mitigate the lift and drag force excursions.

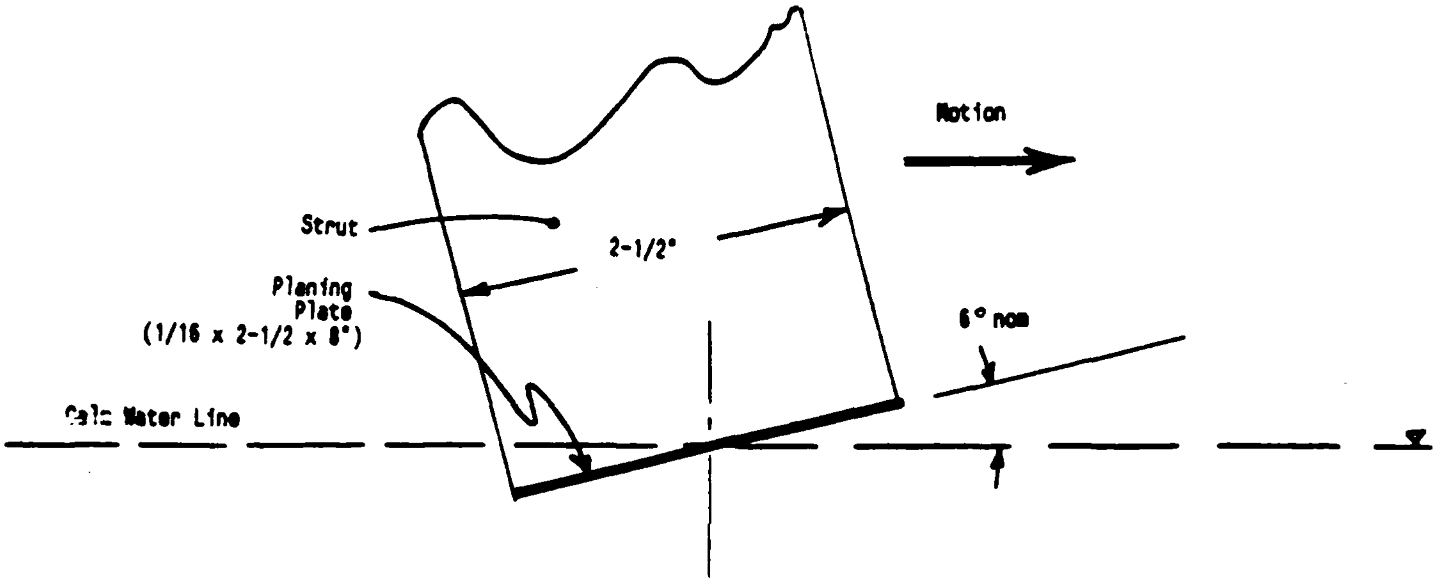


FIGURE 37 - CALM WATER PLANING

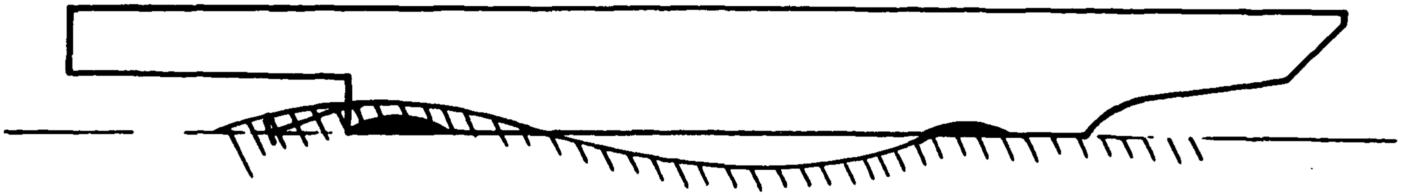


FIGURE 38 - UNFAVORABLE LIFTING SURFACE WAVE INTERACTION (SCHEMATIC ONLY)

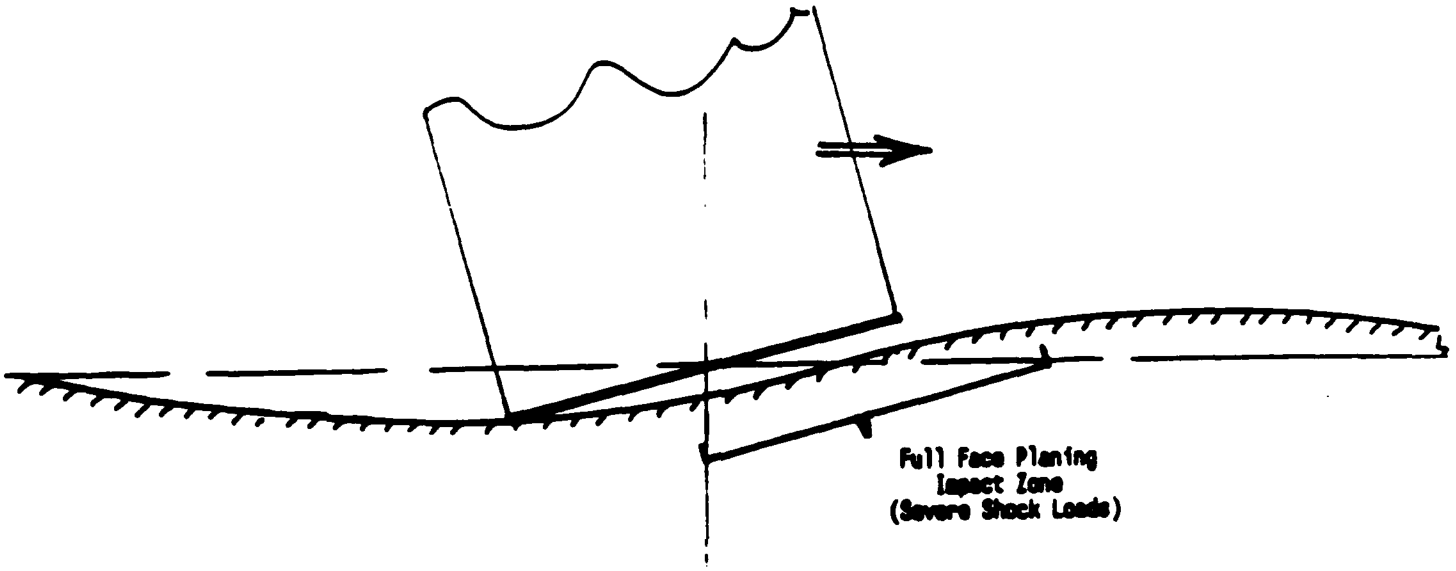


FIGURE 39a - SKIPPING PLANING

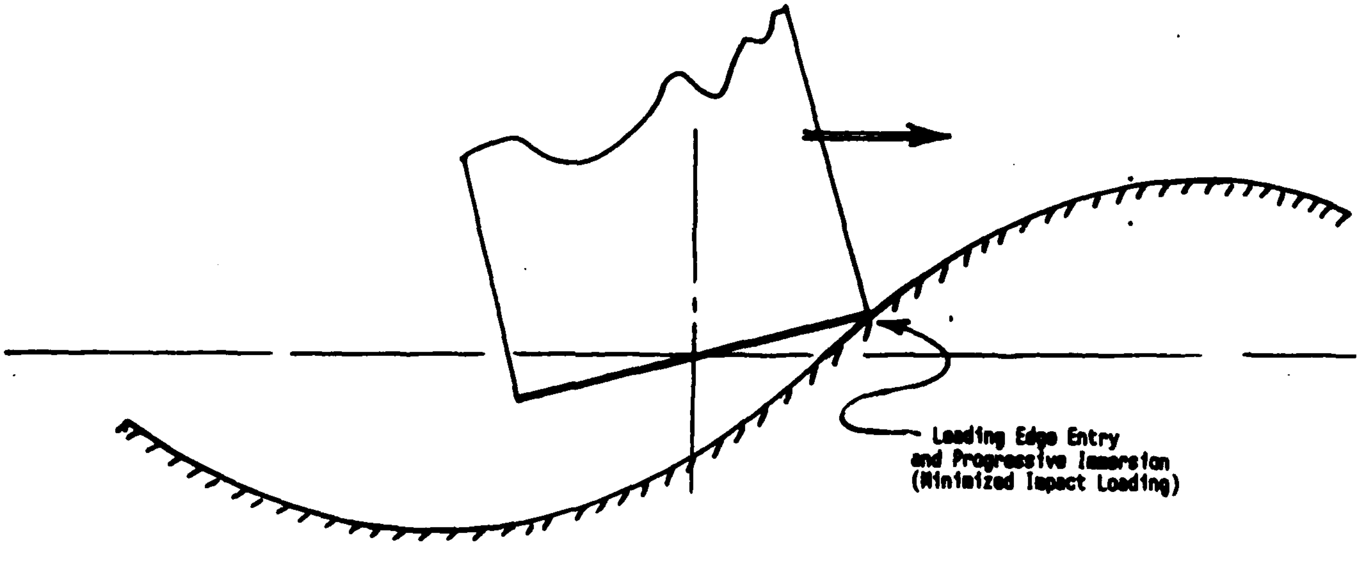


FIGURE 39b - PENETRATION PLANING

FIGURE 39 - PLANING MODES

Perhaps the most significant aspect of the planing plate performance in waves is the dramatic visualization of the difference in the flow field behavior as compared to that in calm water conditions. A schematic of a typical wave encounter is depicted in **Figure 40**. Review of the video recording reveals a highly dynamic situation. On entry the leading edge of the planing plate imparts forward momentum to the displaced water. This causes a forward jet that penetrates into the wave face and rolls up ahead of the planing surface. On the underside there appears to be a subducting jet that alters the bottom lifting forces. The planing plate test results indicate that the lift/drag ratio in sea state operations decreases by 50% at the higher speeds.

It is clear that predictions of planing plate performance in waves based on theory and extrapolations of calm water behavior are not valid in sea state operations. The flow phenomenon is highly dynamic and very transient. If the planing plate phenomenon is to form the core of a new vehicle concept, it needs to be more clearly understood.

6.3 Summary

Hull Hydrodynamic Interaction - In general, Ketron's performance predictions for the WAVESTRIDER (and their drag calculations in particular) ignore the hydrodynamic behavior of the convergent tunnel between the two catamaran hulls. The exploratory tests on this aspect of the WAVESTRIDER concept indicate that the funneling effect of the interhull tunnel is important in the determination of the overall drag of the WAVESTRIDER. While this is not a fundamental problem (the tunnel convergence can be designed out) it does nevertheless indicate the lack of maturity of Ketron's analysis and design methodology. In the first instance, the analysis should have normally provided for the hull interaction as it is normally done in the design of closely coupled catamarans. In the second instance, Ketron should have normally established at least rudimentary model tests, particularly for such a non-conventional hull configuration as the WAVESTRIDER.

Planing Plate Performance - The planing phenomenon of a planing plate configuration as proposed by Ketron for the WAVESTRIDER is not adequately described by their numerical estimating methods. This is a fundamental problem in the WAVESTRIDER concept. Ketron uses steady state values for lift and drag coefficients while the actual operating conditions are extremely dynamic and time-dependent. The exploratory model tests indicate that the lift/drag ratio in waves is approximately one-fourth of the value in calm water. Strictly speaking, the wave penetrating operation of a planing plate is a fundamental research problem and is not mature enough for design.

7. IN-HOUSE CONCEPT DEVELOPMENT

As a part of the evaluation of the WAVESTRIDER concept, the Navy conducted an in-house first cut concept development of a WAVESTRIDER AAVP Transporter. The Navy in-house effort was in two phases. The first was a broadbrush concept developed for a transporter configured for five AAVP-7A1s and a design speed of 40 knots. The second part of the in-house investigation consisted of an independent assessment of a similar vehicle,the HYCAT, configured to emulate the WAVESTRIDER for the AAVP transport role.

