The Development of the Tiltrotor Aircraft

By Martin Maisel

XV-15, NASA 703, in hover flight. (NASA photo, EC80-13848)

Since the early days of powered flight, aircraft visionaries and designers pursued the creation of an aircraft that would provide the elusive capability for vertical takeoff. While achieving controllable hover was challenging enough, practical planners knew that vertical takeoff aircraft had to have sufficient speed and range in forward flight to allow the aircraft to be operationally useful. These capabilities became the fundamental performance goals of as well as the rationale for the tiltrotor aircraft. As it turned out, over half a century would pass before the tiltrotor would evolve from a novel concept to a successful new class of aircraft.

Figure 1: Focke-Wulf Fw-61, first successful helicopter. (From the author's collection)

Early Tiltrotor Aircraft

Although several early helicopter designs achieved various measures of success, the Focke-Wulf Fw-61, which flew in 1936, is widely considered to be the first fully operational helicopter. This aircraft had two laterally displaced (side-by-side) rotors mounted on open frame-outriggers. The Fw-61 was capable of vertical takeoff, sustained hover, low speed maneuverability, and a record helicopter forward flight speed of 112 km/h (70 mph).

Around the time the Fw-61 set the helicopter speed record, several conceptual designs were proposed that appeared to recognize that the maximum attainable speed of the pure helicopter would be limited by the edgewise flight of its rotor. In forward flight the helicopter rotor blades experience an acceleration and deceleration as they "advance" into and "retreat" from the oncoming air stream. As the helicopter exceeds an airspeed of about 170 knots (230 mph), the advancing blade tip encounters near-sonic speeds, resulting in a dramatic increase in drag. At the same time, portions of the retreating blade experience reverse flow and become incapable of producing adequate lift. These fundamental problems result in a limitation of the maximum speed that can be achieved by a conventional helicopter. To eliminate those problems a new

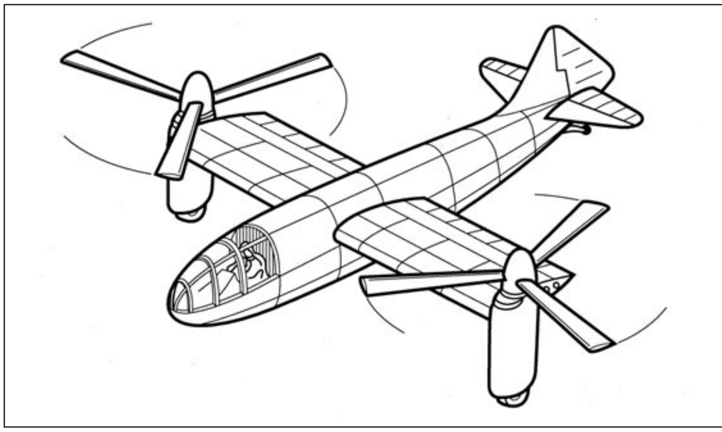

Figure 2: Drawing of the 1937 Baynes Heliplane. (Monograph Figure 9)

Figure 3: Three-view drawing of the Weser Flugzeugbau P.1003 tiltrotor aircraft. (Monograph Figure 10)

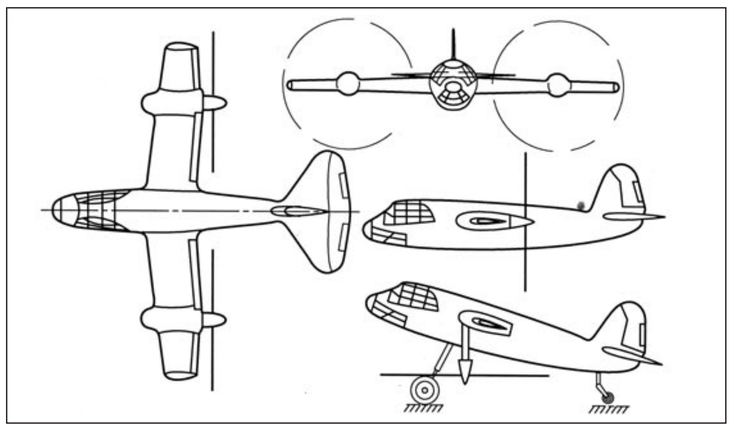

Figure 4: Focke-Achgelis FA269 3-View. (From the author)

aircraft configuration was conceived that could provide helicopter-like hover and low-speed performance while achieving high-speed flight comparable to a conventional fixed-wing aircraft. That configuration is now known as the tiltrotor aircraft.

One of these designs was the Heliplane patented by Leslie E. Baynes in England in the late 1930s. This aircraft was to use large diameter rotors on wing-tip-mounted tiltable nacelles. By moving the rotors from a horizontal plane to a vertical plane, vertical lift could be provided for hover and slow speed flight and propulsive thrust for higher speed cruise flight. In Germany at about the same time, another variant of the tiltrotor configuration was being studied by Dr. A. Rohrbach and Dipl. Ing. Simon of Weser Flugzeugbau GmbH. The P.1003 project, initiated in 1938, tilted not only the wing-tip mounted rotors, but the outboard sections of the wing as well to reduce the "download" on the wing in hover. Inadequate financial backing, however, prevented further development of the Baynes and the Weser aircraft. A later tiltrotor aircraft design, the Fa-269 "convertaplane" by the Focke Achgelis Co., progressed to the mockup stage before the project's assets were destroyed during an allied bombing of the Focke Achgelis facility in 1944, ending the experimental development program. A novel feature of the FA-269 design was that, in hover and helicopter mode, the rotors were located below the wing. After lift off the rotors would be tilted aft to provide thrust as a "pusher propeller" for cruise flight**.**

The First U.S. Army Helicopter

Although the tiltrotor aircraft was being considered by aeronautical visionaries in the late 1930s, it is important to remember that during that period, according to many aviation observers, the practical helicopter had just emerged in the form of the Fw-61. For two enterprising engineers, Dr. Wynn Laurence LePage and Haviland Hull Platt, interested in developing a market in the United States for the helicopter, the

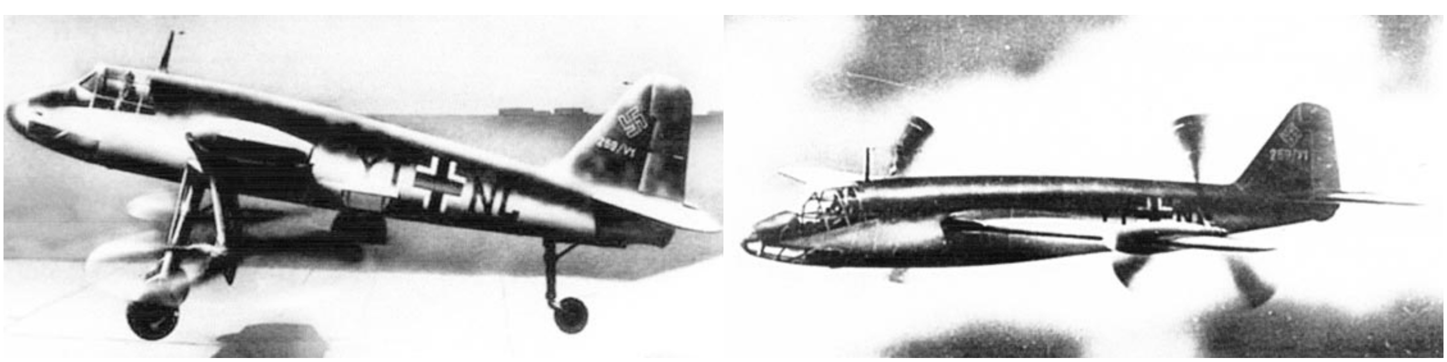

Figure 5: FA269 Hover (Left) & Cruise Mode (Right) artis concept drawings. (From the author)

most direct approach was to emulate the technology successfully demonstrated by the Fw-61. In 1937 LePage traveled to Germany to examine the Fw-61 and to obtain an option to build Focke-Wulf helicopters in the United States. However, due to the deteriorating political conditions between the two countries at that time, the deal was never completed. Nevertheless the Platt-LePage Aircraft Co. was formed in Eddystone, Pa., in November 1938 to develop a helicopter based on the Fw-61 configuration.

Less than two years later, with the design and construction of their first helicopter, the PL-3, more than half finished, the Platt-LePage Aircraft Co. won a competition sponsored by the Material Division of the U.S. Army Air Corps (USAAC). On July 19, 1939, they were awarded a $300,000 contract to provide "a rotary wing aircraft in the interest of adequate national defense" and to deliver seven of the U.S Army's first helicopters, now designated the XR-1 (E**X**perimental **R**otorcraft **1**).

While the similarity of the Platt-LePage PL-3 geometry to the highly publicized Fw-61 was probably a factor in the selection, the PL-3 had one feature that distinguished it from the German design. That was the use of an aerodynamic wing to support the side-by-side rotors, instead of the open framework outrigger structure used on the Fw-61. These cantilevered, high-dihedral wings were designed to develop some lift at higher air speeds to reduce the load carried by the rotors in forward flight.

Unfortunately, in spite of the similarity of the XR-1 configuration to the successful Fw-61, the Platt-LePage Aircraft Co. did not have the technical expertise to correct a number of control, vibration and mechanical problems that occurred during flight tests, and the initial order for the pre-production helicopters was never filled. By early 1942 the AAC decided to focus its rotorcraft procurement efforts on the less complex and technically promising single main-rotor helicopters developed by Igor Sikorsky. Without a production program, the Platt-LePage Aircraft Co. was forced to cease operations in 1946.

The Convertible Aircraft

The Platt-LePage venture, although a failure in producing an Army helicopter, became the unexpected spark-plug for the development of the tiltrotor aircraft in the United States. In 1945 Haviland Platt became interested in the tiltrotor VTOL configuration. An undated artist's drawing of a Platt-LePage tiltrotor

Figure 6: Platt-Lepage XR-1A helicopter. (Ames photo AD98-0209-17)

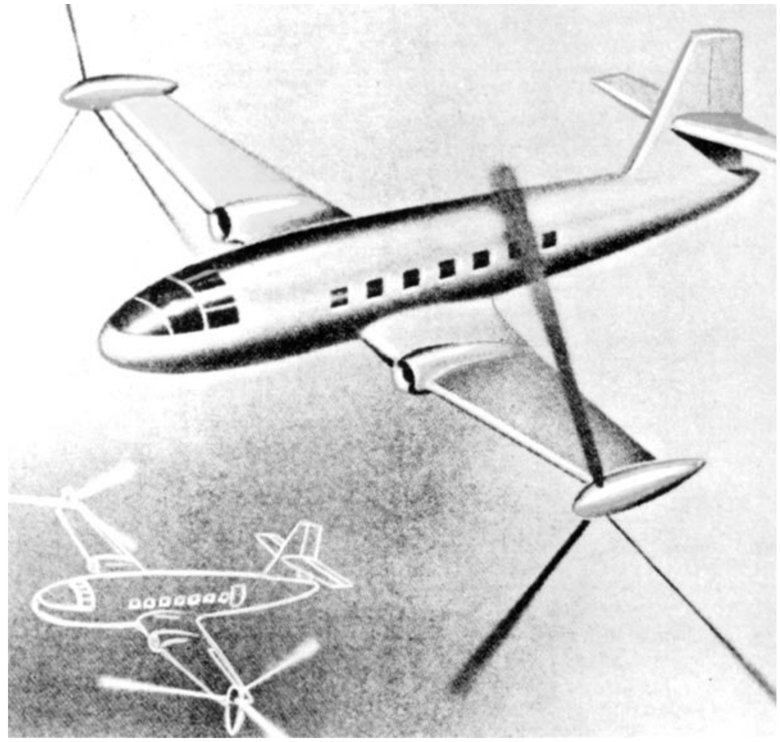

Figure 7: Drawing of the Platt-Lepage tiltrotor aircraft concept, 1947. (Ames photo AD98-0209-22))

transport aircraft design that LePage advocated before the U.S. House Interstate and Foreign Commerce Committee in 1947 is shown in Figure 7. It is not known if the geometry of the XR-1 inspired this interest, nor if Platt was aware of earlier tiltrotor designs in Germany and England, but the resemblance to these configurations is apparent. In 1950 Platt applied for a U.S. patent for a "convertible aircraft" and five years later the tiltrotor aircraft concept patent (number 2,702,168) was awarded to him. The other interesting connection was that a young engineer employed by Platt-LePage named Robert (Bob)

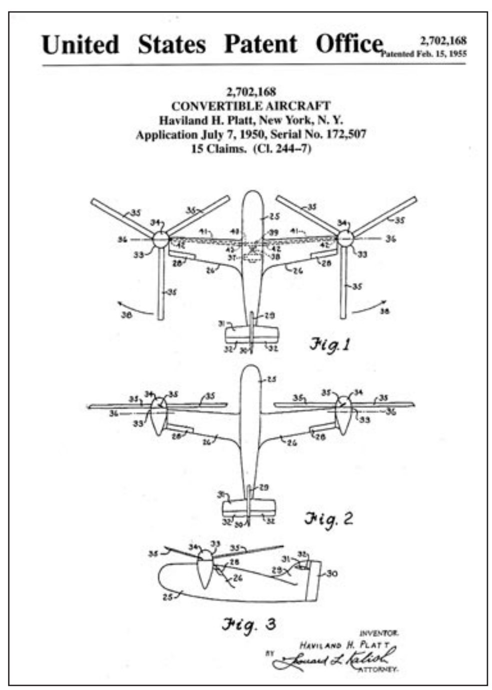

Figure 8: Haviland Platt's convertible aircraft patent 2,702,168, 1950. (U.S. Patent Offfice)

Lichten also became intrigued with the tiltrotor aircraft, possibly due to the influence of his senior manager.

