OPERATIONAL SUITABILITY OF DP-2 VSTOL AIRCRAFT

Anthony A. duPont
President
duPont Aerospace Company, Inc
El Cajon, California.

Curtis B. Rath
Aerodynamicist
duPont Aerospace Company, Inc.
El Cajon, California

Abstract

The DP-2, developed by the duPont Aerospace Company, El Cajon CA, is powered by two V2500 high bypass turbofan engines. The exhaust of the two engines can be vectored through 90 degrees to provide vertical thrust for vertical take off and landing while offering the up and away performance of a transonic commercial transport. The low mixed exhaust temperature, less than 350 °F in a maximum weight hover, permits operation from unprepared surfaces such as sod or asphalt in VSTOL mode. Recently an ONR managed research program tested a 53% scale version of this aircraft in autonomous tethered hover to demonstrate controllability. The program was successfully completed with two precision hovers of over 45 seconds duration each. Performance in a typical mission is described, issues associated with VTOL operation and transition to forward flight are considered, and the effects of assumptions on the range calculations are discussed.

Introduction

The DP-2 was designed to provide vertical take off and landing capability in a transonic transport airplane. The airplane would have all the usual attributes of conventional take off and landing aircraft of this type. These attributes are long range, high cruising speed and low fuel consumption. They are achieved with a high aspect ratio swept wing, cross section area ruling and high bypass turbofan engines. The DP-2 has all of these design features plus large enough high bypass turbofan engines to provide vertical take off and landing through use of vectored thrust. The engine exhaust thrust

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can be vectored from horizontal through vertical to 15 degrees forward of the vertical for trim and thrust reversing. Control vanes located below the thrust vectoring cascade and therefore well below the aircraft center of gravity are used to vector the thrust away from the center of gravity to provide control moments much greater than those available from a bleed air jet control system.

A recently completed ONR managed research program tested a 53% scale version of this aircraft in tethered hover to demonstrate controllability. Almost all the research effort was, by Navy direction, concentrated on autonomous tethered hover. The program was successfully completed with two precision hovers of over 45 seconds duration each. Figure 1 shows a still from the test video. Under control of its onboard computer, the aircraft was required to lift-off then hover for at least 30 seconds within +/- 2 ft laterally, longitudinally, and vertically and limit speeds to less than 2 ft/s laterally and longitudinally, and less than 1 ft/s vertically. The tests were conducted on a 10 foot elevated platform with an open grating deck to minimize ground effect.

Figure 1. Still from hover video demonstrating autonomous precision hover.

The larger engines needed for VTOL operation are a significant weight penalty compared to normal engine sizes, which are almost always determined by take off climb requirements with a failed engine. Several design features were used in the DP-2 to offset, as much as possible, the additional engine weight. Since take off and landing performance no longer depends on the wing, the wing was swept back more than usual and made smaller reducing wing and tail weight. To control the rolling moment after an engine failure in hover, the engines were located side by side in the nose of the aircraft. This arrangement reduces the total wetted area of the airplane relative to conventional configurations, reducing weight and drag.

The additional engine thrust enables the airplane to cruise at higher speeds and higher altitudes than are available with engines sized to meet take off climb requirements. This is a significant advantage. An airplane with engines sized for take off climb will have its best fuel consumption per mile at a speed of about Mach 0.78 regardless of its top speed capability. The minimum fuel consumption speed of the DP-2 is about Mach 0.88, a 12.8% speed improvement. Rapid climb to cruising altitude with the increased thrust also saves fuel.

The resulting aircraft has in-flight performance competitive with conventional transonic transport aircraft with the advantage of vertical or short take off and landing. In evaluating its operational suitability, in particular in comparison to helicopters, it should be remembered that transports make money for their operators only while they are flying, not while hovering. A brief discussion of radius of action shows the range advantages possible with a VSTOL aircraft. One of the design missions for this aircraft is shown in Figure 2.

