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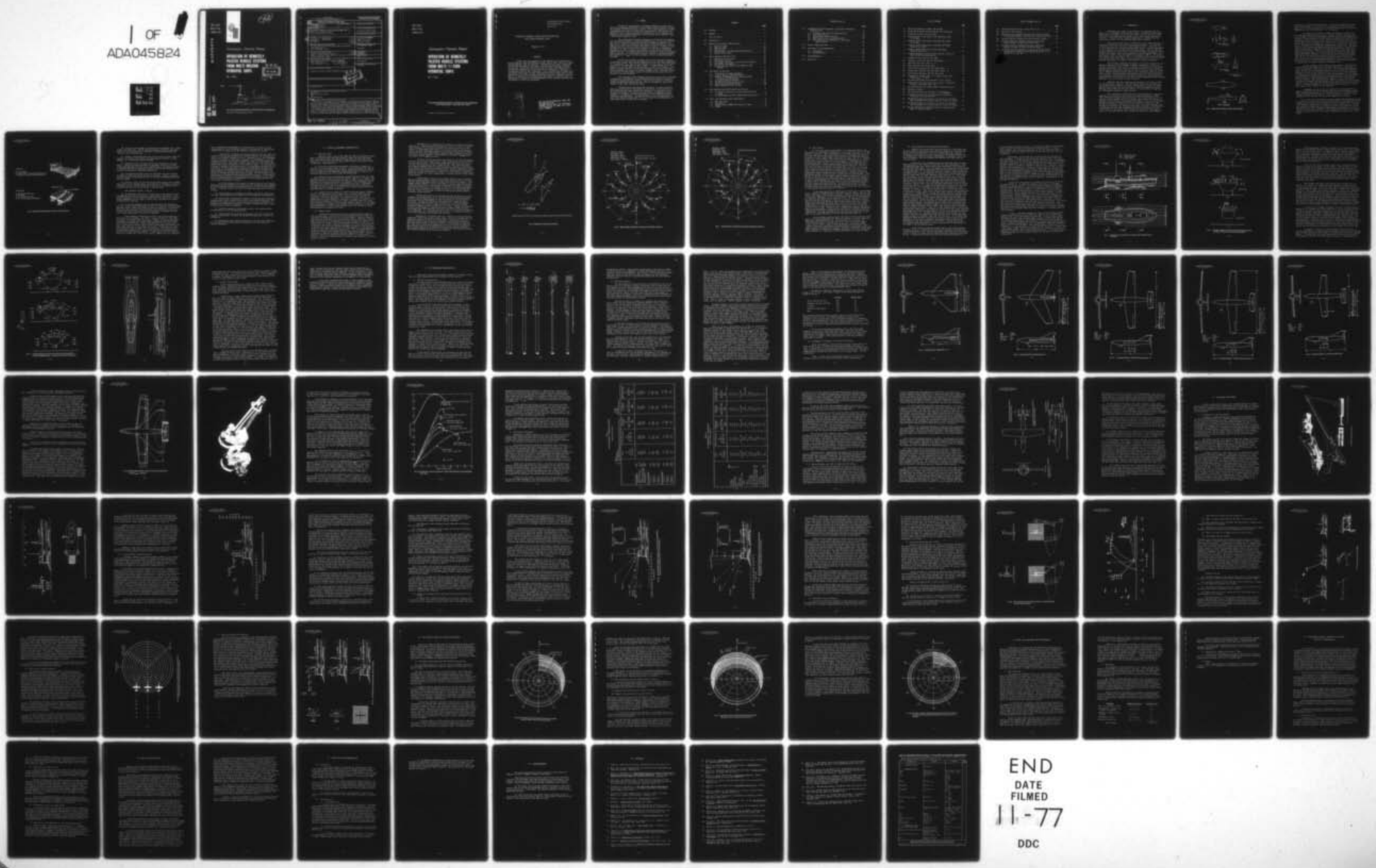

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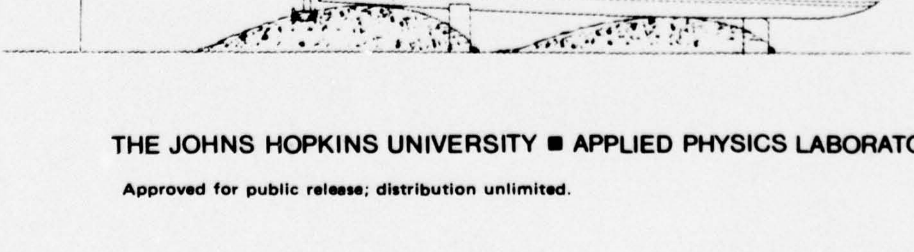
Aeronautics Division Report

OPERATION OF REMOTELY PILOTED VEHICLE SYSTEMS FROM MULTI MISSION HYDROFOIL SHIPS

M. L. HILL



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Maynard L. Hill

ABSTRACT

Results of an investigation of the feasibility of installing an Over-the-Horizon (OTH) Mini Remotely Piloted Vehicle (RPV) system on a Multi-Mission Hydrofoil ship are reported. Analyses have been made of Hydrofoil and Mini-RPV performance, and concepts for RPV launch, mission execution, and aircraft recovery are evaluated in terms of those performance figures to determine compatibility of the concepts with Hydrofoils. Technical problems and risks are also identified. It is concluded that the Hydrofoil's operational environment has some characteristic features which tend to mitigate launch and recovery problems associated with wind, turbulence, and ship motions. A design for an optimized Mini RPV capable of carrying 45 lbs of OTH payload is presented, and optimum Hydrofoil ship handling procedures during operation of RPV's are described.

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1.0 SUMMARY

Results of investigations of launching methods, recovery procedures and aerodynamic performance of Mini Remotely Piloted Vehicles suitable for carrying out OTH missions are reported. The overall objectives of this investigation have been to describe the compatibility of RPV systems with Hydrofoils and to define the technical problems that are involved in integrating an Over-the-Horizon Remotely Piloted Vehicle system (OTH-RPV) into a multi-mission Hydrofoil ship.

The investigation includes an analysis of pertinent environmental and sea-keeping properties of typical Hydrofoil ships, the results of which were used to define with precision those RPV performance characteristics that will be needed for successful performance of the OTH mission. Special emphasis has been placed on launch and recovery concepts. A family of suitable RPV's has been conceived and an analysis of their basic aerodynamic performance is used to predict the capability of each RPV to perform the complete mission. An optimized RPV has been configured, under the stipulation that it must have a crucial property called "velocity for minimum allowable maneuverability," (V_{mam}), and the performance of such a preferred design is described.

Several novel methods of launch and recovery have been conceived on the basis of known Hydrofoil performance and on the predicted capabilities of the optimized RPV. The probable advantages and also the risks and technical problems are enumerated for each concept. A system making use of the concept of a vertical relative landing (VRL) on a pad on the fantail of the Hydrofoil appears feasible, and has the advantage of requiring relatively simple equipment with respect to terminal guidance needs. Alternate methods of recovery, involving remote capture of the RPV while airborne above the Hydrofoil, also look feasible.

The composite of the analyzed information has been used to assemble an estimate of the Hydrofoil ship handling procedures that are considered desirable during launch and recovery. Results are presented in terms of windows of Hydrofoil heading and speed that are allowable in calm (0 knot wind), 16 knot winds, and 24 knot winds.

Questions about the emplacement and amount of above- and below-deck space required by the RPV system are addressed. The interference of RPV operations with other simultaneous missions of the Hydrofoil is predicted to be minimal. The report concludes with a recommended technical approach to accomplish an early demonstration of the feasibility of RPV operations from Hydrofoils. Included besides are some recommendations for long-term research projects that will be of benefit to the advancement of more useful roles for mini RPV's in general.

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2.0 INTRODUCTION

Hydrofoils are a class of ship having a conventional hull and also a set of underwater lifting foils or wings. At speeds near the upper limits that are normally set by the large drag of a hull, the hull can be lifted out of the water and the weight of the vessel becomes supported on the foils. A large decrease in drag accompanies the "takeoff," and top speeds well in excess of top hullborne speed can be realized.

There are two basic types of hydrofoil, both of which have been in commercial and military service for more than two decades. One type has surface-piercing foils, the other, fully-submerged foils. The former type of foils generally have a large dihedral angle, and the outboard extremities of the V-shaped foils protrude above the water surface. The U.S. Navy has operated hydrofoils of this type, but the fully-submerged arrangement, which yields a more stable ride, has been adopted in the more modern ships, such as Highpoint (PCH-1), Plainview (AGEH-1), and Pegasus (PHM-1). All three of these ships, which are shown in Fig. 1, are maneuvered and stabilized through an autopilot system that employs movable control surfaces on the foils in much the same manner as elevators and ailerons are used on aircraft.

The Plainview, Highpoint and Pegasus are currently assigned to the Hydrofoil Special Test Unit (HYSTU), Bremerton, Washington. Each of the vessels is different from the other in details of construction, foil design, autopilot performance, deck layout, propulsion system, and other features. The performance capabilities, however, at least in aspects crucial to operation of Remotely Piloted Vehicles (RPV's), are essentially identical for all three vessels. Because Plainview and Highpoint are more readily available for the special tests that will be needed to demonstrate the feasibility of operating RPV's from hydrofoils, this report deals predominantly with concepts tailored to one or the other of these two ships.

Hydrofoil ships have demonstrated potential in a variety of ASW and surface warfare missions. Both Sea Sparrow and Harpoon missiles have been launched from foilborne platforms. Depth-charge, torpedo, and rapid-gunfire missions have also been performed in calm and rough water trials. The high speed capability and good stability of the platform in rough seas are advantageous features in these missions.

RPV operations from Hydrofoils are desired primarily to provide a capability for over-the-horizon search and target identification (OTH). RPV's fitted with adequate sensing systems to perform OTH missions will be carrying costly payloads, and, also, storage space onboard ship may be too limited to allow attrition rates greater than about one loss per 100 sorties. Reliable recovery systems are therefore an overriding requisite to OTH systems effectiveness. Analyses of costs of RPV's for other missions, such as relay of communications, Sonobuoy monitoring, electronic countermeasures, or harassment may show that expendable vehicles are affordable, but the effectiveness of such systems must include considerations of the high premium on storage and handling space aboard ship, along with replenishment

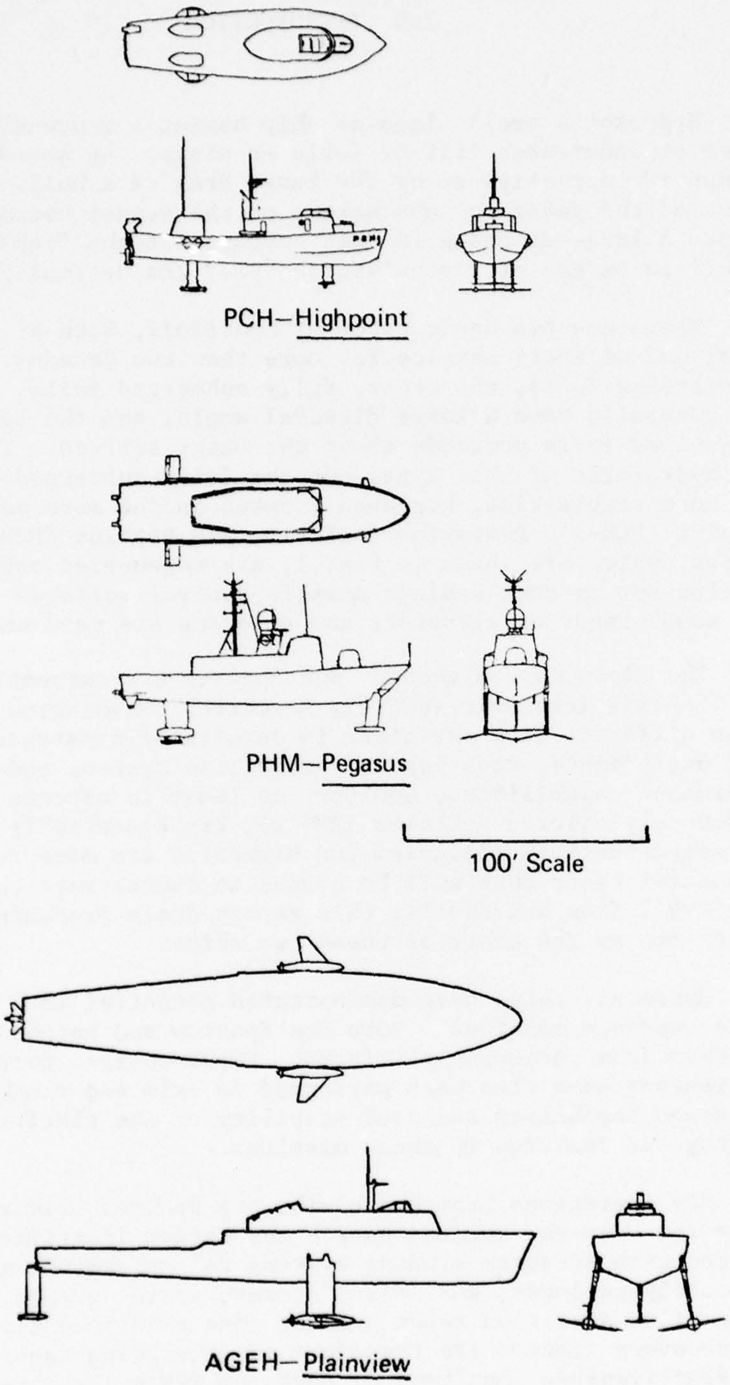


Fig.1 Three View Drawings of AGEH, PCH and PHM

procedures in probable battle scenarios. In any final analysis of a prospective RPV mission, it is likely to be found that a reliable recovery method will contribute greatly to the overall effectiveness of the system, regardless of cost of the vehicle or of its payload.

No attempt will be made to examine the logistics of RPV loss-rate and replenishment in this report. Instead, the main objectives will be to attempt to define the approximate minimum volume and the appropriate location of spaces needed for an RPV system, to describe and evaluate possible methods for launch and recovery, and to determine course and speed options that will be suitable for RPV operations. The discussions in this report will center around mini RPV's in the 150 to 250 lb class, primarily out of consideration of storage and handling-space limitations. The conclusions of this report, although generated on the basis of existing Hydrofoils, should also be applicable to larger Hydrofoils that could be in service in the 1980's. These vessels could be three to four times larger than present Hydrofoils, but they will operate in nearly the same speed ranges with better stability, so that RPV launch and recovery procedures need not be different from any that are successfully demonstrated in the near future. As experience has shown with larger ships, such as FF's space is always at a premium aboard multi-mission ships, and even if the RPV systems prove to be inordinately valuable, it will still be necessary to design them for minimum occupancy of shipboard space.

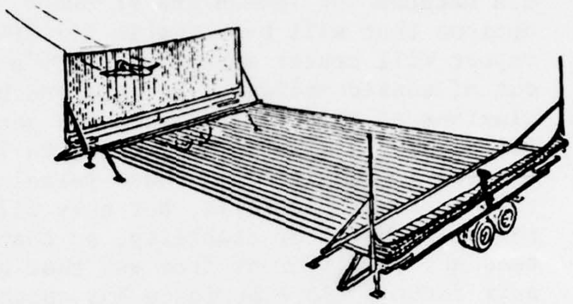
Special emphasis will be placed on the question of how the high speed capability and stable ride of the Hydrofoil might be exploited to solve the paramount problem of RPV recovery. The potential advantages are fairly obvious, for, in simplified terms, one can envision RPV's which are designed not only to stay airborne but also to have good control response at flight speeds that are equal to or less than the Hydrofoil's top speed, thus providing the capability for achieving essentially a zero difference in relative speed, as the RPV approaches the Hydrofoil during any proposed recovery sequence. What this capability implies is that, relative to a controller or automatic guidance system aboard the Hydrofoil, vertical take-off and landings with near-zero departure and impact velocities are possible. (That is, a normal airplane type of horizontal landing appears to follow a near vertical path, relative to the Hydrofoil.)

Arguments pro and con can be raised about the desirability of using a psuedo-VTOL RPV, which we shall call the Vertical Relative Landing (VRL) configuration hereafter. The technical aspects of various recovery concepts are discussed in detail in later sections of this report. In a simplified sense, the case for VRL can be summarized as follows:

(a) It will not be necessary to provide impact-energy-absorbing systems or to supply "roll out" space to bring the horizontal speed component to zero, inasmuch as this reduction in forward speed can be achieved while the RPV is still airborne, just prior to touchdown. Recovery systems using a vertical net, connected through cables to hydraulic snubbers and brakes, for energy absorption, have been successfully demonstrated in land-based tests (Ref. 1, 2) but, as can be seen from Fig. 2, these installations tend to be so unreasonably large that they are not easily accommodated on board present Hydrofoils.

Description

- Trailer–M345
- Vertical barrier–15 feet high by 36 feet wide
- Landing net–60 feet long by 25 feet wide



Performance

- 200–lb RPV at 60 knots
- ≤ 6g loads
- All–weather, day–night
- 15–min emplacement & takedown

Stowed for travel

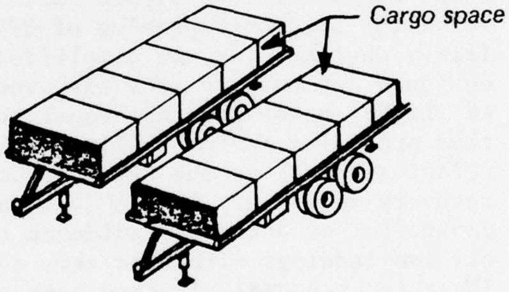


Fig. 2 Aquila RPV Retrieval System Features and Performance

(b) Recovery could be made by touching down and snagging onto a lightweight, horizontal net. The RPV approach heading, relative to ship axis, would not be as restricted as it would be in a high-speed approach and "roll out" into a vertical net.

(c) Because closing velocities will be low, reaction times within the guidance loop may be less critical in determining the accuracy of final homing, i.e., a smaller net may be adequate.

(d) Hydrofoil motions in heavy seas consist primarily of vertical heaves. Such motions will contribute to the impact velocity of a vertically descending RPV, but there is no deterioration in the homing accuracy. In contrast, ship heave would enter directly into the miss distance in a recovery system using a vertically-oriented net.

(e) Low relative approach speeds are attractive from the viewpoint of safety for both crew and for the ship's equipment. Safety is improved besides, because the RPV would not have to fly over the hydrofoil after an aborted landing.

(f) Capture of RPV's in vertical nets generally causes them to tumble with respect to the approach path. This behavior is acceptable in low-wind conditions, but on a vessel travelling at high speed, the relative wind could blow the RPV back out of the net or over the side.

Some arguments against a VRL are:

(a) The Hydrofoil would have to be foilborne at some specified speed and heading, with respect to the wind, during recovery operations. Such singular dedication of the Hydrofoil to RPV operations may not be possible during engagements with an enemy, in which case, inevitable loss of RPV's would have to be expected.

(b) It has been suggested that the long approach times associated with low closing speeds would expose the RPV to a longer and probably larger spectrum of gusts, making the homing problem more difficult. As discussed below, the total exposure to gusts depends on the definition of when the recovery approach is initiated, and the probability of exposure to gusts can be almost independent of the speed of approach.

Final weighing of arguments pro and con will require analysis of test data not yet available. An effort is being initiated to obtain OTH RPV systems for Frigate (FF) class ships. Ideally, it would be desirable to develop a single RPV design that would be compatible with both Frigate class ships and Hydrofoils. However, VRL recovery on the slower speed F.F.'s would not be practical unless the RPV's were made very large or were fitted with parafoils or other high lift devices. Difficulties in coping with turbulence would accompany such configurations, and especially since the horizontal approach into a vertical net has been successfully demonstrated in previous Mini RPV programs, it would appear that such techniques have a high promise for success on F.F. ships. However, use of a vertical net on a Hydrofoil would minimise the opportunities to exploit the high speed capability of the Hydrofoil, because of the problems of tumbling and possible loss or damage to the RPV during its residence in the net.

It should be noted that those flying qualities that are crucial to successful VRL recovery on Hydrofoils would also enhance the probability of success in horizontal landings on F.F.'s. Therefore, one of the recommendations of this report is that those responsible for development of F.F. RPV systems be cognizant of performance features of RPV's that are exploitable on Hydrofoils and on this basis, consider modifications of RPV design that might enhance their reliability on both classes of ships. It seems that the best way to proceed at the present time is to investigate the feasibility of a Hydrofoil VRL RPV system that can employ interchangeable payloads, guidance systems, shipboard-handling systems and as much of the proposed F.F. system hardware as possible, while still providing freedom of choice with respect to optimum airframes and recovery systems. The investigation could include tests to demonstrate horizontal approach techniques. After feasibility demonstration phases of both systems have been carried out, the advantages of specialization for accomplishment of the designated missions can be assessed in quantitative fachion.

It is the purpose of this report to discuss results of an investigation that has been tailored to conform with this freedom-of-choice approach, but which addresses primarily the general question of Hydrofoil-RPV compatibility. In general outline, the tasks that were undertaken can be listed as follows:

(a) Examine Hydrofoil performance and define sea-keeping characteristics that could influence the reliability of RPV operations from Hydrofoils.

(b) Describe RPV configurations capable of delivering good performance during vertical relative launch and recovery from foilborne Hydrofoils, and estimate their range, payload, speed, and other performance parameters of importance to OTH missions, and select candidate configurations best suited to meet overall mission requirements.

(c) Describe concepts for launch and recovery, and evaluate merits and deficiencies of the identified methods.

(d) Identify interface problems and residual technical problems that should be investigated, to define the optimal RPV system and to assure its reliability.

(e) Describe the best technical approach to achieving early demonstration of Hydrofoil-RPV compatibility and feasibility of the launch and recovery procedures.

3.0 HYDROFOIL PERFORMANCE CHARACTERISTICS

3.1 Hydrofoil Speed

Hydrofoil ships, such as PCH, AGEH, and PHM, are operable in three modes, each having upper and lower bounds in speed, but which overlap in such a way that the ships can maintain steady cruise at any speed, from standstill to the upper foilborne limit, which typically is around 50 knots in calm seas. These modes are:

(a) Hullborne-conventional displacement; this mode of operation is useful up to a top speed of about 20 knots. In the hullborne mode, even at very low speeds, the submerged foils supply substantial damping so that the motion of hydrofoils have magnitudes approximately equal to those of conventional ships with five to ten times the displacement.

(b) Hullborne-partial displacement -partial hydrofoil lift; this mode of operation can be used effectively through the range 10 to 27 knots. The Hydrofoil autopilot can be used in this mode to reduce in great measure the amplitude of roll and pitch motions, as compared to the comparable motions experienced by conventional ships in equivalent sea states. Ordinarily, this mode would not be used in its higher-speed range for long-distance cruising, but there would be no limitation to using this mode during short-term RPV launch or recovery operations.

(c) "Takeoff" can be achieved at about 25 knots and stable, foilborne flight can be maintained from 30 knots to the top speed, which is about 50 knots, in calm seas, and some three to five knots less in rough seas (Sea-state 5 or worse conditions). For purposes of this study, it is assumed that any of the Hydrofoils currently in operation or planned for the future will be capable of speeds to 45 knots in any Sea-state, up to the upper Sea-state 5 category. It will become apparent that this set of stipulations constitutes a conservative approach to the problem, i.e., any higher speed capabilities of future vessels should add to the reliability of any RPV system that is operable at 45 knots.

3.2 Relative Winds

A Hydrofoil cruising at 45 knots in a dead-calm wind condition will obviously have a 45-knot relative wind approaching bow-on, when it is following a straight-line track on any given heading. Relative wind will also be within a few degrees of bow-on during turns in calm wind. PCH and AGEH vessels usually do coordinate roll-to-turn maneuvers, in which case relative wind in a calm is still theoretically straight onto the bow. Both vessels have yaw control, obtained by rotating one of the vertical pylons to generate side force, but maximum attainable yaw angles of the ship with respect to its course direction are only a few degrees. As discussed below in the sections about turbulence and recovery, it is envisioned that some amount of crosswind could be beneficial in some recovery schemes, but a few degrees of yaw will probably contribute negligible benefit. Therefore, from the viewpoint of launch and recovery of RPV's, one ground rule is obvious: Any proposed system should be operable under conditions of bow-on winds of 45 knots.

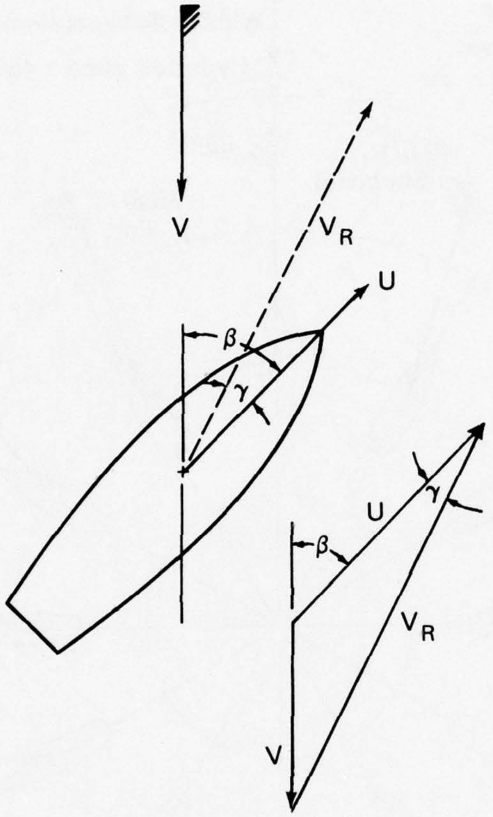
OTH RPV's will be required to be operable at conditions including sea-state 5. Average wind in such conditions is about 24 knots. Figure 3 shows parameters for calculating relative wind direction and speed, as a function of ship heading with respect to true wind direction and velocity. Figure 4 presents calculated values of the relative wind that would result from a wind of 24 knots blowing from 0 degrees, when a Hydrofoil cruises at 45 knots on various headings. (Zero degree ship heading is toward north; zero degree wind is from the north.)

It can be seen in this figure that there are now only two headings for which the wind is straight bow on. These headings are 0° and 180°, or into and with the wind. On the 180° heading, wind velocity would be only 21 knots, well below the 45 knots needed for VRL. Thus, while the calm-wind situation demands that the recovery system be operable in bow-on wind, it is obvious that it would be unsatisfactory to design a launch and recovery system that would always require a bow-on wind. One need only envision an operation two miles from shore in a 24-knot, off-shore wind to realize there would not be ample run space, toward shore, to recover an RPV if such restrictions applied.

Looking again at Fig. 4, it is evident that this set of wind and Hydrofoil speeds produces relative winds having maximum velocities of up to 69 knots and maximum angles across the ship axis of about 33 degrees. This diagram clearly suggests it will be desirable to devise launch and recovery systems which have as few restrictions as possible with regard to relative wind speed and direction. For example, if the only restriction were that a relative wind velocity must be at least 45 knots, it is readily deducible from Fig. 4 that a broad range of Hydrofoil headings and speeds would be acceptable during recovery.

Surface waves tend to be oriented such that the direction of wave propagation is rotated about 45° to the right (in the Northern Hemisphere) from the direction towards which the wind is blowing, but no restrictions are imposed on speed and heading by such differences in wind and wave directions. The amplitude and rate of ship motion is affected somewhat by ship heading with respect to wave direction and, thus, there may be preferable headings for RPV recovery for this reason. Summed up, launch and recovery systems capable of coping with diverse relative-wind directions will impose fewer ship handling restrictions and will allow more flexible use of the Hydrofoil, i.e., the Hydrofoil may not have to be dedicated exclusively to RPV operations during launch and recovery.