The Transcendental Tiltrotor Aircraft

To continue work on rotary wing aircraft as the future prospects of the Platt-LePage company began to fade, Lichten moved to the Kellett Autogiro Co., Philadelphia, Pa., where he worked with Mario Guerrieri, a former Navy fixed- and rotary-wing test pilot. After some fundamental investigations Lichten and Guerrieri decided to demonstrate tilt rotor technology by independently building and flying a small experimental aircraft. Jointly, they founded the Transcendental Aircraft Corp. of New Castle, Del., and, with Lichten as the principle engineer, they initiated the design and fabrication of the Transcendental Model 1-G.

The 1-G was an open-cockpit, single-seat aircraft with counter-rotating, 17-ft diameter, three-bladed rotors located at the tips of its fixed wing. The 1-G design incorporated a fixed tricycle landing gear and a conventional empennage. A four-cylinder Lycoming O-290-A engine, located in the fuselage behind the cockpit, powered the rotors through a two-speed reduction main gearbox, spanwise drive shafts and wing-tip gearboxes.

Although Lichten left Transcendental in 1948 and Guerrieri sold his interests in the company in 1952, the development of the Model 1-G continued with some funding provided by an Army/Air Force contract. The Model 1-G, however, met an unfortunate end. After successfully completing more than 100 flights in a period of just over one year, including partial conversions to within 15 degrees of the airplane mode, a control failure while flying with the rotors tilted partially forward led to a crash and the destruction of the aircraft on July 20, 1955. A second, improved, Transcendental tiltrotor aircraft, the Model 2, was subsequently developed, and although Transcendental became associated with the short-lived Helicopter Division of the Republic Aviation Corp., Farmingdale, N.Y., the failure to gain further government interest ended the venture. While never attaining flight in the airplane mode (but having flown within 15 degrees of airplane mode), the Model 1-G is generally recognized as the first tiltrotor vehicle to successfully operate in the conversion mode of flight.

The Bell XV-3

Long before Transcendental initiated flight tests of the Model 1-G, Bob Lichten had joined Bell Aircraft where he was given the opportunity to further the advancement of the tiltrotor with the research and development resources of a major aircraft company. At Bell, Lichten began the task of developing the technology associated with the tiltrotor aircraft.

In 1951, in response to the joint U.S. Army and U.S. Air Force Convertible Aircraft Program (CAP) Request For Proposal (RFP) for the design of a "convertiplane," the Bell Helicopter Co. proposed the Model 200, a tiltrotor aircraft designed by a team headed by Lichten. Bell considered the tiltrotor to be the right vehicle to meet the CAP mission requirements that included a significant hover duration, low speed maneuvering and agility, and a potential speed and range greater than current helicopters offered. This, and additional factors such as the need for moderate rotor downwash velocities below the hovering aircraft to enable safe rescue operations, made the Model 200, with its large diameter rotors, a viable candidate for the VTOL convertible aircraft mission.

The Army and the Air Force award selected three VTOL vehicles for further investigation under the CAP in October 1953. These included the McDonnell XV-1, a compound helicopter with rotor tip jets and a pusher propeller, the Sikorsky XV-2 single-blade stoppable rotor helicopter, and the Bell Model 200, later designated the XV-3 by the government. Both Bell and McDonnell built flying test beds under CAP contacts while Sikorsky's XV-1 never progressed beyond the drawing board.

Like the Transcendental 1-G, The Bell XV-3 had its Pratt and Whitney R-985-AN-1 engine mounted in the fuselage and powered the rotors through a main (center) gearbox and spanwise shafts to the wing-tip gearboxes. The outboard gearboxes were mounted on a yoke that enabled the rotor shafts to be pivoted from the vertical (for hover and low speed flight) to the horizontal (for cruise flight). An electromechanical linear actuator powered conversion system. An interconnect shaft linked the right and left conversion system to ensure synchronization and to allow conversion with either actuator inoperative.

To accommodate the requirement for a high rotor RPM for the high-thrust hover and helicopter-mode flight and a lower RPM for airplane flight, a two-speed gear-reduction capability was incorporated in the main gearbox. The gear-shift, to be performed while flying in the airplane mode, was accomplished by means of an electrically-controlled hydraulic clutch actuated by a switch in the cockpit.

The Bell contract to build and fly two full-scale "tilting-thrust-vector convertiplanes," however, eventually revealed that the design of a successful tiltrotor aircraft was beyond the technical capability available at the onset of the project. There would be many technical challenges for Lichten and his team.

While Bell was developing its tiltrotor aircraft, the issue of the patent held by Haviland Platt came up. This matter was settled when, according to Platt, Bell "tacitly acknowledged" the priority of Platt's patent by buying it from him.

Early in the XV-3 flight test program significant vibrations occurred that were determined to be caused by a dynamic instability that involved the rotor, the pylon (the rotor shaft and support structure), and the wing structure. Aerodynamic forces and moments generated by the rotors led to structural deformations resulting in oscillations that were observed to increase with time. On October 25, 1956, as Bell test pilot Dick Stansbury moved the rotor shaft forward from the vertical, a severe rotor instability occurred that produced extremely high cockpit vibrations. The subsequent loss of control caused the XV-3 (aircraft tail number 4147) to crash, destroying the aircraft and seriously injuring the pilot.

It was clear that the technically complex problem of the rotor/pylon/wing aeroelastic instability could not be analyzed by the methods in use at that time. Although the tiltrotor aircraft was expected to achieve airspeeds greater than what would be

Figure 9: Transcendental Model 1-G experimental tiltrotor aircraft. (Ames photo AD98-0209-14)

Figure 10: Transcendental Model 2. (Ames photo AD98-0209-12)

Figure 11: McDonnell XV-1. (Ames photo AD98-0209-13)

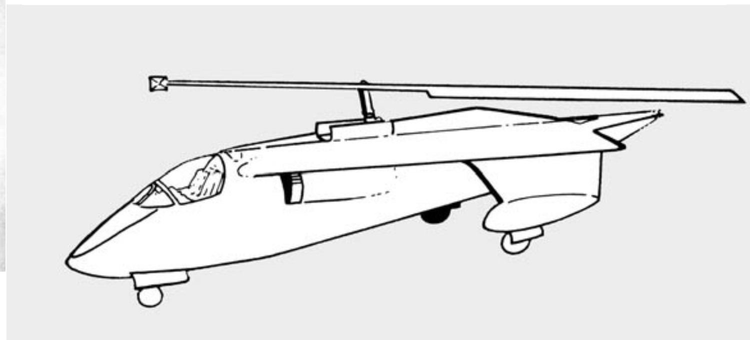

Figure 12: Drawing of the Sikorsky XV-2. (From the author's collection)

Figure 13: Initial configuration of the Bell XV-3. (Ames AC89-0783-3)

Figure 14: Crash of the XV-3 (Bell Photo 217259)

attainable by the helicopter, tiltrotor advocates realized that unless the instability can be eliminated the tiltrotor would never fulfill its promise. For the next 12 years U.S. Government and industry researchers pursued the solution to the aeroelastic instability problem.

The remaining XV-3 (aircraft tail number 4148) was subjected to numerous modifications and to ground, flight[1] and wind tunnel tests (including tests in the NASA Ames Research Center 40-by 80-foot wind tunnel, the nation's largest aircraft test facility).

Figure 15: XV-3 tiltrotor aircraft in the NASA Ames 40- by 80-foot wind tunnel (Ames photo A-37006-5)

Figure 16: Airplane-mode flight of the XV-3 (Bell Photo 028304)

Figure 17: XV-3 tiltrotor aircraft on display in the National Museum of the United States Air Force. (From the author's collection)

By the late 1960s researchers at Bell,[2,3,4,5] Boeing Vertol[6] and NASA[7] developed new analytical tools that unlocked the secrets of the tiltrotor's instability. To verify the new methodology, an additional test in the Ames large-scale wind tunnel was required. This test, conducted in October and November 1968, proceeded extremely well until the final airplane mode test point. Suddenly, with explosive quickness, the rotors and pylons separated from the wings and were blown down the wind tunnel.

The XV-3 was extensively damaged in what initially appeared to be the result of the inability to predict the aeroelastic stability of tiltrotor aircraft. However, careful examination of the damaged structure and the test data revealed this was not the case. The failure was traced to a fatigue crack in the left wingtip. The weakened structure led to the high oscillatory loads that resulted in the subsequent massive failure. In the final analysis, the wind tunnel investigation successfully showed that the stability was predictable[8].

Based on the recently verified analytical tools the new rotor design and changes to the pylon/wing structure were determined to be aeroelastically stable well beyond the aircraft's performance envelope. With these modifications full conversion to airplane mode was eventually accomplished but the performance of the XV-3 was very poor. In hover the aircraft could lift only one pilot and in the airplane mode in level flight it had a maximum speed of 115 knots (155 knots in a dive) – while helicopters of the day could do much better.

At the end of the XV-3 project there were as many questions about the future of the tiltrotor aircraft as there were at the beginning. While the flight tests confirmed the tiltrotor's conversion capability and engineers had new design tools to avoid the instability problem, the underpowered XV-3 had significant deficiencies in its performance and flying qualities. Tiltrotor advocates realized that the concept would not be accepted until there was proof that these issues could be effectively corrected.

After years of storage at several locations, the XV-3 was returned to Bell in January 2004, where Bell volunteers restored the aircraft to a museum display condition. Following the two-year restoration, the XV-3 was transferred to the National Museum of the United States Air Force at Wright-Patterson AFB, Dayton, Ohio, for permanent display as a symbol of the contribution made by the Air Force and the XV-3 to the development of tiltrotor technology.

Technology Development

In spite of the failure of the XV-3 to demonstrate the merits of the tiltrotor aircraft, supporters of the concept in the government and industry were convinced that its technical issues would eventually be resolved and it would meet predicted performance targets. To achieve those objectives, the rotorcraft industry (primarily the Boeing Helicopter Co. (formerly known as Boeing Vertol) and the Bell Helicopter Co.) and government agencies (NASA, the Army and the Air Force) initiated focused research efforts involving design studies, analyses, wind tunnel tests and piloted simulations.

At the NASA Ames Research Center, Woodrow (Woody) Cook, Chief of the Advanced Aircraft Programs Office, and his deputy Wallace (Wally) Deckert (who co-authored the XV-3 Air Force flight test report) were ardent supporters of developing tiltrotor technology. Cook and Deckert joined with Paul Yaggy, the director of the Army Air Mobility Research and Development Laboratory (AMRDL), a research unit co-located at the NASA Ames facility, in co-funding key tiltrotor research projects. While Woody promoted the TRRA project to NASA management, Paul advocated the activity to his command organization, the U.S. Army Material Command.

It should be noted that one of the factors that influenced government and industry leaders to support further development of tiltrotor technology was that it offered the advantage of "low disc loading" rotors while operating in the hover and helicopter modes of flight. Disc loading is defined as the weight of the aircraft divided by the area of the thrust-producer (i.e. the rotor disc area). As illustrated in Figure 18, the "hover efficiency" (the aircraft weight divided by the total horsepower required to hover) diminishes as disc loading is increased. Because of its large diameter rotors the tiltrotor's hover efficiency would be superior to all other types of VTOL aircraft, except the helicopter. Furthermore, the lower disc loading produces an airflow velocity (called "downwash") below a hovering tiltrotor lower than all other VTOL types, again with the exception of the helicopter. In addition, engineers predicted that the tiltrotor

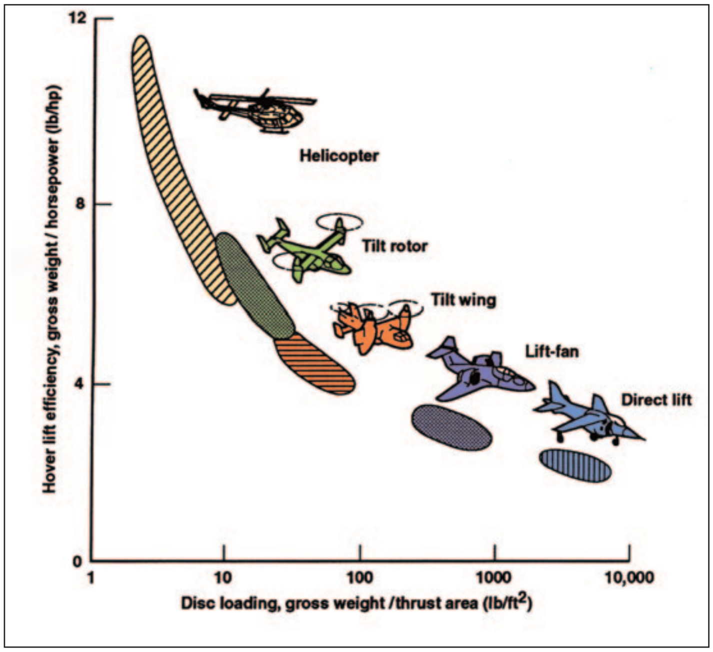

Figure 18: Hover Efficiency vs. Disc Loading. (Line Drawing from the author's collection)

cruise performance would be comparable to a fixed-wing turboprop aircraft, that is - twice as fast and nearly twice as high as a helicopter, with a range much greater than that of the helicopter. The hover efficiency and potential high-speed performance made the tiltrotor aircraft appear to be suitable for a variety of military and civilian missions and applications.

