NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER
Bethesda, Md. 20084

REMOTELY PILOTED VEHICLE/VERTICAL ATTITUDE TAKE-OFF AND LANDING DEMONSTRATION VEHICLE

by
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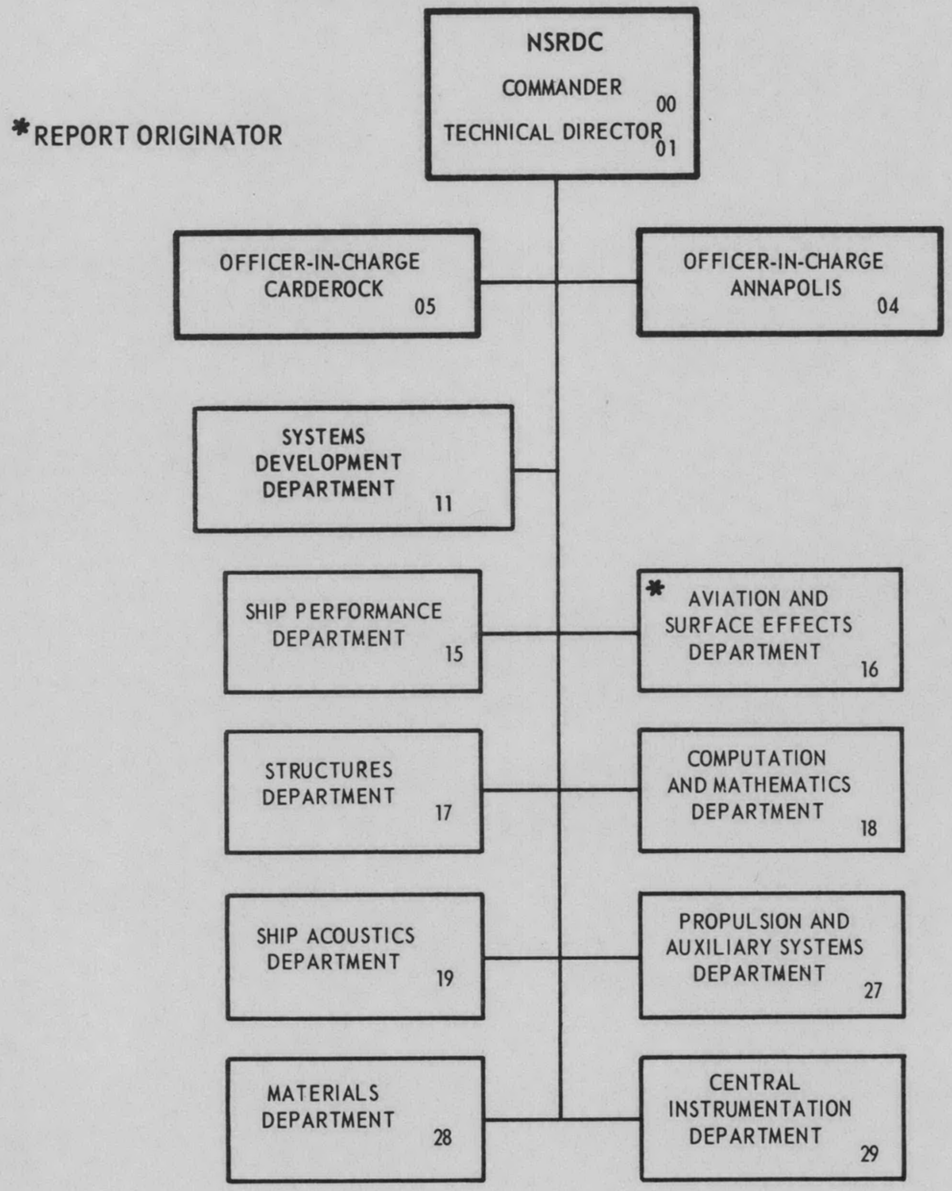

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The design incorporates a close coupled canard/delta wing configuration. Components from the MQM74A target drone as well as the Harpoon missile are utilized. Other Navy laboratories are cooperating in support of engine installation design and test (NWC), guidance and control (NUSC), power circuitry (NATC), and flight tests (PMR/NMC). Flight tests in hover, horizontal flight, transition (at safe altitudes) and ship docking are planned.

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REMOTELY PILOTED VEHICLE/VERTICAL ATTITUDE TAKE-OFF AND LANDING DEMONSTRATION VEHICLE

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ABSTRACT

Launch and recovery of RPV's aboard ship has been identified by the Navy as a major design impact area. Vertical attitude take-off and landing offers attractive advantages to the Navy in that ship/RPV interface problems are alleviated. To assess these advantages the Aviation and Surface Effects Department at the Naval Ship Research and Development Center (NSRDC), has designed and constructed a 560 lb demonstration vehicle. This vehicle during 1975 will be flight tested to assess vertical hover capability of the RPV in the turbulent aerodynamic wake generated by a ships superstructure while underway.

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I. INTRODUCTION

Recent progress in lightweight avionics development offers a potential (through the use of remotely piloted vehicles, RPV's) to solve the politically sensitive prisoner of war issue as well as high costs associated with the use of manned aircraft against heavily defended targets. RPV's are also attractive for missions requiring long endurance (where pilot fatigue can be a factor) and for missions where a highly maneuverable RPV vehicle can be a significant asset (avoiding enemy air to air and surface to air missiles and aircraft).

RPV's are less costly than manned aircraft because they need not be manned-rated. Mission applications can include reconnaissance, target designation, close-in jamming, and strike against heavily defended targets. Taking the man out of the cockpit can yield operational benefits in the areas of manpower requirements, survivability, mission effectiveness, and lifecycle costs. Smaller, non-man rated RPV's will make integration with current as well as advanced ship systems more feasible and could conceivably have minimum impact on launch and recovery aboard ship.

Other services have active hardware programs underway to capitalize on this new avionics technology for the use of RPV's for battlefield surveillance and damage assessment missions. It is therefore not in the Navy's interest to duplicate these efforts but to concentrate on the solution to problems germane to operation of RPV's on the high seas.

The Navy's use of RPV's in this ocean environment is complicated by difficult launch and recovery constraints aboard ship. As Messrs. C. V. Bryan and J. H. Pennington stated recently[1], recovery aboard ship "can drive the entire RPV design" and "it seems unreasonable to perpetuate any total RPV prototype efforts until this problem is addressed".

Over two years ago, at NSRDC, the launch and recovery of RPV's was investigated. Vertical attitude take off and landing (VATOL) was found to offer several unique advantages. In this attitude the RPV can dock at the edge of the ship, attaching itself to a cross bar (barhanger) or in a probe and drogue attachment (Fig. 1). At this location engine exhaust is overboard and does not have an impact on deck space or crew (as is the case with horizontal attitude VTOL vehicles, i.e., Harrier).