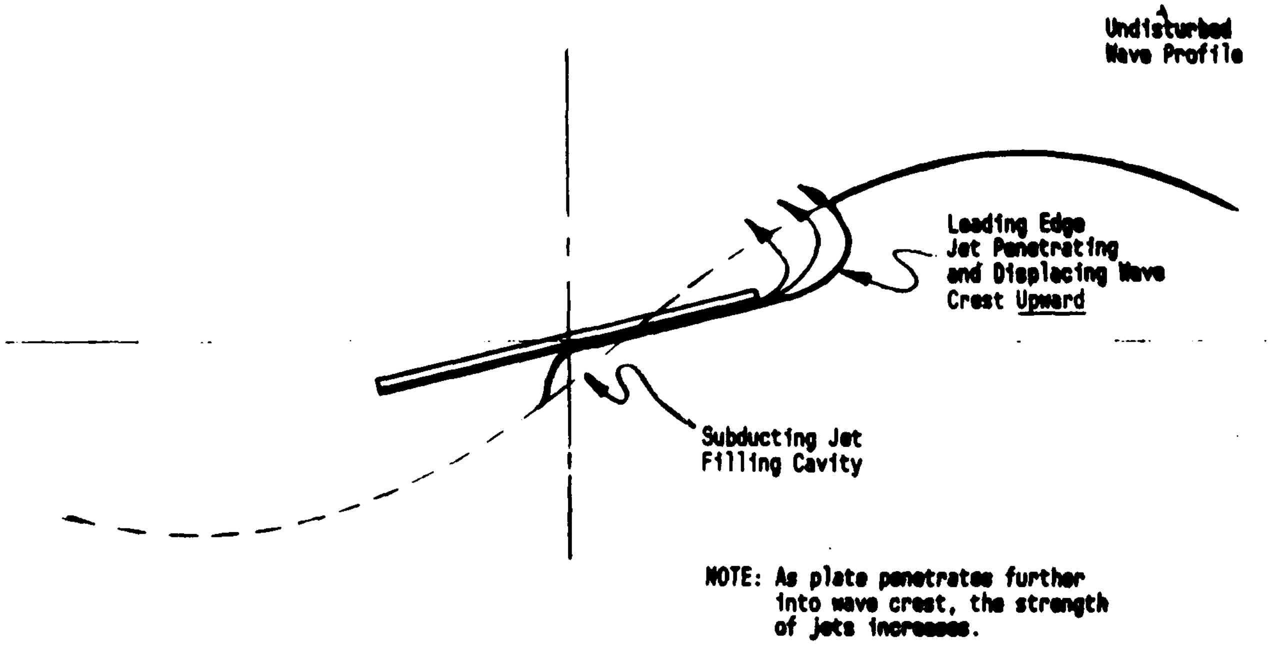


FIGURE 40 - PLANING PENETRATION HYDRODYNAMICS

7.1 In-House Concept Development Results (Excerpt from Reference 42)

The basic arrangement of the Navy's conceptual AAVP Transporter is similar to that of the Surface Effect Ship LVT Transporters which were investigated in Geoff Peters' FY-82 CONFORM study (Reference 36). The center of the Transporter has two lanes for the P-7's to drive straight through. Outboard aft on both sides are deck houses which shelter the control station and the engine intakes and exhausts. (See Figure 41.)

This arrangement was chosen for four reasons: 1) The straight path requires minimum maneuvering by the P-7's; 2) It keeps the P-7's close to centerline and thus minimizes heel problems during loading and discharge; 3) The intake and exhaust trunking will be simple and direct; 4) A ramp can be arranged easily at the bow between the catamaran hulls. It is recognized that the alternative proposed (at least initially) by Ketron with the P-7 lanes outboard may offer somewhat lower weight in the cross structure between the hulls.

The draft limitation imposed by requiring transportability in the well of an LSD-41 means that the catamaran hulls will be wider than what was typical of the earlier 24- and 60-foot WAVESTRIDERs. The tunnel width, and therefore the span of the main foil, will be on the order of one third of the overall beam of the Transporter. This will have an as yet undefined impact on the hydrodynamic behavior of the WAVESTRIDER.

Speed/Power/Fuel

The design goal was for speed "as much over 40 knots as practicable." Preliminary calculations showed that the span of the main foil will need to be on the order of the beam of the craft. This means that, rather than being unwetted as required by Ketron's claimed theory for the remarkable performance of the WAVESTRIDER, the bottoms of the catamaran hulls will be required to contribute to planing lift.

Accordingly, the first estimates for the Navy concept design assume that the main planing surface will be the equivalent of a large, zero deadrise step extending right across the hull from outer chine to outer chine. This step was estimated using data developed by Eugene Clement at the Model Basin in the 1960s. This data shows that a suitable value for aspect ratio is 1.5 and for angle of attack (trim) is 2 degrees. These values were adopted for the initial lift and drag estimates. Lacking guidance from Ketron as to lift distribution on WAVESTRIDER, it was initially assumed that 85% of displacement was carried by the main step/foil. Later estimates were made taking 80% of displacement as the main step/foil load.

The following table summarizes the final results of the Navy drag estimates for the three lifting surfaces at 40 knots speed using the Clement cambered step data of Reference (3).

Displacement		600,000 lbs
Main Step	Span	40.0 feet
	Chord	19.1 feet
	Area	762 sqft
	Drag (40 kts)	26990 lbs

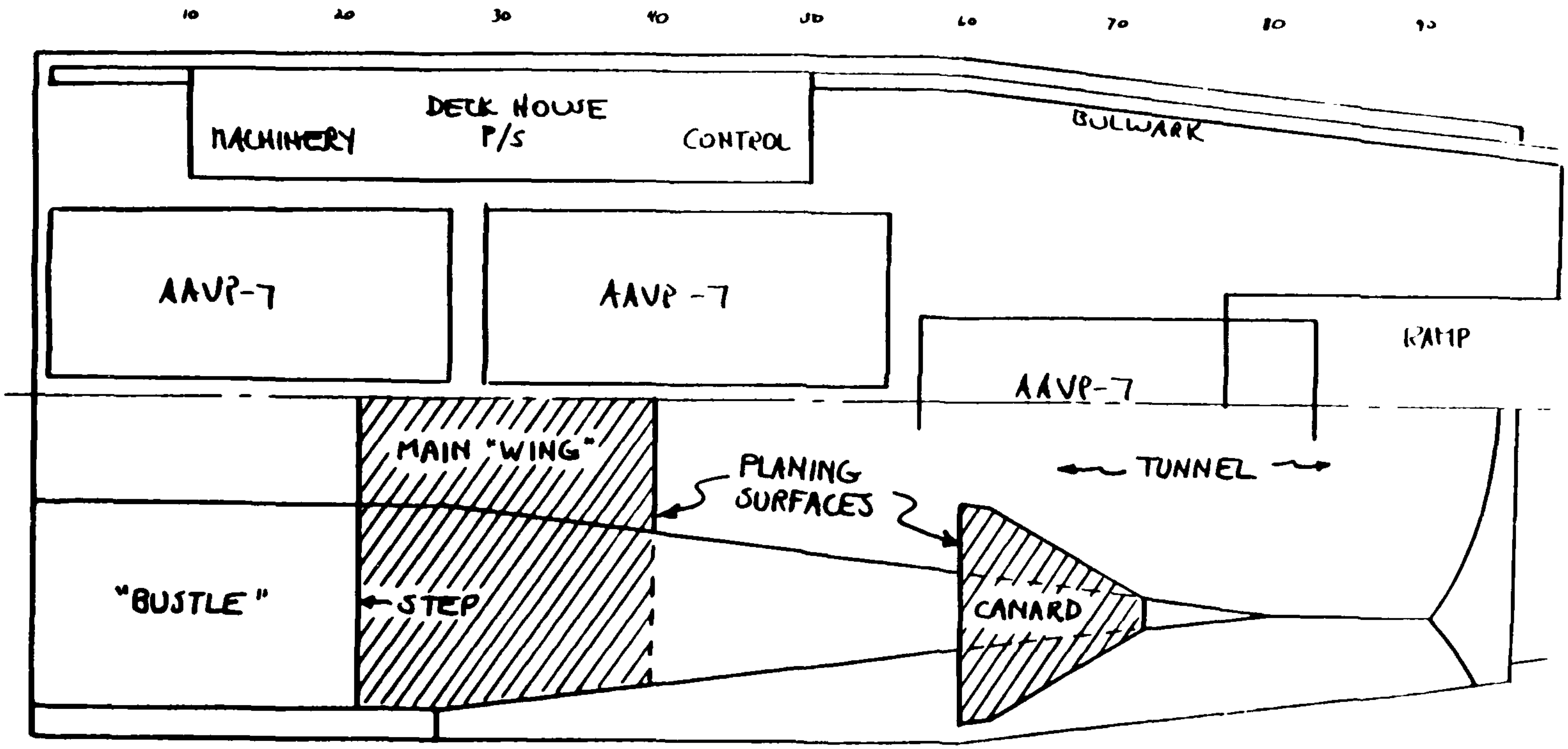


FIGURE 41 - AAVP TRANSPORTER
NAVY CONCEPT DEVELOPMENT OF "WAVESTRIDER" HULL FORM

Canard (each)	Span	14.1 feet
	Chord	6.7 feet
	Area	95 sqft
	Drag (40 kts)	3525 lbs

Clb	.066
Cld	.15
L/D	15.9
Total Drag	34,050 lbs
EHP (40 kts) (incl 40% margin)	5850

Comparing the results obtained by expanding Mr. Clement's Dynaplane model test to the results obtained from expanding only the cambered surfaces showed that there are unidentified interactions between the lifting surfaces in the model test that make the total drag of the model higher than the sum of the predicted drags of the forward and aft surfaces. The implication here is that a margin of 40% may need to be added to the lifting surface drag predictions to account for unknowns in the "real" craft.

A review of Reference 40 revealed that reducing trim to one degree would increase lift/drag to nearly 16 at an aspect ratio of just over 2. Drag predictions were calculated at these parameters with the result that, including the 40% margin, required EHP is 5850. This is within the rating of the Allison 571 KF at an overall propulsive efficiency of 50%.

Propulsion System

Gas turbine engines were selected as the prime movers in the propulsion system. Candidate engines include:

Engine	Horsepower
Allison 501 KF	4330
Allison 570 KF	5100
Allison 571 KF	6000
AVCO TF40B	4000
GE LM500	5450

Qualification testing will be required for all but the Allison 570 KF engine. Higher horsepower output may be achievable.

There have been several CONFORM designs for craft in this speed range. The closest in application to the WAVESTRIDER AAVP Transporter are the more conventional LVT Carriers described in Reference 36. Following is an extract of the discussion of the powering system for these more conventional concepts.

> "The powering system had several options ranging from electric or mechanical drive, to waterjet or propeller, to controllable or fixed pitch propellers, as well as gas turbine or diesel power plants...Only a semisubmerged, supercavitating propeller produced sufficient power at hump and at full speed for the aluminum-gas turbine configuration. At hump speed, the waterjet encountered cavitation

problems in developing sufficient thrust, and at high speed its lower efficiency demanded higher installed power than the propeller."

It is worth noting that a 32-meter LVT Carrier design conducted under the CONFORM Program included a pair of Allison 571 KF turbines driving semisubmerged, controllable pitch, supercavitating propellers. At a full load displacement of 368 tons, it was predicted to exceed the speed requirements of the WAVESTRIDER AAVP Transporter in sea state 3. This more conventional craft is 100 tons heavier than the estimated weight for the 96-foot WAVESTRIDER Transporter.

Very high propulsive efficiency is predicted for the semisubmerged propeller. The technology applied is the same as for the propellers that powered the SES 100B so it is considered to be within the state of the art. (Note that the propulsive efficiency as measured during full scale trials was considerably lower than what had been predicted in the model trials of the propeller.)

Controllable pitch is required to cover the difference in speed potential with and without the AAVP-7s on board.

The Arneson Drive system is attractive for this application. In addition to providing retraction of the propeller when the craft is in the LSD well dock, it allows fine tuning of the propeller submergence in relation to the step trailing edge. It also slews sideways to provide steering forces.

