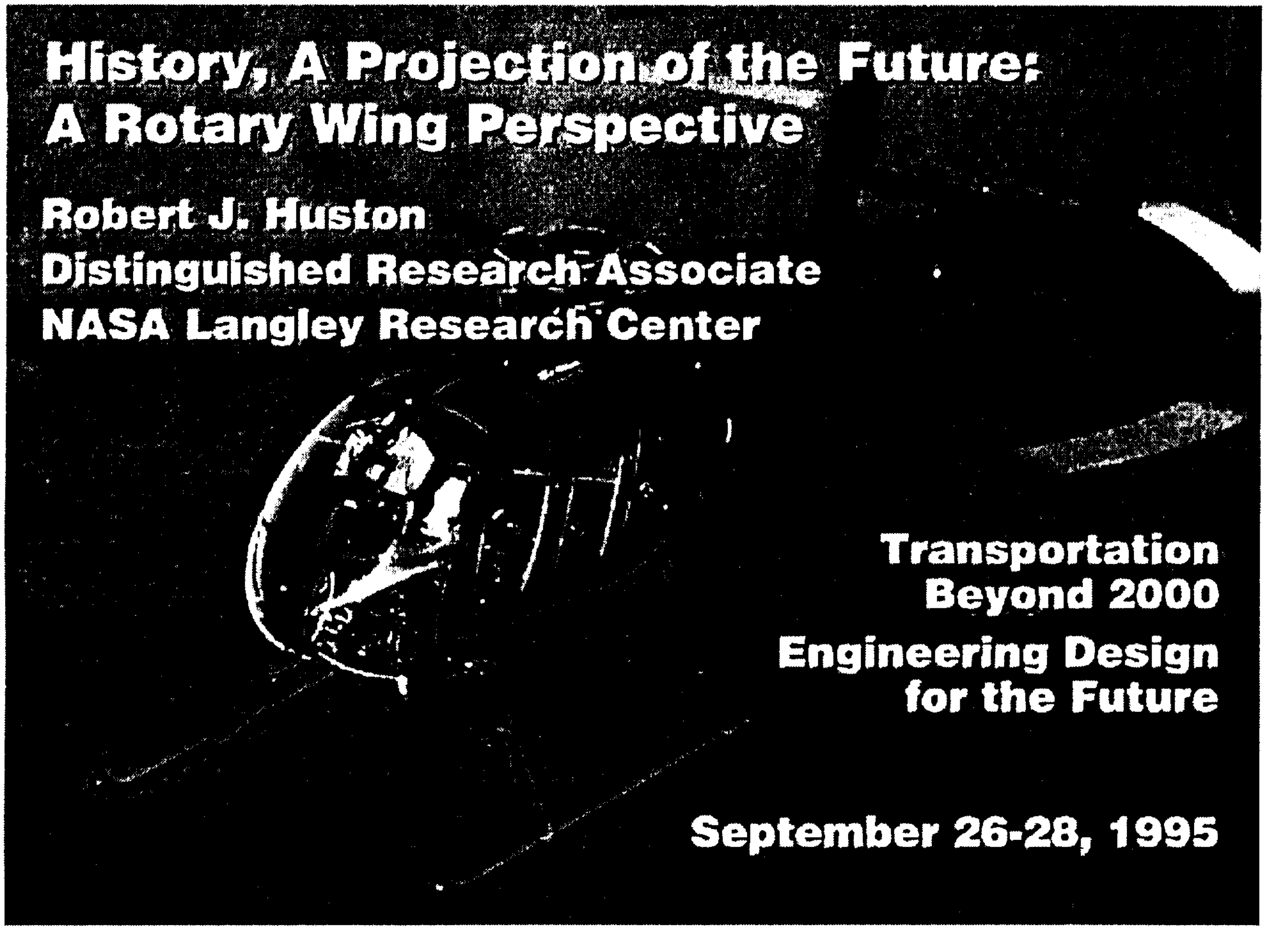
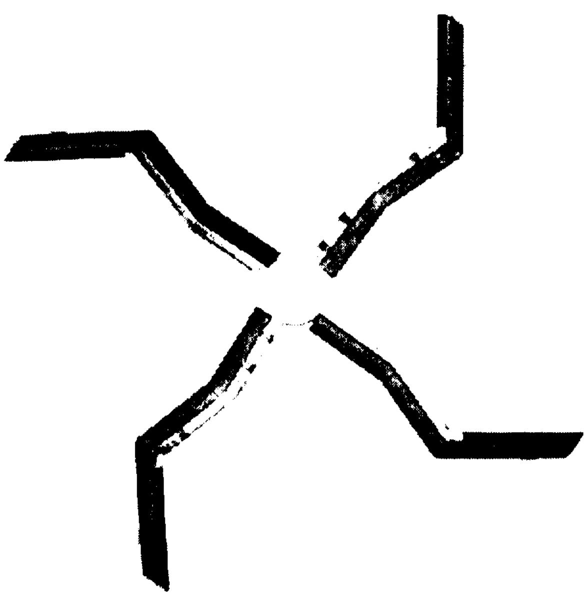

History, A Projection of the Future:
A Rotary Wing Perspective
Robert J. Huston
Distinguished Research Associate
NASA Langley Research Center
Transportation
Beyond 2000
Engineering Design
for the Future
September 26-28, 1995



Rotorcraft engineering is an area that sometimes doesn't get an awful lot of respect. I can substantiate that by quoting Wilbur Wright. The punch line is:

"... The helicopter is much easier to design than the airplane but is worthless when done."

The quote is from the Dayton Herald (Ohio) and was given to my friend Ralph Alex, then the Sikorsky XR4 project engineer, on the occasion of the delivery of the Army's second helicopter to Wright Field in May 1942. (The first was the De Bothezat machine, delivered in 1922.) Several times over several days, Ralph Alex and Igor Sikorsky offered Orville Wright a ride in the Sikorsky helicopter. Wright had politely refused each offer. Finally, Orville explained that he could not accept because he did not believe the machine was practical and, by way of justification, offered a copy of an article containing the previous quote by his brother Wilbur. It should be noted that the XR-4 helicopter, rolled from the factory on December 7, 1941, was the prototype for 129 helicopters delivered to the U. S. Army by September 7, 1944. An additional 488 helicopters (R-5s and R-6s) were built before the end of WW II. (References are given for additional reading on the subject area. Ralph P. Alex, "How Are You Fixed for Blades? The Saga of the Helicopter, Circa 1940-60," published in *The Age of the Helicopter, Vertical Flight,* National Air and Space Museum, 1984.)

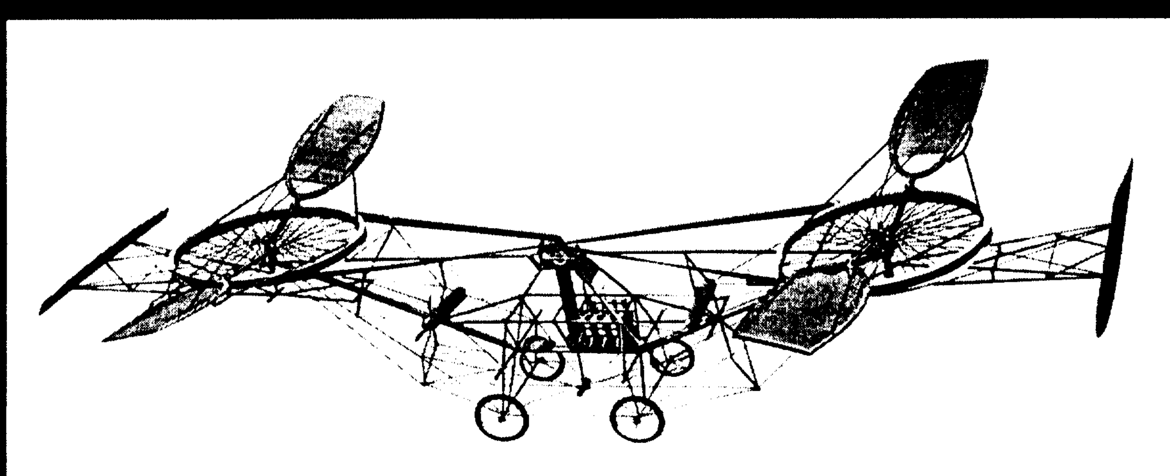
Dayton, Ohio
January 15, 1909

Like all novices, we began with the helicopter (in childhood) but soon saw that it had no future and dropped it. The helicopter does with great labor only what the balloon does without labor, and is no more fitted than the balloon for rapid horizontal flight. If its engine stops it must fall with deathly violence for it can neither float like the balloon nor glide like the aeroplane. The helicopter is much easier to design than the aeroplane but is worthless when done.

- Wilbur Wright

When Wilbur Wright wrote that article, he was already wrong, because the first free flight by a helicopter had already occurred. Most people didn't know about the 20 second flight by Frenchman Paul Cornu on November 13, 1907. Some estimate it was about the 40th attempt to fly a helicopter. Only a couple months earlier, on September 19, 1907, the Breguet brothers' helicopter had flown to a 2 foot height for approximately one minute but it was "restrained" by four helpers at the four corners of the aircraft because it had no means of control. Other inventors followed: Jacob C. H. Ellehammer of Denmark hovered with several short hops in 1912; Raul Pateras de Pescara of Spain first flew a counter-rotating 16-bladed helicopter for one minute on January 11, 1922 with subsequent flights of 10 minute duration & distances of 800 yards; an American Henry Berliner flew both a coaxial helicopter and a side-by-side rotor helicopter in 1920 and 1922; George de Bothezat, who had his "Helicopter Rotors Theory" published by NACA in 1916, flew for one minute 41 seconds on December 18, 1922 in a quad rotor helicopter financed by the U. S. Government; Etienne Oehmichen flying first in 1923, flew a one kilometer circuit on May 4, 1924. By 1936, A Breguet-Dorand helicopter set FAI records of 44 km distance, one hour 2 minutes 50 seconds endurance and 108 km/hr speed. (Jean Boulet, *History of the Helicopter as told by its pioneers, 1907-1956.*. Editions France-Empire,1982.)

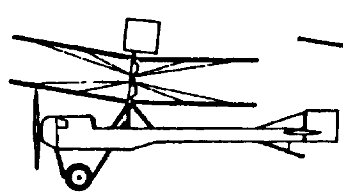
"FIRST" HELICOPTER FLIGHT
Paul Cornu
1907



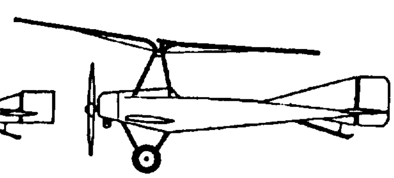
The man who jump started the helicopters was the Spaniard Juan de La Cierva. He developed the Autogiro (his proprietary name) in England during the 1920s. Cierva invented the articulated rotor which has both vertical and horizontally hinges near the blade root end. The concept, which reduces blade moments at the *rotating* hinge to zero, was a defining element in the invention of the first practical helicopters. The figure shows some of Cierva's Autogiro designs. The first three aircraft shown were unsuccessful because the design provided *restraints* to the blade which caused the aircraft to roll over during take-off. Eventually, he found the articulation key to success, then added blade pitch and rotor tilt controls while establishing world wide patents. The C-8 became the catalyst for a partnership between the American Pitcairn and Cierva on August 14, 1929, hence the Pitcairn Cierva Autogiro Company of America (PCA) was formed which further developed the patents. PCA would licensed the patents to other companies. A design manual was supplied to the licensee. (Juan de la Cierva, *Engineering Theory of the Autogiro,* Pitcairn Cierva Autogiro Company of America, 1930; and Frank Kingston Smith, *Legacy of Wings, The Harold F. Pitcairn Story,* Jason Aronson, 1981.)

Cierva's concept of flight was that with the a rotor powered by the "wind," the auto gyro would be the safest type of aircraft to fly. One of the ironies of aviation is that Cierva was killed in the crash of an *airplane* in 1936. He probably never realized that in perfecting the Autogiro rotor, he gave the world the first practical helicopter rotor. (Giorgio Apostolo, *The Illustrated Encyclopedia of Helicopters,* Arnoldo Mondadori Editore S. p. A. Milano, Italy, 1984.)

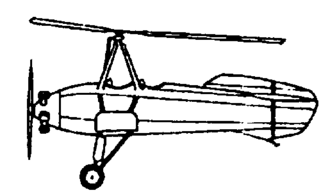
DEVELOPMENT OF LaCIERVA AUTOGIROS



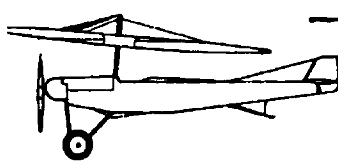
1920 - Cierva C-1, with two rotors.



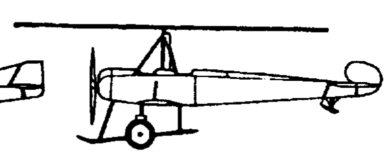
1923 - Cierva C-4.



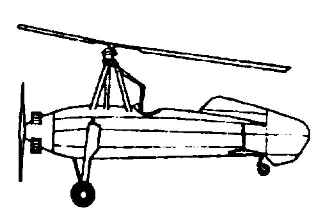
1929 - Cierva C-19, two-seater.



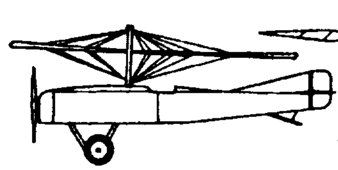
1921 - Cierva C-2.