Calculations of relative winds for a variety of wind and Hydrofoil speeds were carried out as part of this study. Figure 5 is another plot for a Hydrofoil speed of 24 knots in 24-knot winds, to represent a case for which the relative wind velocity can diminish to zero and swing through a 360° angle with respect to the ship. Results of calculations of this type have been used to develop the information in section 6, where an attempt is made to define some of the probable restrictions that will be imposed on ship handling procedures, as a result of the special requirements associated with certain proposed launch and recovery methods.



$$V_R = \left[U^2 + V^2 + 2UV \cdot \cos\beta\right]^{1/2}$$

$$\gamma = \tan^{-1}\left[\frac{V \sin\beta}{U + V\cos\beta}\right]$$

(Positive values or γ mean port relative wind, negative values mean starboard relative wind)

Fig. 3 Parameters for Wind Over the Deck

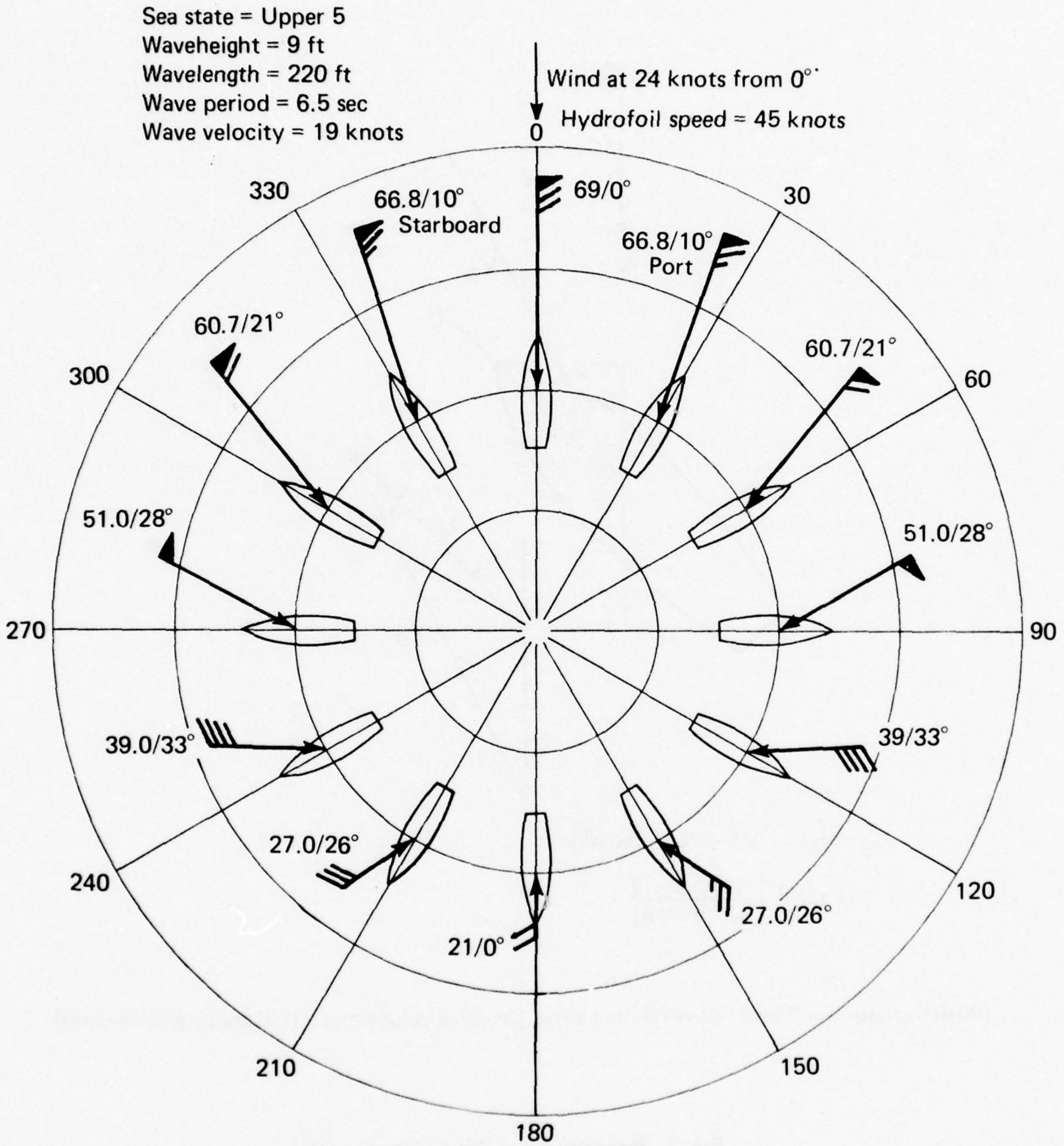


Fig. 4 Relative Winds in Sea State 5 with Hydrofoil Speed at 45 Knots

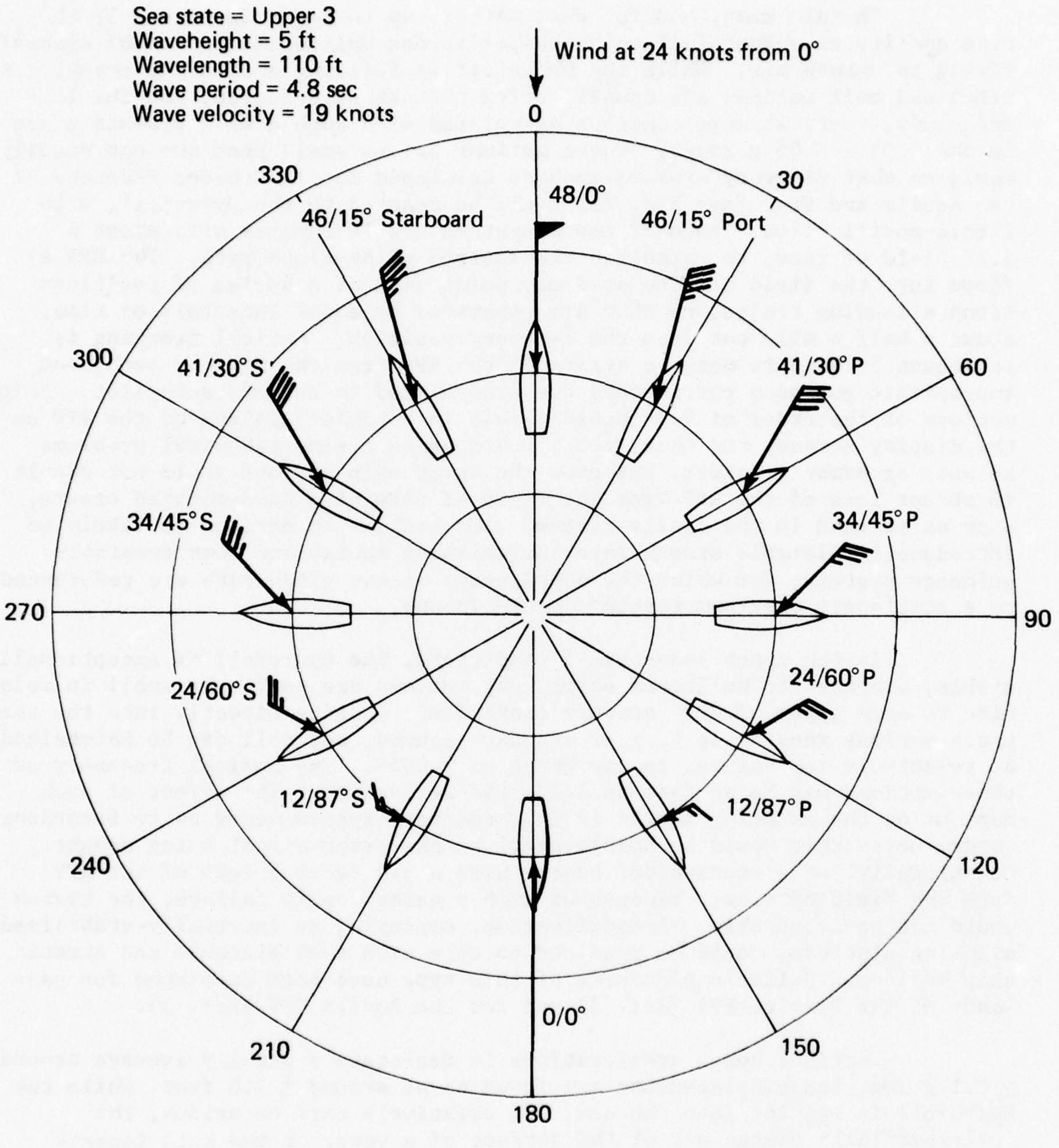


Fig. 5 Relative Winds in Sea State 5 with Hydrofoil Speed at 24 Knots

3.3 Ship Motions

In calm seas, and for that matter, up to upper Sea-state 3, the ride quality of a Hydrofoil on autopilot is not unlike that of a 707 aircraft flying in smooth air. While the Hydrofoil is folliwng a straight track, the pitch and roll motions are usually below a tenth of a degree, and the low-frequency, vertical accelerations associated with such a mild Sea-state are in the 0.01 - 0.05 g range. These motions are so small that one can readily envision that recovery systems such as developed for land-based recovery of the Aquila and Star (see Fig. 2), could be adapted to the Hydrofoil, with little modification. Both of these systems use TV cameras with about a 3.0° field of view, to establish the desired glide-slope path. The RPV is flown into the field of view at a way point (one of a series of positions along a landing trajectory that are separated by equal intervals of time) about a half a mile out from the recovery position. Optical tracking is subsequently used to measure errors of the RPV from the desired path, and appropriate guidance corrections are transmitted to the RPV autopilot. Ship motions of the order of 0.1° would result in notable jiggling of the RPV on the display screen, and this jitter would present some technical problems to auto or human trackers, but even the worst ship motions would not result in abrupt loss of the RPV from the field of view of a hard-mounted camera, such as is used in the Aquila system. Nor would such motions be likely to introduce intolerable errors into the existing Aquila and Star terminal-guidance systems, for which the coordinates of the glide path are referenced to a stationary platform resting on the ground.

In the upper Sea-state 5 conditions, the Hydrofoil is exceptionally stable, compared to hullborne ships, but motions are no longer small in relation to some types of RPV recovery operation. Heading directly into the sea, pitch motions ranging up to ± 1° are experienced, and roll can be maintained at relatively low values, in the range of ± 0.5°. The nominal frequency of these motions may be as fast as 1/2 cycle per second. The effect of such motions on the existing Aquila or Star recovery system would be to intorduce random noise that would be nearly equal to the error signal being sought. Occasionally, on a statistical basis there would occur a loss of the RPV from the field of view. Because of such a catastrophic failure, the system would not be acceptable. A modification, employing an inertially-stabilized sighting platform, would be required to cope with such sizeable and erratic ship motions. Suitable platforms of this type have been developed for payloads of the Praeire RPV (Ref. 3) and for the Aquila RPV (Ref. 1).

Vertical heave accelerations in Sea-state 5 usually average around ± 0.1 g rms, and displacements are found to be around ± 1.0 foot, while the Hydrofoil is heading into the sea. On relatively rare occasions, the foils partially emerge out of the surface of a wave, or the hull impacts on the crest of a wave. Both of these exceptional occurrences produce larger accelerations and motions than experienced on the average. These unwanted events can usually be avoided by reducing the Hydrofoil cruise speed. Such a reduction in speed is an allowable procedure, if the sole requirement during recovery is to maintain a relative wind speed of at least 45 knots.

3.4 Meteorological and Ship-Generated Turbulence

Implicit to any successful recovery system is a requirement that the RPV, guidance loop, and recovery device be designed to cope with wind gusts that are superimposed on the true, steady-state wind. The main technical factors involved in such design are the RPV maneuverability at its approach air speeds, precision of measurement of guidance errors, autopilot performance, and the allowable miss-distance associated with the recovery device.

Relatively little information has been generated about low-speed maneuverability or the response of mini RPV's to gust disturbances. Some in-flight data have been reported about gust disturbances experienced by the APL RPD-1 Delta (Refs. 4,5), and studies of the influence of gusts during recovery have been made in connection with the Aquila RPV (Ref. 6) and with the Star RPV (Ref. 7). In the Aquila analysis, vertical miss-distances were estimated using a computer simulation of recovery that included wind gusts derived from a model for shear turbulence over land (Ref. 8). The results are encouraging, in that they show miss-distances merely of the order of 0.68 feet in the absence of gusts and 2.14 feet in the presence of gusts. Nearly identical predictions were obtained from simulation studies of the Star RPV recovery system. These predictions have been borne out by actual recoveries, wherein none of the miss-distances experienced in the 14 Aquila recoveries carried out to date has exceeded those predicted from the simulation (Ref. 6), and, furthermore, the Star vehicle experienced a miss distance of merely 1.5 feet from net center (Ref. 7), during its only net-recovery test to date. None of the tests have been in very gusty winds, but, on the basis of these results, one can deduce that smaller nets than those currently in use might well be suitable for Aquila and Star, and that still smaller areas might be adequate for "recovery-optimized" RPV systems. To amplify on this point, it can be noted that the Aquila and Star RPV's are not very different from the APL RPD-1 and RPD-2 with regard to aerodynamic layout, stability, control effectiveness, and other factors affecting low-speed maneuverability. APL personnel have not had direct experience from which to judge handling qualities of Aquila or Star, but we have had substantial flight experience with the RPD-1, that included about 100+ normal, flared, landings on runways. About 20 of these landings were in fairly high wind and gust conditions. This experience caused us to report that precision maneuverability during slow approaches is not one of the attractive features of the RPD-1 (Ref. 9). Actually, we have reported that the RPD-1 has poor handling qualities at speeds below about 50 knots and is essentially unmanageable in gusts at airspeeds lower than about 45 knots. It is likely that substantial improvements in precision of recovery could be made by placing emphasis on this crucial performance requirement during the design and development of the next generation of mini RPV's. Some design concepts for achieving such improvements, without impairing mission capability, are discussed in the RPV analysis below.

In the section on recovery in this report, the recovery devices have been sized to be reasonably consistent with predicted miss-distances of Aquila and Star, and one can have reasonable confidence that such systems will be adequate for coping with the meteorologically-caused gusts expected at sea. If meteorological gusts were the only non-steady problem to be overcome during shipboard recovery, it is likely that smaller recovery areas could eventually be used for retrieval of an optimized RPV. It must be noted, however, that turbulence caused by the hull and superstructure of the Hydrofoil may be an equally difficult, if not more difficult, factor to contend with.

Regrettably, not much has been revealed about the intensity of ship turbulence. A search for data about the characteristics of the air-flow and turbulence around Hydrofoils produced one report (Ref. 10) dealing with wind tunnel tests of roll, pitch, and yaw moments caused by cross winds, but which contained no direct information about air-flow direction and turbulence in those air spaces of interest to RPV recovery. The model, however, did have tufts attached to its surface at several locations, and it is possible to use the photographs in the report to make some interpretations of what the flow patterns are likely to be above and along side of the tufted areas. From a simplified aerodynamic point of view, furthermore, the Hydrofoil hull and superstructure can be envisioned as an irregular-shaped lifting body set at a moderate angle of attack, and then known behavior of the flow around lifting bodies can be used to construct a visualization of the general-flow patterns.

Stream lines representing the probable flow pattern over the PCH are shown in Fig. 6. It should be recognized that this is a schematic drawing of uncertain accuracy. For clarity, the curvatures and displacements are shown with what is probably an exaggerated magnitude compared to the real case. The principal features to be noted are: (a) the flow is probably fairly smooth from the bow to a station near the aft end of the superstructure. (b) An inboard flow will occur about midships, to fill in the low pressure region formed by lift of the body and base drag of the superstructure. In all likelihood, this inflow will roll up roughly into a pair of vortices having a diameter about equal to the height from the main deck to the pilot house. The steady-velocity component of flow in this area will be slightly slower than the free-stream velocity. (c) Farther aft, as the flow passes over the two pylon housings, additional vortex patterns will be generated by inflow into the base of the pylons. Aft of the pylon housing, the average velocity will be still lower, and a substantial amount of non-steady rotary and shear turbulence in varying directions will be present.

In Fig. 7 schematic diagrams are shown of the probable, average, tangential-flow patterns at the pilot house (Section P-P), at midships (Section M-M), and at the fantail (Section F-F). In this figure, an RPV has been sketched to show its approximate location, during final approach to possible recovery areas. The notable predictions are that in coming down on a VRL path alongside the pilot house, the RPV would probably experience an unsteady rolling moment of as yet undefinable magnitude, starting at perhaps 10 to 15 feet altitude. This rolling moment is expected to be in a direction to cause the RPV to roll away from the Hydrofoil, a feature which could enhance safety. The rolling moment would be expected to increase in magnitude as the RPV closes on the recovery platform. It is obvious that it would be desirable to put a landing platform as far away from the hull as practicable.

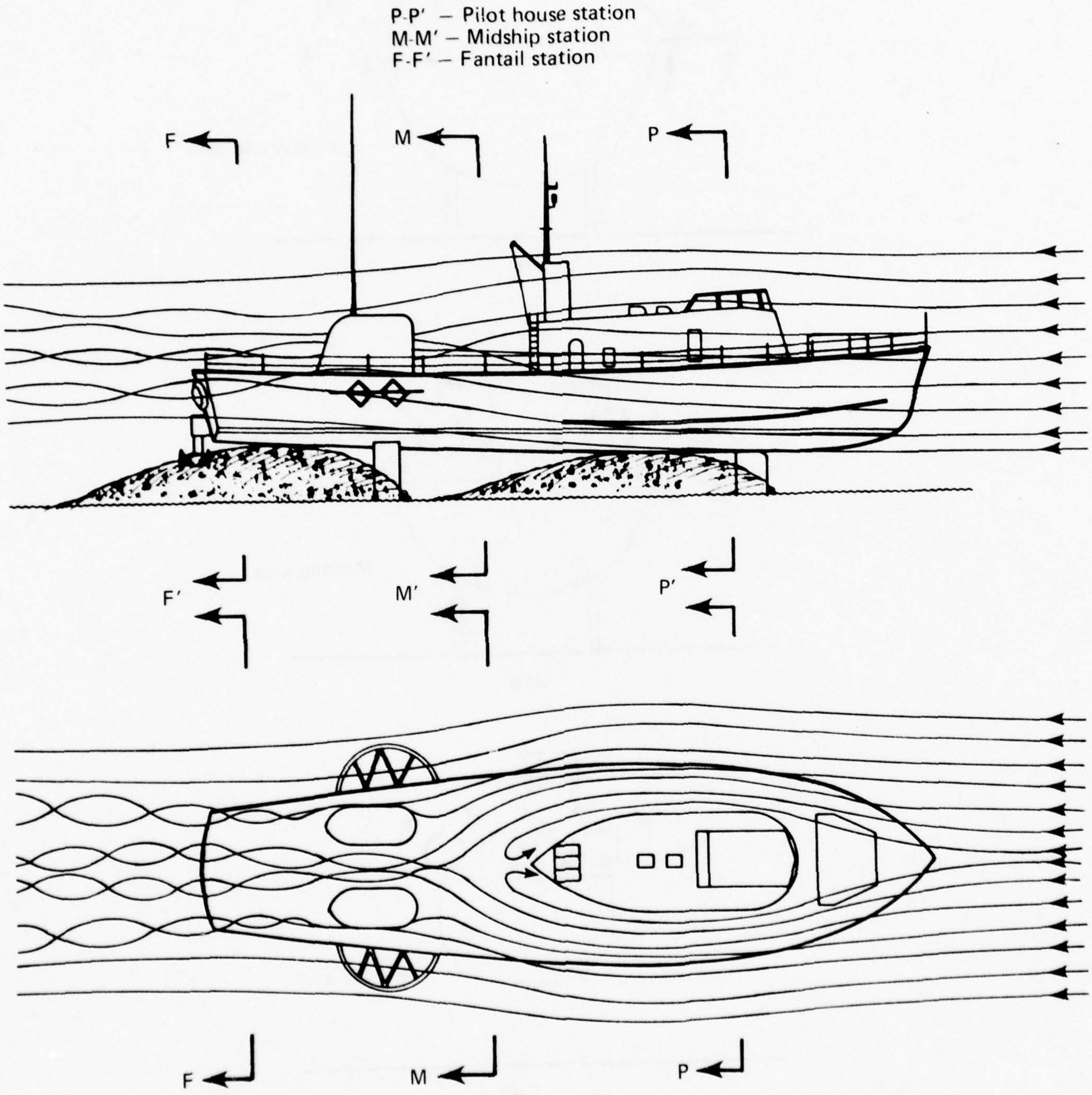


Fig. 6 Probable Airflow Pattern Over Foilborne PCH Headed Directly into Wind

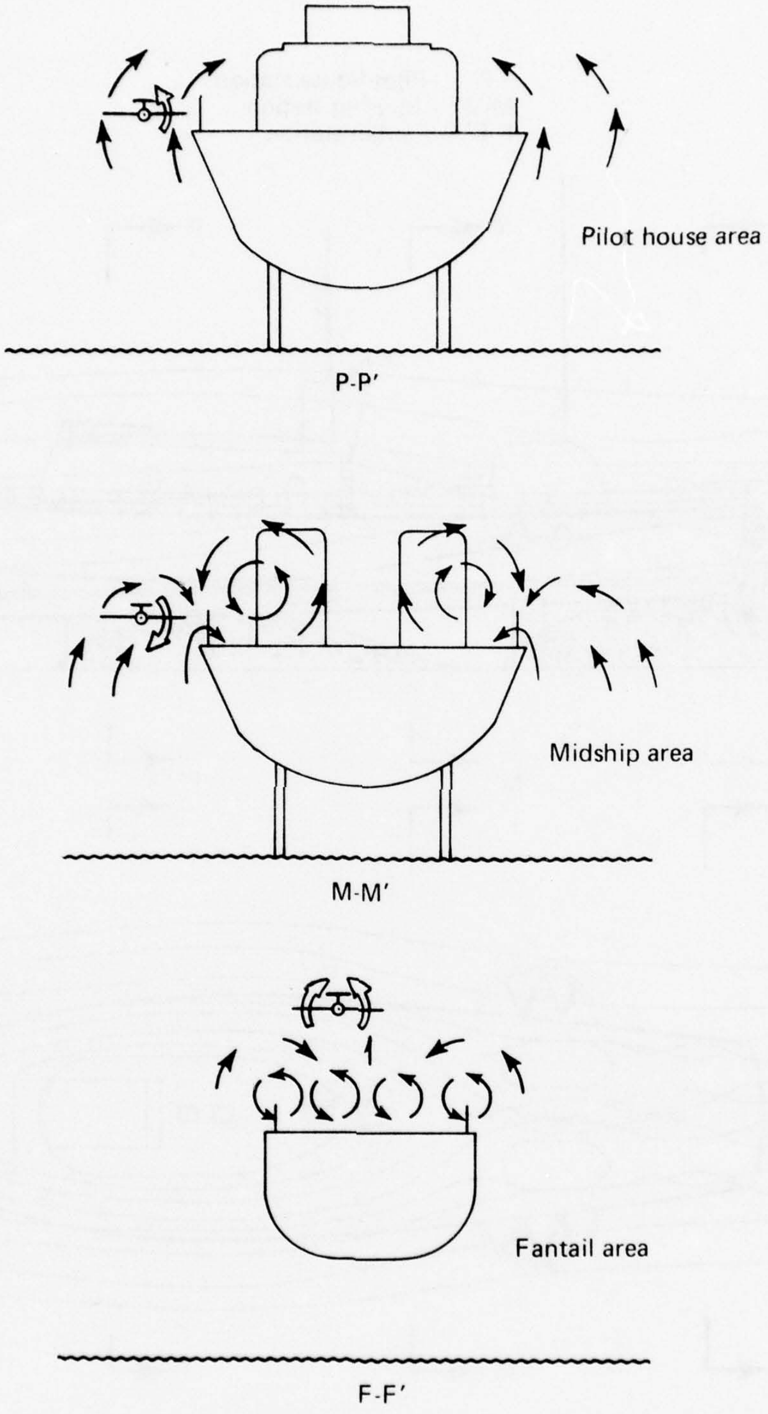


Fig. 7 **Probable Tangential Airflow Around PCH Headed Directly into Wind. (Views are from bow end looking aft)**

An RPV performing a VRL onto a platform or net located alongside midships would probably encounter larger rolling moments than in the forward areas. See Section M-M, Fig. 7. In addition, there could be sizeable side forces produced in this region. The direction of the rolling moments and side forces would probably reverse during a final descent from about a 20-foot altitude. At higher altitudes, the flow effects would tend to turn the RPV away from the Hydrofoil, but at a later time, close to touchdown, the local air currents are likely to be in a direction to cause the RPV to roll in toward the Hydrofoil.

Aft of the two pylon housings, Section F-F, a finer-grained turbulence is likely to be present. In this region, rolling moments and side forces on the RPV may go through rapid reversals with time, even at one relative position with respect to the deck, but as the RPV translates laterally with respect to the ship axis, the erratic flow may be responsible for abrupt changes in the flight trajectory of the RPV. The turbulence will be intense at altitudes below the top of the pylon housing (Ref. 10). The rotary swirls, however, may be of small diameter compared to the RPV wingspan, and, thus, they may not constitute an intolerable barrier to RPV recovery in this area.

The schematic drawings of the near-deck airflow shown in Fig. 6 and Fig. 7 are based on an assumed relative wind that is headed directly into the bow of the ship. In the case under which the relative winds veer in from substantial angles off the bow, the basic turbulence and rotary-flow patterns in each of these areas would be different. Figure 8 is a schematic diagram of the probable rotary flow that would be experienced in the case for which the relative wind is from about 30° to the starboard from the bow. At the pilot-house station, the expectation is that the cross flow would generate larger tangential velocity components and the tendency for the RPV to roll away from the ship during its final approach would be more severe than for bow-on winds. At the midships and the fantail stations, however, the effect of cross flow would probably be to reduce the intensity of rotary flow and also to damp somewhat the shear turbulence along the ship's axis.

A sketch of the probable streamlines about the Plainview AGEH, as shown in Fig. 9, suggests that this vessel may be a more favorable test bed for RPV's. It does not take a trained eye to see that the Plainview is a cleaner aerodynamic shape than is Highpoint, and that the longer clear-run across the fantail of Plainview should allow for more damping of the shear turbulence and vorticity that is generated behind the superstructure. But a word of caution needs to be interjected with regard to this prediction. It is possible, for example, that the cleaner superstructure would generate smaller-diameter, more-persistent vortices, of much higher rotational velocity than those coming off of the PCH superstructure. The consequences of such vortices to the behavior of an RPV during a fantail recovery could be more drastic than the buffetting attributable to the "chopped" flow on the PCH.

In summary, it should be reiterated that these descriptions of the flow patterns are conjectural and are intended to serve only as a general guide in early planning of RPV systems. One need merely look at the diagrams, however, to realize that these flow phenomena have an important bearing on the terminal performance of the RPV, and in consequence, overcoming these

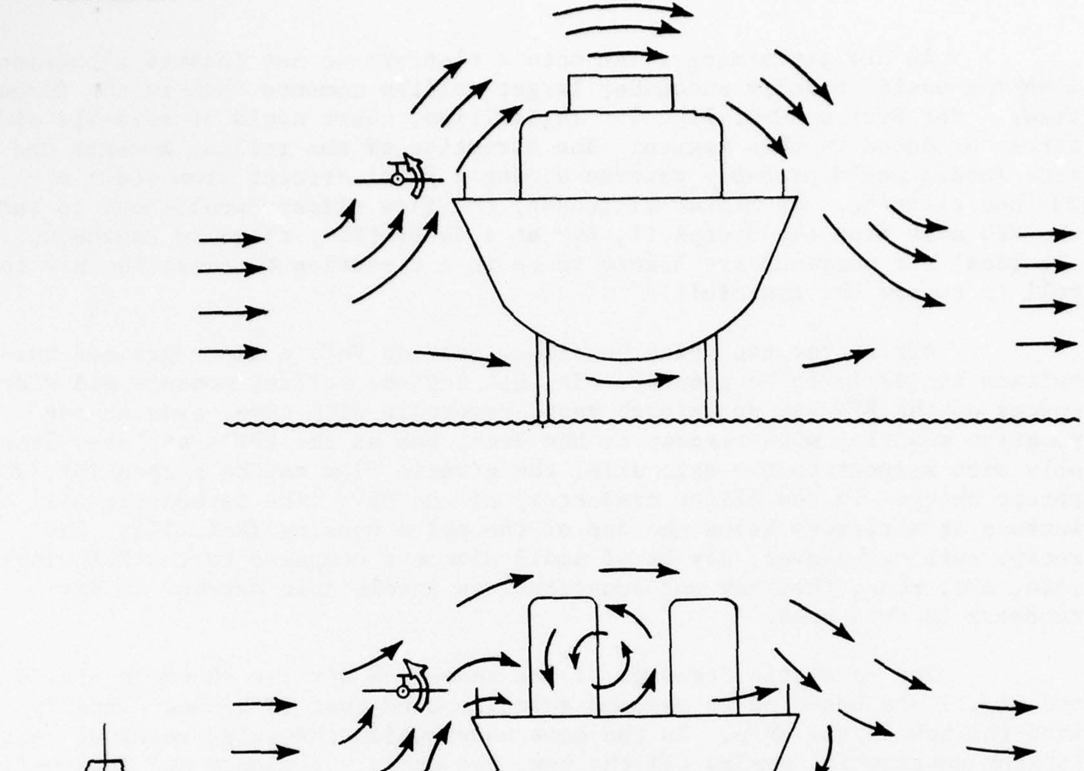


Fig. 8 Probable Tangential Airflow Around PCH with a Relative Wind 30° Off the Starboard Bow. (Views are from Bow end looking aft.)