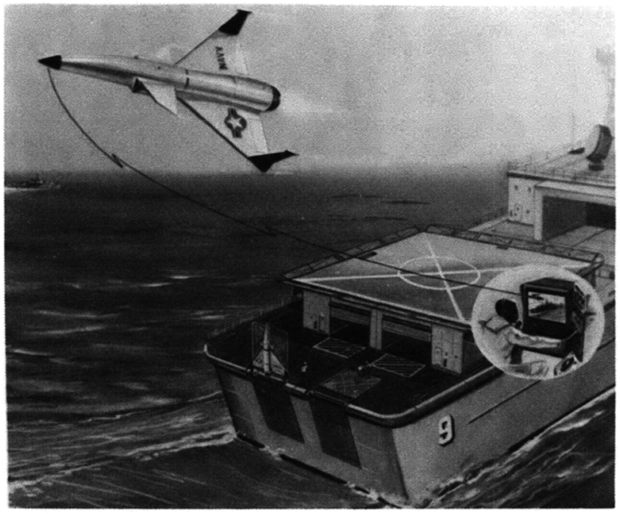

Figure 1 - Vertical Attitude Take-off and Landing RPV's (artists concept)

In case of sudden loss of thrust while approaching the ship, the vehicle will drop into the sea and not on the deck, thereby further increasing operation safety. Deck space for refurbishment of the RPV can be reduced by the use of space at the edge of the deck.

The vertical attitude configuration is a more simple design in that new engine development is not required. For horizontal attitude configurations, expensive new engine development (dedicated engine designs) would be required for each weight class of RPV (as most configuration weights would be much lower than Harriers 20,000 lb weight class). For vertical attitude flying however, existing engines can be utilized since only the engine exhaust plume requires vectoring, with available engine bleed air for roll control.

This concept was first developed and demonstrated successfully nearly 20 years ago by Ryan. In hover their design (the X-13 Vertijet, Fig. 2) used a swiveled nozzle at the engine exhaust for pitch and yaw control and a jet reaction control system located outboard on the wing for roll control. They demonstrated successfully vertical take-off and transition to horizontal flight and also transition from the horizontal flight back to a vertical attitude for landing. The test pilots, P. L. Girard and W. L. Everett, reported[2] that "the problems encountered were surprisingly few."

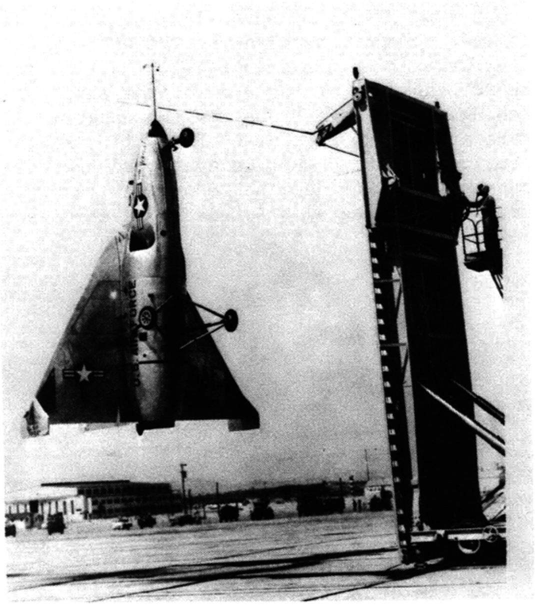

Figure 2 - Ryan X-13, Vertijet

Based on the success of this program, NSRDC initiated an in-house effort to design and develop a small (less than 600 lbs) demonstration vehicle. A vehicle of this size could make use of existing Navy missile and target drone hardware to reduce costs. The vehicle would however be large enough to allow flight test investigations of vertical attitude docking on a ship underway. This would allow an assessment of the possible problems of landing and taking off in the air turbulence generated by the ships superstructure. Also, later on in the program, the problems associated with ship motion can be studied effectively using a demonstration vehicle.

Independent exploritory development (IED) funds were allocated for the program ($280K in FY 1974 and $300K in FY 1975).

II. DEMONSTRATION VEHICLE DESCRIPTION

The NSRDC VATOL RPV demonstration vehicle (Fig. 3) incorporates a delta wing similar to the Ryan Vertijet. The power plant is located at the rear of the aircraft and an aft c.g. exists. A delta wing exhibits an aft center of pressure which alleviates this aft c.g. problem.

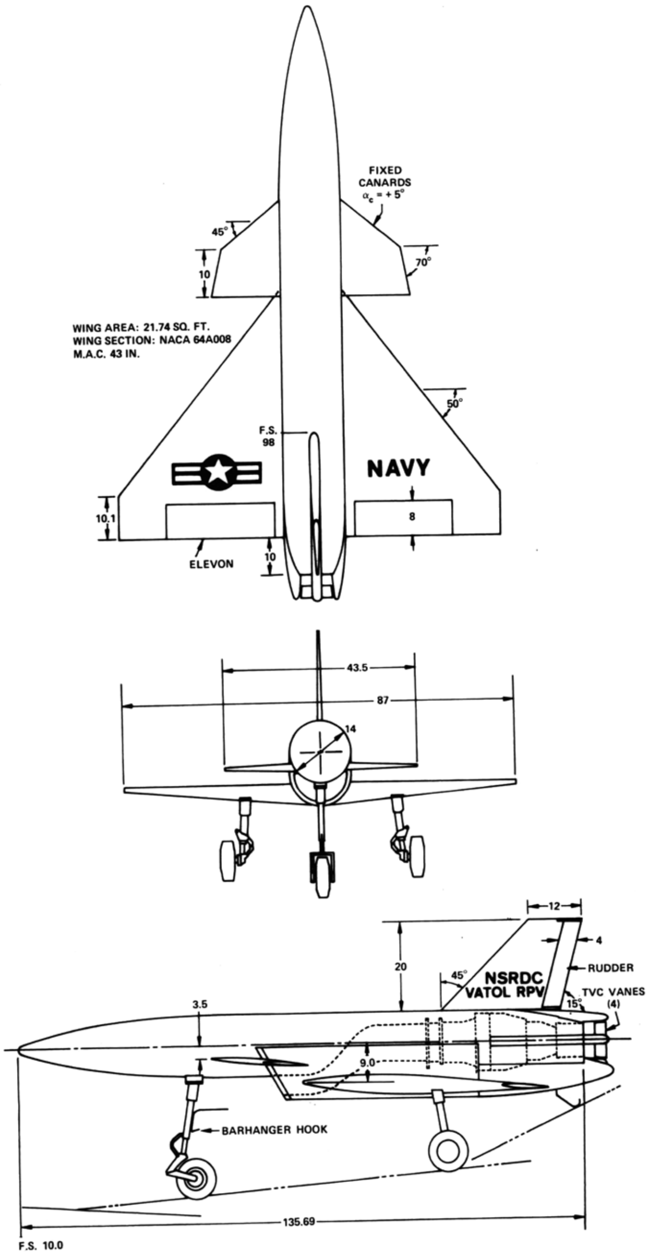

Figure 3 - Descriptive Arrangement

A close coupled (fixed) canard is employed to extend maximum lift (over 50%). This increased lift helps in the transition from horizontal to vertical flight and is also used to reduce horizontal runway landing speed.

A single vertical tail is used for horizontal flight directional stability. Elevons on the wing and a rudder on the vertical tail are used for horizontal flight control. The wing, canard, and vertical tail are constructed of aluminum stringers and plates and covered with high density styrofoam. Layers of fiberglass are bonded to the styrofoam. The elevons and rudder are made of mahogany.

During the initial sizing and design phase a survey of available engines indicated that the Teledyne CAE XJ401 (used in the earlier Harpoon missile design phase) was an attractive engine candidate. It not only can generate 660 lbs (uninstalled, sea level) of static thrust but also possesses an engine mounted d.c. alternator.

This engine was chosen for this design and an aft fuselage structure of aluminum frames and stringers designed around it. The structure is covered with aluminum panels and supports the engine at a single point using a steel ring to support the five engine support pins.

