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ABSTRACT

Using as a baseline the 30-passenger D326 tilt rotor proposed by BHT for offshore oil support, a short takeoff, vertical landing version, the D326 S-V, has been investigated. For comparison purposes, a helicopter with the same level of technology has also been synthesized.

For a 300-nautical-mile radius offshore oil support mission, the D326 transports 30 passengers, the D326 S-V 45 passengers, and the helicopter 52 passengers. Looking at productivity, defined as $\frac{\text{payload x cruise speed}}{\text{weight empty}}$, the D326 S-V is 39 percent more productive than the D326 and 87 percent more productive than the helicopter.

It is concluded that a short takeoff, vertical landing tilt rotor offers a highly productive, energy-efficient aircraft that could find many commercial and military applications. Additional tests of the XV-15 are needed to optimize techniques for short takeoff and vertical landing so that the useful load of aircraft such as the D326 S-V can be maximized.

1. Introduction

The unique combination of high hover performance and efficient long range cruise of the tilt rotor has been confirmed by the Model XV-3 during flight tests conducted in 1960 and, most recently, by the completion of the Bell Helicopter Textron (BHT) flight tests of the XV-15 proof-of-concept tilt rotor, Figure 1. The XV-15 reached a level flight speed of approximately 300 knots in June 1980 and has been evaluated throughout the tilt rotor flight and conversion regimes. It has performed two g's during maneuvers and has demonstrated satisfactory handling qualities during a variety of simulated emergencies. Two XV-15s were manufactured. Both aircraft have completed contractor tests and have been delivered to NASA for continued envelope expansion and operational suitability investigations.

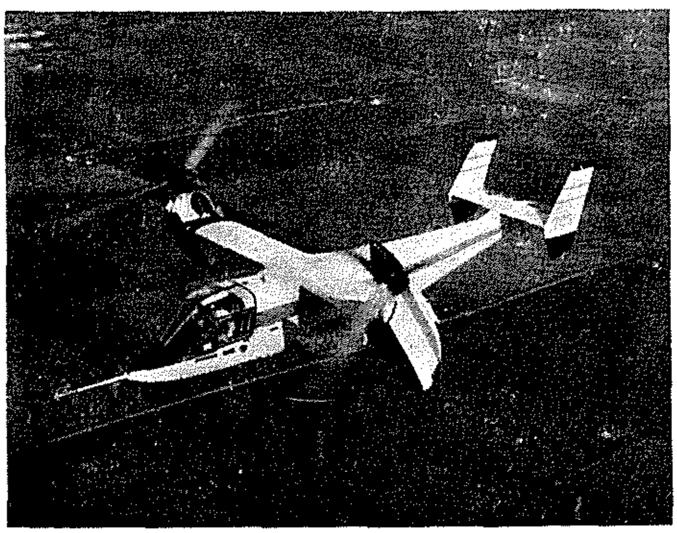

Figure 1. XV-15 Tilt Rotor Converting to Cruise Flight.

The success of the XV-15 flight tests encouraged BHT to design, late in 1979, a commercial tilt rotor, the Model D326, Figure 2, specifically for offshore oil and commuter airline applications. In cruise flight, the Model D326 has a lift-drag ratio over twice as high as that of comparable transport helicopters. The rotors, acting as propellers, have a propulsive efficiency comparable to a well-designed propeller, giving the D326 a cruise speed of 290 knots at 20,000 feet and a range per pound of fuel consumed twice as great as that of a helicopter. These performance attributes of high speed and long range promise to solve the off-shore oil industry's transportation needs, which will become ever more severe as oil exploration moves farther offshore.

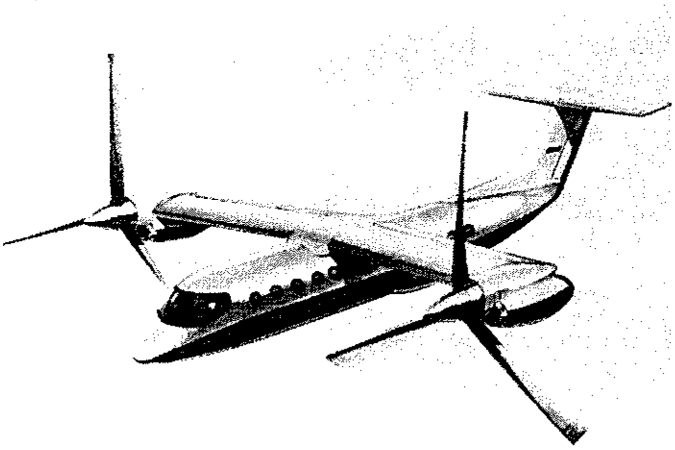

Figure 2. Model D326 Commercial Tilt Rotor.