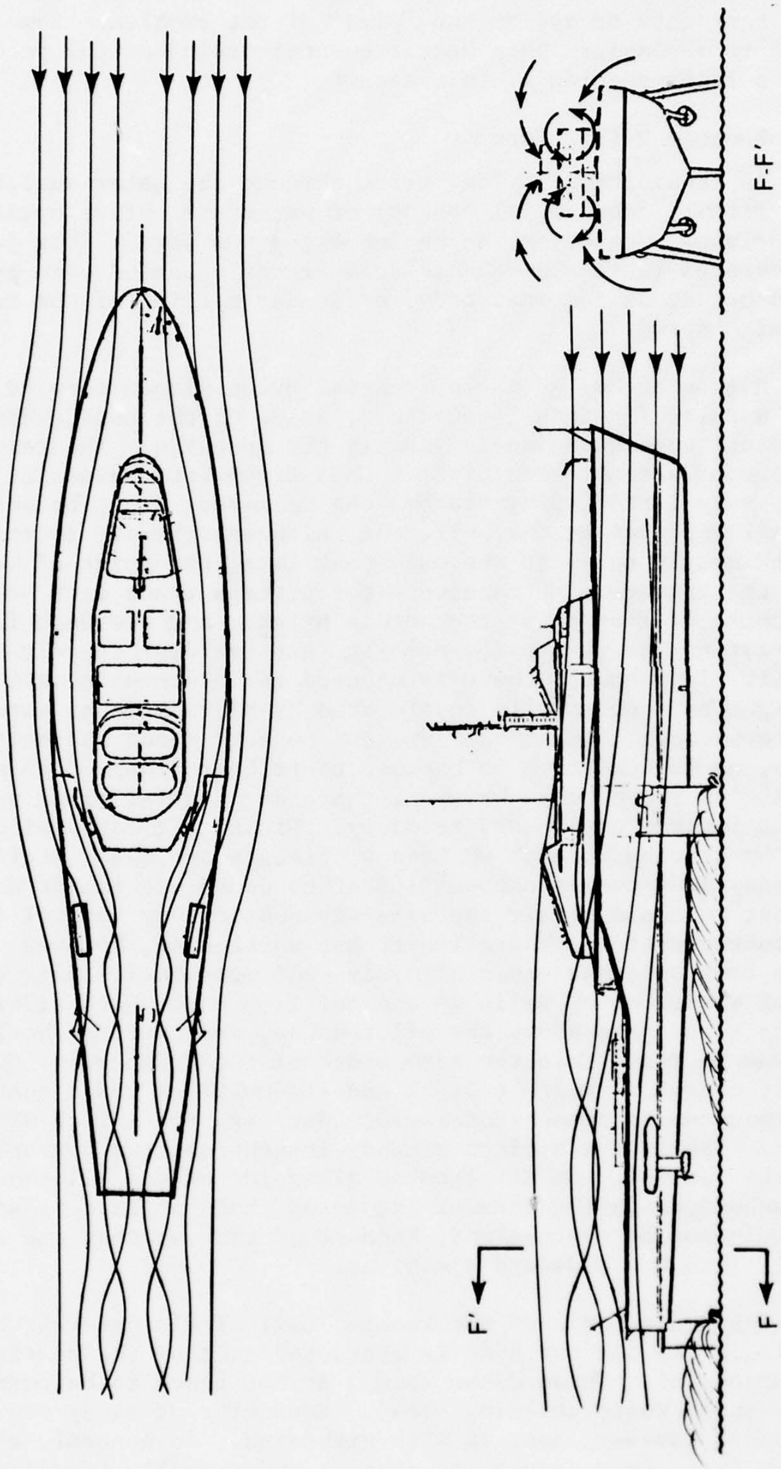


Fig. 9 Probable Airflow Patterns Over AGEH

shortcomings can impose some restrictions on ship handling procedures during launch and recovery. It is fairly obvious that an effort should be initiated to obtain test data to define the "size" of the problem. Some recommended procedures to accomplish this better quantification of the problem are described in a later section of this report.

3.5 Rooster Tails, Spray

As the vertical pylons slice through the water surface during foilborne flight, substantial amounts of water are thrust upwards because of the unbalanced pressures in the submerged bow wave. This jet-entrainment effect generates lenticular-shaped rooster tails behind each pylon. The length and height of the main body, or denser portion of the rooster tails, increase with speed.

Highpoint has a single, central pylon placed forward, under the hull, and a pair of pylons located aft, aside of the hull, whereas the Plainview foil configuration is exactly the opposite. The resulting spray patterns are of a contrasting form. When Highpoint cruises at 45 knots in calm seas, very little spray reaches the main-deck line, because the forward rooster tail impinges on the hull, and, although the aft rooster tails rise to a height nearly equal to the main-deck line, the point of maximum height is behind the transom. No massive water parcels reach deck height. Only minute amounts of fine spray reach this height, and the deck is usually dry, back at least to the rear-pylon housing, and the deck is only misty wet on the fantail. In summary, there is no need for concern in calm seas that the RPV might be accidentally decelerated by hitting dense water spray during an approach. Almost the same can be said about the rooster tails in rough seas, up to Sea-state 5, because their basic shape does not change a great deal. In rough seas, however, there are several other spray problems which might interfere with RPV recovery. First, a great deal of fine spray, generated by slicing through whitecaps, rises above the fantail. The density of this spray is probably not sufficient to cause any impact deceleration of the RPV, but it could impair the effectiveness of any optical systems used in the recovery system. There is yet one worse case, however, in which the hull slaps down onto the crest of a wave and momentarily extrudes a dense fountain of water, which wells up and out from under both sides of the ship, to reach up to heights above the pilot house, and to cover horizontal distances three to five times the beam width of the Hydrofoil. Such spray is essentially opaque to visible light and it doubtless would contain enough mass and momentum to cause inadmissible decelerations of an RPV passing through it. The fountain often extends lengthwise from forward of the pilot house to the fantail. An RPV located alongside of the pilot-house station would be submerged in the core of the spray, but one that is approaching the fantail would not be overwhelmed, because of the way that the spray is split by the hull into two sideward ejections.

The dense parts of the rooster tail of Plainview have a structure that is similar to the one that is characteristic of the rooster tail produced by Highpoint. These dense sprays do not reach to heights above the main deck, at 45 knots cruising speed. Fountains of spray can be extruded in rough seas, however, just as with Highpoint. In general, the chances of any RPV's hitting dense spray are remote, and probably identical with both ships. Because there are two forward, outboard pylons rather than the single one on the centerline, more fine misty spray comes up and over the fantail area of Plainview than on Highpoint. In some conditions of cross wind, the misty spray might reach sufficient density to impair the performance of optical systems, but tests of specific hardware would be needed to ascertain if this possible degradation in performance is a real problem.

In any final operational RPV system, it will probably be found preferable to employ non-optical systems that are more compatible with the naval environment, to obtain the required information needed for terminal guidance. Spray and weather problems can be avoided in early feasibility demonstrations, however, so that the concern expressed here should not be *interpreted to mean that existing systems should be avoided.*

4.0 RPV PERFORMANCE CHARACTERISTICS

Results of a design and performance analysis of a family of mini RPV's for Naval OTH missions will be reported in this section.

4.1 OTH Mission Descriptions

The basic objective of an OTH-RPV system is to provide the following series of capabilities: Ability to launch the RPV at sea, ability to navigate the RPV to a point up to 100 miles distant from the ship, ability to find and identify surface vessel, ability to relay information, and, finally, the ability to return to and be recovered intact on the mother ship. Figure 10 shows schematic representations of two variations of the basic mission, one for which the objective is to fly to a predesignated point and orbit on an arbitrary geometric path (circle, race track, figure 8, etc.) within a fixed radius of the point, and another, for which the RPV is required to follow a geometric "stepladder" search pattern, to map a designated area . Sub-variations of these two missions, including increased time on station and increased winds, are covered in the present analysis.

Typical mini RPV's have speed capabilities comparable to WW I bi-planes, and, as was the case then, modest winds of 25 knots can have notable effects on duration of the mission. The influence of wind will always be to increase the time and fuel required to perform the mission, because the speed increment gained while going downwind does not balance out the retardation entailed in coming back upwind. To emphasize the seriousness of this problem, consider an RPV having a top speed of 50 mph and performing an OTH mission up- and downwind in a 50-mph wind. The RPV could get to a 100 mile downwind target in one hour, but would require an infinite time to return. Winds parallel to the basic mission course are the worst-case situation. No analyses have been made herein of less drastic traverses, made at an angle to the wind. As depicted in Fig. 10, missions in winds are designated as the B' and C' modifications of the basic mission executed in no wind.

The stepladder search pattern used in the analyses was devised to cover a square area, 15 miles on a side. The spacing of the steps of the ladder has been assumed to be 0.75 miles, i.e., ten upwind legs and ten downwind legs, of 15 miles length each. An RPV using a search sensor directed vertically downward, having a 45° field of view, would have to fly at an altitude at least 4780 feet to insure complete surface-search coverage by this pattern. This report will not address the question of whether this pattern is adequate from the viewpoint of visibility, discrimination, and resolution of targets by the sensing devices. Should it be found that lower altitudes or smaller view angles are needed, the total area that can be searched will be smaller, but the quantitative effects of wind on mission duration will remain essentially unchanged.

In the analysis reported here, the assumption was made that the RPV will travel to and from the search area at its maximum dash speed and will perform the search at its best cruise speed (maximum L/D). The results will be reported in terms of minimum time and amount of fuel required to

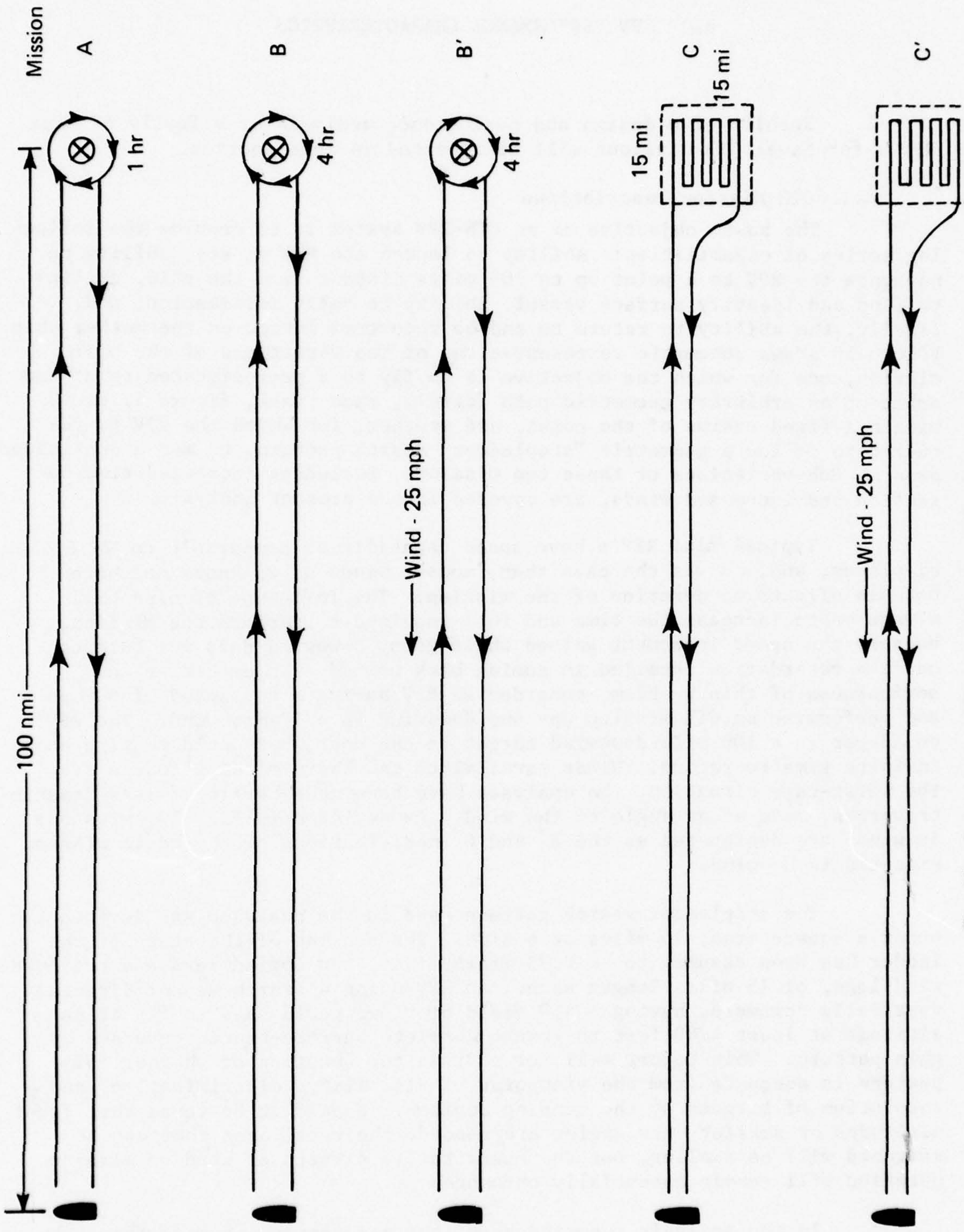


Fig. 10 Schematic of Missions Used for RPV Analysis

accomplish the mission. The geometric search mission time could be reduced by adjusting power to accommodate for upwind and downwind legs, but at the expense of extra fuel consumption. The results of the fuel analysis indicate that there is not a great deal of leeway for adding fuel and, therefore, secondary tradeoffs related to airspeed adjustments have not been analysed in this study.

4.2 RPV Design Methods

The RPV designs to be discussed here are hypothetical, but all are based on the use of propulsion systems, structures, and materials that can be considered to be not only comfortably within the state of the art, but also within the bounds of some demonstrated, low-cost, production techniques. Some of the predictions of aerodynamic performance cannot be taken as quantitative certainties, however, for the reason that only a small amount of applicable data is available on airfoils or complete-airplane performance in the range of Reynolds numbers that is associated with the low-speed regimes that are pertinent to mini-RPV-sized aircraft.

Typical mini RPV's in flight, at or somewhat above their best cruise speed, would be operating at Reynolds numbers of about 2 million. The vast store of data taken at Reynolds numbers from 3 to 10 million (Refs. 11,12) can, therefore, be used with an expectancy of attaining good accuracy in estimation of the best cruise speed, dash speed, range, and duration. During landings at about 45 knots, however, typical RPV's will be operating at mean aerodynamic wing-chord (MAC) Reynolds numbers around 1×10^6 to 0.5×10^6, and the tail and rudder will be experiencing still lower Reynolds numbers. In these lower Reynolds number regimes, peculiarities associated with separation sometimes cause control problems and tend to degrade the basic performance below that predicted on the basis of data gathered at higher speeds.

As has been stressed in the introduction and previous sections of this report, recovery of the RPV appears to be the paramount problem that needs solution before any system can be considered feasible. Since maneuverability is a prime ingredient in the recovery process, the strongest possible emphasis should be placed on achieving good maneuverability at usable approach speeds. Ideally, one would like to achieve this goal without degrading the performance of the vehicle with regard to other parts of the mission.

Consistent with this view, the RPV configurations to be described here have been designed to have good maneuverability at air speeds of 45 knots, so that VRL can be used for recovery on a Hydrofoil. There are no specifications or standard terms to describe the speed needed to achieve a certain acceptable level of maneuverability, for either RPV's or manned aircraft. For purposes of discussion here, this threshold value will be called the velocity for minimum allowable maneuverability (V_{mam}).

A composite of source information has been used to arrive at realistic assumptions about the aerodynamic performance of the hypothetical aircraft to be described. Some generalized Reynolds number extrapolations have been made, using the standard data for infinite wingspan airfoils

(Refs. 11,12,13). These extrapolations were influenced by the general trends seen to hold true for a very limited amount of data taken on model-airplane airfoil sections at Reynolds numbers in the range of 0.021 to 0.168 x 10^6 (Ref. 14). Methods described in Refs. 15,16,17 and 18 have been used to estimate the efficiencies of "whole airplanes". Among the factors involved in such estimates are corrections for finite aspect ratio, for wing planform and lift distribution that are not elliptic, for lift-induced drag, for profile and skin-friction parasite drag, for wing-body interference, and for other minor deviations from idealized aerodynamic conditions. There has been superimposed on the above estimates a certain degree of conservatism, introduced on the basis of aerodynamic experience this writer has accumulated during 30 years of flying a wide variety of designs of radio-controlled aeromodels, some of which were used to establish record performances for altitude, distance, duration, and speed (Refs. 19,20,21). This latter source of information is not amenable to brief scientific description. It is appropriate here to condense the experience related to landing into an axiom: "When it comes to slow-speed landings in gusts, aerodynamic efficiency isn't too important. Control response is what is important."

Sluggish response at low speed is easily explained by the prevalent tendency for control moments that are generated by control surfaces acting at low dynamic pressure to be inadequate. Unexpected directional responses to control inputs are generally attributable to separations of flow that sometimes occur in local regions of the wing, or near deflected control surfaces. Gusts often trigger incipient separations. Such triggering is seldom observed in wind tunnels because most tunnels are designed to have very smooth flow. Out in the real world, the better part of wisdom demands that all experienced pilots, whether they are driving jumbo jets, light planes, RPV's, or radio controlled models, should add a safe margin of airspeed above stall during landing approach and that they should add an extra healthy increment in gusty weather.

There are as yet no specifications as to what the quantitative value of this increment of speed should be for mini RPV's. In the present Hydrofoil problem, it was decided to use a value of V_{mam} that is 1/6th (16.7%) in excess of stall speed. This safety margin may or may not be found to be a sufficiently generous value. The rationale used in arriving at this figure will not be described in detail, but it should be noted that the only case for which a 45 knot V_{mam} is absolutely essential is the case in which the Hydrofoil is operating in calm winds. This situation would represent a case of low meteorological turbulence, and the RPV will have to essentially cope only with ship-created turbulence. As an additional safety margin, there are another 5 knots (10%) of relative wind available from the Hydrofoil under these conditions. In conditions of high windspeed and turbulence, an extra increment of airspeed (and consequently, control response) can be made available by requiring the Hydrofoil to cruise on headings that are somewhat into the wind. While such procedures would impose limits on course and speed options of the Hydrofoil, it may be found that this fix would be preferable to the alternative, which, as will become apparent in the analysis, would be to increase the size of the RPV. Such an increase in size and weight will, of course, lead to the undesirable consequences of forcing acceptance of a larger storage space and a decreased range-speed capability in the main RPV mission.

Based on the foregoing considerations, the RPV design procedure adopted consists of describing the lift curves as a function of angle of attack for the proposed configurations, determining the value of the maximum achievable lift coefficient, and then sizing the vehicle to provide lift equal to the vehicle's weight at a stall speed of 43.1 mph, which is 1/6th less than the V_{mam} of 45 knots. After this sizing procedure is carried out, the lift and drag at higher speed, and the values of lift coefficient at the point of maximum L/D are determined. From these latter values, best cruise speed and the power required at best cruise speed are calculated, along with values of maximum dash speed at maximum available power.

Throughout the analysis, maximum gross takeoff weight has been assumed to be 150 lbs. This figure is based on an assumed allotment of weight as follows:

	Fraction	Weight (lbs)
Sensor Payload and Link	30%	45
Guidance, Control, and Link	20%	30
Airframe	20%	30
Engine and Alternators	15%	22.5
Fuel	15%	22.5

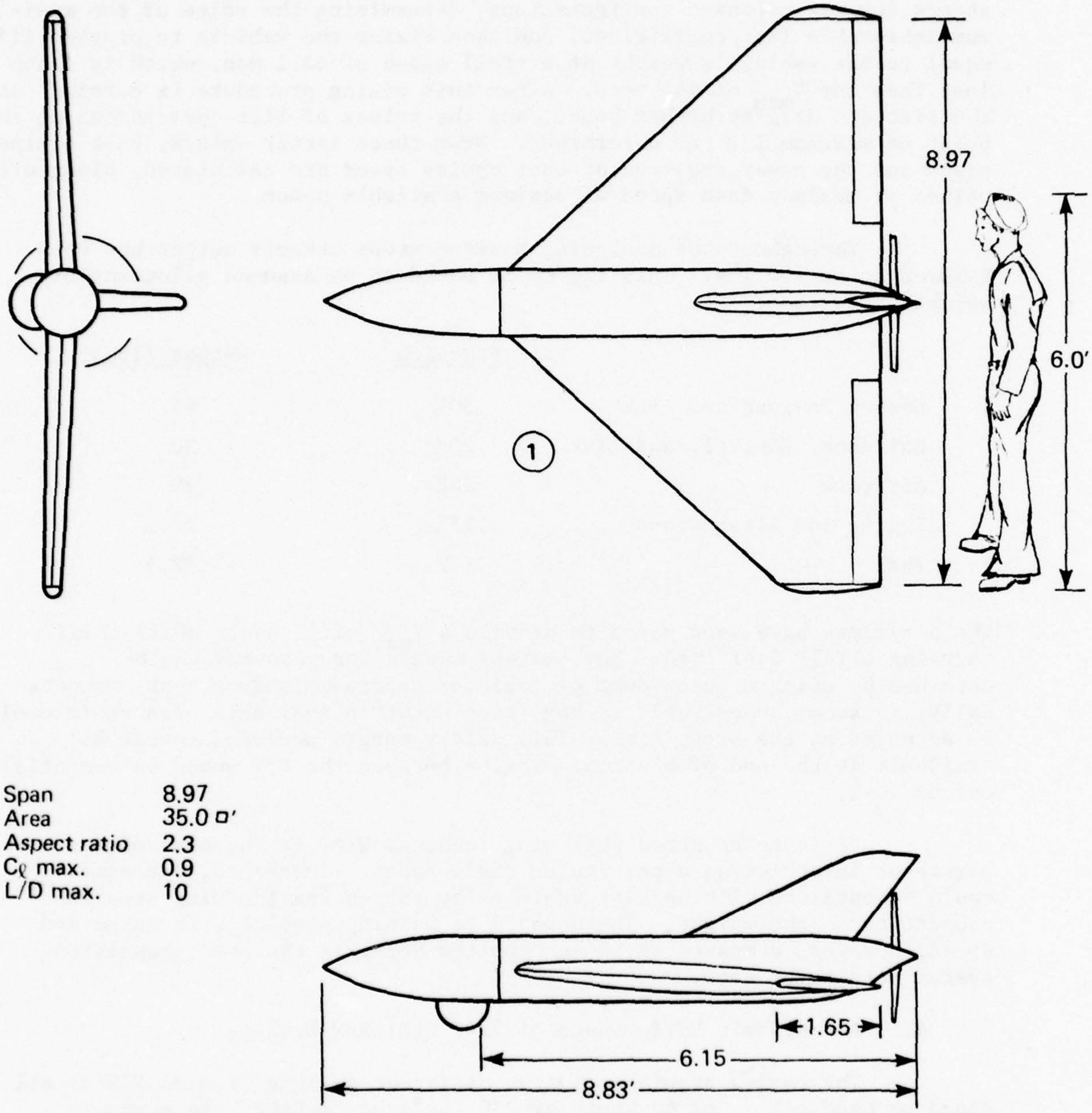
The airframes have been sized to provide a V_{mam} of 45 knots whill still carrying a full fuel load. Some safety margin for recovery can be obtained by using a quick dump of fuel for aborted missions, but pragmatically, it seems undesirable to have such a button available because it could be actuated at the wrong time. This safety margin would of course be available at the end of a normal mission because the RPV would be essentially out of fuel.

It is to be noted that wing loading, W/A, is the controlling parameter in achieving a particular stall speed. Therefore, the same V_{mam} could be obtained with heavier vehicles by increasing the wing area in proportion to the weight. There would be ensuing penalties in range and speed, however, compared to those reported here, if the same propulsion system were to be used.

4.3 Aerodynamic Performance of Five Mini RPV Designs

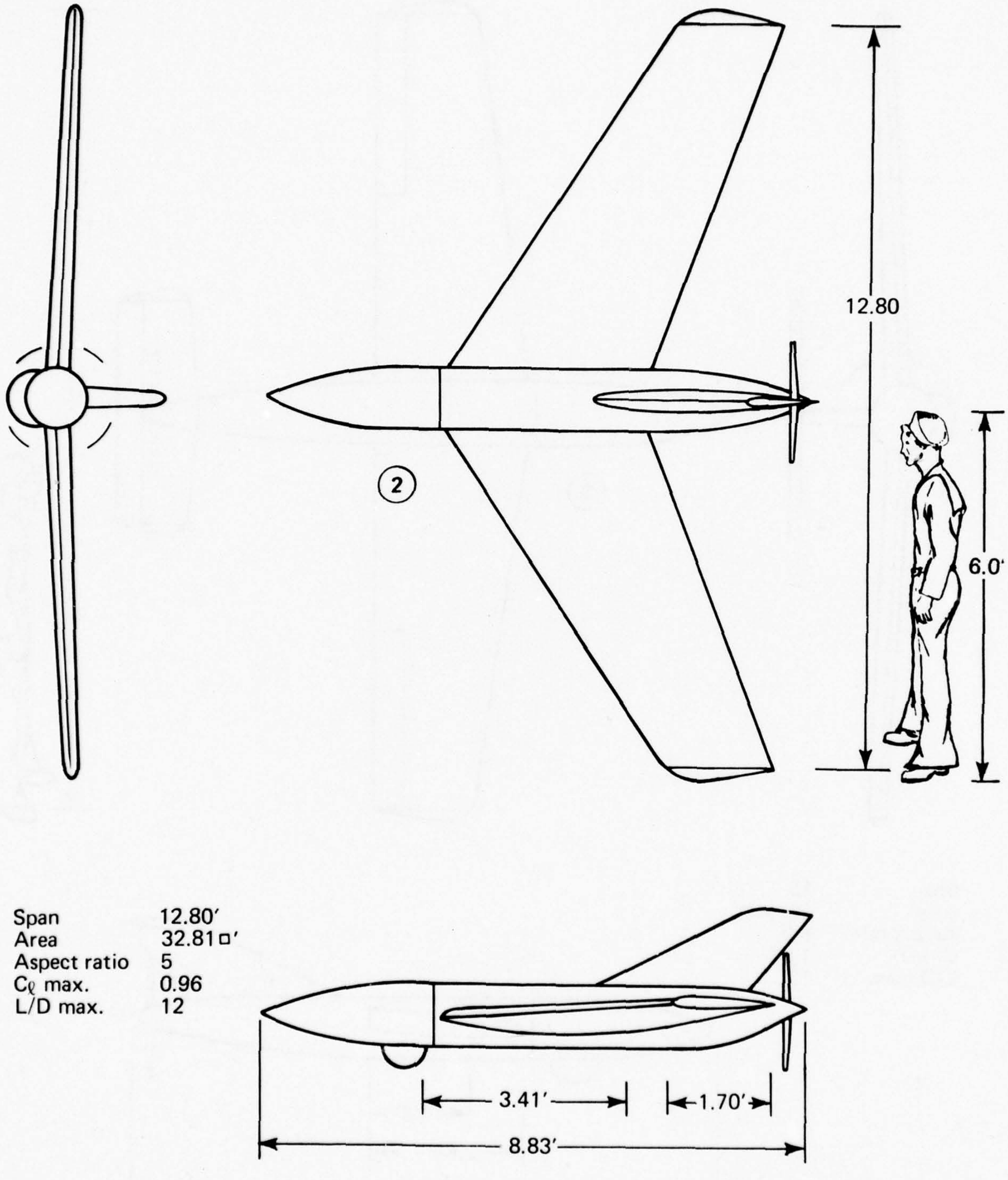
Three-view drawings of five different designs of mini RPV's, all sized to have a V_{mam} of 45 knots at 150 lbs gross weight, are shown in Figs. 11 through 15. A six-foot-tall man has been sketched in each of these views to give a perspective appreciation of the size of the RPV. Mini RPV's resembling these designs have been flown in U.S. programs (Refs. 1,2,3,22 23,24,25,26).