A fiberglass inlet duct supplies air to the engine. It is an "S" shaped duct with a "kidney" shaped entrance, underslung beneath the forward fuselage. The exit shape is circular at the engine inlet attachment. A rubber gasket cushions and seals the engine/inlet interface. The inlet duct area ratio is large (1.10) to reduce pressure and distortion losses of the inlet in hover. The inlet lip is relatively large to minimize flow separation during hover. The aft engine compartment is cooled by an air ejector at the engine tail pipe, designed for maximum pumping with no loss in thrust. Vent openings on the side of the fuselage supply the air to the ejector.

The nose cone and forward fuel tank of the MQM74A target drone is used for the forward section of the RPV fuselage. This structure houses the command and control receiver and decoder for the target drone which is also being used for this purpose by this RPV.

To stabilize the VATOL RPV in flight the Harpoon midcourse guidance unit (MGU) is used. The MGU is an integrated package designed to provide guidance and control from take-off to terminal guidance take-over. It serves as both an autopilot and an inertial navigator by means of an Attitude Reference Assembly (ARA) in a strapped-down inertial sensor configuration, a Digital Computer Autopilot (DCA), and a self-contained power supply. These assemblies are packaged within a 12-inch-diameter by 6-inch-long cylinder weighing 25 lb.

The MGU sends control signals to the elevon and rudder rotary electromechanical actuators via servo amplifiers for horizontal flight control. For control in the vertical attitude (hover), signals are sent to linear electromechanical actuators that drive 4 vanes made of high temperature steel (Hastelloy X) located in the engine exhaust. The use of vanes simplifies the hover control system design compared to the swiveled nozzle used on the Ryan vertijet. In hover the engine is operating near maximum thrust which produces high velocity jet exhaust. Vanes operating in this jet can produce sufficient forces to provide control in pitch, roll, and yaw.

The Harpoon radar altimeter is used to sense altitude in horizontal flight as well as in hover. Radar transmitting and receiving antennas are located flush on the lower wing surface in front of the elevons during horizontal flight. (One on each wing.) As the RPV transitions to a vertical attitude, the antennas are spring loaded and hinged, allowing rotation thru 90° so that altitude can be measured during hover.

The Harpoon signal conditioner and telemetry tray is used to transmit over 60 pieces of information on RPV performance, engine performance, flight control surface position and deflection rates.

A fixed tricycle landing gear (from the BD-5 aircraft) is attached to the wing and nose of the RPV. This allows conventional horizontal take-off and landing capability. A hook is welded to the nose gear to allow vertical docking to a cable attached to a mobile trailer/erector. A hydraulic brake system is employed on the main landing gear that provides braking during landing rollout.

The MQM74A recovery chute is retained. This will allow emergency recovery capability during flight tests. A drag chute is also installed in the fuselage tail cone to assist RPV braking during landing roll-out. The vehicle configuration is summarized in Table 1.

III. AERODYNAMIC CHARACTERISTICS

A 30% scale model of the VATOL RPV was designed and tested in the NSRDC 8' x 10' subsonic tunnel (Fig. 4). The model was tested in the pitch plane up to 45° angle of attack (α) to define the vehicle characteristics for horizontal flight. The vehicle was rotated 90° in roll and the support strut yawed thru 90° so that data could be obtained for hover flight (Fig. 5).

The horizontal flight data was obtained at a dynamic pressure of 60 psf (153 mph). Hover data was obtained at 10 psf (63 mph). The model was rolled thru 180° to obtain the effects of various wind directions on vehicle characteristics, especially rolling moment.

HORIZONTAL FLIGHT AERODYNAMIC CHARACTERISTICS

Pitch plane data was taken at elevon deflections of 0°, -5°, -10° and -20°. Figure 6 presents TRIM C_L and C_D versus angle of attack (α).

Figure 4 - NSRDC VATOL RPV Wind Tunnel Model (30% Scale)

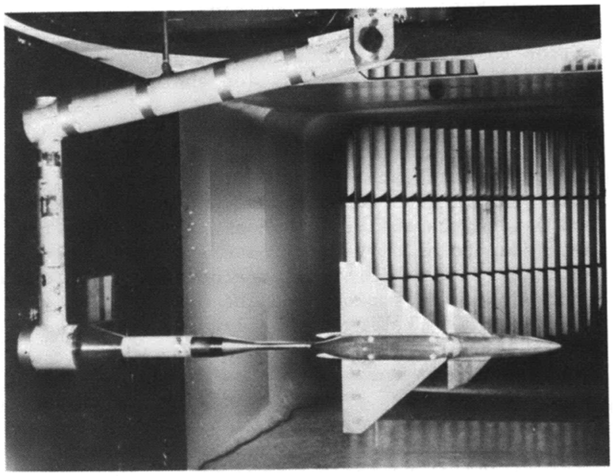

Figure 5 - Hover Position

TABLE 1 - VATOL RPV CONFIGURATION DATA

WING	
Area (total ft^2	21.74
Aspect Ratio	2.42
Taper Ratio	0.16
Span, inches	87.0
Sweepback at LE, deg	50.0
Dihedral, deg	2.8
Incidence, deg	+2
MAC, inches	42.2
Airfoil Section	NACA 64A008
CANARD	
Area (total) ft^2	5.07
Aspect Ratio	0.26
Span, inches	43.5
Sweepback at LE, deg	45/70
Dihedral, deg	0
Incidence, deg	+5
Airfoil Section	NACA 0006
VERTICAL TAIL	
Area (Exposed), ft^2	2.69
Aspect Ratio	1.032
Taper Ratio	0.45
Span, inches (Exposed)	20.0
Sweepback at LE, deg	45.0
Airfoil Section	NACA 0006
CONTROL SURFACES	
Elevon	
Span, inches	25.625
Chord (constant), inches	8.3
Deflection	
T.E. down, deg	10.0
T.E. up, deg	40.0
Rudder	
Span, inches	19.125
Chord (constant) inches	4.0
Deflection, deg	±30
WEIGHTS	
Structure, lb	203.7
Propulsion, lb	105.0
Equipment, lb	159.9
Weight Empty Total, lb	468.62
Fuel (JP-4), lb	94.3
Take-off gross weight, lb	562.9
Touchdown Weight, lb	477.4
C.G. AND INERTIAS	
At take-off, F.S., W.L.	89.75, 11.3
At landing, F.S., W.L.	86.55, 11.67
Moments of Inertia (take-off) (slug-ft^2), I_x, I_y, I_z	113, 17.64, 108
Moments of Inertia (landing) (slug-ft^2), I_x, I_y, I_z	110, 17.2, 105

Figure 7 shows positive longitudinal stability up to 26° α. Longitudinal elevon control is available in pitch up to 36° α.

The lateral-directional stability characteristics are summarized in Figure 8. Directional stability ($+C_{n_\beta}$) is maintained throughout the angle of attack range and actually increases with angle of attack which is contrary to normal aircraft designs. The close coupled canard is responsible for this increased effectiveness.

Positive dihedral effectiveness ($-C_{\ell_\beta}$) also increases with angle of attack. The improved flow over the wing generated by the canard vortex improves wing rolling moment characteristics at large combined angles of attack and sideslip.