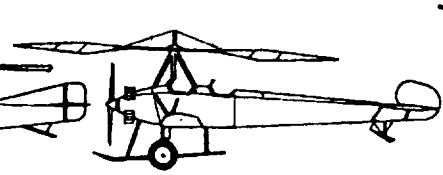
1924 - Cierva C-6.



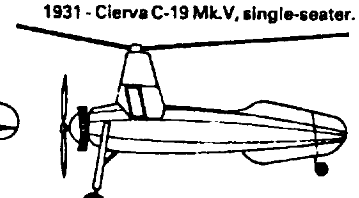
1931 - Cierva C-19 Mk.V, single-seater.



1922 - Cierva C-3.



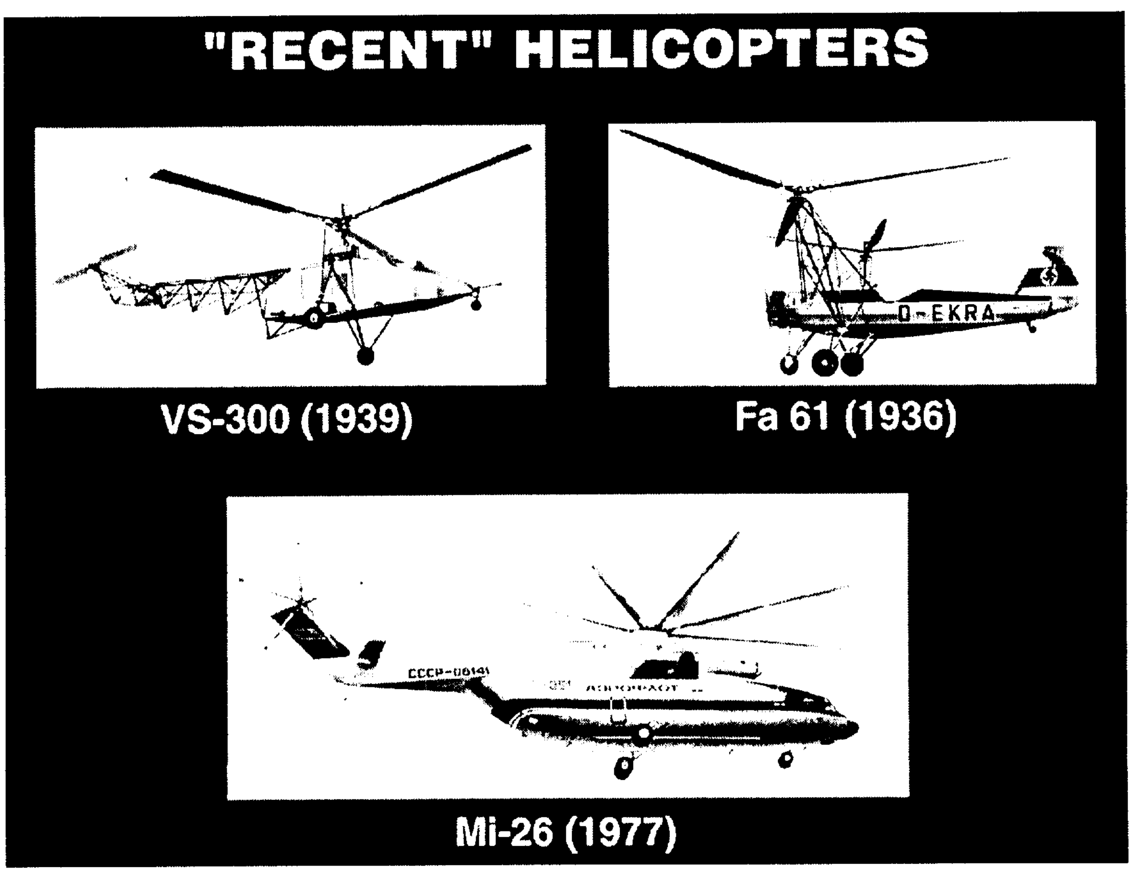
1927 - Cierva C-8, with a two-blade rotor.



1937 - Cierva C-40, two-seater with an enclosed cabin.

After the Autogiro, came the first practical helicopters. The Breguet-Dorand helicopter, a complicated coaxial rotor machine flew in June 1935. The vehicle vibration, dynamics and control were so marginal during early flights that the aircraft was frequently damaged. That aircraft never saw production even though fights continued until the occupation of France. The aircraft was destroyed in a 1943 bombing raid. The first helicopters to lead to production were the Sikorsky VS-300 and the Focke Fa 61. The XR-4, a single main rotor/ tail rotor aircraft, was little more than a dressed-up version of the VS-300. It was the first of over 600 aircraft built during WWII in three models. Hanna Reitsch flew the Fa 61 inside of the Deutschlandhalle of Berlin during February, 1938 and inspired LaPage to design the unsuccessful XR-1. The Fa 61 with side-by-side rotors, led to the Focke Achgelis Fa 223, an aircraft nearly 3 times the weight of the Fa 61. Production facilities were built to produce hundreds of Fa 223 per month but they were bombed several times. Only seventeen aircraft survived the war. After the war, France and Czechoslovakia built Fa 223 aircraft in small quantities from surviving parts. (J. R. Smith and Antony L. Kay, *German Aircraft of the Second World War*, Putman, '72.

In the USSR, the Fa 61 apparently inspired a series of helicopters starting with the Bratukhin Omega but the successful configurations, the coaxial and single rotor designs, came from the Kamov and Mil design bureaus. By 1977, Mil had developed a large single rotor helicopter, the Mil 26, which can lift approximately 25 tons or carry 70 to 100 passengers.. For assessing scale in the figure, the pilot's cockpit of the Mil 26 is about the size of a C-130's cockpit. (Apostolo)

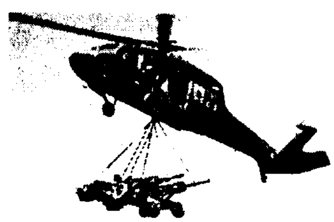


The variety of military uses for helicopter have grown to surpass that of fixed wing aircraft. The first helicopters acquired by the military were used primarily for observation, search and rescue. Mission equipment was added as the size and payload of helicopters grew so that both troop transport and anti-submarine warfare became standard uses. The piston engine Bell Model 47 (military H-13) which first flew in December 1945, received civil certification in March 1946 and saw first military service in December 1946, became the litter bearer of the Korean War and an actor in a TV program called MASH. For a large number of years it was also the basic helicopter trainer in military flight schools.

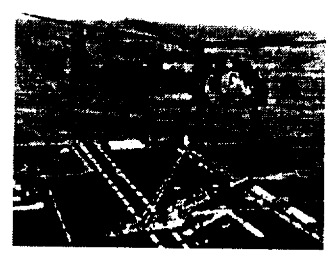
Today, world wide deployment of helicopters is required. If the aircraft can not be folded or disassembled quickly for shipment in a Air Force transport, then the aircraft must be self deployable. In-flight refueling, which became the standard method of keeping Jolly Green Giants (CH-3C/E/F) on station to rescue downed pilots during the Vietnam War has been adopted to most large helicopters and to many smaller special mission aircraft. The Vietnam War demonstrated innovative means of arming transport helicopters. Today, ground attack and ground assault helicopters carry devastating firepower. The first guided missiles fired during Desert Storm were fired from attack helicopters, after a thousand-mile low-altitude dash across the desert, in order to knock out front line radar before the first air bombing assault. Special air-capable ships are now built to carry Marines and their aircraft for sea assault. In the naval environment, helicopters become mine sweepers and carry anti-ship missiles that will destroy a major vessel.

MILITARY HELICOPTERS

World Wide Deployment

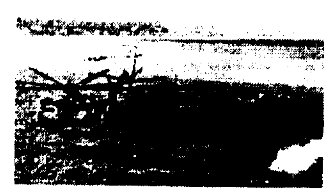


Weapons Supply

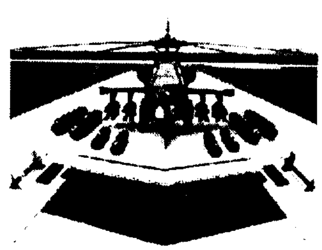


Sea Assault

Ground Assault



Mine Sweeper



Ground Attack

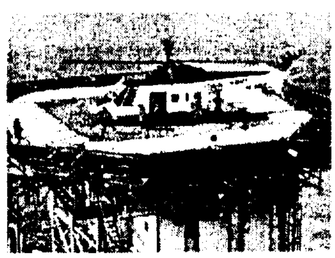
Anti Ship

Bell Aircraft began design of a helicopter in 1941, based on the 13 year private study of the philosopher Arthur Young. The company funded effort resulted in the Model 47, certified in March of 1946. The Young concept used a two-bladed "seesaw" rotor, not an articulated rotor. Cyclic control was transmitted through a stabilizer bar. Over 6000 Bell Model 47 variants were built over the following 30 years. Civilian uses of helicopters were nearly all first tried with a Model 47. A universally accepted use is that of providing emergency medical service (EMS). A popular TV program, MASH, alerted the public to EMS. A Doctor publicized the life saving benefits of providing trauma care within one hour to critical patients and an industry was born. EMS helicopters are used all over the United States and in much of Europe. Counting rescue missions from fires and ship wrecks, it has been estimated that over a million people owe their lives to the use of a helicopter.

Helicopters application is preferred to airplanes for some agricultural treatment. Police helicopters assist patrol cars in traffic and crowd control and in search and rescue missions. Workers are flown to off shore oil rigs around the world. Power line construction in remote areas and even maintenance of insulators is performed by helicopters. A helicopter "truck" was recently introduced to carrying logs, put air conditioners on top of buildings, and that sort of things. In Newport News, a sport helicopter has been designed and demonstrated with production imminent at a cost of about $30,000. The Presidential and executive transport uses have been around for a long time. The one area that has been the least successful is airline use. However, new possibilities exist in the new future.

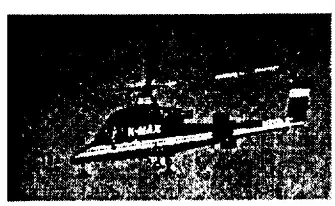
CIVIL HELICOPTERS

Off Shore



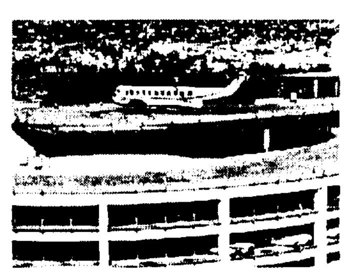
Police

Emergency

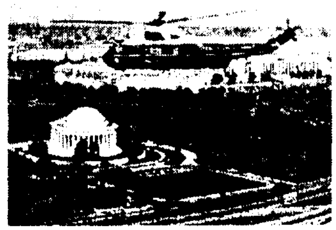


Vertical Lift

Sport



Airline



Executive

All technical areas have made progress and continue to do so because the industry has a focus on advanced technology. The interactive nature of the various elements of the helicopter resulted in frequent surprises to early designers. Early theory and experimental validation was often limited to the parameters of the aircraft just built, not to the next design. Sometimes a "new" dynamic mode was excited that never caused problems in a closely related design. The cause was that rotary wing vehicles required more integration than fixed wing designs. Starting in the '50s, the U. S. industry begin developing a cadre of people who applied scientific methods to understand the interactions between unsteady airloads, blade and airframe dynamics, flight and control system dynamics. Especially important in this regard has been support of AHS graduate study scholarships and the Army's selection of rotorcraft "centers-of-excellence" on which to focus their University research. The Army also placed research staff at the three NASA research centers. From those broad activities, unique rotorcraft analysis and design tools have evolved that are more accurate, user friendly and permit more optimum designs. The revolution in computer speed, capacity, and availability, along with an integrated product approach, is now focused on reducing the cost of rotary wing aircraft. (D.P. Schrage and D.N. Marvis, "Integrated Product-Process Design-Development through Robust Design Simulation: The Key for Affordable Rotorcraft," 51st Forum of the American Helicopter Society, May 1995.)

A byproduct of the advanced technology focus is that old dreams become viable when previous limits are broken by newly developed technology.

ROTARY WING DEVELOPMENT

Technology Achievement and Challenge

- **All technical areas have made progress and continue to do so (examples)**
- **Rotary wing vehicles require more integration than conventional fixed wing**
- **Analysis / design tools have, over time, become both more "user friendly" and accurate and offer more optimum configuration**
- **Shift to computer data base permits integrated product approach (design - analysis cyclic with manufacturing / production)**
- **Old dreams become viable when previous limits are broken by new technology**

Igor Sikorsky dreamed of vertical flight. In 1909, he purchased a 15-hp Anzani engine and attempted to build a helicopter. His first attempt was unsuccessful. His second attempt, after considerable experimentation, "was nearly able to lift its own weight from the ground." He became convinced him that the available technology was insufficient to build a practical helicopter. He turned his attention to airplanes, designing and building the first four engine aircraft, flying boats and amphibious craft but keep dreaming of a helicopter. In 1931, he filed for a U.S.. patent on a helicopter design with a single main rotor, cyclic pitch control and a shaft driven tail rotor. The cyclic pitch control used trailing edge flaps on the main rotor blades. The helicopter became his full time focus in the spring of 1939. He made his first "tethered" flight with the 1092 lb. VS-300 helicopter on September 14, 1939 using a 65-hp Lycoming engine. Aviation power plants had matured 30 years. (Sergei I. Sikorsky, "The Development of the VS-300," *Top Technology Achievements in the History of Vertical Flight*, published by The American Helicopter Society, 1994.)

