NASA Technical Memorandum 81244 AVRADCOM Technical Report 80-A-15

(NASA-TM-81244) THE XV-15 TILT ROTOR RESEARCH AIRCRAFT (NASA) 21 p HC A02/MF A01 CSCL 01C
N81-10054
Unclas
G3/05 29070

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Daniel C. Dugan, Ronald G. Erhart, and
Laurel G. Schroers

September 1980

NASA
National Aeronautics and
Space Administration

United States Army
Aviation Research
and Development
Command

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Daniel C. Dugan, Ames Research Center, NASA, Moffett Field, California
Ronald G. Erhart, Bell Helicopter Textron, Fort Worth, Texas
Laurel G. Schroers, Aeromechanics Laboratory, U.S. Army Research and Technology Laboratories (AVRADCOM)

National Aeronautics and Space Administration
Ames Research Center
Moffett Field, California 94035

United States Army
Aviation Research and Development Command
St. Louis, Missouri 63166

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Daniel C. Dugan (M)
NASA-Ames Research Center

Ronald G. Erhart (M)
Bell Helicopter Textron

Laurel G. Schroers
Aeromechanics Laboratory
U.S. Army Research and Technology Laboratories (AVRADCOM)

INTRODUCTION

The XV-15 Tilt Rotor Research Aircraft Program is a joint NASA/Army program to develop and evaluate tilt rotor technology for civil and military applications. Navy participation in the program began one year ago as a result of their interest in the tilt rotor concept. The XV-15 evolved from the XV-3 "Convertiplane" of the 1950's (fig. 1). Although the XV-3 successfully demonstrated the concept and was able to perform conversions between the helicopter and airplane modes, it was very limited by deficiencies in performance, aeroelastic stability, and handling qualities. After a design competition, Bell Helicopter Textron was awarded a contract in 1973 to build two tilt rotor research aircraft.

The potential of the tilt rotor concept can be illustrated by comparing various VTOL concepts in terms of hover and cruise performance (fig. 2). It is difficult to surpass the hovering capability of the helicopter, given its low disc loading. However, the highly twisted blades of the tilt rotor provide hovering performance that compares favorably, even though its disc loading is somewhat higher than that of the helicopter. The blades provide efficiency that the helicopter is denied because the helicopter rotor must provide both thrust and lift in forward flight. Considering cruise performance (fig. 3), the tilt rotor is also promising because of its speed and yet it retains the benefits that are derived from much lower disc loadings than other concepts. It combines some of the better features of both helicopters and airplanes and can be superior to either in some areas, including fuel efficiency and noise levels.

Before discussing the design characteristics of the aircraft, a brief review of the program chronology is appropriate.

- Simulations at Ames Research Center . . . 1973-1980
- Egress System Test. . . . . July 1975
- No. 1 XV-15 Rollout . . . . October 1976
- Ground Tie-Down Testing . . . . . . January-May 1977
- Hover Tests (Aircraft No. 1). . . . . May 1977
- Wind-Tunnel Tests (Aircraft No. 1). . May-June 1978
- Contractor Flight Tests (Aircraft No. 2). . . . . April 1979-July 1980

DESIGN CHARACTERISTICS

General

The XV-15 aircraft is powered by two Lycoming T-53 turboshaft engines, which have been uprated and modified for both vertical and horizontal operation. The three-blade proprotors are 25 ft in diameter and the blade twist is 45° from root to tip. They are gimbal-mounted to the hub with an elastomeric spring for flapping restraint. The wing span is 32 ft from spinner to spinner and the aircraft is 42 ft long, excluding the instrumentation boom. Aircraft dimensions are shown on the three-view drawing in figure 4. Wing loading is 77 lb/ft^2, and disc loading at the design gross weight of 13,000 lb is 13.2 lb/ft^2. The XV-15 carries 1,475 lb of fuel, which allows a research flight of about 1 hr. It is equipped with LW-3B rocket seats which provide a 0-altitude/0-airspeed recovery capability for the crew. This seat is also installed in the USAF and USMC OV-10A aircraft.

Control System

In the helicopter mode, the XV-15 can be considered as a lateral-tandem helicopter similar in some respects to operational tandems such as the CH-46 or CH-47 (fig. 5). For vertical control, collective blade pitch is applied simultaneously to both rotors by the pilot's power lever. The throttles are linked to the power lever to provide direct engine response. Lateral stick displacement provides roll control through differential collective pitch changes, and yaw is controlled by differential cyclic inputs through the pedals. Longitudinal stick inputs command cyclic pitch changes to both rotors to allow fore and aft translation. During flight in the helicopter mode, the airplane controls are being actuated; however, they are ineffective at low speeds. As the pilot initiates the conversion process, the rotor controls are mechanically phased out as the nacelles move down and the conventional elevator, flaperons, and rudder become effective. A look at a cockpit sketch depicts the controls arrangement (fig. 6). Most of the instrumentation and gages are standard, with a few exceptions that will be mentioned later.

Pilot selected rpm is maintained by a blade pitch or beta governor. In the helicopter mode, blade pitch inputs from the governor are superimposed on collective pitch inputs from the power lever and lateral stick. As the XV-15 is converted to the airplane mode, collective pitch inputs from the pilot are phased out. A manual wheel for control of rpm is available should the dual channel (or primary and secondary) governor go off line or fail. After conversion to the airplane mode, rpm is reduced for improved airplane performance.

Stability and control augmentation (SCAS) are provided by a three-axis rate system with a pitch and roll attitude retention feature. Both feed-forward and feedback loops are used to tailor response characteristics, and SCAS gains are varied with nacelle angle. Flight with SCAS off has been demonstrated, and it is not considered a safety-of-flight failure. A force-feel system (FFS) provides stick and pedal forces proportional to control displacements. Force gradients are increased with speed through a dynamic pressure ("q") sensor. Control forces are high but manageable during flight with FFS off.

Three independent systems provide hydraulic power to the flight controls. For normal operation, two primary systems provide 3,000 psi output for the flight controls; however, either system can power the controls if the other is inoperative. The utility hydraulic system serves as emergency backup for one of the primary systems.

Conversion System

The interconnected, hydraulically powered conversion system provides controlled tilt of the nacelles through 95° of travel (fig. 7). The system is triply redundant in that either of the two primary conversion actuators, powered by separate hydraulic and electrical sources, permits conversion. In the event of dual hydraulic failure, the third system can provide power for conversion to the STOL or helicopter modes. This can be accomplished even with complete loss of electrical power. This degree of redundancy was designed into the XV-15 because it cannot be landed in the airplane mode.