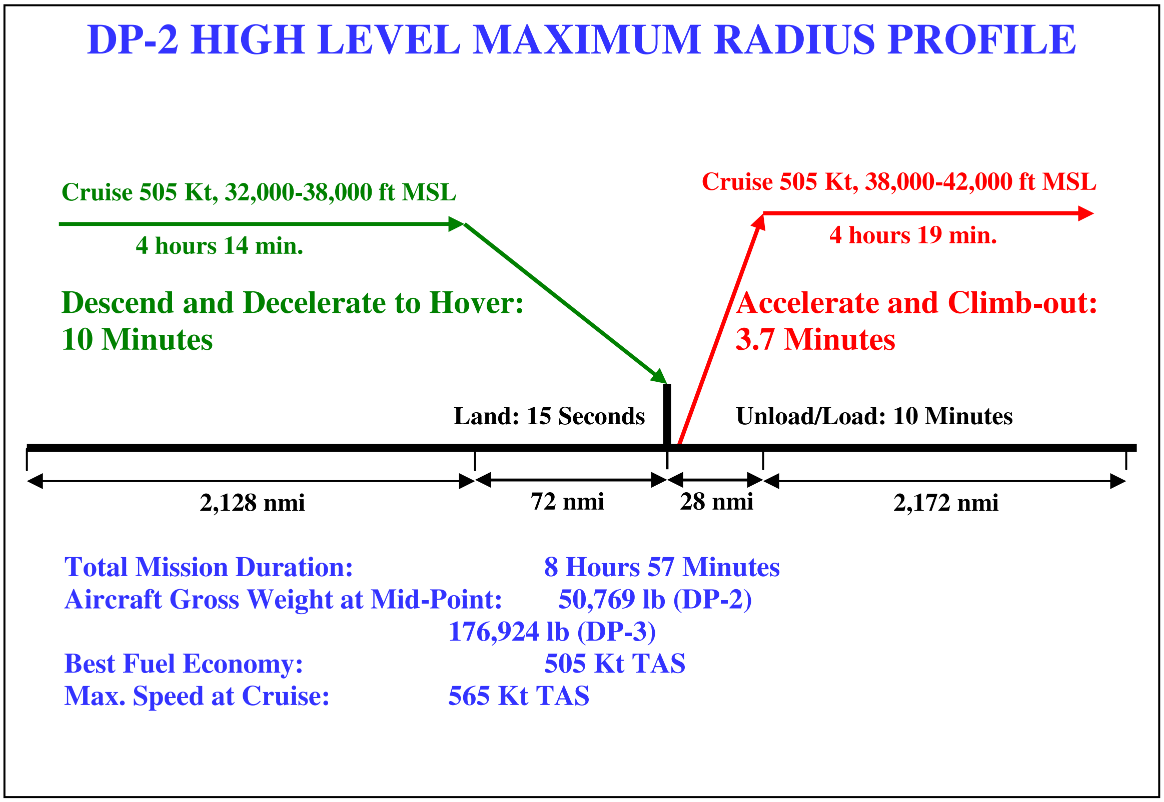

Figure 2. High altitude mission to unprepared landing site.

The mission starts with a very short take off, 800 feet over a 50 foot obstacle, if both engines are operating, or 1,800 feet if one engine fails at the critical point in the take off, accomplished by starting down the runway in forward thrust and almost immediately vectoring the thrust to 60 degrees from the horizontal followed by a normal acceleration to wing borne flight with the thrust in the horizontal position. In 4.4 minutes the aircraft is at the initial cruising altitude of 32,000 feet. Four hours and 14 minutes after take off, descent is started from the final cruising altitude of 38,000 feet, 2,128 mile from the take off point. It takes 10 minutes and 72 nautical miles to descend and decelerate to the hover. Landing from the hover can be immediately or 15 seconds later if some air taxiing to the final landing spot is required. After unloading and reloading the aircraft, nominally 10 minutes for combat troops in a DP-2, the aircraft makes a vertical take off reaching the initial cruising altitude for the return flight of 38,000 feet in 3.7 minutes. After flying 2,200 nautical miles from the mid mission point the aircraft executes a vertical landing 4 hours and 23 minutes after take off.

The DP-2 was designed for long range infiltration or exfiltration of a nominal five ton payload where a short field was available for the initial take off at a gross weight about one third higher than the maximum vertical take off weight. This capability allows for a much higher initial fuel load. Under these conditions the radius of action is 2,200 nautical miles if the entire mission can be flown at the optimum altitude for the current aircraft weight. A vertical landing and take off are accomplished at the mission mid point. If the entire mission has to be accomplished hugging the ground, nominally at sea level, which is the worst case, the radius decreases to 1,000 nautical miles.

This range performance results from efficient conventional transport design and low empty weight fraction due to all composite construction. The speed performance results from the engine sizing for VTOL operation and the low drag wing design that becomes feasible due to the vectored thrust lift.

The rest of paper focuses on aspects of arising from hover and transition to and from forward flight and the effects of assumptions on the range calculations.

HOVERING

The aircraft in hover, lowering troops by fast rope is depicted in

Figure **3**. The low mixed exhaust temperature, less than 350 °F in a maximum weight hover, permits operation from unprepared surfaces such as sod or asphalt in VSTOL mode. The exhaust flow pattern in hover is a fast moving single stream under the center of the aircraft which contacts the ground and spreads outward at a very much reduced velocity. In the region outside the vertical jet and above the outward moving ground-wash the air is relatively still, facilitating fast rope operations.

Figure 3. Depiction of fast rope exit from hovering DP-2.

In hover the downwash and outwash pattern of the DP-2 is significantly different from a helicopter or tilt-rotor. A small cross section, fast moving column of air under the center of gravity impacts the ground and spreads out laterally at a much reduced velocity. Away from the vertical column of fast moving air and above the outflow the air is relatively still. This is a much more benign environment for fast roping, as depicted in Figure **3**, and other operations in hover such as winching up personnel or cargo.

