An Overview of the History of Vertical and/or Short Take-Off and Landing (V/STOL) Aircraft

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V/STOL Wheel of Mis-Fortune

V/STOL Aircraft and Propulsion Concepts

Depicted here are the various types of Vertical and Short Take-Off and Landing (V/STOL) aircraft which have been tested over the past 45 years. All were built to be flown, but only three (shown in bold) have led to operational aircraft. In fact, the Harrier is the only V/STOL aircraft in service today.

The Joint Strike Fighter concept demonstrators (shown in blue), are scheduled to fly in 2000; one of these concepts will serve as the basis for development of an aircraft to replace the Harrier.
V/STOL Jet Wheel
The Quest for Supersonic V/STOL

Planned vs achieved maximum speed (clean) for V/STOL fighter aircraft

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V/STOL Considerations

• Balance
  – Thrust and cg
• Control
  – Yaw, pitch, roll
  – Hover, transition, cruise
• Propulsion System
  – Volume, development cost/time, thrust matching
• Human Factors
  – Pilot workload, orientation, noise
• Environmental
  – Hot gas re-ingestion, footprint
V/STOL Wheel of Mis-Fortune

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Same Propulsion System for Hover and Forward Flight

- Uses a single propulsion system
- Alters the direction of thrust for hover or cruise
- Can also alter the attitude of the aircraft itself
Tilt Shaft/Rotor

- Rotating blades function like rotors in vertical flight, like propellers in forward flight
- Rotors are long articulated blades
- Blades have cyclic pitch control for hover
- Power plants remain stationary
- Power shaft pivots from vertical to horizontal

Same Propulsion System for Hover and Forward Flight
1. Transcendental Model 1G

- Powered by a single 160 hp Lycoming O-290-A engine
- Three bladed 17 ft rotors
- Manual two speed reduction box
- Rotor speed
  - Hover: 240 rpm
  - Horizontal Flight: 633 rpm
- Three concentric shafts controlled tilt angle, cyclic pitch and collective pitch
- Suffered from dynamic stability problems
- Required three minutes to transition 82° during conversion

**Flight Milestones**

- 6 July 1954 - First vertical flight
- December 1954 - First horizontal flight
- 1957 - Testing concluded
- Model 1G flew over 100 flights and logged 20 hours of flight time
2. Bell XV-3

- Powered by a 450 hp P&W R-985 radial engine
- Single 24 ft two-bladed semi-rigid rotor
- Manual two-speed gear box similar to Transcendental 1G
- Three-bladed rotor instability led to a two bladed design
- Conversion over the full 90° could be conducted in 10 seconds
- Significant manipulation of pitch and throttle controls required during conversion
- Inadequate power and high weight growth precluded the XV-3 from hovering out of ground effect

Flight Milestones
- August 1955 - First vertical flight
- 18 December 1958 - Full conversion by second prototype
- 1965 - Damaged in wind tunnel test
- Made over 250 flights including 110 full conversions
Tilt Prop

- Uses propellers instead of rotors
  - Has collective but no cyclic pitch control
  - Has short, rigid blades
  - Has a high degree of twist
3. Curtiss-Wright X-100

- Powered by an 860 bhp Lycoming YT53-L-1 mounted on the fuselage
- Two 10 ft diameter tilting fiberglass propellers on the wingtips
- Engine exhaust at the rear of fuselage was used for pitch and yaw control in hover
- Roll control provided by differential propeller pitch
- Used to prove the Tilt Prop concept for use on the Curtiss-Wright X-19
- Used “radial force” instead of wing lift for conventional flight
- Control in hover was weak due to low exhaust gas velocity

**Flight Milestones**
- September 1959 - First vertical flight
- March 1960 - First short take-off
- April 1960 - First and only conversion
- October 1961 - Testing concluded
4. Curtiss-Wright X-19

- Originally civil executive transport
- Powered by two 2,650 shp Lycoming T55-L-7 turboshaft engines
- Two tandem wings with a three-bladed 13 ft, wide chord, high twist propeller at each end
- Diagonally opposed propellers rotated in same direction to eliminate gyroscopic and torque effects
- Roll, pitch and yaw were controlled by differential propeller pitch
- Plagued by control system and other mechanical problems

Flight Milestones
- 20 November 1963 - First vertical flight
- 25 August 1965 - Crash due to transmission failure
- Made over 50 flights but logged only 4 hours of flight time
Tilt Ducts