Structural Design

The first cut at Group 1 (Structures) weight was based on a combination of personal experience in the design of patrol and landing craft and comparison with six sets of weight data for craft of similar size. Aluminum is assumed to be the material of choice, although it may prove possible to trade off speed against the greater durability of steel construction.

Smeared thickness (plating plus longitudinal stiffeners treated as an average pounds-per-square-foot weight) of the hull bottom, sides, and main deck was taken as 1/2". Bulkheads average 5/16" and the deckhouse averages about 1/4". Other major components were estimated similarly. Mast, foundations, and other smaller components were taken from the historical data.

A 1966 report by John Bader of DTNSRDC on Landing Craft Structures shows the following smeared thickness weights (lbs/sqft):

		LCM(8) (Aluminum)	LCU (Aluminum)
Bottom:	Smeared Weight	8.1	7.1
	Plating Thickness	3/8	3/8
Side:	Smeared Weight	6.2	6.8
	Plating Thickness	3/8	3/8
Deck:	Smeared Weight	8.0	10.5
	Plating Thickness	3/8	1/2

The cargo deck of the LCAC is fabricated from a custom extrusion that includes the equivalent of 3/8" aluminum plating supported by 5" deep stringers at 9" intervals. Transverse bulkheads are spaced every 4.5 feet. The deck houses are of 1/8" aluminum. The ramp is constructed from 3/8 plate top and bottom with stiffeners every nine inches. The underside was designed to 30 psi forward and 7 psi aft. The design was done to as-welded yield against "limit" loads defined as once or twice in the craft life. A second check was done of (1.5 x limit load) versus ultimate, as-welded. For critical fatigue loads, the allowable stress was 8500 psi.

It was agreed with Ketron that the Allen-Jones method of predicting bottom design pressure was acceptable for the WAVESTRIDER AAVP Transporter. This includes taking 3g as the acceleration limit.

The Navy concept uses 56 psi for the design pressure on a typical panel of the bottom planing surface. At 14300 psi allowable stress for 5086 aluminum (providing for fatigue), bottom plating works out to approximately 1/2" thick. As a result, a smeared thickness equivalent weight of 10 lbs/sq-foot was used for the triangular bottom surfaces. The same weight was used under the bustles aft in order to provide for the fatigue effects of the propellers.

Since the tunnel and lower parts of the outboard sides are concave in shape, it is expected that they will go directly into tension under the 3g area load. Very thin plate can support this load. However, thickness was kept at 1/4" in the Navy concept to reduce vulnerability to damage from floating objects.

Weight Estimates

Weight data from six Navy designs were used as the source for estimates for the WAVESTRIDER weights. This data was also made available to Ketron. The six craft are: PHM hydrofoil patrol craft, LCAC air cushion landing craft, LCM-9 design study for a high-speed aluminum planing landing craft, LCU 135 low tech steel landing craft, and two LVT Carrier design studies for surface effect landing craft.

Because the PHM has extensive habitability, weapons systems, and C3 equipment, its weight fraction data is considerably different from that of the landing craft. Therefore it was not included in the weight fraction averages that were calculated for comparison to the WAVESTRIDER Transporter.

The weight estimate for the Navy concept design of the WAVESTRIDER Transporter was assembled by selecting representative weights from the craft which were most nearly similar to the WAVESTRIDER. For example, the LCU, being steel and having live-aboard habitability provisions, was useful only as a double check for auxiliary systems weights. The LCAC, LCM-9, and the two LVT Carriers were the primary sources used. However, there is a noticeable difference in the Group 5 weight fraction for WAVESTRIDER and canard foils which appear in WAVESTRIDER's Group 5 have no counterpart in the other craft.

Risk

In declining order of importance, the risks associated with the WAVESTRIDER Transporter are considered to be:

- Propulsor: The WAVESTRIDER is breaking new ground in terms of inflow complexity. The diameter restrictions imposed by docking in the LSD-41 exacerbate the problem. The development of a suitable propulsor may prove impossible within reasonable time and cost.

- Seakeeping: The low, wide bow may simply prevent takeoff in waves. The low tunnel mandated by docking in the LSD-41 may lead to unacceptable ride quality in the wave-piercing mode. Low freeboard may lead to dangerous deck flooding.

- Drag Prediction: Hydrodynamic complexity, lack of performance data, and rudimentary or incomplete Ketron prediction models combine to reduce confidence in WAVESTRIDER drag predictions. However, the contractual speed requirements is low (40 knots) and plenty of horsepower is available. Whether the Transporter achieves 40 knots depends more on the difficulty of solving the propulsion problem than on drag prediction.

- Lift: It appears that the main lifting surface of the WAVESTRIDER Transporter is of too small area to provide the necessary lift, particularly at takeoff speeds.

- Weight: Particular attention will be needed in the final design of the main deck and superstructure, the ramp and its handling system, the ship fittings, and maintenance/spares provisions.

Conclusions

The in-house concept development showed that the structural estimates by Ketron are reasonably close to Navy practice in many areas but light in others. In total, however, the Ketron light ship weight is about 26 percent lighter than that for the Navy concept. Most of this difference is in structure and fabrication and implies that the WAVESTRIDER will be vulnerable to damage in well-deck operations. Slamming and torsional racking loads will be very difficult to predict.

The in-house design verified that the installed power (12,000 horsepower) is adequate to deliver the required minimum 40-knot speed provided that the major difficulty of designing and developing suitable propulsor can be overcome. It should be noted that while the Navy design is expected to require nearly all of the available horsepower to achieve 40 knots, Ketron predicts that their design will achieve more than 70 knots. A speed of 70 knots is considered to be very unlikely.

In addition to the weight disparity and the risk associated with propulsor design, major risk remains in the areas of hump speed drag and thrust prediction, sizing of the main lifting surface, takeoff in waves, and seakeeping. Propulsor design and seakeeping each have the strong potential of being impossible to resolve within the constraints of the AAVP Transporter.

The state-of-the-art of WAVESTRIDER design is not yet up to the rigorous challenge posed by the design of an operational Navy craft. The WAVESTRIDER hull form is still in the early stages of development. Many pitfalls lie in its path, especially when the attempt is made to apply it to very heavily loaded craft.

7.2 HYCAT Configuration Comparison

The key purpose of this effort was to obtain data about HYCAT in an arrangement and configuration that would closely emulate Ketron's 96-foot WAVESTRIDER AAVP Transporter. This would provide a third independent check on Ketron's concept development.

HYCAT Configuration

HYCAT, **Figure** 42, is a hybrid marine vehicle concept which utilizes a combination of both hydrostatic and hydrodynamic support. It was invented by Dr. Dale Calkins, now of the University of Washington. Dr. Calkins was contracted to provide an emulated WAVESTRIDER Hullform based upon HYCAT calculations and performance analysis. The HYdrofoil CATamaran (HYCAT) configuration combines a planing catamaran hull form with two fully submerged hydrofoils mounted in tandem in a fore and aft configuration. The hull form is developed by adding a high deadrise sidehull along the keel of each catamaran demihull. The sidehull, which, in addition to the hydrofoils, is the only portion immersed when operating foilborne, provides buoyancy support. Spray strips act as discontinuities which separate the flow and provide dynamic lift in addition to the lift of the submerged hydrofoils.

Stability in the heave, pitch, and roll is achieved through the displacement dependent sidehull buoyancy, and the rate and displacement dependent lift developed by the spray strips and hydrofoils. HYCAT has been shown to have resistance and motion characteristics midway between those of surface piercing hydrofoil and a conventional fully submerged hydrofoil.

WAVESTRIDER Equivalent Considerations

Geometry: The 96-foot WAVESTRIDER Transporter configuration developed by Ketron was used as the basis for the geometry. Specifically, the dimensions were:

Length, overall = 96.0 feet
Beam = 47.4 feet
Length/Beam ratio = 2.025

This compares with the baseline HYCAT configuration dimensions:

Length, overall = 80.63 feet
Beam = 30.0 feet
Length/Beam ratio = 2.6875

Displacement: Two displacements were used:

a) Full load displacement = 255.61 LT
b) Light ship displacement = 136.62 LT

Frontal Area: The frontal area of the WAVESTRIDER configuration is proportionately smaller than that of the HYCAT configuration for the same beam. This was accounted for by modifying the

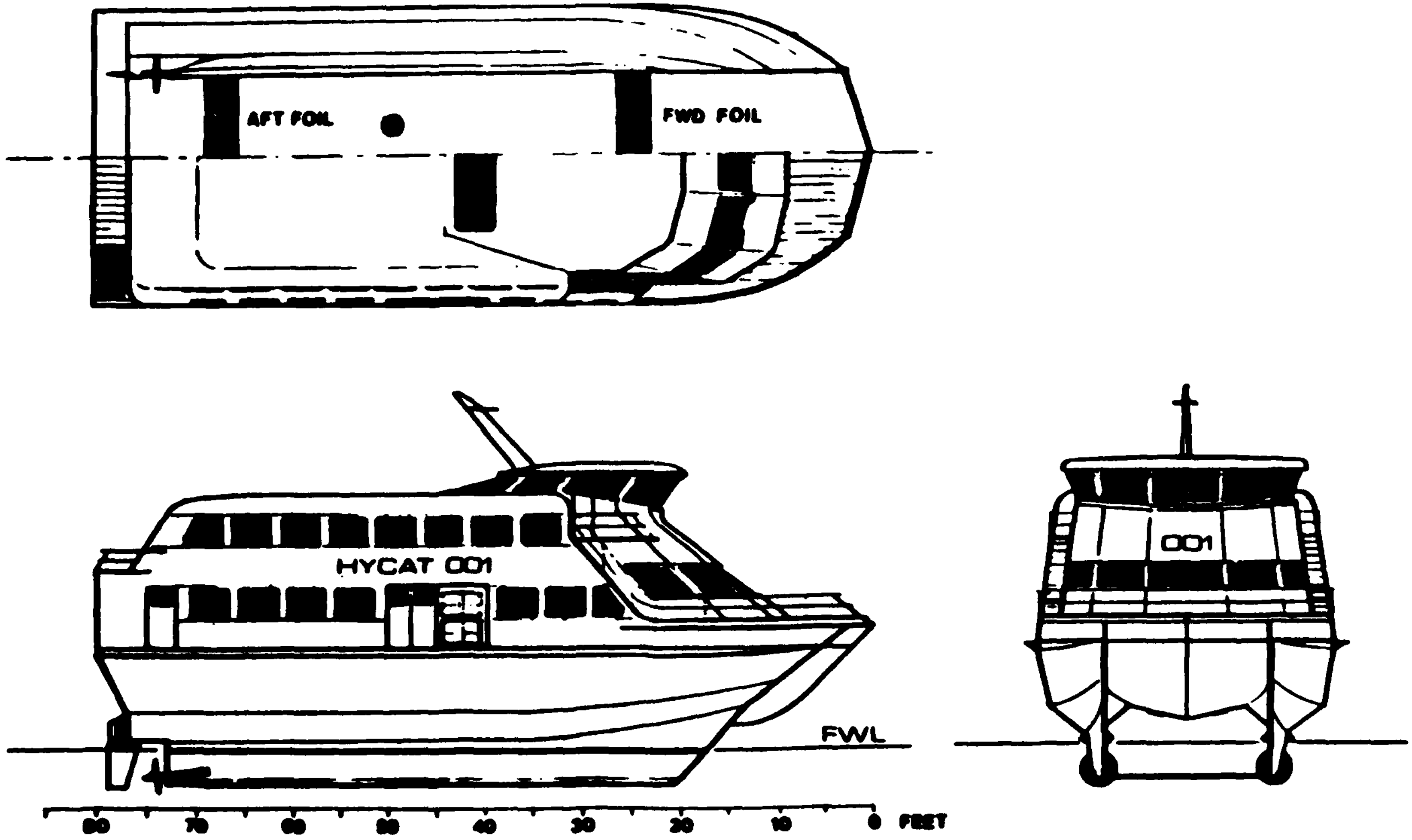


FIGURE 42 - HYCAT CONFIGURATION

program to reduce the frontal area. Therefore the lower portion of the hullform is that of HYCAT, while the upper portion is that of WAVESTRIDER, and thus will have the proper aerodynamic drag level.