We must acknowledge that it was the light weight reciprocating engine that really made the *practical* helicopter possible but it was the first generation free turbine that began to make it productive. The first generation turbine was introduced in the helicopters that carried the Vietnam war. The T-53 is the engine that powered the Vietnam ambulance helicopter - which became the Vietnam weapons carrier, (and then the Vietnam attack helicopter). (Henry Morrow, "Helicopter Turbine Engines," *Top Technology Achievements in the History of Vertical Flight*, published by The American Helicopter Society, 1994.)

TECHNOLOGY ACHIEVEMENT
Powerplant Improvements

Light weight reciprocating engines made the helicopter possible

1st generation free-turbine turboshaft engines made helicopters productive

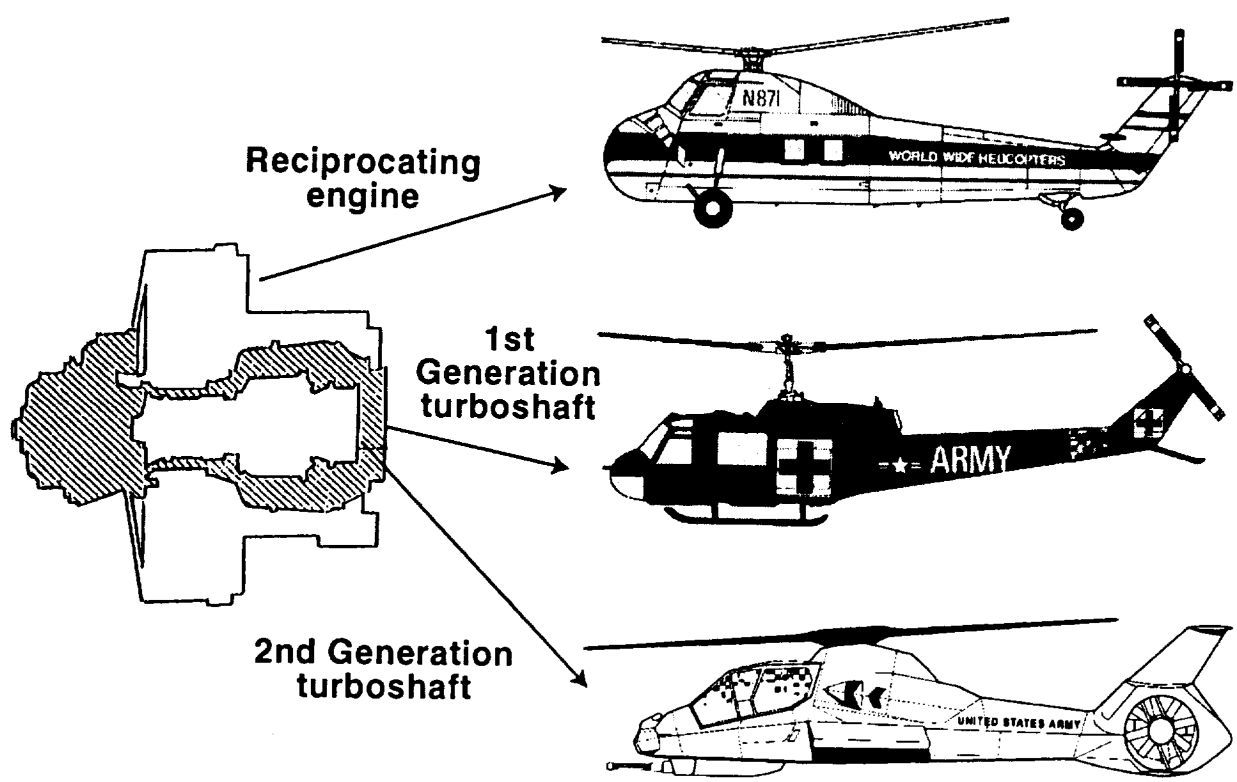
2nd generation turboshaft engines made helicopter efficient

	Reciprocating	1st Generation	2nd Generation
Engine weight/ Aircraft gross weight	0.12	0.04	0.02
SFC, lb fuel/HP/HR	0.45	0.65	0.45

A second-generation turbine engine, derived from the Modern Technology Engine (MTE) Program, is installed in the current Sikorsky-Boeing Comanche (RAH-66). That engine now has fuel consumption rates typical of piston engines along with another step reduction in the actual weight. In comparing the size of specific 800 HP demonstrator engines; the cross section of the second generation turbine engine is approximately half that of the first generation turbine engine; and the first generation turbine engine is approximately half that of an 800 HP piston engine. Advanced technology resulted in favorable weight and sfc impacts along with an engine volume reduction. The volume reduction reduces the airframe drag (the rotor propulsive force requirement) while increasing the rotor lifting efficiency. The impact of engine improvements are not obvious in direct comparison between different generation aircraft because the gains are absorbed by new requirements. For example, current engine installations must consider one-engine out, hot-day hover, minimum vertical rate of climb and maneuver requirements along with vehicle/engine signature and particle separation issues.

TECHNOLOGY ACHIEVEMENT

Powerplant Improvement



The safety and reliability of rotorcraft have significantly improved over time. An important change in rotor construction was a gradual change from wood, to metal, to composites. Early Autogiro blades were primarily wood and fabric with some metal fittings. Pitcairn introduced steel spars. Many early helicopters used the same techniques with a few using built-up all metal blades and others using laminated wood covered by fiberglass. At least one helicopter company fabricated their early production blades primarily from fiberglass. The early metal-component rotors often suffered from fatigue cracks. That can ruin your whole day. Today, most rotors systems utilize composites or specially prepared titanium parts as we progress toward advance composites hubs and blades. New rotor designs can now be designed insensitive to fatigue damage as a result of the inherent characteristics of composites.

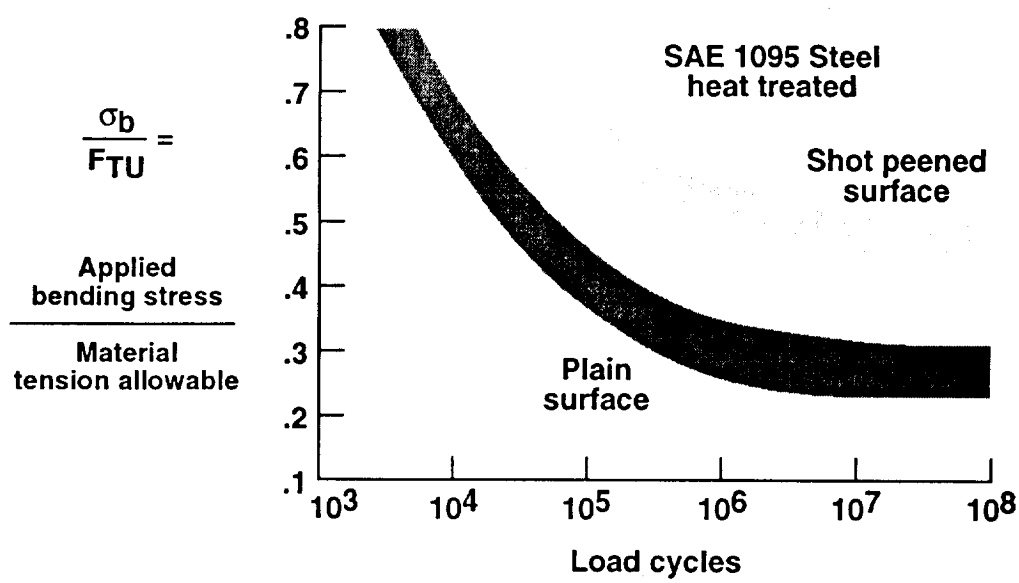
Metal component life is increasing primarily due to increased knowledge of fatigue design and test procedures as applied to dynamic components. The surface of critical metal components are now especially prepared to avoid rubbing and fretting damage. For example, the chart shows one preparation wherein shot peening, which changes the surface properties of the metal, is used to obtain a substantial improvement in the fatigue properties of the system. In the future, design will emphasis probabilistic approaches but actual component life will be "on-condition" depending heavily upon system health and usage monitoring. (Richard M. Carlson, "Reliable Dynamic Components," *Top Technology Achievements in the History of Vertical Flight,* published by the American Helicopter Society, 1994.)

TECHNOLOGY ACHIEVEMENT

Safety and Reliability

Rotor Composites: • Insensitive to fatigue

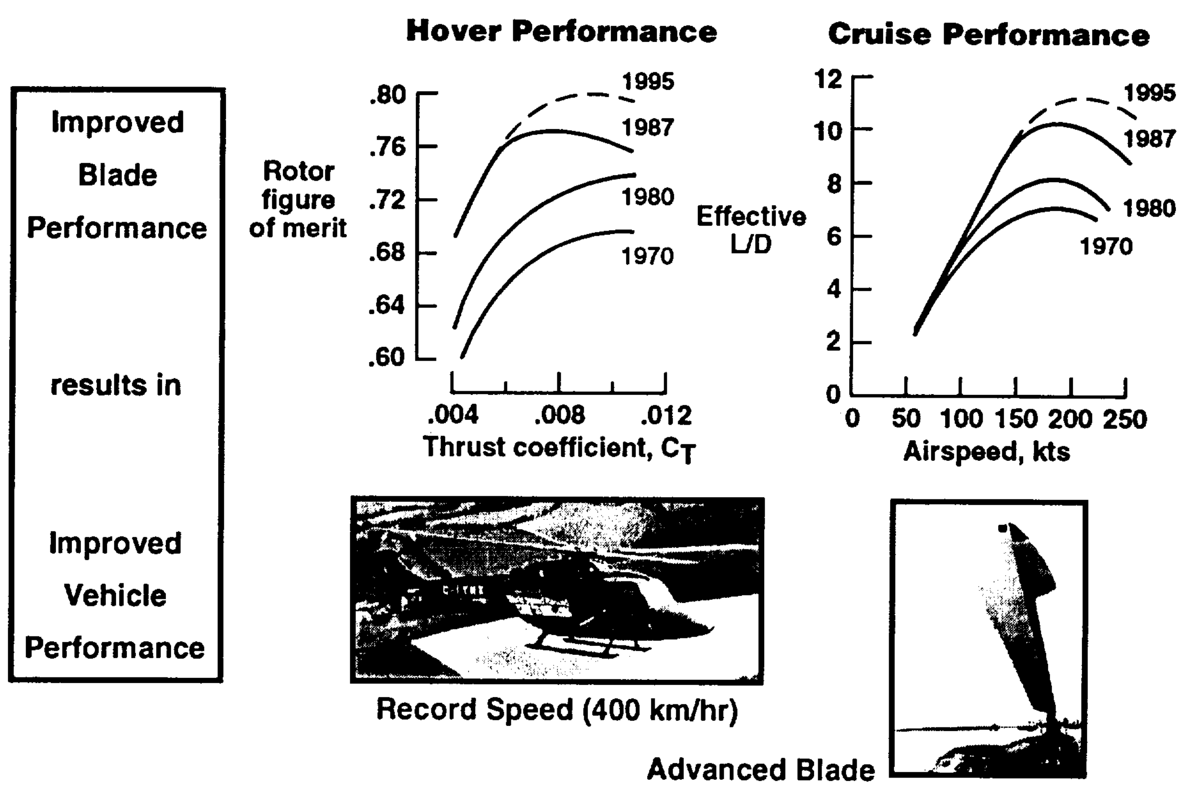
Dynamic Components: • Special surface preparation



A combination of new airfoils, more optimum planforms, greater design flexibility, and better analysis for integrating the rotor into the airframe has resulted in improved overall vehicle performance. For example, an experimental BERP blade (British Experimental Rotor Program), when installed on a Westland Lynx, set a speed record for conventional helicopters of 400 km/hour. Three versions of the EH 101 and two versions of the Lynx now use the BERP blade. These improvements occurred gradually. Since the first rotor with a cambered airfoil was installed on the CH-46, significant rotor performance improvements have occurred. The figures show that the hover figure of merit and cruise performance has increased over the years as the result of a collection of synergistic improvements. Additional improvements are expected. (Kenneth I. Grina, "Development of Helicopter Design Capability Progress from 1970 to 1993," The 1993 Nikolsky Lecture, *Journal of the American Helicopter Society*, Vol. 39, (1), Jan. 1994).

TECHNOLOGY ACHIEVEMENT

Rotors



Rotor technology has made giant strides since the earliest helicopters. Most early rotors used the 0012 airfoil or an equivalent uncambered airfoil. The local velocity of a blade tip in forward flight is near sonic speed on the advancing side of the rotor and is near stall on the retreating side. These condition get more extreme as the helicopter goes faster and as the helicopter maneuvers. The rotor airfoil operates between these extremes once each revolution. The airfoil must be designed to provide the best compromise between good stall characteristics and good sonic characteristics. Because of this unique requirement, a family of special airfoils for rotory wing applications have been developed. The blade planform and twist variation can also be tailored to increase the efficiency of a rotor. The blade material improvements over time has also influence the natural frequencies and structural response to the unsteady airloads experienced.