Adequate lateral-directional control is provided by the elevons and rudder. Aileron effectiveness ($C_{\ell_{\delta a}} = -.002$) is maintained up to angles

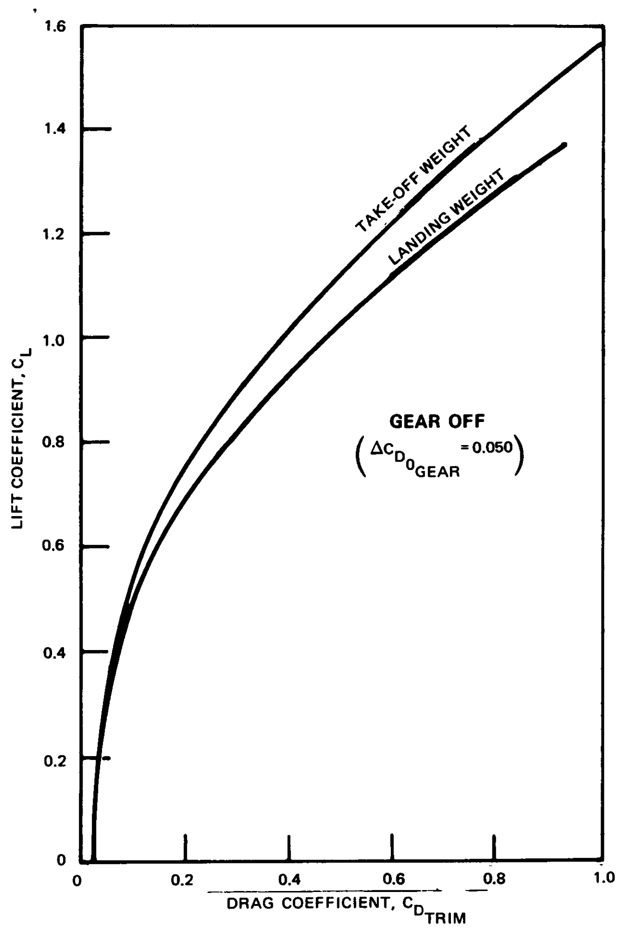

Figure 6 - Trim Lift Coefficient versus Trim Drag Coefficient

of attack of 30 degrees and is retained at large angles of sideslip (over 15 degrees). The elevon travel is from +10 degrees to -40 degrees (trailing edge up). The rudder is effective $C_{Y_{\delta R}} = .0026$ up to stall (30 degrees) and at high sideslip angles. Rudder travel is ±30 degrees. This insures positive directional control during transition to hover flight.

Dynamic rotary derivatives were estimated based on available data for similar aircraft (F-106) and modified as required to include the effects of the canard. Analytical techniques available in the Stability and Control DATCOM were used to include the effect of the Canard.

HOVER FLIGHT AERODYNAMIC CHARACTERISTICS

Aerodynamic test data was generated at an angle of attack of 90°. The model was also rotated 180° about the vertical axis to determine the maximum forces and moments due to winds while in the hover mode.

Maximum rolling moment coefficient ($C_\ell = -.138$) occurred at a roll angle of 170 degrees as measured from a plane thru the RPV center line and containing the vertical tail. The maximum pitching moment coefficient ($C_m = .148$) at lift-off weight occurs at a roll angle normal to the wind (180°). Maximum yawing moment ($C_n = .092$) occurs at a roll angle of 140°. Maximum normal force coefficient ($C_N - 1.84$) and side force coefficient ($C_Y = .87$) occurs at roll angles of 0° and 120°, respectively.

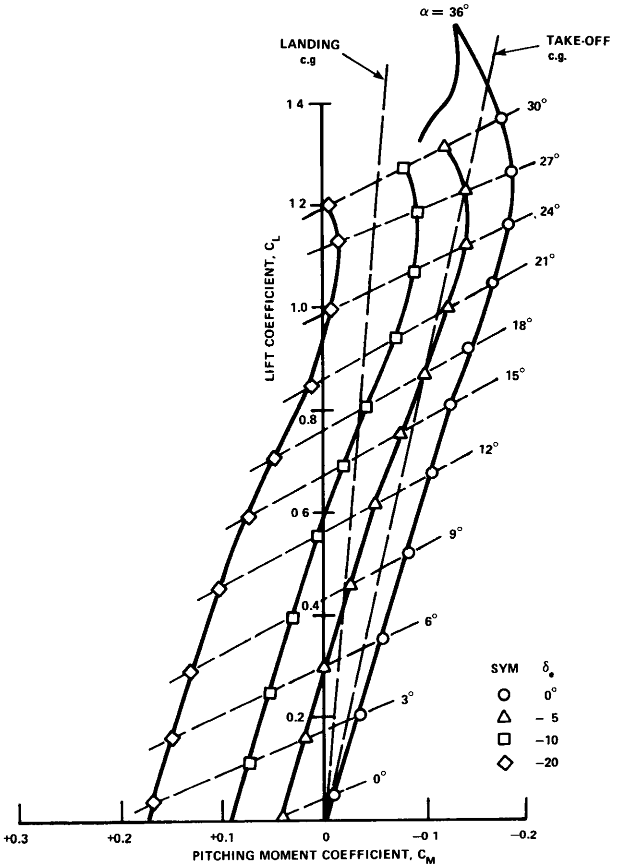

Figure 7 - Longitudinal Stability

The forces and moments these coefficients generate are a function of the wind speed at take-off and landing. For example, at 30 knots the wind dynamic pressure (q) is only 3.0 psf and the resulting maximum forces and moments on the RPV are as follows:

Rolling moment = 27.6 ft - lb (take-off c.g.)
Pitching moment = 29.6 ft - lb (take-off c.g.)
Yawing moment = 18.4 ft - lb (take-off c.g.)
Normal force = 119.6 lb
Side force = 56.6 lb

These forces and moments are within the jet vane control power capability (that will be discussed in Section V). Of course in calm winds these forces and moments are zero.

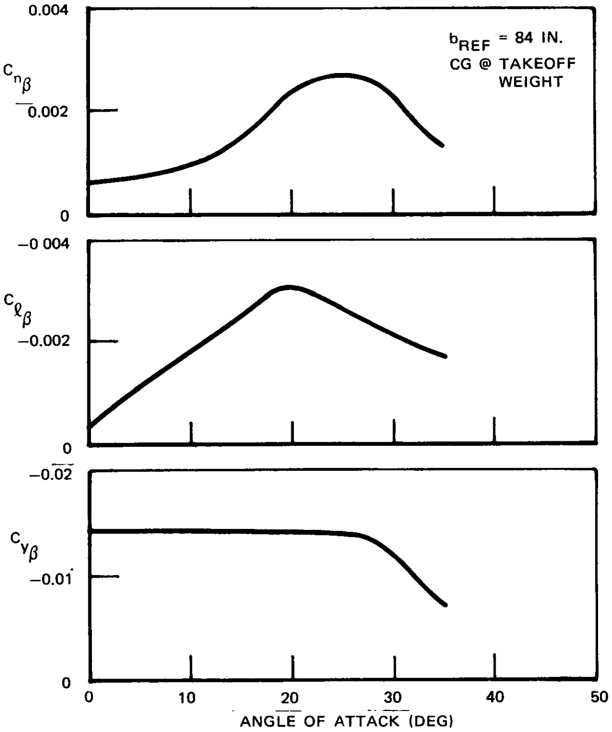

Figure 8 - Lateral-Directional Stability Characteristic

IV. JET VANE PERFORMANCE

The Ryan Vertijet used a swiveled nozzle at the engine exhaust for pitch and yaw control and engine throttling for axial control. For roll control they bled air off the engine compressor to reaction jets near the wing tip. Roll control was marginal on the X-13 in transition due to low thrust levels required in the initial phase of transition to prevent altitude zooming[2]. It was suggested that a drag brake could be used to reduce forward flight speed to eliminate this problem. The NSRDC RPV employs a drag chute for this purpose.