Outwash data from the half size DP-1 was obtained on a 4.5 foot high test stand, with a rake located 20 feet aft from the center of the vertical exhaust stream, on the engine center line, in single engine operation at 2,628 lbs uninstalled gross thrust. Figure 4 shows that the peak velocity at the scaled cargo door location is less than 60 knots, and the height of the outflow is close to the ground, from knee high to at the most waist high when scaled up to the DP-2. The temperature was nearly constant through the profile at 135 ^{o}F.

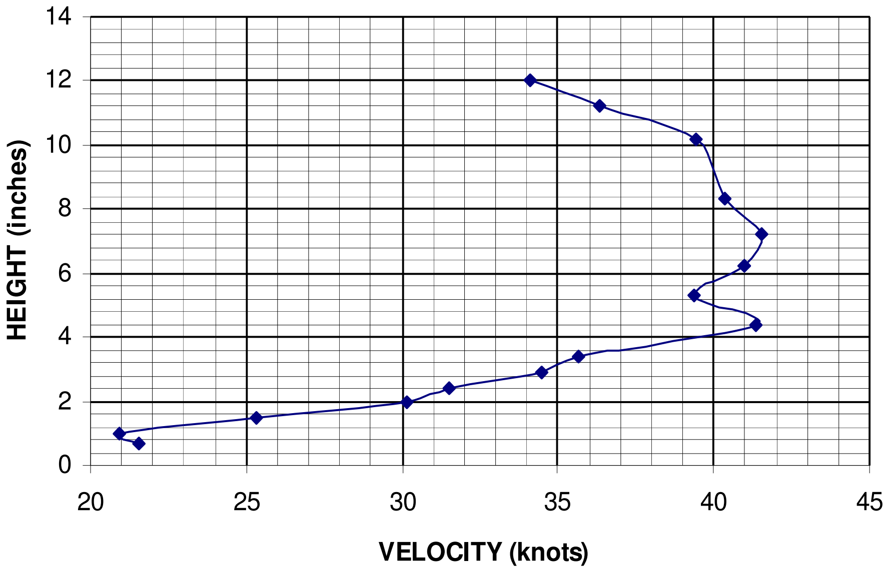

Figure 4. Outwash profile at cargo door location, single engine, 2628 lbs thrust.

More recent testing in ground effect provided data with the aircraft directly at ground level with both engines operating. This data was measured by five rakes spaced on six inch increments on each side of the aircraft centerline 21 feet aft of the nozzles. At similar total thrust level, 2,744 lbs, compared to the single engine test the outwash velocity is considerably higher, 88 knots maximum (Figure 5. The temperature was 139 ^{o}F. The higher velocities are attributed to the lower height. Height above ground rapidly diminishes the peak velocities.