Helicopter operators serving the offshore oil industry indicated, during subsequent discussions, that helicopter flights frequently originate at commercial airports. For instance, several operators serve the North Sea oil fields from the Aberdeen, Scotland airport. In other cases, the helicopters take off from heliports that are sized for a high volume of movements per day and, therefore, offer at least a 1000-foot takeoff run. For example, the heliport at BHT's main plant in Fort Worth, Texas, Figure 3, has a length from fence to fence of approximately 1100 feet.

The ready availability of fields that permit at least a 1000-foot takeoff run led to speculation about increasing the useful load of a tilt rotor. If the requirement to take off vertically is relaxed, the useful load can be increased until one of two limitations is reached. Either the gross weight reaches that at which the takeoff run to clear a 35-foot obstacle is 1000 feet, or it reaches the weight which, after subtracting the fuel consumed enroute, permits the tilt rotor to land and take off at midmission with the desired level of vertical flight performance.

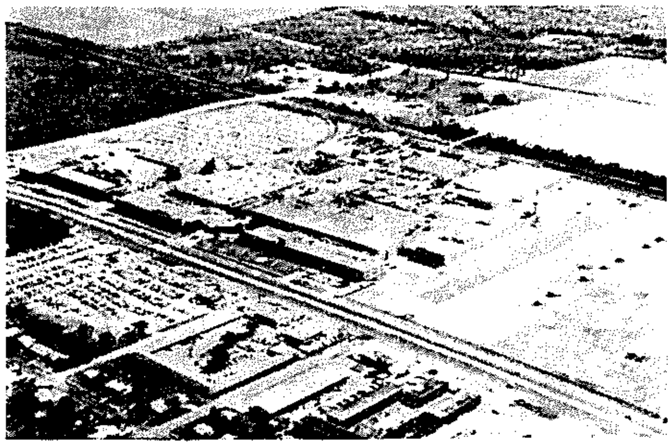

Figure 3. BHT Main Plant and Heliport.

There are many other applications, both commercial and military, where a short takeoff would be acceptable, but where good vertical flight performance is mandatory at some point in the mission. For instance, operating as an air taxi, such an aircraft could originate at a major hub airport and carry passengers to outlying communities where it would be desirable to land as close to the population center as possible, preferably at a heliport.

For search and rescue, takeoff is frequently from a fixed-wing airfield. By making a short takeoff run with a large fuel load, the tilt rotor could search for extended periods of time. Upon locating stranded personnel, the aircraft must hover out-of-ground effect to use a rescue hoist. If the gross weight is too high, fuel weight can be reduced by use of jettisonable fuel tanks or a fuel dump system.

Looking at the military logistics transport problem, should conflict occur in Europe, supplies could be unloaded from ships in western France and transloaded to tilt rotors of the type we are considering. Making a short takeoff run, they could fly at high speed to the vicinity of the combat area landing wherever a helicopter can land and delivering the supplies close to the combat units. On the return trip, the aircraft could operate as a VTOL medical evacuation transport.

The unfortunate attempt by the U.S. military to rescue the hostages held in Teheran is another obvious military application for an aircraft of this type. Following a short takeoff from the deck of the aircraft carrier Nimitz, tilt rotors of the size described in this paper could have flown to Teheran, made a vertical landing to rescue the hostages, and then returned to the Nimitz without refueling. The changing international political situation indicates that we can anticipate an increasing number of events, such as the occupation of the U.S. Embassy in Teheran, that will make the need for suitable rescue aircraft urgent.

It has long been recognized that the useful load of helicopters and tilt rotors can be increased by making a short takeoff run. A helicopter is probably operated as an STOL more often than as a vertical takeoff aircraft, particularly when it operates at the gross weight at which it can hover in ground effect but not out of ground effect. If the helicopter gross weight is further increased, it can still take off by making a short ground run. The advantages of operating a helicopter as an STOL are discussed at some length by Mil', Reference 1, in which he compares the STOL performance of a helicopter with a STOL fixed-wing aircraft.

During flight evaluation of the XV-3, Figure 4, the U.S. Air Force recognized the potential of STOL operation for a tilt rotor and conducted a series of STOL tests. The results of these tests are reported in Reference 2, where it is noted that the tilt rotor has a number of attributes that make it well-suited for STOL applications.

During more recent design studies conducted by BHT under NASA contract, the STOL potential of the tilt rotor was well-documented, Reference 3. In this study, the wing, drive system, engines, and rotors from a tilt rotor designed for VTOL were retained, while the balance of the aircraft was modified into an STOL. Substantial gains in useful load resulted, and a number of advantageous stability and control characteristics were identified.