Powerplants: The powerplants were assumed to be two Allison 571 KF gas turbines. Data from Allison shows a continuous rating of 6445 SHP each at an ambient temperature of 59 deg F for a total of 12890 SHP. However, the 6000 SHP rating (12000 total) provided by DTRC was used in the analysis.

Rudders: A second modification to the program was to reduce the size of the rudders. Ketron's 96-foot WAVESTRIDER employs the Arneson Marine Drive-ASD-18 propulsion units with semi-submerged propellers. These units have a small skeg for directional control in addition to the thrust vectoring capability of the drive. The size of the rudders were reduced to reflect this geometry.

Overall Propulsive Coefficient: The overall propulsive coefficient (OPC) as a function of speed was developed from detailed studies done for HYCAT using a fully submerged propeller. The speed range covered was from 15 to 45 knots. This was adjusted to from 15 to 80 knots to cover the expected range of the WAVESTRIDER configuration. It was assumed that a semi-submerged propeller, necessary for the higher operational speeds anticipated for the WAVESTRIDER configuration, could be selected that would provide an equivalent OPC. The OPC is comprised of the following components:

a) Thrust deduction factor
b) Wake fraction factor
c) Relative rotative efficiency
d) Mechanical efficiency
e) Propeller efficiency

Equivalent HYCAT Data Runs

HYCAT is supported by fully submerged hydrofoils and, as such, is not designed to operate at speeds much above 50 knots. This is due to cavitation which becomes a problem as speed increases. This is controlled during the configuration generation process by varying the geometric aspect ratio of the hydrofoils. As the aspect ratio is decreased, the foil cavitation speed (speed at which incipient cavitation occurs) increases. However, the hydrofoil drag also increases thus affecting the performance and maximum speed. Past studies on HYCAT have shown that the optimum aspect ratio is between 4.0 and 6.0. It should be emphasized that the performance estimates are for calm water operation at a hull trim angle of zero degrees.

A total of six data sets were generated, three foil aspect ratios (4, 5, and 6) at the full load displacement, and three foil aspect ratios (4, 5, and 6) at the reduced displacement. Each data set contains the following information:

a) Hull geometry
b) Foil geometry

c) Sidehull geometry
d) Weight statement
e) Support statement
f) Performance (foilborne) statement
    Foil configuration
    Drag
    Lift/Drag Ratio

The HYCAT configuration will become foilborne at a speed between 20 and 25 knots. The hydrofoils are assumed to have incidence control so that the foil lift coefficient, and consequently the hull trim, can be controlled. The minimum foilborne speed is controlled by the maximum lift coefficient which can be obtained without stalling. After foilborne operation is achieved, the hull trim angle is reduced to zero degrees by adjusting the foil incidence angles.

Study Results

Three figures were generated for each data set. These include the resistance, lift/drag ratio and SHP required as a function of speed. The program was first run for the full load displacement. These runs determined the hydrofoil thickness/chord ratios for each of the aspect ratio configurations. These same thickness/chord ratios were then used for the reduced displacement runs.

Figure 43 represents total calm water resistance for three aspect ratios for the hydrofoils. The difference is very small (less than 5%). The significance, however, is in the drag of the side hulls. The side hulls account for approximately 50% of the total drag at low speed, i.e. 20 knots, and in excess of 60% at the higher speeds. This again confirms that the hull hydrodynamics (lift and drag) are significant and cannot be neglected.

8. DISCUSSION OF CRITICAL ISSUES

Much has been put forward by Ketron regarding the vehicle concept, lift and drag coefficients, and bridging functions. The hydrodynamic problem of the WAVESTRIDER system is extremely complex, even in calm water. Sea state predictions are addressed by imposing a constant drag margin. In reality the WAVESTRIDER operates in at least three completely different modes:

a) At LOW SPEED the vehicle is in a fully buoyant mode. Under full load conditions the tunnel between the hulls is completely submerged. Hydrodynamically the craft can be treated as a low aspect ratio barge with rather substantial damping plates and unusually high wetted surfaces.

b) At SUB-HUMP SPEED the WAVESTRIDER is partially supported by dynamic lift on the planing surfaces and partially by buoyancy of the side hulls. The hydrodynamic interaction between the various hulls and appendages is extremely complex and appears not to be well understood.

c) At HIGH SPEED (post-hump) and CRUISING SPEED the craft is ideally supported by dynamic lift alone. This may be true in calm

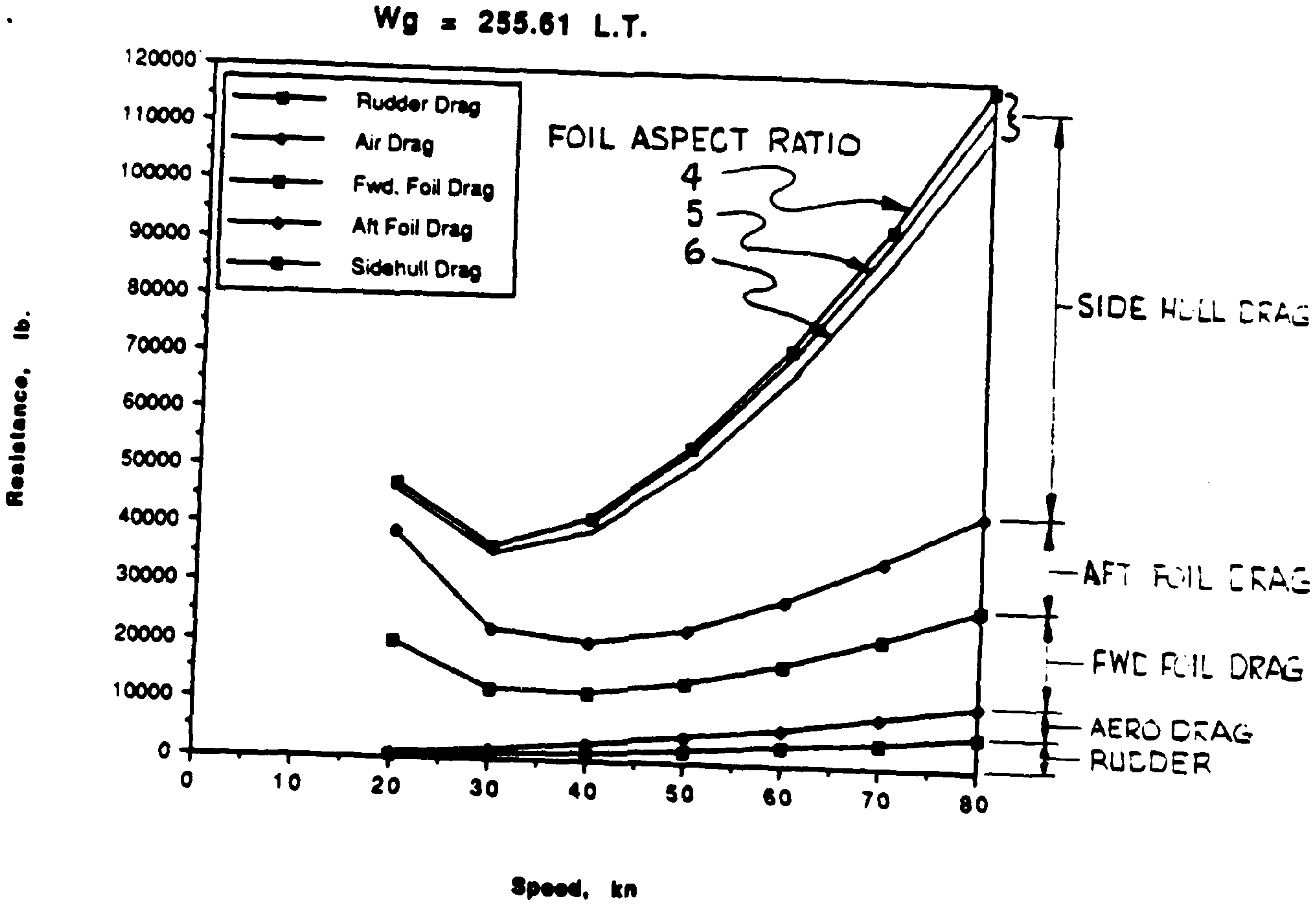


FIGURE 43 - HYCAT TOTAL DRAG SENSITIVITY TO ASPECT RATIO

water, at one design speed, and with a single load-out condition. In a sea state, however, the craft performance is determined by a complex hydrodynamic synergism. (The dramatic dynamics of this synergism can be seen in the video tapes of runs of the 24-foot craft even in relatively calm water.) The planing surfaces now behave more like ventilated hydrofoils, and part of the wave mass passes over them and encounters the hulls and cross-structure of the craft. In this sea state condition, it is doubtful that the assumptions about free surface behavior (favorable interference of waves generated by planing surfaces) are valid.

The issues related to the WAVESTRIDER as an AAVP Transporter can be grouped into two broad categories. The more serious of these, the possible "show stoppers", deal with the fundamental aspects of the concept and its understanding. These technology issues are central to a viable WAVESTRIDER vehicle. There is a second collection of possible problems that are not necessarily fatal flaws, but, at best, demonstrate a lack of technological maturity to allow confident design.

8.1 Technology Issues

Take-Off Operation

An issue associated with the WAVESTRIDER concept conflicting with mission requirements is that of low freeboard. **Figure 44** provides a perspective of 1/3 and 1/10 highest waves in sea state 3. It is seen that at full load, the top of the tunnel is below the calm water surface and that the crests of some waves exceed the top deck level. There is a possibility of "green" water on deck. The impact on the stability of the craft has not been clearly addressed. This is an important issue, because "green" water will impact overall stability (particularly in roll), may limit the center of gravity travel and disposition of the payload, and may affect the tie-down loads on deck. Green water on deck also represents an added mass to the craft and is likely to impact the "take-off" power requirements unfavorably.

Sea State Operations

A generic and fundamental issue in the WAVESTRIDER concept is the "at speed" flight attitude of the craft with respect to the actual surface profile in a sea state.

In a sea state and at a given speed, the WAVESTRIDER will establish a "flight" level relative to the wave system. Depending on the loading (psf) on the lifting surfaces, the craft will "fly" somewhere between the crest height (for low foil loads) and the wave trough (for high loads). The relative significance is depicted in **Figure 45**. It is evident that it now becomes impossible to avoid contact between at least a portion of the wave mass and the hull structure of the craft. It does not appear that the interaction of the wave mass with the hulls has been addressed. This is an important issue in that the interaction will be reflected in the total craft resistance and spray generation.