- Ducts can increase propeller thrust by as much as 50% due to Bernoulli Effect
- Ducts provide additional lift during forward flight
- Propeller pitch and deflector vanes in downwash control aircraft in hover and transition

Same Propulsion System for Hover and Forward Flight
5. Doak 16 VZ-4

- Powered by a single 860 bhp Lycoming YT53 engine
- One 4 ft eight-bladed tilting duct propeller on each wing-tip
- Transition from hover to 200 kt could be performed in less than 20 seconds
- Variable inlet guide vanes used for roll control in hover
- Engine exhaust gases deflected at fuselage rear for pitch and yaw control
- Deceleration and descent had to be carefully controlled to prevent duct lip from stalling
- Suffered from lack of control power

Flight Milestones
- 1957 - Aircraft is built
- 15 February 1958 - First flight
- Completed over 50 hours of testing proving tilt duct concept
6. Bell X-22A

- Powered by four cross-linked 1,250 shp GE YT58-GE-8D turboshift engines
- The engines had 35% excess power in case one engine failed in hover
- Four 7 ft diameter three-bladed ducted propellers
- The ducts rotated non-differentially from 0° to 95°
- Hover control was possible through differential propeller pitch
- The propeller ducts provided a significant amount of aerodynamic lift during forward flight
- Maximum speed was 315 mph
- Limited payload and range
- V/STOL testbed until 1980

Flight Milestones
- March 1966 - First vertical flight
- January 1967 - Second prototype performed complete transitions
- 20 July 1968 - Set record for hovering at altitude of 8,000 ft
- Flew until 1980 and logged about 200 hours of flight time
7. Nord 500 Cadet

- Design and built by the French Nord company (later part of Aérospatiale)
- Powered by two 317 shp Allison T63-A-5A engines
- Used two large five-bladed duct propellers
- Four control vanes in a diamond shape controlled yaw (differentially) and pitch (collectively)
- This configuration selected to try to expand airflow in hover and compress it during horizontal flight
- The project was cancelled without further testing after July 1968

**Flight Milestones**

- 23 July 1968 - Second aircraft makes tethered hover
- Program cancelled without further testing
Tilt Wing

- Tilting entire wing
  - Increased aerodynamic flow over lifting and control surfaces during transition
  - Minimizes lift loss due to downwash in hover

- Additional method of control during hover is required
  - Tail jet
  - Tail rotor

- Ailerons change from roll control in forward flight to yaw control in hover

- During hover control is difficult in wind gusts due to “barn door effect” of wing in the vertical position

Same Propulsion System for Hover and Forward Flight
8. Vertol 76 VZ-2

- Powered by a single 860 hp Lycoming YT53-L-1 engine
- Two 9.5 ft three bladed propellers power by a cross shaft through the wings
- Fuselage was built of metal tube construction
- Used a two seat helicopter-like cockpit
- In hover, pitch and yaw control provided by two ducted propellers in the tail
- Aerodynamic controls were phased in during transition until the tail propellers were no longer needed for horizontal flight
- Poor control power

**Flight Milestones**
- 13 August 1957 - First vertical flight
- 7 January 1958 - First horizontal flight
- 15 July 1958 - First conversions
- 1965 - Testing concluded
- Made over 450 flights and 34 conversions
9. Hiller X-18

- Powered by two wing-mounted 7,100 eshp Allison T40-A-14 turboshaft engines
- Pitch control thrust provided by one Westinghouse J34 turbojet
- Was able to complete only partial conversions with wing angles up to 33°
- Grounded after 20th flight due to propeller pitch control problem
- Continued to test ground effects before it was damaged in a test stand failure
- Turboprop engine electric pitch control too slow for hover control
- Never achieved hover flight

Flight Milestones
- December 1958 - extensive ground testing of loaded aircraft
- 24 November 1959 - first conventional flight
- Never completed full conversion to hover flight
10. LTV-Hiller-Ryan XC-142

- Powered by four-cross linked 3,080 shp GE T64-GE-1 engines
- Four 15.5 ft diameter four-bladed propellers
- Roll was controlled by differential propeller pitch
- Pitch was controlled by an 8 ft three-bladed variable pitch tail rotor
- Yaw was controlled by ailerons powered by propeller slipstream
- Suffered from excessive vibration and noise, resulting in high pilot workload as well as cross-shaft and gear box failures due to wing flexing