The requirement for high performance of the tiltrotor aircraft in both hover and cruise was seen to be critical if the concept was to be a success, so a series of government-sponsored rotor design studies were conducted in the late 1960s and early 1970s. The challenge was to design a rotor configuration that would provide high performance in the hover operating condition as well as the very lightly-loaded cruise mode of flight. To verify the static (hover) performance predictions, tests of 13-foot diameter model rotors were conducted at the Air Force Aero Propulsion Laboratory propeller test facility, Wright-Patterson Air Force Base, Ohio. The model rotors were then tested in the cruise mode from low airplane flight speeds up to a high-speed flight Mach number of 0.85 in the 8-meter (26 feet) diameter test section of the ONERA (Office National d'Etudes et de Recherches Aerospatiales) S-1 wind tunnel in Modane-Avrieux, France.

Since the XV-3 program it was known that the large diameter rotors mounted on the wingtips of the tiltrotor aircraft could produce forces and moments that could flex the structure while flying in the airplane mode. If the rotor, pylon and wing were not properly designed, these forces and moments could produce an aeroelastic instability that could lead to the destruction of the aircraft. Therefore, among the most significant events during the technology development phase were the tests of a Bell and a Boeing full-scale rotor, pylon and semi-span wing in the 40-by-80 foot wind tunnel at the NASA Ames Research Center, Mountain View, California. These tests validated the recently developed analytical methodology used to predict the aeroelastic stability of the tiltrotor aircraft. That confirmation, coupled with simulator-verified control law to improve flight dynamics and handling qualities and the results of the hover and cruise-mode rotor performance tests, provided the foundation for Army and NASA advocates of the tiltrotor aircraft to propose a new "proof-of-concept" tiltrotor aircraft.

The XV-15 Project

With the favorable results of the recent tiltrotor technology investigations in hand, Robert L. Johnson, Assistant Secretary of the Army, for Research and Development, and Roy P. Jackson, NASA Associate Administrator for Advanced Research and Development signed an agreement in November 1971 for the joint development and operation of tiltrotor proof-of-concept research vehicles at the Ames Research Center. Under that agreement, the joint Army/NASA Tiltrotor Research Aircraft (TRRA) Project Office was formed at Ames. Both parties agreed to equally share in the funding of the project and the




(LEFT to RIGHT) ***Figure 19:*** *13-ft diameter model hover rotor performance test at the Air Force Aero Propulsion Laboratory propeller test facility, Wright-Patterson Air Force Base, Ohio (Ames photo A98-0209-6)* ***Figure 20:*** *13 ft diameter model rotor cruise-mode performance test in the ONERA S-1 wind tunnel in Modane-Avrieux, France (Ames photo A98-0209-5)* ***Figure 21:*** *Aeroelastic stability test of the Bell 25 ft diameter rotor on a semi-span wing in the NASA Ames 40-by 80-foot wind tunnel (Ames photo AC70-3476)* ***Figure 22:*** *Aeroelastic stability test of the Boeing 26 ft diameter rotor on a semi-span wing in the NASA Ames 40-by 80-foot wind tunnel. (Ames photo A72-5255)*

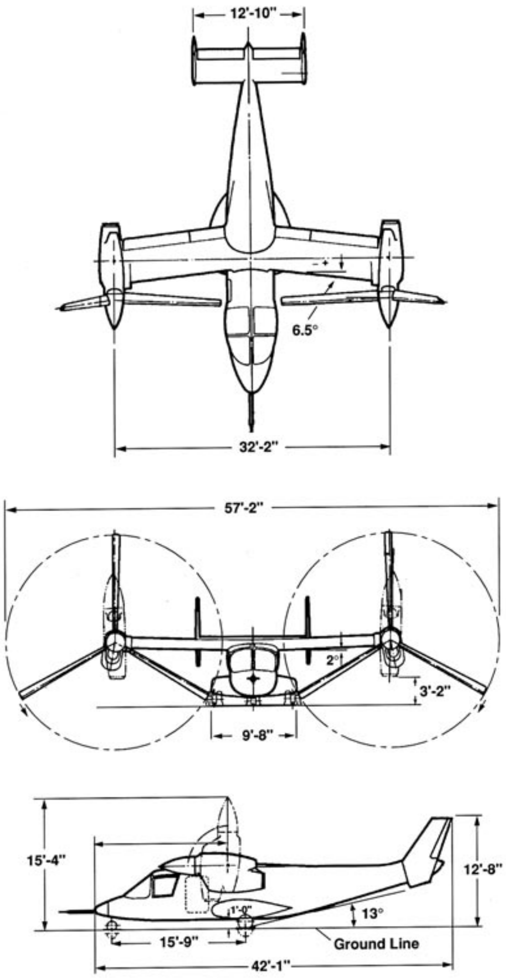

Figure 23: Three-view drawing of the Bell Model 301 tiltrotor research aircraft. (From the author's collection)

staffing of the government project office. At the start of the project David Few of NASA was selected as the manager of the TRRA Project Office. His deputy manger was Dean Borgman of the Army AMRDL.

In the following years the TRRA acquired a staff of engineers with expertise in the various critical tiltrotor technologies. These included Kip Edenborough formerly employed at Bell, Gary Churchill, John Magee and the author from Boeing Vertol, Shorty Schroers, Dave Chappell, Lt. Col. Cliff McKiethan and Lt. Col. Jim Brown from the Army, and Jim Weiberg, John Hemiup, Demo Giulianetti, Robbie Robinson and Mike Bondi from NASA. U.S. Army Lt. Col. Dan Dugan, attached to the AMRDL, was designated as the project pilot.

The initial tasks of the TRRA Project Office involved the management of on-going tiltrotor investigations, the development of a project plan and a model specification document for the research aircraft, and the preparation of a statement of work (SOW) for the Phase I competitive studies that would define the new tiltrotor research aircraft. The NASA/Army Project Plan described the technical objectives and management plan and identified the government funding, facilities and manpower requirements of the project. The project plan, first released in April 1972, was revised two times (once in April 1973 and again in September 1974) to reduce the scope and cost of the project and improve the system and flight safety plan.

Following an open solicitation for bids, four proposals were received for the Phase I effort. Submittals from Grumman Aerospace, Sikorsky Aircraft, Boeing Vertol and the Bell Helicopter Co. were evaluated and on October 20, 1972, Boeing Vertol and Bell were selected to perform the aircraft definition studies under fixed price contracts of $0.5M each. In addition to a cost proposal, these analytical studies addressed the performance, noise, stability and control, and structural loads and dynamics of the proposed aircraft as well as the definition of the critical structures, a maintenance and inspection plan, tooling and fabrication plans and component and integrated test plans. On January 22, 1973, Boeing and Bell delivered their proposals to the Ames Research Center. Each set of proposal documents consisted of 12 volumes weighing about 30 pounds.

The Bell Proposal was based on the Model 300, a tiltrotor aircraft developed in-house on IR&D (Independent Research and Development) funding. The proposed aircraft (now called the Bell 301, utilized a 25-ft diameter gimbaled rotor design that had been extensively wind tunnel tested at Ames. The engines, mounted on wing-tip nacelles, tilted with the rotor as a unit. As a result of earlier wind tunnel model-scale tests, the 301 incorporated an "H" empennage configuration to improve directional stability (the model 300 utilized a single vertical fin). For the Model 301 Bell elected to use the landing gear hardware developed for the Canadair CL-84. By retracting the main landing gear into sponsons on the sides of the fuselage the cabin space remained clear for the installation of research equipment.

Boeing provided a proposal based on the new Model 222. That aircraft used Boeing-developed 26-ft diameter soft-in-plane hingeless rotors on wing tip nacelles that only tilted the rotors. This rotor/wing design had been shown to be aeroelastically stable in an earlier Ames wind tunnel test. For the Model 222 the engines were mounted in fixed wing-tip nacelles. Another interesting feature of the 222 was the use of leading edge "umbrella" flaps as well as full-span trailing edge flaps to reduce

Figure 24: Artist drawing of the Boeing Vertol Model 222 tiltrotor research aircraft (Ames photo AC86-0140-1)*

the "download" on the wing while in hover. The 222 also used a fuselage, landing gear and empennage from a Mitsubishi Mu-2J to minimize development costs.

A Source Evaluation Board was convened at Ames to assess the bids. While both proposals were found to be competitive, the Bell proposal was determined to offer significant technical and cost risk reductions. In September 1973 a contract to build and flight test two tiltrotor research aircraft was awarded to the Bell Helicopter Co..

The new flight vehicles, designated the XV-15, would be designed to provide "proof-of-concept" for the tiltrotor aircraft. As defined in the project plan, the fundamental proof-of-concept tasks were to:

- verify rotor/pylon/wing dynamic stability and aircraft performance over the entire operational envelope;
- conduct an initial assessment of handling qualities;
- investigate tiltrotor aircraft gust sensitivities; and
- investigate downwash and noise

The project plan also defined secondary objectives that were not part of the initial contracted effort. These are summarized as follows:

- evaluate gust and load alleviation systems;
- perform thorough handling qualities evaluations and identify where additional V/STOL research in this area is required;
- develop and investigate terminal area operational methods and procedures to reduce congestion and noise and increase safety;
- determine V/STOL navigation/guidance requirements and evaluate automatic landing systems;
- evaluate potential benefits of applying tiltrotor capabilities to Army missions;
- provide data for development of design and operational criteria for potential civil and military tiltrotor aircraft; and
- investigate alternate or advanced rotor concepts or configuration modifications.

It was recognized that the appearance of any major uncorrectable deficiency would likely end the government's interest in the concept.

Development of the XV-15

Sadly, the person most responsible for promoting the development of the tiltrotor would not live to see the tiltrotor research aircraft project. Bob Lichten, Bell's director of advanced engineering and chief engineer for the XV-3 project, died on September 18, 1971, following an automobile accident. With the loss of Bob Lichten, Ken Wernicke became the lead engineer for tiltrotor aircraft at Bell. Bell's chief design engineer for the XV-15 project was George Carter.

Much had changed since the days of the XV-3. Based on recently developed and verified analyses, the rotor/pylon/wing design of the XV-15 was configured to be dynamically stable throughout and beyond the predicted flight envelope. The government-furnished turbo-shaft engines (a variant of the Lycoming T-53-L-13B) housed in the XV-15's tiltable wing-tip-mounted nacelles and the highly-twisted rotor blades were selected to provide high levels of hover performance while yielding sufficient thrust for high-speed forward flight. Electronic flight controls were installed to enhance handling qualities and flight stability. It was an entirely new ballgame.

Safety played a key role in the design of the XV-15. To ensure that both rotors would continue to be powered in the event of an engine failure, a cross-shaft connected the two wing-tip transmissions. The transmission design incorporated a sprag clutch that would automatically disconnect an engine if it failed. In addition, the XV-15 had three independent transmission-driven 3000-psi hydraulic systems. Automatic shuttle valves were provided on critical dual-tandem flight control actuators that would switch to the utility (back-up) hydraulic system upon the loss of one of the primary hydraulic systems. Extension of the tricycle landing gear, normally powered by the utility hydraulic system, would automatically be switched to a 3000-psi pneumatic system for a one-time deployment if the utility hydraulic system became dedicated to the flight controls.

The aircraft also incorporated two engine-driven electrical systems. Each of the 300-ampere generators could provide sufficient power to accommodate the aircraft's peak electrical load requirements. The nacelles were tilted by screw-jack actuators and, like the XV-3, an interconnect shaft connecting the two conversion actuators ensured that both nacelles were always at the same angle throughout the conversion process. The interconnect shaft also provided the ability to tilt both nacelles simultaneously in the event of a power failure on one side.

In addition, lightweight crash-resistant fuel cells developed by Uniroyal Inc. of Mishawaka, Ind., were installed in the wing to provide fuel containment in case of damage to the wing structure.

The distinctive 6.5-degrees forward sweep of the wing leading edge (shown in Figure 23) ensured adequate clearance in airplane-mode flight due to flapping of the gimbaled rotor under extreme maneuver or gust conditions.

