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TILT ROTOR V/STOL AIRCRAFT TECHNOLOGY

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1.0 Abstract

This paper summarizes current tilt rotor technology and discusses the operational concept of this class aircraft. The basis for selecting the tilt rotor from a spectrum of V/STOL aircraft options spanning the subsonic speed range is presented. The development of tilt rotor technology starting with the XV-3 Convertiplane program is reviewed resulting in a summary of the rationale behind the configuration of the XV-15. Descriptions of the XV-15 aircraft and its present program are included. Future applications are discussed and the role of an operational demonstrator aircraft is identified. Conclusions are presented concerning projected tilt rotor productivity, current tilt rotor technology status, and future steps. An extensive list of references is provided.

2.0 Introduction

Bell Helicopter Textron is currently preparing the XV-15 Tilt Rotor Research Aircraft, Figure 1, for its first flight. The effort is the culmination of a period of development of tilt rotor technology begun in the 1950's with the XV-3 Convertiplane.

The tilt rotor aircraft is the one of several V/STOL aircraft options which promises the greatest improvement in productivity over the helicopter. Like the helicopter, it can make vertical takeoffs so that its operation does not depend on the time and cost of installing, maintaining (and defending) runways. It hovers with sufficient fuel economy that it can perform rescue or "skyhook" utility tasks which may require hours to complete. It has reasonably low downwash velocities so that men, materiel, and the landing site can remain functional below it. It has good fuel economy and maneuverability at low speeds making it suitable for terminal operations, shipboard approaches, and loiter operations. It can autorotate so that in the event of power failure it can make slow-speed landings, improving its chances of survival over the airplane. It can take off with significant payload increases at overload gross weights by making short take-off (STO) runs when airstrips are available.

But, it also differs from a helicopter. It can, by tilting its wing-tip mounted rotors forward, fly quietly and easily at speeds twice those of a helicopter with better fuel economy, ride qualities, and lower vibration. In the event of power failure, the rotors can be tilted from the airplane to the helicopter mode to initiate autorotation. When necessary, it can fly continuously with its rotors partially tilted so that wing and rotor lift components can be added for low-speed maneuvering. The promises of economy and versatility of the tilt rotor are compelling arguments for its development.

3.0 Productivity Basis for the Tilt Rotor

3.1 Productivity Background

A fundamental basis for selecting the tilt rotor from several possible V/STOL aircraft options is aircraft productivity. Certainly, productivity is not the only selection criterion, but it reflects operational economy of possible aircraft options after other standards have been met (such as noise levels, response time, compactness, ride qualities). Productivity represents a maximum capability to produce return on investment in civil operations, or to sustain a maximum force level for given resources in military operations.

During the 1960's, several VTOL productivity comparisons showed the promise of the tilt rotor, References 1 through 10. Since those studies, advancements have been made in both power plant and helicopter technology. It therefore becomes necessary to take a fresh look at contemporary projections on a common basis.

3.2 A Basic Productivity Approach

This section presents the results of productivity comparisons of the helicopter, compound helicopter (Advancing Blade Concept), tilt rotor, tilt wing, lift/cruise fan, and vectored thrust aircraft. These V/STOL aircraft types span the subsonic speed range and straddle other types such as the tilt propeller, tilt duct, and augmentor wing.

In a basic range mission, productivity, PR, may be defined as:

Example Units

(1) $$PR = \frac{P_M D_M}{C_M}$$ (lb-mile/$)

where, P_M = mission payload

D_M = mission distance

C_M = mission direct costs (aircraft initial, maintenance, fuel, and crew elements; no overhead)

By substituting the variables which contribute to mission direct costs, the productivity expression becomes:

(2) $$P_R = \left[\frac{T_L}{K_1 C_{WA}}\right] \left[\frac{P_M D_M}{(WE + K_2 WF_M) T_M}\right]$$ (lb-mile/$)

where, in the first bracketed term,

C_{WA} = initial aircraft cost per pound of weight empty ($/lb)

$K_1 = 1 + \frac{\text{Lifetime Maintenance Costs + Lifetime Crew Costs}}{\text{Initial Aircraft Cost + Lifetime Fuel Costs}}$ (-)

and, T_L = Aircraft life in flight hours (hr)

As disk loading is increased across the spectrum for the various V/STOL types, the aircraft cost per pound, C_{WA}, will tend upward because a higher percentage of aircraft weight will be devoted to the engine (the highest cost per pound item of the lift-propulsion systems considered). However, the factor, K_1, will probably tend downward because it is likely that the denominator in the expression for K_1 increases relative to the numerator as disk loading is increased. If K_1 and C_{WA} tend to compensate, then the productivity, PR, is most tangibly represented by the second bracketed term, the productivity index, PI. Without more detailed information concerning the relative maintenance costs of the various V/STOL types, the productivity, PR, will be considered in this paper to be proportional to the productivity index, PI.

In the second bracketed term, the productivity index, the new variables are:

T_M = mission time in flight hours (hr)

WE = aircraft weight empty (lb)

WF_M = fuel needed per mission (lb)

and, $$K_2 = \frac{\text{(Cost per pound of fuel)}}{\text{(Cost per pound of aircraft weight empty}} \times \frac{\text{(Aircraft life)}}{\text{(Mission time)}}$$ (-)

An approximation for K_2 can be made for all V/STOL types by selecting a type of operation and assigning typical values. For example, in a V/STOL utility operation:

Cost per pound of fuel = \$.05 (33¢ per gallon)
Cost per pound of aircraft = \$250 (with basic avionics, 300 produced)
Aircraft life = 7500 hours
Average mission time = 1.5 hours
Therefore, K_2 = 1.0

The productivity index simplifies to:

(3) $$PI_{UTIL.} = \frac{P_M D_M}{(WE + WF_M) T_M}$$ (lb-mi/lb-hr)

In commerical airline operations, K_2 can have values of approximately 5 to 10 due to customarily higher values of aircraft life and lower aircraft costs per pound. Such values of K_2 would further emphasize the importance of fuel-conservative aircraft such as the tilt rotor. However, for the following comparisons, the productivity index for a (military or civil) utility-type V/STOL mission is used.

For simplified linear productivity analyses, weight empty fractions and fuel flow fractions for a mission are assumed independent of gross weight. The payload, weight empty and mission fuel load in equation (3) may be divided by gross weight. Then, the productivity index becomes:

$$(4) \qquad PI_{UTIL.} = \frac{(PM/GW)\ D_M}{(WE/GW + WF_M/GW)T_M} \qquad \text{(mi/hr)}$$

where, $P_M/GW = 1 - WE/GW + WF_M/GW$

and includes an allowance for crew and trapped fluids.