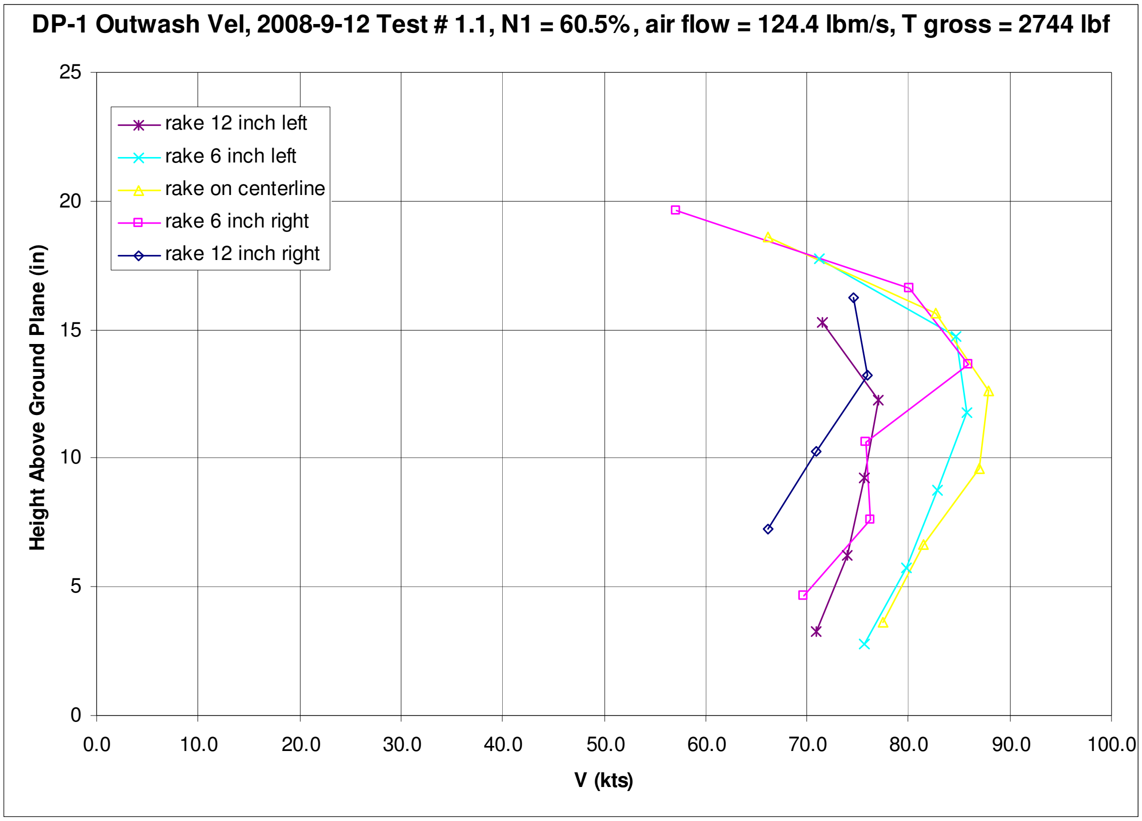

Figure 5. Jet outwash velocity, both engines operating, 2,744 lbs total uninstalled gross thrust, zero height.

On the ground at maximum DP-1 total hover thrust, 7,500 lbs, the peak measured velocities were 157 knots (Figure 6). At this high power setting, the temperature recorded at the rakes was 183 ^{o}F.

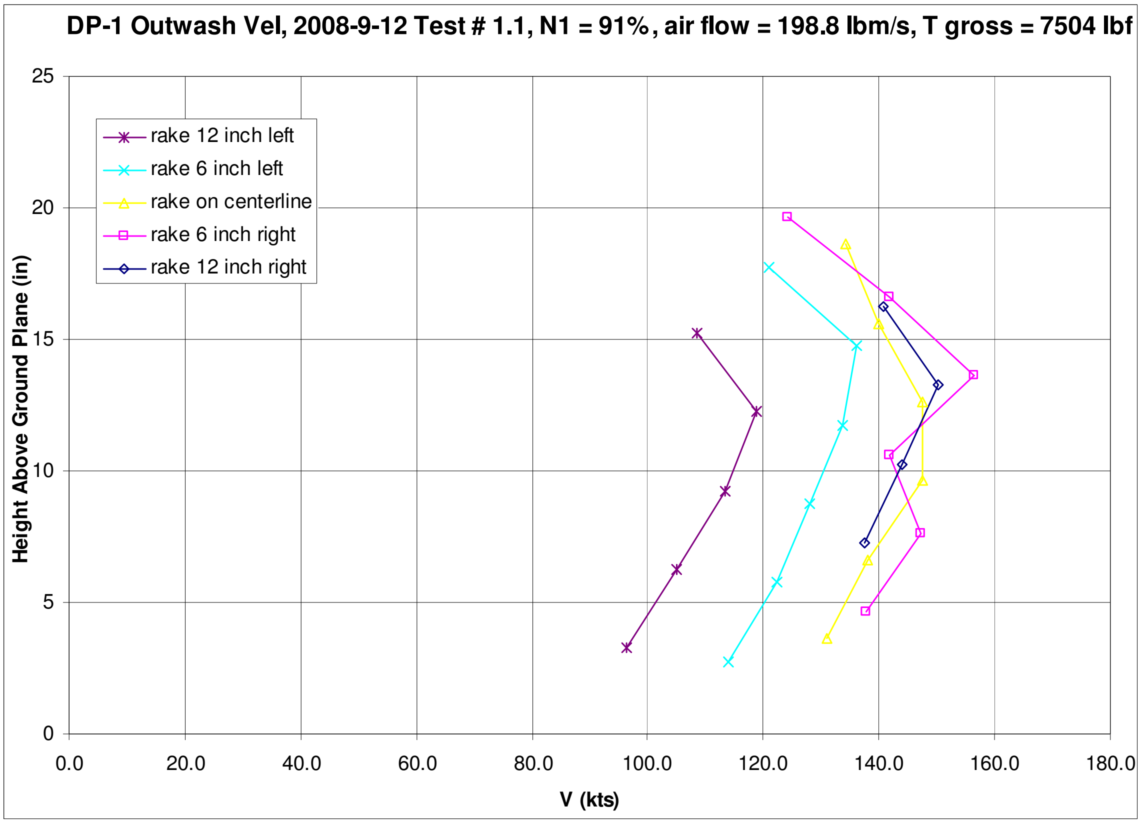

Figure 6. Jet outwash velocity, both engines operating at full hover thrust, 7,500 lbs total, zero height.