It is against this background of tilt rotor design studies and flight tests that it was decided to investigate the design modifications to the D326 that would be necessary to capitalize on its increased useful load if a short ground run could be made for takeoff. With these modifications for short takeoff, the necessary midmission hover performance to operate from offshore oil rigs would be retained. This paper presents the initial results of this investigation.

2. XV-15 Short Takeoff Performance

Preliminary short takeoff tests have been conducted with the XV-15. For each takeoff, the pilot monitored engine torque to limit power available. Tests were conducted with power limited to as low as 50 percent of maximum continuous power. Figure 5 shows the XV-15 with rotors converted 30 degrees forward as it rotates following a short ground run.

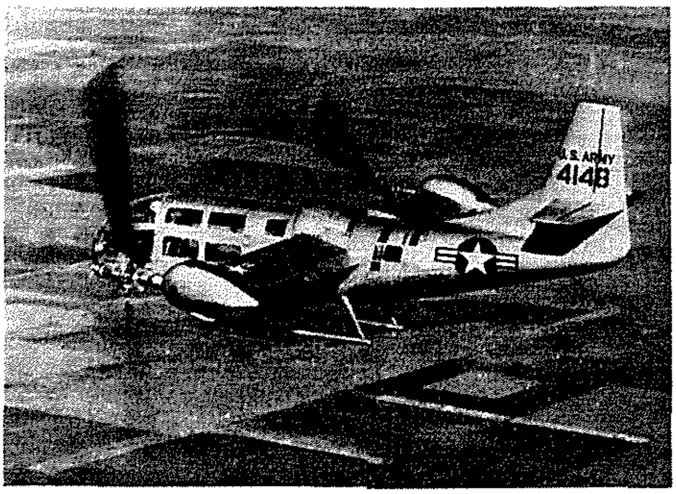

Figure 4. XV-3 Tilt Rotor.

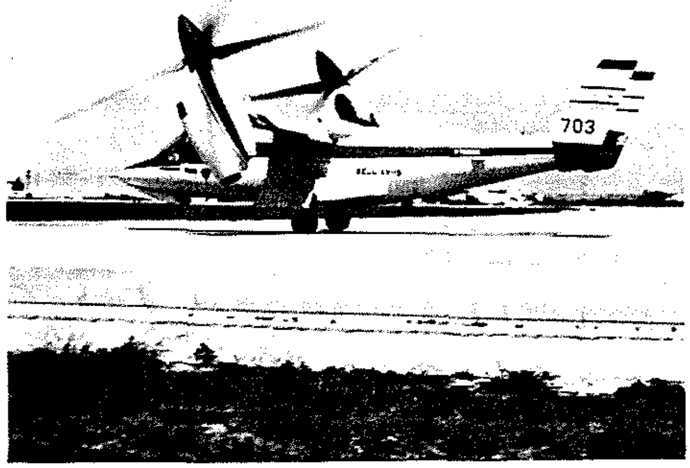

Figure 5. XV-15 Initiating Rotation During Short Takeoff Evaluation.

Figure 6 shows a time history of the short takeoff with power limited to 70 percent of maximum continuous power. Airspeed increased rapidly to the rotation speed used for this test, 65 knots. The XV-15 was airborne 13.5 seconds after start of the ground run. Integrating time and airspeed gives a distance to liftoff of 620 feet and a distance to clear a 35-foot obstacle of 1250 feet. Shortly after breaking ground, the XV-15 landing gear is retracted and it is converted to cruise configuration. While these tests were preliminary and no effort was made to minimize takeoff distance, they did confirm the excellent performance and handling qualities of the XV-15 while making short takeoffs at power settings substantially less than those needed for vertical takeoff.

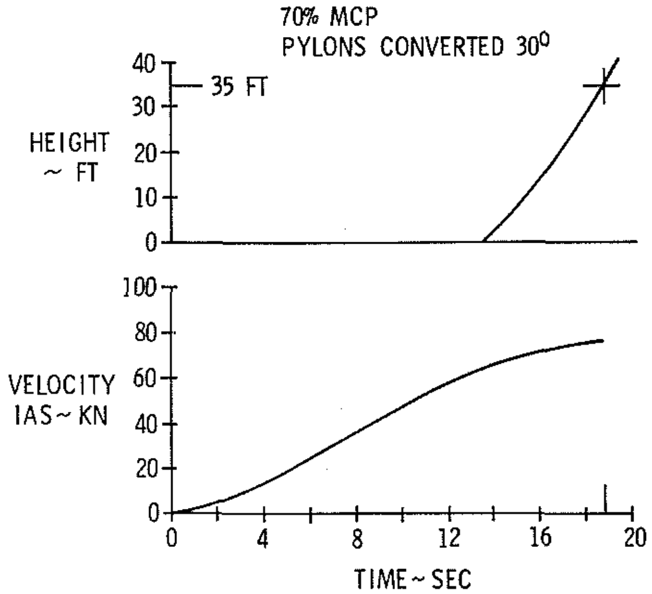

Figure 6. Time History of XV-15 Short Takeoff at Reduced Power.