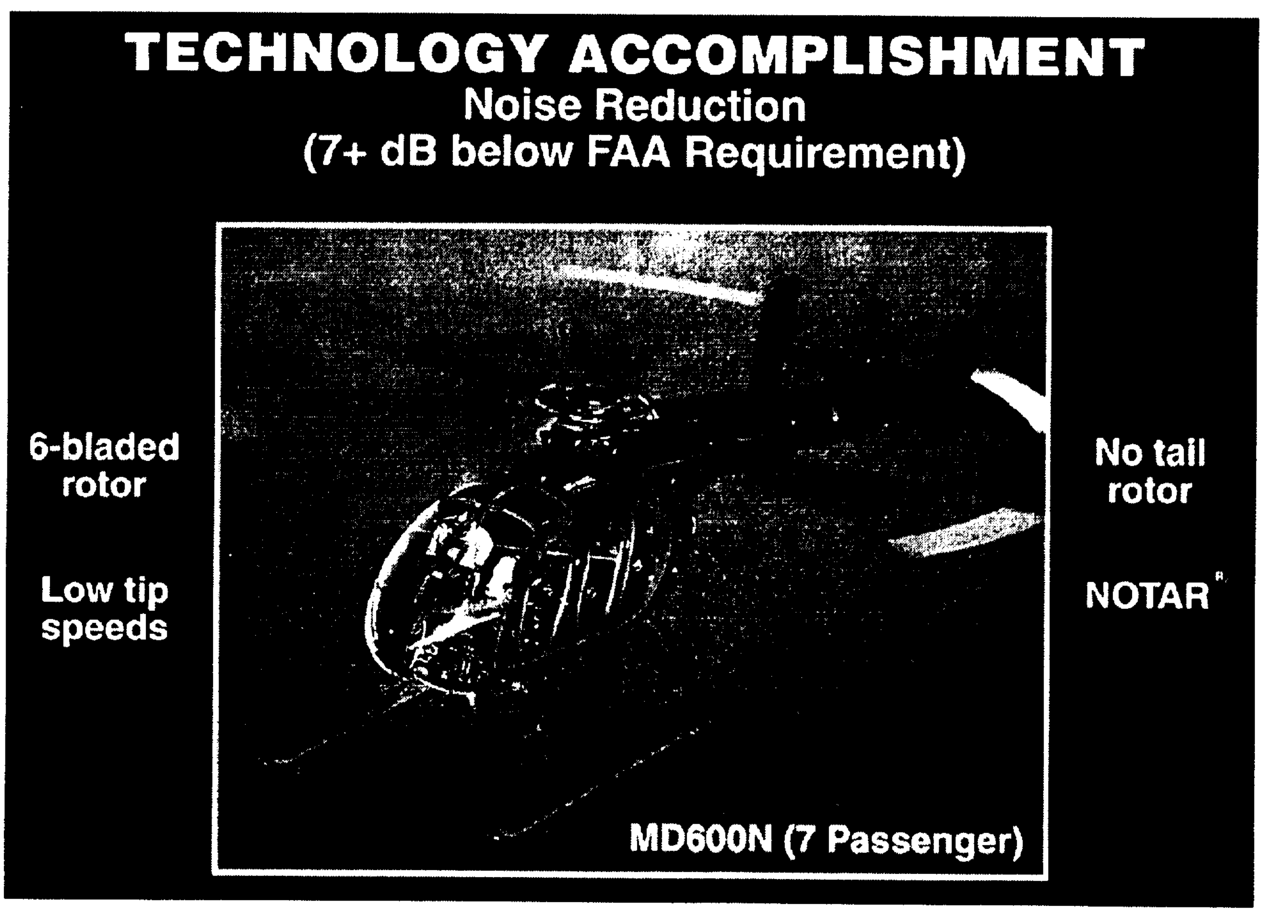
The method of blade "articulation" has also changed over time as complex hinges and dampers give away to elastomerics and structural bending. Eventually, rotor performance will further improve as elastic articulation replaces the clap-trap of hinges and dampers still in use on most helicopters today. Analysis is being developed now that will integrate the dynamic interactions of non steady aerodynamics, non-isomeric and non-linear structures, and flight maneuvers that is required before elastic articulation can become standard on new rotors. (Alfred Gessow, "Advanced Rotor Geometries," *Top Technology Achievements in the History of Vertical Flight,* published by the American Helicopter Society, 1994.)

TECHNOLOGY ACHIEVEMENT

Rotors

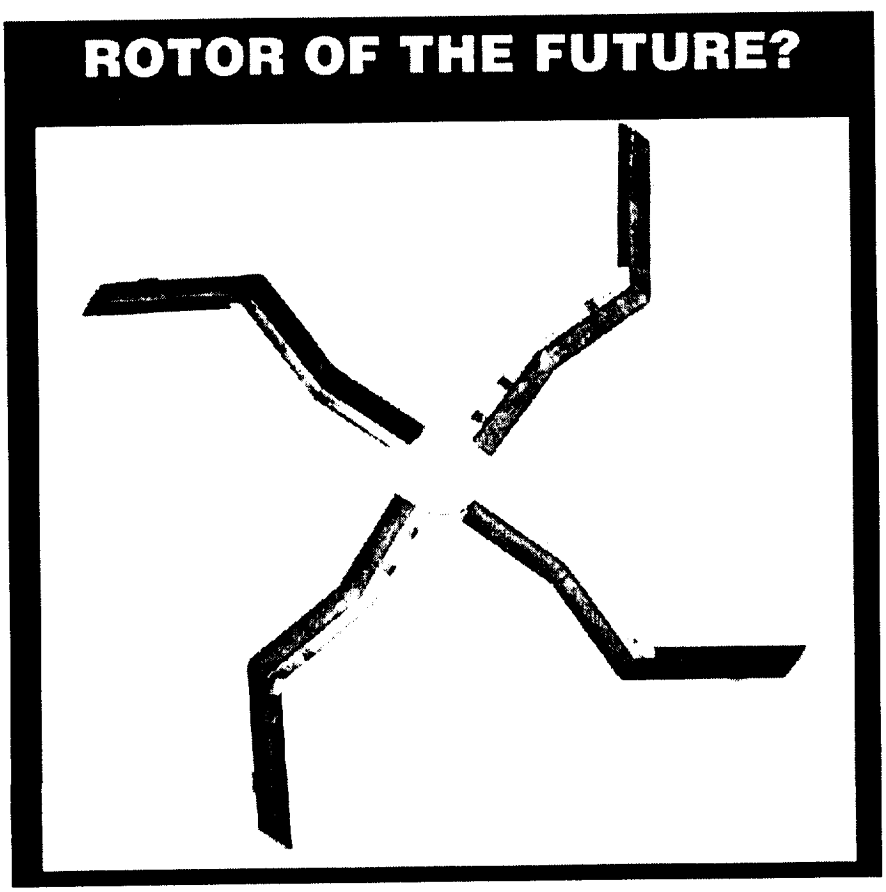
	Past	Current	Future
Airfoils	NACA 0012 NACA 0015 V23010-1.58	SC 1095 FX 69 H 098 VR-7 HH-02	VR-11X Lockheed rotor airfoil
Planform	Rectangular	Tapered Special tips	Integrated and optimized
Structure	Metal	Composite	Advanced composite
Articulation	Mechanisms • Hinges • Dampers	Composites and elastomerics	Elastic articulation

This is a McDonnell Douglas MD600N, a new 7-passenger aircraft that is ready for production. It is the great grandchild of the Light Observation Helicopter of the pre-Vietnam era. The family resemblance to the OH-4 helicopter is probably the only thing unchanged. The designers eliminated the tail rotor by substituting a pneumatic device called the NOTAR®, enlarged the airframe, installing the latest version of the Allison 250-C47 engine (700 shp. derated to 575 shp), increased the number of blades from 4 to 6, and slowed the main rotor a little. The result is a 4150 lb aircraft capable of: picking up 140 percent of its empty weight; hovering at 10,500 feet; a sea level climb of 1,700 ft/min.; a maximum speed of 175 mph with a cruise speed of 154 mph over a 446 mile range. They now have a very fast, efficient, low operating cost, seven passenger aircraft which is also more than 7 dB below the FAA noise requirement. Similar technology is available across the industry in a variety of vehicle classes. The industry now recognizes that low noise designs may actually be more efficient. (Evan A. Fradenburgh, "The First 50 Years Were Fine . . . But What Should We Do for an Encore,?" The 1994 Nikolsky Lecture, *Journal of the American Helicopter Society*, Vol. 40, (1), Jan. 1995)



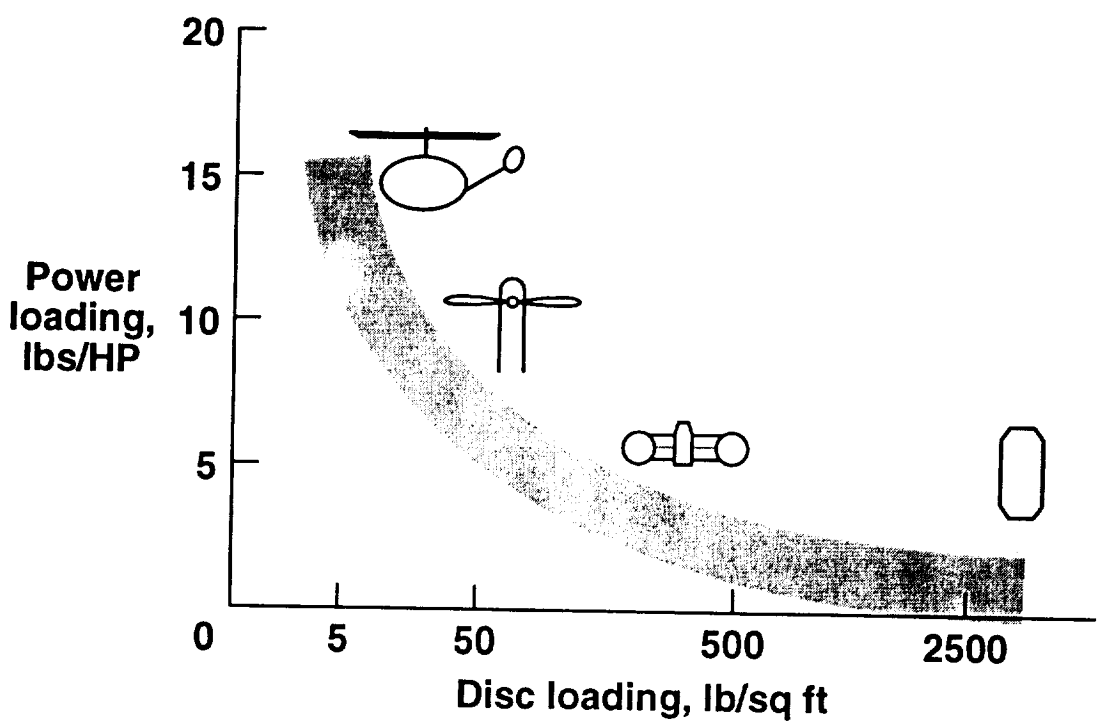
What can we expect to see in the future? This photograph shows a rotor concept that may look a little bit weird. The concept may not work today but I suggest that this is the direction rotor design will proceed in the next 5 to 15 years. Dr. Thomas F. Brooks sees this type of rotor as *the* approach to reducing overall rotor noise. This blade concept reduces blade vortex impact and sonic shocks, the two sources of rotor "blade-bang" noise notable with the Vietnam era Huey helicopter still flying. The promise of this concept, augmented with leading edge spoilers and a trailing edge device, is another step increase in vehicle capability. Aerodynamic, vibration, and noise control devices on the blades will including active controls and smart structures. (R. Barrett, *Intelligent Rotor Blade Actuation through Directionally Attached Piezoelectric Crystals,* University of Maryland Thesis, 1993.)

The elements of a helicopter include a fuselage structure, an engine, a transmission and drive train, controls, mission systems and the rotor(s) system. Considering the advanced technology in development within the aerospace industry, the rotor and perhaps the drive system are probably the principal elements of the helicopter that requires a unique research focus. Assuming rotorcraft application efforts continue, broad based research in materials, structures (including smart structures), propulsion, electronics, control theory (and integrated design), mission systems and production will be applied to the helicopter. Much of it will be applied before airplane applications (principally because of the relative scale of operations) but always at least parallel to airplane developments.



A helicopter may be the first aircraft to actually hover but a very large number of Vertical Take Off and Landing (VTOL) aircraft have been conceived, some built and flown, but only a hand full have been successful. In comparing VTOL types, it is appropriate to note that the helicopter is only a short segment on a curve of continuous VTOL concepts. The figure compares power loading versus disc loading for a variety of hovering vehicles ranging from helicopters to a simple jet engine hovering device. Helicopters, typically from 5 to 14 lb/sq. ft disc loading, enjoy the high hover efficiencies required for long duration hover or low speed maneuvers. As may be evident from the figure, one way to proceed into forward flight is simply to tilt the lifting device, providing a vertical plus a horizontal component of lift. It should be pointed out that only aircraft that cluster on the two ends of the power loading/disc loading curve (the helicopter and the jet VTOL) have gone into production to date. (D.P. Schrage, "The Rotary Wing Aircraft Conceptual Design Process, Technical Specialist Meeting of the American Helicopter Society, April 1989.)