Resistance

A generic - and probably the most problematic - technology issue appears to arise in the drag and hence powering prediction capability. The methods that have been used to date by Mr. Payne and Ketron are incomplete and inadequate. Drag

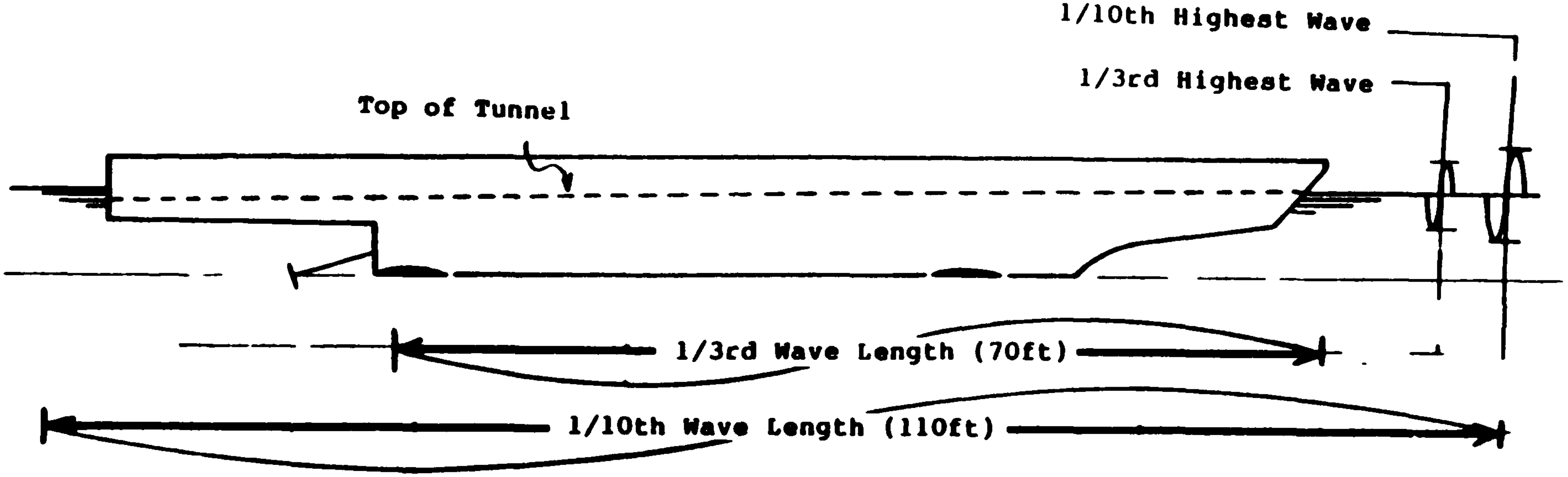


FIGURE 44 - SEA STATE 3 AND WAVESTRIDER SIZE RELATION

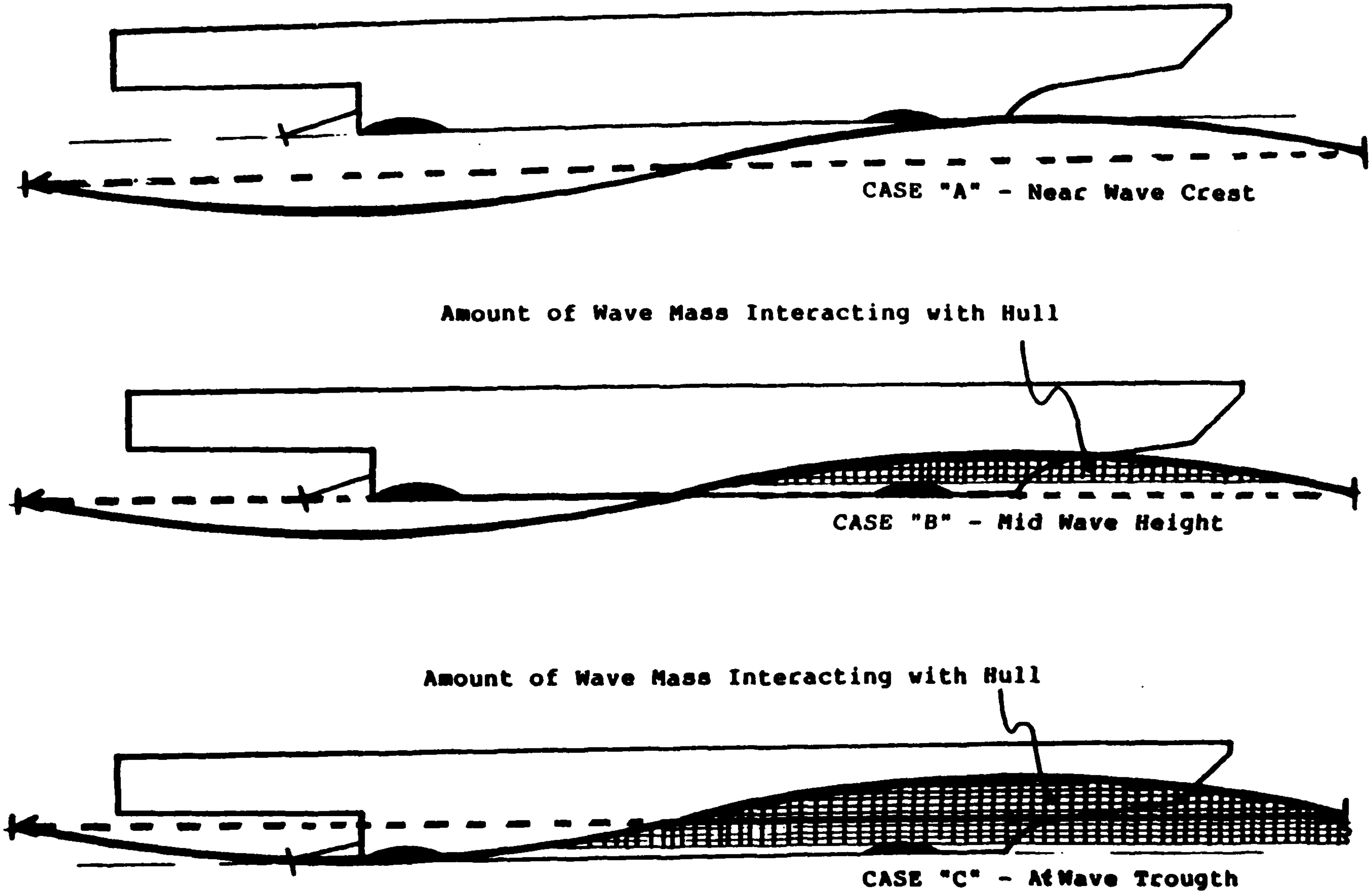


FIGURE 45 - OPERATING LEVEL OF HULL RELATIVE TO WAVESTRIDER

components of the WAVESTRIDER vehicle that need to be addressed are many, and include the following:

- Wave making drag of side hulls.
- Wave making drag of cross-structure.
- Interference drag of side hulls and cross-structure.
- Induced drag of side hulls.
- Viscous drag of side hulls.
- Viscous drag of cross-structure.
- Wave drag of planing surfaces - bow and main.
- Induced drag of planing surfaces - bow and main.
- Interference drag of bow surface and side hull.
- Interference drag of main surface and side hull.
- Wetting and momentum drag of tunnel.
- Upper surface spray momentum drag.
- Propeller plume interference drag.
- Propeller shaft drag.

Each of the above will have varying degrees of significance depending upon the regime in which the craft is operating. The relative significance will depend on:

- Speed of the craft (sub or post hump).
- Loadout (depth of submergence).
- Geometry (foil angles).
- Sea state.

Sufficiently detailed methodology for the calculation of drag has not been provided by Ketron. From information that has been made available, it appears that the planing surface drag is the dominant resistance element that has been considered by Ketron (and most others seem to be minimized or ignored).

Transient Conditions

The WAVESTRIDER is exposed to a number of deviations from normal steady state operation (gusts, abnormal waves, and take-off and landing transients). Of these the "take-off" is clearly one of the most critical. The WAVESTRIDER must accelerate from a buoyant attitude as shown in **Figure 46a** to some "flight" attitude depicted in **Figure 46b** where dynamic planing lift dominates - and all this in sea state 3. The treatment of this problem is even more difficult than the calm water predictions.

In the initiation of the take-off sequence, the craft is fully buoyant and the tunnel is essentially wet (full of water). The tunnel zone is actually a convergent flowpassage with the narrowest section at the main planing surface station (**Figure 47**). It is not clear how this feature impacts the drag of the craft and how the lift of the main wing is altered.

Even if it can be argued that "normal", fully loaded "flight" occurs with the foils near the wave crests, the take-off will encounter severe hull interaction with a significant wave mass of water. This situation may give rise to severe spray generation. With two adjacent hulls, the spray interaction will become even more