Control of conversion is accomplished by a spring-loaded-to-center switch ("coolie hat") located on the power lever (fig. 8). Operated by the pilot's left thumb, the switch can be actuated for a continuous conversion at 7.5° per second or actuated and released as often as desired during the conversion. The human factors design aspects of the conversion switch location and actuation have been very acceptable to XV-15 pilots in combination with the power lever control motions. A conversion angle indicator (fig. 9) on the instrument panel provides the pilot with a numerical and pictorial nacelle position. The angle logic chosen was 0° for the airplane mode and 90° for the helicopter mode.

Propulsion System

The modified T-53 engines and main transmissions are located in the wing tip nacelles (fig. 10). Single-engine flight capability is provided by a transmission cross shaft which allows one engine to drive both prop-rotors. At the design gross weight of 13,000 lb, the XV-15 is too heavy to hover on one engine, but it can maintain altitude in forward flight. Single-engine capability has been demonstrated by simulated failures and one actual engine failure which occurred last December. It is interesting to compare the flight envelopes of two other aircraft powered by T-53 engines — the UH-1H helicopter and the OV-1 Mohawk turboprop (fig. 11).

FLIGHT TEST RESULTS

In the spring of 1977, the first XV-15 flew for a total of 3 hr at the Bell flight test facility at Arlington, Texas. This was a brief evaluation of the hover mode and all flying was conducted below 100 ft at speeds up to 40 knots. The contractor flight test program on aircraft No. 2 began at Arlington in April 1979, and continued until July 23, 1980. During that period, 57 flight hours were accumulated on 76 test flights.

Ground Handling

Ground handling characteristics have been excellent. Nosewheel steering was not incorporated in the design and has been found to be unnecessary. A tight turning radius is available to the pilot, using only differential cyclic control. There is a tendency for the XV-15 to lean into the turns while taxiing; however, the wing can be kept level with a small application of lateral control. Moving the nacelles ±5° from the vertical provides a natural and responsive means of accelerating and decelerating the aircraft during ground operations and eliminates any requirement for longitudinal cyclic inputs.

Hover

A wide hover envelope was demonstrated which included sideward and rearward flight to 25 knots, aft translations to 10 knots, and precision turns over a spot. Vertical takeoffs are routine and they are performed as in any helicopter, by maintaining attitude and position as collective pitch is applied. Noise levels are low both in the cockpit and outside of the aircraft. With the engines and transmissions located at the wing tips, the noise is more like that of a turboprop airplane than that of a helicopter. Vibration levels are also low. The XV-15 does generate small perturbations within a few feet of the runway or helipad when landing vertically. There is also a small but noticeable "suckdown" when landing vertically or at low forward speeds, but it can be easily compensated for by the pilot with small power lever inputs. As with conventional tandem rotor helicopters, the XV-15 does not seem to be affected by wind direction in hovering flight. It is a stable hover platform which allows precision with a low pilot workload.

Hover performance data have shown that the XV-15, at its design gross weight of 13,000 lb, can hover in ground effect (IGE) at 11,200 ft pressure altitude on a standard day and at 3,950 ft on a 95° F day (fig. 12). Out of ground effect (OGE) those altitudes are reduced to 7,600 ft and 1,100 ft, respectively. As previously stated, however, single engine hover is not possible.

Running or simulated STOL takeoffs have been performed using up to 30° forward tilt of the rotor and approximately one half the power available. The aircraft accelerates rapidly and flies off the runway at 65 to 75 knots.

Conversion

So far nothing very unusual has been said about the XV-15 as a helicopter. It can take off vertically or after a short roll on the runway and it hovers well. The conversion process, however, is one of the unique features of the aircraft and it can be accomplished with comfort and ease. That is unusual in a VTOL aircraft. A routine technique developed is to accelerate to 60 to 80 knots indicated airspeed (KIAS), using 10° to 20° of forward tilt (nacelle position of 80° or 70°) while retracting the landing gear. A continuous conversion to airplane mode (0°) is then initiated at 7.5° of tilt per second. During this maneuver, 0.4 g acceleration can be achieved – the helicopter pilot's equivalent of afterburner. A little longitudinal trim is used to compensate for the nose-down pitching moment, but control forces are light and pitch attitude is easy to control. During this process, rotor control authority is mechanically phased out with nacelle angle as the transition from rotor lift to wing lift occurs. Flap configuration is changed as desired within placard limits. The conversion is a low-workload, straightforward process which has been comfortable to all of the pilots who have flown the XV-15. Of course, the conversion may be stopped at any point; the aircraft can then be flown at some intermediate tilt angle at speeds up to limits established by component loads and not by handling qualities restrictions. A wide speed-power "bucket" exists which can be utilized for the desired speed and fuel flow. Figure 13 illustrates the range of speeds available for a particular horsepower by selection of nacelle angle. This capability provides flexibility in planning missions that might require an aircraft to hover, loiter, and accelerate to higher cruise or dash speeds.

Once the XV-15 has completed conversion to the 0° nacelle angle, the nacelles are "locked" down using a small toggle switch just forward of the conversion switch on the pilot's power lever control head. This forces the nacelles against downstops with hydraulic pressure preload, thus providing additional aeroelastic stiffness to the nacelle/wing combination. The pilot then reduces rpm from 98% (589) to 86% (517) with the rpm governor "beep" switch. Although propulsive efficiency is greater at 76% (458 rpm), the higher rpm is being used at present to reduce vibratory loads on the conversion spindles and engine coupling gearboxes. Load monitoring limits were established to avoid fatigue damage to any of the XV-15 components.

Airplane Mode

Flight in the airplane mode is routine once you get used to those big 25-ft props just outside the cockpit. Control forces have been increased through the FFS, and aircraft trimmability and control harmony are acceptable. To date, only a limited amount of maneuvering has been conducted during flight envelope expansion. Although the aircraft is designed for +3 g to -1 g, only +1.5 g with some excursions to 2 g has been investigated in the contractor test program. In turning flight the XV-15 feels like a larger aircraft. Turns are precise and well coordinated with minimum pilot effort.