Evaluations of weight empty fractions and data for deriving fuel fractions are available for aircraft designs of similar level of technology, vertical takeoff temperature and altitude conditions, and mission profiles. (For example, see References 11 through 14 associated with Navy Sea Control Aircraft studies.) Weight empty fractions were derived or tabulated directly from several industry sources (for example, Bell, Boeing, Canadair, Hawker, McDonnell-Douglas, and Sikorsky), and compiled by vehicle type. A mean weight empty fraction was then derived for each type aircraft in the 20,000- to 35,000-pound weight class and modified, where necessary, to reflect vertical takeoff capability at sea level on a 90°F day. The results are illustrated in Figure 2. Fuel fractions for a mission can be determined by knowing fuel-flow fractions for hover and cruise flight and specifying the time spent in each mode based on the assumed flight profile. Estimates were made of fuel-flow fractions in hover and are presented in Figure 3 versus the parameter disk loading. (Disk loading for turbofan lift types is defined as ambient pressure multiplied by the fan pressure ratio minus one.) Fuel-flow fractions in cruise depend on items such as aircraft L/D, propulsive efficiencies, and specific fuel consumptions. Estimates, based on a utility-type fuselage, of fuel-flow fractions are shown in Figure 4 versus true airspeed. Helicopter and compound helicopter data are shown for a cruise altitude of 5000 feet and the others are shown for 10,000 feet. Additional data are shown for the tilt rotor cruising at 20,000 feet and the lift/cruise fan at 30,000 feet. Lift/cruise fan aircraft cruise specifics were obtained from Reference 15, and for the vectored thrust aircraft from Reference 16.

3.3 Productivity Evaluations

Based on data given in Figures 2, 3, and 4 and mission profiles having hover and cruise segments, the terms needed to evaluate the productivity index can be evaluated. Two simple missions were examined. One is a dash mission and the other is a simple range mission.

In the dash mission, a vertical takeoff is assumed at sea level, 90°F conditions. The time at hover fuel-flow is one minute plus a time allowance for climb to cruise altitude. The aircraft dashes out 100 n.mi, cruises back at best range speed and lands with 10 percent reserve fuel. Since this is a linear analysis (i.e., weight empty fractions, hover fuel-flow fractions and cruise fuel-flow fractions are independent of gross weight), no specific payload need be designated. The results are shown in Figure 5 as productivity index versus response time to mid-mission. This is clearly an example where the aircraft with the highest productivity (the tilt rotor) does not meet a possible stringent standard for the quickest response time. The vectored thrust aircraft best meets such a standard.

In the simple range mission, the aircraft hover fuel flow rate is applied for six minutes plus the time to climb to cruise altitude. The aircraft fly at best productivity speeds (faster than best range speed) for various ranges up to their maximum consistent with a vertical takeoff at sea level on a 90°F day. Ten percent reserve fuel is maintained. Figure 6 shows the relative productivity of each type at the productivity cruise speed used.

The tilt rotor has the highest productivity and range capability of the types considered. Its productivity is better than the helicopter above ranges of approximately 50 n.mi.* In the same missions, if the payload were specified, Figure 7 shows that the tilt rotor can be expected to require higher gross weights than the helicopter until the design range increases to approximately 500 to 600 m.mi., primarily due to its higher weight-empty fraction. Also indicated in Figure 7 is the effect of an overload takeoff and cruise at 20,000 feet on tilt rotor range. All the types considered have associated range extension capabilities by cruising at altitude and with overload short takeoff runs although the helicopter cruises best below approximately 10,000 feet. One of the most significant results of this comparison is the fuel to payload ratio versus range, Figure 8. The tilt rotor at 300 knots and cruising at 10,000 feet will require less fuel than all other V/STOL types above a range of

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*The results shown in Figures 6, 7, and 8 are affected by the ground rules established for the simple range mission as shown in Figure 6.

approximately 60 n.mi. In an increasingly energy-conscious society, this frugality takes on special significance.

4.0 Tilt Rotor Technology Development

4.1 The XV-3 Program

The XV-3 convertiplane, Figure 9, resulted from research and development in the early 1950's aimed at improving the productivity of the helicopter. This early tilt rotor aircraft had a design gross weight of 4700 pounds, used two 25-foot, 3-bladed, fully-articulated main rotors and was powered by a Pratt and Whitney R-985 engine of 450 horsepower. Initial flight tests in the two-aircraft program began in 1955. Damping of the rotors and soft-mounted pylons proved inadequate leading to serious mechanical instability problems encountered in helicopter-mode flight. The XV-3 was modified with two-bladed semi-rigid rotors of the type used on the Bell Model 47 helicopter. After undergoing NASA tests in the 40- x 80-foot wind tunnel at Moffett Field, the aircraft completed a flight test program reported in References 17 through 19. In flight tests from 1958 through 1961, the XV-3 demonstrated full conversions between helicopter and airplane modes flight; simulated power-off reconversions from the airplane mode to helicopter autorotation; and overload short takeoff capability with rotors partially tilted.

The feasibility of the conversion process was demonstrated with the XV-3. However, the flight and wind-tunnel test programs indicated areas in need of improvement, References 20 and 21. The aircraft did not realize its speed potential in airplane mode due, in part, to the low blade twist of the modified rotors and low engine power. Also, short-period flight modes had insufficient damping. The wind-tunnel tests indicated a rotor-pylon oscillation that became less damped as airplane-mode speeds increased. It was this last problem that clearly demanded a full understanding and engineering solutions before the tilt rotor concept could progress to its full potential.

4.2 Continuing Analyses and Tests

In the early 1960's, Bell Helicopter initiated an extensive program of theoretical and dynamic model research to resolve the problems uncovered by the XV-3 and to develop technology for the design of future tilt rotor aircraft. The program yielded a fundamental understanding of rotor/pylon phenomena and explained the behavior of the XV-3 in flight and in the wind tunnel. Its results were reported in References 22 through 25.

The basic aerodynamic causes of turboprop nacelle whirl flutter and rotor-pylon instability are closely related. In the case of the rotor, however, the problem is more complex because of the blade flapping degree of freedom. The unstable forces that the rotor exerts upon its supporting structure in the airplane mode have two primary causes. First, the rotor generates static lift forces proportional to the angle of attack. Since these forces act ahead of the wing structure, they are statically unstable, and they tend to decrease the effective stiffness of the wing. Second, gyroscopic moments cause forces in the plane of the rotor disk when the rotor has an angular pitching rate. At the high inflow ratios typical of airplane mode flight, these forces can become significant. The direction of these forces is such that they apply negative damping to dynamic motions of the rotor's supporting structure. In addition, these forces affect flight mode stability of the aircraft.