Figure 11 shows a Delta-planform RPV similar to the Star RPV (Teledyne Ryan) and to the RPD-1 and the RPD-2 (APL) configurations.



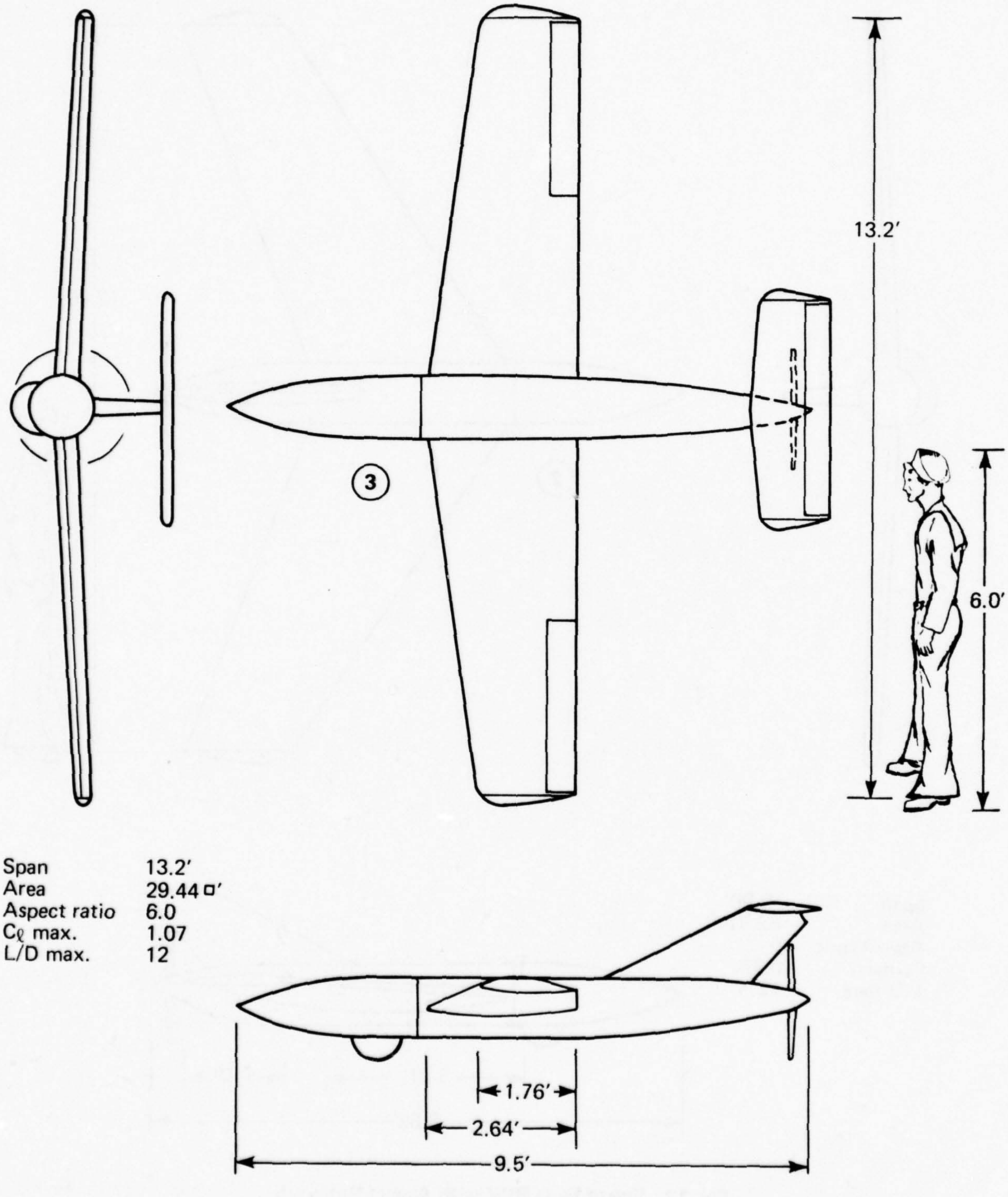
Span	8.97
Area	35.0 □′
Aspect ratio	2.3
C_ℓ max.	0.9
L/D max.	10

Fig. 11 Delta RPV with Aspect Ratio = 2.3



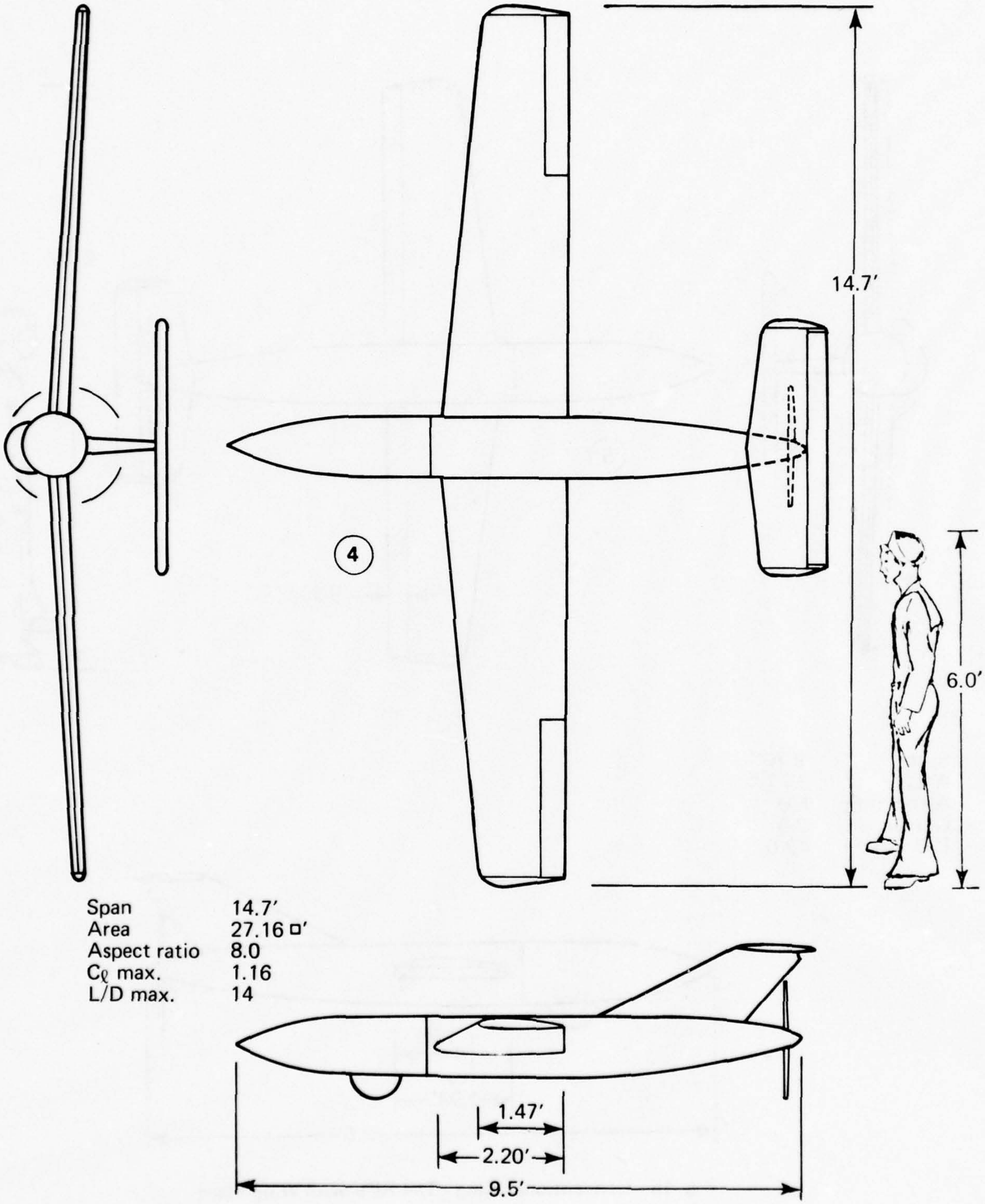
Span	12.80'
Area	32.81□'
Aspect ratio	5
C_ℓ max.	0.96
L/D max.	12

Fig. 12 Swept Wing RPV with Aspect Ratio = 5



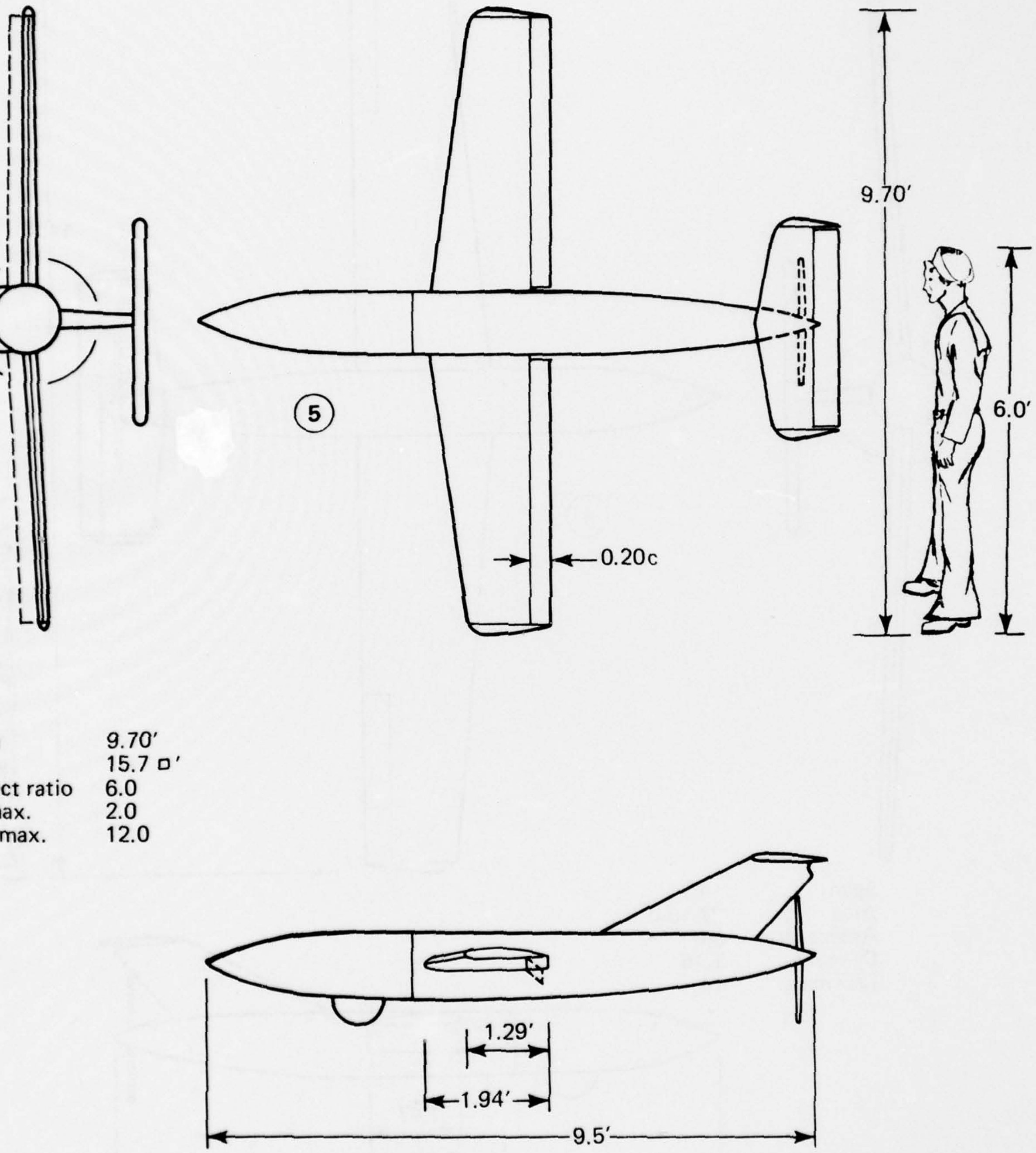
Span	13.2'
Area	29.44 □'
Aspect ratio	6.0
C_ℓ max.	1.07
L/D max.	12

Fig. 13 Conventional Wing - Tail RPV with Aspect Ratio = 6



Span	14.7'
Area	27.16 □'
Aspect ratio	8.0
C_ℓ max.	1.16
L/D max.	14

Fig. 14 Conventional Wing - Tail RPV with Aspect Ratio = 8



Span	9.70′
Area	15.7 □′
Aspect ratio	6.0
C_ℓ max.	2.0
L/D max.	12.0

Fig. 15 Conventional Wing - Tail RPV with Wing Flaps

Figure 12 describes a swept, flying-wing design similar to Aquila RPV (Lockheed) and to the Sky Eye RPV (Development Sciences).

Figure 13 shows an RPV having a conventional wing and horizontal stabilizer with the wing being of aspect ratio 6. The Ford Aerospace and Communications Corp. Praeire is nearly equivalent to this vehicle except that the Praeire has its engine and propeller mounted on a pylon at the trailing edge of the wing instead of being a pure pusher configuration, as shown in this design. Generally speaking, one can expect a slightly improved aerodynamic efficiency from a pusher propeller, as compared to a tractor or mid-ship pusher, because the fuselage and central portion of the wing are not engulfed in the high-speed, turbulent prop wash. The consequent longer runs of laminar flow and thin boundary layers of the pure pusher can provide some improved high-speed performance. The benefits are minimal, however, and, at low landing speeds, the advantages are probably negligible. The main benefits of a pusher propeller are that it provides a clear view forward for search sensors and that exhaust oils are kept from depositing on lenses or windows that might be in use as part of the payload.

Figure 14 is an identical layout to the one shown in Fig. 13, except that the wing is designed with an aspect ratio of 8 instead of 6. The nearest existing equivalents to this configuration are the Melpar E100 RPV and the Boeing Expendable Mini RPV.

Figure 15 shows a conventional wing-tail design having a wing aspect ratio of 6. The wing is fitted with full-span flaps of a width equal to 20% of the average wing chord, and which can be deflected downward to 45°. So far as is known, no previous or present mini RPV's have incorporated high-lift devices.

In Fig. 16 the planforms of all five designs are presented pictorially, in superimposed position, to show a comparison of the size of all the designs.

Several general features are assumed or selected to be common to all five vehicles. For example, all fuselages are 12" in diameter and circular in cross section throughout their length, except for a protruding optical dome or radome, which has been assumed to be a 10" diameter hemisphere for all designs. All aircraft are assumed to be powered by the McCulloch 101A engine, or by an equivalent installation that is fitted with an extension shaft, in a manner similar to engines developed for the RPD-2 vehicle (Ref. 27). A photograph of this engine is shown in Fig. 17. The length of the extension shaft will have to be longer for some designs, but this adjustment cannot be expected to add significant weight or to create any new mechanical problems in respect either to the integrity of the shaft or in regard to additional complexities of a shock-mounting system. All aircraft are expected to be designed with detachable wings and with at least one ring joint for parting the fuselage. This ring joint is intended to be located just forward of the intersection of the wing and fuselage. In most designs, different payloads could be installed in separate nose cones and be interchangeable. The length of the extension shaft is intended to be used

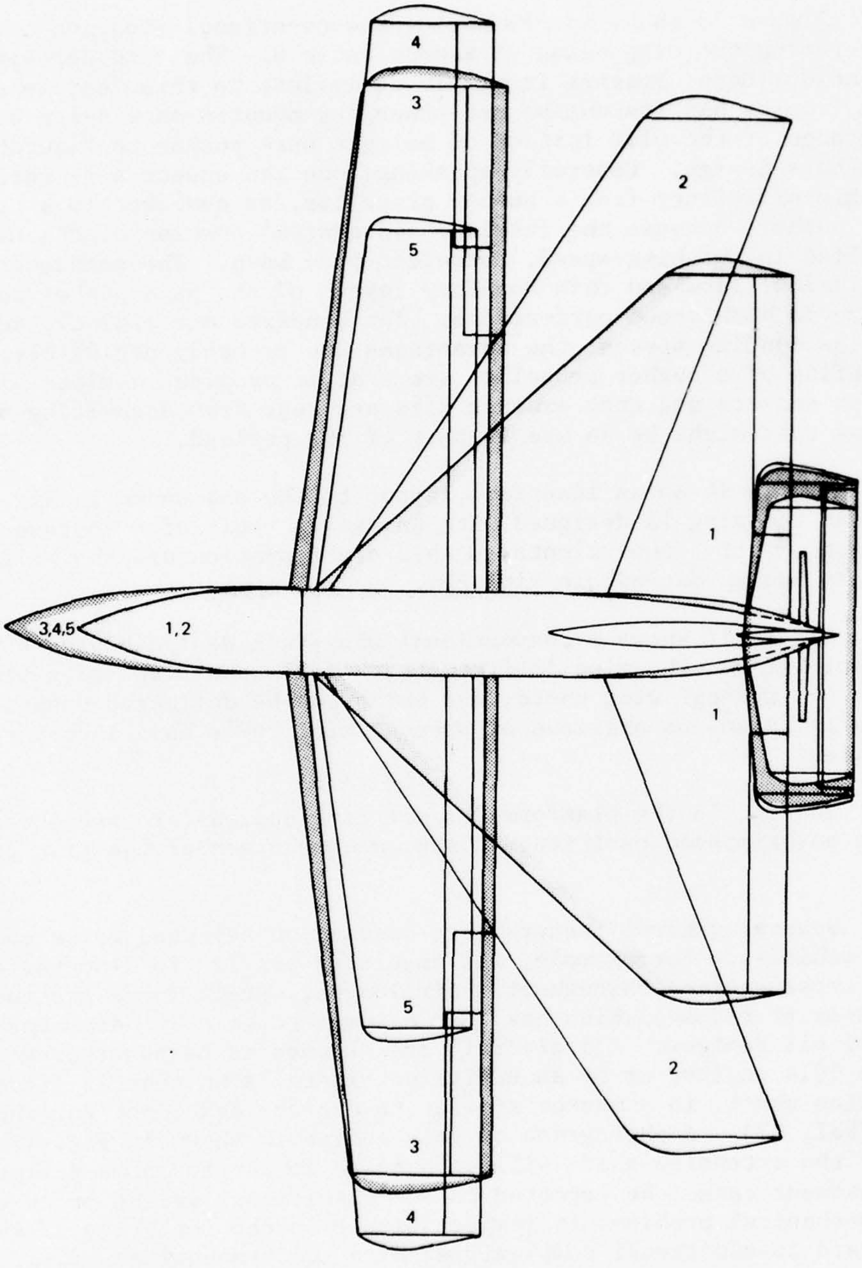


Fig. 16 Superimposed Planform Views of A Family of Mini RPV's Having V_{mam} = 45 Knots

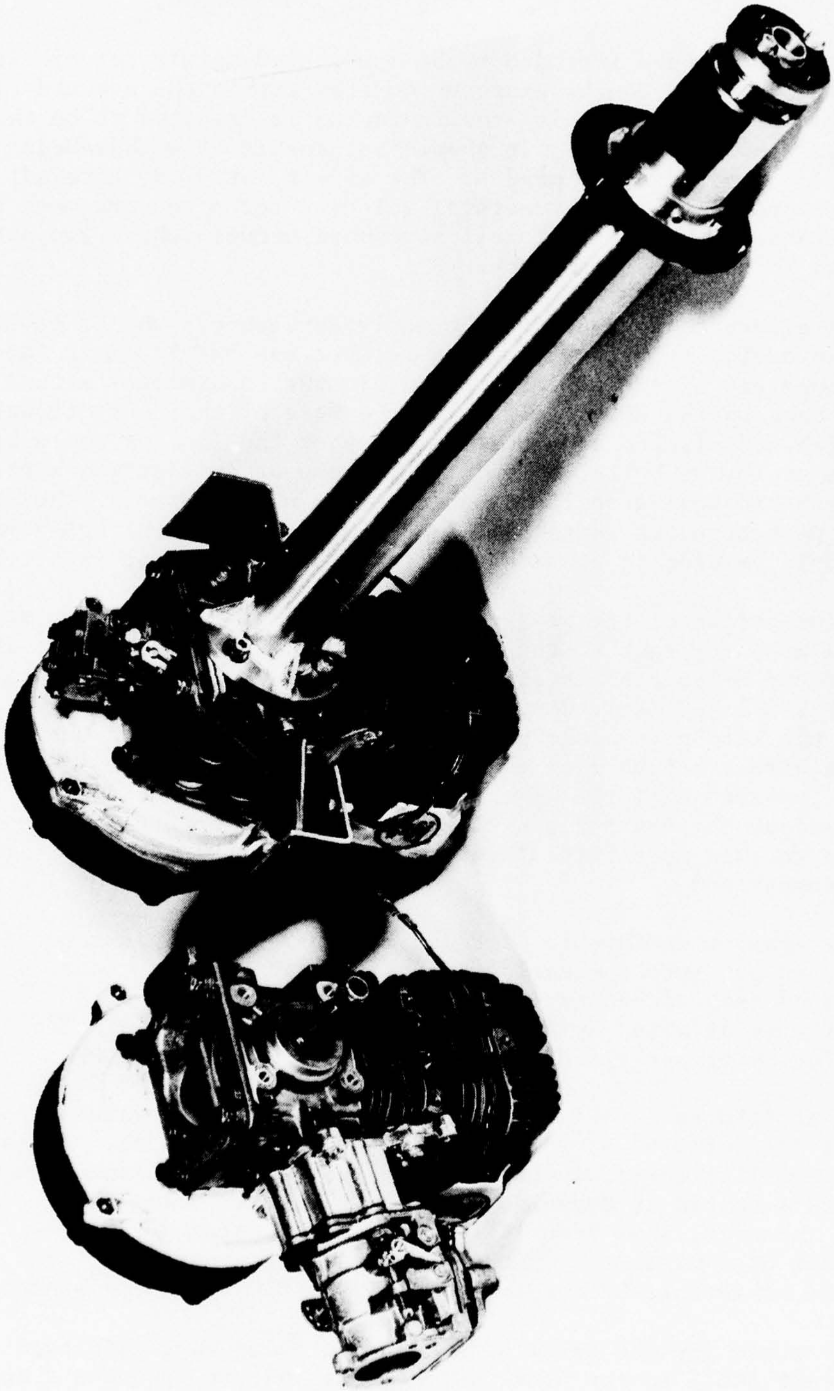


Fig. 17 One Modified and One Stock McCulloch 91 B/1 Engine

to control the final location needed to establish a satisfactory position for the center of gravity. All fuel tanks are to be installed in the wing near the C.G. to avoid C.G. shifts during fuel consumption.

All aircraft are intended to be fabricated mainly out of fiberglass and epoxy resin and they can be expected to stay within the assumed airframe weight fraction of 20%. The Delta configuration is expected to be the most structurally efficient vehicle. It should be capable of withstanding loads of 30 g's during maneuvers or impacts. The aspect ratio 8 aircraft cannot be expected to provide a safe structural solution for maneuvers much above 4 g. The remaining vehicles will fall somewhere between these two extremes with regard to structural efficiency.

All aircraft, at least in the early development phase, could be fitted with an emergency recovery parachute that may be stowed in the vertical fin and deployed out of the top of the fin, in the same manner as has been successfully used on the RPD-2 Delta. In the case of the conventional aircraft for which stabilizers are located on top of the fin, it would be necessary to use explosive bolts, solenoids, or some other ejection system to cast free the horizontal stabilizer, which in turn can serve as the drogue to pull out the parachute. Airbags similar to those used on the RPD-2 for shock absorbers could be used to provide flotation in the event of in-flight failures.

A comparison of the predicted lift curves (at the common stall speed of 43.1 mph) for each of the five RPV configurations is shown in Fig.18. The curve for the Delta configuration is based on wind tunnel data taken on the full size RPD-1 RPV (Ref. 28), and was modified only slightly to take into account the larger fuselage of the design proposed here. Curves for the remaining aircraft have been estimated using the procedures discussed previously. Cambered airfoils have been used in some of the designs, but all curves, except the one for the flapped wing, have been shifted on the ordinate axis to show zero lift at zero angle of attack, so as to simplify the overall comparison.

The maximum achievable lift coefficient ($C_{\ell\ max}$) is the critical quantity that enters into the evaluation of V_s or V_{mam}. The slope of the lift curve is of only secondary importance to specification of V_{mam}. Pitch maneuverability is affected by this lift curve slope, but the effects can be compensated for by proper sizing of the stabilizer and elevators.

It is fitting first of all to examine the $C_{\ell\ max}$ values typical of handbook data for infinite airfoils at large Reynolds numbers. As seen in Fig. 18, maximum lift coefficients of up to 1.6 can be achieved with many types of airfoil tested at Reynolds numbers of 6 million and above. Most all airfoils, however, show about a 15% drop, to a value around 1.4, at a Reynolds number of 3 million. Neither of these values of $C_{\ell\ max}$ can be expected to be achievable by complete mini RPV's flying at low speeds.

The curve for the Delta configuration shows that this type of vehicle does not stall in the usual sense. Instead, it produces a continually growing value of the lift coefficient as it is pitched up to angles as large as 45°. As a result of this characteristic, the achievable lift coefficient is usually dictated by an upper limit on the angle of attack that is

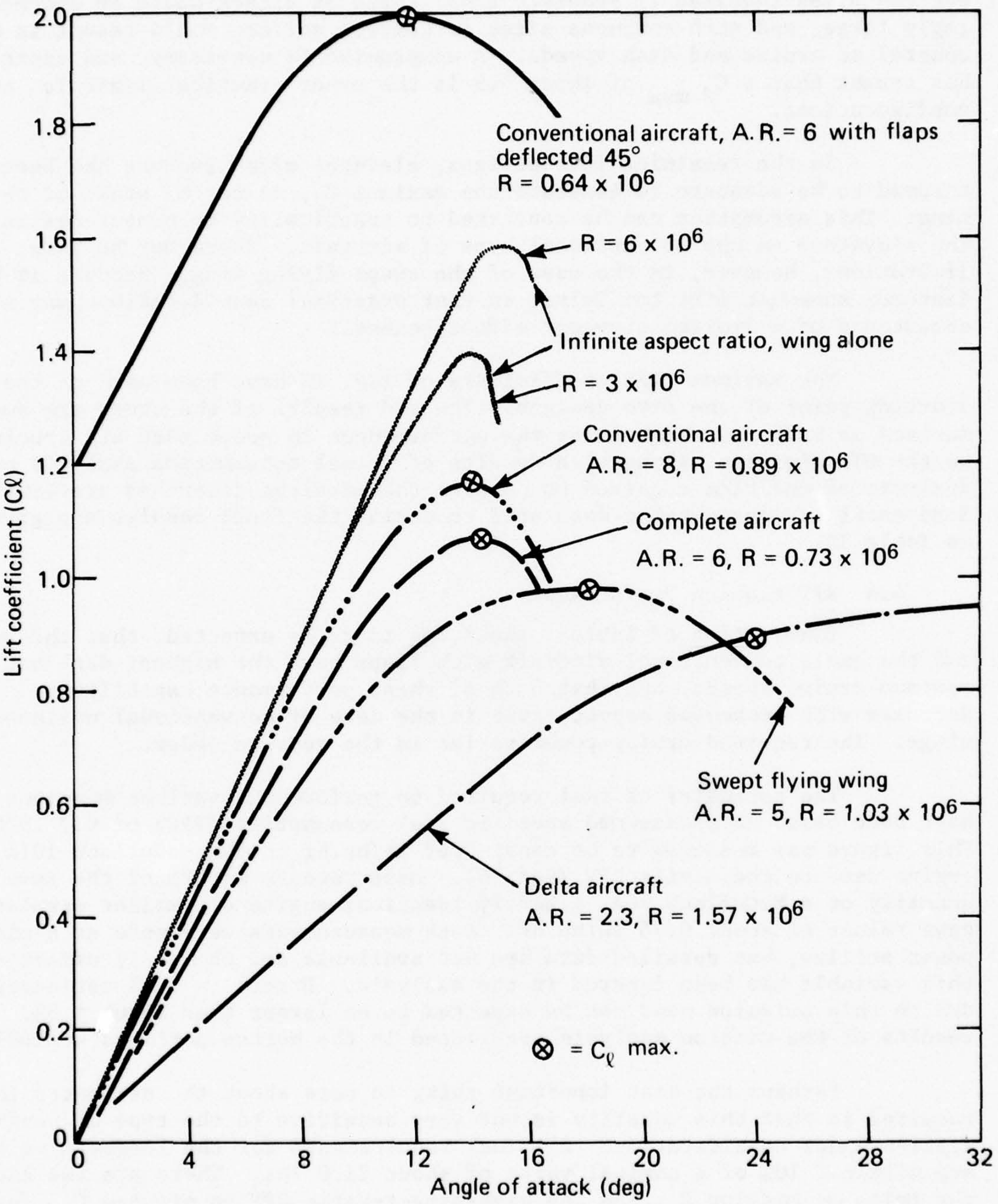


Fig. 18 Comparison of the Lift Curves for a Family of Mini-RPVS at Their Stall Speed (43.1 mph)

realizable at maximum elevator deflection. Large elevator surfaces and deflection would therefore be desirable for achieving slow landing speeds, but the sizes required to generate a 45° angle of attack would be exceedingly large, and such enormous sizes of control surface would result in over control at cruise and dash speeds. A compromise is necessary, and experience has taught that a $C_{\ell\ max}$ of about 0.9 is the upper practical limit for Delta configurations.