3. <u>Tilt Rotor Suitability for Short Takeoff</u>

There are many inherent characteristics of a tilt rotor that make it particularly well-suited to operate as a short takeoff aircraft.

- When partially converted, the large static thrust of the rotors gives a high forward acceleration while retaining a substantial component of thrust in the vertical direction to assist in liftoff. Figure 7(a) shows the force vectors from the rotors of the D326 as it starts its takeoff run partially converted. With the pylons converted 25 degrees and with full forward cyclic, the rotor tip path planes are inclined 37 degrees. The component of thrust providing propulsive force is 0.60T, which (assuming that the rotor thrust is approximately equal to the gross weight) gives a 0.60g initial forward acceleration. At the same time, the component of thrust acting vertically to provide lift is 0.80T. Only a 20 percent reduction in vertical thrust gives 60 percent of the rotor thrust for forward propulsion.

  During a takeoff run, at rotation speed, aft cyclic is used to rotate the fuselage 12 degrees nose up. With six degrees aft cyclic pitch, the rotor tip path planes are now inclined seven degrees forward, Figure 7(b). The forward component of rotor thrust is 0.12T, sufficient to continue accelerating the aircraft, while the vertical component is increased to 0.99T, very close to 100 percent of the available rotor thrust.

- The large control forces available through the direct cyclic control of the rotors assures strong and precise control, even at zero airspeed. This overcomes one of the principal deficiencies of conventional fixed-wing STOL aircraft, that of providing sufficient control at low airspeeds.

- By varying the conversion angle, a wide range of approach flight paths are available to the pilot. This has been demonstrated by the XV-3 and the XV-15 and enables the tilt rotor to operate outside of the normal fixed-wing aircraft approach patterns.

- Both in takeoff and cruise flight, the tilt rotor is unusually quiet, an essential attribute if it is to operate from community centers. The absence of main rotor overlap and a tail rotor eliminates noise generated by rotor interference. The rotor tip speed in cruise is reduced to approximately 80 percent of takeoff tip speed, further reducing the noise.

- The rotor transmissions are interconnected so that, in case of engine failure, the remaining engines will continue to drive both rotors. There is no adverse yaw following engine failure and, consequently, pilot workload is much reduced.

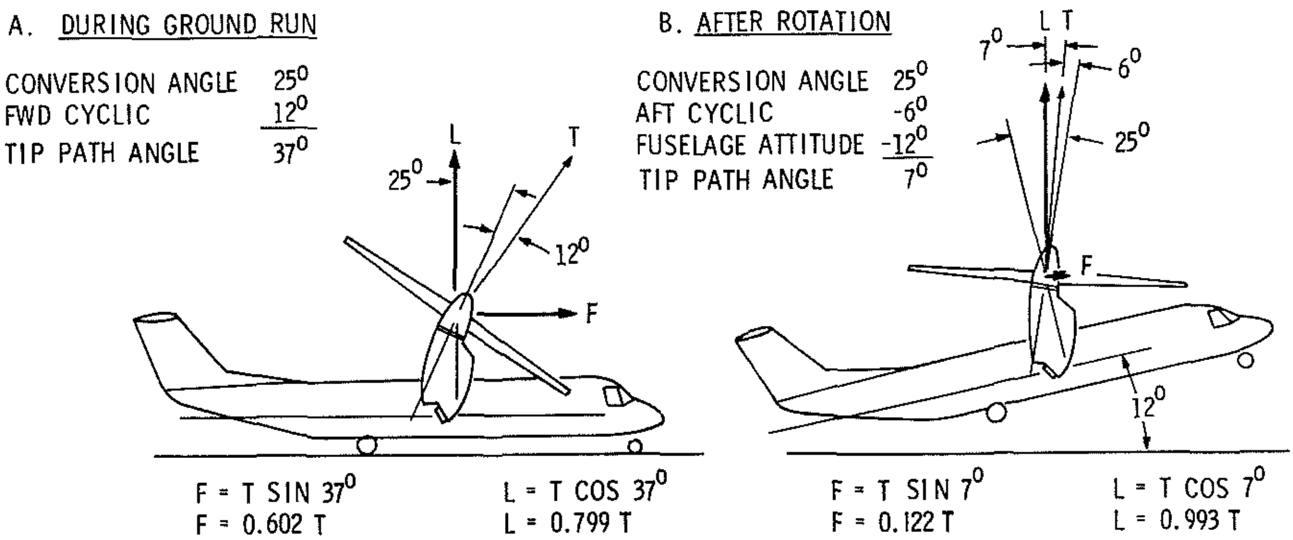

Figure 7. Rotor Force Components During Short Takeoff.