Vibration levels are low to moderate for most flight conditions. In gusty air, the XV-15 response is unusual. Instead of the vertical accelerations felt in most airplanes, the tilt rotor has a longitudinal response that has been labeled "chugging." It is caused by transient changes in blade angle of attack, which produce large propeller thrust changes. In moderate turbulence, the fore and aft motion is uncomfortable to the pilots but it is believed that governor and SCAS modifications can alleviate the problem. The same levels of turbulence produced an uncomfortable vertical response in the Super King Air chase airplane.

Unaccelerated stalls in the airplane mode are very docile; they occur at 95 to 100 KIAS, an angle of attack of about 16°, and a gross weight of 12,000 to 13,000 lb. They are characterized by light buffet followed by an increase in sink rate with no rolling or pitching. Recovery is effected by release of aft stick pressure. As would be expected, the large prop-rotors produce a lot of drag when power is reduced to idle and it requires sink rates exceeding 3,000 ft/min to maintain 150 KIAS in this condition. At higher speeds, the vertical speed indicator pegs at 3,500 ft/min; however, sink rates of approximately 4,500 ft/min can be achieved at 190 KIAS. This does permit rapid deceleration and descent from altitude to the deck without going through the reconversion procedure.

External noise generated by the XV-15 in airplane mode flight is very low. It has not yet been accurately measured, but qualitative reports from ground observers indicated that they could not hear the tilt rotor approaching at 200 knots and 500 ft above the ground. As the aircraft passed overhead in a climbing turn, only a blade noise described as "swishing" was noted. Noise measurements will be taken as the flight test program proceeds.

Reconversion

The reconversion from airplane mode to helicopter mode is also a low-workload procedure. A 20° flap position is selected below 220 KIAS as the XV-15 is decelerated by power reduction. Prior to initiating the reconversion, the rotor rpm must be increased from 86% to 98%. If the nacelles are unlocked at airplane rpm, a warning light alerts the pilot to an improper rpm condition. If the nacelles are moved, an audio warning is triggered to remind the pilot to increase rpm. After the XV-15 is decelerated to 170 KIAS, a continuous reconversion can then be made by holding the conversion switch aft until the desired angle is reached. The XV-15 decelerates very rapidly, generating a positive pitching moment which can be easily controlled with small forward stick inputs. Flaps are lowered as desired with 40° normally selected as the nacelle angle passes 60° The last thing the pilot does during reconversion is to look out to one side and watch chase zip by while its pilot looks for a drag chute or an anchor.

Autorotation

Steady-state autorotations have been entered from the helicopter and intermediate tilt modes. Entry conditions have included 30° of forward tilt. For the simulated dual-engine failures, nacelles were raised to the 95° position with flaps set at 20°. Autorotational rotor rpm could be stabilized at 92% at 80 KIAS with a sink rate of approximately 3,100 ft/min. All autorotations have been terminated at altitude with power recoveries.

Landing

The various landing configurations and maneuvers demonstrated by the XV-15 have shown that precise and soft touchdowns can be made with low pilot workload. Whether the approach terminates at a hover or with a roll on landing on the runway, the XV-15 is easy to land. A typical approach configuration is with the landing gear extended, flaps at 40°, and nacelles anywhere from the 70° position to 95°. Flare for touchdown or hover can be accomplished with a conventional pitch attitude change or by a nacelle flare to the 90° position. The latter method takes advantage of the capability to tilt the thrust vector independently of body attitude. During a roll on landing, the XV-15 pilot has a positive control of touchdown sink rate. By modulating rotor thrust with the power lever, smooth approaches and soft touchdowns become routine, even for initial pilot flights. This is satisfying to the pilot, and the aspects of passenger comfort for future tilt rotor applications should not be overlooked. Passengers get unhappy and somewhat apprehensive about hard landings when they occur in conventional aircraft and the shuddering and shaking experienced in many helicopters as they decelerate to hover or landing certainly detract from commercial passenger acceptance.

Flight Envelope

The conversion corridor, which can also be called the tilt-mode flight envelope, is approximately 50 knots wide (fig. 14). It allows both rapid and slow conversions between the modes, with pilot attention required primarily to insure that the aircraft is on speed at the starting points of the conversion or reconversion. The XV-15 accelerates and decelerates well within the corridor so the pilot does not have to divert his attention to any conversion schedule. As loads predictions are refined and modifications are made to the aircraft, this corridor will be expanded. This will allow a wider range of airspeeds for any particular nacelle angle as the XV-15 is flown in the tilt mode.

Some of the stabilized airspeed points that have been flown to date, and the boundaries of the predicted envelope, are shown in figure 15.

PROGRAM PLANS

The No. 1 XV-15 is located at Ames Research Center, Moffett Field, California. Its refurbishment and modification were completed this year after extensive wind-tunnel testing. A period of ground tie-down testing was completed in August 1980, and the aircraft is in the final stages of inspection and preparation for the government proof-of-concept testing. This will include testing within the established flight envelope and a concept evaluation phase by NASA and the military services.

The No. 2 XV-15, which completed the contractor flight test program in July 1980, was delivered to Dryden Flight Research Center, Edwards AFB, California, on August 13, 1980. After initial ground runs and shakedown flights, an envelope expansion phase of flight testing will begin. This will include expansion of the conversion corridor and of the maneuvering envelope along with additional aeroelastic structural stability investigations and single-engine performance testing.

CONCLUSION

The XV-15 tilt rotor has exhibited excellent handling qualities in all modes of flight. In the helicopter mode it is a stable platform that allows precision hover and agility with low pilot workload. Vibration levels are low as are both internal and external noise levels. The conversion procedure is uncomplicated by schedules, and it is easy to perform. During the conversion or reconversion, acceleration or deceleration are impressive and make it difficult for conventional helicopters or airplanes to stay with the XV-15. Handling qualities are excellent within the airplane mode envelope investigated to date; however, gust response is unusual. Although internal noise levels are up somewhat in the airplane mode, external noise levels are very low. Overall, the XV-15 is a versatile and unique aircraft which is demonstrating technology that has the potential for widespread civil and military application.