A practical demonstration of fast roping capability was conducted in 2003 in which the plane captain walked up and grabbed the fast rope while both engines were operating at hover thrust at 10.5 feet altitude, Figure 7. Close observation of the test video shows that the wind on his clothing is primarily on his legs. The end of the rope was not weighted. The sensation of walking around underneath the aircraft is similar to wading in a trout stream. There is a noticeable force on your lower legs, so you have to keep your feet near the ground as you move around.

Figure 7. Test of fast rope below DP-1 at cargo door station at hover thrust.

Engine Failure During Transtion

If an engine fails during transition from hover to forward flight the pilot can either fly out on the remaining engine if he is above the upper boundary of the keep out zone, familiarly termed the “dead man” zone, or land safely if he is below the lower boundary. The upper and lower boundaries of the “dead man” zone have been determined analytically and are compared to heavy rotary wing aircraft in Figure 8.

The upper boundary of the “dead man” zone is determined by the ability to accelerate to flying speed from that combination of speed and altitude without contacting the ground. The lower boundary is the combination of speed and altitude that permit landing without exceeding the design limits of the landing gear, 15 ft/s rate of descent.

The ability of a pilot to accelerate out from and slow to the hover while staying below the lower boundary of the “dead man” zone has been demonstrated by piloted simulations. Typical results are shown in Figure 9 and Figure 10

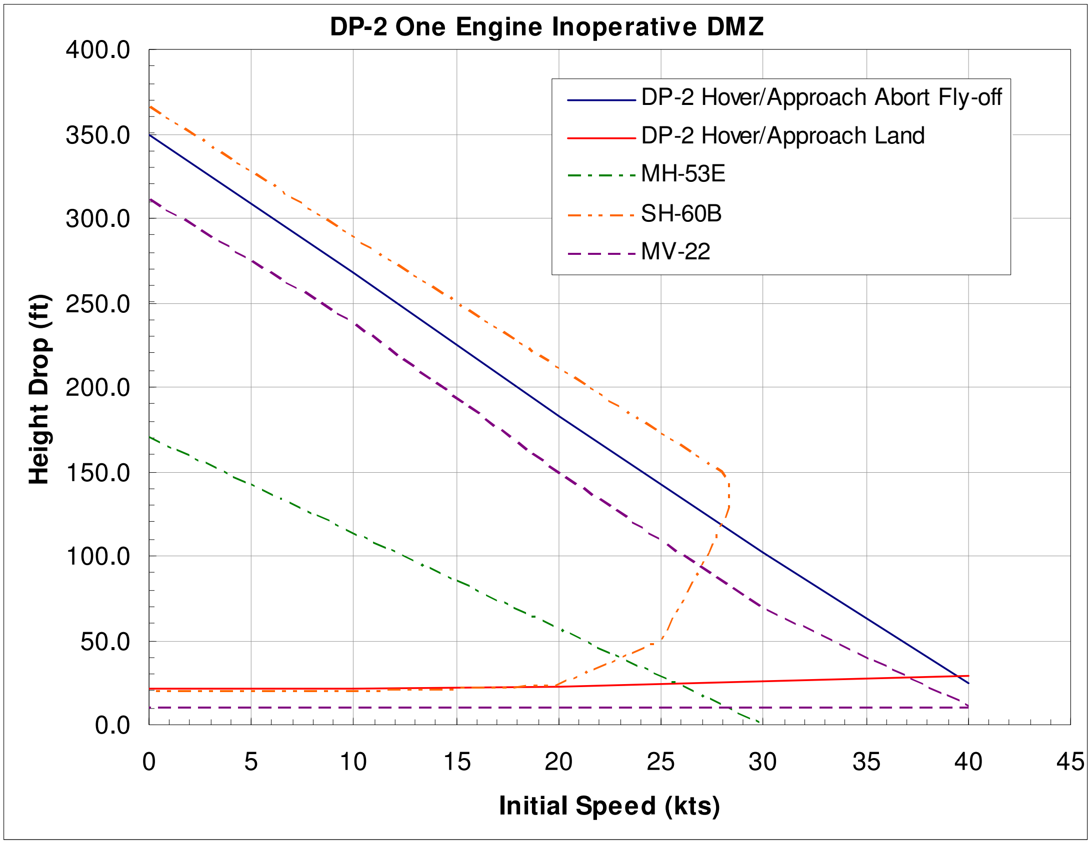

Figure 8. "Dead Man" zones, DP-2 at 48,200 lbs landing weight.