- As fuel is burned off, the tilt rotor can revert to its vertical operational mode to take advantage of smaller takeoff and landing areas. This offers interesting possibilities to increase the applications where the aircraft can be effectively employed.
- As speed is increased from hover, the side-by-side rotors require significantly less power to create thrust. This occurs because of the decrease in induced power from the high effective aspect ratio of the principal lift-producing devices, the rotors. This favorable characteristic of helicopters with side-by-side rotors, such as the McDonnell XHJH-1 and Kamov KA-22 "Hoop," has been noted many times in the literature and has been confirmed by XV-3 and XV-15 flight tests.

For the case of the XV-15, several speed-power polars are shown in Figure 8. The speed-power polar with the rotors in vertical flight configuration (90 degrees) illustrates that by accelerating to the relatively low speed of about 40 knots, the XV-15 power required to maintain level flight is reduced to approximately 50 percent of the power required to hover. This figure also shows the large increase in speed that occurs as the rotors are converted at constant power. If, for instance, power is held at 1600 shp, as the rotors are converted, the speed will increase from approximately 90 to 180 knots CAS at constant wing flap angle.

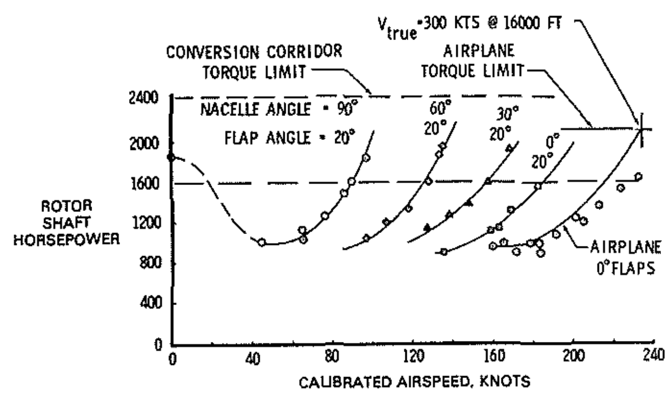

Figure 8. XV-15 Speed-Power Polars at Constant Conversion Angles.

4. Short Takeoff-Vertical Landing Derivative of the D326

The baseline D326 VTOL was designed to carry 30 passengers at a cruise speed of 290 knots for a 300-nautical-mile radius. It hovers at 1000 feet out of ground effect on a ISA +20°C day at a takeoff gross weight of 37,000 pounds. The level of technology upon which the twin-engine design was based is contemporary, and the latest version of the General Electric T64 engine is installed. Designed specifically to serve the offshore oil industry and commuter airlines, the D326 is described in greater detail in Reference 4.

An investigation of the performance demands of a short takeoff, vertical landing derivative of the D326 (referred to hereafter as D326 S-V) led to the conclusion that the critical design condition would be engine failure during takeoff from an oil rig. This would establish the required combination of installed engine power and associated midmission gross weight. As a design constraint, it was decided that no changes would be made to the rotors and drive system of the basic D326, but that alternate engine installations could be considered.

Since one-engine-inoperative performance is critical at midmission, the benefits from installing more than two engines were investigated. The D326 transmission design power is 6850 shp. If this power rating were selected as the installed power with one engine inoperative, the maximum weight at midmission can be determined. Table 1 shows the shaft horsepower required for two, three, and four engines in the D326 S-V. The power ratings are predicated on the assumption that the two and one-half minute OEI rating of the engines is 120 percent of the intermediate rated power (IRP).

Table 1. Installed Engine Power for Maximum Midmission Hover Performance

	Number of Engines		
	2	3	4
OEI SHP[1]	6850	6850	6850
IRP Total Installed[2]	11417	8562	7611
IRP/Engine	5708	2854	1902

[1]D326 transmission rating is 6850 shp
[2]2-1/2 minute OEI rating = 120% IRP

Table 1 shows that for the twin-engine version of the D326, an engine with an IRP of 5708 shp would be required to maximize the midmission hover performance. In reality, the T64 engines selected for the D326 have an IRP of 4330 shp. It is this power rating that gives the D326, in its original VTOL configuration, the hover out-of-ground-effect performance at takeoff originally specified, 1000 feet, ISA + 20°C day.