Based on their experience and capabilities, Bell elected to design, fabricate and qualify the critical components of the XV-15 in-house. These included the rotors, the transmissions and the wing. Major elements were subcontracted when expertise or cost issues dictated the use of outside sources. The detail design and fabrication of the fuselage and empennage was subcontracted to Rockwell International at their Tulsa, Okla., facility.

It is interesting to note that, unlike helicopters, the rotors of the tiltrotor aircraft do not pass over the cockpit allowing the installation of North American Rockwell LW-3B "zero-zero" ejection seats (i.e. capable of a safe ejection at ground level with zero airspeed) for the side-by-side crew of two. Upon completion of a fuselage forward section, a functional test of the simultaneous firing of the ejection seats using anthropomorphic dummies was conducted that verified adequate clearance from the window frames and other cockpit structural components.

LEFT - *Figure 25: Simultaneous static test firing of ejection seats. (Ames photo AC75-1602)* **RIGHT** - *Figure 26: Ground tie-down test facility at Bell's Arlington, Tex., Flight Test Center. (Bell photo 304932)*

Other major subcontractors included the Hydraulic Research and Manufacturing Co. (HR&M) for the flight control hydraulic actuators and reservoirs, the Steel Products Engineering Co. (SPECO) for the conversion system, and the Calspan Corp. for the design of the automatic flight control system.

Another critical design requirement was the need to transfer high-pressure hydraulic fluids, fuel and high-temperature engine bleed air from the tilting nacelles to the fixed airframe. This required the use of "swivel" fittings. Furthermore, because of the design criteria to avoid the simultaneous loss of critical hydraulic systems that provide power to the flight control actuators, each of the three hydraulic systems employed a different swivel fitting design at the wing/nacelle joint. The Dumont Aviation Division of Litton Industries, Lakewood, Calif., designed, fabricated and qualified these components.

The main transmission gearbox that Bell planned to use for the XV-15 was originally designed for the Bell Model 300, which used a Pratt and Whitney PT-6 engine. The government, however, elected to provide a variant of the Lycoming T53 turbo-shaft engine for the XV-15 project. That decision was based on the availability of that engine in large numbers in the Army inventory, its higher power allowing for potential aircraft weight growth, and that it had previously been modified to operate in the vertical mode on the Canadair CL-84 tilt-wing VTOL aircraft. To allow the previously designed main gearbox to be used with the modified T53 engine (now designated the LTC1K-4K), an "engine-coupling gearbox" was needed to increase the 22,000 RPM output of the LTC1K-4K engine to the 30,000 RPM transmission-design input speed of the PT-6 engine.

The development of the main transmission and engine-coupling gearbox proved to be troublesome. The gearboxes were subjected to an extensive test-rig qualification program that led to modifications of gear designs, the gear and shaft welding process, bearing designs, and lubrication and cooling arrangements. Ultimately torque limits were established to ensure a safe operating life for the transmission. Those torque limits essentially de-rated the engine and impacted maximum airspeeds from sea level to about 16,000 ft.

The problems encountered during the developmental testing of the transmissions led to the government decision to have Bell conduct an extensive ground qualification run prior to flight operations. These qualification tests were conducted on an elevated ground tie-down facility at Bell's Arlington, Tex., Flight Test Center that allowed the rotors to be operated in all modes – from helicopter to cruise.

XV-15 Flight and Wind Tunnel Tests

Following a series of systems, ground tie-down and ground-taxi tests, the XV-15 became airborne for the first time on May 3, 1977, at the Arlington, Tex., Municipal Airport, with Bell's Ron Erhart and Dorman Cannon at the controls. The initial flight test explored only helicopter mode operations in XV-15 N702NA. Army/NASA project pilot Lt. Col. Dan Dugan participated in the flight test activity during the initial hover and air-taxi evaluation period. NASA Ames test pilot Ron Gerdes later joined Lt. Col. Dugan in government test and demonstration flights of the XV-15.

In accordance with the TRRA Project Plan, the research aircraft was to be tested in the NASA Ames 40-by-80 foot wind tunnel prior to the expansion of the flight envelope to evaluate aerodynamic characteristics and to check out the structure and systems under operational conditions. Following the brief helicopter mode flight tests at Bell, XV-15 N702NA was transported to the NASA Ames Research Center where, from May through June 1978, it was evaluated in the Ames test facility. NASA's Jim Weiberg was the principal investigator for this test series[9].

The wind tunnel tests revealed that some XV-15 structural components needed to be strengthened prior to its return to flight. One of the most significant problems was the occurrence of high empennage oscillatory loads that appeared in helicopter and conversion mode forward flight. It was determined that, in low speed flight, strong rotor trailing tip vortices past in close proximity to the vertical tail surfaces causing the excitation.

Figure 27: XV-15 tiltrotor research aircraft in the NASA Ames 40-by 80-foot wind tunnel. (Ames photo AC78-0579-3)

Following the wind tunnel test program structural changes were made to accommodate these loads.

By 1978 the cost impacts of resolving XV-15 development problems, coupled with the sustained high levels of inflation during the mid-1970s, had threatened the ability of the Army and NASA to continue with the planned two-aircraft TRRA flight test activity. At that time the Naval Air Systems Command (NAVAIR) had been charged by Congress to "evaluate the capabilities and cost effectiveness of current and future platform aircraft and weapon systems combinations." The aircraft to be considered by the Navy included VTOL and V/STOL types. One of the leading advocates for naval VTOL capability was Hal Andrews, head of the Aerodynamics and Hydrodynamics Branch, Airframe Division of NAVAIR. Discussions between the NASA/Army TRRA Project Office and NAVAIR produced a collaboration agreement that provided an infusion of $4.0M of Navy funds into the program between 1979 and 1981. The Navy funds permitted the refurbishment of N702NA for flight (it had been previously configured for the wind tunnel test), the acquisition of required spare parts, and the continuation of the contractor flight test activity. In addition, the XV-15 would participate in a shipboard evaluation in support of NAVAIR's interest in investigating future VTOL aircraft systems.

With funding now available to continue work, Bell initiated a flight program with the second XV-15 (N703NA) on April 23, 1979 at the Arlington Flight Test Center. The Bell pilots assigned to the envelope expansion were Ron Erhart and Dorman Cannon, the pilots who performed the initial helicopter -mode test flights in 1977. Bell's test director was Shep Blackman.

While Bell favored an aggressive envelope expansion program, the government Project Office and the Ames Airworthiness and Flight Safety Review Board directed Bell to employ a cautious approach. Expansion was to be performed in small airspeed and nacelle angle increments and a thorough analysis of the test data was required prior to the next configuration and airspeed condition. All flights were to be monitored in real time from a ground-based control room.

To ensure flight safety and to collect a comprehensive data-base, a digital on-board data acquisition system was installed in each XV-15 aircraft. That system provided over 200 sensors that measured an array of temperature, load, torque, pressure, and position parameters. All data were recorded on a wide-band 12-channel magnetic tape recorder installed in the cabin. In addition, over 30 key items were transmitted to the control room and displayed on strip-chart recorders that were monitored in real-time by project engineers. The engineers would alert the test director, who was in contact with the test pilots, if allowable limit values were approached or exceeded.

After more than three months of expanding the flight envelope with carefully planned incremental steps, the first full in-flight conversion from helicopter-to-airplane mode was accomplished on July 24, 1979. For the higher risk high-speed aeroelastic stability tests, the aircraft was transported to NASA's Dryden Flight Research Center (DFRC) at Edwards Air Force Base near Mojave, California. The initial Proof-of-Concept high-speed aeroelastic stability tests were conducted over the Edwards flight test range between October 1980 and May 1981. Later in the program additional aeroelastic stability tests were conducted that employed flaperon and rotor collective-pitch electro-hydraulic actuators to excite a range of wing/pylon/rotor frequencies. These tests provided proof of the desired stability and provided data to further verify the analytical methodology.

The Paris Air Show

By early 1981 the XV-15 had sufficiently explored the flight envelope in all flight modes to verify all design-critical issues. With much work yet to be done, it was becoming apparent that the XV-15 would accomplish its goal of providing the "proof-of-concept" for the tiltrotor aircraft. The Army/NASA Project Office and Bell decided that the emerging new technology should be demonstrated before a wider aviation community. The venue for that public debut would be the renowned Paris Air Show.

Participation of the XV-15 at the Paris Air Show was a cooperative effort involving the U.S. Army, NASA, U.S. Air Force and Bell. Dr. Irving Statler, who replaced Paul Yaggy as Director of the Army Air Mobility Research and Development Laboratory, advocated the showing of the XV-15 at the Paris event to Secretary of the Air Force, Dr. Hans Mark. Dr. Mark, who had been the Director of the NASA Ames Research Center when the TRRA project was initiated, arranged for the USAF Military Airlift Command to transport XV-15 N702NA and supporting equipment to Farnborough, England, onboard a MAC C-5A and a C-141 aircraft.

After reassembly and check flights, the XV-15 was ferried to Le Bourget, Paris, France, on June 1, 1981. During the 10-day air show, the XV-15 was the only aircraft to perform flight demonstrations daily and on schedule. The appearance of the XV-15 at Paris garnered the attention of Senator Barry Goldwater, Chairman of the Senate Armed Services Committee and John Lehman, Secretary of the Navy. Later, both Senator Goldwater and Secretary Lehman requested and received demonstration flights in the XV-15. It appears that their experiences were instrumental in obtaining the support of Congress and of the Administration for the future acquisition of

Figure 28: XV-15 en route to the Paris Air Show, June 1, 1981. (Ames photo AC82-0108)

the military tiltrotor aircraft, the V-22 Osprey. Senator Goldwater and Secretary Lehman were among the first of the 419 guest pilots to fly in the experimental XV-15.

The XV-15 would appear at the Paris Air Show again in 1995 – that time it would be displayed along side a developmental model of the first production tiltrotor aircraft, the V-22 Osprey.

Flight Tests and Demonstrations

In the early 1980s funding limitations continued to afflict the government's tiltrotor program. To continue the development of the concept, it was decided to bail N702NA to Bell to allow further demonstrations and evaluations of the tiltrotor for potential military and civilian missions. Under the bailment agreement, Bell acquired airworthiness responsibility for that aircraft. NASA and the Army would operate XV-15 N703NA at Ames with a focus of exploring related technologies including control law development and handling qualities,[10,11] flight dynamics,[12] structural loads and stability,[13,14] performance[15,16,17] and acoustics[18].

Initial military evaluations by Bell included nap-of-the-earth flights at Ft. Huachuca, Ariz., and demonstration flights at a Marine Harrier flight facility in Yuma, Arizona. Those operations were followed by a series of shipboard evaluations on the U.S. Navy amphibious assault ship *USS Tripoli* (LHP 10) in July 1982. Lt. Cmdr. John Ball from the Naval Air Test Center, Patuxent River, Maryland and Bell's Dorman Cannon performed the Navy's evaluations.[19] The XV-15 successfully completed 54 shipboard operations with no adverse effects noted.

In September of 1984 the Bell XV-15 team embarked on tour to demonstrate the civil and military potential of this aircraft type. This three-week adventure was managed by Ron Reber, Bell's Program Manager and Lt. Col. McKiethan, Army liaison for the government Project Office. Demonstration and evaluation flights were conducted at Ft. Rucker, Ala., the U.S. Navy Flight Test Center at Patuxent River, Md., the Quantico Marine Corps Air Station, Va., Bolling Air Force Base, Ft. Belvoir, Va., the Pentagon and the New York Port Authority heliport at the base of the World Trade Center, Manhattan.

In the following years Bell conducted additional XV-15 flight demonstration atlocations such as Chicago, Ill., Dayton, Ohio, and McDill AFB, Tampa, Fla., (home of the U.S. Special Operations Command).

Flight Incidents

As XV-15 N702NA was approaching Arlington Municipal Airport following a flight demonstration for senior government personnel on December 5, 1979, the aircraft experienced a sudden engine failure. The failed right engine was immediately disengaged from the rotor drive system by the automatic clutch, allowing the operating left engine to drive both rotors by transmitting power through the cross-shaft to the right rotor. The drive system and flight controls worked as planned and an uneventful single-engine roll-on landing was completed with the nacelles set at 70 degrees. It was later determined that a fatigue crack in one of the aft bearing support struts led to the sudden engine stoppage.