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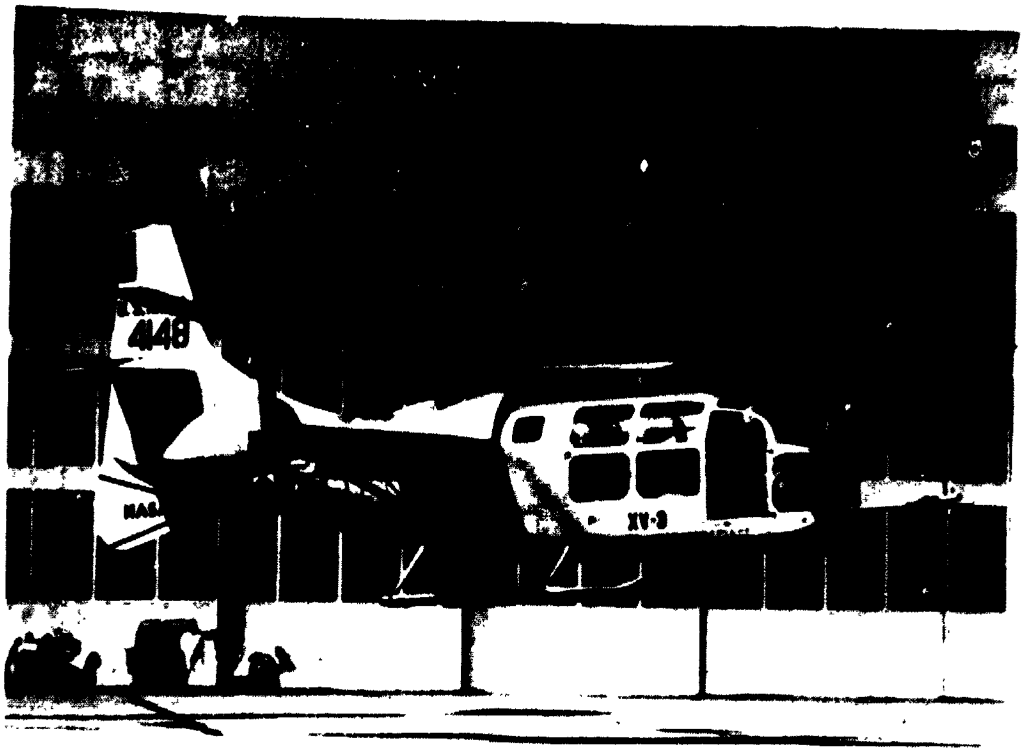

Figure 1. XV-3 "Convertiplane."

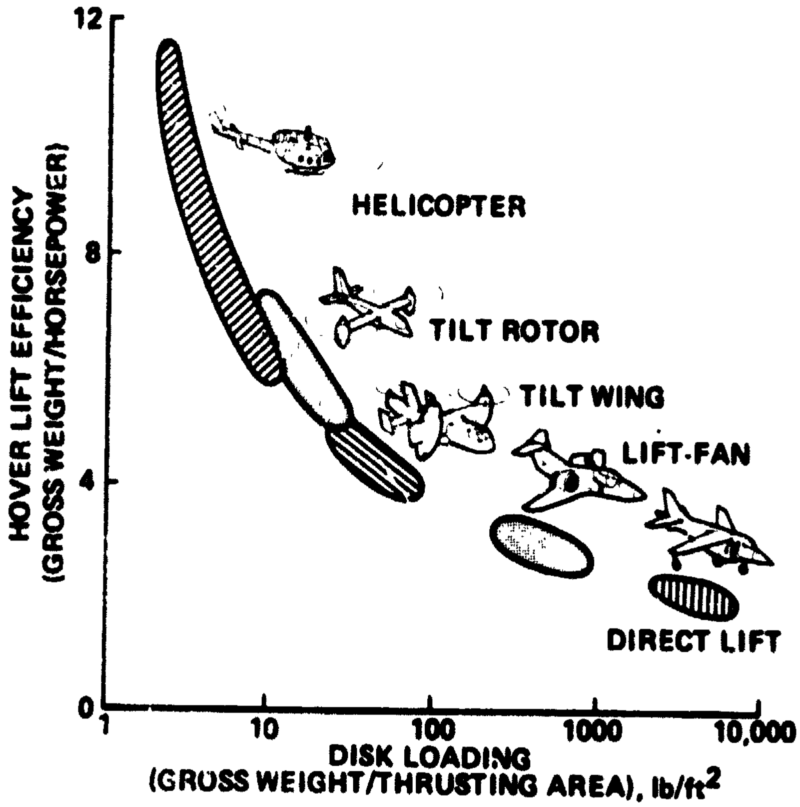

Figure 2. Hover efficiency.

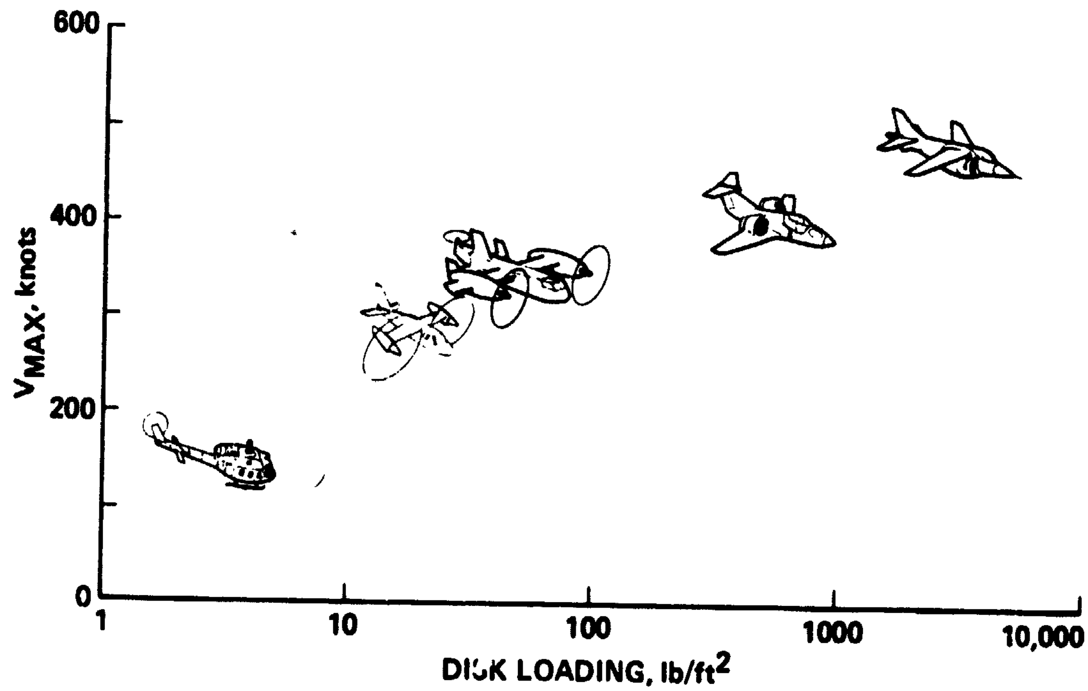

Figure 3. Cruise performance.