If a tri-engine version of the D326 were to be designed, an engine with an IRP of 2854 shp would be required, whereas if a four-engine version were designed, an engine with 1902 shp would be required.

It is desirable in a tilt rotor to install the engines in the wing tip nacelles, so that each engine drives directly into the transmission. This unloads the interconnect shaft during normal operation and provides an additional element of safety in the unlikely event of interconnect shaft failure. It has been shown by flight simulation studies that it would be possible to continue to fly a tilt rotor following failure of the interconnect shaft, since the rotors do not overlap. Therefore, a four-engine configuration was selected for the D326 S-V.

Having established the installed power to provide 6850 shp with one engine inoperative, the corresponding D326 S-V gross weight to hover IGE was found to be 40,700 pounds. Hover IGE with one engine inoperative is a criterion found to fairly represent the zero wind takeoff performance of a helicopter or tilt rotor from a restricted area such as an oil rig platform, assuming that one engine fails at the most critical point in the takeoff path.

With the midmission gross weight set at 40,700 pounds, and assuming that the design will be optimized around the same 300-nautical-mile radius with 45-minute fuel reserve as was used for the D326, the takeoff gross weight can be determined. Several design iterations of the D326 S-V were performed to adjust the weight empty for the installation of four engines and for the increased number of passengers that can be carried. It was found that a 45-passenger version with the drive system, rotors, and other equipment features of the D326, as originally derived for the offshore oil mission, would have a weight empty of 27,238 pounds. The additional 15 passengers are accommodated by plugs added to the D326 fuselage just forward and just aft of the wing, as shown in Figure 9. The weights of the original D326 and the D326 S-V are compared in Table 2.

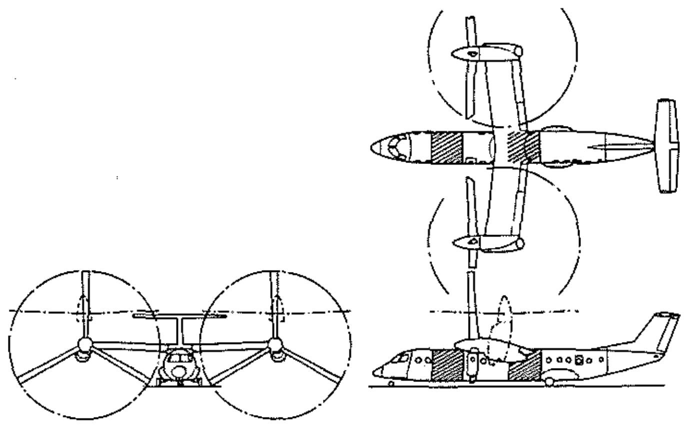

Figure 9. Model D326 S-V.

Table 2. Weight Comparison

	D326	D326 S-V
Rotor	2905	2905
Wing	2598	2598
Tail	488	488
Body	3708	4420
Landing Gear	1500	1713
Flight Controls	1363	1363
Engine Section	574	724
Propulsion	5413	6253
Instruments	293	313
Hydraulics	294	327
Electrical	965	1000
Avionics	458	458
Furnishings & Equipment	2642	3190
Environmental Control	722	918
APU	338	338
Trapped Fluids	212	230
Weight Empty	24473	27238
Design Gross Weight	37000	43300

In considering the changes in weight empty in progressing from the 30-place D326 to the 45-place S-V version, there are four areas that deserve comment.

- The airframe weight is increased to reflect the change in fuselage length and structure to support 15 additional seats. It is significant that the wing weight is not changed, since it is designed primarily by stiffness and the rotor thrust acting at the tips of the wing in vertical flight. Since the drive system power rating, the rotor maximum aerodynamic thrust, and the stiffness required in cruise flight are the same for the two configurations, the wing weight is unchanged.
- The landing gear weight is increased to reflect the increase in design gross weight. Normal design synthesis methods are used to arrive at the new landing gear weight.
- The engine section and propulsion system group weights are increased to account for the added weight of the four-engine installation with its associated cowling, firewalls, drive system, and accessories.
- Other changes are made to the hydraulics, electrical, environmental control system, furnishings and equipment to account for the increased fuselage length and number of passengers carried.

Having established the D326 S-V weights and OEI performance at midmission, it is now necessary to look at the takeoff performance. Figure 10 shows the rotor thrust and wing lift during a short takeoff at 1000 feet, ISA + 20°C, plotted as a function of distance from start. The maximum aerodynamic rotor thrust is decreased to 95 percent to remain in the linear range, and a further reduction of approximately 10 percent is made to provide a margin for roll control. The resulting rotor thrust is the maximum that can be used for lift and forward propulsion.