Flight Milestones
- 29 September 1964 - First conventional flight
- 29 December 1964 - First vertical flight
- 11 January 1965 - First complete transition
- Logged 420 flight hours with 39 different pilots
11. Canadair CL-84 Dynavert

- Powered by two wing-mounted 1450 shp Lycoming T53-LTC1K-4A turboprop engines
- Two cross-linked 14 ft four-bladed propellers
- Pitch control provided by two counter-rotating two-bladed horizontal propellers
- Roll control provided by differential propeller pitch
- Yaw control provided by the ailerons
- Extensively evaluated, including demonstrations on amphibious ships and the Pentagon helipad
- Two test aircraft destroyed

Flight Milestones
- May 1965 - First vertical flight
- December 1965 - First conventional flight
- Cancelled due to lack of interest by the government
Tilt Rotor / Tilt Jet

**Tilt Rotor**
- Aircraft tilts the rotor for transition from vertical to horizontal flight
- Like Tilt Wing, the engines tilt together with the rotors

**Tilt Jet**
- Like Tilt Rotor but jet engine powered
- The entire propulsion system rotates from vertical for hover to horizontal for conventional flight
12. Bell XV-15

- Powered by two 1,550 shp Lycoming T53-LTC1K-4K turboshift engines
- Two 25 ft diameter three-bladed rotors
- Engines and rotors were cross linked and tilted through 90°
- Low speed control by cyclic and collective blade angle adjustments
- Conducted extensive tests:
  - Shipboard Landings (USS Tripoli)
  - Dive tests (397 mph)
- This aircraft was tested extensively in the wind tunnel
- Led to Bell Boeing V-22 and Bell 609

**Flight Milestones**

- 3 May 1977 - First vertical flight
- 24 July 1979 - First complete transition
- By 1986 - Had completed 1,500 transitions and logged 530 flight hours
13. Bell Boeing V-22 Osprey

- Powered by two wing tip mounted Allison T406-AD-400 engines
- The engines are cross-shafted and rated at 6,140 shp for take-off
- Two 38 ft three bladed rotors
- A total of 523 aircraft will be built for the Marine Corps, Navy and Air Force
- Can carry 24 troops or 864 cubic feet of cargo
- Normal take-off weight 47,500 lb
- Combat range 600 miles
- Maximum ferry range 2,400 miles
- Maximum speed 400 mph
- Only V/STOL transport aircraft in production

Flight Milestones
- 19 March 1989 - First flight
- 14 September 1989 - First transition
- By the end of 1996 it had over 1,100 hours of flight testing
- 5 February 1997 - First “production representative” aircraft flight
14. Bell 65 Air Test Vehicle (ATV)

- Assembled from parts of existing commercial aircraft
- Powered by two 1,000 lb Fairchild J-44 missile turbojet engines mounted on each side of the aircraft
- Engines could be tilted from vertical to horizontal
- Hover control was provided by Turbomeca Palouste turbo-compressor reaction jets at the wing tips
- Had inadequate thrust to complete transition from vertical to horizontal flight
- Cancelled in favor of the Bell X-14 project

**Flight Milestones**

- 16 November 1954 - First vertical flight
- 1955 - First horizontal flight
- 1955 - Program cancelled by Bell
Deflected Slipstream

- The propeller slipstream is deflected 90° downward with trailing flaps which form a “bucket”
- The deflected propeller thrust is used for lift

Same Propulsion System for Hover and Forward Flight
15. Robertson VTOL

- Powered by two supercharged 340 hp Lycoming GSO-480 engines
- Wing had a sliding flap system with a double-slotted full span trailing edge flap providing all control
- Flaps were retracted into low aspect ratio wing for horizontal flight
- All fuel and oil stored in wing tip tanks which acted as endplates
- Tanks capped the wing “buckets” theoretically improving efficiency
- Further aircraft development not pursued

Flight Milestones
- October 1956 - Robertson Aircraft Corporation is formed
- 8 January 1957 - Aircraft makes only tethered flight
16. Ryan 92 VZ-3 Vertiplane

- Powered by a 1,000 shp Lycoming T53-L-1 turboshaft engine
- One metal three-bladed Harzell propeller on each side
- Propellers were ahead and below wing so the produced slip-stream flowed directly into the bucket formed by extended double flaps and deflected downwards for lift
- Differential propeller pitch was used for roll control
- Engine exhaust at tail was used for pitch and yaw control until tail surfaces could be effective
- Engines failed to provide sufficient thrust to hover without a headwind