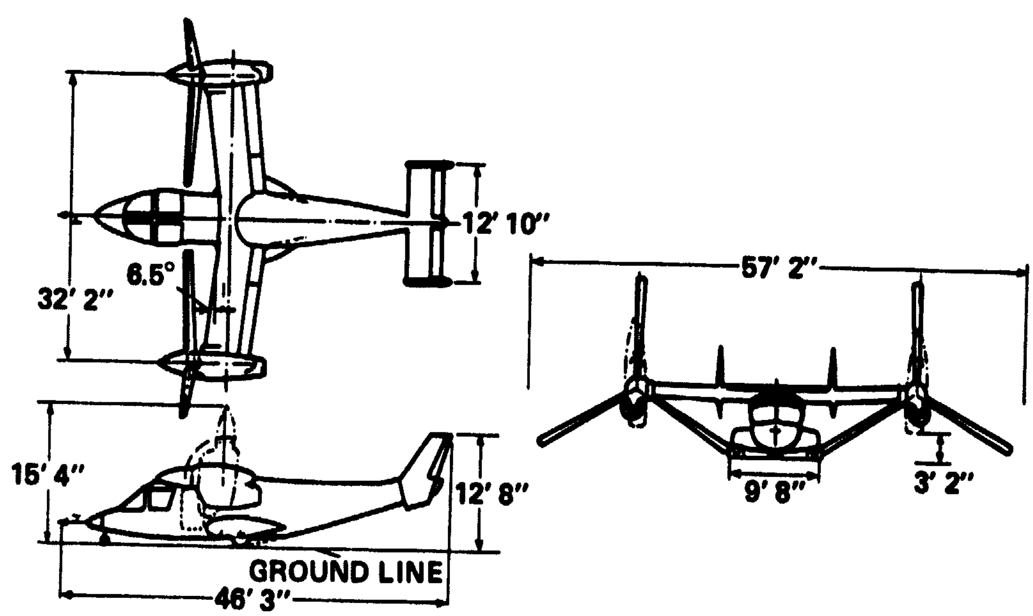

Figure 4. XV-15 dimensions.

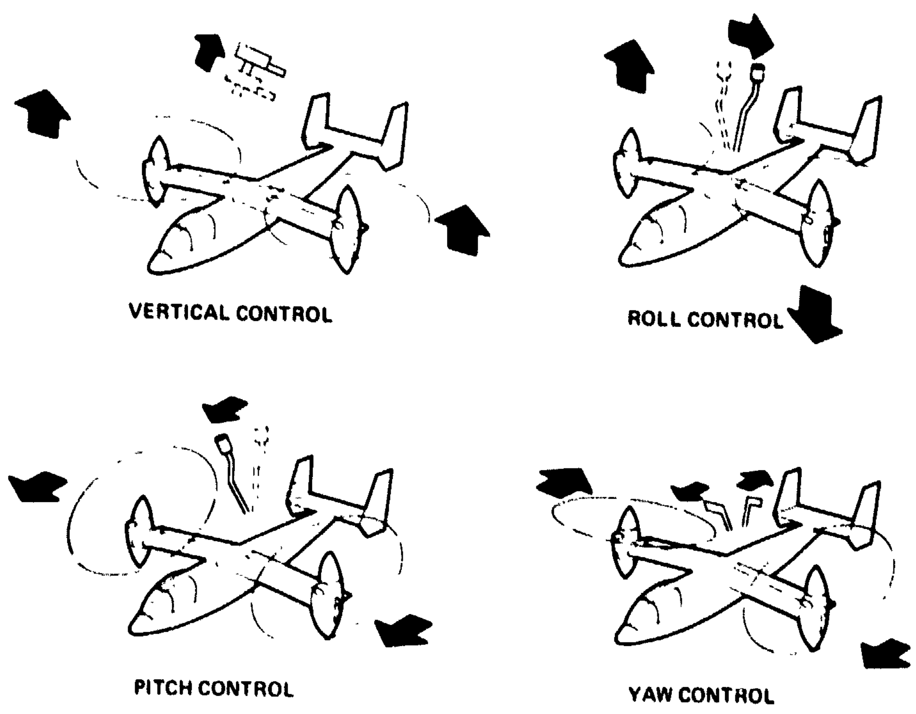

Figure 5. Control system.

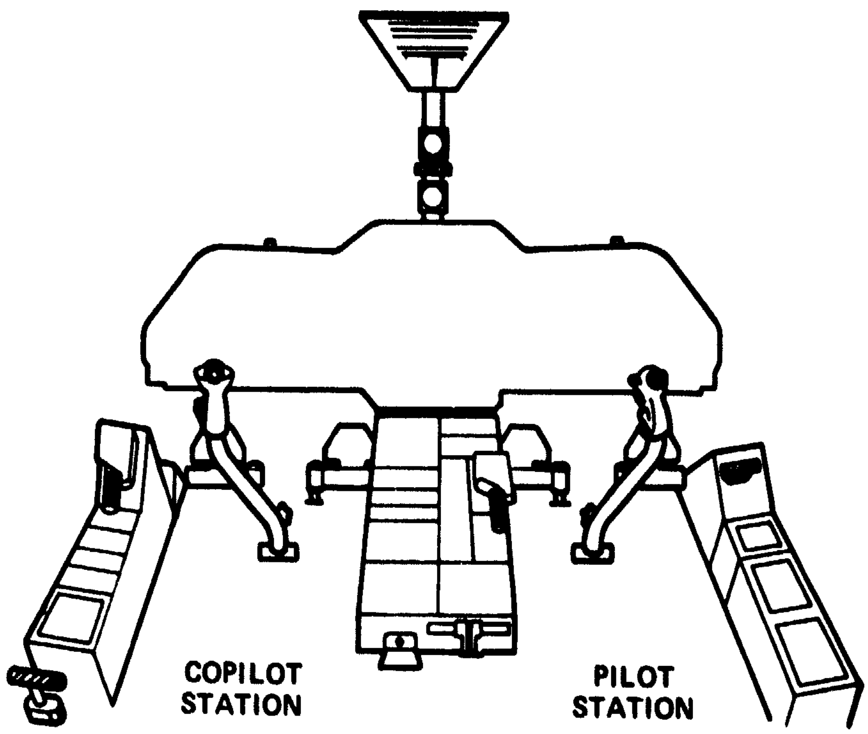

Figure 6. Cockpit arrangement.