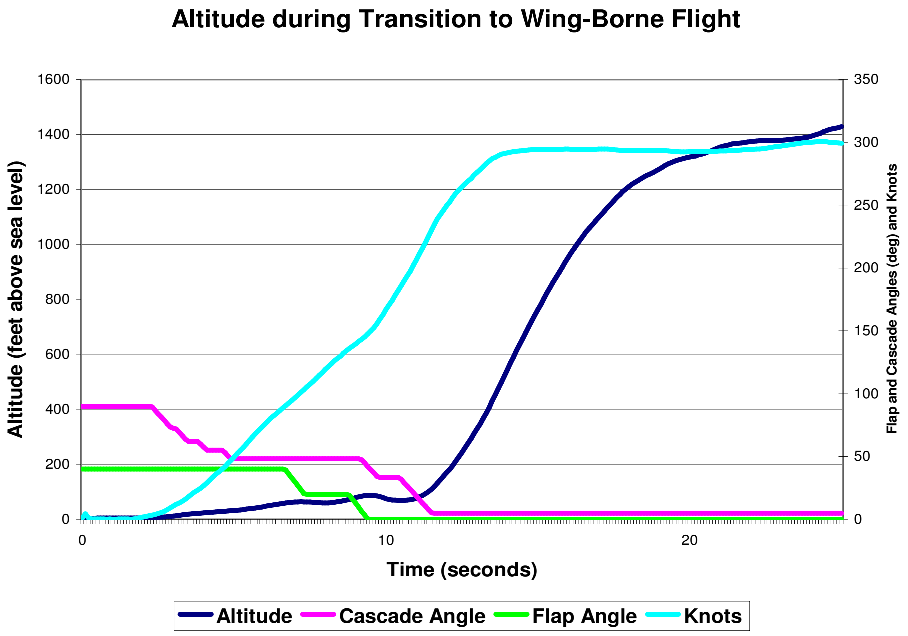

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Figure 9. Acceleration from hover.

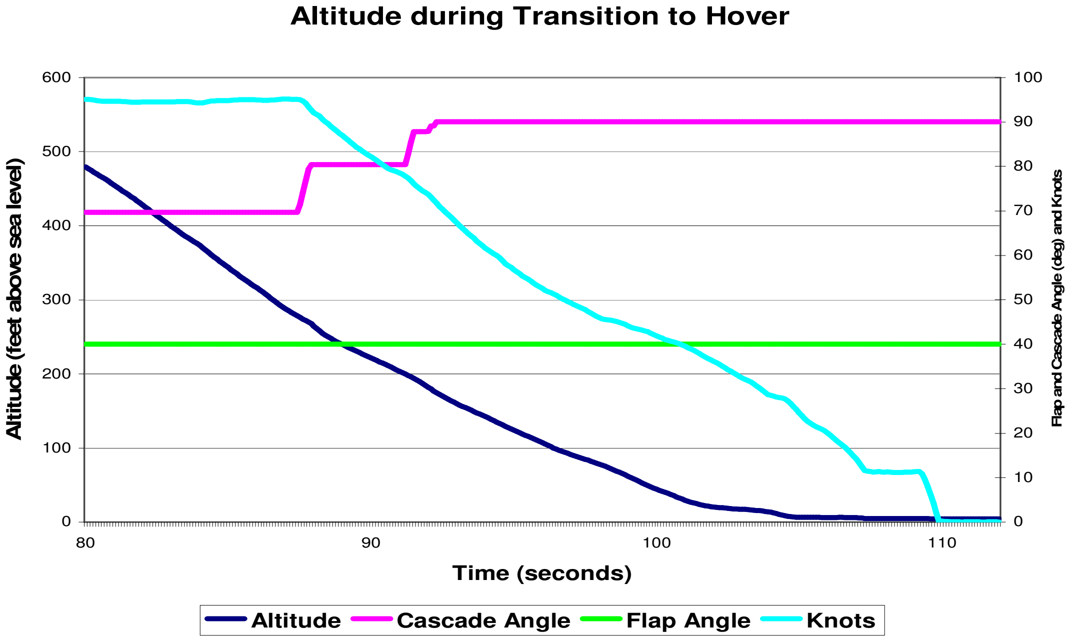


Figure 10. Deceleration to hover.

The ability of a pilot to duplicate the analytical simulation of recovery from an engine failure at near hover conditions is shown in the simulation results of Figure 11.