Several design approaches may be taken to mitigate these destabilizing effects. The approach ultimately selected as the simplest and most reliable was high-pylon support stiffness as compared to the flexibly-mounted pylon used on the XV-3 with its dependence on dampers. As forward speed increases, so does the required stiffness. Young and Lytwyn of the Boeing-Vertol Company, Reference 26, have shown however that the rotor-pylon system can be stabilized by appropriate tuning of the blade flapping frequency. The optimum tuning, approximately 1.1 to 1.2 cycles per revolution, minimizes the pylon-mounting stiffness requirements for dynamic stability. In this case, the necessary pylon stiffness is much less than that required for either a rigid propeller or a freely hinged rotor. The blade flapping frequency is tuned by using flapping restraint or hub-moment springs with a spring rate that gives the desired rate. Analyses and tests conducted at Bell Helicopter confirmed the findings of Young and Lytwyn. However, the requirements for rotor flapping and loads during maneuvers and gusts must also be considered in the selection of a value of flapping restraint. The present approach selected by Bell combines maximum pylon mounting stiffness with a moderate hub spring on a stiff-inplane gimbaled rotor. The inevitable rotor flapping is accommodated with minimum blade loads and the hub-moment spring used also augments pitch control moments in the helicopter mode of flight.

The other approaches considered for rotor-pylon stability included positive pitch flap coupling (negative δ_3), swashplate/pylon coupling on a soft pylon suspension, rotor focusing and automatic flapping control. A common theoretical basis for controlling rotor-pylon instability underlies these approaches. Those applicable to a soft pylon suspension were extensively wind-tunnel tested on the second XV-3 in 1967. The ability to control whether the test configuration would be lightly or highly damped was demonstrated up to maximum tunnel speeds. The theoretical basis for rotor-pylon stability had been confirmed. As a result, the stiff pylon approach was adopted. This includes mounting the rotor pylon to the wing-tip without the dependence on a soft-suspension, using a torsionally-stiff wing, and retaining the positive pitch flap coupling feature.

4.3 The Army Composite Aircraft Program

In 1965, the U.S. Army established the Composite Aircraft Program to combine in one aircraft the good hover characteristics of the helicopter and the efficient high-speed cruise characteristics of the airplane. This program extended the technology for the tilt rotor and produced the Model 266 aircraft design having a gross weight of 28,000 pounds. The technology efforts completed in 1967 made extensive use of modern computer techniques and scaled force and scaled powered aeroelastic models. Results are reported in Reference 27.

The research aircraft program which was planned to follow would have demonstrated the mission capabilities of the low-disk-loading VTOL aircraft and establish that the level of technology was adequate for a system development program. The research aircraft program was not undertaken, however, primarily because of a lack of R&D funding and the absence of a well-defined mission requirement.

4.4 The Bell Model 300 Program

Bell management recognized that there was a need for full-scale verification of the technology that developed since the XV-3 and for achievement of the Army Composite Program objective--the demonstration of the mission potential of the low-disk-loading approach to VTOL. In 1968, the company initiated a program aimed in this direction. It included the design and fabrication of a 25-foot diameter rotor for a technology demonstrator tilt rotor aircraft small enough to be tested in the Ames 40- x 80-foot wind tunnel. The aircraft was designated the Model 300. The preliminary design provided sufficient data for scaled model and full-scale component testing to verify the performance, stability, and aeroelastic solutions selected. Technology development accelerated in 1969 when the Air Force Flight Dynamics Laboratory, the Army Aeronautical Research Laboratory, and the NASA-Ames Research Center initiated technology programs for the tilt rotor and the fold proprotor (an advanced tilt rotor configuration for missions requiring high subsonic dash speeds, References 28 and 29). Several contracts were awarded to Bell and other companies for studies, model tests, and tunnel testing of full-scale tilt rotors.

4.5 Scaled-Model Tests for the Model 300 Aircraft

The scaled-model test program was set up at Bell in 1968 to confirm the Model 300 design which benefited from several thousand hours of tilt rotor wind tunnel testing before the Model 300 program began. An aerodynamic and a full-span powered aeroelastic model was designed and fabricated to meet the following objectives:

- Confirm airframe performance and stability characteristics.
- Confirm dynamic design criteria for placing natural frequencies and limiting vibration levels and oscillatory loads.
- Demonstrate the aircraft to be free from flutter or other aeroelastic instability by testing the aeroelastic model at the required flutter-free equivalent airspeeds and Mach numbers.
- Confirm that the aircraft flight modes are adequately damped.

The model test program completed to date is summarized in Table I. A photo of the aeroelastic model undergoing powered conversion testing in October 1972 is shown in Figure 10. Results of these programs are reported in References 30 through 32. In some of the references cited, the correlation with full-scale component tests, described below, are presented.

4.6 Full-Scale Component Tests

In 1969, the NASA-Ames Research Center and the Army Aeronautical Laboratory contracted with Bell for tunnel tests of the 25-foot tilt rotor and for design studies of a tilt-rotor research aircraft, Reference 33. The Bell rotor completed its low-power, high-rpm whirl tests on a Bell test stand in May 1970, completed its first tunnel test in July 1970, and its second tunnel test in December 1970. The July test verified rotor-pylon stability in the windmilling airplane mode at high advance ratios. (Rotor-pylon stability is higher for powered flight.) The rotor was unpowered and mounted on a scaled-stiffness wing support. The second test determined performance and loads through the tilt range from helicopter to airplane mode flight. For this test, the rotor was mounted on a powered stand. The results of these tests are reported in Reference 34. Additional tests of related transmission development are also reported in Reference 35. The rotor was then tested in 1973 on the Wright Field whirl tower to high powers and rpm for determining additional hover performance data, Reference 36. The latest test, Figure 11, in the Ames 40- x 80-foot wind tunnel (November 1975) covered the autorotation range of angles of attack and rpm, and are reported in Reference 37.

4.7 Technology Summary

A summary of the basic tilt rotor technology as it was developed in this program can be represented (in part) by the key features of the tilt rotor aircraft design approach now used. These are shown in Table II.

Examples of some of the aircraft characteristics that this approach leads to are shown in Figures 12 through 15. A summary of the rotor-pylon damping versus speed obtained from full-scale and scaled aeroelastic model tests is presented in Figure 12. Adequate damping exists beyond the flight speed envelope of the aircraft. Short-period characteristics of the aircraft in the airplane mode are stable without electronic stability augmentation over the range of conditions shown in Figure 13. Propulsive efficiency test envelopes, Figure 14, exceed 90. The actual operating efficiencies during cruise can exceed .8 over a wide range of speeds. Hover figures of merit with existing and promising new airfoils are plotted in Figure 15. An operating rotor figure of merit of .8 can be expected. When combined with the low disk loading of the tilt rotor, hovering efficiency approximates that of the helicopter.