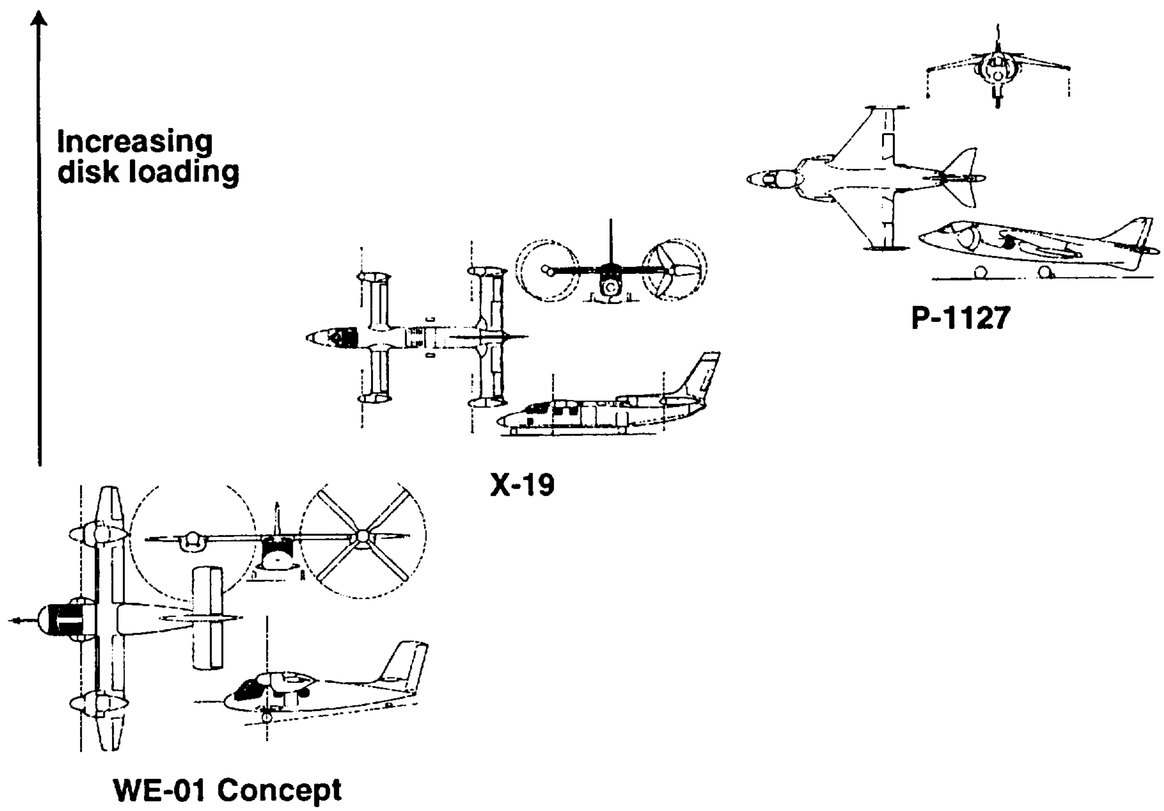
HOVER EFFICIENCY OF VTOL CONCEPTS



The figure shows three possible VTOL concepts that tilt the lifting device to convert from a hovering aircraft to one capable of forward flight. The first is an early 1950s Westland tiltrotor concept where the pylons of side-by-side rotors pivot near the wing tips to transition from hover to forward flight. The middle concept, demonstrated by the Curtiss-Wright X-19 aircraft in 1965, pivots the propeller shafts at the tips of tandem-wings. The Hawker P1127, an example of a high disc loading deflected jet concept, hovered in 1960 and converted in 1961. This concept, which balances on four columns of air from bifurcated compressor and jet exhaust nozzles, evolved into today's McDonnell Douglas AV-8B. The power loading of a jet VTOL aircraft has reached a minimum with the implication that hovering this high speed aircraft, for even a few minutes, takes a lot of fuel.

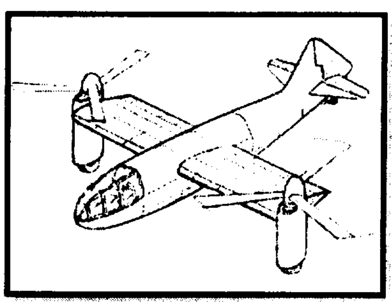
Two aircraft concepts deserve some special note. The tiltrotor has a long history of false starts. In the middle of development troubles with the tiltrotor, the tilt wing concept burst on the scene. The tilt wing had been well researched by NASA. In both vehicles the shaft of the rotor or propeller is tilted, in the later case the shaft is fixed on the wing and the wing must be inclined to tilt the lifting device. Conceptually, both aircraft could have the same disk loading, however in practice, a conceptual tilt wing is usually designed to have up to eight times the disc loading of the tiltrotor. (R. L. Lichten, L. M. Graham, and K. G. Wernicke, "A Survey of Low-Disc-Loading VTOL Aircraft Designs," AIAA Paper 65-756, Nov. 1965.)

TILTING LIFT DEVICE

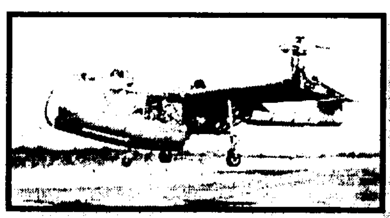


The earliest tiltrotor concepts came in the early days of practical helicopters, sometimes from the same inventors. Tiltrotor concepts in Britain and Germany were under study at the same time as early U. S. patents were granted. The Focke Achgelis Fa 269, with a rotor *behind* the wing, was designed as a fighter. This concept of a dispersed fighter never flew and most design information was destroyed. Immediately after the war, a couple of tiltrotor aircraft were built by Transcendental in the U. S. The first crashed in flight test, the second flew successfully but the company failed. Bob Lichten, responsible for the Transcendental design, moved on to Bell Helicopter where he designed the *piston-engine* powered XV-3 and became the cheerleader for the tiltrotor concept. The XV-3 demonstrated conversion from "helicopter mode" to "airplane mode" and most of the technical problems of the concept. Because of the potential offered by the concept, a great deal of research was done by NASA, the Army, Bell Helicopter and later, Boeing Helicopter on the technical issues identified in flight and through wind tunnel tests of the XV-3 aircraft. The history of the final two aircraft, the XV-15 and V-22 will be covered later. Both of these aircraft are still flying. (Robert L. Lichten, "Design Problems and Solutions for Five Types of Low-Disc-Loading, High-Speed VTOL Aircraft," presented at 7th ICAS, September, 1970 and Robert R. Lynn, "The Rebirth of the Tiltrotor," The 1992 Alexander A. Nikolsky Lecture, *Journal of the American Helicopter Society*, Vol 38, (1), Jan. 1993).

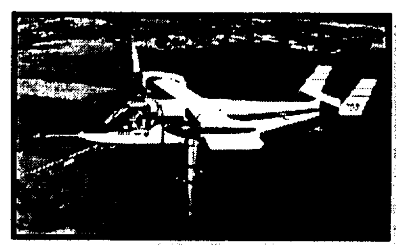
TILTROTOR



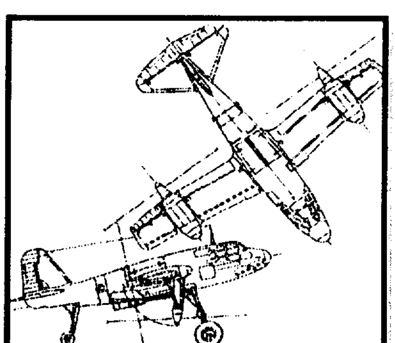
Baynes Concept
(1937)



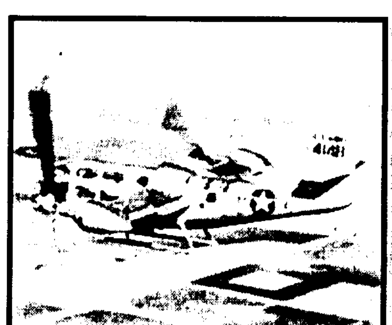
Transcendential 1G
(1954)



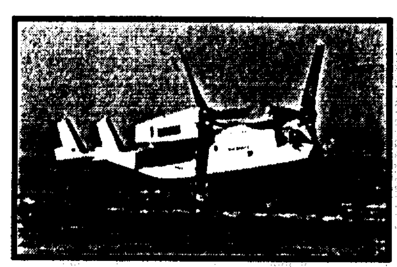
XV-15
(1979)



Fa 269 Project
(1941-1944)



XV-3
(1955)

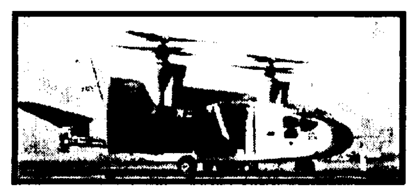


V22
(1989)

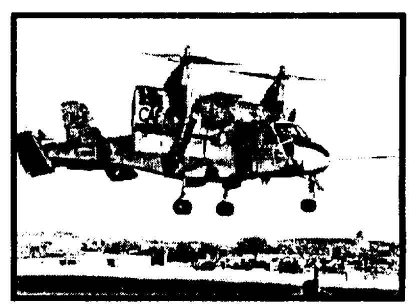
Turning to the competitor concept, the tilt wing aircraft offers higher cruise speeds at the cost of hover efficiency (the disc loading/power loading trade). Vertol (Boeing) built the *turbine* powered VZ-2 and demonstrated successful conversion from hover to forward flight. Hiller built the unsuccessful X-18 from pieces and parts of other aircraft. The concept was carried to the next higher engineering level by the turbine powered XC-142A and CL-84 aircraft. Five XC-142As were built by a partnership team of LTV-Hiller-Ryan while two CL-84s were built by Canadair. All were sponsored by the government. Each aircraft contributed to the fundamental knowledge necessary to develop a production tilt wing aircraft. The major handicap of the XC-142A was excessive noise in low speed flight and landing. Some minor aerodynamic/dynamic issues needed to be resolved. An Air Force focus on a VTOL C-130 replacement, the Light Intratheater Transport (LIT), led to selection of the tilt wing concept in 1969 by the Air Force Development Command. Unfortunately, the Tactical Air Command wanted a jet airplane and the tilt wing concept was dead. The U. S. government investment had topped a billion (in 1995 dollars). (John Schneider, "Out of the Past-Progress? Whatever Happened to the Tilt Wing," pages 56-59, *Vertiflite*, , Vol 41, No. 3, May/Jun. 1995.)

TILT WING

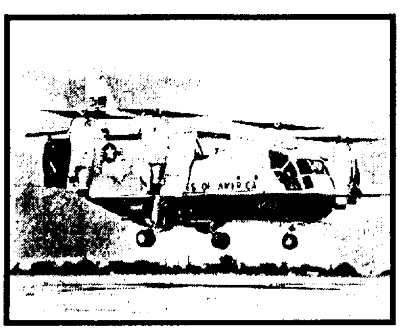
VZ-2 (1957)



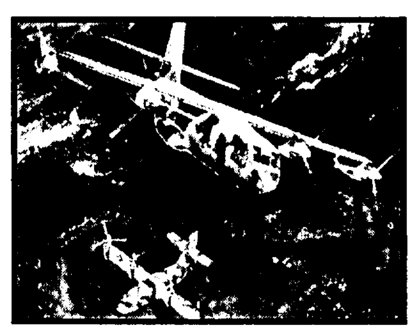
X-18 (1959)



CL-84 (1965)



XC-142A (1964)



AF LIT CONCEPT (1969)

In contrast, the Army valued speed but needed only a modest increase over the speed of a helicopter. The early tiltrotor vehicles were all piston engine powered and appeared limited vis-a-vis the turbine-powered tilt-wing vehicles. In addition, all prior tiltrotor vehicles had dynamics problems with solutions yet to be demonstrated at full scale. But studies showed a turbine-powered tiltrotor could provide speeds beyond the compound helicopters flying at that time and still provide most of the low speed advantages of the helicopter. NASA and the Army sponsored a joint development of a "proof-of-concept" tiltrotor aircraft, the turbine powered XV-15, which was spectacularly successful (Figure 17). Demonstrations with the XV-15 across the United States and flights with "pilot-qualified" Senators and Representatives helped sell the concept. One of the key factors of government interest has been the potential for civil/military dual use which was acknowledged early. (Raoul Hafner, "The Case for the Convertible Rotor," Tenth Cierva Memorial Lecture, *The Aeronautical Journal of the Royal Aeronautical Society*, Vol. 75, Aug., Sep. 1971.)