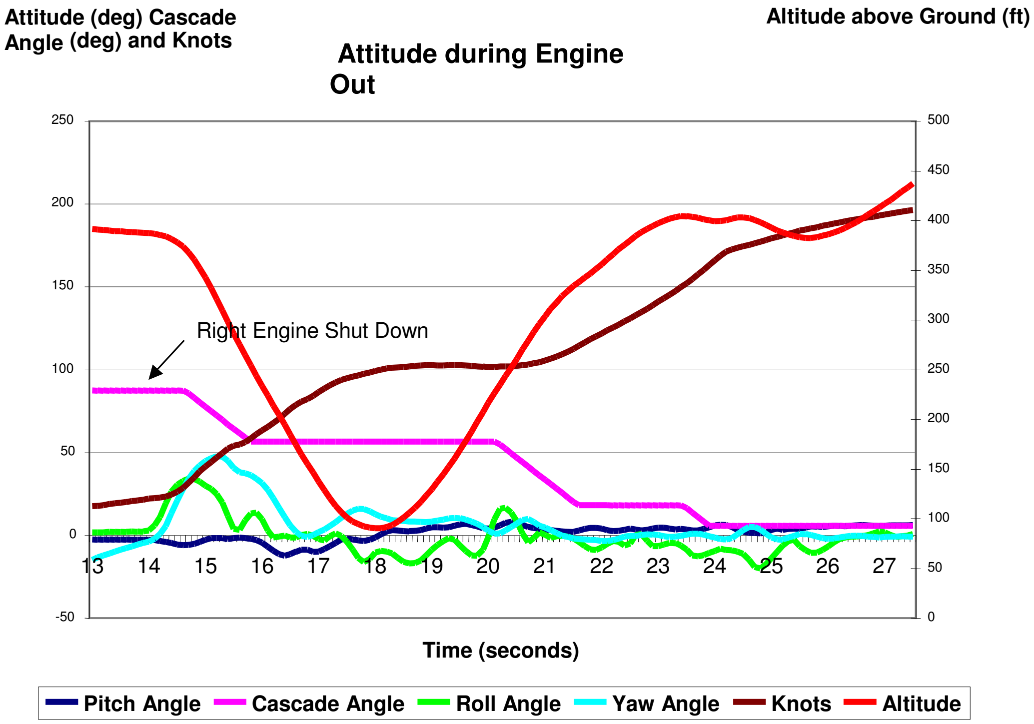


Figure 11. Recovery from an engine failure.

Operating in Brownout Conditions

An important question is the ability to operate in brownout conditions. Figure 12 shows a V-22 hovering above the dust cloud it has generated, and Figure 13 shows one way of dealing with this problem; the V-22 is air taxing fast enough to stay ahead of the dust.

Figure 12. V-22 in hover over dust cloud.

Figure 13. V-22 running ahead of dust cloud.

If a vertical landing has to be accomplished in brownout conditions, synthetic vision provides a method of doing it safely. Synthetic vision has been certified by the FAA for business aircraft. Using it is just like making a vertical landing in the simulator, as shown in Figure 14. An important feature of high bypass turbofan engines is the fan's ability to centrifuge particles away from the gas generator to avoid serious FOD. The impact of rocks on fan blades is much less detrimental than it is on the smaller compressor blades.

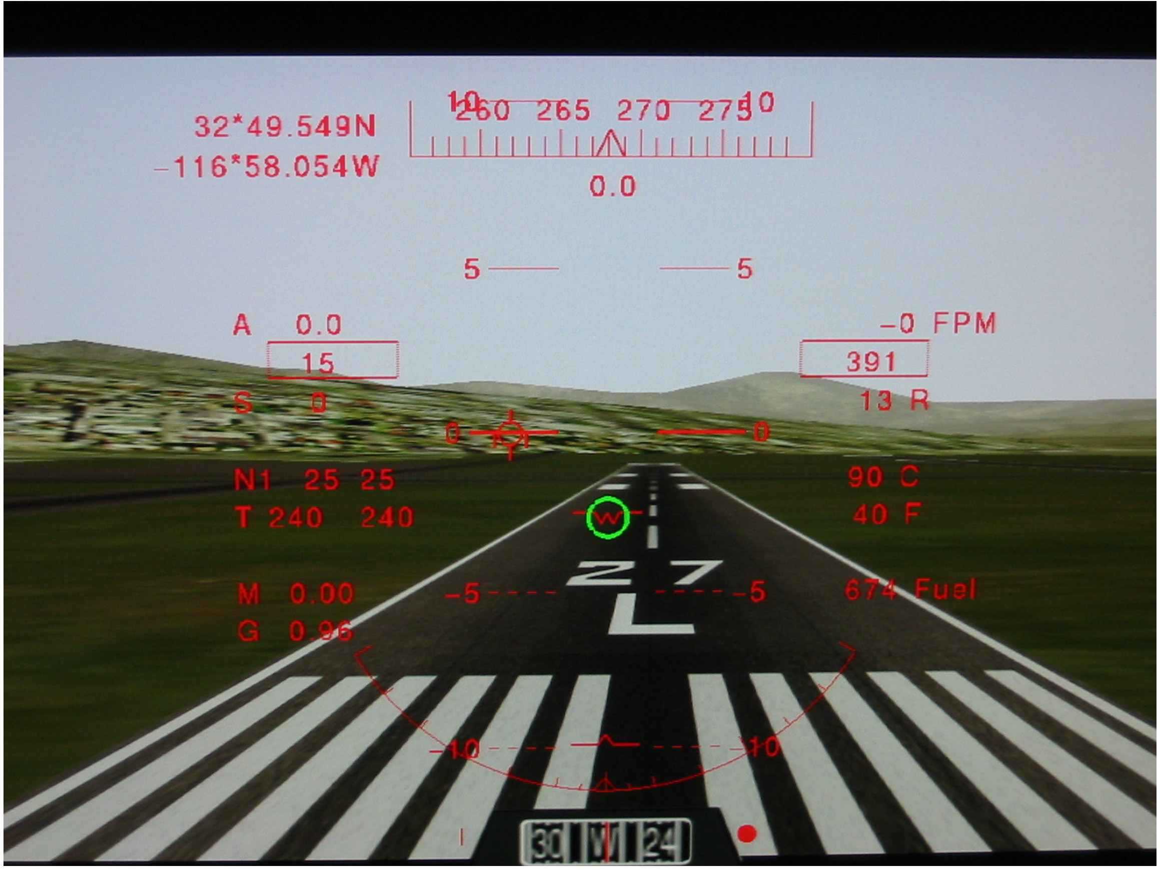
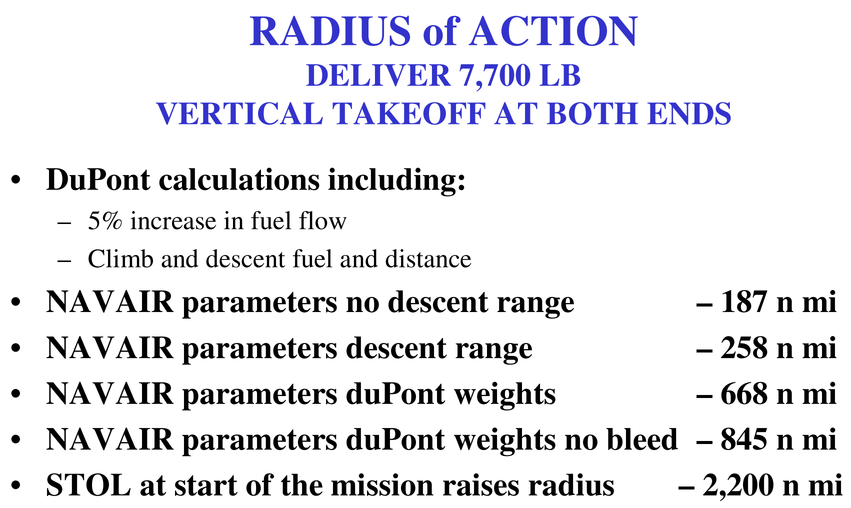