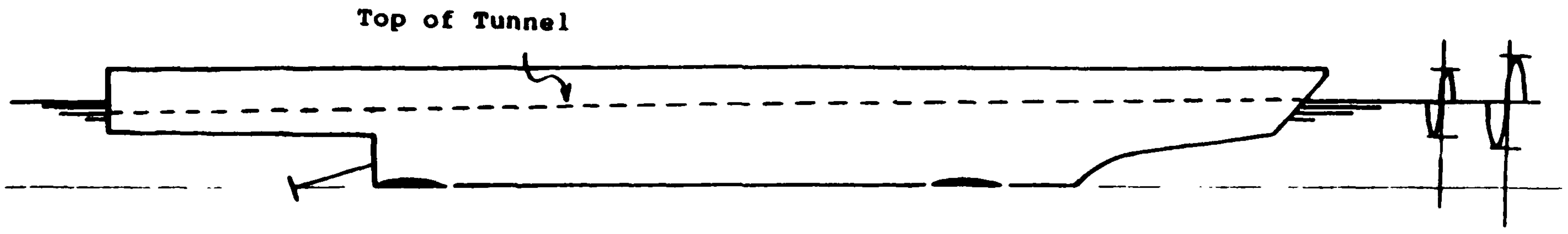


FIGURE 46a - BUOYANT MODE - LOW SPEED

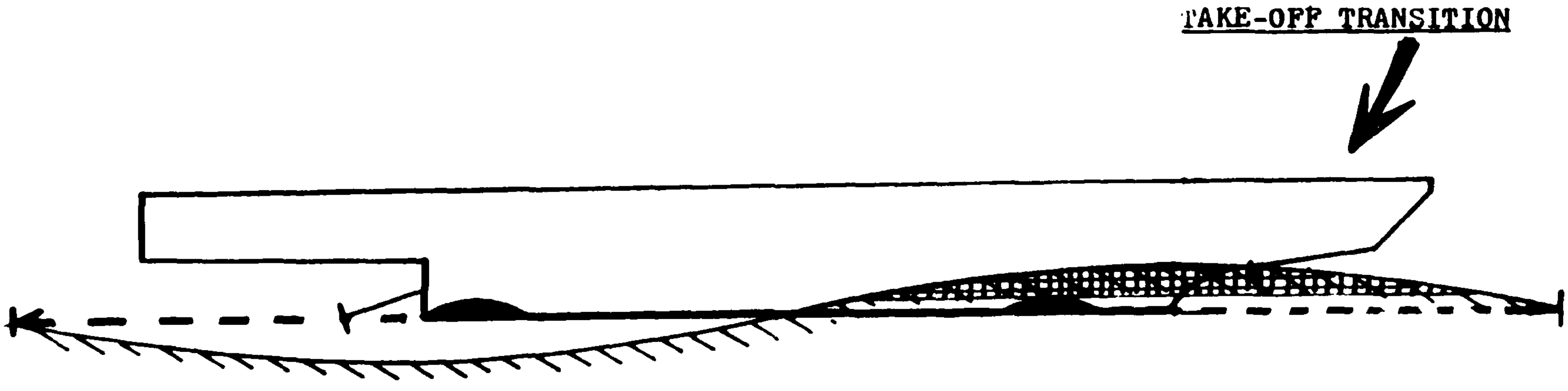


FIGURE 46b - DYNAMIC LIFT SUPPORT

FIGURE 46 - TRANSIENT CONDITIONS

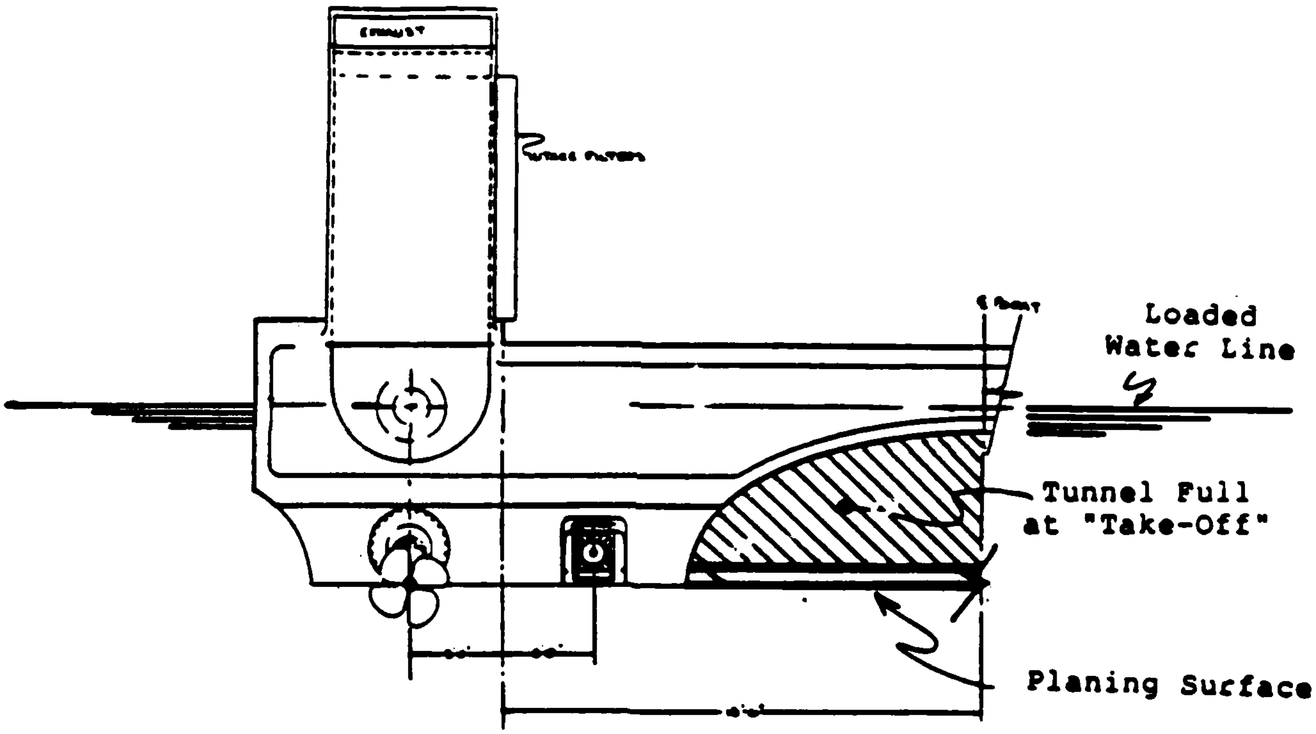


FIGURE 47 - TUNNEL-FOIL INTERACTION

complex (**Figure** 48). It has not been made clear how drag is affected nor what this does to the ride quality and directional control of the craft.

Motion Prediction

The last, but still quite important generic issue of the WAVESTRIDER concept deals with the motion characteristics of the vehicle. It is in the ride quality area that many otherwise successful vehicle concepts experience severe limitations, particularly in heave and surge accelerations. Proponents of the WAVESTRIDER (Mr. Payne and Ketron) have strongly articulated their confidence in the craft's mild behavior and (to a lesser degree) in their ability to predict craft accelerations. Evidence, on the other hand, appears to be quite to the contrary. The only "operating" WAVESTRIDER craft is said to have a very "skittish" behavior and unacceptably severe ride quality in realistic sea states.

Motion prediction of the WAVESTRIDER is understandably difficult. The theoretical model of the vehicle dynamics presented by Ketron is a relatively rudimentary (by their own statement) formulation of a spring damper mass system with heave as the only degree of freedom.

It does not appear that the proposed model is sufficiently mature to allow realistic prediction of craft accelerations and ride quality. The situation is further complicated by the proposed mechanical design associated with ride quality. As an example, it is proposed that the lifting surfaces would twist and warp to shed some of the load spikes. This approach has not yet been made to work satisfactorily even in the relatively benign world of aviation.

In summary, there are five generic technology issues inherent in the WAVESTRIDER concept. These are:

a) Lifting surface interaction and its validity over the operating envelope of the WAVESTRIDER.

b) Resistance and powering predictions that reflect craft complexity.

c) Behavior and performance in transient conditions such as take-off.

d) Sea state operation and the impact of a sea state on the WAVESTRIDER performance.

e) Dynamic behavior, motion, and ride quality prediction.

From the information available, these issues do not appear to have been examined to the degree necessary to proceed to the design phase of the WAVESTRIDER vehicle. Further, the investigation and evaluation conducted to date would indicated that when these issues are properly addressed,many of them will result in substantial increases in the theoretical drag predictions for the WAVESTRIDER hullform, and these increases will serve to reduce the efficacy of the WAVESTRIDER, making the concept infeasible for the proposed use as an AAVP Transporter (not to mention any other mission).

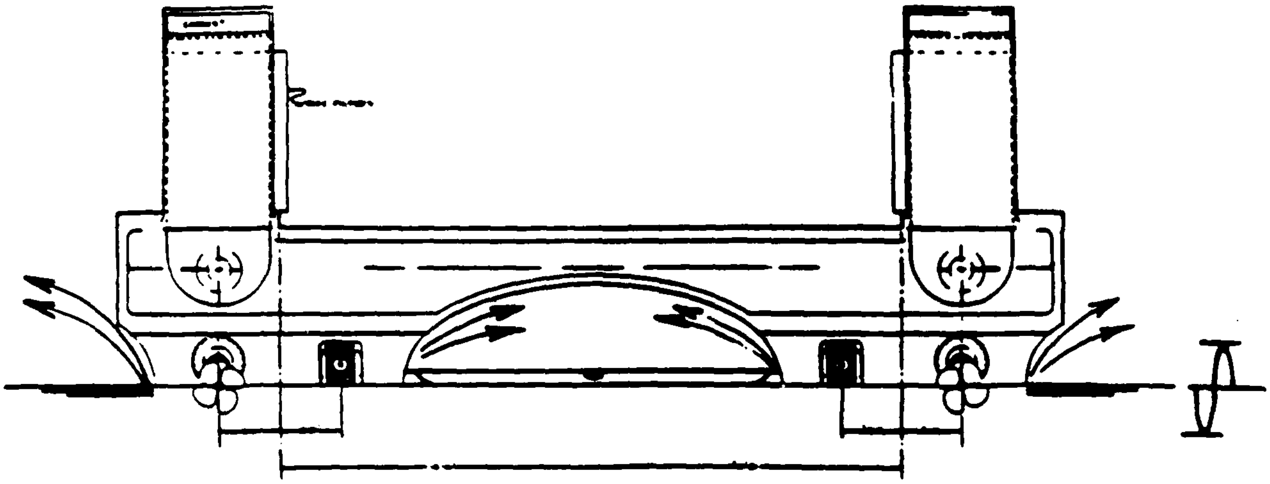


FIGURE 48 - TUNNEL INTERNAL FLOW

8.2 Technical Design Questions

The following technical design questions fall into a category where there is technical uncertainty and concern, but where technical resolutions would seem possible. The following items are also either specific and unique to the WAVESTRIDER concept or are mission related.

Propeller at Take-Off. A possible problem associated with the specific propulsor selected (Arneson) is that of broaching. In the upper speed range of the take-off sequence (near hump speed), the craft will likely be in a "semi-contouring" mode (**Figures 49** and **50**). It is likely that at some speed the propeller depth of submergence will be varying and may even broach. Conversely, if the propellers are depressed to avoid the possibility of broaching, then the drag of the propeller shaft may become critical.

Propeller Rooster Tail. Surface running ventilated propellers generate a significant fountaining or "rooster tail," which, while picturesque, represents an energy loss. The configurations shown by Ketron locate the propeller under a stern overhang or bustle. It would be expected that the rooster tail will impinge on the overhang and result in a drag penalty (**Figure 51**). There may have to be some adjustment to the design or a rooster tail flow management structure added.

Propeller Side-Thrust. The surface propellers will generate significant side thrusts. These thrusts are balanced when propellers have opposite rotation and equal submergence. In a sea state, however, one propeller or the other may broach. The resultant thrust imbalance does not seem to have been considered. Although less significant than other issues, it is of non-trivial concern. Since the WAVESTRIDER is basically point or line supported (on the bow canards and the beam foil), the extraneous and variable lateral loads will possibly impact control, stability, and maneuvering. In other applications of surface propellers (hydroplanes and SES 100B), the lateral propeller force has been of considerable concern.

Structural Loads. The WAVESTRIDER configuration depends on support or lift at the two bow corners and across the beam at the main planing wing. This arrangement is likely to result in severe racking loads on the cross-structure, particularly in quartering sea states. It is dangerous to think of the craft as having an LCAC-type structure. The LCAC is an air cushion supported craft, where the weight is borne uniformly by the cushion air pressure over the entire planform of the vehicle. The WAVESTRIDER is point and line supported, and additional structure must be provided to "carry over" the point loads. At the projected speeds of 40+ knots, the WAVESTRIDER structural weight fraction is likely to have to be greater than that of catamarans and tunnel hulls.

Power Plant Availability. There are two broad categories of available gas turbine marine power plants. There is a selection of engines up to approximately 6000 hp. From 6000 hp to approximately 15,000 hp, there does not exist a single marinized off-the-shelf engine. Allison-Marine indicates that:

- The current 571 marine engine is rated at 6000 hp.

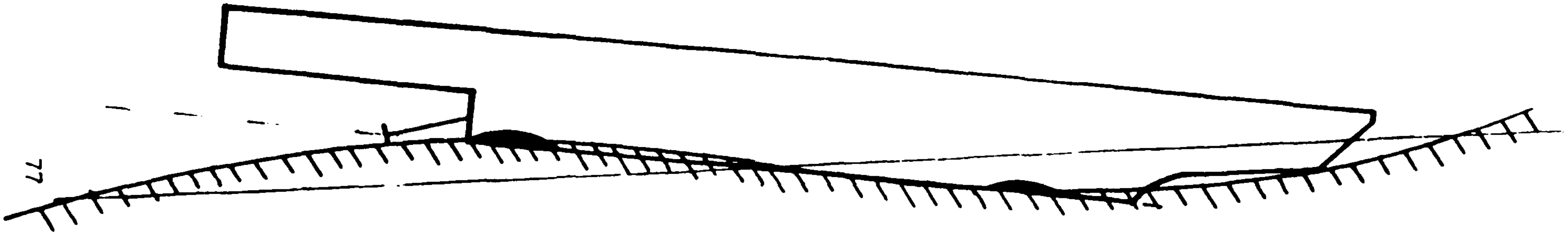


FIGURE 49 - POSSIBLE PROPELLER TRANSIENT CONDITION AT "TAKE-OFF"