In the remaining four designs, elevator effectiveness has been assumed to be adequate to generate the maximum C_{ℓ}, as set by stall of the wing. This assumption can be converted to practicality by proper design of the elevators on the conventional type of aircraft. There may be some limitations, however, in the case of the swept flying wing, because it has features somewhat like the Delta, so that practical considerations may force acceptance of a limited elevator effectiveness.

The maximum lift coefficients of Fig. 18 have been used as the starting point of the five designs. The end results of the study are summarized on Table I, which lists the performances in speed that are crucial to the OTH missions, along with results of a fuel consumption analysis and analysis of the time required to perform the missions described previously. Some ancillary aerodynamic data used to derive the final results are given in Table II.

4.4 RPV Mission Performance

Examination of Table I shows, as is to be expected, that the Delta and the small conventional aircraft with flaps have the highest dash and optimum cruise speeds, and that both of these performance capabilities decrease with increased aspect ratio in the case of conventional unflapped wings. The required cruise power varies in the reverse order.

The estimates of fuel required to perform the various missions have been based on an assumed specific fuel consumption (SFC) of 0.7 lb/hp.hr. This figure was measured to be about 0.68 lb/hp.hr on the McCulloch 101A engine used on the Aquila RPV (Ref. 6). Measurements at APL of the same quantity on a McCulloch 90A, a nearly identical engine of smaller displacement, gave values of about 0.75 lb/hp.hr. Both measurements were made at a mid-power setting, but detailed data are not available and the small effect of this variable has been ignored in the analysis. Errors in fuel estimates due to this omission need not be expected to be larger than about ± 5%. The results of the mission analysis are listed in the bottom portions of Table I.

Perhaps the most important thing to note about the estimated fuel required is that this quantity is not very sensitive to the type of configuration under consideration. All fuel requirements for the longer missions are within ± 10% of a nominal value of about 21.0 lbs. There are two cases, the Delta on Mission B', and the high-aspect-ratio RPV on mission C', for which the required amount of fuel exceeds the 22.5 lbs allotted, but these two exceptions are only about 1% over the limit, and can be ignored.

Looking for fine points, one can see that the high-aspect-ratio RPV offers a small advantage in the orbiting missions B and B', but it is the poorest choice for the mapping mission in windy conditions (C'). The Delta

TABLE I

RPV CONFIGURATION - PERFORMANCE VARIATIONS

Design Specifications

1. Engine 11 BHP
2. Gross Weight 150 lbs
3. V_s (Stall Speed) 43.1 mph
4. V_{mam} (Speed for Minimum Allowable Maneuverability, 1.15 V_s) 51.75 mph (45 knots)

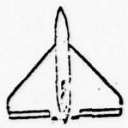
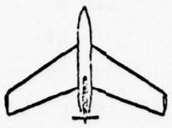
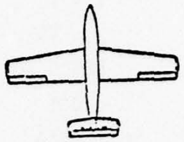
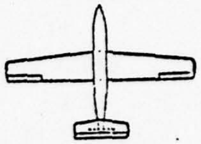
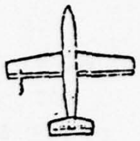
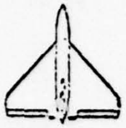
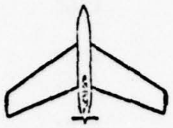
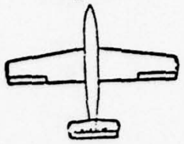
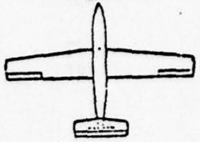
		Delta	Swept flying wing	Conventional wing-tail	Conventional wing-tail	Conventional wint-tail w/.20C flaps
						
Design Features	**Unit**					
Aspect Ratio		2.3	5	6	8	6
Wing Area required	(sq ft)	35.0	32.81	29.44	27.16	15.7
Span	(ft)	8.97	12.80	13.2	14.7	9.70
Optimum Cruise Speed	(mpn)	85.8	70.4	62.9	55.8	82.3
Required Cruise Power	(BHP)	4.30	2.97	2.61	2.05	3.41
Maximum Speed	(mph)	148	134	123	119	151
Fuel Required for						
Mission A	(lbs)	13.4	13.6	14.3	14.3	12.6
Mission B	(lbs)	22.4	19.7	19.9	18.6	19.9
Mission B′	(lbs)	22.7	20.3	20.44	19.2	20.0
Mission C	(lbs)	20.86	20.3	21.1	20.4	18.9
Mission C′	(lbs)	21.8	21.9	23.2	22.9	20.0
Time Required for						
Mission A	(hrs)	2.35	2.49	2.63	2.68	2.32
Mission B	(hrs)	5.35	5.49	5.63	5.68	5.32
Mission B′	(hrs)	5.39	5.55	5.69	5.75	5.36
Mission C	(hrs)	4.8	5.8	6.4	7.1	5.0
Mission C′	(hrs)	5.2	6.4	7.4	8.5	5.4

TABLE II

RPV CONFIGURATIONS - ANCILLARY DATA

(Used to Derive Table I)

	Unit	Delta 	Swept flying wing 	Conventional wing-tail 	Conventional wing-tail 	Conventional wing-tail w/0.20C flaps 
Tip Chord	ft	1.65	1.70	1.76	1.47	1.29
Root Chord	ft	6.15	3.41	2.64	2.20	1.94
Average Chord	ft	3.90	2.56	2.20	1.83	1.62
Span	ft	8.97	12.80	13.20	14.70	9.70
Aspect Ratio		2.3	5	6	8	.6
Reynolds No. at V_s		1.57×10^6	1.03×10^6	0.89×10^6	0.73×10^6	0.64×10^6
C_ℓ Max		0.90	0.96	1.07	1.16	2.0
C_{do}		0.012	0.016	0.022	0.026	0.024 (flaps
L/D Max		10	12	12	14	12
C_d at L/D Max		0.024	0.032	0.044	0.052	0.048
C_ℓ at L/D Max		0.24	0.38	0.53	0.73	0.58
Cruise Speed at L/D Max	mph	85.8	70.4	62.9	55.9	82.3
Parasite Max Dash Speed	mph	150	137	127	123	154
C_ℓ at Dash		0.076	0.094	0.12	0.14	0.16
L/D at Dash		6.3	5.9	5.6	5.3	6.6
Induced drag ΔV	mph	2	3	4	5	3
Max Dash Speed ($V_p - \Delta V$)	mph	148	134	123	119	151

is inferior to all other designs in the orbiting missions, but not in the mapping mission. The smaller, flapped-wing, conventional airplane would be the preferred choice if the estimated required fuel were to be the criterion for judgement of design excellence. This RPV uses less fuel than any of the other aircraft in any of the mapping (C and C') missions, and is only just perceptibly outperformed by the flying wing and by the high-aspect-ratio configuration in orbiting missions B and B'.

To sum up, all of the fuel consumption figures are very close to each other, and fall within the desired design-weight fraction. This quantity does not play a decisive role in choice of the optimum RPV.

The time required to perform a mission will be important in the envisioned operational scenarios. It will be seen from Table I that all configurations require about the same amount of time for the orbiting missions A, B, and B'. There are, however, notable deteriorations in comparison to the performance obtained with the Delta, which is fastest, in the cases of the high-aspect-ratio configurations executing mapping missions C and C'. These deficiencies are a reflection of the relatively low optimum cruising speeds of the latter vehicles. The flapped-wing version of a conventional airplane, because of its small size and correspondingly low drag in its clean condition (flaps up), is essentially equal in performance to that of the Delta, in both the orbiting and mapping missions.

The results of this comparison can be summed up by nearly the same statement as the one made about the fuel required. There are not strong driving deficiencies or advantages, and final choice of the optimum configuration can be made on the basis of factors other than the aerodynamic and propulsion performance that prevails during actual conduct of the downrange mission. Size of the assembled vehicle, storage volume, ruggedness and resistance to manhandling, for example, can be cited as the more pertinent factors in choice of a favorable design. Perhaps of more importance and benefit, maneuverability during recovery can be singled out as the cardinal decisive factor in acceptance of a workable design.

The small-sized, flapped-wing configuration has the best overall mission capability and is compatible with the utilitarian requirements of small storage space and ease of handling. As will become apparent in the next section, this configuration also has more potential for obtaining maximum control at V_{mam} than does the Delta, which would probably be the best second choice, primarily on the basis of its compactness and ruggedness.

4.5 Optimized-Design, Mini RPV for Hydrofoil OTH Systems

There is really only one practical recourse to resort to for improvement of the low-speed maneuverability of a Delta having any given wing loading; that is to increase the size and deflections of the control surfaces. There are upper limits, however, to what can be done in this direction, because modifications of this type result in an over-responsive aircraft at high speed, which in turn causes problems in achieving stable autopilot control during dash and cruise flight. These latter difficulties can be mitigated by using precision, high-speed servos, highly-engineered autopilots, and other expedients, but all of these fixes tend to be costly and sometimes troublesome from the reliability point of view. As alternatives to upgrading the maneuverability of the Delta, one could propose forward (canard) surfaces (which are not without peculiarities), retractable wing-tip flippers, leading-edge flaps or slots, and still other gadgets, but all of these modifications would reduce the ruggedness of the Delta, which constitutes its predominant advantage in recovery operations, and none of these upgrading aids would be quite as effective as what can be done to optimize the maneuverability of a conventional wing and tail configuration.

It can be predicted that high control effectiveness in roll and pitch will be the primary requirement for successful execution of a VRL onto a Hydrofoil platform. For some types of proposed recovery systems, an effective yaw control would also be essential. In addition, provision of a rapid method for adjusting air speed, without affecting the basic trim of the aircraft, would be helpful. This control would be used to compensate for changes in air speed associated with horizontal shear gusts encountered during a VRL. Responsive metering of the engine thrust via accurate throttle control might, at first glance, be considered for achieving this quick air-speed adjustment, but this method would require a very reproducible and rapid engine-throttle response which is difficult to achieve in practice.

Figure 19 is a three-view drawing of a mini RPV that incorporates some practical devices and methods for achieving maximum maneuverability in slow-speed flight. This RPV is basically the same as the small, flapped-wing RPV described in the earlier mission analyses. The following features have been added, with indication of the salient reason for their adoption here:

(a) A shroud is placed around the propeller. This shroud would not be expected to have a significant affect on mission-range performance because the drag of the shroud is expected to be nearly balanced out by an increase in thrust. One important function of the shroud is to prevent the propeller from tangling in nets or bumping into landing platforms.

(b) The second function of the shroud is to provide a mount for a movable rudder located in the high-energy, propeller blast. Rather than being submerged within the shroud, the rudder is shown to be mounted on an extension, so that its effect on propeller efficiency during cruise and dash will be minimal. In this outboard location, the rudder can be expected besides to provide larger yaw moments than a rudder positioned inside the shroud. The effectiveness of such control surfaces has been demonstrated and is documented (Ref. 29). The rudder and its supports are intended to be made frangible, and they have to be replaced as necessary, but ample strength could be retained in the shroud design to withstand landing impacts.

(c) Drag brakes, consisting of flaps pivoting out of the sides of the fuselage just in front of the propeller shroud, can be used to make rapid adjustments in air speed. Due to their location in front of the shroud, the drag plates are expected to have extra effectiveness, above that associated with their simple drag area, because they choke off some of the flow into the propeller. In the intended normal flight procedure the throttle is set to provide sufficient thrust for a level-flight airspeed somewhat above V_{mam} while the drag brakes are retracted. It is intended that drag plates be manipulated to hold the aircraft on a fixed approach line, as the

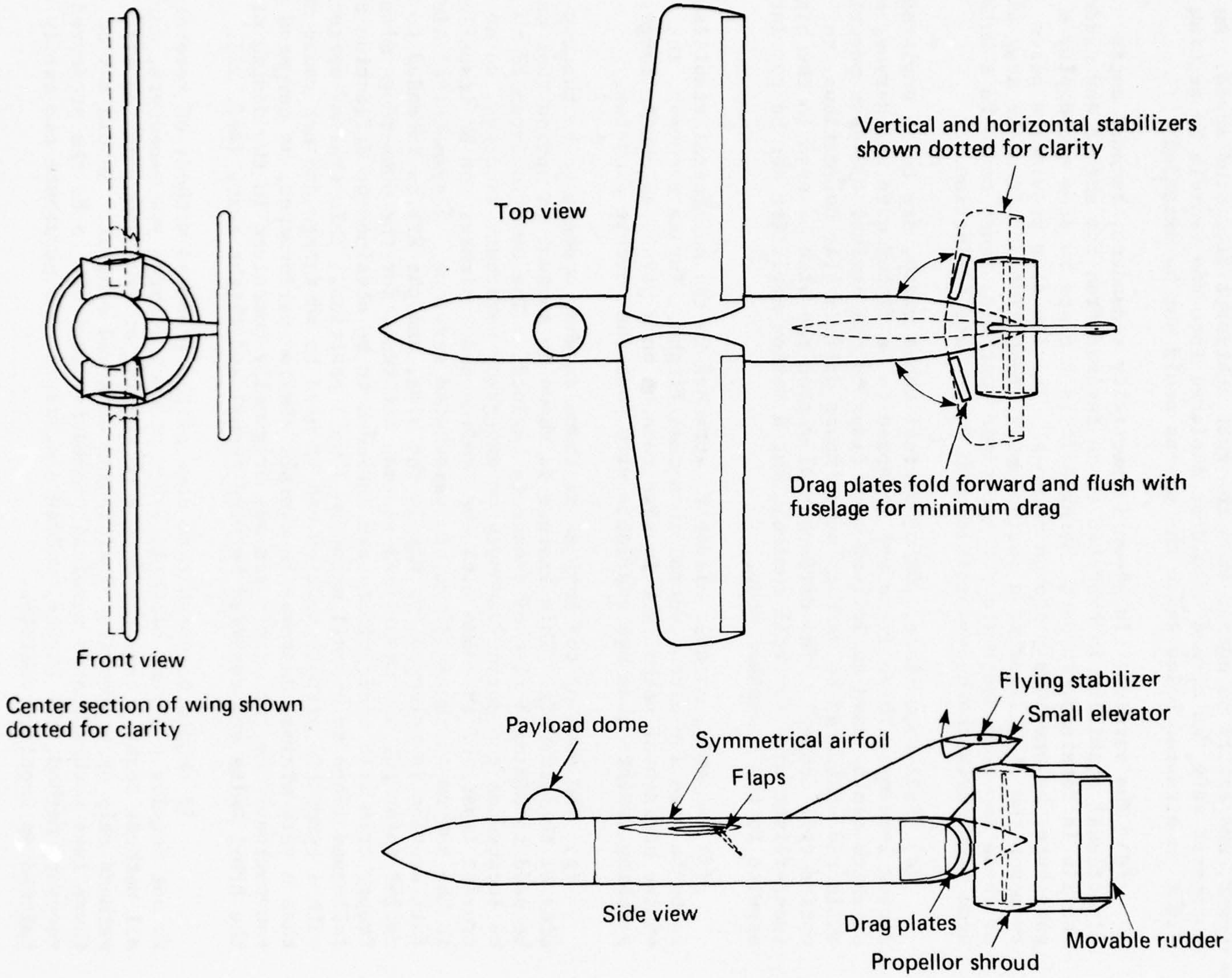


Fig. 19 Mini RPV Optimized for Maneuverability During Recovery

RPV descends in VRL, in the presence of horizontal gusts. That is, the plates are to be closed to overcome a gust deviation upward of nominal wind speed, and are to be opened when the gust subtracts from wind speed. An automatic safe "go around" could be designed into the vehicle by setting a limit on airspeed below which the plates could not be extended.

(d) The vertical fin shown is partially redundant, because ample directional stability is expected to be derived from the shroud and rudder. The fin is retained, in part, because it is a place to stow and deploy a parachute, by previously proven methods. The fin also provides a place to mount the stabilizer at a sufficiently great distance from the drag plates. If these two components are put too close together, there could be a bothersome pitch-trim change associated with drag-plate deflection.

(e) Full-span flaps, 20% of airfoil chord width, are to be employed during landing. These flaps are intended to be fitted with two servos, one of which can be used to deflect both flaps to the nominal 45°-down position, while the other can be used to superimpose differential deflections, to obtain roll control. The differential motion can also be used in the high-speed-flight mode for roll control, but a motion amplifier can be put into service in the low-speed mode.

(f) A small, movable elevator, attached to the horizontal stabilizer, is to be used for pitch control in normal flight. During recovery, the entire horizontal stabilizer is also rotated on a pivot, to obtain larger pitching moments than are available with just the movable elevator.

(g) The dome of the payload is shown on what appears to be the top side of the aircraft. This feature is shown to suggest an option that can be used to minimize risk of damage to payloads. The dome is intended to be located on top during recovery or emergency parachute landings, so as to prevent impact of the dome with the landing pad. Airbags can be installed in the bottom of the fuselage, in parachuted versions. A symmetrical airfoil section is selected for use in the wing, and the RPV is intended to be rolled inverted, and stabilized in that attitude, for the down-range mission. Proper trim lift coefficients are intended to be obtained by deflecting the full-span flaps to a small negative ("up") position. This type of operation with a symmetric airfoil section can be used to advantage and not cause more than a very minimal decrease in overall mission performance, as compared to conventional designs. The idea was originally conceived in the design of the RPD-1 Delta and verified by wind tunnel and flight tests (Ref. 28).

It should be noted that some of the proposed methods of recovery do not require a strong capability for producing large yaw maneuvers, nor do all methods require that the engine be running at touchdown, nor do all methods rely upon precision positioning or speed control. Should any of these less sophisticated terminal procedures turn out to be the preferred recovery method, the shroud, rudder, dragbrakes, and parachute can easily be omitted on tactical vehicles.

5.0 RPV LAUNCH AND RECOVERY

In this section of the report, some conceptual methods for launch from and recovery of mini RPV's on Hydrofoils will be described. An attempt will be made to identify possible deficiencies and critical technical problems that should be explored to verify the feasibility of each of the proposed recovery methods.

5.1 Installation of Launch Equipment

A variety of launch methods have been successfully demonstrated in previous land-based RPV tests. Pneumatic launchers, such as shown in Fig. 20, have been found most practical. Engineering principles involved in the design of such launchers are well understood (Ref. 30) and, if it is deemed desirable to be able to launch RPV's from a Hydrofoil when it is at a standstill, a pneumatic launcher can be provided for this sort of exercise. The length of such launchers is dictated by the maximum allowable acceleration of the RPV. Allowable limits on acceleration are typically set by limitations on components of the payloads rather than by consideration of the airframe structural integrity, and, therefore, launchers of the size shown in Fig. 20 are required for a standstill launch, unless a special effort is made to harden the payload.

The launch of an RPV can be greatly simplified, however, by exploiting the high-speed capability of the Hydrofoil. Even if the RPV has a V_{mam} that is 20 to 30 mph above Hydrofoil speed, a relatively short pneumatic launcher would suffice to achieve flight speed. An RPV designed to have V_{mam} equal to or less than Hydrofoil speed could be launched in a still simpler manner, similar to dropping of stores or RPV's from aircraft. For such cases no acceleration prior to release is needed.

A schematic diagram is given as Fig. 21 of a launching boom, shown as it might be installed on Highpoint. This figure also shows two locations that are considered favorable for the installation of landing nets, which will be discussed subsequently. A launch system is shown on the port side, just aft of the pilot house. The RPV is attached to a boom which allows the RPV to be swung, from a servicing position on the main deck, out over the side to the launching position. At the outer end of the boom, the mounting rail for the RPV is fitted with a horizontal swivel that can be locked during servicing, but which is freed, to allow the RPV to weathercock with the relative wind, when it is extended out over the side. The RPV in its launch position then is at about 25 feet altitude, headed directly into the relative wind. The RPV could be located above or below the boom and allowed to climb off the launcher or drop away. In Fig. 21, it is suggested that it will be dropped like a store from a rail underneath the swivel. Final choice would be based on mechanical and safety considerations. Strain gauges on the launching rail can be monitored, to make certain that excess thrust over drag is being delivered by the engine for a clean flyaway.

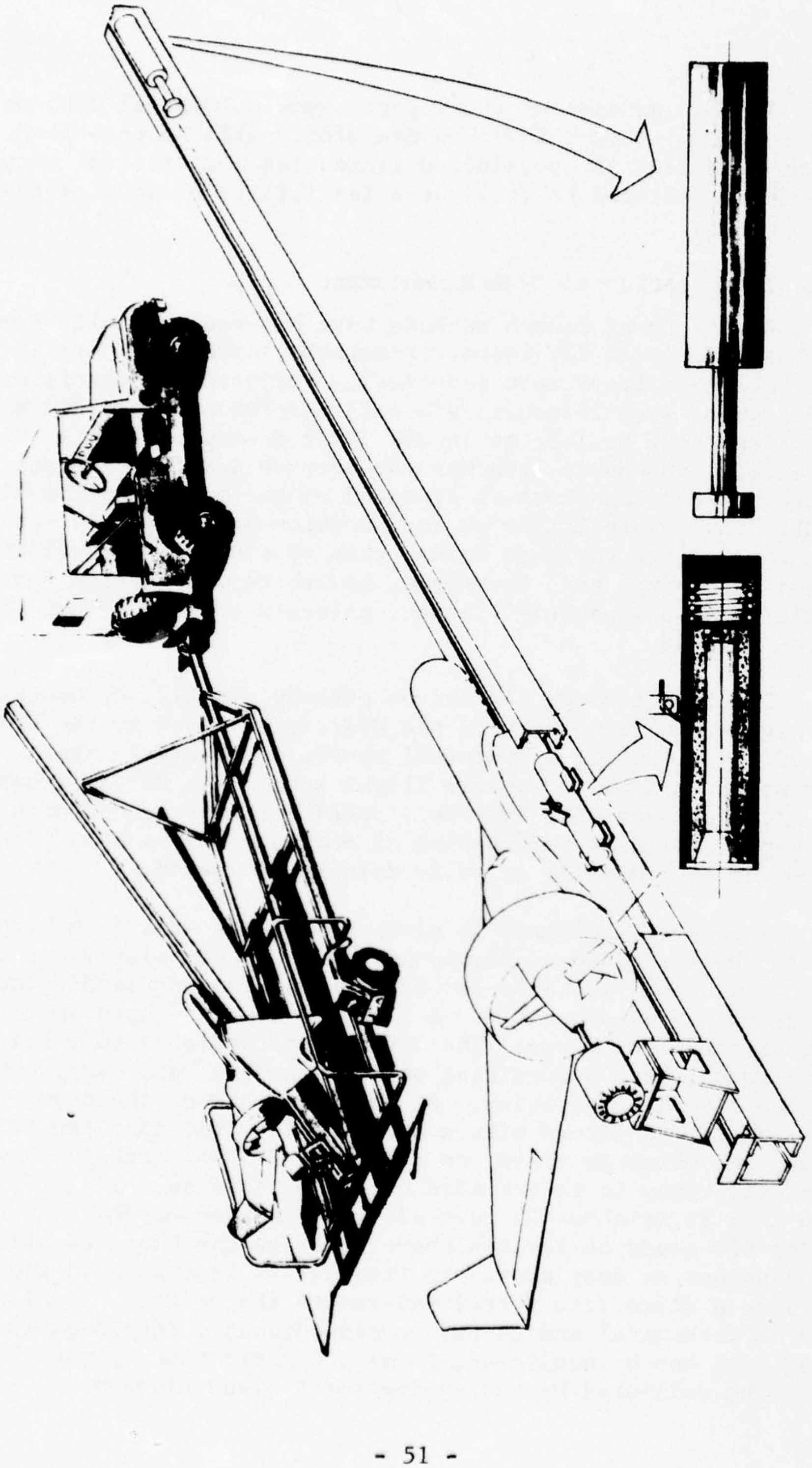


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Fig. 20 Pneumatic Launcher

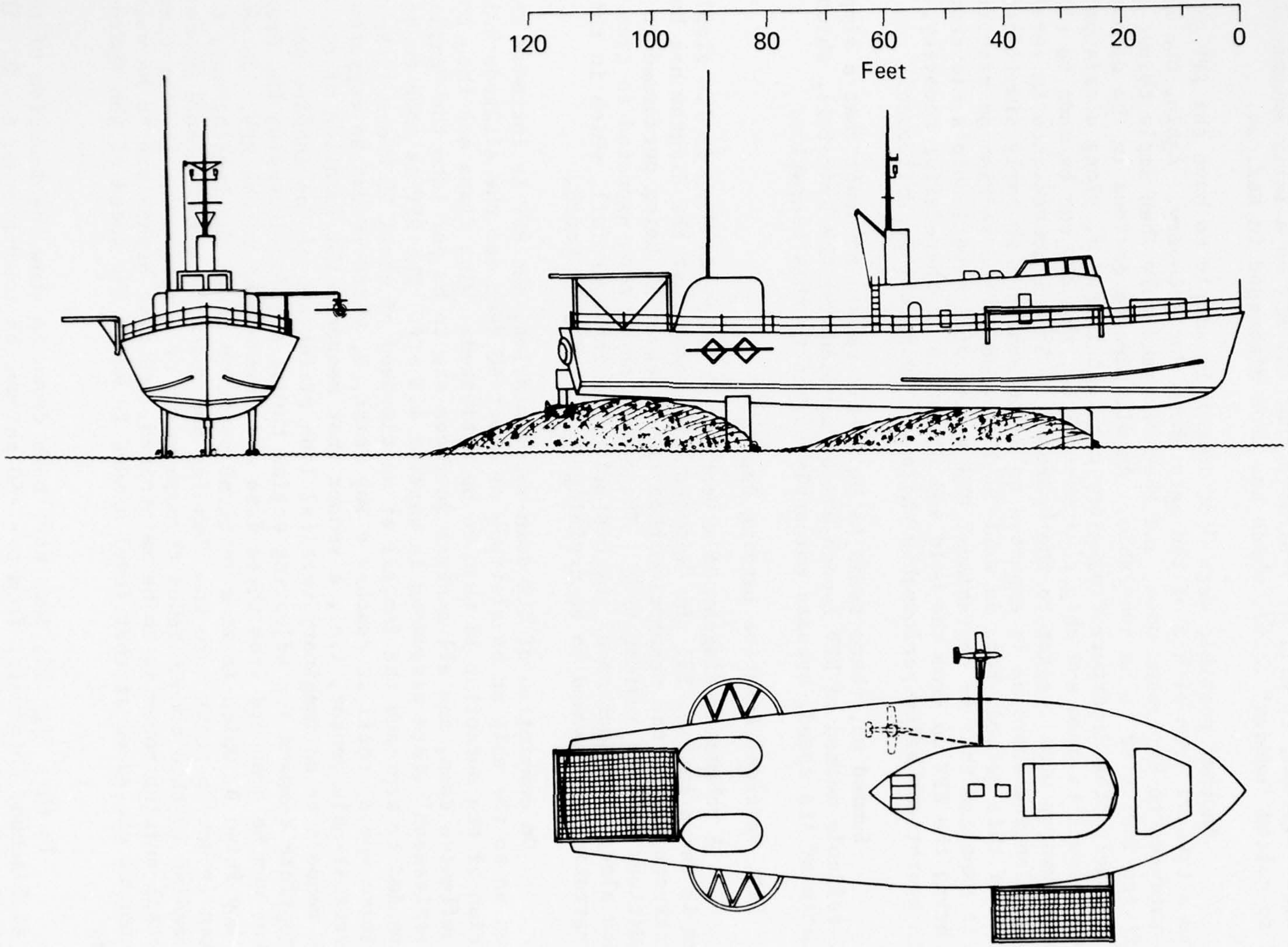


Fig. 21 RPV Launch and Recovery Equipment on PCH Highpoint

In early tests of the concept, servicing, engine starting, and transport of the RPV over the side could be carried out with the Hydrofoil in the hullborne mode, so that winds and handling problems would be minimal. In later systems, it will be desirable that the RPV be a fully automated, or so called "wooden" round, which has been discussed in Ref. 24.