Figure 14. Still from simulation video.

Effects of Assumptions on Range

NAVAIR has studied the DP-2 and calculated its radius of action in a helicopter type mode where a vertical take off instead of a short take off is required at the beginning of the mission. The radius of action that resulted from their work is 187 nautical miles presented in reference 1. This radius is typical of helicopters. If more realistic assumptions are used the radius is increased considerably as shown in Table 1.

Table 1. Radius as affected by assumptions.



RADIUS of ACTION

DELIVER 7,700 LB
VERTICAL TAKEOFF AT BOTH ENDS

- **DuPont calculations including:**
    - 5% increase in fuel flow
    - Climb and descent fuel and distance
- **NAVAIR parameters no descent range – 187 n mi**
- **NAVAIR parameters descent range – 258 n mi**
- **NAVAIR parameters duPont weights – 668 n mi**
- **NAVAIR parameters duPont weights no bleed – 845 n mi**
- **STOL at start of the mission raises radius – 2,200 n mi**

NAVAIR assumed no descent range, maybe that is a realistic assumption for helicopters, but the descent range for a transonic aircraft is considerable, extending the radius from 187 to 258 nautical miles.

NAVAIR also had some very high component weights derived from their group of historical aircraft. This was especially true for the electrical system, flight controls, tail surfaces and fuselage. When more realistic weights are used (based on measured DP-1 component weights) the radius is extended to 668 nautical miles from 258 nautical miles.

NAVAIR assessed a 4% bleed penalty, which reduced the take off thrust and therefore the take off weight by 2,569 pounds. There are no systems on the DP-2 which use bleed air other than the air conditioning system, which typically does not use bleed air at sea level. Even if bleed air were used for air conditioning it would be turned off for a maximum performance take off. If it were used, the air conditioning bleed air results in a small fraction of 1 % thrust penalty, 0.36%. Eliminating the bleed air penalty assessed by NAVAIR increases the radius to 845 nautical miles.

With an STOL takeoff and a higher fuel load the radius is extended to 2,200 nautical miles with more payload capacity.

Conclusions

The DP-2 has range and speed competitive or superior to conventional fixed-wing transports and the versatility of short or vertical take-offs and landings. The jet ground outwash is manageable and diminishes quickly with height above the ground. The keep-out zone for one engine inoperative scenarios is similar to heavy rotary wing aircraft.

References

[1] Kinzer, J., “The DP-2 Jet Lift vertical Takeoff and Landing Aircraft Advanced Technology Demonstration Program”, presented at the American Helicopter Society 64th Annual Forum, Montreal, Canada, April 2008.