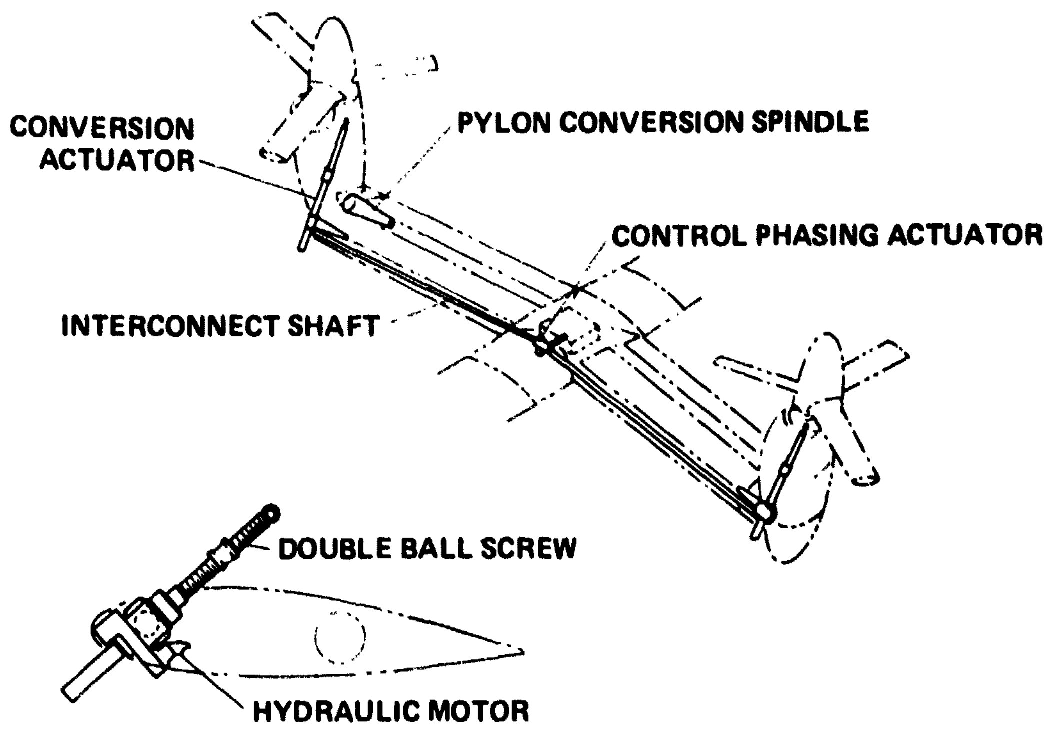

Figure 7. Conversion system.

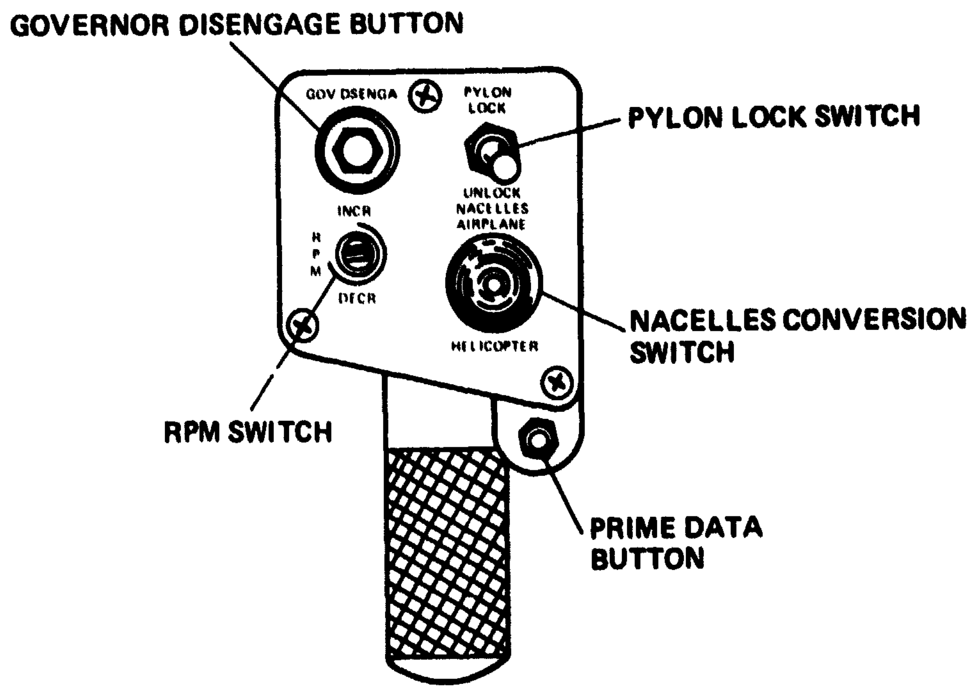

Figure 8. Power lever grip.

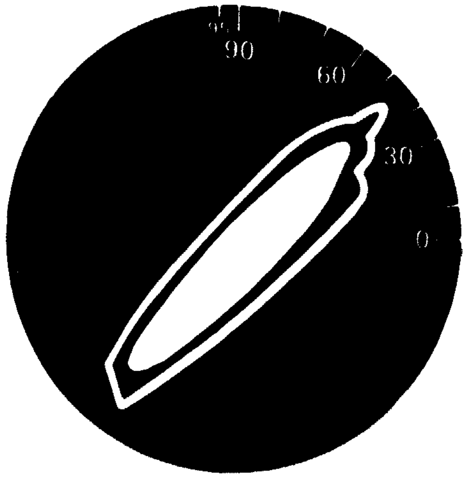

Figure 9. Conversion angle indicator.