TILTROTOR vs. TILT WING

Tilt Wing

- 1st versions turbine powered
- 3 of 4 versions flown successfully
  - Some low speed aerodynamic problems
  - Low speed noise was excessive
  - Conventional turbo-prop cruise speeds (~375 mph)
- Air Force considered for Light Intra Theater Transport
  - Preferred choice of AFDC (developer)
  - TAC (user) wanted jet airplane

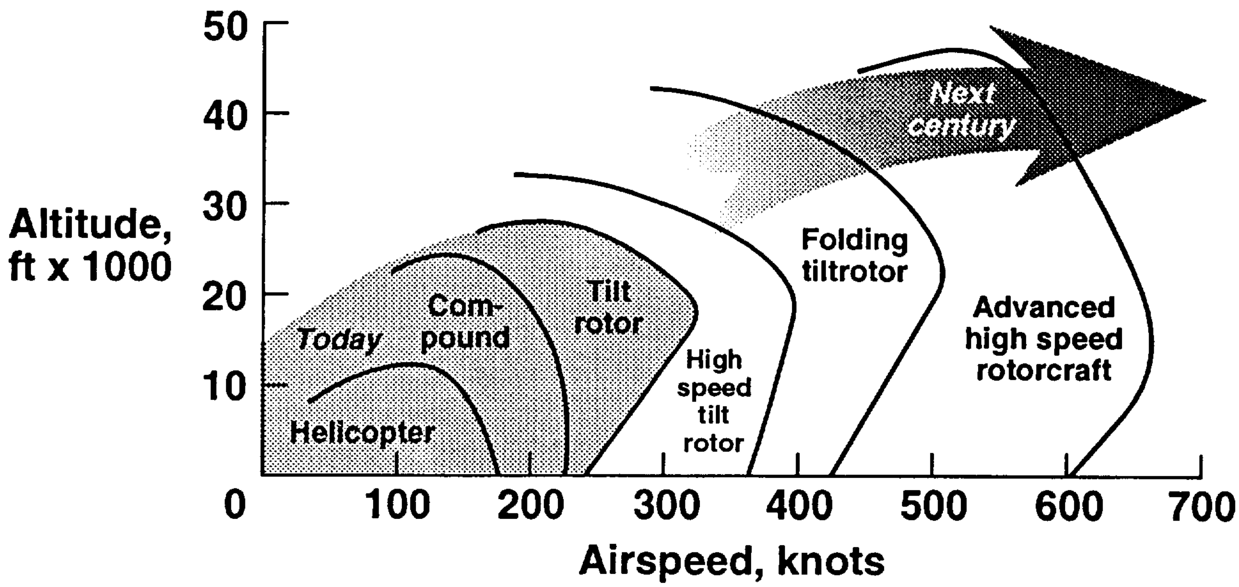
Tiltrotor

- 1st versions unimpressive
  - Piston-engine powered
  - Dynamic problems
  - Potential appeared limited
- NASA / Army began "proof-of-concept" development
  - Logical next step beyond pure and compound helicopters
  - Turbine powered XV-15
  - Successful beyond expectations
- Civil military "dual-use" potential obvious

How does the tiltrotor compare with other rotary wing types? The figure compares the flight envelope of existing and demonstration aircraft with some futuristic conceptual rotary wing types. The shaded area shows the airspeed and altitude capability of existing helicopters, compound helicopters and the two tiltrotor types currently flying (the XV-15 and V-22). (D.P. Schrage, "The Rotary Wing Aircraft Conceptual Design Process, Technical Specialist Meeting of the American Helicopter Society, Apr. 1989.)

The futuristic concepts are based on the assumption that a rotor can be designed and build that can be folded and retracted or stopped for high speed flight. A variety of concepts have been studied in considerable depth that show promise *today*, if expected technical advances are assumed. All offer the hope that a high speed aircraft can be built that will hover efficiently. (P. W. Theriault, I. H. Culver, and L. Celniker, "Considerations Relative to Stopping a Rotor in Forward Flight," paper given at 20th Forum of the American Helicopter Society, May 1964; and L. Celniker, R. M. Carlson, and R. E. Donham, "Stopped and Slow Rotor Aircraft Configuration," SAE Paper 650806, Oct. 1965; and J. D. Eisenberg and J. V. Bowles, "Folding Tiltrotor Demonstrator Feasibility Study," paper given at the 40th Forum of the American Helicopter Society, May 1985.)

ENVELOPES OF ROTORCRAFT



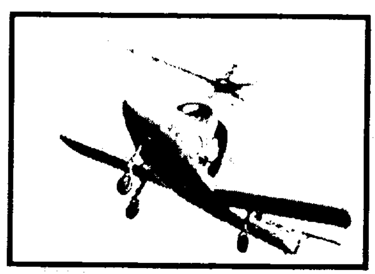
The compound helicopter, the aircraft concept that falls between the helicopter and the tiltrotor, showed promise, almost went into production, but fell by the wayside. As Autogyros became mature, the wings were removed. As helicopters developed, designers began to add wings and/or auxiliary propulsion with the goal of speed.

An early British compound, the Fairey Gyrodyne, used a tractor propeller on the right wing tip to set a speed record of 200 km/hr on June 28, 1948. A 525 hp Alvis Leonides radial engine drove both the propeller and a 3-bladed main rotor. The propeller also provided the necessary torque balance. A latter version, called the Jet Gyrodyne, used the Leonides to power pressure jets at the blade tips of a two-bladed rotor as well as two pusher propellers on the wing tips. This concept worked out some of the details for a later and much larger compound, the Fairey Rotordyne.

The dual engine French S.O. 1310 "Farfadet" fell by the wayside for lack of development funds due to the Algeria conflict. A nose turboprop engine and propeller was supplemented by a turbocompressor pumping air to blade tip-jet thrust units where fuel was injected. McDonnell also built a tip-jet driven aircraft, the XV-1, but the dual compressors were driven by a singe piston engine. In forward flight, the engine also powered a pusher propeller. The blades were mounted on a gimbaled hub. All of these compounds had complicated dual control systems, one for "helicopter" flight, one for "airplane" flight. None of these went beyond simple exploration of the flight envelope.

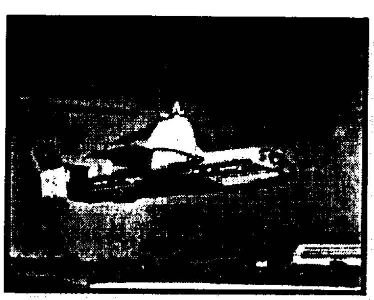
COMPOUND HELICOPTERS

Gyrodyne
(1947)

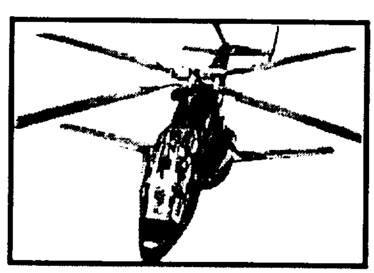


S.O. 1310
(1953)

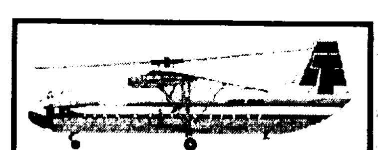
XV-1
(1954)



Rotodyne
(1957)



AH-56A
(1967)



Mi 12
(1968)

The compound helicopters that nearly saw production were the Lockheed AH-56A and the 40/48 passenger Fairey Rotodyne. A U. S. firm became a licensee for the 39,000 lb Rotodyne because of its commercial potential. Studies showed that the 160 knot Rotodyne, city center to city center, has shorter times than jet airplanes on stage lengths less than 380 nm. The Rotodyne rotor was tip-jet powered. Two 2,900 SHP Napier Eland turboshaft engines powered both propellers and a tip-jet air compressor. Fuel was added and burned at the tips for hover and low speed flight. In cruise, the rotor is in autorotation (shades of Cierva) with the propellers receiving maximum power. Selection of the tip-jet concept resulted in a 10 to 15 percent reduction in gross weight vs a rotor-transmission and tail rotor. However, the tip jets were extremely *noisy*. Fairey demonstrating the Rotodyne to the public in down town London just before the government ordered a consolidation of helicopter firms. The government canceled the program by leaving it homeless . (G. S. Hislop, "The Fairey Rotodyne," paper given at a meeting of The Helicopter Association of Great Britain and The Royal Aeronautical Society, Nov. 1958.)

The single engine AH-56A, designed as a 225 knot ground attack aircraft with unique weapon systems and sensors, was considered a priority need for Vietnam and quickly ordered into production. Flight tests were interrupted by some coupled aeroelastic/ control problems. The Army requested a "cure," when the cure was slow, the Army changed requirements and canceled the program. (R. M. Carlson, R. E. Donham, R. A. Blay, and D. W. H. Godfrey, "Extending Helicopter Speed Performance," Lockheed Horizons, sixth Issue, Jul. 1967.)

COMPOUND HELICOPTERS

Issues

- **Rotodyne**
  - **World wide commercial interest for airlines**
  - **Excessive noise from tip burning**
  - **Government support cancelled after public demonstration**

- **AH-56**
  - **High speed, agile ground attack aircraft**
  - **Ahead of its peers**
  - **Aeroelastic / control problems encountered**
  - **Army put production contract on hold pending "cure"**
  - **Army changed requirements and cancelled contract**

The Russian Mi 12 side-by-side rotor helicopter (figure 21) holds the record for rotary wing size with a gross weight of nearly a quarter million pounds (105,000 kg). Each 5-bladed rotor has a diameter of 35 meters (114 ft. 10 in.). The Mil design bureau used the engine-transmission-rotor from the Mi 6/Mi 10 series, mounted them on the tips of strut-braced inverse-tapered wings attached to a large cargo fuselage. They first flew the Mi 12 in 1968 and showed it at the 1971 Paris Air Show. The M-12 was abandoned in favor of the Mi 26 which is commercially available today. Cancellation of the Mi 12 is *believed* to be due to technical issues. Considering the Russian design philosophy: "Make it simple; Make it rugged; Make it work," once serious technical issues arise, cancellation appears logical.

This lack of success with the aircraft raises the question: Is there a size limit to helicopters? The Mi 6 and Mil 10 are very successful, so the component systems were not the problem. Integration of two systems into an awkward wing-fuselage structure may be a problem. Development of the 8-bladed, 32 meter rotor for the 49,500 kg Mi 26 appears to follow conservative western practice. Perhaps the Mi 12 experiment tried to stretch the *existing* rotors too far. (Henry G. Smith, "Size Effects on the Design of Large Rotor Systems," paper given at 27th Annual Forum of the American Helicopter Society, May, 1971 and J. J. Schneider, "The Influence of Propulsion Systems on Extremely Large Helicopter Design," paper given at 25th Annual Forum of the American Helicopter Society, May 1969.)

RUSSIAN DESIGN PHILOSOPHY

Make it SIMPLE

Make it RUGGED

Make it WORK

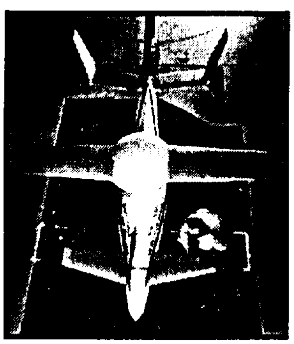
- Mikhail Leontievitch MIL

Gerald P. Herrick is the inspiration for rotary wing concepts that push the flight envelope. In 1931, he flew a biplane, the HV-1, that was equipped with a top wing that could be unlocked in flight to permit autorotation. The upper wing airfoil section was symmetrical to allow it to work in both modes. Herrick persevered and by 1937 he successfully converted the HV-2A from airplane flight to autorotation. The HV-2A hangs from the ceiling in the Garber facility in Silver Hill, MY today.

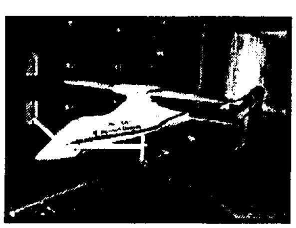
The concept of a "wing" that would provide lift either rotating or non-rotating has led to at least three additional concepts. The first, the Rotor Wing concepts, started with a symmetric delta wing wherein extended wing "tips" became the rotor blades. (The third blade is added to the forward spike of the delta). Two offshoots of the delta follow logically. The first, a 4-bladed rotor (4 wing panels) called the X-Wing. The second, a 2-bladed rotor (2 wing panels) termed the Canard Rotor Wing (CRW). Model tests have determined the basics of all three configurations.

(R. M. Carlson, R. E. Donham, R. A. Blay, and D. W. H. Godfrey, "Extending Helicopter Speed Performance," Lockheed Horizons, Sixth Issue Jul. 1967; and L. Ludi, "Composite Aircraft Design," paper given at 23rd Forum of the American Helicopter Society, May 1967; and R. J. Huston and J. P. Shivers, "A Wind-Tunnel and Analytical Study of the Conversion from Wing Lift to Rotor Lift on a Composite-Lift VTOL Aircraft," NASA TN D-5256, 1969.)

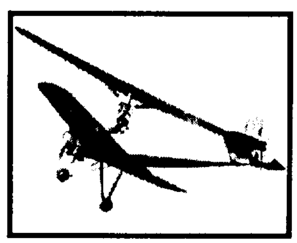
STOPPED ROTORS



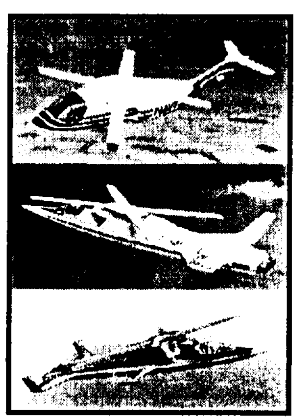
Canard Rotor Wing Concept (CRW)



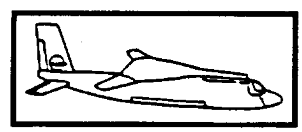
Tunnel Tests (1993)



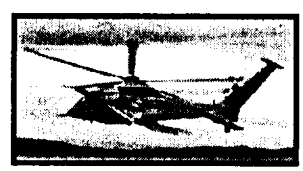
Herrick HV-2A (1937)



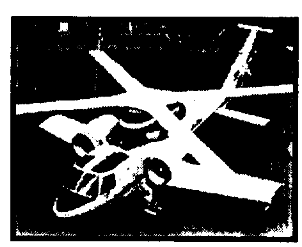
X-Wing Concepts



Rotor Wing Concept (1967)



RSRA



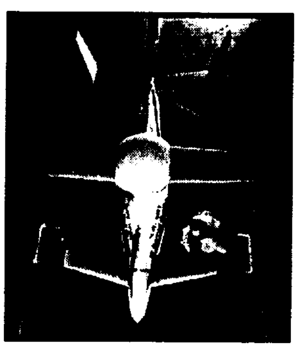
X-Wing on RSRA (1986)

The X-Wing concept, coupled with circulation control, was the subject of considerable R&D effort by the Navy and NASA. A flight demonstrator X-Wing was built and installed on the Rotor Systems Research Aircraft (RSRA) in the late 1980s. The program ran into a combination of practical issues that led to termination, the coupling of a difficult control requirement with the lack of budget. Electronic, pneumatic, aerodynamic, and structural solutions are required before that concept can be considered viable. Navy R&D work continues at a low level. (R. J. Huston, J. L. Jenkins, Jr, and J. L. Shipley, "The Rotor Systems Research Aircraft (RSRA)," AGARD Conference Proceedings No. 233, *Rotorcraft Design*, May 1977; and A. W. Linden and J. C. Biggers, "X-Wing Potential for Navy Applications, paper presented at the 41st Forum of the American Helicopter Society, May 1985.)