The NSRDC VATOL RPV uses jet vanes in the engine exhaust for hover control (Figure 9). This is done primarily for design simplicity and lower cost. The vanes were originally sized to provide recommended angular accelerations in pitch, roll and yaw based on handling qualities criteria for V/STOL aircraft specified in MIL-F-83300. These accelerations are:

Pitch:	0.5 radians/sec^2
Roll:	3.0 radians/sec^2
Yaw:	0.6 radians/sec^2

The vanes were sized to generate these general levels of acceleration at small vane deflection angles. The resulting vane chord is 2.5 inches. Guidance and control simulations performed by NUSC confirmed the adequacy of this vane design (see Section V) even though vane performance in roll is lower than originally estimated.

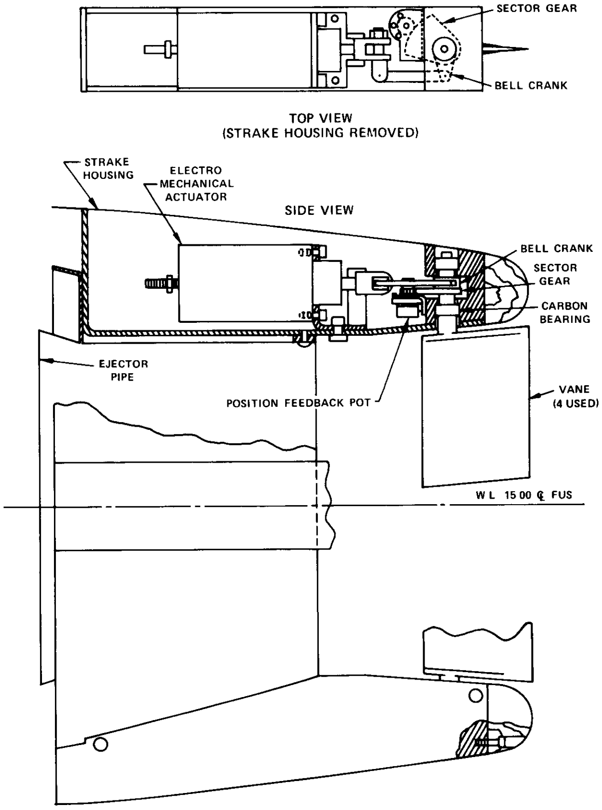

Figure 9 - Jet Vane Assembly

At take-off weight (560 lb) the vane angular acceleration control power in pitch ($\ddot{\alpha}$) is:

$$\ddot{\alpha} = \frac{\partial M}{\partial \delta_v} \delta_v \cdot \frac{1}{I_x}, \text{ radians/sec}^2$$

Vane control moment per degree vane deflection ($\partial M/\partial \delta_v$) is 19.2 ft-lb/degree (= $C_{L_{\delta_v}} x_v q_e S_v$).

The estimated vane lift curve slope ($C_{L_{\delta_v}}$) is .05 per degree vane deflection for a vane chord (c_v) equal to 2.5 inches and 6% thick airfoil section (NACA 0006). The vane area (S_v) affected by the engine exhaust is 16.70 in^2 (two vanes). Engine exhaust dynamic pressure (q_e) is 1410 psf in hover (thrust = 560 lbs). The average value of q_e over the vane is 825 psf due to mixing of boundary layer flow. The moment arm (x_v) from the c.g. to the vane is approximately 48 inches. The vehicle moment of inertia in pitch (I_x) is 113 slug-ft^2. The resulting pitch acceleration is 0.169

radians/sec^2 using 2 vanes. 2.95° deflection would result in an acceleration in pitch of 0.5 radians/sec^2.

In roll, the vane angular acceleration control power ($\ddot{\phi}$) is:

$$= \frac{\partial L}{\partial \delta_v} \delta_v, \frac{1}{I_y}, \text{ radians/sec}^2$$

Vane roll control moment per degree deflection ($\partial L/\partial \delta_v$) is low, 1.48 ft-lb per degree ($= 4\, C_{L_{\delta v}}\, (\ell m)\, q_e\, S_v$) since the vane moment arm in roll (ℓm) is relatively short, only 1.825 inches. The moment of inertia in roll (I_y) of 17.64 slug-ft^2 helps to offset the short vane roll moment arm. The resulting roll acceleration is low, only 0.084 radians/sec^2 per degree vane deflection. However it is sufficient for control of the vehicle in low winds (see Section V).

In yaw, the vane angular acceleration control power ($\ddot{\beta}$) is:

$$\ddot{\beta} = \frac{\partial N}{\partial \delta_v} \delta v \,.\, \frac{1}{I_z}, \text{ radians/sec}^2$$

Vane yaw control moment per degree deflection ($\partial N/\partial \delta_v$) is the same as in pitch (19.2 ft-lb/degrees) for 2 vanes. The vane moment arm in yaw is also the same as in pitch (48 inches). The vehicle moment of inertia in yaw is 108 slug-ft^2. Vane angular acceleration in yaw is 0.1773 radians/sec^2 per degree vane deflection. 3.38° deflection will result in an acceleration in yaw of 0.6 radians/sec^2 .

During engine installation tests (recently completed at NWC, China Lake, California) one of the vanes was mounted to a balance and forces and mounts measured. This data is presently being analyzed.

V. PERFORMANCE

The NSRDC VATOL RPV flys from hover, transitions to horizontal attitude and flys a prescribed mission before returning to land vertically on board the ship. The engine thrust required varies significantly during this mission, from maximum thrust in hover to near minimum thrust in cruise (at a speed for maximum range). During the horizontal flight phase the lowest thrust setting is required during landing approach.

The Harpoon engine fuel control was modified to allow engine RPM to be reduced to as low a value as possible. The lowest RPM obtainable without extensive fuel control redesign was 70% of maximum rpm. The engine specific fuel consumption (SFC), already high at maximum RPM (1.2), gets even higher at 70% RPM approaching a value of (2.0).

The high sfc's for these small turbojet engines impacts flight endurance time and range. However, range is not a factor in this design as we are primarily interested in take-off and landing demonstrations. Most of the demonstration flights are planned to take much shorter time to maximize the number of docking attempts.

The Teledyne CAE engine used in this design incorporates sealed greased bearings that require repacking after about an hour's operation. Operations at high RPM (where bearing grease is rapidly consumed) must be minimized to insure long engine operating time and life.

The test program also calls for a horizontal flight test phase to demonstrate in flight control capability. Also the initial free flight transitions are planned to take place at a safe altitude. In the event transition to hover cannot take place, landing gears are provided to allow a conventional runway landing.

HORIZONTAL FLIGHT PHASE

The Harpoon turbojet engine has the thrust capability to fly the RPV near sonic speeds (with the landing gear removed). However, to minimize structural design complexity, for this demonstration vehicle, a top flight speed of 400 knots at 5,000 ft is imposed.

For maximum range, lower flight speeds are required with the attached landing gear. For example, maximum range at a constant altitude of 5,000 ft occurs at $M = 0.4$. The range at this speed is 147 n. mi. Thrust required is 231 lbs and the flight time is 0.491 hours (29.5 minutes). The RPV uses 76 lb of fuel (out of a total available of 94 lb).