Flight Milestones
- 21 January 1959 - First flight
- February 1959 - Grounded by a flight accident
- February 1960 - NASA test flights
- Continued flying until 1961 - Testing low-speed V/STOL handling characteristics
17. Fairchild 224 VZ-5 Fledgling

- Powered by one 1,024 shp General Electric YT58-GE-2 turboshaft engine
- Four three bladed Harzell metal propellers
- Aircraft could rest on two main wheels and tail skid, providing 30° of inherent rotation to enhance the bucket’s effectiveness
- Small rotors at the top of T-tail controlled pitch during hover
- Aircraft never flew

Flight Milestones

- Late 1959 - Tether tests conducted
Vectored Thrust

- The jet engine exhaust is vectored to create a vertical or horizontal motion
18. Bell X-14

- Built from Beech T-34 fuselage and tail, Bonanza wing
- Powered by two ASV8 Viper engines
- Used a planar array of diverter vanes to vector the engine exhaust
- Reaction control jets on wings and tail
- Eventually was fitted with a digital fly-by-wire control system
- Lack of ejection seat limited hover testing to very low and very high altitudes
- The discovery of the suckdown phenomenon led to lengthening of the landing gear
- Served as a V/STOL testbed until 1981

Flight Milestones
- 17 February 1957 - First vertical flight
- 24 May 1958 - First transition
- 1960 - More powerful GE J85 engines installed and transferred to NASA
19. Hawker P.1127 Kestrel

- P.1127 powered by one 11,000 lb thrust Bristol Pegasus 2 engine
- Bifurcated jetpipe and vectoring front and rear nozzles
- Control power was low which combined with suck down resulted in high pilot work load
- Hot gas ingestion problem was overcome with a low forward speed in takeoff and landing
- A tripartite program involving the UK, US and Germany funded nine improved Kestrels with a 15,500 lb Pegasus 5 engine
- The Kestrel paved the way for the Harrier

**Flight Milestones**
- 19 November 1960 - First vertical flight
- 7 July 1962 - First conventional flight
- 12 September 1962 - First double transition
- 1962 - Tripartite program initiated
20. Yakovlev Yak-36 Freehand

- Powered by two non-afterburning Soyuz Tumanskiy/Khatchaturov R27-300 turbojet engines (13,000 lb)
- Engines were fitted with louvered nozzles which were vectorable through 90° and exhausted at the center of gravity (c.g.)
- Engine bleed air was used for reaction control at the wingtips, tailcone and the tip of nose “probe”
- Retractable doors reduced hot gas reingestion
- Only capable of vertical take-offs and landings
- This technology demonstrator led to the Yak-38 Forger

**Flight Milestones**
- 9 January 1963 - First vertical flight
- 16 September 1963 - First transition to horizontal flight
- 7 July 1967 - First public display at the Domodedovo Air Show
21. British Aerospace / Boeing Harrier

- Follow-on to the Hawker Kestrel
- Operated by the USMC, UK RAF and RN, Spain, Italy, India and Thailand
- UK RAF version powered by 19,000 lb Pegasus Mk 101
- USMC AV-8A powered by the 21,500 lb Pegasus 11
- AV-8B Harrier II has a more powerful engine (23,800 lb), a larger composite supercritical wing and optimized Lift Improvement Devices (LIDs)
- The Harrier II has double the payload and range when making short takeoffs
- Only V/STOL aircraft in service

**Flight Milestones**

- 31 August 1966 - First flight for production designed aircraft
- 1 April 1969 - Enters service with UK RAF
- 1969 - USMC purchase first AV-8A
- 1974 - McDonnell Douglas begins development of AV-8B Harrier II
- 1978 - First flight of the Sea Harrier
22. Boeing X-32B

- The X-32 is a concept demonstrator for the Joint Strike Fighter (JSF) program
- Powered by a derivative of the Pratt & Whitney F119 engine with Rolls-Royce lift components
- In short take-off and landing mode the engine closes the vectorable cruise nozzle and opens two lift nozzles at the aircraft c.g.
- The X-32 has a chin inlet and blended delta wing

Flight Milestones
- 1994 - ASTOVL contract awarded
- 1995 - 94% scale model of the P&W YF119 was tested
- 1996 - Selection as JSF demonstrator
- 2001 - First flight of prototype
Tail Sitters

- Entire aircraft points straight up
- The entire thrust of propulsion system is converted directly to vertical lift
- Easy to take-off in vertical direction
- Considerably more difficult to land facing in the opposite direction of aircraft travel