Another possible method of launch is simply to have the RPV perform a takeoff from either of the nets shown for recovery. Again, the RPV is intended to be locked down, and then released only when ample thrust and lift are indicated to be available. As will become obvious in the discussion of recovery, the departure trajectory can lean rearward, along a safe path with respect to crew and ship equipment, i.e., the RPV can be made to climb out backwards with respect to the Hydrofoil. Some inconvenience in servicing and engine starting is expected to be encountered in early simplified tests of this method, but, as will be discussed in the section on recovery, it is expected that an operational OTH system will have a ship's elevator to bring the RPV up from the hold and to return it there after recovery, both operations being performable while the Hydrofoil is foilborne.

Summed up, there seems to be little reason to doubt that a simple and reliable method of RPV launch can be devised for the Hydrofoil, which because of its speed, appears eminently suited to this operation.

5.2 Vertical Relative Landing Recovery

A schematic diagram of a Vertical Relative Landing in its simplest form is shown in Fig. 22. By "simplest" is meant that the diagram has been constructed using the assumption that the maneuver is being performed in conditions of zero ambient wind. The operation is then expected to take place along a projection of the centerline of the Hydrofoil, which in this illustration is assumed to be cruising at a steady 45 knots.

On completion of its down-range mission, the RPV is intended to be flown up to the ship at an altitude of about 60 feet and the altitude-hold portion of the autopilot is then to be activated. Wing flaps are then to be deflected down, and all control surfaces are to be put into the "amplified effectiveness" state discussed in section 4.5 e,f. The RPV is then to be commanded to approach the fantail at an airspeed of about 50 knots (5 knots relative speed) until it reaches a Way Point, B, where it can be captured by a vertical-hold sensor, i.e., a sensor that measures the location of the RPV with respect to an imaginary vertical line rising out of the landing net. Appropriate command for adjusting engine thrust and for extending the drag brakes can be computed from these data and transmitted to the RPV. On reaching Way Point B, which is at a vertical position above the landing net, the system is set to start into the "landing and recovery mode." Final descent to landing is then accomplished through means of a mild down-elevator command. Constant surplus power is to be maintained, and drag brakes are to be used to control air speed at that level needed to match the speed of the Hydrofoil.

In this Fig. 22, dots have been drawn to show the location of the RPV at 5 second intervals, from t = -60 seconds to touchdown at t = 0. The final descent rate is shown here to be 1 foot per second. Touchdown on a

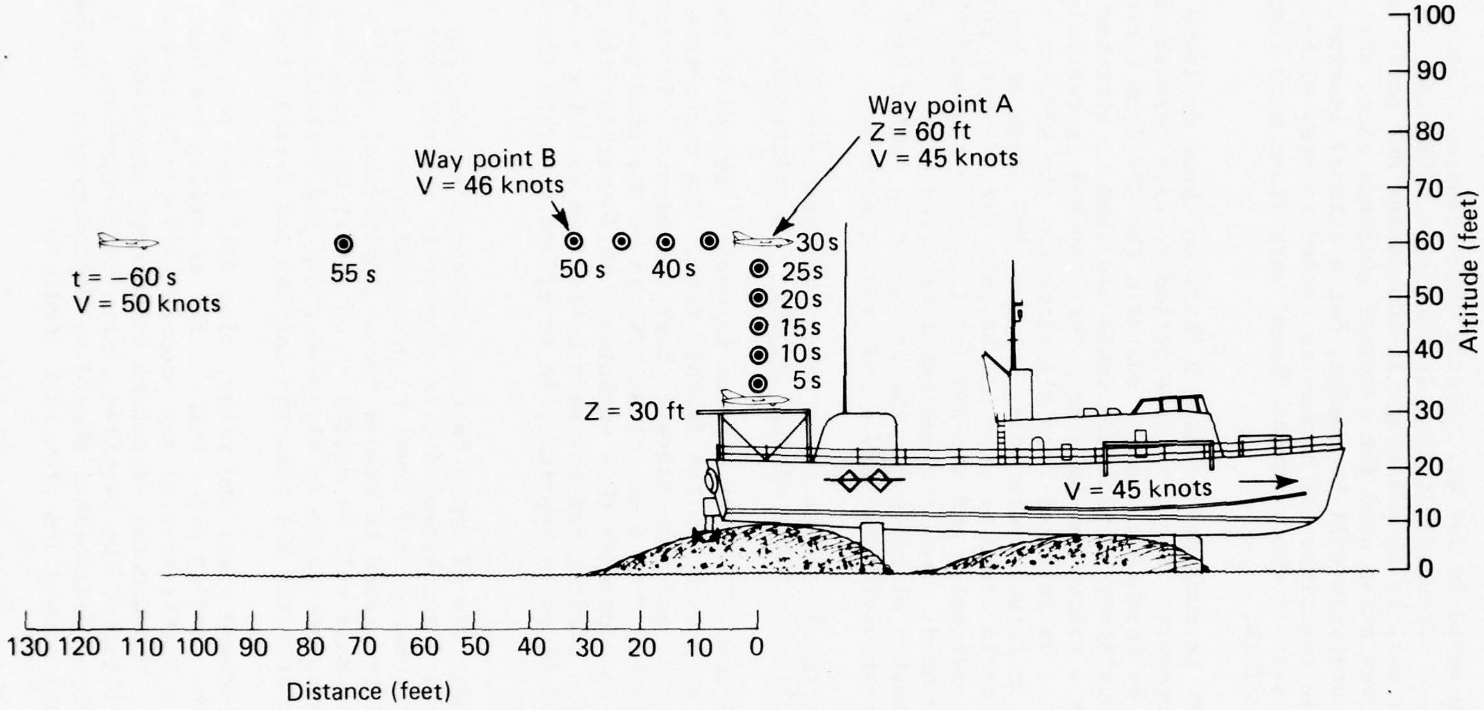


Fig. 22 Approach Trajectory for Vertical Relative Landing in Conditions of No Ambient Wind

net at this slow speed is far more gentle than required. Some benefits of faster descent are discussed later. It should be noted that the stable ride of the Hydrofoil will be an advantage in the design and performance of distance measuring equipment used for terminal guidance along this short descent path. Detailed analysis will be needed, but a cursory examination indicates that an RPV could negotiate the maneuvers needed to stay within allowable error distances even if the vertical "beam" were fixed with respect to the axes of the Hydrofoil.

The RPV is intended to have a "harpoon" hook deployed out of its bottom during recovery. The hook is expected to pass through the mesh of the landing net on touchdown, and so restrain the RPV from taking off inadvertently. An auxiliary restraining cable can then be attached from underneath the net by a remote manipulator. Once the RPV is restrained by this cable, the net can be released from all sides and the RPV can be lowered to the main deck. On future Hydrofoils, where an RPV elevator has been suggested, the restraining cable could be expected to pull the RPV onto the center of the elevator automatically and the RPV (still within the net) then would be lowered into the hold. Handling equipment (or crew) could then remove the RPV from the elevator platform and the net would be pulled back up and readied to retrieve additional RPV's that may be airborne.

The critical uncertainties about this proposed concept have been mentioned in earlier sections of this report. To reiterate, they are:

(a) Turbulence, of as yet unknown intensity, caused by the ship superstructure, will be present in the fantail area. The turbulence will have rotational, lateral, and fore-and-aft shear components. It cannot be predicted with certainty that a practical RPV can be designed to have adequate maneuverability to cope with this turbulence while maintaining the desired descent path. The landing pad has been postulated as being elevated to the top of the Hydrofoil pylon housings, in an effort to avoid the most intense areas of turbulence.

(b) In conditions of gusts in the fore-and-aft direction, the RPV will tend to move forward and backward with respect to the vertical line, if its airspeed is kept constant and equal to Hydrofoil speed. Rapid adjustments in airspeed will be needed to remove these longitudinal oscillations. Further analyses and test data will be needed to show that the proposed speed brakes can provide an adequate range in airspeed and a sufficiently rapid accelerative control to keep the RPV over the landing pad during final descent.

(c) The sideward gusts and rotary flow will tend to blow the RPV off to the side of the landing pad. Methods for achieving the best possible lateral-control effectiveness of any proposed RPV can be devised and tested in wind tunnels. Measurement of actual turbulence experienced on the Hydrofoil is needed to define the required control effectiveness. A reasonably secure assessment of feasibility should be forthcoming on the basis of the combined information obtained from such studies.

(d) The RPV design shown here is based on an expectation that a lift coefficient of 2.0 can be steadily achieved with the proposed high-lift devices while those devices are concomitantly being used to provide roll control. This expectation should be verified in wind tunnel tests and through checkout flight tests made in gusts. The RPV will have to be made correspondingly larger to decrease wing loading, if this value of lift coefficient cannot be reliably obtained in gusty conditions.

Some features of this proposed concept that make it attractive are the following:

(a) The system is compatible with concepts for storage and handling of RPV's on advanced-concept Hydrofoils.

(b) The operation can be considered a safe one with regard to ship's crew or equipment. The design intent has been to provide for an inherently safe "go around." The aircraft is expected to be flying under normal conditions with excess thrust and with partially extended drag brakes, at an airspeed safely above stall. Retraction of the drag brakes and application of some up-elevator command will result in a climb and in an airspeed reduction that will cause the RPV to rise back over the transom. A system for aborted landings could be devised to be automatically activated at an air speed that is below V_{mam} but which is nonetheless safely above stall speed. Then, if a tail-on gust of large magnitude occurs during the landing phase, the vehicle would automatically go around. Correspondingly, limits could be imposed on the allowable lateral-position errors.

(c) Neither vertical heave motions of the ship nor deviations of the vertical descent rate of the RPV are expected to affect the accuracy of homing on the landing pad. (Variations in descent rate in gusts present one of the most difficult problems to systems in which the RPV makes a horizontal approach to a vertical net (Ref. 6).

(d) In principle, the VRL approach can be made directly into the wind, regardless of the direction of relative wind with respect to the ship, so long as the relative wind exceeds V_{mam}. This desirable feature removes any requirements for the RPV to be able to maintain large average yaw angles during terminal guidance.

(e) There is a possibility that this system can be made more reliable in gusty winds than in dead calm. The reasoning behind this statement is that the amount of gustiness is basically related to ambient wind speed. In the presence of ambient wind, the Hydrofoil heading can be adjusted to superimpose the wind speed onto the 45 knots of Hydrofoil speed. This effective increase in wind speed allows RPV approaches to be conducted at air speeds well above V_{mam}. Basic control response of the aircraft is expected to improve to a greater degree than the increased level of response that is required to counteract the turbulence.

5.3 Landings at Maximum Descent Speed and along Non-Vertical Trajectories.

A typical bird's feather free-falls at a velocity of about 1 foot per second. Impact of an RPV into a horizontal net at this speed would be a gentle event. An impact at 5 feet per second onto a horizontal net would be entirely acceptable, because even a small deflection in the net of 4 inches would prevent impact loads from exceeding 0.1 g. Obviously therefore, a descent speed of 5 ft/sec is not the maximum allowable. In addition, the net also is capable of absorbing some forward momentum. These two favorable characteristics of the net landing prompt one to inquire as to what advantages might be derived by using higher descent speeds and non-vertical descent paths.

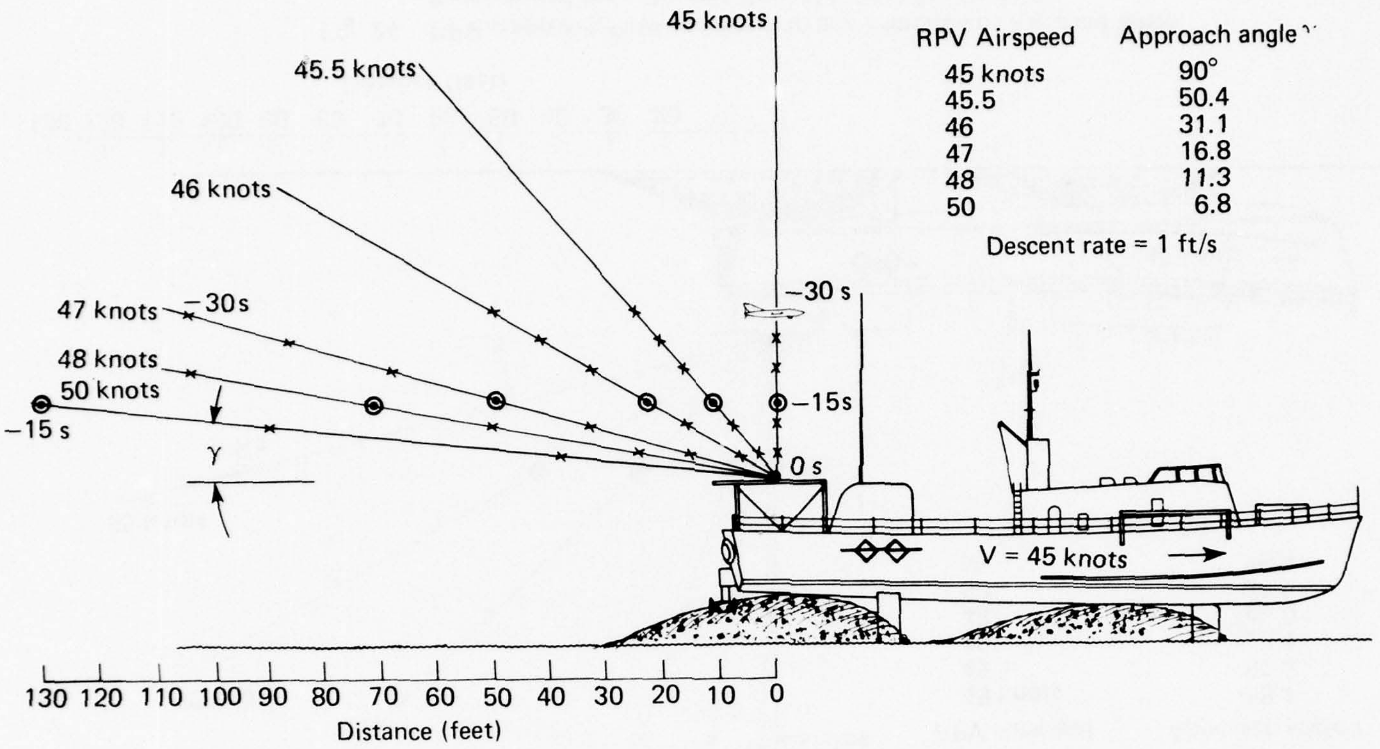
It can easily be appreciated that it would not be sensible to prolong the descent from Way Point A (Fig. 22) any longer than necessary, inasmuch as this delay would only increase the probability of arrival of a large gust disturbance during the landing. Possible benefits of a non-vertical descent are perhaps less obvious, but, in a simple sense, one can realize that if the RPV is to overtake the Hydrofoil during descent, it would have to have an excess velocity increment above that needed for vertical descent. This excess speed would contribute towards improved control response of the RPV and possibly would provide improved accuracy in homing on the net.

The benefits of both of the aforementioned variables will become evident from study of Figs. 23 and 24. These figures show the descent trajectories relative to the Hydrofoil that would result at different RPV air speeds when the descent rate is restrained to 1 ft/sec (Fig. 23) and 5 ft/sec (Fig. 24). The"x" points on the figure mark the location of the RPV on each trajectory at 5 second intervals. The large circles on Fig. 23 show where the RPV would be on each trajectory at t = -15 seconds.

The vertical descent trajectory of Fig. 23 is the same as that shown in the preceding Fig. 22. Figure 23 shows that at 1 ft/sec descent, the approach trajectory angle is quite sensitive to excess air speed. An excess air speed of 0.5 knot would tilt the required approach trajectory rearward to an angle of about 50° with respect to horizontal. At 50 knots air speed, or 5 knots differential, the approach angle would be only 6.8°.

In the vertical approach, fore-and-aft horizontal drift of the RPV due to airspeed-and-gust mismatch would be the dominant source of longitudinal miss-distance errors. In the flatter trajectories, altitude errors would predominate. There appears to be some approach path near 45° that would be optimum, but the precise angle would be influenced by how well the speed brakes work in comparison to the control response of the vehicle in pitch.

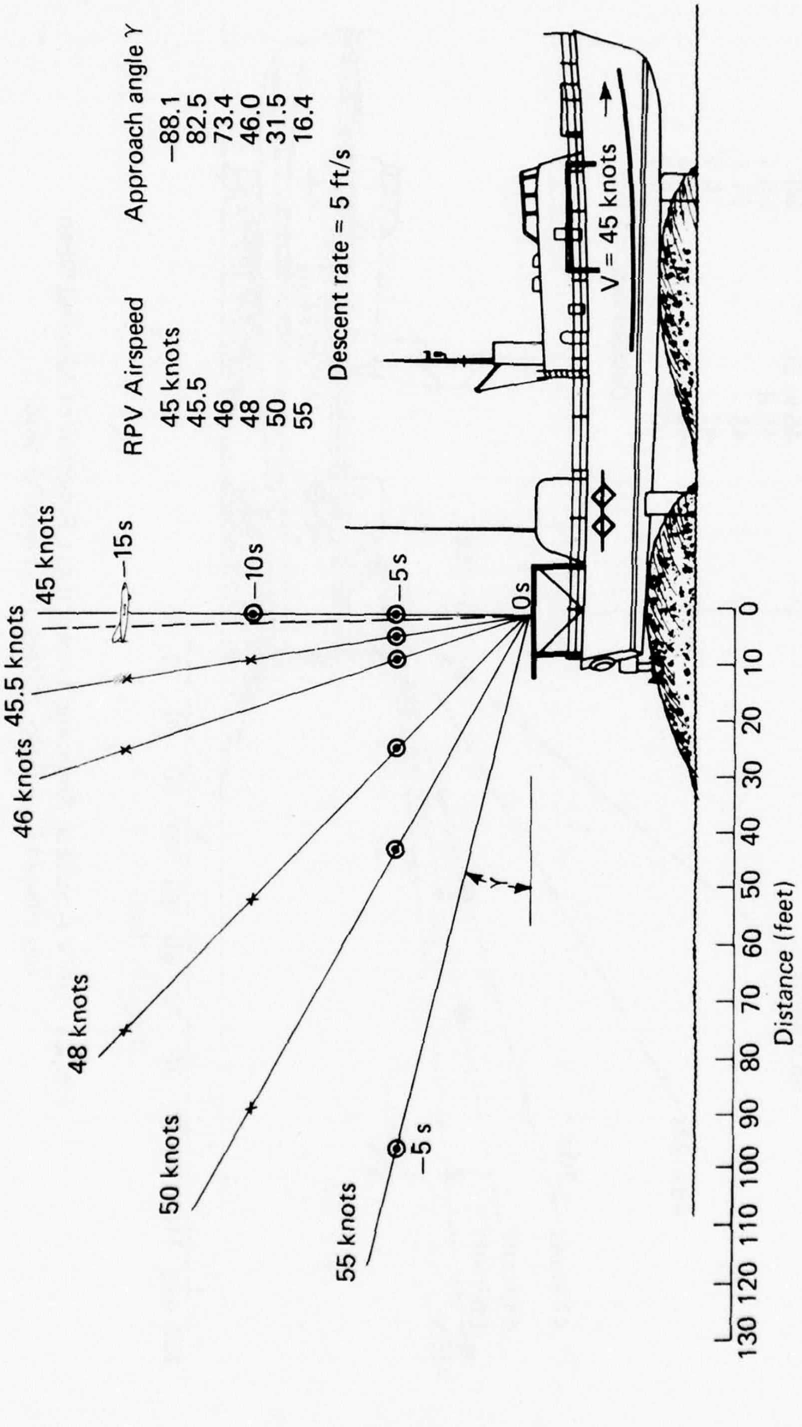
In case the faster descent rate of 5 ft/sec is used, Fig. 24, it will be seen that the effect of speed differential is substantially less than for the slow descent rate. A 3-knot differential (48 knots RPV air speed) tilts the approach angle about the same amount as a 0.5-knot differential at 1 ft/sec descent. Summed up, in terms of maneuverability during landing, these two figures suggest that an increase in air speed of 3 knots (an increase of 13% in dynamic pressure and, thus, an increase of 13% in control effectiveness) can be obtained (at near optimum approach angles) by the expedient of allowing the RPV to descend at a rate of 5 ft/sec instead of 1 ft/sec. Still more control effectiveness and less exposure to gusts could be obtained using faster descent rates.



RPV Airspeed	Approach angle γ
45 knots	90°
45.5	50.4
46	31.1
47	16.8
48	11.3
50	6.8

Descent rate = 1 ft/s

Fig. 23 RPV Approach Angle and Location as a Function of Airspeed When Programmed for a Descent Rate of 1 Foot Per Second



RPV Airspeed	Approach angle γ
45 knots	−88.1
45.5	82.5
46	73.4
48	46.0
50	31.5
55	16.4

Descent rate = 5 ft/s

Fig. 24 **RPV Approach Path and Position as a Function of Airspeed When Programmed for a Descent Rate of 5 Feet Per Second**

Other information, such as estimates about drift speeds and miss-distance due to gust pulses, can be derived from plots of the type shown in Figs. 23 and 24, but it would be of questionable value to pursue this facet of the investigation further, without detailed knowledge of the RPV characteristics. It appears, too, that the best orientation of the net for achieving minimum miss-distance would be at an angle normal to the optimum approach path. This slewing of the net may be a rather cumbersome arrangement, however, that would conflict with the concept of being able to lower the RPV into the hold of the Hydrofoil. Inasmuch as most of the envisioned optimization changes would produce only second-order improvements in homing accuracy, it is recommended that the simple horizontal net and vertical approach be pursued in any early efforts to demonstrate recovery by this method.

There has been a small amount of testing done by APL personnel that is relevant to the concepts discussed above. In 1974 we received an inquiry about the feasibility of RPV recovery on Hydrofoils (Ref. 31). Exploratory tests of the Vertical Relative Landing concept were performed on a runway at Beltsville Agricultural Center, using a truck and a typical, radio-controlled, aerobatic model. The model weighed about 7 lbs, had a wing loading of about 1.5 lbs/sq ft, and had faster control response than can be expected of a mini RPV. The model was fitted with a throttle, but not with flaps or speed brakes. The pilot and crew rode on the bed of the flat truck and practiced flying in formation with the truck as it moved along the runway at about 35 mph, which was not much above the stall speed of the model. Numerous touch and go landings were made on the runway alongside the truck; most touched down within a selected area the size of the truck bed (about 10 ft x 10 ft, located about 15 ft aside of the truck). "Hovering" flight directly over the cab of the truck was also found to be relatively easy to accomplish. Except for the hazards of being cut by the propeller, a crewman could probably have reached up and retrieved the model by gripping the landing gear.

Other experience was logged by the author of this report during development of an R.C. model that was used to establish a world record for distance. The flight was done using a convertible automobile to transport the pilot from near Buffalo, N.Y., to near Albany, N.Y., on the New York State Thruway, as the model flew overhead. During test flights, the model was often brought down to within 20 feet of the convertible in a "hovering" mode, so that performance of the engine could be audibly checked.

It must be recognized that there are major technical differences between model airplanes and mini RPV's and that mistakes can be made by banking upon unwarranted extrapolations of model-airplane technology. Nevertheless, the experiences reported above have a modicum of validity for this application in that they essentially prove that if adequate maneuverability can be achieved, the concept of a vertical relative landing is attainable in practice.

5.4 Alternative Recovery Methods.

In the event that ship turbulence in the fantail area is found to be intolerable, vertical relative landings, as discussed above, might be performed on a net located alongside the pilot house, as shown in Fig. 21.

All principles of guidance and control would be the same. There would be no easy way, however, to bring the RPV aboard and get it into a storage area without forcing the Hydrofoil to go hullborne and having a crew carry the RPV to a storage area. One might devise a manipulating arm to lift the RPV aboard while the Hydrofoil is still foilborne. Such a manipulator arm is suggested in Fig. 25, which shows a possible alternative method for recovery. Here it is suggested that the RPV would fly alongside the Hydrofoil at slow relative speed, a "harpoon" hook on the nose would pass through the net, the RPV engine would be shut down and equivalent thrust would subsequently be supplied by the Hydrofoil, through the net attachment. The RPV would be assumed to be flyable in a stable autopilot mode and to be able to support its own weight, until the manipulator hand grasps the RPV. The only real virtue of this system is that it does not impose requirements for rapid adjustment of air speed.

5.5 Fly-Around Winch Retrieval of RPV's

Figure 26, taken from Ref. 32, shows a concept for recovery of an RPV onboard a D.E. class vessel, wherein a steerable aerobody (or "fish") is lowered on a cable from the RPV and is captured in a V-shaped set of booms extending rearward from the fantail. When the aerobody reaches the apex of the booms, the cable is transferred to a winch on the fantail. Special harness arrangements at the RPV-end of the cable are proposed in Ref. 32 to cause an abrupt pitch-up moment when the aerobody is engaged at the ship. The RPV then performs a 360° turn maneuver, the cable being simultaneously reeled in during the turn, but the cable need not be kept taught during the turn. After some 16 seconds, the RPV arrives down wind of the D.E. at a location where the tow cable becomes taught. A kite-type harness attached to the RPV is used to generate high angles of attack. Roll commands to the RPV keep it level while it is being reeled into a landing pad on the fantail. Rapid winching-in of the cable could be used to increase the airspeed of the RPV above the speed of the Destroyer Escort vessel.

Similar sketches for recovery on a Hydrofoil were included in the referenced document. In the case of the Hydrofoil the crossover turn maneuver, to convert to kite-type flight dynamics, was replaced by a simple backward (relative) flight path at constant altitude. As a result, a substantially shorter cable can be used with the Hydrofoil installation.

Some of the deficiencies of this concept are:

(a) A cable of sufficient strength and length for the cross-over maneuver weighs about 10 lbs, and an equally heavy aerobody is needed, else the cable takes a much shallower catenary shape than the one shown. The shorter system suitable for the Hydrofoil probably has a weight of at least 10 lbs.

(b) The RPV has to be flown at a precisely controlled altitude, to have the aerobody properly located so as to engage the capture booms.

(c) Oscillations in the catenary shape can be expected to cause intolerable altitude changes and lateral shifts of the aerobody, unless it is fitted with active pitch and yaw controls.