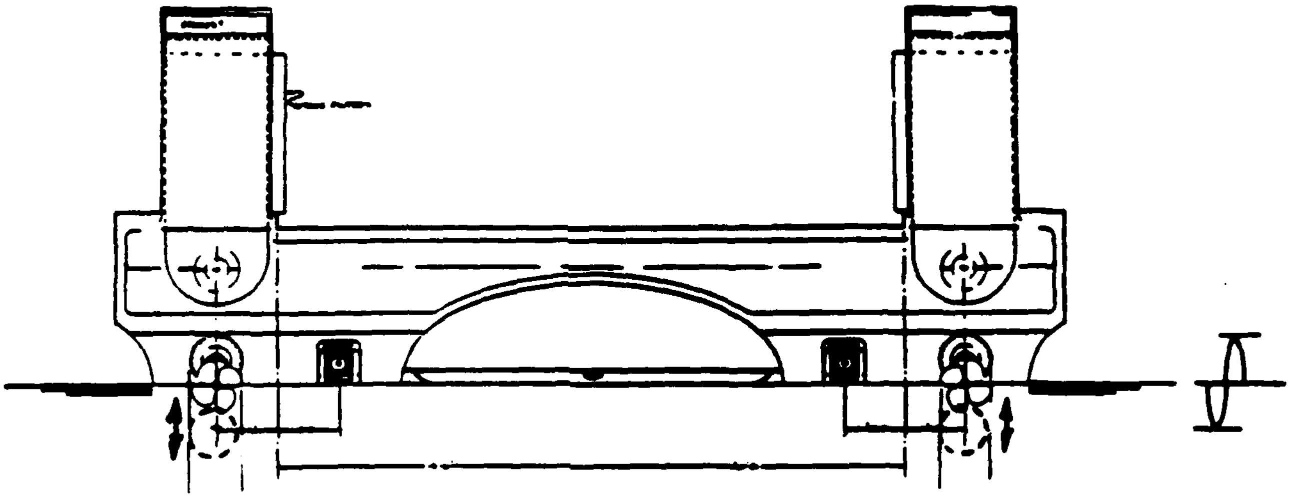


FIGURE 50 - SEA STATE 3 IMPACT ON PROPELLER OPERATION

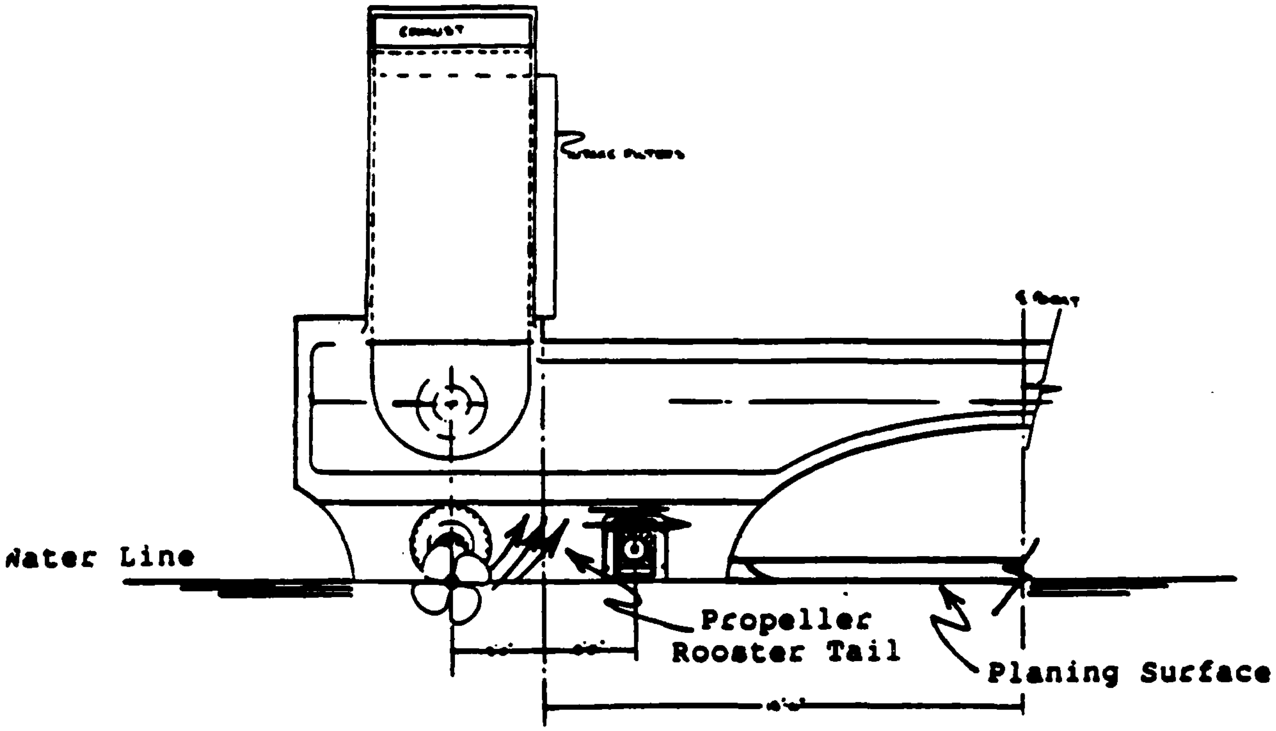


FIGURE 51 - "ROOSTER TAIL" INTERFERENCE

- The 578 engine, a derivative of the 571, was developed by increasing the cycle pressure ratio (compressor stages are added).
- Marinization of the 578 engine has not been seriously considered by Allison. If sufficient market is developed, then, of course, marinization would be undertaken (three to five years).
- The 8000 hp @ 100 deg. F value is achieved by decreasing the "Mean Time to Removal" (MTR) from 7000 hours to 2500 hours.

From the preceding, to reach Ketron's predicted speeds, it follows that the WAVESTRIDER resistance needs to be confidently predicted or else a power margin must be provided that may entail four engines - at least in the near term.

9. SUMMARY/CONCLUSION

The following seven points can be considered as summarizing the Navy's evaluation of the WAVESTRIDER concept:

- The WAVESTRIDER concept depends on a complex interaction among dynamic planing surfaces, craft hulls, and propulsors. This interaction is not well documented either numerically or experimentally - even in calm water.
- Ketron's resistance predictions and the fundamental drag formulation is severely incomplete and inadequate. All indications are that tunnel hull hydrodynamics are critical and that tunnel hydrodynamics were <u>not</u> considered in Ketron's formulation of drag.
- In sea state conditions, Ketron's performance prediction capability appears nonexistent.
- Measured drag generally exceeds Ketron's predicted drag by a factor of two or more.
- The fundamental principles and the associated technology base - at least as revealed to date - do not appear to be mature enough to allow a confident prediction and design of the proposed WAVESTRIDER AAVP Transporter.
- Ketron's design program does not appear to follow a systematic or traditional design cycle. There is an appearance of a patch-together program with serious and fundamental difficulties ignored or neglected. Even if the fundamental issues are resolved, serious attempts need to be made at system optimization, trade-off analysis, and ship/shore interface problems.
- The overall state of the art of WAVESTRIDER technology appears extremely limited. The configurations appear to be products of intuition and cut-and-try experimentation.

In conclusion, the WAVESTRIDER concept is basically flawed. The claims made by Mr. Peter R. Payne, and Ketron, Inc., the company that employed him, were greatly exaggerated and were not confirmed by prototypes or model tests. From analysis, model tests, and at-sea trials, it is clear that the WAVESTRIDER will not make the predicted speed (>70 knots) or the required speed (>40 knots) and that significant improvements are unlikely. Furthermore, again based on analysis, model tests and at-sea trials, and in spite of claims to the contrary, the ride quality of the WAVESTRIDER will be unacceptable for the anticipated mission. In addition, the WAVESTRIDER hullform is not considered suitable for use as an AAVP Transporter because it is not conducive to wide payload variations (as would be experienced in actual operations) and it is not compatible with well deck restrictions.

It is for these reasons that one can reasonably conclude that:

- The WAVESTRIDER concept is not sufficiently developed to allow confident design.

- The WAVESTRIDER concept won't work.

APPENDIX A

KEY PEOPLE INVOLVED IN WAVESTRIDER EVALUATION

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Dr. Eli Zimet, Director AAW/AUW/SAT Directorate, OCNR 21
Mr. James Gagorik, Surface Ship Technology Area Manager, OCNR 211, Program Manager for WAVESTRIDER Evaluation
COL Jim Kirschner, Marine Corps Liaison, OCNR 216 (until 1989)
Ms. Anna Mae Weston, Contracting Officer, OCNR 1512
Mr. John Travers, Associate Contracting Officer, OCNR 1512B (until 1989)

Navy - Marine Corps Research, Development and Acquisition Command (MCRDAC)

Dr. David Vaughn, Director, Warfare Technology Directorate (MCRDAC AW)
LCOL G. Solhan, MCRDAC AWT
MAJ Rick Jensen, MCRDAC AWT
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Ms. Mary Money, Code 1209, Contract Administrator

Mr. Peter Silvia, Surface Ship Division, Code 1222, Ship Design

Mr. John Hoyt, Special Ship and Ocean Systems Dynamics Branch, DTRC 1562, Test Engineer
Mr. Roland Young, Special Ship and Ocean Systems Dynamics Branch, DTRC 1562, Test Engineer

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LCDR Gregory Groves, Officer-in-Charge of SESSO, DTRC 1232
GSMC James Harder, Senior Chief
ET1 Gerald Williams, Data Collector
BM2 Stephen Lyons, Operator
BM2 Shawn Farwell, Operator
QM1 Michael Matto, Maintenance and Repair
EN3 Danny Wyatt, Maintenance and Repair

Navy - Naval Sea Systems Command

CDR James Young, PMS 300-4, Provider of the 24-foot Craft

Navy - NAVSEA Combat Systems Engineering Station, Norfolk, VA

Mr. Steven Denny, Head, T&E Division, SEABAT 63
Mrs. Lisa Almeter, Test Engineer
Mr. Kurt Shields, Brave Test Operator
Mr. Mark Hoggard, Design Support

Navy - Support Contractors

Mr. Joseph Sladky, Kinetics Group

Mr. Dale Calkins, University of Washington, Inventor of HYCAT

Mr. George Ranes, Lead Engineer, MAR, Inc.
Mr. James Simmons, Engineer, MAR, Inc.
Mr. David Kaysen, Engineer, MAR, Inc.
Ms. Susan Menze, Publications Coordinator, MAR, Inc.

Mr. John Adams, Vice President, Maratime Dynamics, Inc.

Ketron, Incorporated

Mr. John Kettelle, President
Mr. Bruce Kettelle, Program Manager
Ms. Mitzi Bosco, Program Assistant
Mr. Anthony Dahm, Contract Negotiator

KAI (Ketron Annapolis, Inc.) (a wholly owned subsidiary of Ketron, Inc.)

Mr. Peter Payne, President (until 1989)
Ms. Becky Benner, Office Administrator
Mr. Robert Dayton
Mr. James Durham
Mr. Henry (Rusty) Wilson
Mr. Bent Nielson
Ms. Tina Zurflieh

Ketron - Support Contractors

Mr. Charles Baum, Ch Eng at A&G Boatyard
Mr. Frank Benedict, Consultant (later, an employee of KAI)

APPENDIX B:

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APPENDIX C:

EXPLORATORY REQUIREMENTS AND STANDARDS FOR APPLYING THE WAVESTRIDER HULLFORM TO THE TRANSPORTATION OF TRACKED AMPHIBIAN VEHICLES (AAV-P7A1)

EXPLORATORY REQUIREMENTS AND STANDARDS

1.0 OBJECTIVE

The objective of this document is to define the parameters within which the WAVESTRIDER hullform will be evaluated. The context of those parameters is a landing craft that will be transportable in the well dock of an LSD-41 Class amphibious assault ship and one that will carry a number of USMC tracked amphibian vehicles.

2.0 REQUIREMENTS

2.1 PAYLOAD

The tracked amphibian vehicle that the craft is to transport is the USMC Assault Amphibian Vehicle, Personnel, Model 7A1 (AAV-P7A1). This Marine Corps vehicle is 26.1 ft long, 10.7 ft wide, 10.2 ft high and it weighs 23.8 long tons. It has a 3-man crew and carries 25 combat-equipped troops. Detailed information is given in the attached Technical Data Sheet.

The WAVESTRIDER craft is intended to transport between four and nine AAV-P7A1s. A nominal 95 ft WAVESTRIDER shall carry from four to six AAV-P7A1s, while a larger craft (nominally 135 ft) shall carry up to nine AAV-P7A1s. The final number of AAV-P7A1s to be carried shall be selected so as to minimize the total number in a well deck while satisfying the dimensional limitations of the following section.

2.2 DIMENSIONAL LIMITATIONS

At least three (and possibly four) WAVESTRIDER craft shall fit within a well dock that is 440 ft long and 48.5 ft wide. Attention is directed to the maximum depth of water available in the flooded well dock: 10 ft at the aft end reducing linearly to 6 ft at the forward end of the well. The overall height from the ship's well dock to the overhead is 27.5 ft.

Well dock space is extremely valuable. The landing craft shall make efficient use of the available space.

Structural limitations of the well dock deck in terms of overall and point load capacity shall be taken into consideration in the design of the keel configuration of the craft.

The overall height of the craft must reflect consideration of roll and pitch of the craft in the well dock.

2.3 ENVIRONMENT

The craft shall be fully operable in Sea-State 3, including launching of all AAV-P7A1s. Performance in Sea-State 5 shall be estimated.

The craft shall be fully operable in ambient air temperatures consistent with LCAC requirements (i.e., from 10°F (with an LCAC type cold weather kit) to 125°F with a relative humidity of zero to 100 percent and in water temperatures from 28°F to 85°F).

2.4 SPEED

Speed at full load displacement shall be as much over 40 knots as practicable.

2.5 RANGE

Full load displacement fuel capacity shall be 10 percent over what is required for two round trips in Sea State 3 as follows: 100 nautical miles into the beach at full power with a full cargo of AAV-P7A1s and troops and 100 nautical miles return at full power with no cargo, plus one hour loiter in between the round trips.