5.0 The XV-15 Tilt Rotor Research Aircraft Program

In July 1973, Bell Helicopter was awarded a NASA-Army contract for the fabrication and test of two tilt rotor research aircraft. The aircraft is similar in design to the earlier Bell Model 300 with the following major differences:

- The vertically qualified T53 engine (LTC1K-4K), similar to that used in the CL84 tilt wing aircraft, was substituted for the PT6 engines planned for the Model 300. The T53 engine is more powerful and development cost (for vertical operation) was substantially lower.

- External landing gear pods were added to accommodate a cheaper "off-the-shelf" CL84 landing gear.

Increased weight and transmission complexity were required to accommodate these changes. A three-view of the XV-15 is shown in Figure 16. Design data are presented in Table III, and performance data in the helicopter conversion and airplane modes are presented in Table IV.

The program schedule illustrated in Figure 17 includes completion of the aircraft design in the area of fuselage, controls and subsystems, subsystem and ground tests, hover and wind-tunnel tests with Aircraft No. 1, and contractor flight tests with Aircraft No. 2.

The design of the control system has drawn heavily on extensive mathematical modeling of the aircraft control laws. Refinements have been incorporated on the basis of pilot reactions in the 6-degree-of-freedom Flight Simulator for Advanced Aircraft (FSAA), Figure 18, at the Ames Research Center, References 38 and 39. The XV-15 uses mechanical linkages between the pilot controls and the hydraulic boost actuators at the swashplate and control surfaces. The linkage ratios are mechanically modified in a mixing box during rotor tilting to accommodate the changing requirements on the rotor and fixed- wing controls. Much of the effort in the controls area has been aimed at optimizing the variations of linkage ratios and insuring that control system stiffness and free-play are acceptable. The incorporation of a stability and control augmentation system (used primarily for low-speed helicopter-mode flight) and a force-feel system, each having separate hydraulic actuators, has resulted in a fairly sophisticated control system.

Subsystem tests for the transmission, the control system, the conversion system, the landing gear, etc., have been completed or are nearing completion. A photo of Aircraft No. 1 in May 1976 as it was prior to delivery to the Bell Experimental Flight Facility is shown in Figure 19. Build-up for system ground tests is continuing and first flight is planned for early 1977.

6.0 Tilt Rotor Aircraft Applications

Conceptual design studies of the tilt rotor for several applications have been recently completed. These encompass a range of gross weights from approximately 8000 to 55,000 pounds. The missions are representative of civil as well as military operational requirements, References 40 and 41. A display model of a versatile utility/transport aircraft in the 17,000- to 20,000-pound gross weight class is shown in Figure 20. The assumed technology level includes use of improved airfoils to optimize the rotor efficiency for hover, conversion and airplane flight modes, and to insure good low-speed lift and cruise L/D's with light-weight, high-thickness wing sections. The rotor, wing, tail surfaces, and portions of the body are of composite structure to improve corrosion resistance or maintain stiffness with reduced weight. Fly-by-wire controls, rather than mechanical linkages, are used to improve operational flexibility, decrease the number of hydraulic actuators, and reduce weight. Advanced technology engines in the 2500 horsepower class are used which provide substantially improved specific fuel consumption and specific weight compared to the engines used in the XV-15. The lift-propulsion system (rotors, drive, engines, and wing) would fill a wide range of uses through fuselage design changes for alternate missions.

When the present XV-15 research program has been completed, an operational demonstrator version can help bridge the gap between research and operational aircraft. By removing the constraints which have been necessary with the current research program, the results will include not only reductions in weight empty fraction and in fuel consumption, but ultimately in improved reliability and reduced maintenance.

7.0 Conclusions

(a) The tilt rotor promises the highest productivity of all V/STOL aircraft options including the helicopter above ranges of approximately 50 n.mi. Below that range, the helicopter remains the most productive V/STOL aircraft option.

(b) At ranges beyond approximately 50 to 60 n.mi., the tilt rotor requires the least fuel of all other V/STOL aircraft types to carry a specified payload at best productivity speeds.

(c) Tilt rotor technology has been developed to the point of minimizing the risks associated with problems identified by the XV-3 Convertiplane. Remaining risks are in the area of aircraft hardware development and are not foreseen to be associated with the tilt rotor concept.

(d) Advanced components for an operational demonstrator version of the XV-15 are logically next in the area of technology development. Airfoils, composite structures, fly-by-wire controls, and modern power plants are the disciplines that would be employed.

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TABLE I. SUMMARY OF MODEL TEST PROGRAM

DATE	TEST NUMBER/TUNNEL	TYPE OF TEST
Mar 1969/ Jan 1970	LSWT 311-LTV-Dallas	Aerodynamic
	Aerodynamic Data with Initial Empennage Design; Flow Visualization and Vortex Generator Investigation	
Aug 1969/ Feb 1970	LSWT 321-LTV-Dallas	Aeroelastic
	Semispan Wing Test--Frequency, Damping, and Vibration Data	
Aug 1970	TDT 174-NASA-Langley	Aeroelastic
	Full-Span Test--Proprotor Stability Characteristics, Vibration and Loads, and Aircraft Stability Data Including Compressibility Effects--Single Tail	
Oct 1970	LSWT 360-LTV-Dallas	Aeroelastic
	Isolated Proprotor/Airframe--Proprotor and Airframe Static Derivatives--H-Force	
Oct 1970	LSWT 361-LTV-Dallas	Aerodynamic
	Verification of Similarity of Aeroelastic and Aerodynamic Model with Effects of Rod Mount	
Jan 1971	LSWT 366-LTV-Dallas	Aerodynamic
	Empennage Configuration Investigation--H-Tail Data	
Aug 1971	TDT 195-NASA-Langley	Aerodynamic
	Proprotor and Airframe Static Derivatives Including Reynolds Number and Mach Number Effects	
Nov 1971	LSWT 383-LTV-Dallas	Aeroelastic
	Empennage Flutter Test--H-Tail Empennage Flutter Characteristics Including Flutter Point with Reduced Stiffness Horizontal Tail Spar	
Mar 1972	TDT 205-NASA-Langley	Aeroelastic
	Full-Span Test--Proprotor Stability Characteristics, Vibration and Loads, and Aircraft Stability Data Including Compressibility Effects--H-Tail	
Aug 1972	V/STOL 31-NASA-Langley	Powered Force
	Powered Force Model of a 1/10 Scale, D270 Tilt Rotor Aircraft Design, Rotor Power & Thrust Derivatives--Rotor/Wing Downwash	
Sept 1972	LSWT 408-LTV-Dallas	Aerodynamic
	Pressure Distribution, Pylon Conversion Angle Effect, and Control Effectiveness Test to Refine Aerodynamic Data	
Oct 1972	Bell Facility	Aeroelastic
	Powered Hover Tests to Determine Ground Interference Effects	
Jan 1973	LSWT 418/421-LTV-Dallas	Aeroelastic
	Full-Span Test--Powered Tests to Obtain Force and Moment Data, Aeroelastic Stability Boundaries, and Control Power in Hover (IGE/OGE), Conversion and Airplane	
Aug 1973	AARL 142-NASA-Ames	Aerodynamic
	301 Configuration-Investigate the Effect of Landing Gear Pod Configurations	