Another engine failure occurred on September 7, 1983, while N702NA was hovering at a wheel height of about 15 feet. A failed fuel control unit produced a sudden fuel starvation, and the low height did not allow sufficient time for the crew to

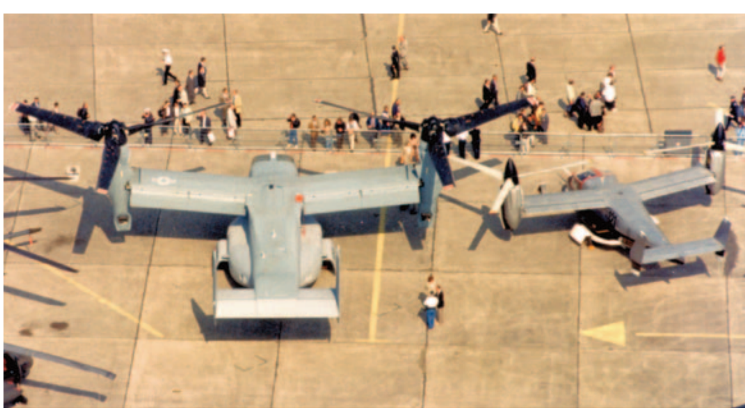

Figure 29: XV-15 along side of the V-22 Osprey at the Paris Air Show, 1995. (Bell Photo 042900)

Figure 30: XV-15 shipboard evaluations on the USS Tripoli. *(Ames photo AC82-0612)*

Figure 31: XV-15 on display at the National Air and Space Museum. (From the author's collection)

respond by increasing power on the operating engine to arrest the rapid descent. In spite of the hard landing, the cross-shaft system again worked as it was designed to and the event caused no damage to the aircraft.

On September 6, 1991, during tests of an experimental rotor blade on XV-15 N703NA, an inboard cuff fairing became partially detached causing severe vibrations. The NASA pilots, Rickey Simmons and George Tucker declared an emergency and were able to land the aircraft safely. Although the oscillatory loads and resulting fatigue damage were high for a single event, it was determined that the aircraft would be safe to fly again. However, the experimental blades would require a modification of the cuff retention design to make them airworthy – a modification that was never completed. NASA headquarters decided to terminate XV-15 flight operations at Ames and the aircraft was placed in temporary storage.

An event nearly one year later changed the plans for that aircraft.

At the conclusion of a brief guest pilot demonstration at Bell on August 20, 1992, while in a low hover, XV-15 N702NA suddenly began an un-commanded roll to the right. The aircraft rolled to an inverted attitude and struck the ground breaking the steel rotor blades and fracturing the wing at the root. The inverted attitude and proximity to the ground prevented the use of the ejection seats. The flight crew, Ron Erhart of Bell and guest pilot Guy Dabadie, chief test pilot for Eurocopter, France, were rescued through the broken side windows with only minor injuries. No fire occurred after the crash, due in part to the crashworthy fuel cells that contained most of the remaining fuel.

The accident investigation conducted by the National Transportation Safety Board (NTSB) found that the loss of control was due to a critical nut backing off from the rotor blade collective angle hydraulic actuator. Furthermore, it was determined that the nut backed off because it had not been secured by a cotter pin as required. The crash, therefore, was caused by human error and was not due to any inherent characteristic of the tiltrotor aircraft.

With the loss of N702NA Bell sought a means of continuing their tiltrotor flight evaluation and demonstration efforts. Since there were no plans on the horizon to operate the XV-15 at Ames, the government agreed to bail that aircraft to Bell. N703NA was returned to flight status by Bell and it served as the prime demonstrator of tiltrotor technology for the next decade.

Conclusion of the XV-15 Project

On July 11, 2003, Bell conducted the last research flight with the XV-15. That test concluded 26 years of research (1977-2003) - the longest research span for any "X" plane. The XV-15 Tiltrotor Research Aircraft successfully achieved all of the proof-of-concept objectives and many of the secondary goals defined in the 1972 Project Plan. The TRRA performed hundreds of conversions from the helicopter mode to cruise flight and back and acquired hundreds of hours of data during the flight program. The data collected during the XV-15 flight program would serve as a basis for the development of future military and civilian tiltrotor aircraft.

The CEO of Bell Helicopter, Mr. Mike Redenbaugh, became the last and 419th guest pilot to fly in the XV-15 – the greatest number of pilots for any "X" plane.

In September 2003 XV-15 N703NA was ferried to the National Air and Space Museum (NASM) Udvar-Hazy Center at Dulles International Airport and was subsequently placed on permanent display at the new NASM facility.

The December 2003 issue of the National Geographic Society periodical recognized the XV-15 as one of the 47 most important aircraft of the first century of flight.

Production Tiltrotor Aircraft

Figure 32: Two Marine MV-22s contour flying on a National Park. (Bell Helicopter photo, 268035)

The V-22 Osprey

In 1982 the U.S. Army, the U.S. Air Force and the U.S. Marines, seeking a replacement for the venerable, but aging CH-46 helicopter, conducted a study to identify the VTOL vehicle that would be best suited for current and future vertical lift missions. Scientists, engineers and military personnel from each military service and from NASA participated in the four-month study at the NASA Ames Research Center that examined conventional helicopters, compound helicopters (with auxiliary propulsion), fan-in-wing aircraft and tiltrotor aircraft. Parameters such as operational effectiveness, cost effectiveness, life-cycle costs, combat survivability and maintainability were evaluated for a number of diverse military missions. The study concluded that the tiltrotor aircraft best met the requirements and Congress subsequently authorized funding to initiate the design and development of the JVX (Joint Vertical Experimental) program. Release of the funding to the contractor, however, was withheld for about a year by the Secretary of Defense who had preferred the funding be used for other procurements. The logjam was broken when the Secretary of Defense was threatened with contempt of Congress charges and work on the JVX (later designated the V-22) was initiated.

Since only Bell had experience in designing, building and flying a tiltrotor aircraft, the issue of "sole-sourcing" such a potentially large government contract was a possible show-stopper. In what might be considered to be a "stroke of genius," the probable challenge to the sole-source contract was eliminated when the only likely competitor, Boeing, was asked to join Bell in a joint venture, thereby creating the Bell-Boeing V-22 team. Full-scale development was authorized in December 1986. Bell, with its XV-15 experience, was responsible for the design of the wing, nacelles, rotors, drive system and tail surfaces. The Boeing Military Aircraft Mobility Division (formerly the Boeing Helicopter Division), having significant experience in composite materials, designed the fuselage and was also responsible for the V-22's cockpit, avionics and flight controls.

Figure 33: V-22 Osprey with wings and rotors folded. (From the author's collection)

It should be noted that the intended multi-service application of the V-22 imposed significant, and often conflicting requirements that influenced the design of the aircraft. One example is the Navy and Marines need to operate off of amphibious assault ships (such as light "Wasp-class" carriers). For shipboard compatibility, the rotor blades had to fold and the wing rotated over the fuselage to minimize the aircraft's footprint for shipboard storage, impacting the aircraft's weight and complexity. Furthermore, the requirement to operate on the carrier deck adjacent to the island, while maintaining a safe distance from the deck edge restricted the wing-span and rotor diameter. The resulting 38 ft diameter of the Osprey's rotors requires more power and produces higher downwash velocities than a larger rotor would. The higher downwash affects ground personnel and increases "brown-out" conditions when operating in a dusty environment.

The design of the critical dynamic elements of the V-22 drew heavily from Bell's experience with the XV-15 Tiltrotor Research Aircraft. Key features of the XV-15, such as the three-bladed rotor, engines mounted in tilting nacelles, a forward-swept thick wing, cross-shafts connecting the nacelle gear-boxes and conversion system, and an "H" vertical tail, were incorporated in the Osprey.

The V-22 is superior to the CH-46 helicopter that it replaced in every critical performance parameter. It is capable of carrying 24 combat troops over 250 nm and can cruise at 225 knots. It can also transport an external load of 10,000 pounds over 60 nm. Its speed and range provide significant tactical advantages to the military commander.

The V-22 had its share of problems. Among the configuration changes influenced by the Marine management early in the program was the use of a throttle-type control like

Figure 34: Presidential transport squadron, HMX-1, MV-22 with New York City backdrop. (Bell Helicopter photo, 268032)

the one used in the VTOL Harrier, instead of a helicopter collective lever. During one developmental test at Boeing the pilots found they could not control roll properly after they lifted to a hover. After erratically dancing around for several seconds the aircraft was finally planted on the ground. The pilot, with lots of helicopter experience, intended to reduce the power – but pushed the throttle forward (the helicopter collective lever would be pushed down to reduce power). The aircraft again jumped into the air and again began to gyrate wildly in roll until a nacelle and rotor contacted the ground, leading to the loss of the aircraft, but fortunately without injury to the two-man crew.

It was later discovered that the loss of roll control was due to the incorrect installation of roll sensors, which produced a roll opposite to the input command. The use of the throttle contributed to the crash because of the poor "human engineering" of that control. The throttle was subsequently modified to improve the input/response arrangement.

Further accidents plagued the early years of the Osprey program. After completing environmental testing in Florida, a V-22 in transit back to the Boeing test facility in Maryland, converted from the airplane mode to the helicopter mode over the Potomac River in preparation for landing at the Quantico Marine Base. Flammable fluids that had collected in the nacelle during the flight suddenly ignited. The flash fire severed a composite rotor shaft resulting in a crash into the Potomac killing all seven people onboard. The rotor shaft was subsequently changed to a metal component to tolerate high temperature conditions and other design changes resolved the fluid leaks.

Tragedy struck again on April 9, 2000, during a night training exercise at Marana Regional Airport, Arizona. One aircraft in a flight of two V-22s descended rapidly to avoid overflying the intended landing spot. The aircraft crashed causing the loss of 19 Marines. An investigation determined that the pilot had exceeded the allowable descent rate that resulted in the loss of rotor lift. This was due to a condition called the "vortex ring" state in which the induced flow below the descending rotor is sucked back into the rotor, creating a no-lift "donut" vortex instead of the thrust-producing downwash. This phenomenon exists for all rotor-lift aircraft. To avoid further occurrences, automatic warnings were provided to alert the crew if they are approaching airspeed and descent conditions where the vortex ring state could develop and improvements in flight training were made.

Another fatal accident occurred on December 11, 2000, near Jacksonville, N.C., after a hydraulic line failed. The complex automatic flight control system was not properly programmed to handle that failure and the loss of control resulted in the aircraft descending into terrain, killing all four onboard. After another long stand-down the flight control digital code was modified and the V-22 returned to flight status.

While none of the accidents were specifically attributable to the tiltrotor concept (but were charged to design, maintenance or pilot error causes) they nevertheless provided ammunition to industry and government advocates of other aircraft systems that were competing for Department of Defense (DoD) funding. The Marines, however, pressed Congress to continue the development of the Osprey that they were depending on for enhancing their future war-fighting capabilities. The Marine Corps request proved to be persuasive and V-22 production funding was approved.

Initial operational capability (IOC) was achieved in June 2007, nearly seven decades after the tiltrotor concept was proposed by Baynes in England. In September 2007 the first 10 V-22s were deployed to a combat zone. In the sandy environment of Iraq engine life and other maintenance problems had resulted in a lower-than-target mission capable availability rate (not unexpected for the first use of a new aircraft system), but the aircraft had received high grades for its effectiveness from flight crews and commanding officers.

In November 2009 MV-22s were deployed to Afghanistan where they played key roles in the conflict with the Taliban. By February 2011, Marine Commandant Gen. James Amos stated that the Ospreys in Afghanistan had surpassed 100,000 flight hours and were "the safest airplane, or close to the safest airplane" in the Marine Corps inventory. Marine Corps Col. Matt Kelly reported in April 2018 that the V-22 is "the most in-demand aircraft in the Department of Defense …Every combatant commander wants the V-22…. because it can respond to such a wide range of crises and contingencies."

By early 2017 the Osprey fleet exceeded 400,000 flight hours.

Current plans call for a fleet of 360 Marine MV-22s, 48 Navy MV-22s and 50 Air Force Special Operations CV-22s. The Navy has announced that their Ospreys, now designated as the CMV-22B, will replace the aging Northrup Grumman C-2 Greyhound for carrier onboard delivery (COD) duties.

In addition to ongoing military operations of the V-22, several MV-22 Ospreys have been configured to support the Marine One presidential transport squadron.

International sales of the Osprey are also evolving. In early

2017 Japan was the first foreign country slated to receive five V-22s for their Self Defense Force. Other nations that have expressed an interest in acquiring the Osprey include India, Israel, South Korea, and the United Arab Emirates.

With the speed of a fixed-wing airplane and the hovering ability of a helicopter the V-22 Osprey provides more capability to the array of military missions than any other aircraft. The tiltrotor aircraft is here to stay.

Future Tiltrotor Aircraft

The AW-609

Figure 35: AW-609 civil tiltrotor aircraft. (AugustaWestland photo)

With the technological success of the XV-15 and the V-22 program as a foundation, the Bell-Boeing Team began work on a civil tiltrotor aircraft, the BB-609. This aircraft was to be a 6- to 9-place, pressurized cabin, executive transport with a VTOL gross weight of about 16,800 lb (nearly 25% heavier than the XV-15) and a maximum speed of 315 mph. When Boeing decided to limit its Bell-Boeing tiltrotor work to military vehicles only, Bell found a new partner, Agusta (an Italian helicopter manufacturer, currently operating as Leonardo), and the aircraft was re-designated the BA-609.

In 2009 Bell elected to withdraw from the BA-609 development program (but would continue to support certification efforts) and the project was continued under AgustaWestland management. The AW-609 has been undergoing extensive testing to meet FAA and European certification requirements. Certification of this new aircraft type presented challenges with the regulatory agencies requiring the aircraft to meet helicopter, fixed wing and new tiltrotor criteria.