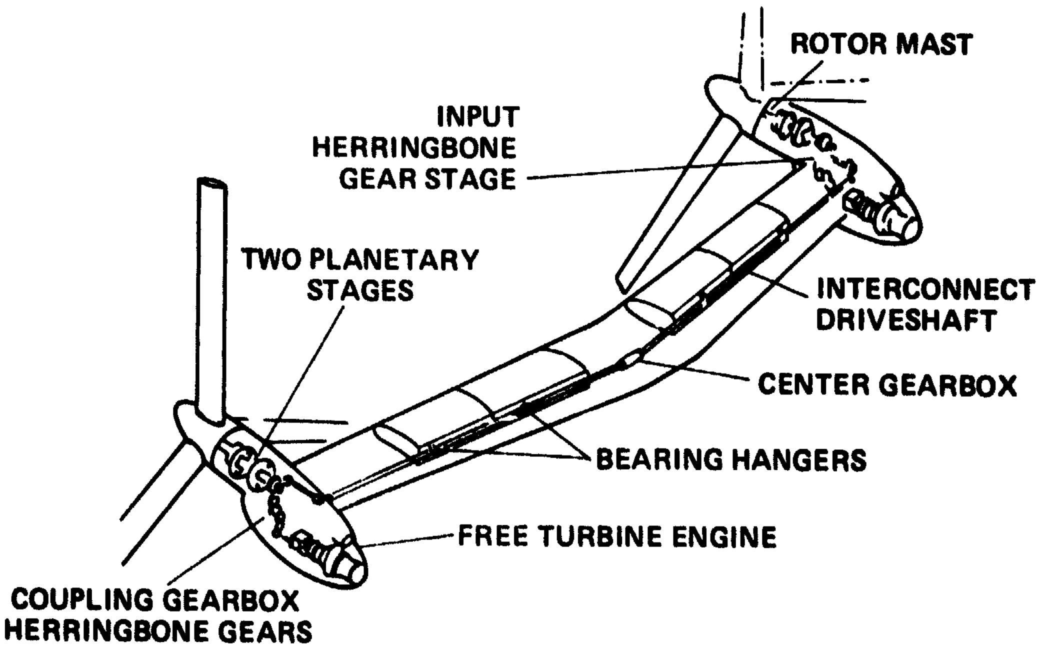

Figure 10. Propulsion system.

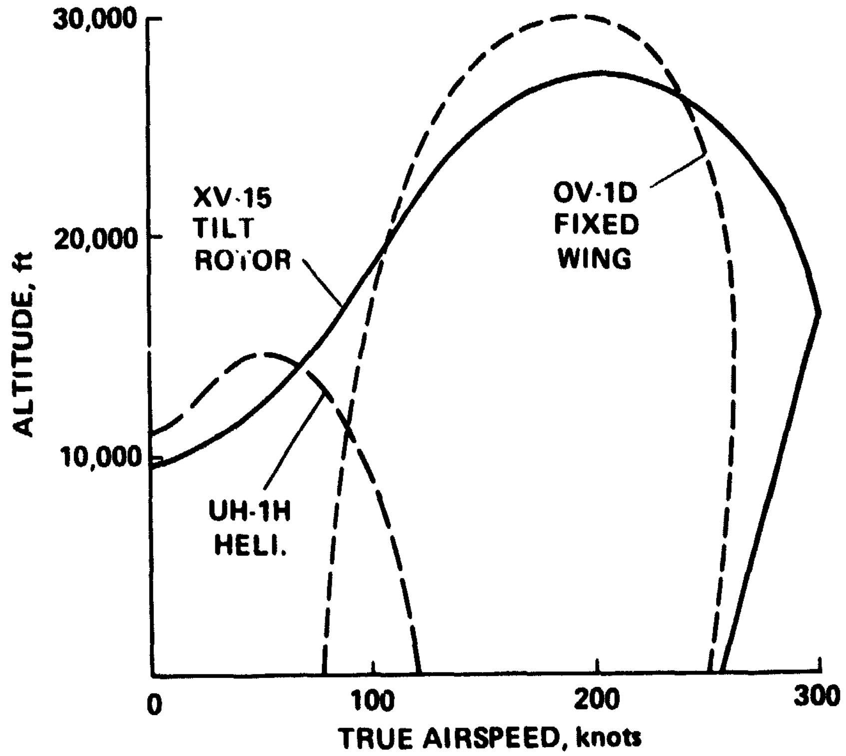

Figure 11. Flight envelope comparison.

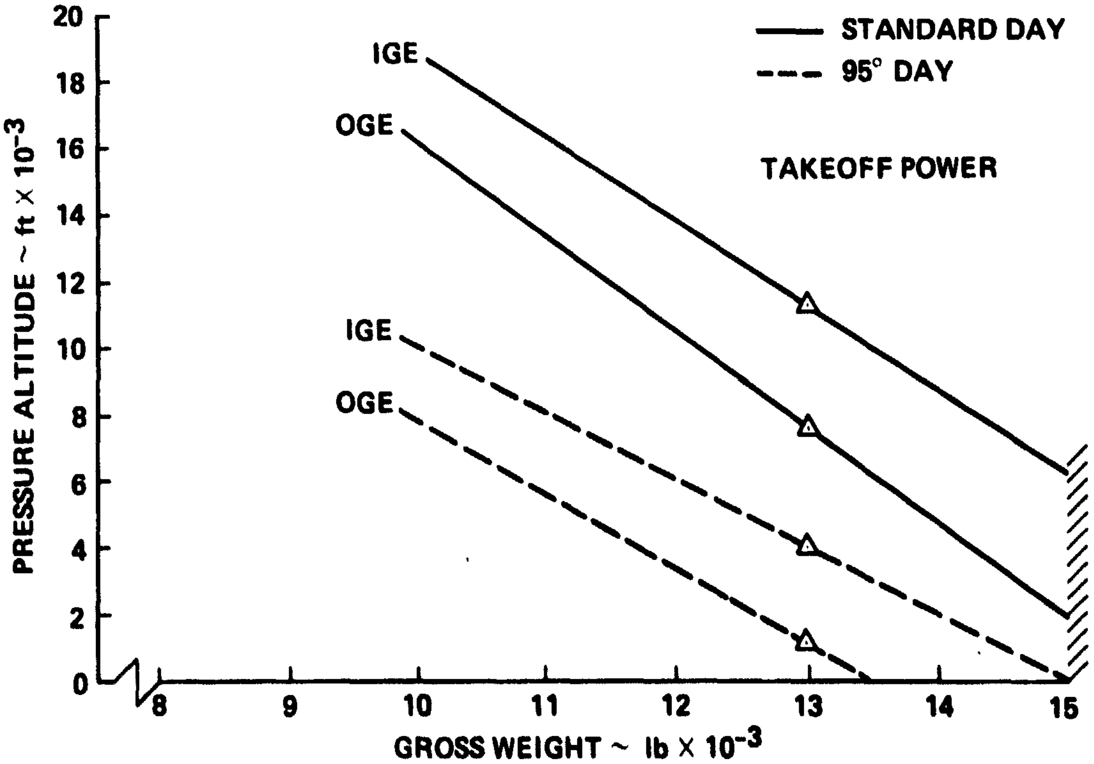

Figure 12. XV-15 hover performance.