Time to climb to 5,000 ft is 8.8 sec and the RPV uses only 6 lb of fuel. A typical mission would last 34.5 minutes at this altitude assuming 2 minutes are used in landing (hover mode) and 5% fuel reserve is used.

Take-off occurs at a speed of 120 knots where nose wheel lift off occurs. The wing incidence is 2° and the landing gear is designed to support the airframe at 5°. This results in a total wing angle of attack of 7° during ground roll. With maximum elevon deflection (full trailing edge up, -40°) maximum nose up pitching moment is generated to lift the nose wheel and allow rotation of the RPV about the main gear. Ground roll is about 600 ft at an engine thrust of 546 lb and a tire friction coefficient of .03.

Landing in the horizontal mode is complicated by the fact that the engine RPM can only be controlled down to about 70% of maximum RPM. The resulting thrust (about 100 lb) is large for this size vehicle. Engine shutdown during landing approach is not desirable as a wave-off situation might occur.

A computer study was made to search for a pull-up maneuver that would allow power-on recovery. Flared landings with pull-out at 50 ft altitude (at a sink rate of 5 fps) were made at various g levels. At an approach flight speed of 168 fps (M = .15), and at an altitude of 124 ft, a 1.02 g flare maneuver will pull the RPV up (sink rate goes from 11 fps to 5 fps). The flare maneuver takes 9 seconds and engine minimum thrust is 100 lb. From 50 ft the RPV flys (at a constant 5 fps sink rate) for another 11 seconds until touchdown occurs at a speed of 126 fps. (V_{STALL} is 113 fps.) The angle of attack is 25° at touchdown. The main landing gear can be braked to slow the RPV after touchdown.

HOVER FLIGHT PHASE

In hover, vanes in the engine exhaust generate control forces and moments to stabilize the RPV. The Naval Underwater Systems Center (NUSC) at Newport, R.I., has the Harpoon MGU simulated on their computer. They performed the stability and control analysis for hover flight. The following discussion is based on their analysis.

The computer model simulates engine RPM from 70% to 100% on a first order lag with a 0.35 sec time constant. The thrust is then calculated for two linear segments based on RPM.

RPM = 1/0.35 (RPMC-RPM), where RPMC is the commanded RPM

THRUST = .00394(RPM) for RPM from 0 to 29950 (= .046 (RPM)-1217 for RPM from 29951 to 40800)

The vane maximum available control deflection assumed was 5° with a slew rate of 100°/sec. The simulation used a first order lag model with a time constant of .0100 seconds. The vanes (two in the pitch and yaw planes) generate lift of 2.4 lb/deg. This results in pitching and yawing moments of 19.2 ft-lb/deg. The moment of inertia in pitch is 113 slug-ft^2 at lift-off weight. RPV rolling moment of inertia is 17.64 slug-ft^2. The vane rolling moment control capability is 1.48 ft-lb/deg (4 vanes).

The engine controller model calculates the speed command (RPM) as the integral of:

$$RPM = K_x \, (XC - X) + K_{\dot{x}} \, \dot{x} + K_{\ddot{x}} \, X_o$$

where X is the distance along the vertical axis (altitude), X_o is the body longitudinal axis, XC is the commanded altitude and K_x, $K_{\dot{x}}$, $K_{\ddot{x}}$ are gains. This type of engine controller was used since it does not require a speed command reference. That is, we need not know the engine speed necessary to support the vehicle as a function of weight. The term K_x (XC-X) will automatically adjust the speed command as weight changes. The engine controller gains are:

$K_x = 300$

$K_{\dot{x}} = -850$

$K_{\ddot{x}} = 1,000$

The vehicle response during hover simulations indicate that this type of engine controller yields acceptable performance for hover.

The autopilot used to issue commands to the thrust deflector vanes in pitch is:

drc = deflector vane command

θ = pitch angle

θ_c = pitch angle command

z = distance along axis parallel to earth (horizontal distance)

z_c = z command

k_θ, $k_{\dot{\theta}}$, k_z, $k_{\dot{z}}$ = gains (= 2.0, 1.0, 1.0, -3.0)

In one simulation (Fig. 10) the vehicle was dropped with zero thrust, and position offsets of z = 40 ft, y = -40 ft, with a -45° pitch angle (θ). The engine controller and thrust deflector autopilot then directed the vehicle to the desired location of x = z = 0. The roll angle in Fig. 10 is due to engine unrestrained start up torques. In a typical launch with the vehicle on the erector roll motion could not occur. The data indicated that X and z maneuvers using thrust deflector vanes and an engine controller yield a reasonable response.

To get an estimate of the effects of crosswinds in hover, several simulations were made. A constant wind speed of 26 knots was assumed. The simulation indicated that an equilibrium position occurred at a horizontal displacement of 12.5 ft, at a pitch angle off the vertical of 8 degrees.

Wind gusts (up to 58 knots) produced larger horizontal displacements (25 ft) and larger pitch angles (up to 50°) but the vehicle was controllable. Of course, during testing, operations need not proceed on windy days. NUSC is also analyzing the RPV's stability and control performance in transition and hover. This information will be programmed into the MGU prior to these flight test phases.

VI. ENGINE INSTALLATION TESTS

Tests were recently made of the Harpoon engine installed in the NSRDC VATOL RPV fuselage structure (Figure 11). The tests were conducted at the Naval Weapons Center, China Lake, California. The purpose was to measure installed thrust, inlet distortion and pressure recovery, cooling air ejector performance, and jet vane performance. The overall objectives were achieved with encouraging results in that the performance of the installed engine and inlet was very satisfactory. The engine/fuselage structure was mounted to a steel framework test stand at the fuselage wing mounting pads. The test stand was raised just off the ground and supported by 4 cables (at each corner). A chain was attached to

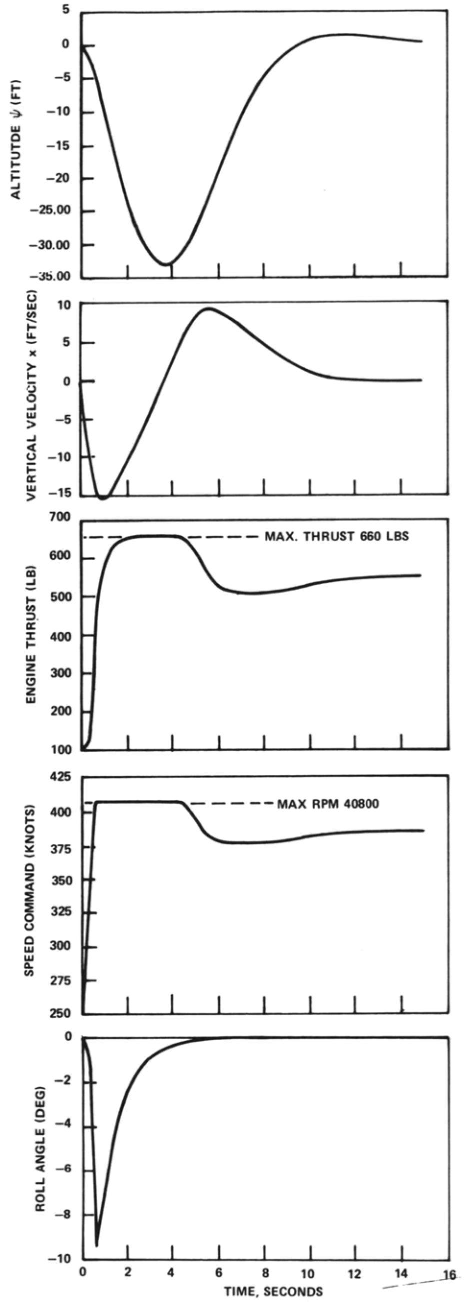

Figure 10 - Engine Controller Performance During Launch

the stand and a 1,000 lb load cell to measure thrust. To measure inlet performance, pressure rakes were installed at 8 radial positions at the engine inlet station of the duct. Also rakes were installed in the throat of the air ejector at the base of the engine. Three jet vanes in the engine exhaust area were actuated by electromechanical linear actuators. The fourth vane was mounted to an NSRDC wind tunnel balance to measure vane performance.