TABLE II. KEY FEATURES OF MODEL 300 DESIGN APPROACH

DESIGN FEATURE	REASON FOR SELECTION
Torsionally stiff wing and stiff pylon-to-wing attachment	Ample stability margin at low technical risk
Forward-swept wing planform	Ample clearance (12 degrees) for flapping in severe maneuvers and gust encounters
Gimbaled, stiff-inplane, over-mass-balanced proprotor	Proprotor loads not sensitive to flapping Air and ground resonance problems avoided Blade pitch-flap-lag instabilities and stall flutter problems avoided
Large tail volume, H configuration	Good damping of Dutch roll and short-period flight modes

TABLE III. XV-15 DESIGN DATA

Design gross weight	13,000 lb
Maximum gross weight	15,000 lb
Weight empty	9,580 lb
Power Plant	
Mfg. and model	(2) Lycoming LTC1K-4K
Normal/Military power*	2500/2800 hp
Takeoff/contingency power*	3100/3600 hp
*2 engines (total)	
Rotor	
Diameter/blade chord	25 ft/14 in.
No. of blades per rotor	3
RPM-helicopter design operating	565 rpm
-airplane	458 rpm
Wing	
Span/area	34.6 ft/181 sq ft
Flap/flaperon area	11.0/20.2 sq ft
Empennage	
Horizontal/vertical area	50.25/50.5 sq ft
Elevator/rudder area	13.0/7.5 sq ft

TABLE IV. XV-15 PERFORMANCE SUMMARY[1]

Hover ceiling		
Standard day - OGE/IGE		9,300/12,200 ft
35°C - OGE/IGE		2,500/ 5,400 ft
Gross weight to hover OGE, SL, 90°F		14,600 lb
Conversion corridor[2]		
Conversion angle:	90 to 75 deg	0-140 kt
	45 degrees	70-170 kt
	0 degree	100-170 kt
Airplane flight		
Max cruise speed, NRP		303 kt @ 16,200 ft
Max level speed, TOP		322 kt @ 13,000 ft
Max single engine speed, CTP		240 kt @ 10,000 ft
Max rate of climb		2,875 ft/min
Service ceiling		>25,000 ft
Range:	10,000 ft[3]	330 nm @ 220 kt
	20,000 ft[3]	408 nm @ 250 kt
STO distance @ 15,000 lb, 5,000 ft altitude & 35°C		1,400 ft

NOTES:
[1] Design gross weight except as noted
[2] Flaps down, 565 rotor.rpm, SLS
[3] 1490 lb internal wing tank fuel, 99% LRC

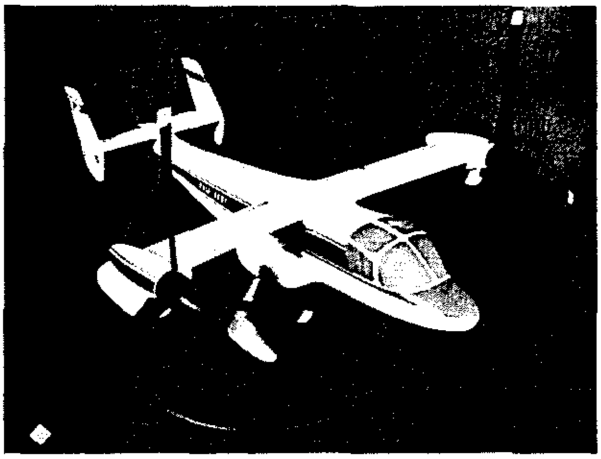
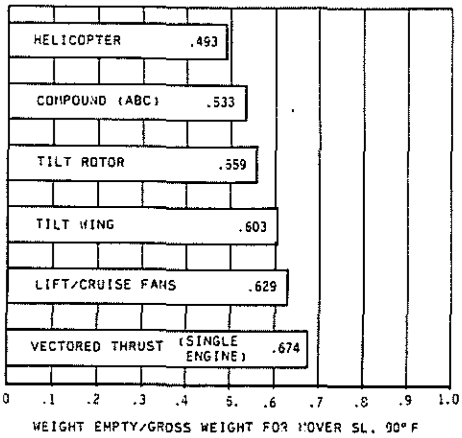


Figure 1. The NASA/Army/Bell XV-15 Tilt Rotor Research Aircraft.



- FRACTIONS ARE FOR THE 20,000 TO 35,000 LB GW CLASS
- ALL TYPES USE TWIN ENGINES EXCEPT AS NOTED
- DATA BASED ON ADVANCED DESIGNS FROM SEVERAL SOURCES

Figure 2. Weight Empty Fractions of Advanced V/STOL Aircraft.

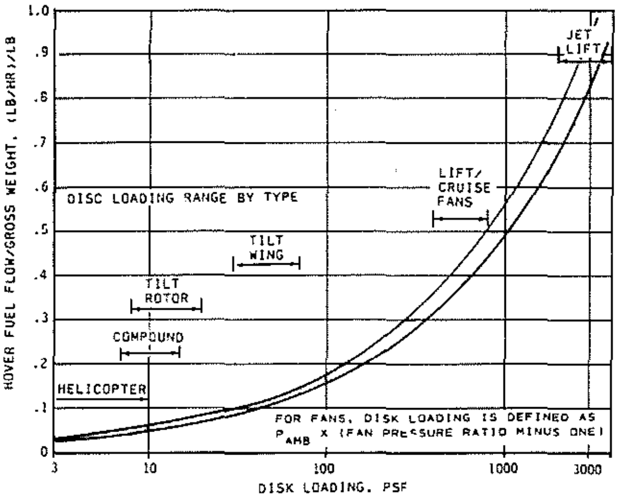


Figure 3. Hover Fuel-Flow Fractions of V/STOL Aircraft.