On October 30, 2015, one of the prototype AW-609 aircraft crashed, killing two test pilots, during a high speed test flight. The crash investigation identified a fault in the fly-by-wire flight control laws that led to a divergent "Dutch roll" instability and the subsequent failure of the aircraft's tail structure. Design modifications were made and the AW-609 returned to flight-testing in July 2016.

Currently, 60 advanced orders are on the books and AgustaWestland projects a market of 700 aircraft over 20 years. Certification is expected to be awarded in 2019 and initial deliveries are anticipated to be made soon after. The AW-609 will be manufactured at AgustaWestland's plant in Philadelphia, Pennsylvania.

Bell V-280 Valor

Figure 35: Bell V-280 Valor – proposed DoD Future Vertical Lift aircraft - during its first flight. (Bell Helicopter photo)

Recognizing that the U.S. Army's rotorcraft fleet was aging and remanufacturing and upgrades of existing helicopters has its limits, the Department of Defense established the Future Vertical Lift (FVL) program to identify rotorcraft that take advantage of new technology. The product of the FVL effort would be the identification of a vehicle that provides higher speed, greater range, improved reliability, and is easier and less expensive to maintain and operate than rotorcraft in the current inventory.

To meet these requirements, Bell Helicopter is proposing a third-generation tiltrotor designated the Bell V-280 Valor. Unlike the XV-15, the V-22 and the AW-609, the Valor wing is not swept forward and only the rotor tilts, not the engine. The aircraft is designed to have a cruise speed of 320 mph (280 knots) and a ferry range of 2,400 miles. Combat range will be 580 to 920 miles.

Outlook

The future of the tiltrotor aircraft remains promising. It is clear that military roles for the type are likely to continue to develop. The specialized needs of the military user allow the high costs associated with the power and complexity required to provide vertical lift capability to be accepted. We will soon find out if the demand for a civil VTOL aircraft with the cruise speed and range of a fixed wing executive turboprop airplane will be great enough to justify the initial and operating costs, compared to other vehicle types.

The V-22 Osprey was the first tiltrotor aircraft to go into production – but it probably would not be the last. ✈

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[19] Ball, J. C.; DuFresne, D. A., "Shipboard Evaluation of the XV-15 Tilt-rotor Research Aircraft." NATC Report No. RW-54R-82, April 18, 1983.

Appendix - Tiltrotor Aircraft Technical Data

Figure A1: Transcendental Model 1-G Experimental Tiltrotor Aircraft. (From the author's collection)

Transcendental 1-G

The Transcendental Aircraft Corp. Model 1-G was a single-seat convertible rotorcraft with two counter-rotating three-bladed rotors located at the tips of its fixed wing. The high-wing Model 1-G incorporated a conventional empennage and a fixed tricycle landing gear. When the rotors were placed in the horizontal plane, they acted as normal helicopter rotors. The rotors could also be tilted forward 82 degrees to perform as traction propellers of a conventional fixed-wing aircraft. In this configuration lift was provided by the wing. The four-cylinder Lycoming O-290-A, located in the fuselage behind the cockpit, powered the rotors through a two-speed reduction main gear box, span-wise drive shaft and outboard gearboxes. In the helicopter mode, at the engine's maximum output of 3,000 RPM, the rotors rotated at 633 RPM. The rotor blade-angle control system employed two concentric tubes around the rotor shaft emanating from the outboard gearboxes. One of these tubes controlled cyclic blade pitch and the other the collective pitch. The change of the rotor position from the helicopter to the aircraft configuration was accomplished in approximately three minutes.

Model 1-G Characteristics

Powerplant . . . . .One Lycoming O-290-A
Brake horsepower . . . . 160 HP @ 3,000 RPM
Length . . . . 26 ft
Height . . . . 7 ft
Wing
Span. . . . . 21 ft
Area. . . . . 63 sq ft
Chord. . . . . 3 ft
Loading . . . . 27.7 lb/sq ft

Airfoil section . . . . NACA 23015
Width. . . . . 38 ft (to outer tip of rotor disc)

Rotor

No. of rotors . . . . 2, interconnected
Type. . . . . articulated
Blades/rotor 3
Diameter . . . . 17 ft
Chord. . . . . 4 in
Disc loading . . . . 3.6 lb/sq ft

Rotational speed

Helicopter mode . . . . 633 rpm

Weight

Empty . . . . 1,450 lb
Gross . . . . 1,750 lb

No. of seats 1

XV-3 (Final configuration)

The XV-3 was a fixed mid-wing VTOL research aircraft developed by the Bell Helicopter Co. to explore the flight characteristics of the tiltrotor aircraft. The initial XV-3 design incorporated a two-bladed rotor mounted on an extended shaft assembly at each wing tip. However, modifications to eliminated a rotor/pylon/wing aeroelastic instability included changing to a three-bladed rotor and a reduction of the rotor shaft length. The rotors could be rotated over a range of 90-degrees to permit hover and helicopter, conversion, and airplane-modes of flight. The aircraft had a conventional empennage plus a ventral fin below the vertical fin and rudder and used a skid type landing gear. Small wheels could be attached for rolling takeoff and landing tests. The wing incorporated half-span 20 percent wing chord flaps and 22.5 percent wing chord ailerons. Fuselage-to-wing tip struts were incorporated to increase the stiffness of the wing as part of the modifications to ensure aeroelastic structural stability.

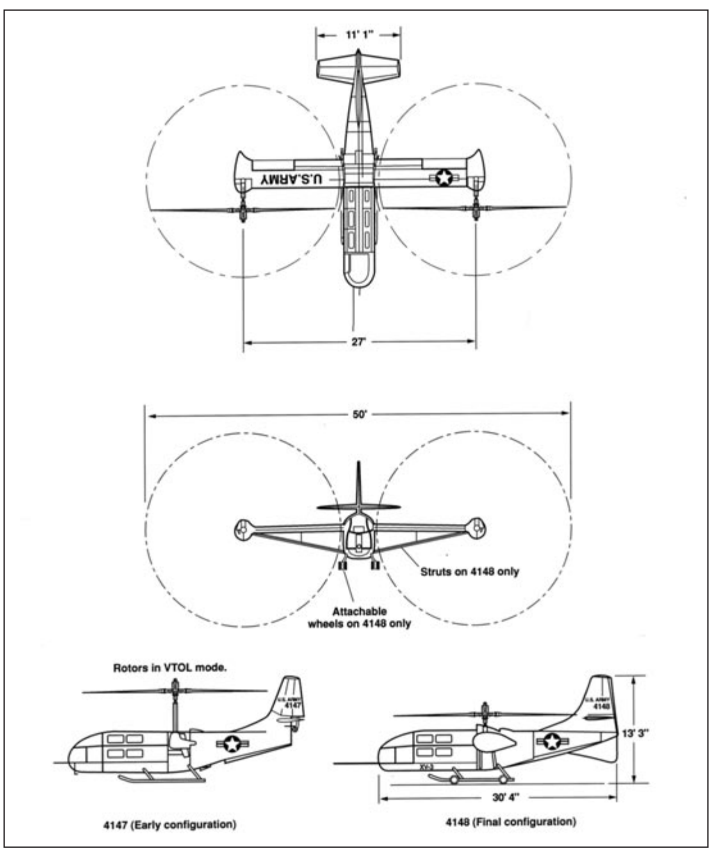

Figure A-2: XV-3 3-view. (From the authors collection)

A supercharged Pratt and Whitney R-985-AN-1 reciprocating radial engine was mounted in the fuselage aft of the wing center section. The standard rating for this engine is 450 BHP at 2,300 rpm but, to increase performance for test purposes, the manufacturer authorized operation at 2,400 rpm for takeoff, hovering and STOL flight conditions. Power was transferred from the engine to the rotors through a short flexible-coupled drive shaft to the main (center) transmission located between the wing center section spars. To accommodate the requirement for a high rotor RPM for the high-thrust helicopter flight, and a lower RPM for airplane flight, the XV-3 incorporated a two-speed gear reduction capability in the center transmission. The gear-shift, performed while flying in the airplane mode, was accomplished by means of an electrically controlled hydraulic clutch actuated by a switch in the cockpit. From the main gearbox, flexible-coupled shafts extended spanwise to the outboard wing tip (outboard) transmissions. The rotor shafts extended from the outboard transmissions normal to the input drive shaft. The outboard transmissions were mounted on yokes that enabled the rotor shafts to be pivoted from the vertical to the horizontal.

The cockpit contained helicopter-type controls: a cyclic control stick, a collective-pitch stick with a twist grip throttle, and rudder pedals. The longitudinal cyclic rotor controls were mechanically reduced as the airplane mode configuration was approached. In the airplane mode no longitudinal cyclic response was provided. The differential collective controls (lateral stick inputs) were also reduced but one-third of the helicopter mode control was retained in airplane flight to increase maneuverability. The collective pitch was also automatically increased in the airplane mode to correspond to the required operating range. The longitudinal, lateral, and ollective controls were hydraulically boosted.

There was no stability or control augmentation installed in the XV-3 and it did not have lateral cyclic rotor controls. The conversion system was powered by an electromechanical linear actuator connected to each outboard transmission yoke and was controlled by a "beep" switch on the cyclic stick. An interconnect shaft linked the right and left conversion systems to ensure synchronization and to allow conversion with either actuator inoperative. The rotors could be returned to the helicopter position by means of a hydraulic emergency reconversion clutch in the event of a complete electrical failure.

XV-*3 Characteristics (Final Configuration)*

Powerplant . . . . One Pratt and Whitney R-985-AN-1 reciprocating radial engine

Brake horsepower . . . . 450 @ 2,300 RPM

Length . . . . 30 ft 4 in

Height . . . . 13 ft 3 in

Wing

Span. . . . . 31 ft 2 in

Area. . . . . 116.0 sq ft
Chord (constant) . . . . 3.75 ft
Airfoil section . . . . NACA 23021
Sweep/dihedral . . . . 0 degrees
Aspect ratio 8.4
Width. . . . . 50 ft (to outer tip of rotor disc)

Horizontal tail
Span. . . . . 11ft 1 in
Area. . . . . 32.6 sq ft
Chord. . . . . 3 ft 10 in
Airfoil section
root . . . . NACA 0015
tip . . . . NACA 0012
Aspect ratio 3.8
Leading edge sweep . . . . 9.5 degrees

Vertical tail
Area. . . . . 32.8 sq ft
Airfoil section . . . . NACA 0012
Aspect ratio 1.33
Leading edge sweep . . . . 20 degrees

Rotor
No. of rotors . . . . 2, interconnected
Blades/rotor (final) 3
Diameter . . . . 23 ft
Disc loading . . . . 5.66 lb/sq ft
Airfoil section . . . . NACA 0015

Rotational speed
Helicopter mode . . . . 532 rpm
Airplane mode. . . . . 324 rpm

Weight
Design . . . . 4,,700 lb
Empty . . . . 4,205 lb
Actual gross (at engine start) . . . . . 4,890 lb
Standard fuel . . . . 280 lb (600 lb capacity)
Instrumentation . . . . 160 lb

No. of seats 1

XV-15

The XV-15 tiltrotor research aircraft was designed by the Bell Helicopter Co. [1] to be representative of the class of VTOL aircraft that employs large-diameter, low-disc-loading, wingtip-mounted rotors that provide the thrust for vertical lift and forward flight. The XV-15 was sized to meet two requirements. First, it had to be large enough to properly demonstrate the performance, flight- and structural-dynamics, acoustics, and handling qualities of this vehicle class. Second, it had to be small enough to be accommodated in the test section of the NASA Ames 40- by 80-foot wind tunnel for aerodynamics, loads, and systems performance evaluations. The XV-15 has 25-foot diameter rotors and a design gross weight of 13,000 pounds.

Two Lycoming T-53-L-13B engines, modified for vertical starting and running (designated the LTC1K-4K), were installed in the wingtip nacelles. These engines are rated at 1,550 SHP (shaft horsepower) for takeoff, with a normal (continuous operation) rating of 1,250 SHP. The engines drove the rotors through main transmissions also located in each nacelle. The two rotors were also linked by a cross shaft system that allowed both rotors to continue to be powered after the shut down of one engine. Upon the loss of a single engine during flight, the failed engine was disengaged from the drive system by an automatic clutch. Because of transmission continuous torque limitations, the engines on the XV-15 were not operated above 1,160 SHP in the helicopter mode. A cross-shaft center gearbox located below the wing in the fuselage accommodated the 6.5-degree forward wing sweep that was required to obtain rotor-to-wing clearance (due to possible rotor flapping) in airplane mode flight. The free turbine engines permitted the rotor speed to be reduced during airplane mode flight to improve performance and reduce cruise noise.