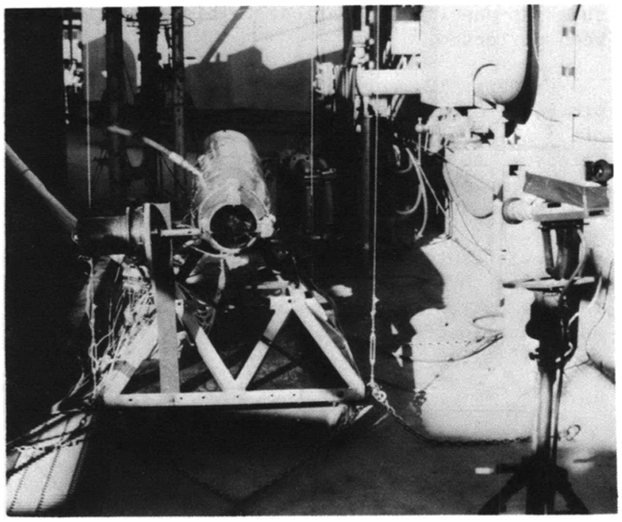

Figure 11 - NWC Engine Installation Test Set-Up (rear view)

Table 2 presents the engine performance characteristics at selected engine speeds. The highest thrust measured (541 lbs) was at 98.0 percent of maximum RPM (39,984). (To attain maximum (100%) RPM, the wired-in potentiometer that is used in the fuel control circuitry to control RPM, has to be switched out of the fuel control circuit.) These data, extrapolated to 100% RPM result in a thrust of 575 lbs.

TABLE 2 - INSTALLED ENGINE PERFORMANCE

Run	N_C(RPM)	F_N/δ,lb	EGT,°F	$\dot{W}_a$,GPM	Remarks
6	38,027	442	1,285	1.40	
8	37,531	432	1,170	1.27	
9	36,686	391	1,125	1.14	
10	35,257	334	1,030	0.97	
11	31,949	229	955	--	
18	39,969	541	1,425	1.60	Vanes Removed
19	38,686	527	1,340	1.54	Ejector Removed

N_C = corrected rotor speed, $N/\sqrt{T_{T_2}\ °R/518.7}$

F_N/δ = corrected net jet thrust

EGT = exhaust gas temperature, engine core flow, turbine exit, °F, stagnation

$\dot{W}_a$ = fuel flow (JP-4, gallons/minute)

The air cooling ejector, located at the engine exhaust, was removed in Run 10. This resulted in a significant increase in thrust (about 50 lbs). The lower thrust was due to a restriction of airflow because of insufficient area clearance between the engine and fuselage structure (at one frame location). This situation has been corrected.

In Fig. 12, corrected thrust and speed are plotted from test data, with the ejector on and off. Also, uninstalled engine thrust data from Teledyne CAE are shown for comparison. The ejector off point is about 5% below the Teledyne data and is comparable to the installed thrust loss experienced in most aircraft designs. These data extrapolated to 100% RPM indicate that a maximum installed thrust level of 625 lbs can be achieved. The RPV current weight is 560 lbs. A thrust/weight ratio of 1.12 can therefore be obtained and will allow vertical take-off.

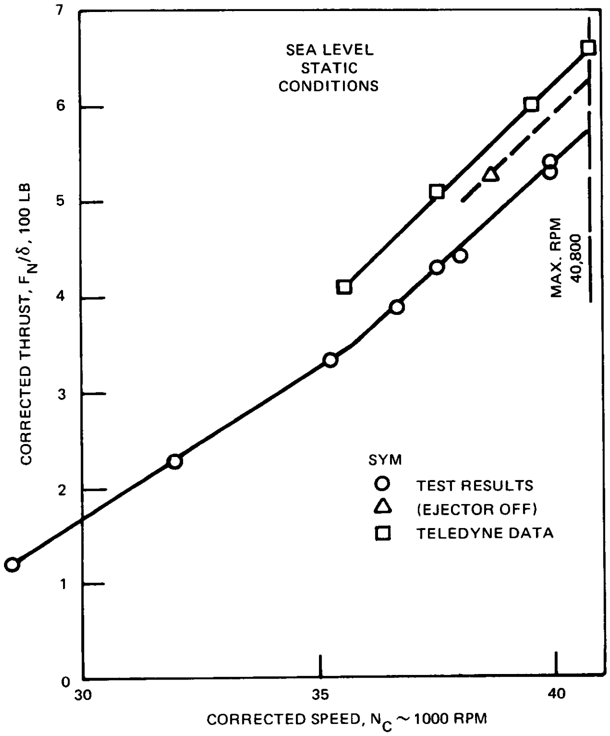

Figure 12 - Corrected Thrust

A minimum thrust of 123 lbs was measured at 69.9% RPM (Run 5) with the ejector on. Low thrust capability is desired in the program to enable a power-on flared landing maneuver at touchdown during the horizontal flight test phase.

Total operating time on the engine during the tests was approximately 56 minutes. An engine vibration increase was noted in Run 21 and the engine was shut down. The only external damage noted to the engine was to the upper exhaust pipe temperature probe. It was bent back off the vertical some 30°. Also, the base of the probe was starting to crack. This engine (S/N T-E20022) was disassembled at Teledyne CAE in Toledo, Ohio to have the greased bearings repacked. A final examination of the internal condition of the engine showed no internal damage.

Pressure tubes and a mercury manometer board were used to measure the inlet air duct pressure recovery and distortion using the pressure rakes installed in the duct at the engine inlet. Several runs were analyzed and an average recovery factor of 97% was noted. The measured distortion was about 5%. These data are presented in Table 4. During the tests, unsteady engine operation was observed (the mercury in the manometer tubes was oscillating). Most of this activity was occurring in those tubes reading the pressures at the bottom quadrant of the engine inlet. It was not possible to determine if this was due to unsteady flow in the inlet, high boost pump pressure, or engine fuel control governor. A pressure transducer was used to measure the pressure on one of these probes as close to the engine inlet as possible. This transducer measured much lower pressure oscillations than the mercury manometer tubes indicating a possible amplification due to manometer tube length. Engine speed during the runs was steady so that these inlet pressure oscillations are not felt to be of significance at this time.

TABLE 3 - INLET PERFORMANCE

Run	Pressure Recovery	Distortion*	Remarks
6	0.9771	4.36%	
8	0.9725	5.27%	
9	0.9769	4.68%	
10	0.9773	4.12%	
11	0.9843	2.97%	
18	0.9623	4.57%	Vanes removed
19	0.9671	5.69%	Ejector removed

* $p_{max} - p_{min}/p_{avg}$

While the adverse effect on thrust of the air cooling ejector was noted earlier, its cooling capability was very good. The fuselage skin temperatures in the engine area stayed below 160°F even though the air temperature was near 100°F. The highest airframe structural temperature recorded in the vicinity of the engine exhaust was 265° (Run 15) at the jet vane bearing housing. This is much lower than earlier expected when due to the close proximity of the engine's exhaust (EGT measured as high as 1425°F, Run 18) high temperatures were expected at the vane support structure.