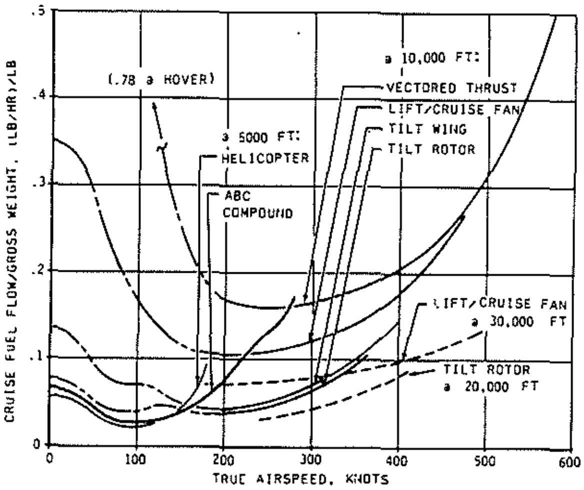


Figure 4. Cruise Fuel-Flow Fractions of V/STOL Aircraft.

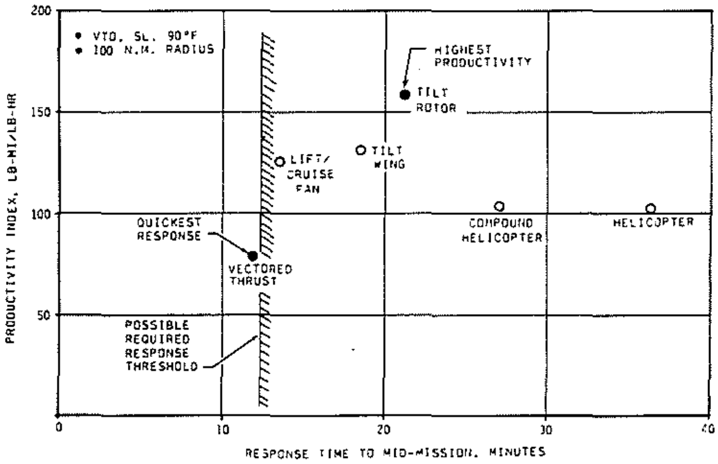


Figure 5. Productivity and Response Time for a Dash Mission.

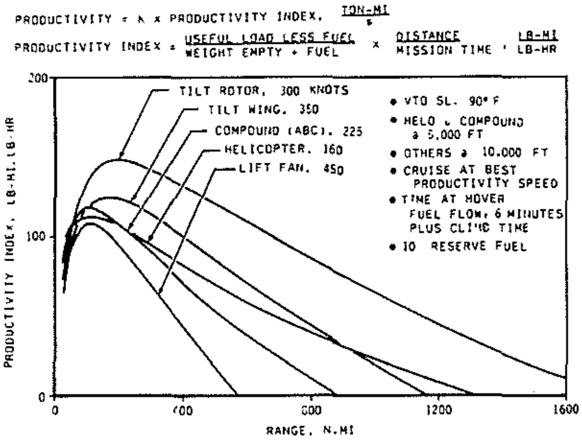


Figure 6. Productivity for a Simple Range Mission.

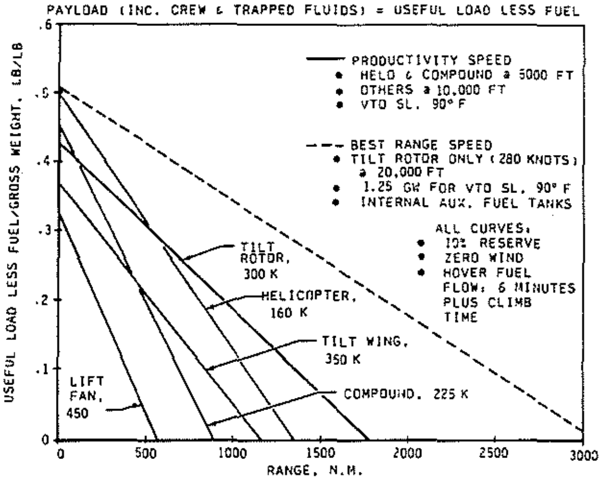


Figure 7. Payload Fractions for a Simple Range Mission.

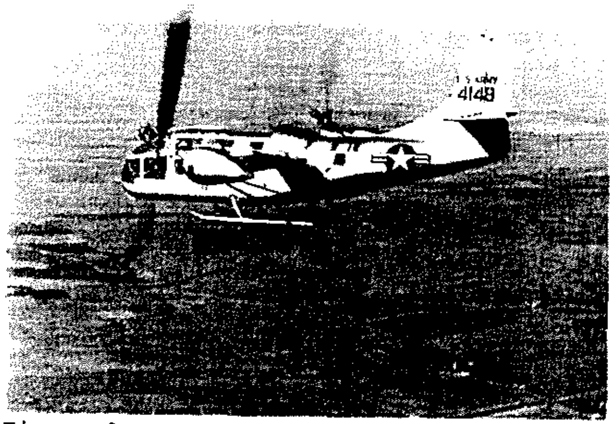


Figure 9. The XV-3 Convertiplane.

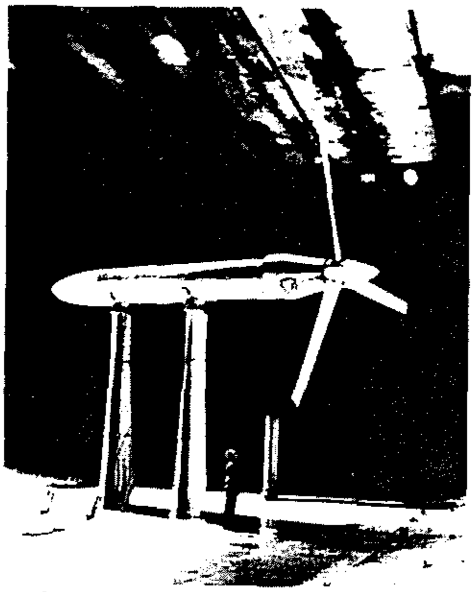


Figure 11. Autorotation Tests of a Full-scale, 25-foot, Tilt Rotor.

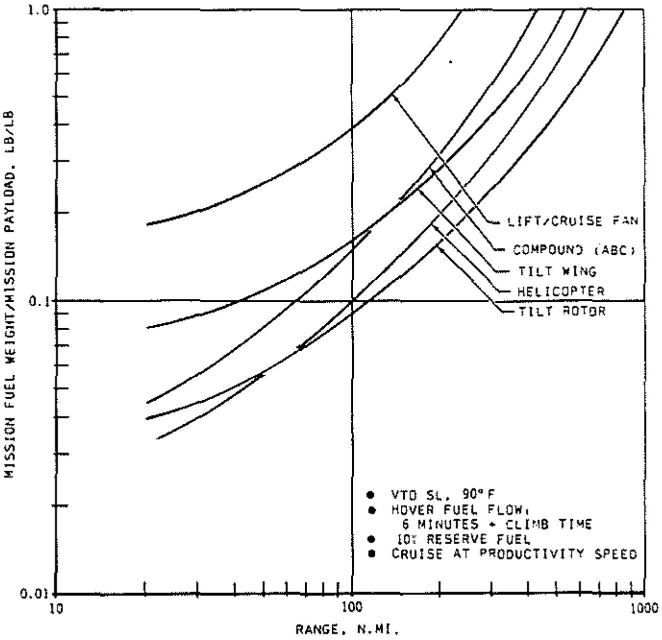


Figure 8. Fuel/Payload for a Simple Range Mission.