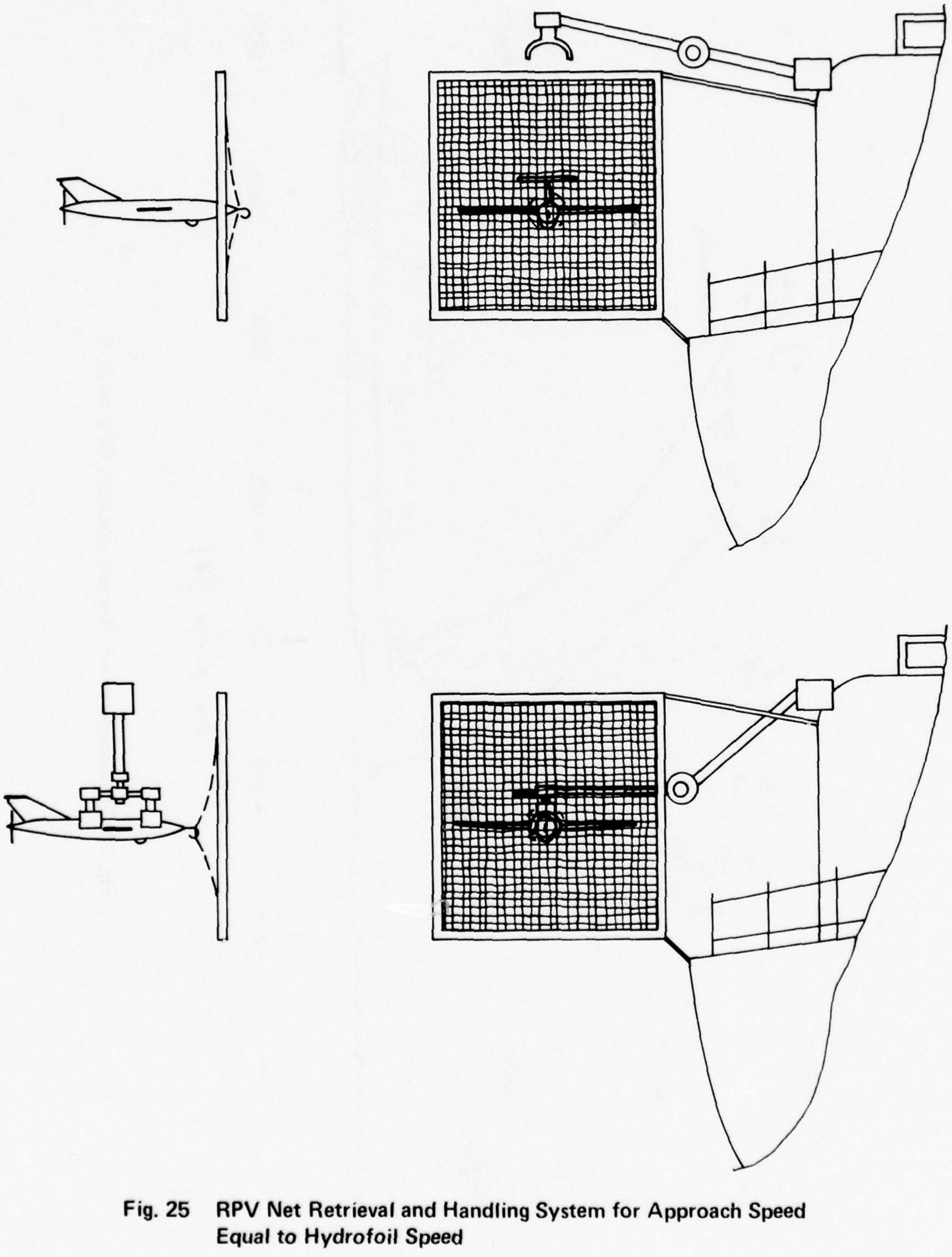


Fig. 25 RPV Net Retrieval and Handling System for Approach Speed Equal to Hydrofoil Speed

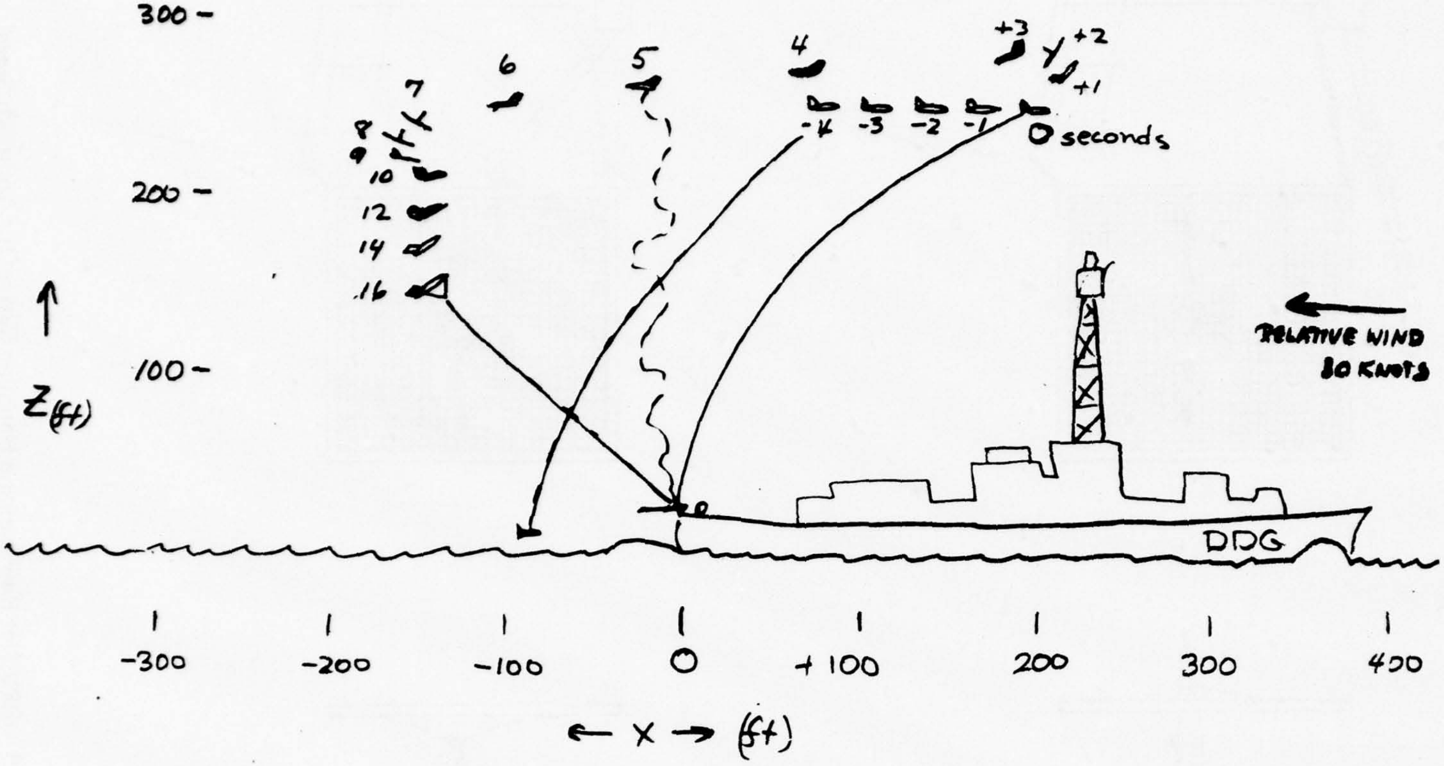


Fig. 26 Fly-Around Winch Recovery of Mini RPV on D. E.

Some attractive features of the concept are:

(a) There is little hazard that the RPV will crash into the ship.

(b) Ship turbulence is not a problem, and the effects of ambient meteorological turbulence are minimal.

(c) The RPV does not have to perform precision maneuvers during terminal guidance, because the recovery path is established by the aerobody.

(d) There is no need for a highly precise air-speed control.

(e) The landing pad can be small.

A modification of this concept which appears entirely workable is shown in Fig. 27. Here it is proposed that a kite or parafoil be flown on a strong cable above the Hydrofoil. A V-shaped capture guide, that is stowed along the fuselage sides during the RPV mission, is intended to be extended forward of the nose of the RPV. The RPV is flown towards the kite cable, at slow relative speed, on a path that eventually brings a hook on the nose into engagement with the cable. Thrust on the engine is then decreased and up-elevator is commanded. The RPV then slides backwards on the line, losing some altitude in the process. Well before the RPV drops to the water surface, however, the nose hook exerts tension on a release device (similar to an air-hose connector) that releases the parafoil. Simultaneiously, the reaction force on the nose hook causes the hook to relocate in a position such that the kite-line tension is applied at a point near the center of gravity of the RPV. The engine is then shut down completely, an additional up-elevator command is given to generate high angles of attack, and the roll and yaw controls are used to stabilize the aircraft as it is slowly winched down onto the landing pad. This latter portion of the operation is similar to winch launching of man-carrying soaring gliders, which is widely practiced in Europe.

Problem areas are:

(a) Precision guidance on the lateral course prior to line engagement is needed, because of the relatively narrow permissible entry-gate width.

(b) Lateral oscillations of the kite may create difficulties in engagement. A very stable kite appears to be needed.

(c) Acute RPV oscillations may be set up when the cable length becomes very short and the RPV is immersed in ship turbulence.

(d) Metal parts on the nose cone may interfere with radar seekers or other equipment in the payload.

This system has all of the attractive features of the previously described catenary-cable system. In addition, this system appears to be tolerant of broad variations in RPV approach altitude and is essentially unaffected by ship motions or by variations in the relative-wind direction. It is estimated that the installed weight of the additional equipment needed on the RPV comes to less than 2 lbs.

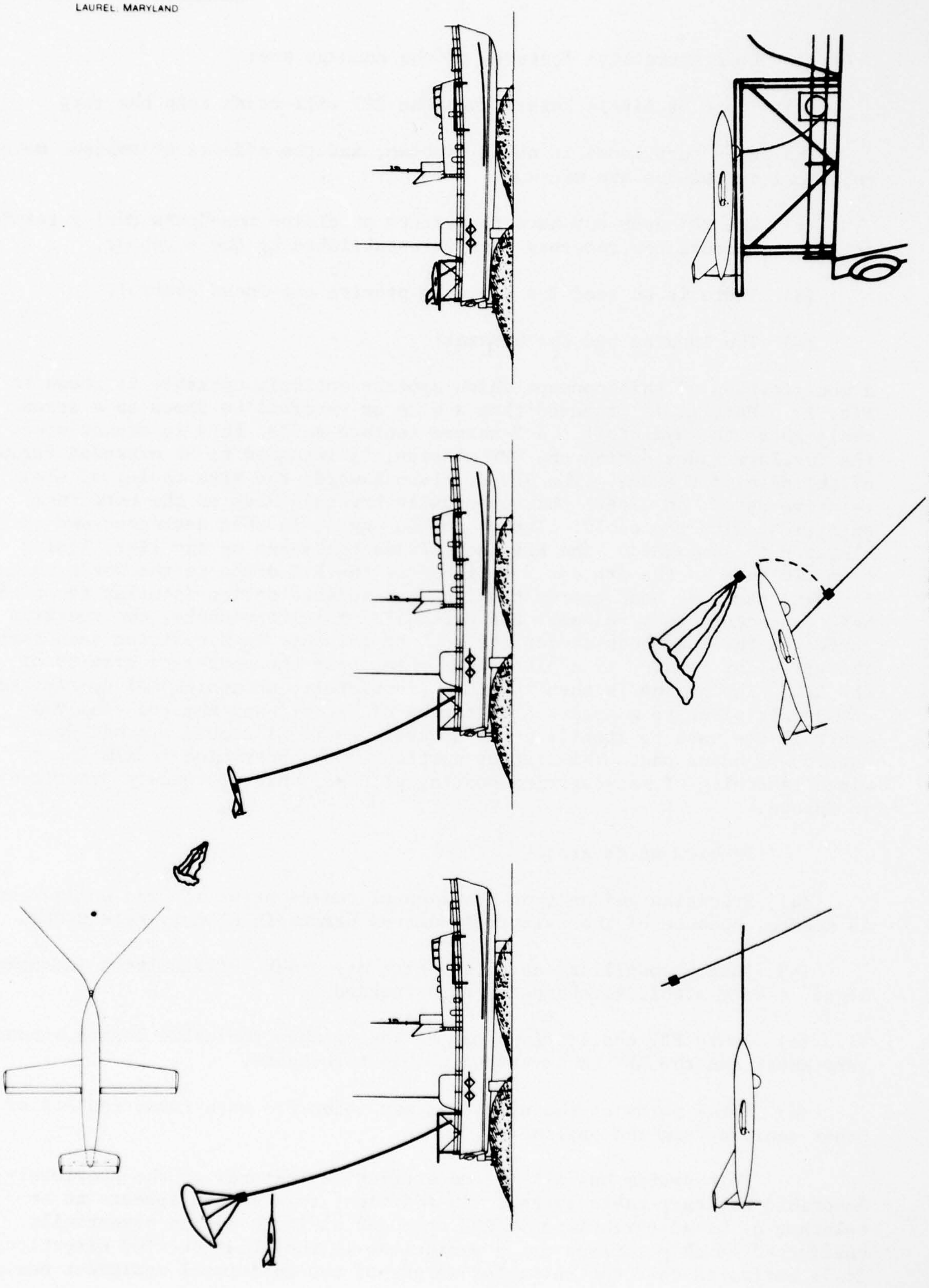


Fig. 27 Recovery of RPV by Winch

A possible alternative method can be visualized for employing the kite. If the kite were made large enough to generate large tensile loads on the line, the RPV, after engaging the line with its nose ring, might be made to fly, in level flight, down along the line by applying down-elevator and maintaining thrust about equal to RPV drag. The kite line would be retained in position for subsequent recoveries. It should be recognized that a descent along the kite tether-line would be almost exactly the same maneuver as proposed in the previous section 5.3 concerning non-vertical descents. Here, however, the tether-line, rather than a complex optical or microwave system, sets up the descent path. In addition to setting up the path, the line provides strong yaw-control forces, to maintain heading, and sufficient thrust and drag force is furnished automatically to compensate for gusts. A great deal of the paraphernalia proposed for the RPV to accomplish vertical landings might well be omitted for this simpler method of recovery.

It is to be noted that the engagement ring could probably be located at the apex of the wing-fuselage intersection on one side of the fuselage so as to avoid interference with any R.F. payloads.

5.6 Electrostatic Terminal Guidance

The accurate lateral guidance required in the above-proposed recovery method would be complex and expensive to achieve using distance-measuring equipment located on the Hydrofoil. Application of the principles employed in electrostatic autopilots (Refs. 33,34,35,36,37) might be used to simplify in great measure the problem of guiding the RPV into the cable. One envisioned method would involve application of a DC or AC potential of about 5.0 kV to the cable. As a result of this potential, a decreasing, but substantial, electric field, extending radially out to about 10 meters, can be expected to surround the cable, as shown in Fig. 28. Electric-field sensors, similar to those used on electrostatic autopilots, are intended to be installed on the tips of the V probe, as shown in this Fig. 28. With appropriate feedback to the yaw control on the RPV, the RPV could be made to home on the cable automatically, for only under conditions for which the sensors are at equal and opposite radial positions do the sensors produce a null or "no turn" signal. A system could also be devised to detect when the sensors have just passed the cable, to initiate automatic, sequenced commands for the thrust changes required to complete the recovery.

The principles involved in such a homing system are well understood and have been demonstrated in many laboratory experiments conducted at APL. There is no hazard associated with the 5.0 kV cable, inasmuch as the current needed to charge the cable can be in the nano ampere (10^{-9}A) range, and the power supply can be made harmless. In principle, this homing device should be usable in all types of weather.

It is also possible to envision methods whereby electrostatic sensing might be used to assist in homing on nets during the vertical relative landings or low angle glide paths discussed earlier in this report. Thorough descriptions of these concepts would require effort beyond the scope of the present report. Patent disclosures on some of these concepts and associated devices have been submitted to the Navy (Refs. 38,39).

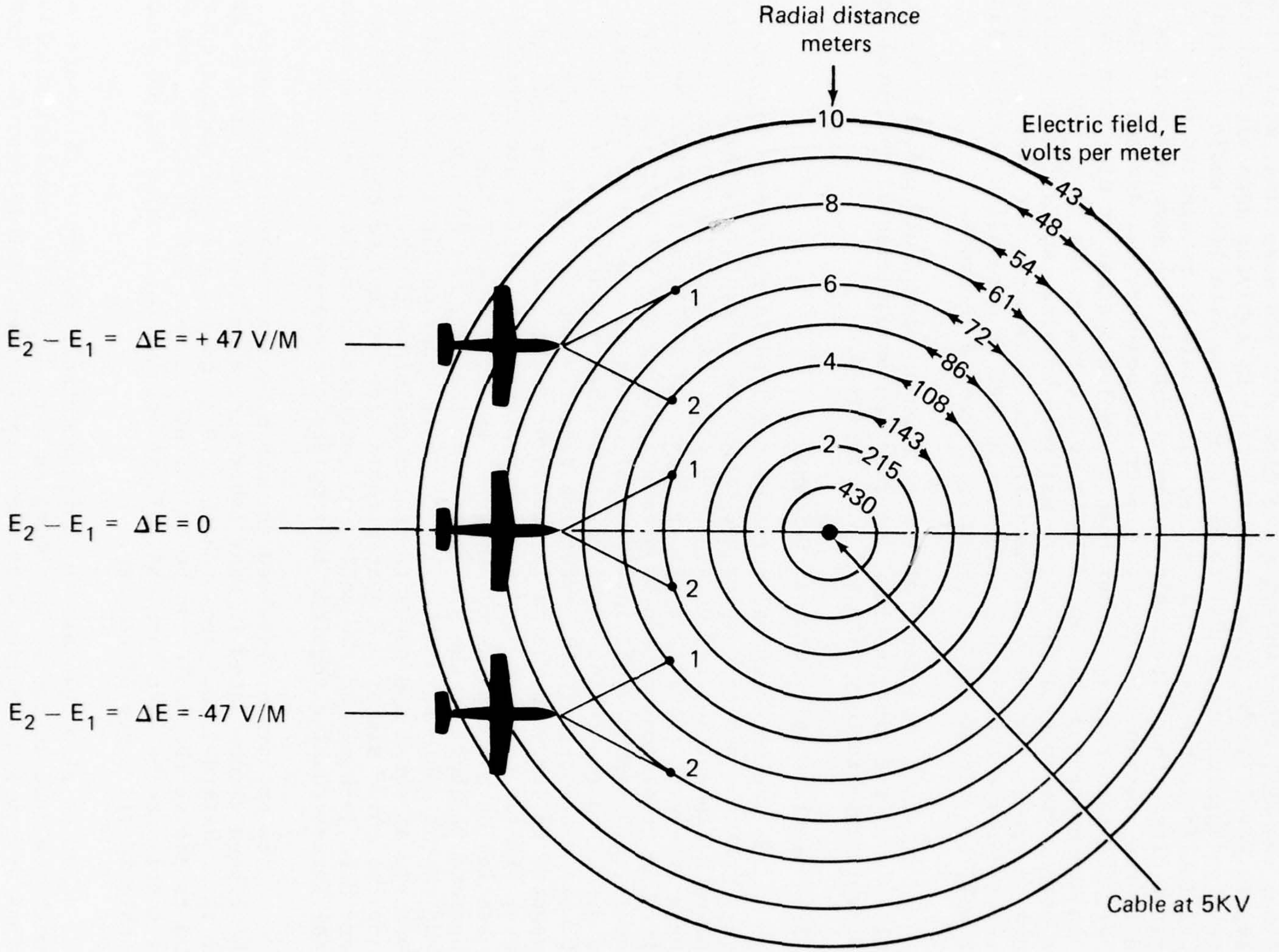


Fig. 28 Approximate Scale Drawing Depicting Electrostatic Method for Terminal Guidance of an RPV Into a Retrieving Cable.

5.7 Fixed Installation for Recovery

The towing of kites as suggested in the preceding sections may be unduly awkward and would sometimes interfere with other Hydrofoil operations. Therefore it may not be practical to employ kites in tactical situations. However, the combined principles of electrostatic sensing and a taught line to guide the RPV during vertical descent are attractive concepts because the possible simplicity could significantly reduce payload weight as well as cost of the total RPV system. Recognizing this, it is suggested that the feasibility of a system as shown in Fig. 29 be examined. Here it is suggested that a boom of flexible composite material (epoxy-graphite fiber or fiberglass) be used to suspend a line under tension at an angle that is suitable for a relatively slow speed descent of the RPV. Normally, the RPV would close onto the line at near zero horizontal velocity, but the elasticity of the boom would provide a means to absorb energy associated with a finite (but limited) velocity difference. It is also suggested in this figure that the capture mechanism on the RPV could be located at the crotch of the wing and fuselage, rather than at the nose. In this location the mechanism would not interfere with forward looking radar or optics contained in the nose cone. A yawing moment would result from this attachment at any time thrust is not equal to drag. However, the yawing moment is likely to be quite small and easily controlled by means of the rudder.

The sketch in Fig. 29 is approximately a scale representation of a system that would provide an RPV approach altitude window nearly 30 feet high. In principle, the electrostatic lateral guidance system could be expected to be made effective to distances ± 15 feet to either side of the guide wire. Particularly when one recognizes that the approach to this large target area can be made at very slow relative speed it seems likely that the guidance problems will be relatively easy to solve and that the system has the potential of performing well in gusty conditions.

Experience has taught that simplicity and reliability are often good companions, whereas sophistication is fickle and cavorts with either failure or success, depending on how much money is spent. It is strongly recommended that the above discussed methods of recovery be examined, in spite of the probability that some critics will accuse the Navy of playing with kites and other toy-like ideas.

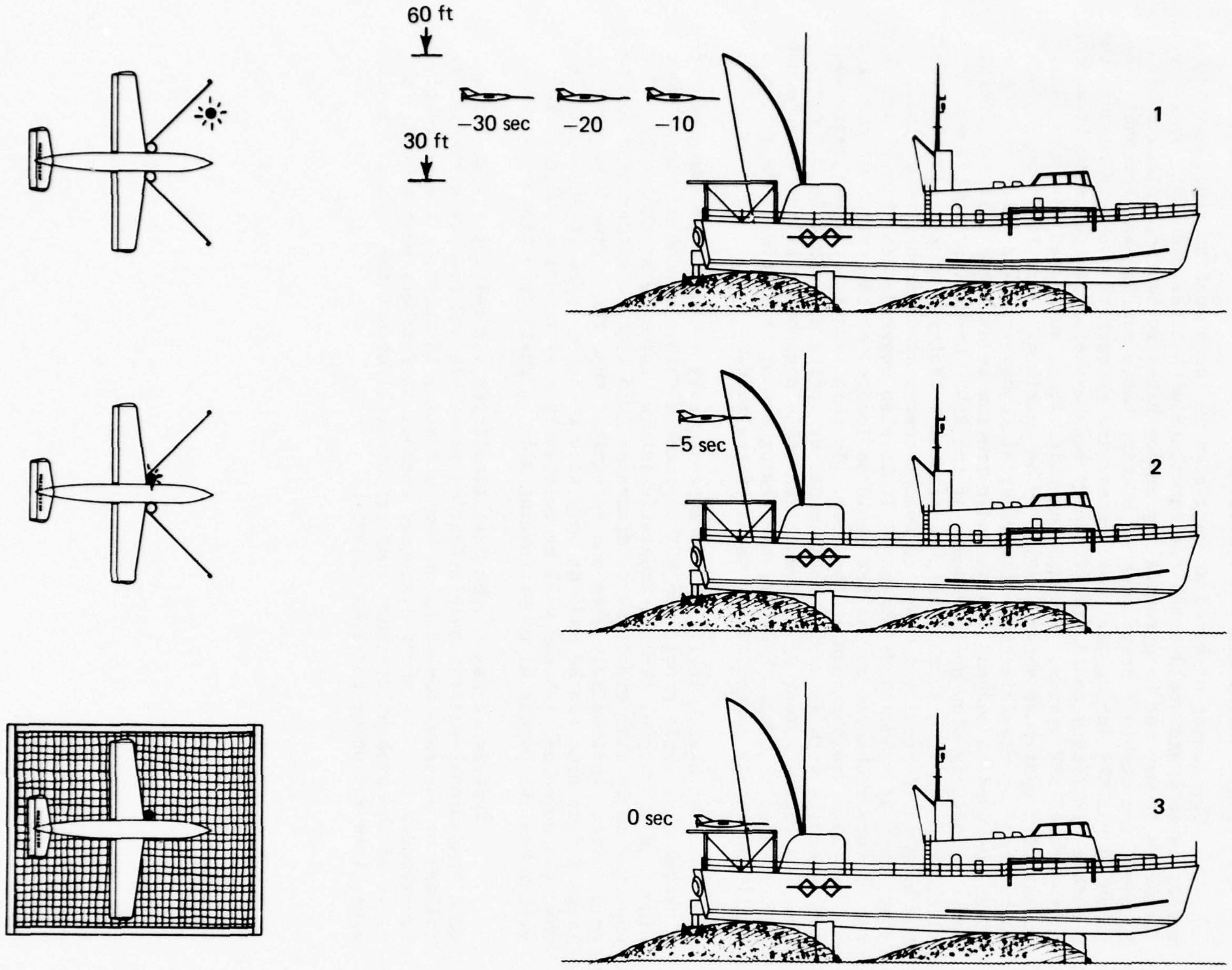


Fig. 29 Vertical Relative Landing Using Wire Terminal Guidance

6.0 SHIP HANDLING DURING RPV LAUNCH AND RECOVERY

Based on a composite assessment of the preceding sections of this report, some estimates can be made as to how and when special requirements of the RPV launch and recovery operation will dictate manuevering procedures of the Hydrofoil. It would be desirable to be able to list the RPV requirements in accurate detail, but it will be recognized that these specifications must be described in general terms until such time as a specific recovery method is chosen and until information about the actual performance of the selected RPV is available. Fortunately, there are only a few special requirements and they are amenable to generalized description.

6.1 RPV Launch Requirements and Ship Handling During Launch

(a) As discussed above, to avoid the need for pneumatic launchers or for alternative RPV acceleration schemes, relative wind speed must be at least 45 knots.

(b) For an over-the-side drop on the port side, a restriction will probably have to be imposed on relative wind direction, for, if the wind direction is at a large angle from starboard, substantial and possibly intolerable rotary turbulence can be expected on the port side. Winds coming from small angles to starboard will probably be tolerable, but it will be assumed here that the allowable relative wind vector extends only from 0° to any angle off the port bow for purposes of defining maneuvering procedures during launch.

(c) Maximum relative wind speed should not exceed 65 knots. This figure is estimated to be the maximum speed of the proposed RPV with its flaps extended. One can argue that this restriction need not be imposed because the vehicle can be launched with flaps up. Special effort will already have been invested, however, in development of the autopilot to optimize RPV performance for the low-speed configuration. Additional unnecessary effort would have to be expended to make the autopilot fully compatible with launch (or recovery) in the clean configuration.

Maneuvering "windows", consistent with the above three RPV system requirements, for ambient wind conditions of calm (0 knots), 16 knots, and 24 knots are shown in Fig. 30. The full circle shown for calm simply reflects that there would be no restrictions on heading, because relative wind would always be bow-on. Hydrofoil speed would have to be maintained above 45 knots. An outer boundary, representing 50 knots top speed of the Hydrofoil, is also shown. Thus, in calm, the RPV could be launched without interrupting other concomitant missions of the Hydrofoil, so long as those missions are being carried out while the Hydrofoil is foilborne. Turns or straight-line cruise could be allowable.

In ambient winds of 16 and 24 knots, the requirement to maintain the relative wind off the port bow rules out headings to port of the wind direction, and the requirement for a relative wind speed between 45 and 64 knots imposes some restirctions on Hydrofoil speed. Allowable Hydrofoil

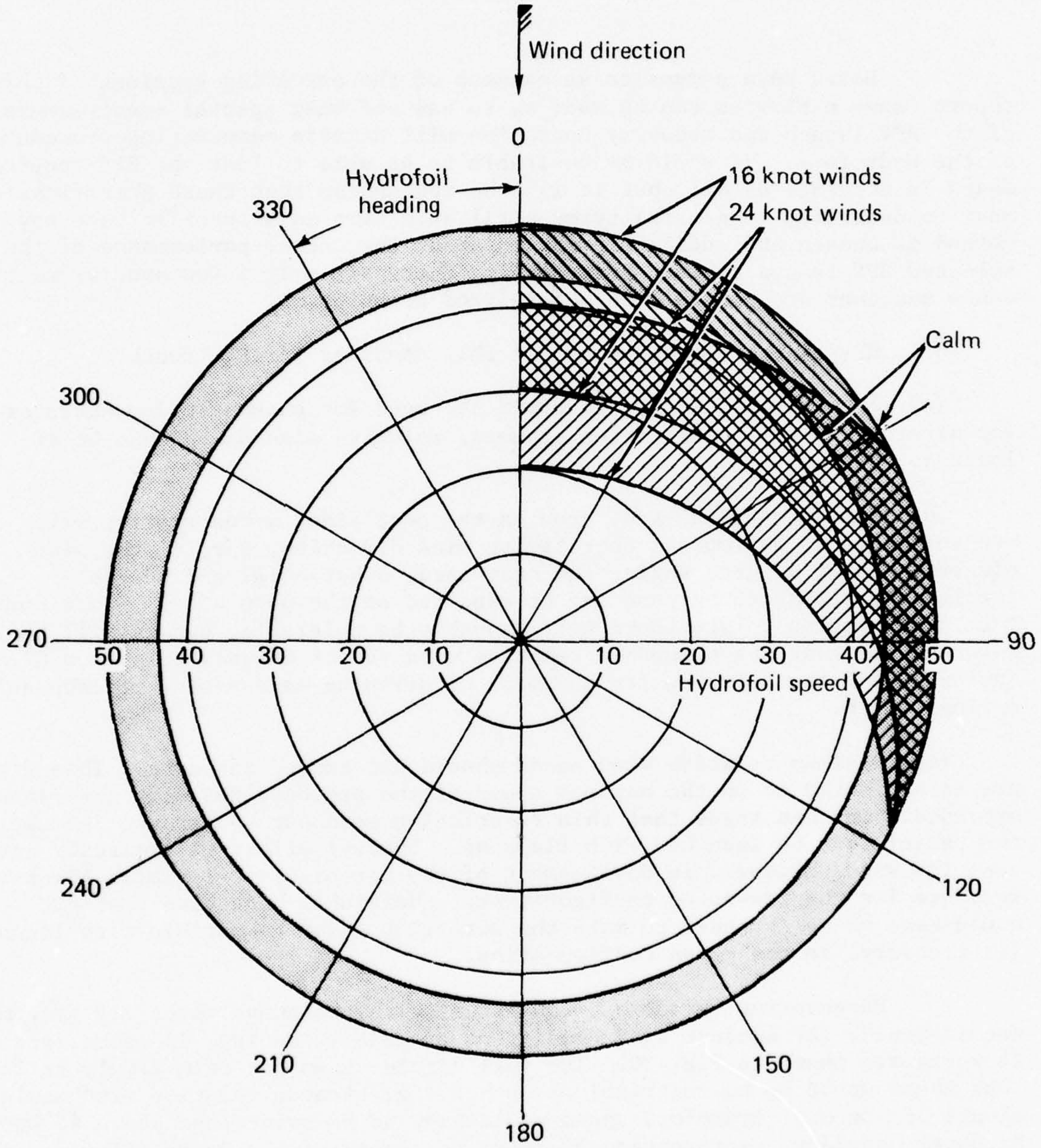


Fig. 30 Allowable Hydrofoil Handling Procedures During RPV Launch in Calm, 16 Knot and 24 Knot Winds

headings and speeds are depicted by the shaded areas of Fig. 30. Headings of up to about 100° to starboard of wind direction are allowable in 16 and 24 knot winds. The minimum allowable Hydrofoil speed in 16 knot winds would be about 29 knots, and about 21 knots in 24 knot winds.