The flight controls in the hover and helicopter modes resembled those of a lateral-tandem rotor helicopter. While the fixed-wing control surfaces remained active at all times, the primary low speed control forces and moments were provided by rotor collective- and cyclic-blade angle (pitch) changes. Differential collective pitch produced aircraft roll and differential cyclic pitch resulted in yaw motions, as depicted in Figure A-3. The rotor rpm was regulated by automatic control of the collective pitch. To reduce the hover performance loss resulting from the rotor's wake impinging on the surface of the wing, the inboard flaps could be lowered to preset deflection positions. The outboard wing control surfaces were also deflected down when the flaps are deployed, but to a displacement less than two thirds of the flap position. The outboard wing control surfaces served as ailerons in high-speed flight and were referred to as "flaperons." During conversion from helicopter flight to airplane mode flight, the helicopter-type control inputs to the rotor were mechanically phased out and the conventional airplane control surfaces provided all flight path control forces and moments. By the time the nacelles were

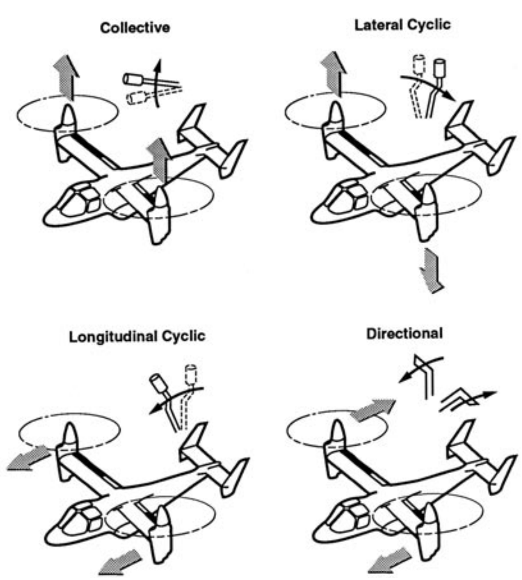

Figure A-3: XV-15 Hover-Mode Rotor Control. (From the authors collection)

[1] Bell developed the XV-15 Tiltrotor Research Aircraft under contract to the U.S. Army and NASA.

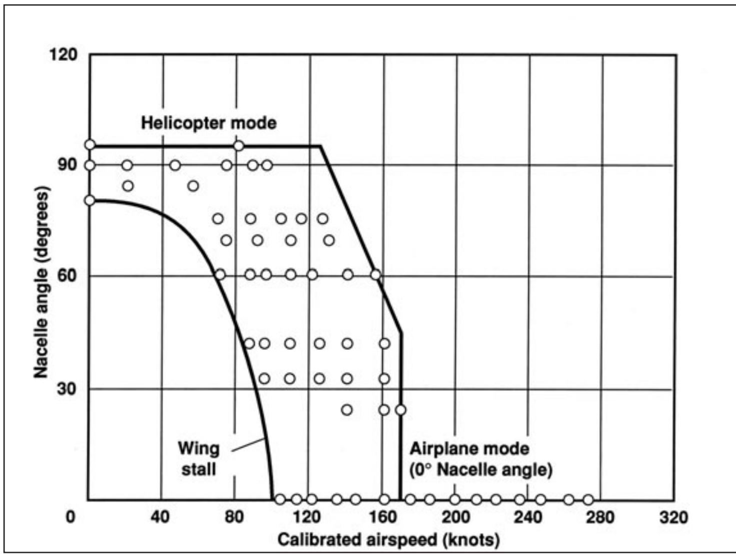

Figure A-4: XV-15 Conversion Envelope

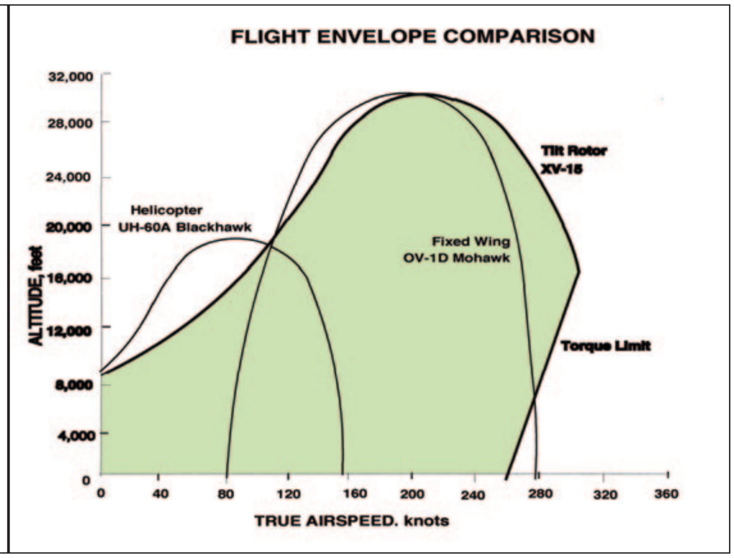

Figure A-5: Height-Velocity Flight Envelope Comparison

in the airplane position, the power lever inputs to the rotor were nulled and the total control of the collective pitch was transferred to the automatic rpm governor.

A stability and control augmentation system (SCAS) was provided with a three-axis (pitch, roll, and yaw) rate system that included a pitch and roll attitude retention feature. SCAS characteristics were continuously varied from the helicopter to the airplane modes as a function of conversion angle to provide appropriate rate damping and control augmentation. The pitch and roll axes had dual channels and the yaw axis had a single channel system. SCAS-off flight was routinely evaluated and demonstrated and, although damping and control are degraded, the XV-15 was still quite safe to fly, albeit with a higher pilot workload. A force feel system (FFS) provided stick and pedal forces proportional to control displacements while isolating the pilot's controls from SCAS feedback forces. Force gradients were increased and trim rates were decreased with airspeed through an airspeed sensor. With the FFS off, pitch trim was available at a reduced rate and control forces were high but manageable.

The XV-15 aircraft had three independent transmission-driven 3000-psi hydraulic systems. The pump for each system was geared to the rotor side of the transmission clutch so that full hydraulic power could be provided with both engines shut down, as long as the rotors are turning within the normal speed range. Automatic shuttle valves were provided on some critical flight control actuators that switched the utility hydraulic system onto the critical actuator in the event of the loss of one of the primary hydraulic systems. The tricycle landing gear, operated by the utility hydraulic system, was automatically switched to a 3,000-psi pneumatic backup system for a one-time deployment when the normal hydraulics source became dedicated to the flight controls.

The electrical system included two engine-mounted 300-ampere starter-generators. Each generator provided sufficient power to accommodate the aircraft's peak electrical load requirements. The XV-15's electrical system consisted of two 28-volt dc busses and two 600 VA solid-state inverters for AC power. Automatic dc bus interconnection was provided with pilot-controlled override switches in the cockpit. A 13-ampere-hour battery was connected to each dc bus during normal operation to prevent the bus voltage from dropping excessively during bus switching operations. The batteries also provided a self-contained engine-start capability.

The nacelles were tilted by ball-screw-jack actuators with hydraulic motors and electrically-powered servo valves. The rotor axes could be rotated from 5 degrees aft of vertical for rearward flight or autorotation, to 90 degrees (vertical), the normal position for hover and helicopter flight, and to 0 degrees (horizontal) for airplane mode flight. A triply redundant hydraulic power supply was provided for the conversion system because the XV-15 could not be landed in the airplane mode without destroying the rotor system. In the event of total electrical failure, the pilot still had mechanical access to hydraulic power to convert to the helicopter mode. The conversion system interconnect shaft maintained both nacelles at the same angle and provided power to drive the nacelle conversion in the event of a total power failure on one side. The pilot could select the normal 7.5 degrees per second continuous conversion rate (which performed the conversion in 12 seconds) or a slower rate of 1.5 degrees per second. The conversion could be stopped and steady flight performed at any point in the conversion envelope.

Fuel was supplied to each engine by separate fuel systems contained in each wing. Each system had two lightweight crash-resistant fuel cells which were interconnected to form a single tank. An electrically driven submerged boost pump was located at the lowest point of each tank. Interconnect valves and lines permitted fuel transfer between tanks or supplying fuel to both engines from the same tank. With a complete loss of electrical power to both boost pumps, adequate fuel flow would be maintained by the engine-driven pumps up to an altitude of 10,000 feet. The 1,436 pounds of fuel carried in the wing allowed a flight of one hour. For ferry operations, Bell developed a removable internal tank that extends the duration of flight to more than two hours.

An environmental control system provided ventilation and temperature control. An air-cycle environmental control unit mounted in the aft fuselage was powered by bleed-air from the right engine. Each crew seat was equipped with an oxygen system supplied from a 1,800-psi oxygen cylinder. Adequate oxygen for a one-hour flight with a 20 percent reserve was carried onboard.

The design of the XV-15 TRRA incorporated many features and system redundancies intended to enhance the safety of this vehicle. Some of these are not expected to be included in civil aircraft of its weight class and, therefore, must be considered when evaluating the XV-15's weight and payload capacity. Among the additional items was the North American Rockwell Model LW-3B ejection seats, capable of removing the crew members in flight or from a zero airspeed, ground-level (zero-zero) normal attitude condition. The ejection seats could be triggered independently or simultaneously by pilot command. In addition, the overhead and side windows could be removed by a mild detonator cord placed around the window frames. The window removal could be initiated from within the cockpit or from an external lever located under a door on the nose cone.

As an example of the overall performance capabilities of the XV-15, the height-velocity flight envelope is shown in Figure A-5. That figure shows that the tiltrotor aircraft could operate over a range of airspeeds and altitudes similar to the combined capability of a helicopter and fixed-wing aircraft. Figure A-6 (next page) illustrates the variation of power with airspeed for a range of nacelle angles from helicopter- to airplane-mode flight. The XV-15 could operate over a wide range of airspeeds at power levels well below that required for hover.

A cutaway drawing of the XV-15 illustrating its major components is given in Figure A-7.

XV-15 Characteristics

Powerplant. . . . . . . Two Lycoming LTC1K-4K turboshaft engines (modified T53-L13B)

Horsepower ratings
- Contingency (2 minutes). . . . .1802 SHP
- Takeoff (10 minutes). . . . . . . .1550 SHP
- Normal (max. continuous) . . . 1250 SHP

Length . . . . 42 ft 1 in (not including nose boom)

Width . . . . 57 ft 2 in (to outer tip of rotor discs)

Height . . . . 12 ft 8 in

Wing
- Span. . . . . 32 ft 2 in
- Area. . . . . 169.0 sq ft
- Chord (constant) . . . . 5 ft 3 in
- Airfoil section . . . . NACA 64A223 Mod.
- Sweep . . . . -6.5 degrees
- Dihedral. . . . . 2.0 degrees
- Aspect ratio 6.12

Horizontal tail
- Span. . . . . 12 ft 10 in
- Area. . . . . 50.25 sq ft
- Chord. . . . . 3 ft 11 in
- Airfoil section . . . . NACA 64A015
- Aspect ratio 3.27

Vertical tail
- Area. . . . . 50.5 sq ft
- Airfoil section . . . . NACA 0009
- Mean Aerodynamic Chord . . . . 3.72 ft
- Aspect Ratio 2.33