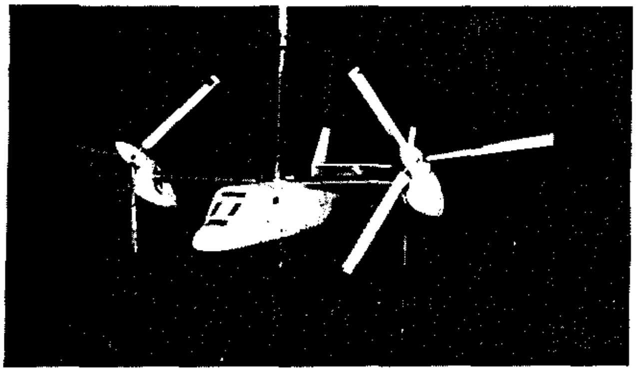


Figure 10. Conversion Mode Tests of a Semi-Freeflight Powered Aeroelastic Tilt Rotor Model.

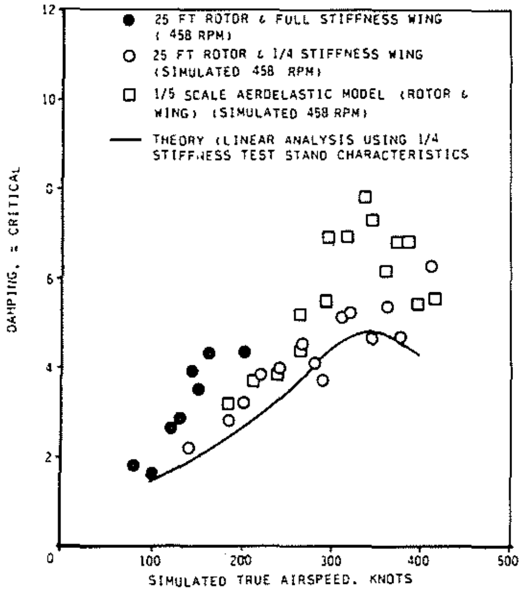


Figure 12. Correlation of Dynamic Stability - Small Scale, Full-Scale, and Theory.

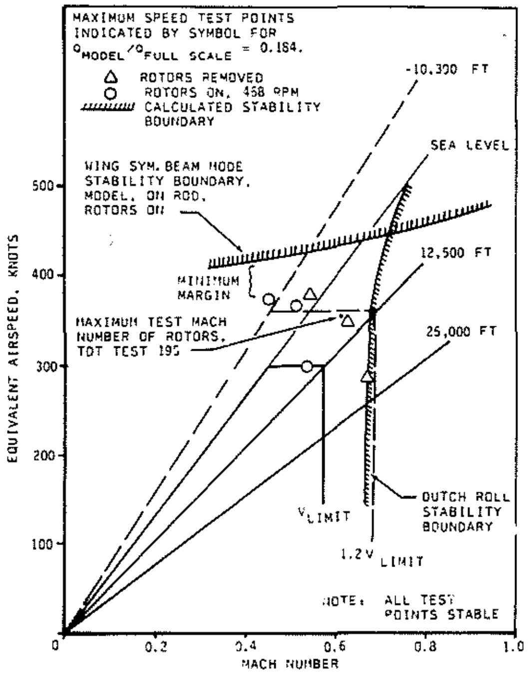


Figure 13. Verification of Dynamic and Flight Stability With Semi-Freeflight Aeroelastic Model in Freon.

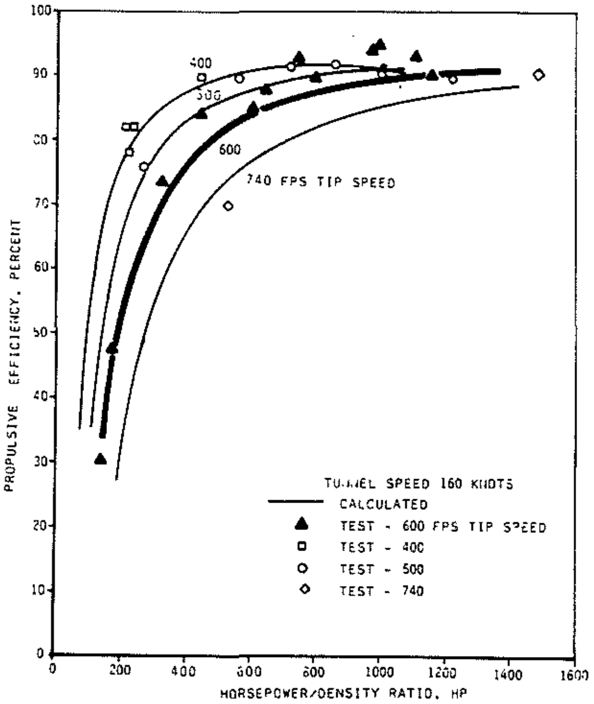


Figure 14. Full-Scale Propulsive Efficiency Test Data.

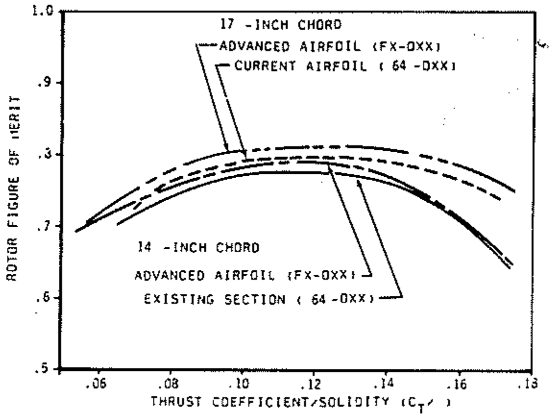


Figure 15. Tilt Rotor Hover Figure of Merit.