These latter restrictions may result in a demand that the course of the Hydrofoil be changed during RPV launch if the Hydrofoil is performing another mission for which the objective is to go in a straight line from one point to another. Banking on the assumptions that the RPV could be readied while the Hydrofoil is on the desired heading for its primary mission and that the RPV could be launched during a one-minute period on a heading within the depicted windows, the delay introduced into the prime mission can be easily estimated. Taking the worst case, for which the Hydrofoil is required to be travelling with the wind for its prime mission, launch of the RPV would require a 180° turn, cruise on a reverse heading for 1 minute, followed by a second 180° turn. Total time of delay for the Hydrofoil to arrive back at the point at which the launch interruption was initiated would be of the order of five minutes.

Ship motions are not expected to introduce any difficulties in the launch operation. It will be recognized from Fig. 30, however, that in conditions of high winds, slow Hydrofoil speeds are allowable and this relationship might be used to minimize ship motions, if desired.

6.2 RPV Requirements and Ship Handling During Recovery

As discussed previously, neither the vertical relative landing on the fantail nor the proposed winch methods of recovery would be expected to present restrictions with regard to the direction of the relative wind. Only two requirements would appear to be necessary:

(a) Relative wind speed must be at least 45 knots.

(b) Relative wind speed may not exceed 65 knots.

Imposition of these requirements on the Hydrofoil results in the allowable maneuvering procedures shown in Fig. 31. Again, as in launch operations, full 360° freedom of choice of heading at speeds from 45 to 50 knots would be allowable in calm conditions. Broad windows of speed and heading are also available in 16 and 24 knot winds. Headings of more than 100° to port or starboard of wind direction would be acceptable at either wind speed. Allowable Hydrofoil speeds for the most part are comfortably within the foilborne speed range of the Hydrofoil.

It is worth noting that if the RPV were to be launched by means of a takeoff from the fantail landing pad, then Fig. 31 rather than Fig. 30 would apply to the launching operation.

The same rationale as was presented in the launch discussion about delays introduced into other Hydrofoil missions would apply to the recovery operation. The actual landing operation would take about 1 minute and this interval would be the only time during recovery that the Hydrofoil would have to be diverted from other mission headings. In this case, there would

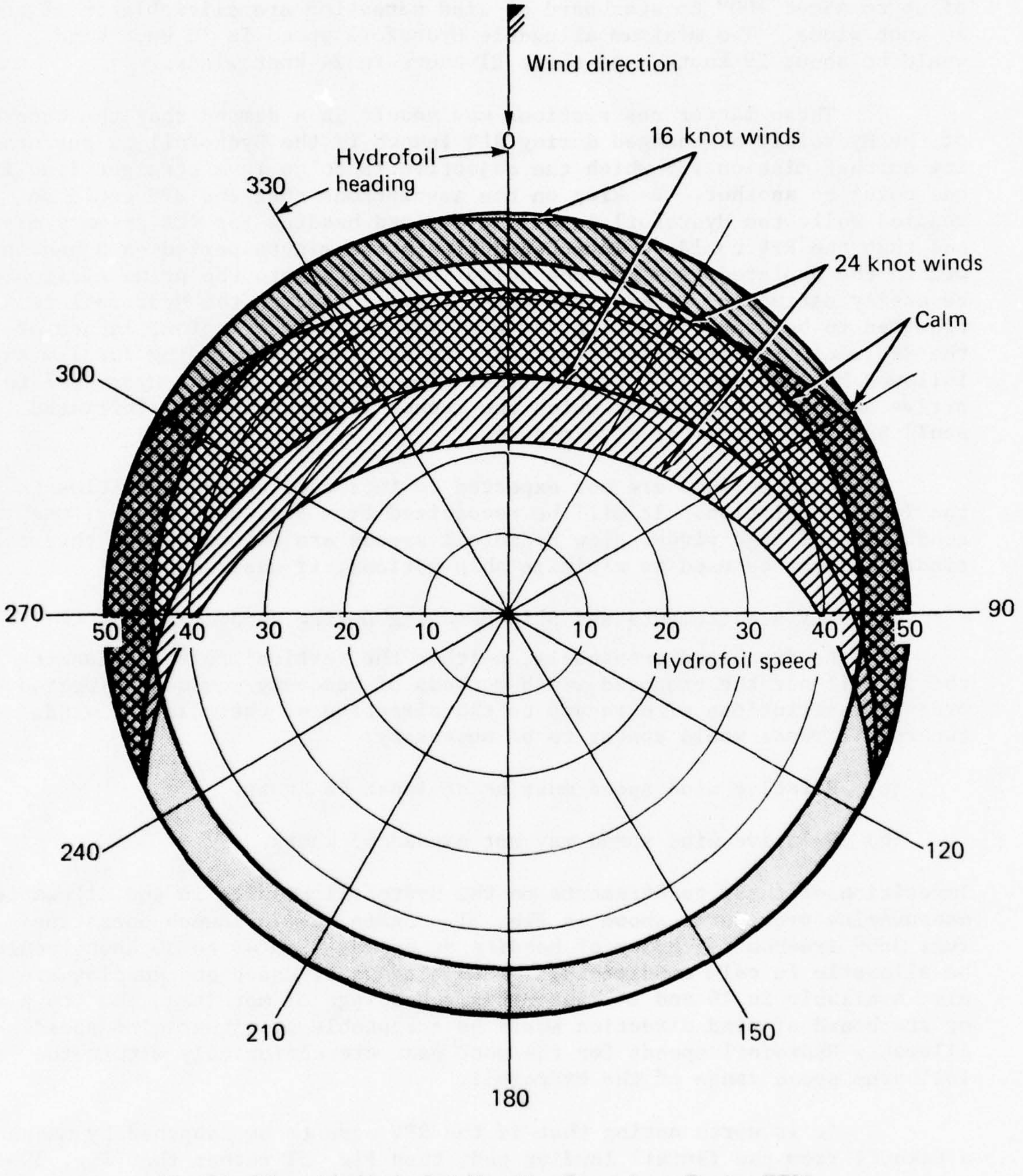


Fig. 31 Allowable Hydrofoil Handling Procedures During RPV Recovery in Calm, 16 Knot and 24 Knot Winds

never be a requirement for a full 180° turn, so that the total delay to the prime mission would, therefore, in general, be smaller than the one entailed at launch.

In the event that non-vertical landings or landings on the side-mounted net shown in Fig. 21 are found to be the preferred method of recovery, some additional restriction on the recovery windows shown in Fig. 31 would probably have to be enforced. The restirctions would not be expected to be of an important nature in the case of the optimum non-vertical descent angles to the fantail that were discussed in section 5.3, because these angles are still relatively steep, and flight could be made directly into the relative wind. However, if, for some reason, a terminal guidance system that requires a long shallow approach along, the direction of the ship's axis, with the RPV aligned with the ship's axis, were to be used, then there may be some limits imposed because of the maximum achievable steady yaw angles of which the RPV is capable. Likewise, long, shallow approaches to or vertical landings on the side-mounted net would entail some limits on heading. The worst case of any of these imagined systems would not be expected to restrict the allowable relative-wind directions to angles confined to less than 15° of bow-on. Maneuvering windows for the hypothetical case for which relative wind direction must be held within 15° on the port side of bow-on are shown in Fig. 32. It is seen here that a range of headings, up to about 60°, is still available under this restriction.

It will probably be found in actual experience that there are optimum regions within these windows that would be preferred and used if RPV launch or retrieval has the top priority in relation to other missions the Hydrofoil may be performing. These optimum locations will be influenced by RPV maneuverability, as a function of its air speed, by ship motions as a function of ship's speed and direction with respect to wave direction, and by regions of minimum ship turbulence and vorticity, as a function of relative-wind direction. A best guess would be that these optimum regions will be near the middle of the windows, which for the most part, would result in stipulated Hydrofoil speeds that fall comfortably in the middle of the foilborne speed range.

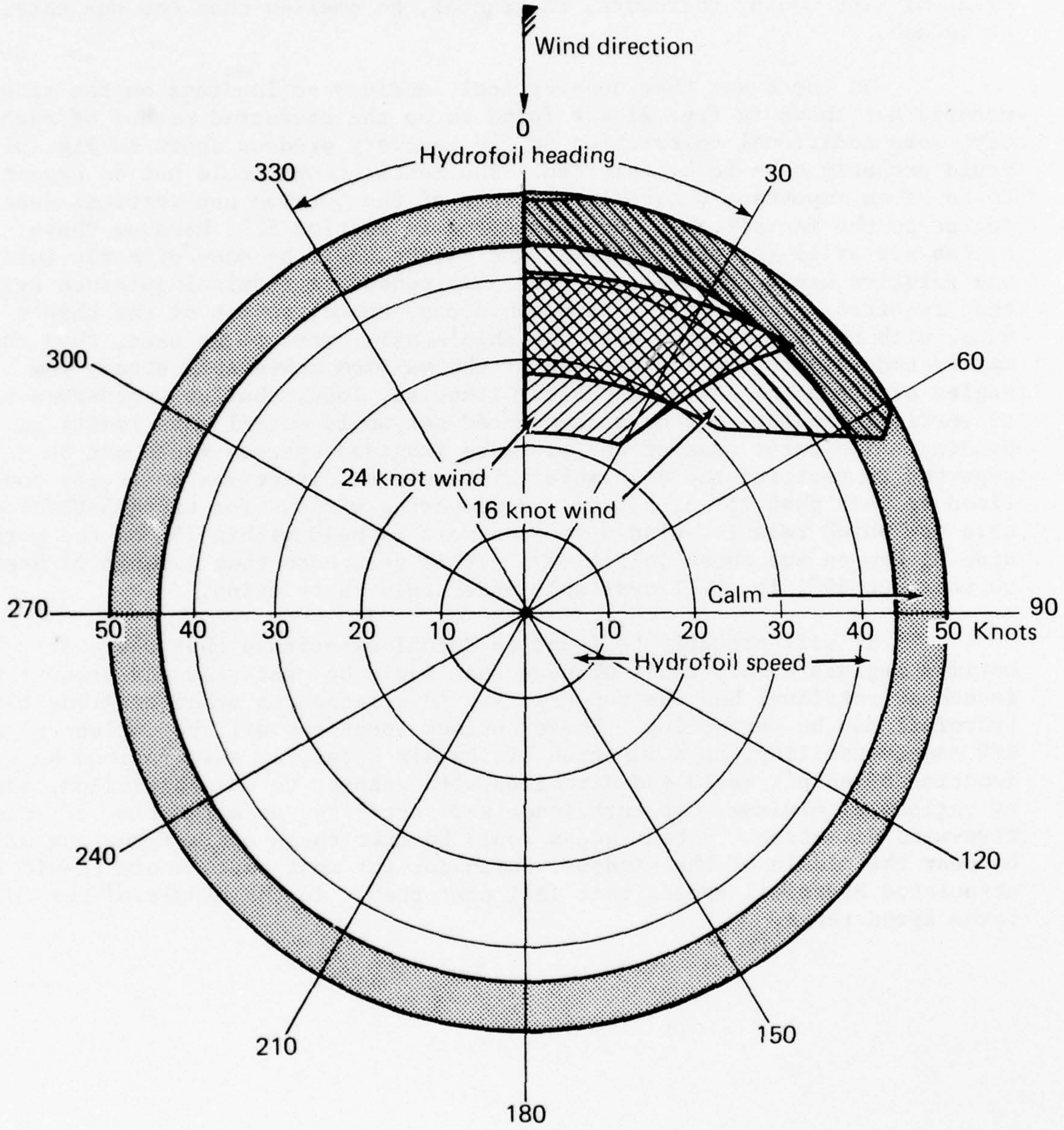


Fig. 32 Allowable Hydrofoil Handling Procedures During RPV Launch and Recovery by Methods Requiring Relative Wind to be Within 15° of Port Bow.

7.0 ABOVE- AND BELOW-DECK SPACE REQUIREMENTS

Integration of an operational RPV system with a multi-mission Hydrofoil will require a careful systems approach, to achieve maximum RPV utility with minimum interference to other ship functions. Equipment of the type discussed in this report can be installed and operated from existing Hydrofoils, but there would be some interferences that could be avoided in advanced Hydrofoils. It would be premature to attempt to define the RPV "real estate" requirements in great detail at this juncture, for an answer is needed to the crucial question of whether launch and recovery operations could be carried out on the fantail or at some other location where an elevator to the hold can be installed. An early demonstration of launch and recovery procedures is therefore highly desirable. For purposes of estimating occupancy-space assignment on advanced Hydrofoils, however, it will be assumed here that the fantail is a suitable area for conducting RPV operations.

7.1 Main Deck Space

The landing pad suggested in Fig. 21 is directly over a choice area for installation of launchers for missiles, depth charges, torpedoes, rockets and perhaps still other types of vertically-launched weapons. It will be recalled from earlier discussions in Section 2 of this report, however, that it will be desirable to have this pad at as high an altitude above the main deck as practicable, so as to avoid ship turbulence. It will also be recalled that this pad does not have to be an extremely rugged and heavy structure, because the anticipated loads are quite small. As sketched in Fig. 21, the pad is high enough to be a "roof" over the top of most launchers and one could envision a system for which the main frame of the net would be mounted on rollers, to allow the pad to be translated forward to uncover launchers emplaced underneath it. Inclusion of this feature would impose restrictions on alternate weapons only during the actual recovery of RPV's. In most scenarios, it would not be expected that simultaneous operations would be required of all weapon systems, but airborne RPV's would have to be sacrificed if such situations are met.

If a shifting net is installed, vertically-oriented launchers in the midships area could not ordinarily be used simultaneously with similar launchers in the aft area. The RPV landing net itself could be made removable, to allow more systems to be operable simultaneously. Furthermore, it is not likely that RPV's will be needed in an all-out, close-in engagement with an enemy, and in that case, if the frame were in the way of any required systems, the frame itself could be ejected over the fantail and be replaced by a collapsible spare at a later time.

Figure 21 shows launch equipment that would occupy space on the main deck in the midships area. This arrangement is suggested primarily as an expedient for handling RPV's during early demonstrations on existing Hydrofoils. An over-the-side launch from a boom on the fantail would be just as feasible, and an even simpler system, capitalizing on a take-off from the landing pad, might be possible. Automatic handling equipment would be required for these operations, however, because of the inaccessibility of the RPV when up on the landing pad.

Summed up, a system may be envisioned for which the main requirements for space on the main deck would be limited to the amount needed for installation of an elevator for transporting RPV's from the hold to the main deck. Based on the dimensions of the mini RPV's discussed herein, an elevator 10 feet by 10 feet would be adequate to handle air-ready vehicles. As a contingency for handling midi (medium size) RPV's in the 300 to 600 lb range, a larger elevator should perhaps be postulated for planning purposes, but the size cannot be readily estimated now. One of the final recommendations of this report is that an assessment should be made of the feasibility of operating midi RPV's by using techniques discussed herein, or by other methods.

7.2 Hold Space

The assumption of the availability of an elevator automatically imposes a requirement for equal space in the hold. The total swept volume of the elevator would essentially have to be dedicated to the RPV system. Additional floor space in the hold, adjacent to the elevator and nearly equal in size to the expanse of elevator area, would be needed for handling and assembling RPV's

The number of flight-ready RPV's that will be required has not yet been defined. On the basis of the aforementioned space assignments, one flight-ready RPV could be stored on the elevator in its lowered position and another could be stored in the adjacent over-hauling area. Interchange of these two units would have to be by means of an over-under passage of the RPV's, a mildly awkward but not impossible operation, the need for which would not normally be expected to arise.

Storage volume for each additional, assembled, flight-ready RPV of the size shown in Fig. 19 would be about 290 cu ft, having dimensions 9.5 x 10.5 x 2.9 feet. The shapes and volumes of spaces needed for storage of RPV's, separated into components that could be readily assembled, are listed below:

Component	Dimensions (feet)	Volume (cu ft)
Nose cone, payload, & dome	1 x 1.5 x 3.2	4.8
Aft fuselage, vertical fin, engine, & propeller	1 x 2.8 x 6.2	17.4
Propeller, shroud, & Yaw rudder	2 x 2 x 2	8.0
Wing panels (2 ea.)	2 x 4.6 x 0.7	6.4
Horizontal stabilizer	.24 x 1.5 x 3.5	1.3
Total volume		37.9 cu ft

Additional hold space would be needed for systems-check equipment and fuel storage. Gasoline is the preferred fuel. One hundred gallons would suffice for 38 RPV missions of the longer type shown on Fig. 10.

It is likely that a minimum crew of four would be assigned to RPV operations and maintenance. Berth space, lockers, etc., would be required for these personnel.

7.3 Communications Command and Control C^3 Space

Equipment for RPV guidance and display would be best installed in the C^3 area of the ship. Space would be needed for an RPV pilot, a payload operator, and for about 125 cu ft of electronic gear.

7.4 Weight

Total installed weight of a system with 10 RPV's is estimated to be about 2 tons. The elevator and its machinery are excluded from this estimate.

8.0 RECOMMENDED TECHNICAL APPROACH TO NEAR-TERM FEASIBILITY DEMONSTRATION

The feasibility of a mini RPV system for Hydrofoils hinges strongly on finding solutions to technical problems associated with the RPV recovery operation. Concepts and hardware that appear workable are described in this report. The environment during recovery, however, has not been well chacterized and it is therefore not possible to define in a quantitative way what levels of sophistication of terminal guidance and RPV maneuverability would be needed to convert these concepts into reliable, all-weather systems. A sound technical approach should therefore start with the gathering of elementary information about the environment. It is not envisioned, however, that a tremendous bank of environmental data will be needed, and it would appear highly profitable to initiate tests of some of the principal features of the recovery concepts while such environmental data are being gathered. Accordingly, execution of the following schedule of tasks is recommended.

8.1 Turbulence and Vorticity Characterizations.

Wind tunnel models of Highpoint and Plainview are available from previous tests at NSRDC. It is recommended that these models be fitted with miniature rakes of tufts and ribbons at crucial locations. Observations of turbulence and vortical flows should then be documented by still and motion pictures or by T.V. taping, for a variety of relative wind directions and for velocities scaled to simulate 45 knots (and even at higher speeds) for the full-scale ships.

Identical rakes of ribbons, full scale should be mounted on the PCH and on the AGEH, and appropriate cameras should be installed to make photographs during foilborne operations. It would seem possible to collect most of the needed data by piggybacking upon other test-runs carried out by the ships. One knowledgeable person onboard could keep an appropriate log of ambient winds, hydrofoil speeds, relative-wind directions, etc.

Several small gust vanes, as developed for RPV gust-disturbance tests, (Ref. 4) should be mounted at selected locations on the fantail to obtain 3-axis recordings of the fine-scale turbulence close to the landing pad area.

If sufficient priority is established to dedicate the ship to several days of tests for obtaining such airflow information it would be more efficient to do so.

8.2 Kite-Towing Tests

A stable kite of arbitrary size should be selected and installed on a winch on the PCH and on the AGEH. Motions of this kite could be recorded by means of picture recordings. Long ribbons should be attached to the line at various altitudes, and these ribbons should be visible in the motion pictures, to allow assessment of lateral-gust intensity.

A load cell should be installed, to measure tension on the line to the kite. The kite could then be flown at selected altitudes, up to 500 feet in the (meteorological) boundary layer. Variations in tension would give a measure of the intensity of the longitudinal shear gusts at various altitudes in the layer.

8.3 Scaled Tests of RPV's Motions

Low-cost, scale models of an RPV, fitted with model airplane radio-control equipment should be flown with a man in the control loop to obtain a hands-on assessment of the magnitude of the problems associated with the various recovery concepts. Initial tests could be performed on a runway, using a truck to simulate the Hydrofoil.

The radio equipment in these models should be installed in watertight containers, so that flights could be conducted from the PCH and from the AGEH. A simplified over-the-side boom would be the only equipment that would need to be installed on the Hydrofoil. Fuel for flights of about 1 hr duration could be provided, and the model could be landed on the water and subsequently picked up, with little risk of damage. Data recording would be primarily in the form of motion pictures, accompanied by voice-recorded annotations. On-board recoveries could be attempted if suitable hardware were installed.

The above-recommended scale models would be expected to weigh between 10 and 20 lbs and would be sufficiently frangible that there would be little risk of damaging ship's equipment. Safety procedures would dictate that the models be flown aside of or behind the pilot house.

8.4 Wind-Tunnel Tests of an Optimized RPV

A wind-tunnel model of an RPV that includes features recommended in Section 4.5 of this report should be fabricated and tested in a suitable wind tunnel to quantify its aerodynamic characteristics. These tests could be carried out with the design shown in Fig. 19 and could be started at the same time as the aforementioned sea-trials. The results should be sufficiently general to be applicable to modified designs, capable of higher speeds or larger payloads, should these improvements become required features of operational OTH RPV's.

8.5 Status Review, and Commitment to Full-Scale Demonstrations

Based on results of the above-described efforts, it should be possible to make reliable judgments about the feasibility of each of the recovery concepts described here (and others that will doubtless be devised as the work progresses). Hardware to perform tests associated with the preferred methods could be procured to specifications that would meet the requirements for an operational OTH RPV, and, thus, fully meaningful demonstrations could be carried out with such realistic equipment.

9.0 AREAS OF ADDITIONAL WORK

Scanning over the shapes of typical mini RPV's that have been tested during the past 6 years, one might wonder if those who generated the interest in this class of vehicle also passed a rule that "Mini RPV's should not look like airplanes."

This remark is not intended to belittle the products that have resulted from the innovative efforts of the pioneers in Mini-RPV design. Odd shapes may be best for fulfilling requirements. The remark is intended only to drive home the point that most mini RPV's have turned out to be strange configurations, to which it is difficult to apply all of the well-known methods of defining stability and control for conventional aircraft. But, this point is not itself what is most important. The basic difficulty arises because these strange configurations are expected to fly in a strange region of Reynolds numbers, for which there is a notable lack of accurate wind tunnel data for use in estimating stability and control behavior. As discussed in Section 4.2 on the guidelines to be followed in mini RPV design, peculiarities in flow behavior in these low-speed regimes might introduce unexpected problems in what would otherwise be a highly-workable, mini RPV system.

An applied research program aimed at achieving maximum stability and control at typical mini RPV speeds could well be of inordinate benefit to the improved performance of a broad range of mini RPV systems that are presently being envisioned. There can be no argument that previously-authorized, modest research programs dealing with basics of the control of missiles at supersonic speeds have proved their worth many times over. In the mini RPV field, answers are needed to questions about flow separation from control surfaces, about the efficiency of small shrouded and unshrouded propellers, about the drag of scoops and plates, and about the use of spoilers and high lift devices, as well as about other characteristic attributes of mini RPV's.

Individual programs and project offices typically do not have sufficient time or funds to carry out fundamental or applied research programs that could be of benefit to future programs. Responsibility for such planning lies elsewhere. It is hoped that long-range efforts devoted to the solution of mini RPV problems will soon be recognized as an area where the results could have significant impact on the success of operational systems.

One possible method of retrieval of mini RPV's that employs electrostatic principles for terminal guidance is described in Section 5.6 of this report. While it has been stated that there is adequate understanding at hand to support the expectation that such envisioned devices will be workable, there remain several fundamental and practical questions which need to be investigated. Results of an investigation in this area could have broad application to other facets and features of mini RPV systems that have been proposed for a variety of missions. It is recommended that means be found to carry out the needed work on such useful adaptations of electrostatic guidance concepts (a description of which is beyond the scope of this report).

Electrostatic autopilots (Ref. 33) have been found useful in previous RPV programs, as a result of which important military capabilities have been demonstrated (Ref. 40). Because this sort of autopilot is not capable of satisfactory performance in some types of adverse weather, however, doubts have surfaced about the applicability of such devices to operational RPV systems. Such apprehension is understandable, but it does not follow that apprehension is justified from a long-term viewpoint. Even if electrostatic autopilots should be found to be of limited use in tactical weapons systems, there are areas where the technology could provide excellent low-cost autopilots for use, in for example, targets, or for studies of stability and control of mini RPV's in slow-speed flight in the real world of gusts, or for proving-in concepts for launch and recovery. It is regrettable that the potential of electrostatic technology is largely being neglected, and it is hoped that means will soon be found to progress more diligently towards reaping the fruitful promise of such new developments.

With regard to the overall subject of operation of RPV's from Hydrofoils, work should be initiated, as soon as a recovery method is demonstrated to be feasible, on the problems of integrating the system into advanced Hydrofoil ships. Methods for automation of the mission, interaction of the RPV system with other weapons systems, storage, replenishment, and total logistics could and should be accurately assessed.

Finally, it would be advantageous to allot some funds at an early date to an effort to investigate how any of the techniques described here can be modified to be made workable from Frigate (FF) ships.

10. CONCLUSIONS AND RECOMMENDATIONS

10.1 Conclusions

1. Mini RPV's capable of performing the OTH mission of about seven hours duration while carrying 45 lbs of payload at maximum speeds of about 150 mph and optimum cruise speeds around 80 mph appear to be fully compatible with multi-mission Hydrofoil ships. Suitable RPV's could be made using low-cost construction techniques and powered by off-the-shelf engines. These estimates are based on envisioned vehicles of 150 lbs gross weight having a wing span of about 9.5 feet.

2. Several methods for launch and recovery appear feasible. The high speed of the Hydrofoil is a distinct advantage, because launch and recovery can be made at low relative speeds between the Hydrofoil and the RPV. The relatively benign ship motions experienced during foilborne operations, even in rough seas, will serve to mitigate some otherwise complex problems in the terminal guidance systems.

3. A mini RPV system could be integrated with a multi-mission Hydrofoil with minimal interference upon other weapons systems of the Hydrofoil.

10.2 Recommendations

It is recommended that:

1. Effort should be initiated as soon as possible to: (a) characterize experimentally the nature of the turbulence surrounding a foilborne Hydrofoil, so that optimum emplacement of launch and recovery equipment can be defined; (b) measure turbulence at altitudes up to about 500 feet, using towed kites, and evaluate the feasibility of recovery methods involving attachment of an airborne RPV to a tether line, and (c) demonstrate that adequate RPV control effectiveness can be achieved to perform vertical relative landings on Hydrofoils, by determining the RPV behavior through means of wind-tunnel tests of an RPV configuration described herein, and by means of flight tests of dynamically-scaled models. Plans for a near-term feasibility of demonstration should be drawn up as soon as sufficient data from the above experiments are at hand.

2. Full-scale feasibility demonstrations should be made using RPV hardware that has been attested to have adequate performance to execute the OTH mission.

3. An evaluation should be made of the feasibility of extending the applicability of these concepts (or of generating similar solutions) to handle higher-speed, heavier midi RPV's in the 200 to 600 lb class.

4. The Hydrofoil Program Office should maintain close contact with personnel of the Naval Air Systems Command charged with development of RPV systems for Frigate (FF) class ships, so that the highest possible degree of compatibility and interchangeable hardware will be maintained, and so that mutually useful information about progress in both areas will be transferred between the projects.

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