During the ground run prior to rotation, the maximum rotor thrust is limited by the transmission torque limit. As the ground run commences, two important aerodynamic effects occur. First, the side-by-side rotor configuration of the tilt rotor, as has already been noted, decreases substantially the induced power required at low forward speeds. This increases the rotor thrust available for a given input torque and is shown in Figure 10 by the positive slope to the transmission-limited rotor thrust curve just prior to fuselage rotation. Second, as the aircraft gains forward speed, the download on the wing caused by the rotors, about 7 percent of the rotor thrust in hover, is eliminated.

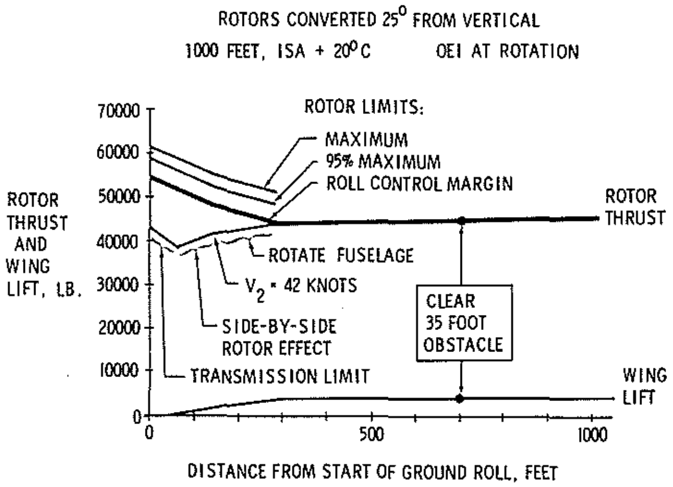

Figure 10. Model D326 S-V Short Takeoff Performance.

The rotation speed, V_2, used for tilt rotor takeoff performance is similar to that used for fixed wing aircraft, where V_2 is defined as the greater of 1.2 times stall airspeed or 1.1 times the minimum control airspeed. Since the tilt rotor has an interconnect shaft and the powerful control from the rotors is essentially independent of speed (over the speed range used in takeoff), the minimum control airspeed is not critical. Therefore, for the tilt rotor, V_2 has been defined as 1.2 times the stall airspeed or the stall airspeed plus 15 knots, whichever is greater. For the D326 S-V, stall airspeed is 27 knots, giving a V_2 of 42 knots.

Following a short ground run of about 200 feet, the rotation speed, V_2 = 42 knots, is reached. At 42 knots, the wing lift, based on a C_L of 1.6, is 3980 pounds. While this sounds low, it must be remembered that in vertical flight, the wing contributes a download of about 2590 pounds. The net contribution of the wing when comparing vertical takeoff to short takeoff performance is approximately 6570 pounds, very close to the difference between the D326 VTOL gross weight of 37,000 pounds and its S-V gross weight of 43,300 pounds.

If, at the point of rotation, V_2, one engine fails, the remaining power available equals the transmission limit and matches that required to produce the maximum rotor thrust after appropriate reductions have been made to assure adequate control. The aircraft is now flying on the rotor thrust limit as it continues to climb and accelerate into forward flight.

Following the takeoff limits shown in Figure 10, the takeoff distance at 1000 feet, ISA + 20°C day, to clear a 35-foot obstacle is 700 feet, assuming that one engine fails at V_2 speed. This more than meets the criterion established at the beginning of this study, 1000 feet.

5. D326 S-V Performance

The D326 S-V performance has been estimated for two applications, North Sea offshore oil support and search and rescue. For offshore oil support, the aircraft, when equipped with all required emergency equipment for operation over the North Sea, carries 45 passengers 300 nautical miles out to an oil rig while cruising at 20,000 feet at a speed of 300 knots. A 45-minute fuel reserve is carried and all fuel flow is five percent conservative. Figure 11 shows the payload-range for the North Sea mission, comparing the original D326 with the S-V version and with a new technology helicopter.

The helicopter was derived based on the same installed power and level of technology as the D326 S-V using BHT design synthesis methodology. It can carry 52 passengers for a radius of 300 nautical miles with an in-ground-effect takeoff gross weight of 51,500 pounds and an empty weight of 27,530 pounds. This empty weight is close to that of the D326 S-V.