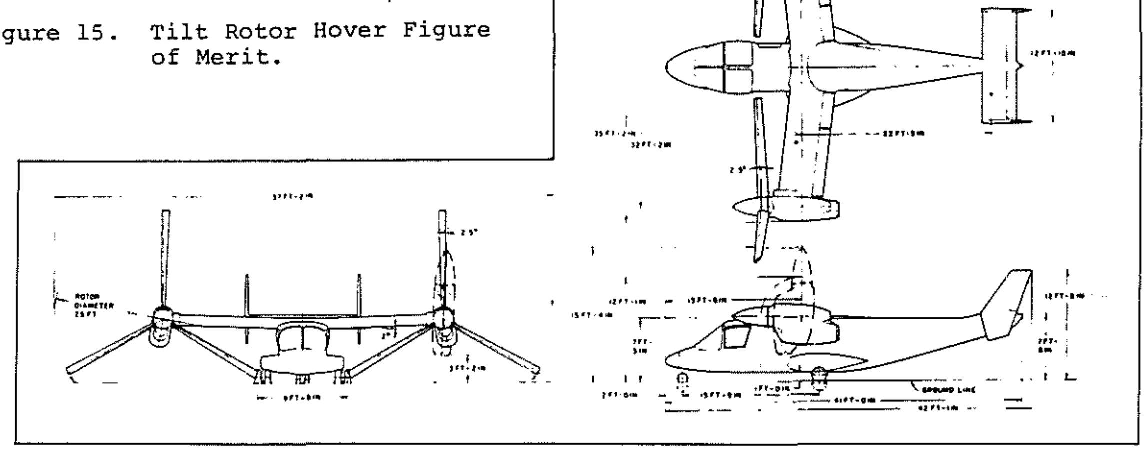


Figure 16. Three-View, XV-15 Tilt Rotor Aircraft.

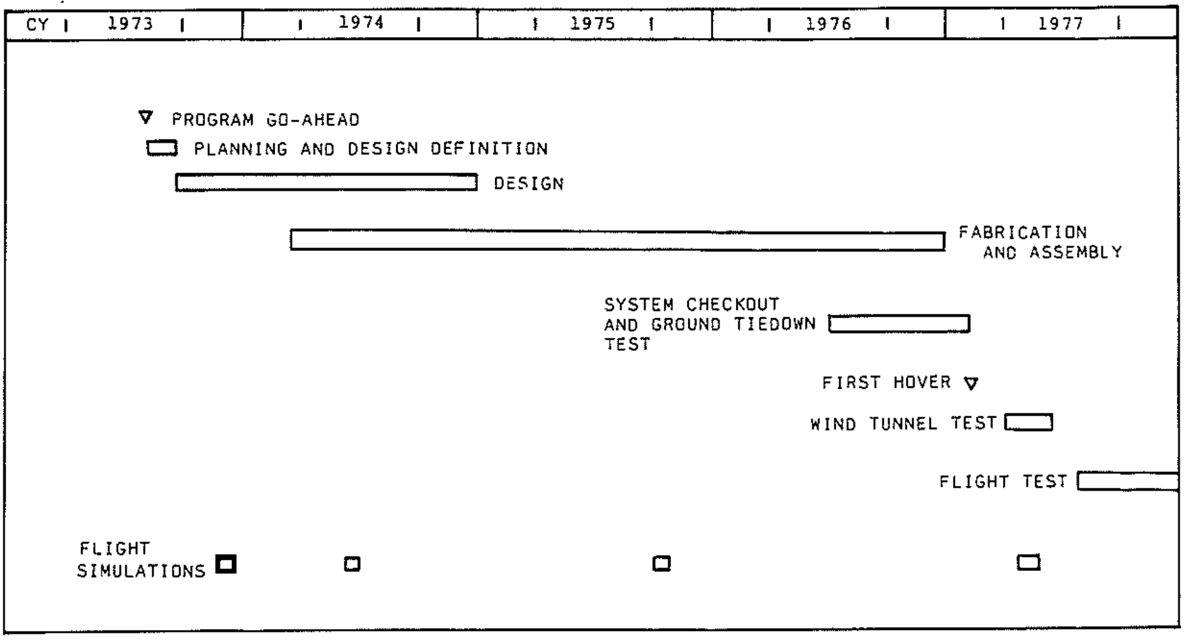


Figure 17. XV-15 Program Schedule.

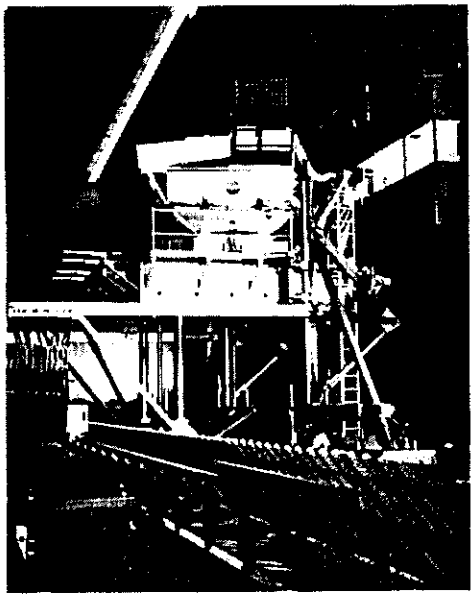


Figure 18. Flight Simulator for Advanced Aircraft, Ames Research Center.

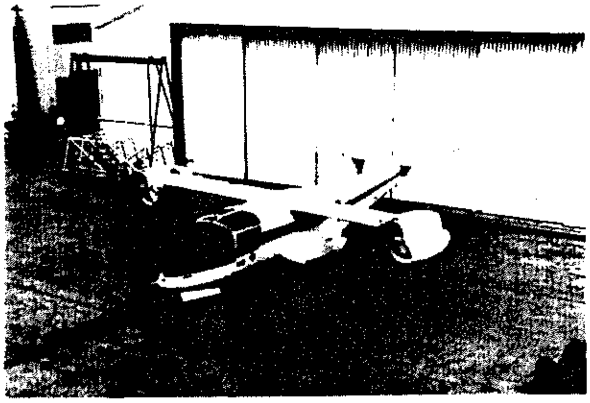


Figure 19. XV-15 Status, Aircraft #1, May 1976.

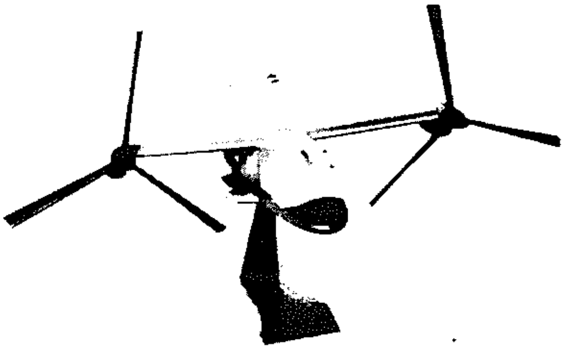


Figure 20. Utility Tilt Rotor Aircraft Conceptual Design.