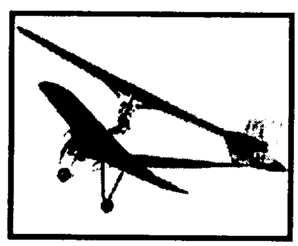
The Canard Rotor Wing (CRW) is basically a three surface airplane. The center surface operates either rotating or fixed. The CRW was tested in a Langley tunnel during 1993 and continues to be the subject of substantial industry R&D efforts.

Some external aerodynamic details need to be fixed inorder to approach excellent performance in both configurations. For example, both the X-wing and the CRW use airfoils with front-to-rear symmetry. Somehow, both ends of the airfoil must use some mechanism (mechanical or pneumatic) to obtain the full Kutta condition of smooth flow from the "trailing edge," no matter which way the external flow.

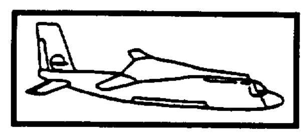
STOPPED ROTORS



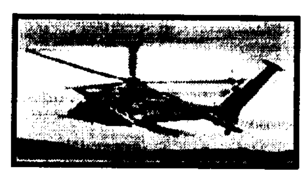
Canard Rotor Wing Concept (CRW)



Herrick HV-2A (1937)

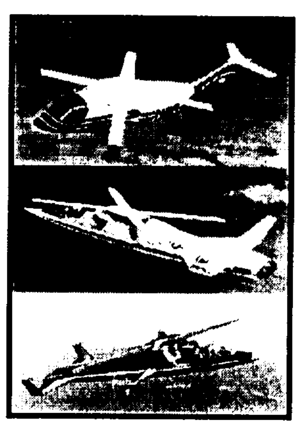


Rotor Wing Concept (1967)

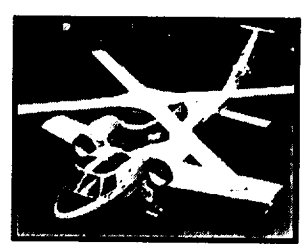


RSRA

Tunnel Tests (1993)



X-Wing Concepts

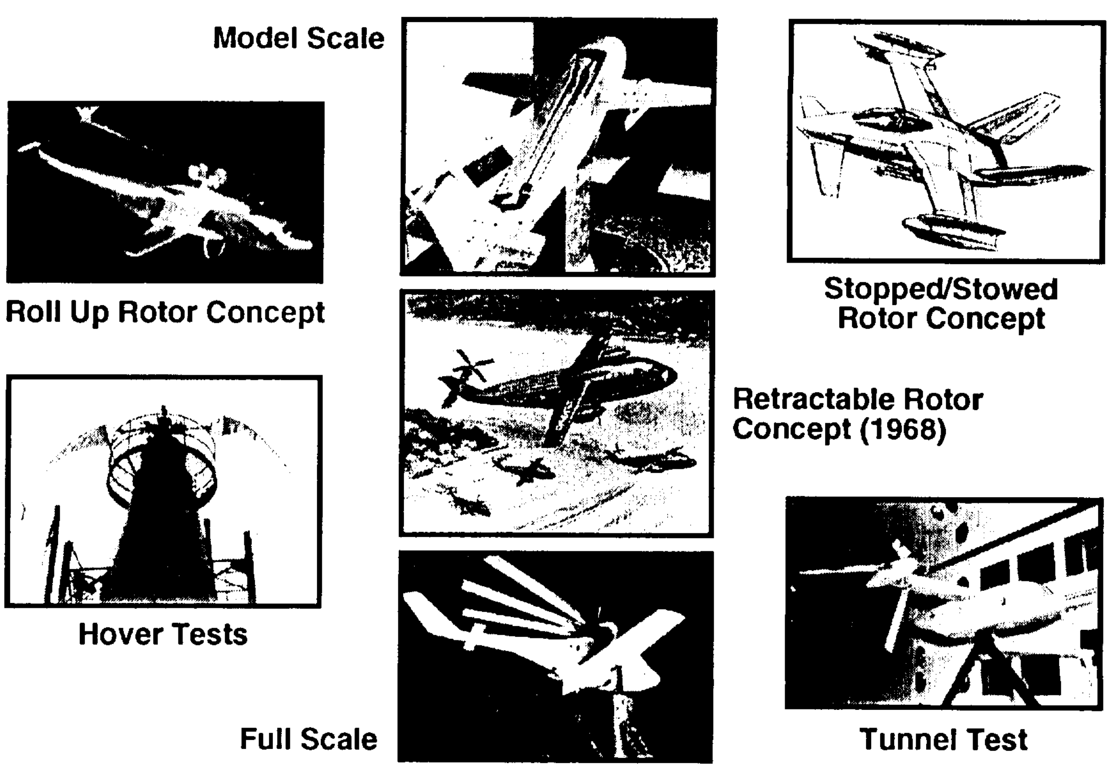


X-Wing on RSRA (1986)

In the quest for efficient hover performance *and* high speed flight, an alternative to stopping the rotor and using it as a wing is to vary the geometry of the rotor in-flight so as to remove it from the airflow. One concepts that would give that result is the "roll up" rotor. The rotor imitates a tape measure & is retracted into the hub.

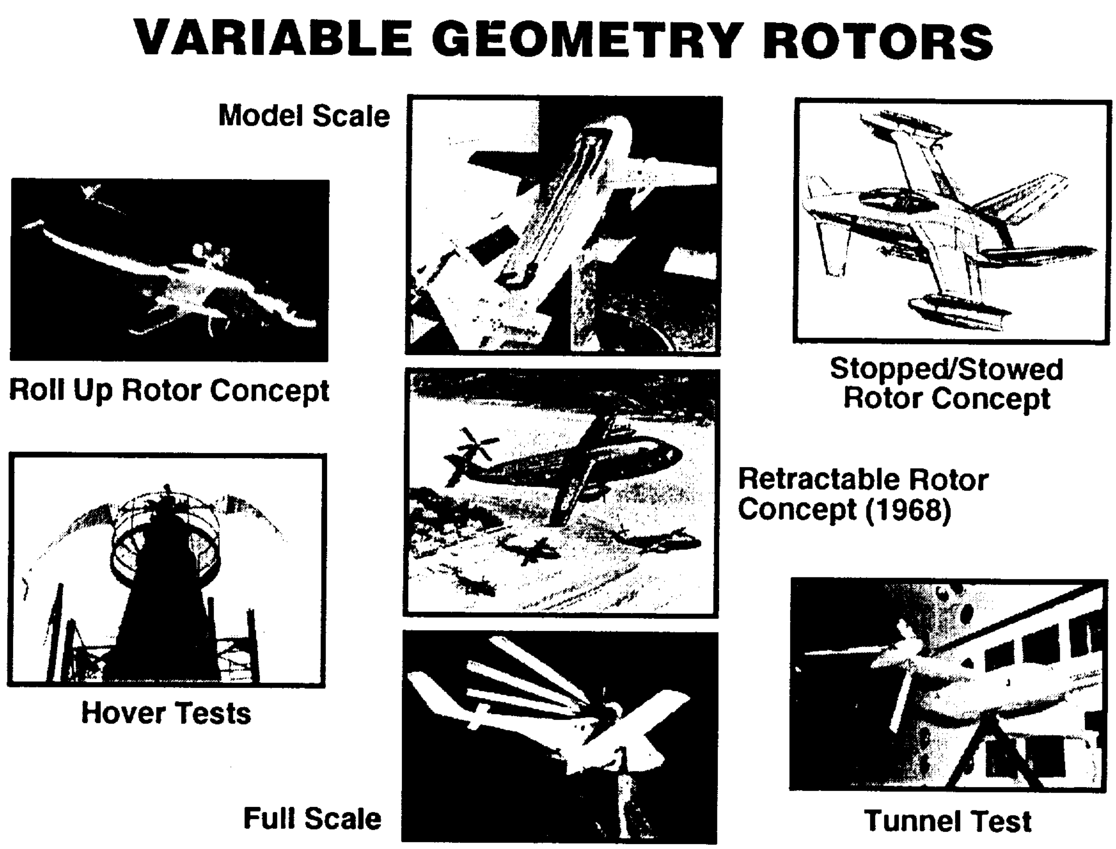
One approach to rolling up the rotor is nicknamed the "rag" rotor. Hovering test with a "rag" rotor were done at Langley in the late 1960s. The flexible rotor blade evaluated had a fabric airfoil surface fastened to cables (or flexible rods) at the leading and trailing edges. A tip weight with a stabilizer vane bridged the outboard end of the cables. The inboard end of the blade was connected to a collective pitch mechanism. The spanwise variation of the blade chord is in the shape of a catenary, so that the centrifugal force of the blade tip maintains the fabric in tension during rotation. Essentially, the blade has no static flapwise or torsional stiffness and the interaction of aerodynamic and centrifugal forces determine the behavior of the blade. The experimental limitation on the rotor was basically luffing, i.e., sail boat luffing. Analysis indicated that the most efficient way to eliminate luffing would be to add chordwise stiffeners (sail battens?) which would still permit the blade to be retracted. Research was halted at that point. However, adding battens opens the possibility of active control-smart structures battens which could control blade camber, local blade pitch and give excellent performance. A concept abandon becomes feasible again with 1990's technology. (M. M. Winston, "An Investigation of Extremely Flexible Rotors," NASA TND-4465, 1968 and "A Hovering Investigation of an Extremely Flexible Lifting Rotor," NASA TND-4820, 1968.)

VARIABLE GEOMETRY ROTORS



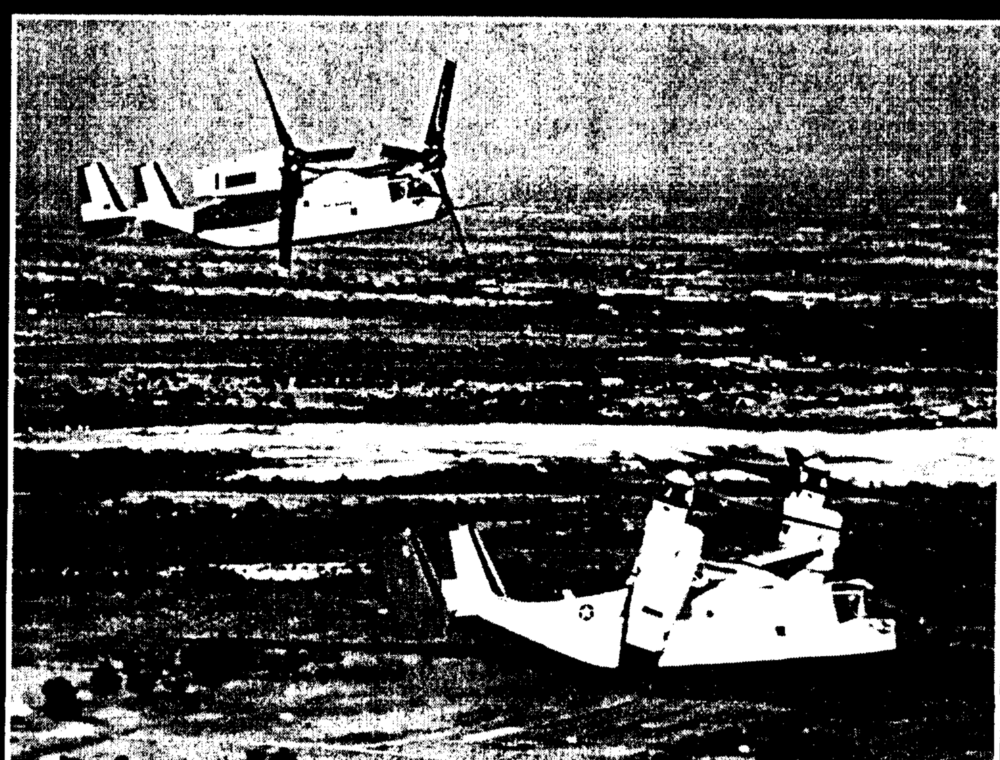
The remaining approaches to retracting and stowing a rotor have been well investigated over the years. Model and full scale tunnel tests of stopped rotor systems for compound helicopters and tiltrotor aircraft have been successful with no "show stoppers." Of the two concepts, the tiltrotor approach appears to be the most benign where the rotor is slowed and stopped, much like feathering a propeller, and then folded into a nacelle. The "horizontal rotor" stop and fold approach does have a variety of load variations that must to be successfully navigated. (W. D. Jepson and R. G. Carlson, "Wind Tunnel Investigation of a High Speed Stowed Rotor Aircraft," SAE Paper No. 680280, given at the SAE Air Transportation Meeting, 1968; and J. A. DeTore and T. M. Gaffey, "The Stopped-Rotor Variant of the Proprotor VTOL Aircraft," paper given at the AIAA/AHS/VTOL Research, Design and Operations Meeting, Feb. 1969.)