While jet vane performance is still undergoing analysis, engine exhaust swirl was noted (during the test) when the three vane actuators were unlocked. Preliminary vane balance test data indicates the swirl angle to be small (α for zero lift is about -3.0°).

An engine alone vertical test (of 5 minutes duration) was also performed at NWC to assess bearing wear with the engine in a vertical position. No bearing wear was observed after engine disassembly, indicating vertical attitude has little effect on engine operation and life.

VII. FUTURE FLIGHT TESTS

The flight test phase of the project encompasses 4 phases; tethered hover tests, horizontal flight tests, transition tests, and ship interface tests. Plans call for all of these tests to be completed during FY 1976.

TETHERED HOVER TESTS

The tethered hover tests are planned this summer at NSRDC. A crane will be used to support the RPV in the vertical attitude. A support bar attached to the nose of the RPV will allow it to be supported by the crane. In this attitude the autopilot/jet vane performance capability to hover the vehicle will be measured.

A control cable attached to the RPV will allow override commands to allow translation fore and aft and sideways, rotation about the vertical axis, and some vertical motion to measure liftoff capability. An electrical power cable and an instrumentation cable will also be provided.

The Harpoon telemetry package will be used. The transmitted data will be carried by the instrumentation cable to ground recorder equipment located in a mobile van.

A Brush recorder will monitor in real time the engine front and rear bearing temperature, engine RPM and exhaust gas temperature, the mid-course guidance unit pitch and roll angle readings, engine speed command and radar altimeter reading of altitude.

Control of the RPV will be from a control console through the use of an umbilical cable attached to the RPV. The umbilical cable will pass from the RPV J box up the crane support cable, down the crane boom and over to the van for control operations and telemetry data acquisition.

The console for the ground controller will have means to provide an emergency STOP command to the RPV engine in case of malfunction. The Mid-course Guidance Unit (MGU) on board the RPV will also be programmed to sense engine overspeed, jet vane hardover position or actuator failure and to automatically shut down the engine.

The Teledyne XJ402 turbojet will be started by compressed air in the horizontal attitude. A pyrotechnic ignitor will be used for ignition at idle speed initially. After idle RPM and ignition have taken place the air supply is manually disconnected. The RPV is then raised to the desired test attitude (90°) by a hydraulic lift on a trailer/erector. The engine RPM is increased until hover thrust is obtained.

A trailer/erector is being designed and built to allow engine start-up in the horizontal attitude and then rotate the vehicle vertically for the tethered hover tests. Ten hover flights are planned. Fuel on board will allow the engine to operate about 10 minutes. After 6 flights the engine has to be removed and sent to Teledyne CAE to have the bearings repacked. A second engine is available as backup.

THE HORIZONTAL FLIGHT TEST PHASE

The horizontal flights will be made to verify adequate aerodynamic in-flight control of the vehicle. Five flights are scheduled this fall at the Pacific Missile Range, Pt. Mugu, California. These flights will be made from the 10,000 ft. runway on San Nicholas Island. After horizontal take-off the RPV will climb to 1000 ft. under the command and control of a ground controller.

Level flight cruise at 1000 ft. will be demonstrated. Level turns will be demonstrated at constant altitude. The RPV will be kept in sight of the ground controller during all operations. Horizontal landings will be demonstrated at the end of each flight.

An emergency recovery parachute can be used if the engine fails in flight. However, the RPV will generally be close enough to the airfield to allow dead stick landings at the field.

The flights will average about 15 minutes or less. Fuel on board will allow flights up to 35 minutes.

The RPV will have a fixed tricycle landing gear to enable horizontal take-off and landing. This will allow untethered tests at safe altitudes, later on in the program, to demonstrate transition from horizontal altitudes to vertical attitudes and the reverse. But first, tests must be performed to show that the RPV possesses adequate stability and control characteristics in horizontal flight. The RPV will be remotely controlled using the MQM 74A ground controller (modified for our RPV).

The RPV will contain the MQM 74A target drone command and control equipment. The radio receiving set is designed as a flight control receiver, consisting of the radio receiver, the command signal decoder and the antenna. The radio receiver and decoder are employed with ground station equipment consisting of a UHF transmitter and controller/coder.

Space is provided in the nose cone for the installation of two antennas, one for the AN/APX-71 identification subsystem and one for the AN/DPN-78 transponder. The identification subsystem uses an airborne transponder in conjunction with a system of electronic identification. The system provides automatic radar identification of the RPV, to all suitably equipped aircraft, surface ships and ground forces, operating within the operational range of the RPV. Additional radar augmentation is provided by the installation of AN/DPN-77 or AN/DPN-78 transponders. This subsystem is used by target tracking radars to track the target during its mission.

The RPV will use the Harpoon telemetry transmitter/receiver and conditioner. The frequencies for telemetry will be 2252.5 and 2212.5 MHz.

The ground control station equipment is normally located on site with the radar tracking equipment when out-of-sight RPV control is planned. The controller operator is positioned to utilize the radar system plotting board.

TRANSITION TEST PHASE

Transition from horizontal flight to vertical flight will be attempted first at 5000 ft to allow enough altitude margin for recovery in the event a problem arises. Support equipment will be the same as for the horizontal test phase with the exception that the control of transition will occur from a stationed helicopter in the near vicinity of the transition event. The ground control equipment will be aboard the helicopter along with a controller.

After successful demonstration of transition at altitude the RPV will be flown back to the runway for normal horizontal attitude recovery. Eventually a landing will be made at the trailer/erector on the ground. The transition test flights are planned at San Nicholas Island starting in the late fall of 1975.

SHIP INTERFACE TESTS

After completion of the transition test phase the RPV will be flown behind a naval vessel while underway at various speeds to assess the ship's air wake on the RPV's hover capability. The trailer/erector will be bolted to the fan tail of a Navy vessel for docking tests. The following classes of ships can accommodate the RPV from the fantail:

DE	GARCIA class
DEG	GROOKS class
DDG	MITSCHER class
DLG	LEAHY class
DLGN	BAINBRIDGE class
DLGN	TRUXTUN class

These ships can utilize the fantail deck area aft of the gun or missile mount. These tests are planned to start late in 1975. Five test flights are planned.

VIII. SUMMARY

Vertical attitude takeoff and landing (VATOL) offers an attractive solution to the Navy's launch and recovery of "midi" RPV's aboard ship. The NSRDC VATOL demonstration vehicle provides the Navy with a valuable tool to assess vertical docking while the ship is underway.

Jet vane control for hover flight is also an important concept that will be evaluated during flight tests. Analysis indicates that the vanes could also be used for horizontal flight on some configurations, eliminating the need for aerodynamic control surfaces. This would simplify an operational vehicle design.

The close-coupled canard delta wing configuration exhibits superior aerodynamic characteristics. Higher lift generated by the canard results in easier transition from horizontal to vertical flight. This increased lift also allows touchdown speeds for conventional runway landings.

Finally, VATOL RPV vehicles impact on ship operations is minimal in that only the edge of the deck is used for launch and recovery. Ship safety is enhanced in that jet engine exhaust is overboard. A malfunctioning VATOL RPV would drop into the sea and not crash on the ships deck.

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