Fuel type shall be Navy Standard Diesel Fuel Marine (DFM). Fuel weight shall be 52.5 pounds per cubic foot. Fueling connections shall be those used for LCAC class landing craft.

2.6 OTHER REQUIREMENTS

Crew size is five men.

Habitability for the crew shall be (comparable to LCAC). The ventilation system shall not include protection against chemical or biological agents or nuclear fallout; however, the arrangement and size of all hatches and controls shall permit access and operation by crew members wearing full protective equipment.

Ride quality shall result in accelerations lower than the 4-hour limit of MIL-STD-1472B.

Peacetime operation and training requires that the craft shall comply fully with anti-pollution laws, and on-board and far-field noise limits, as identified in the General Specification for Ships of the United States Navy (NAVSEA S9AA0-AA-SPN-010-LP-007-4100) and applicable OPNAV instructions.

3.0 STANDARDS

3.1 MARGINS

Margins applied to the design shall be as follows:

CATEGORY	ACQUISITION	SERVICE LIFE
Weight	17% Groups 1-7	5% Full Load (Except cargo)
KG	12% Groups 1-7	0.5 ft Full Load
Electrical	11%	20%
Propulsion power	8% at full speed	Predict speed at service life displacement
Propulsion thrust	25% at hump speed	
Tank volume	5%	--

3.2 HYDROSTATICS

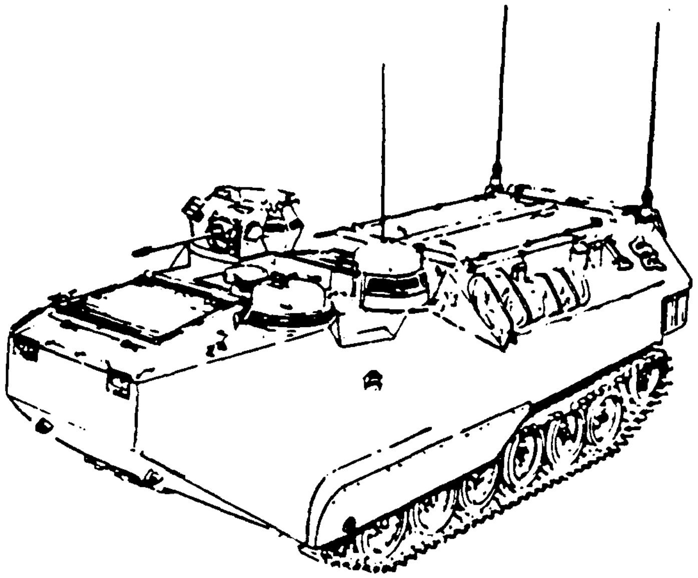
At full load displacement, the reserve buoyancy, subdivision, and damaged stability of the craft shall be such as to allow it to survive damage at any point along its length affecting any two adjoining compartments. The damage shall be assumed to extend inboard to the craft's centerline.

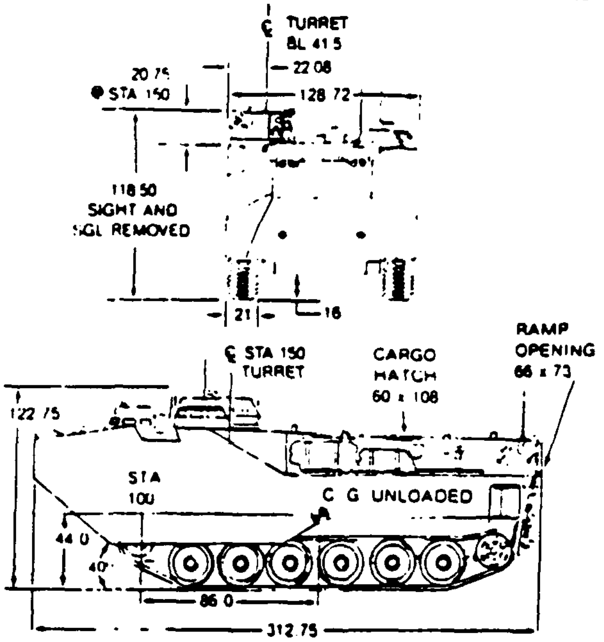
3.3 CARGO TIEDOWNS

Cargo tiedowns shall be similar in size and pattern of placement to those currently used in the LCAC class for securing cargo vehicles. Structural reinforcement shall be provided to keep the cargo vehicles secured in Sea State 5.

TECHNICAL DATA SHEET NAVSEA CODE PMS-310

VEHICLE: AAVP7A1
TYPE: ASSAULT AMPHIBIAN VEHICLE, PERSONNEL, MODEL 7A1 (Assault Amphibian Personnel and Cargo Carrier) June 1984





1. GENERAL

- Weight (Cargo Loaded): 53,305 Pounds
- Crew: 3
- Weight Unloaded (Less Crew and Fuel): 41,467 Pounds
- Maximum Load Capacity: 25 Combat Equipped Troops or 10,000 Pounds of Cargo
- Center of Gravity:
  - Unloaded: 44.0 Inches Above Ground, 86.0 Inches from Station 100.0
  - Loaded: 42.6 Inches Above Ground, 98.6 Inches from Station 100.0
- Maximum Sea Water Draft (Cargo Loaded): 68.7 Inches
  - Freeboard to Driver's Hatch Coaming: 33.6 Inches
  - Freeboard to Inlet of Air Aspirator Valve: 35.8 Inches
- Unit Ground Pressure (Cargo Loaded, Zero Penetration): 8.0 PSI
- Fuel Capacity: 171 Gallons

2. PERFORMANCE

- Gross Horsepower to Weight Ratio: 15.0 HP/Ton
- Net Horsepower to Weight Ratio: 10.0 HP/Ton
- Drawbar Pull (Maximum at Stall Tractive Effort): 42,644 Pounds on Level Firm Terrain
- Cruising Range:
  - Land at 25 MPH: 300 Miles
  - Water at 2,600 RPM: 7 Hours
- Cruising Speed:
  - Land: 20 to 30 MPH
  - Water: 6 MPH
- Maximum Speed Forward:
  - Land: 45 MPH
  - Water: 8.2 MPH
- Maximum Speed Reverse:
  - Land: 12 MPH
  - Water: 4.5 MPH
- Obstacle Ability: 8-Foot Trench Span, 3-Foot Vertical Wall
- Maximum Forward Grade (Cargo Loaded): 60%
- Maximum Side Slope (Cargo Loaded): 40%
- Ground Clearance (Cargo Loaded): 16 Inches
- Minimum Turning Radius
  - Land: Pivot
  - Water: Pivot
- Surf Ability: Negotiate 6-Foot Plunging Surf, Combat Loaded and Survive 10-Foot Plunging Surf Without Sustaining Mission Failure

3. ENGINE

- Make: Cummins
- Model: VT400
- Type: 4 Cycle 8 Cylinder, 90° Vee, Water Cooled, Turbocharged
- Bore: 5.5 Inches
- Stroke: 4.75 Inches
- Displacement: 903 Cubic Inches
- Compression Ratio: 15.5:1
- Fuel: Multifuel
- Rated Horsepower: 400 ± 5% at 2800 RPM with DF-2
- Rated Torque: 825 ft-lbs ± 5% at 2050 RPM with DF-2
- Oil Capacity (Dry): 6.5 Gallons
- Oil Capacity (Wet): 4.5 Gallons
- Coolant System Capacity: 30 Gallons

4. POWER TRAIN

- Transmission: NavSea HS-400-3A1
- Type: Hydraulic Torque Converter, Parallel Shaft Gear Arrangement
- Maximum Converter Torque Multiplication: 2.83:1
- Gear Ratios, Forward:
  - First Speed: 8.27:1
  - Second Speed: 4.63:1
  - Third Speed: 2.25:1
  - Fourth Speed: 1.27:1
  - Reverse uses First and Second Speed Ratios
- Final Drive Ratio: 3.06:1
- Overall Maximum Torque Ratio (Engine to Sprocket): 70.8:1
- Transmission Oil Capacity: 23 Gallons (with Oil Coolers, Filters, Lines)

5. RUNNING GEAR

- Type: Torsion Bar and Tube Suspension, Front Sprocket, Raised Rear Idler
- Number of Wheels: 6 Rubber Tired Dual per Side 26 Inch Diameter
- Number of Return Idlers: 1 per Side, 20 Inch Diameter Wheels
- Sprocket
  - Number of Teeth: 11
  - Feet per Revolution: 5.5
- Track
  - Type: Steel, Single Pin, Rubber Bushed, with Replaceable Pads

Number of Shock Absorbers: 3 per Side
Number of Blocks: 85 Maximum per Side
Pitch: 6 Inches
Weight per Block: 34 Pounds Maximum
Weight per Side: 2890 Pounds Maximum

6. WATER PROPULSION

Water Jet Pumps
Capacity: 14,000 GPM
Thrust: 3,025 Pounds Static
Quantity: 2
Location: Port and Starboard, Aft
Steering and Reverse by Jet Deflectors

7. ELECTRICAL

Nominal Voltage: 24 VDC
Generator: 300 Amp
Battery:
Volts: 12
Type: 6TN
Quantity: 4

8. COMMUNICATIONS

Radio:
AN/VRC-44 Radio Set 1
AN/VRC-46 Radio Set 1
COMSEC Equipment:
TSEC/KY-57 Voice Security Set: 4
AN/VIC-2(V) Intercom System: 5 Stations

9. ARMOR

Permanent Hull: Aluminum Armor Plate
Ramp Outer: 1.000 Inch
Ramp Inner: .500 Inch
Sides: 1.750, 1.395 and 1.222 Inches
Top: 1.185 Inches
Bottom: 1.185 Inches
Stern: 1.395 Inches

10. FIRE EXTINGUISHERS

Portable:
Number of Cylinders: 1
Location: Port Stanchion
Capacity: 2¾ Pounds Halon 1301
Manual Fire Suppression System
Troop Compartment
Number of Cylinders: 1
Location: Port Sponson
Capacity: 17 Pounds Halon 1301
Engine Compartment
Number of Cylinders: 2
Location: Driver's Compartment
Aft Engine Compartment Bulkhead
Capacity: 7 Pounds Each Halon 1301

11. VISION AND SIGHTING EQUIPMENT

Driver's Station:
Direct Vision Blocks: 7
Driver's Night Vision Device, AN/VVS-2(V)1A: 1
(NSN 5855-01-096-0871)
Commander's Station:
Direct Vision Blocks: 7
Periscope, M27: 1
Armament Station:
Direct Vision Blocks: 8
Direct Ring Sight: 1
Indirect Optical Sight:
8 × Power NavSea P/N 2588526
1 × Power with Projected Reticle
Ramp:
Direct Vision Block: 1

12. CARGO COMPARTMENT

Length: 13.5 Feet
Width: 6.0 Feet
Height: 5.5 Feet
Volume: 445.5 Cubic Feet
Capacity: 25 Combat Equipped Troops

13. ARMAMENT AND AMMUNITION

Weight (Combat Ready, less Gunner): 1535 Pounds
Caliber .50 Machine Gun, M85
Traverse: 360 Degrees
Elevation: 60 Degrees
Depression: 15 Degrees
Power Control System: Electric-Manual
Ammunition: Caliber .50, 400 Ready Rounds, in Vehicle Stowage for 7 Caliber .50 Ammunition Boxes
Rate of Fire (Cyclic):
High 1050 Rds/Min
Low 450 Rds/Min
Muzzle Velocity 2840 FPS
Range (Maximum) 7275 Yds
M16A1, 5.56mm Rifle, Quantity: 3 (Troop Issue)
M257 Smoke Grenade Launchers, Quantity: 8

14. NAVIGATION EQUIPMENT

Magnetic Navigation Set

15. OTHER

Accessory Equipment:
Visor Kit, NavSea P/N 2587015
Litter Kit, NavSea P/N 5428676
Winterization Kit, NavSea P/N 2600063
Mine Clearance System Kit, 154 MOD 0
Contractor: FMC Corporation
Date First Prototype: 1979
Date First Production Vehicle: 1983

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