All convertible aircraft require a convertible engine. Dedicating an engine to only a single mode of flight is unacceptable. NASA recognized this years ago and built a convertible TF-34 engine. The process involved modifying a full scale engine to permit either jet power or shaft power extraction or suitable combinations of either. The convertible features of the modified engine were then demonstrated on a ground test stand. This technology is now on the shelf. (K. L. Abdalla and A. Brooks, "TF34 Convertible Engine System Technology Program," paper given at the 38th Forum of the American Helicopter Society, May, 1982; J. C. Gill and J. D. Sauer, "Convertible Engines for Fold Tilt Rotor Aircraft and ABC Rotorcraft," paper given at 38th Forum of the American Helicopter Society, May, 1982.)



The V-22 Osprey tiltrotor resulted from a long, unplanned, spasmodic process that reached maturity just as the USMC needed a CH-46 replacement. In December 1981, DOD set a requirement for a Joint Services Advanced Lift Aircraft (JVX) capable of multiple missions for the Army, Navy, USAF, Marine Corps and Special Operations Forces. Bell and Boeing formed a limited partnership in April 1982 and a $1.8 billion Navy fixed-price contract (for the Marine version only) was awarded Bell/Boeing on April 28, 1986 for six aircraft. An FAA/NASA/DOD study of the potential civil applications of tiltrotor technology concluded that "tiltrotors could capture 1/3 to 2/3 of the high-density, short-haul air traffic market." A potential market greater than 1400 aircraft was projected. On June 16, 1988, the FAA established a set of goals for vertiport development and certification, air traffic control modernization, and readiness for tiltrotor demonstrations and certification. On August 12, 1988, the Bell/Boeing team and Allison announced application for civil certification of the tiltrotor aircraft and engines, respectively. On March 19, 1989, the V-22 made its first hover. On April 25, 1989, the Secretary of Defense announced the V-22 program was to be cut from the 1990 budget. Congress keep the program alive until a new administration revived the program. A 4-ship Engineering Manufacturing Development contract was signed May 3, 1993 with the first EMD aircraft scheduled to fly in December 1996. A production commitment is expected early in 1996. (Boeing Commercial Airplane Company, "Civil Tiltrotor Missions and Applications: A Research Study for FAA/NASA/DOD," NASA CR 177452, Jul. 1987 and R. J. Huston, R. A. Golub, and J. C. Yu, "Noise Considerations for Tiltrotor," AIAA Paper No. 89-2359, Jul. 1989.)

V-22 OSPREY TILTROTOR



"The case for the convertible rotor" was made by Raoul Hafner 25 years ago. In his technical, economic and social study of European transportation, he found a short haul VTOL system to have the capability to take over significant portions of both rail and conventional airline traffic, as long as its primary operation was separate from CTOL airports and with independent VTOL ports and air traffic control systems. The "convertible rotor" in his analysis was an auto stabilized tiltrotor.

The 1991 US. National Transport Policy assessment found that 21 primary airports currently experience more than 20,000 hours of delay per year. The airlines cost for these delays is about $5 billion per year. A twelve urban-vertiport network in the NE Corridor, and the 165 tiltrotor aircraft to serve it, would cost ~ $4-6 billion and serve 12 million passenger per year. With tiltrotor transports carrying short haul passengers, the primary airports will eliminate delays due to airport capacity, a few long haul transports carrying a large number of people will substitute for large number of short haul transports carrying a few people. This is possible because, on average, commuter airplanes typically account for 30 percent of the airport usage while carrying 5 percent of the passengers. ***The tiltrotor has dual use potential.***

(NASA/FAA Study of Commercial Tiltrotor Missions and Applications, Feb. 1991; and Massachusetts Institute of Technology, *Strategic Policy Development for Short Haul Intercity Transport: The Case of Tiltrotor vs. Maglev,* Cambridge, MA Jan. 1990; and Office of Technical Assessment, *New Ways, Tiltrotor Aircraft and Maglev Vehicles,* Washington, D. C., October 1991 report to Congress.)

"DUAL-USE" POTENTIAL OF THE MILITARY TILTROTOR

- **U.S. National Transportation Policy assessment of airport congestion**
  - **Twenty-one primary airports now experience more than 20,000 hours of annual delays**
  - **Cost to airlines and U.S. business exceed $5 billion yearly**
- **For half of the $4 to $6 billion cost of a single new airport**
  - **Entire network of 12 urban vertiports**
  - **Including 165 40-seat tiltrotor aircraft**
  - **"Could be installed in the congested corridor between Boston and Washington, D.C., serving 12 million passengers per year"***

****Source: NASA/FAA Study of Commercial Tiltrotor Missions and Applications, February 1991***

The NASA/FAA study that determined that tiltrotors could capture 1/3 to 2/3 of the high-density, short-haul air traffic market, also identified the international passenger demand for 40-passenger tiltrotor aircraft by world region. A 1990 business analysis performed for the Department of Commence projected that the first decade of a civil tiltrotor program would produce:

20,000 direct jobs in the United States,
190,000 indirect jobs in the United States,
$20 billion in increased exports, and
$125 billion increase in national economic activity.

(N. Augustine, *Report on Civil Tiltrotor to Federal Aviation Administration*, Washington, D.C., Jun. 1990; and Bell/Boeing/NASA Ames Research Center, *Civil Tiltrotor Missions and Applications Phase II: The Commercial Passenger Market - Final Report*, Seattle, WA, NASA CR 177576, Feb. 1991; Transportation Systems Center, *Civil Tiltrotor Industrial Base Impact Study*, Department of Commerce Study, Cambridge, MA, Apr. 1988; and Hoyle, Tanner & Associates, *CTR Aircraft Feasibility Study for State of California*,, Londonderry, NH, Sep. 1989; Pacific Basin Development Council, *Study of Commercial Feasibility of Tiltrotor/VTOL Technology in U.S. Pacific Insular Areas*, Honolulu, Jun. 1989;and DOT/FAA/AOR-100/93/013, Civil Tiltrotor Northeast Corridor Delay Analysis, Jun. 1994)

ECONOMICAL IMPACT OF CIVIL TILTROTOR

	Region	Number of Aircraft
Year 2000 Market Demand for a 40-seat Civil Tiltrotor* (Passenger Service Only)	North America	1,270
	Europe	615
	Oceania	240
	Japan	500
	Total	2,625

**Source: NASA/FAA Study of Commercial Tiltrotor Missions and Applications, February 1991*

As a result of the many favorable studies indicating the dual use potential of tiltrotor technology, NASA has established a **Short Haul Civil Tiltrotor** (SHCT) Program, essentially level funded for 8 years, with the LONG TERM GOAL of creating by 2010, a $5 - $7 billion per year new **civil tiltrotor aircraft market** while off loading major airports of a large portion of the short haul traffic.

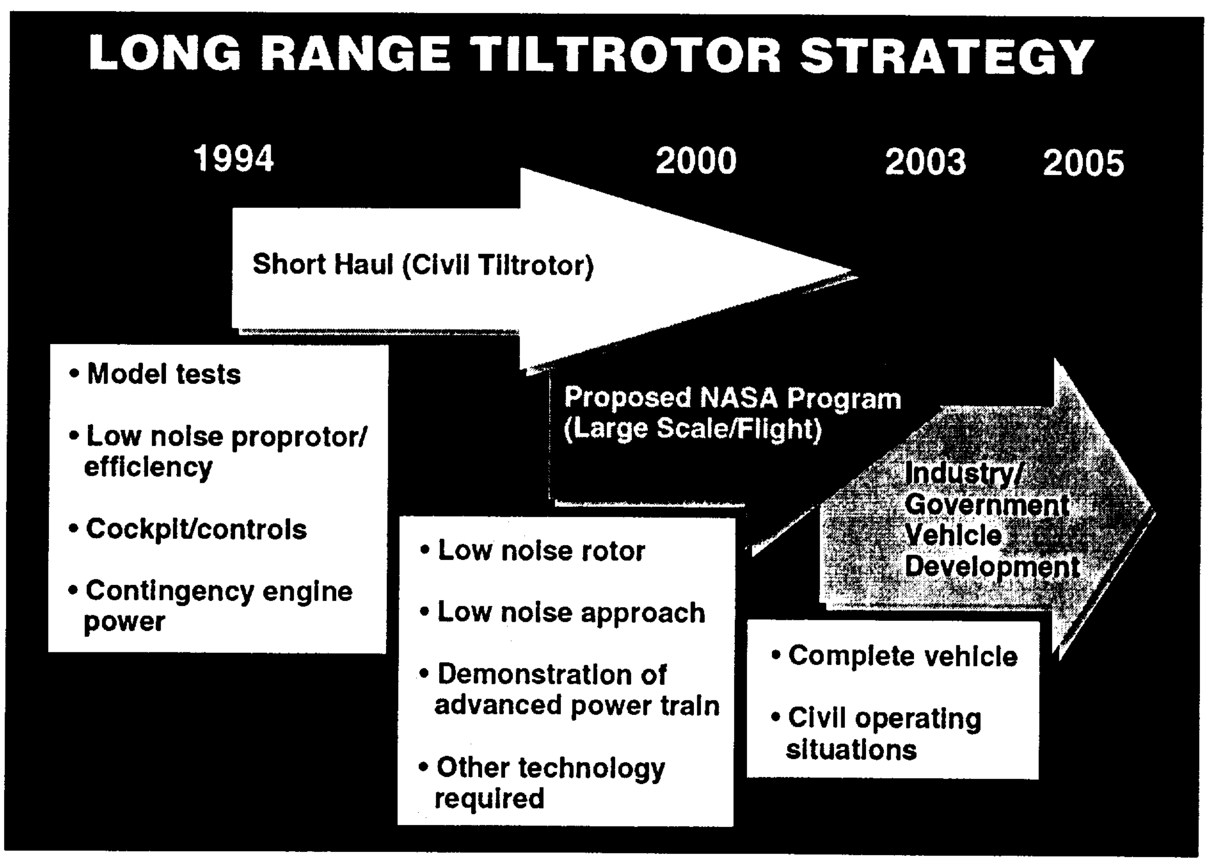
The **near term objectives** (by 2001) are:

To develop the critical technologies for **reducing rotor noise for a tiltrotor** by 6 dB A relative to current technology while maintaining efficient performance and loads.

To develop the operating procedures and critical cockpit technologies for executing safe (Level 1 Handling Qualities), efficient, **low noise (6 dB A reduction) terminal area approaches** to all weather conditions.

To develop and demonstrate the critical technology for providing **contingency power** for tiltrotor engines (in lieu of excessive installed power) to achieve cost effective One Engine Inoperative (OEI) tiltrotor operation in all flight conditions.

To define and analyze the design characteristics of a notional advanced civil tiltrotor that **integrates technology from** SHCT and other sources and which will serve as point design for market, economic, and feasibility studies for both government and industry.



A short haul civil tiltrotor infrastructure will involve: multiple intermodel vertiports chosen to complement existing road, light rail, subway and long haul air services while minimizing approach and take-off noise; an air traffic management system tailored to permit vertiport access independent of CTOL airport traffic; secure ground facilities capable of providing normal passenger support functions as well as support of vertiport operational personnel; and support of tiltrotor and helicopter aircraft and air crews.

Vertiports will add a new dimension in transportation. Selection of sites will provide strong economic stimulus for adjacent business growth and even housing. Low noise tiltrotors and helicopters ***will be*** "good neighbors." New jobs will be generated. Individuals will evidence pride in a community that moves forward as world leaders in aviation.

(Hoyle, Tanner & Associates, *VTOL Intercity Feasibility - Executive Summary for Port Authority NY & NJ*, Londonderry, NH, Jun. 1987)

Conclusions and Observations about The Future of Rotorcraft.

Rotary wing aircraft will exist in many forms in the future. The range of uses will continue to increase. The number of helicopters will increase and civil tiltrotors will become familiar in both military and civilian applications. External forces will act to push down the cost of design, manufacture, and operation of rotary wing aircraft.

Many "lifting" jobs will continue to be done by a helicopter because they can not be done by anything else at a reasonable price. The low-disk-loading helicopter will continue to be the most efficient vehicle for operations into restricted areas and for low speed flight involving hover until "anti-gravity" is a reality. The laws of physics have not yet been repealed.

Helicopters and tiltrotor aircraft (and perhaps even some higher disk loading VTOL aircraft) will compete with fixed wing aircraft in short haul passenger systems when the "real cost" of the overall systems is recognized in the accounting.

Once tiltrotor vehicles become routine, some one will stop and fold the rotor (or just reel it in) and the aircraft, at the same power level, will gain 100 knots. A new revolution in transportation will begin.

The march of technology will not leave rotary wing vehicles behind. Generic technology advances in electronics, aerodynamics, propulsion, power, structures and so forth, will be integrated into the latest rotary wing designs.

The revolution in low cost electronics, coupled with the Global Positioning Satellite System, offers a promise that cost will also decrease. When the reliability of electronics system is acceptable, automated flight control and navigation systems will permit push-button personal travel from grandmother's house to urban neighborhoods by low-cost rotary wing vehicles. When fuel cell technology permits the development of hypercars, visionaries will apply fuel cells to rotary wing vehicles.

(AUTHOR'S NOTE: The paragraphs of this paper include a brief history of the development of the helicopter to the current level of technology. The selection of pioneers and specific aircraft to emphasis are the sole responsibility of the author. Everyone in the business will recognize that I have left out major players, innovative technology, and major elements of the story.)