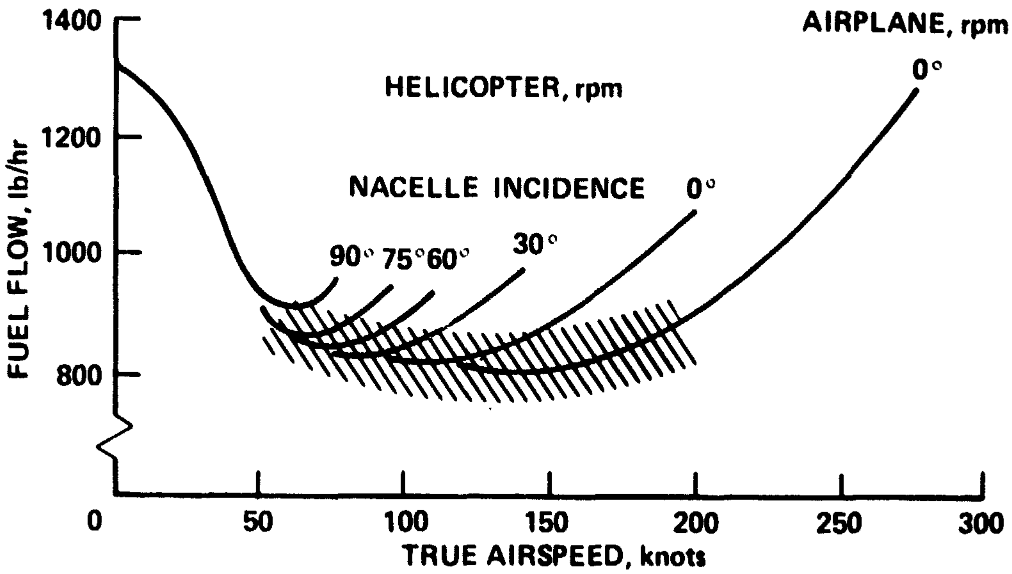

Figure 13. Level flight performance options.

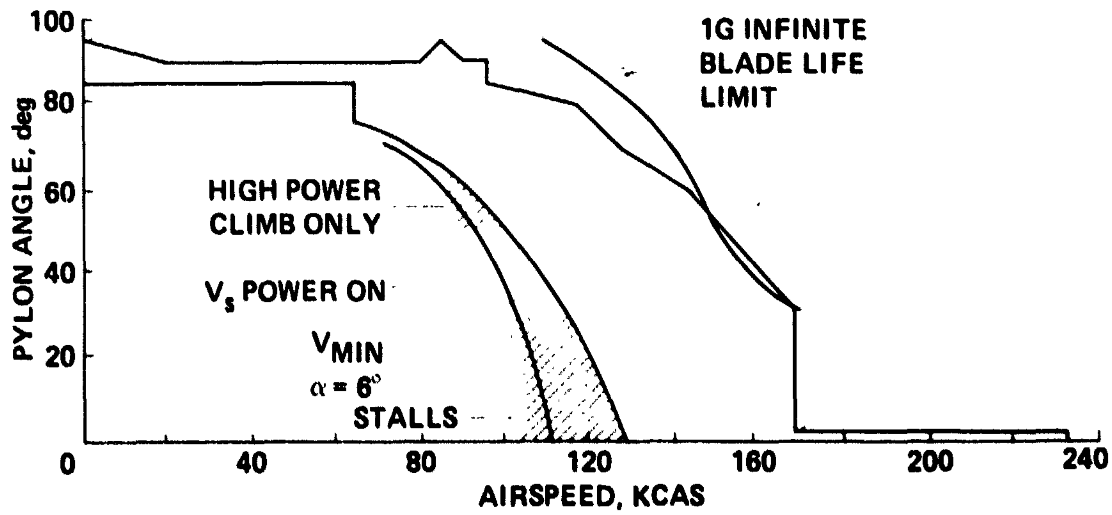

Figure 14. Conversion corridor.

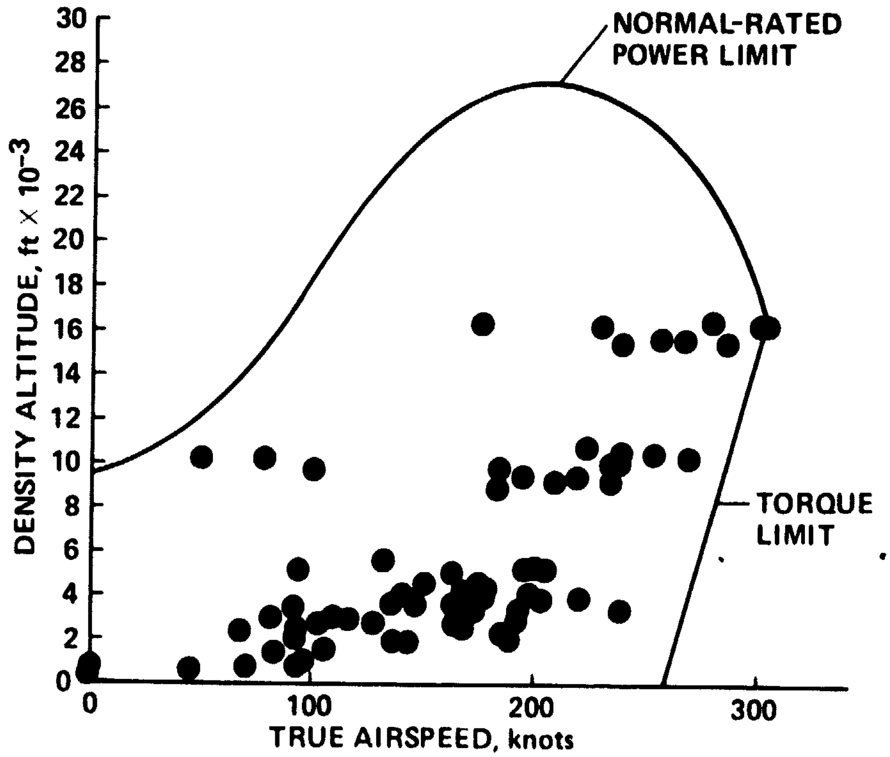

Figure 15. Airspeed altitude envelope.