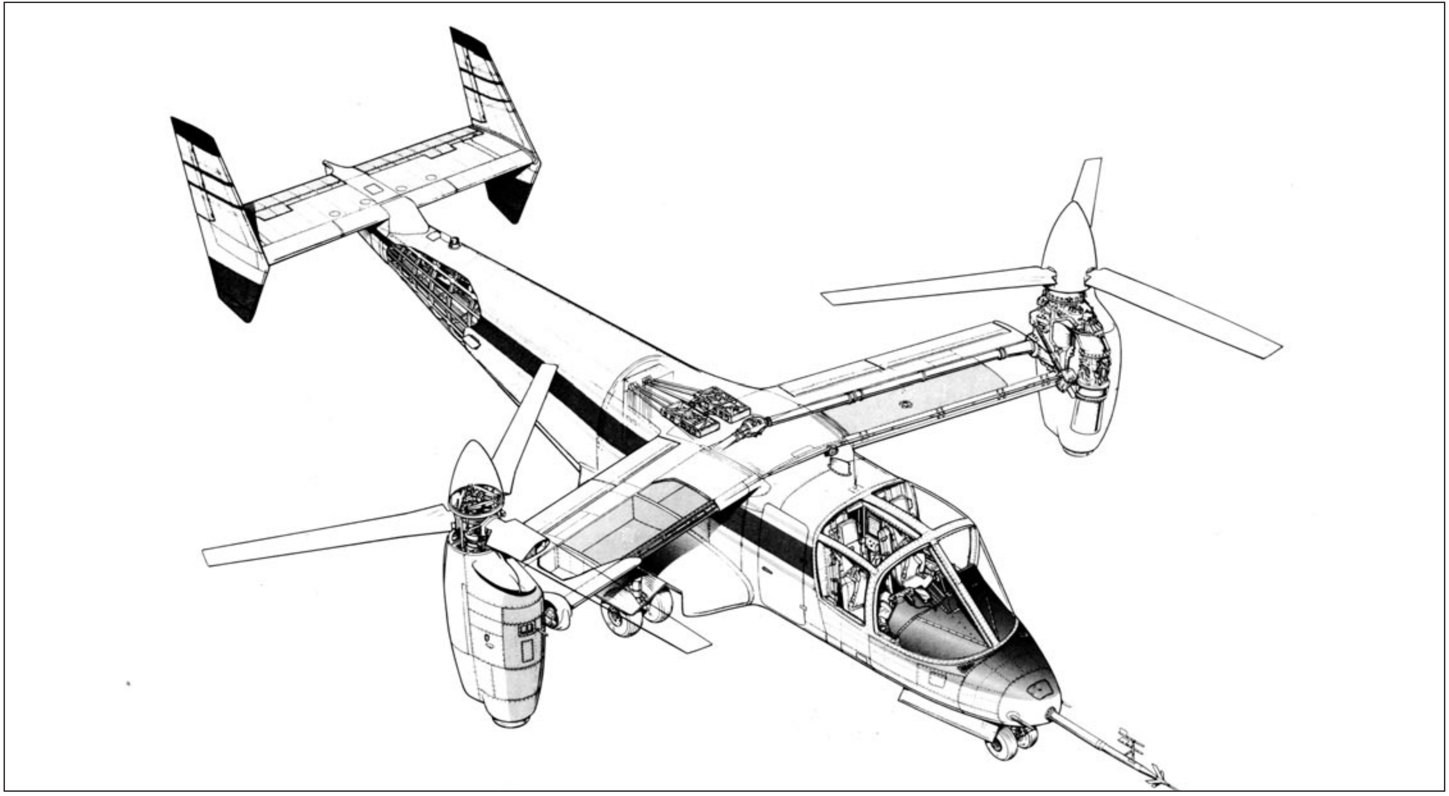

Figure A-7: XV-15 Cutaway Drawing

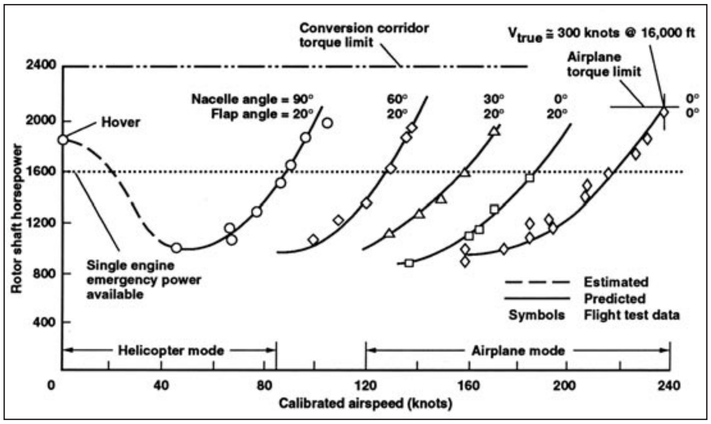

Figure A-6: SHP vs Airspeed for a range of nacelle positions.

Rotor
No. of rotors . . . . 2, interconnected
Blades/rotor 3
Diameter . . . . 25 ft
Chord (constant) . . . . 14.0 in
Solidity 0.089
Disc loading . . . . 13.2 lb/sq ft
Twist, geometric (spinner to tip). . . . 36 degrees
Rotational speed
Helicopter mode . . . . 589 rpm
Airplane mode. . . . . 517 rpm
Weight
Design . . . . 13,000 lb
Maximum. 15,000 lb
Empty . . . . 10,083 lb
Actual gross (at engine start) . . . . . 13,248 lb
Fuel . . . . 1,436 lb
Research instrumentation . . . . 1,148 lb
No. of seats 2

V-22A

The V-22 is a twin engine, medium-lift, tiltrotor aircraft that combines the speed, range, and fuel efficiency of a turboprop aircraft with the slow flight and hover capabilities of a helicopter. The altitude/velocity flight envelope of the V-22 is compared to that of a helicopter and fixed-wing aircraft in figure A-9.

The airframe is constructed primarily of graphite-reinforced epoxy composite material that provides improved strength, corrosion resistance, and damage tolerance compared to typical metal construction. The V-22 design incorporates redundant and separated flight control, electrical, and hydraulic systems to enhance battle damage survivability.

The cargo compartment of the V-22 measures approximately 6x6x24 feet. The cabin is fitted with crash-resistant foldaway seats for 24 fully-equipped combat troops. The fuselage has a rear loading ramp which, when closed, comprises the lower portion of the aft fuselage section. An entry door is located on the right side of the fuselage. The aircraft is not pressurized.

The V-22 has a retractable tricycle landing gear. The nose gear retracts aft while the main gear retracts into sponsons on each side of the fuselage.

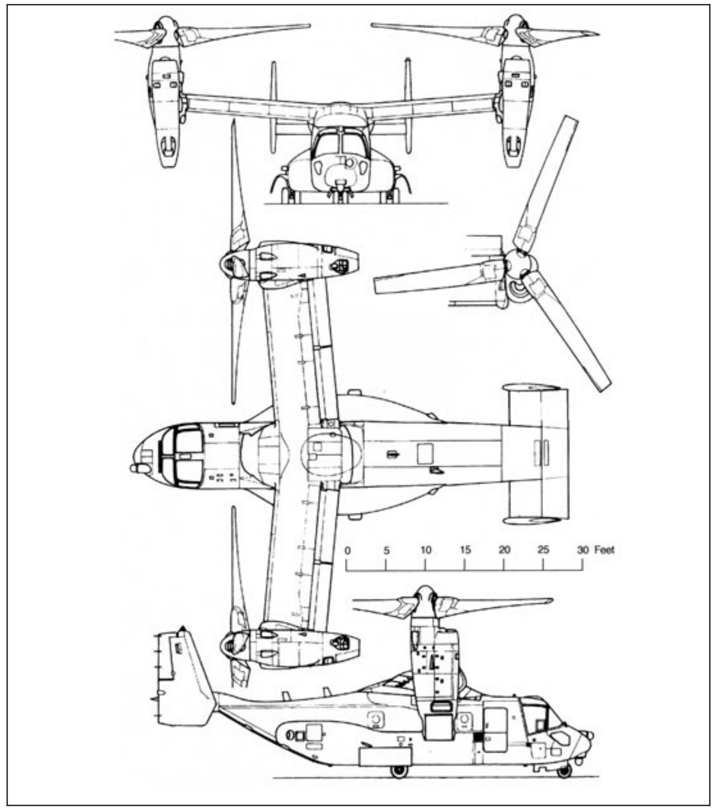

Figure A-8: V-22 Three View Drawing

The empennage consists of a constant chord horizontal stabilizer and two vertical stabilizers with swept-back leading edges. The "H" tail resembles the configuration successfully demonstrated on the XV-15 Tiltrotor Research Aircraft and minimizes the height of the vertical fins for shipboard stowage.

The constant chord wing is swept forward to provide adequate clearance from the rotor in the event of maximum blade flapping during cruise-mode extreme maneuvers or gust encounters. The wing structural assembly consists of the wing torque box, and the nacelle support structure. Electrical de-icing boots are installed in the leading edges of the wings, the tailfins and the rotor blades.

The conversion mechanism consists of a wing tip mounted conversion spindle along with the conversion actuator. The conversion mechanisms are connected by a cross-shaft that ensures synchronization and provides the ability to complete a conversion if one of the systems fails. A down-stop structure provides the support between the nacelle structure and the wing during airplane mode flight.

Power is provided by two Rolls-Royce Allison T406-AE-1107 turboshaft engines, each with a takeoff rating of 6,150 SHP (shaft horsepower) and a continuous rating of 5,890 SHP. The engines, driving counter-rotating 38 ft diameter, 3-bladed rotors, are installed in the V-22's wing-tip-mounted tilting nacelles. They have full-authority digital engine controls (FADEC), with analog backup, and an automatic fire extinguisher system. The interconnect shaft that connects the wing-tip rotor transmissions through a mid-wing gearbox

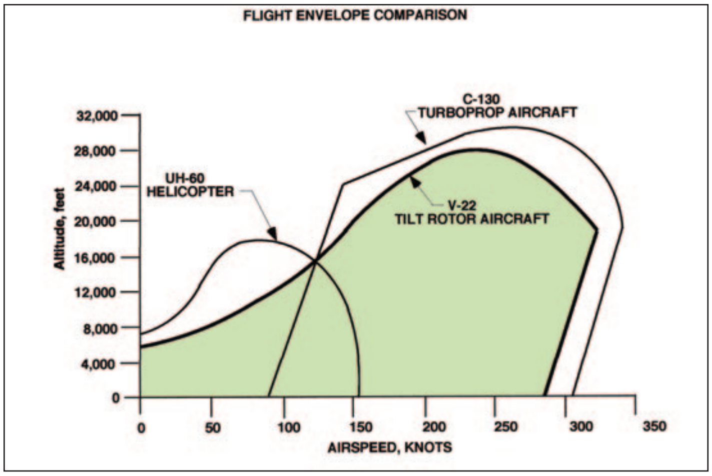

Figure A-9: V-22 Height/Velocity Envelope

maintains rotor synchronization and allows both rotors to be powered in the event of a single engine failure.

In addition to wing and sponson self-sealing nitrogen-inerting fuel cells, the installation of auxiliary internal tanks in the cabin along with an aerial refueling capability, provides the V-22 with the ability to self-deploy worldwide. Ground refueling points are located on each wing and in the front of the right sponson.

The pilot (right seat), copilot and crew chief stations are equipped with crashworthy armored seats. The cockpit flight controls are conventional and include a stick, rudder pedals and a throttle lever mounted to the left of each seat. For hover and helicopter flight, stick, rudder and thrust control lever inputs provide rotor collective and cyclic pitch changes. In helicopter mode flight the throttle provides collective pitch inputs to both rotors. Lateral stick motion provides differential collective pitch producing a roll, longitudinal stick motion yields rotor longitudinal cyclic pitch for fore-or-aft flight, and rudder pedal input produces differential longitudinal cyclic pitch for yaw control.

The aircraft employs "glass cockpit" technology with four multifunction displays — two each for pilot and copilot. In addition, the instrument panel provides a central status and alarm display and a small monochrome status display. A Night Vision System and a Honeywell integrated helmet display are also provided.

The flight controls are managed by a triply redundant digital fly-by-wire system. Airplane mode flight control surfaces are conventional and include rudders, elevators, and twin "elevons" in each wing.

The nacelle angles and flight speeds between the helicopter mode and the airplane mode is referred to as the "conversion envelope". In addition to the process of transitioning between helicopter and airplane flight, the V-22 can operate over a range of airspeeds of about 100 knots at any nacelle angle throughout the conversion process. The minimum time to transition from hover to the airplane flight mode is 12 seconds.

Two independent 5,000 psi hydraulic systems and a backup hydraulic system power the flight controls. An auxiliary power unit (APU) turbine, in the rear of the wing center section, is used to drive two electrical generators and an air compressor. The APU is required for engine start and the blade and wing fold/stow operation. The aircraft has an onboard oxygen generator system to eliminate the need to stock crew oxygen bottles, and a similar nitrogen generation system for fuel tank pressurization.

Dual cargo hooks beneath the fuselage can carry external sling loads up to 15,000 pounds and up to 10,000 pounds can be carried using only one hook.

The V-22 rotor-blade-fold and wing-rotation system reduces the footprint of the aircraft for stowage on U.S. Navy amphibious ships and light assault carriers. The automatic process first folds all rotor blades inboard, then rotates the nacelles from the vertical (helicopter) position to the airplane orientation, and next rotates the wing over the fuselage. When folded, the V-22 fits into a space 63 feet long, 18 feet 5 inches wide, and 18 feet high.

V-22 Characteristics

Powerplant. . . . . Two Rolls-Royce Allison T406/AE 1107C Liberty turboshaft engines
- Horsepower ratings
  - Takeoff (10 minutes). . . . . 6150 SHP
  - Normal (max. continuous) . . . 5890 SHP

Length . . . . 57 ft 4 in
Width . . . . 84 ft 7 in (to outer tip of rotor discs)
Height (Nacelles Vertical) . . . . 22 ft 1 in
Wing
- Span. . . . . 45 ft 10 in
- Area . . . . 382 sq ft
- Chord (constant) . . . . 8 ft 0.9 in
- Airfoil section . . . . Bell A-821201
- Sweep . . . . -7 degrees
- Aspect ratio 5.1

Horizontal tail
- Span. . . . . 18 ft 5 in

Rotor
- No. of rotors . . . . 2, interconnected
- Blades/rotor 3
- Diameter . . . . 38 ft 1 in
- Solidity 0.114
- Disc loading at 47,500 lb GW . . . . . 20.9 lb/sq ft

Rotational speed
- Helicopter mode . . . . 397 rpm
- Airplane mode . . . . 333 rpm

Weight
- Empty . . . . 33,140 lb
- Maximum Rolling Takeoff . . . . 57,000 lb
- Maximum Self-Deploy Takeoff . . . 60,500 lb
- Maximum Vertical Takeoff . . . . . . 52,870 lb
- Internal Payload . . . . 20,000 lb
- External Load (Single Hook) . . . . . 10,000 lb
- External Load (Dual Hook) . . . . . . 12,500 lb
- Fuel (MV-22) . . . . 9850 lb
- Fuel (CV-22) . . . . 13,850 lb

Basic Crew (CV-22) 3
No. of Cabin Troop Seats 24