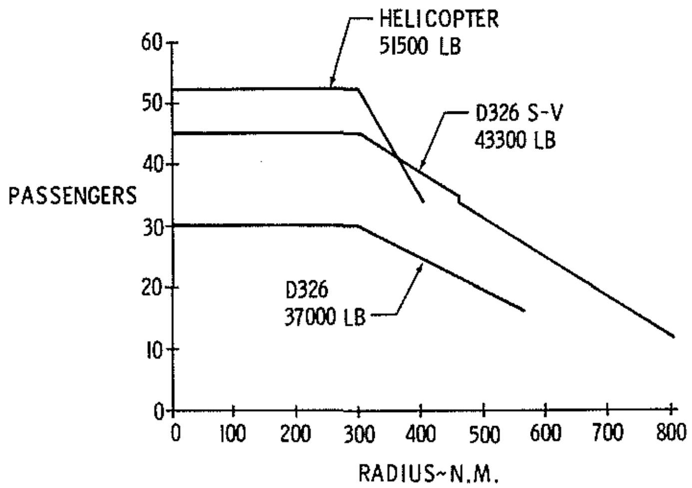

Figure 11. North Sea Offshore Oil Mission Comparison.

The payload of the D326 S-V exceeds that of the original D326 by 50 percent. The helicopter has a slightly greater payload than the D326 S-V, 52 passengers compared to 45 at a radius of 300 nautical miles. If it is necessary to transport 30 passengers (the original design payload of the D326), the D326 S-V can fly a radius of 530 nautical miles, 77 percent farther than the D326. Auxiliary fuel tanks would be installed for a radius over 450 nautical miles. With its long range, the D326 S-V is self-deployable worldwide.

For a true comparison of the three aircraft, one must look at productivity. To give an indication of relative cost, productivity is defined as:

$$\frac{\text{payload x cruise speed}}{\text{weight empty}}$$

Table 3 summarizes the key parameters of the three aircraft for the North Sea oil support application, assuming a 300-nautical-mile radius mission. Both tilt rotors exceed the productivity of the helicopter. The D326 S-V has a productivity 39 percent greater than the original D326 and 87 percent greater than the comparable-technology helicopter.

Table 3. Aircraft Comparison - North Sea Oil Support

	D326 VTOL	D326 S-V	Helicopter
Gross Weight	37,000 lb	43,300 lb	51,500 lb
Weight Empty	24,473 lb	27,238 lb	27,530 lb
WE/GW	0.661	0.629	0.534
No. of Passengers	30	45	52
Cruise Speed	290 kn	300 kn	140 kn
Productivity[1]	71.10 kn	99.13 kn	52.89 kn
Fuel Consumed, 300 nm radius	4,751 lb	5,154 lb	11,520 lb
Seat miles/lb of fuel	3.79	5.24	2.71
Seat miles/hr/lb of fuel	1.83	2.62	0.63

[1]Productivity = $\frac{\text{Payload x Cruise Speed}}{\text{Weight Empty}}$

With today's rapidly escalating fuel costs, it is also interesting to compare the seat miles per pound of fuel consumed by each aircraft. The D326 S-V transports 93 percent more seat miles per pound of fuel than the helicopter. If speed is factored into the comparison to give relative productivity per pound of fuel consumed, the D326 produces approximately three times and the D326 S-V produces more than four times as many seat miles per hour per pound of fuel as the helicopter.

For the search and rescue version of the D326 S-V, it is assumed that the 30-passenger fuselage of the original D326 would be retained. Taking off at the STO gross weight of 43,300 pounds, the D326 S-V can fly out 200 nautical miles at 300 knots and search for more than six hours at sea level. Depending on when the survivors are sighted, up to 30 can be rescued while hovering out of ground effect. If the survivors are located early in the mission, the fuel load would be reduced by jettisoning fuel carried in wing-mounted fuel tanks or by dumping fuel carried in internal tanks until the gross weight is reduced to approximately 34,000 pounds. At this weight, the aircraft can easily hover out of ground effect at sea level on an ISA + 20°C day, even after rescuing 30 persons.

6. Conclusions and Recommendations

- A version of the D326 tilt rotor with increased useful load that takes off following a short ground run and lands vertically at midmission offers an attractive cost-effective and energy-efficient aircraft for many commercial and military applications. This aircraft, the D326 S-V, combines the advantages of the high static thrust of low-disc-loading rotors with efficient lift from a wing to maximize productivity and seat miles flown per pound of fuel consumed.

- Since the maximum takeoff gross weight is contingent upon the one-engine-inoperative vertical flight performance at midmission, an investigation of landing and takeoff techniques should be made to determine the highest practicable gross weight when operating from a restricted area, such as an oil rig platform. Flight tests are also needed to further define techniques to minimize the takeoff distance at mission origin. The XV-15 would provide an excellent research aircraft for this purpose.

- A detailed design study of the tilt rotor described in this paper is needed to optimize the various design parameters and to maximize the benefits of the short takeoff, vertical landing configuration.

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