Same Propulsion System for Hover and Forward Flight
23. Lockheed XFV-1

- Powered by two 5,500 eshp Allison YT40-A-14 engines
- Two 16 ft counter-rotating three-bladed Curtiss-Wright propellers with electric pitch control
- Hover control was by the same large aerodynamic surfaces used in level flight, as each was bathed in propeller slipstream
- The “X” shaped tail arrangement minimized downwash masking
- Control in hover was very weak, and the pilot had difficulty in determining sink, climb, and rotation from normal visual cues
- No vertical take-off or landings attempted

Flight Milestones
- March 1954 - Aircraft fitted with conventional landing gear and made first flight
- 27 conventional flights were made
- Complete transitions completed above 1,000 ft
24. Convair XFY-1 Pogo

- Similar to the Lockheed XFV-1
- Powered by one Allison YT40-A-14 engine
- Used two Curtiss-Wright counter-rotating three blade propellers
- Control in hover for the XFY-1 were the same as for conventional flight, but provided only limited control power
- The seat was inclined 45° toward the instrument panel for vertical flight
- Ventral fin below wing could be jettisoned for emergency horizontal landing
- The engine and control systems were considered inadequate

**Flight Milestones**

- April 1954 - First tethered flight
- 1 August 1954 - First free vertical flight
- 2 November 1954 - First transition
- November 1956 - Last flight
25. Ryan X-13 Vertijet

- This aircraft had a short pole ending in a hook under the nose
- The hook was used to capture a wire on a vertical trailer bed
- The trailer could be lowered for ground transport
- Engine thrust was vectored to provide pitch and yaw control in hover
- Roll control was provided by puffer jets at the wing tips
- The first prototype was fitted with conventional landing gear and made full transitions
- The Air Force did not continue development because of the lack of an operational requirement

Flight Milestones

- 10 December 1955 - First prototype makes horizontal flight
- 11 April 1957 - Second prototype makes vertical take off, transition, and vertical landing using the hook system
26. SNECMA C450 Coléoptère

- Powered by a 7,700 lb Atar 101E turbojet
- Four small fins were mounted on the 10.5 ft diameter annular wing
- Hover control provided by tilting vanes in the nozzle
- In forward flight, the small fins deflected the air for control
- Two small nose strakes were extended to facilitate a pitch up moment in transition to vertical flight
- The Coléoptère never achieved transition
- The program was cancelled because of an increased emphasis on air superiority and attack roles

**Flight Milestones**

- 17 April 1959 - First tethered hover
- 3 May 1959 - First untethered hover
- 25 July 1959 - Aircraft falls into oscillations about all three axis and crashes while attempting to transition from hover at 2,000 ft
Separate Power Plant for Hover

• Used two separate groups of power plants
  – One for hover
  – One for cruise
Lift + Cruise

- Used vertically-mounted lift engines for hover
  - Optimized to produce a large amount of thrust for a short duration
  - Used only for take-off and landing
27. Short SC.1

- Four 2,130 lb Rolls-Royce RB.108 lift engines mounted on gimbals in the center fuselage
- One 2,130 lb Rolls-Royce RB.108 cruise engine in the rear of aircraft
- The hover engines were started by ground carts for take-off or by cruise engine bleed air in flight
- Bleed air from the four lift engines, tail and wing tip reaction jets were used for control at low speeds
- Experienced typical suck-down and hot-gas ingestion problems
- Pilot work load very high during landing
- High fuel consumption by lift engines

Flight Milestones
- 2 April 1957 - First CTOL flight
- 26 May 1958 - First tethered flight
- 25 October 1958 - First vertical flight
- 6 April 1960 - First transition
- Flew until 1967
28. Dassault Balzac V

- Built by the French Dassault company
- Eight 2,130 lb Rolls-Royce RB.108 engines for vertical flight
- One 4,850 lb Bristol Orpheus engine for cruise
- Lift engines were separated by main landing gear to balance center of gravity
- Each engine lift pair shared an inlet door and exhaust door
- 50% scale (by weight) demonstrator for Mirage III-V
- During transition all the lift engine doors created high drag
- Resulted in two fatal accidents and was subsequently cancelled

**Flight Milestones**
- 12 October 1962 - First tethered flight
- 18 October 1962 - First free vertical flight
- 1 March 1963 - First conventional flight
29. Dassault Mirage III V

- Built by the French Dassault company
- Eight 5,400 lb RB.162-31 lift engines
- One 18,250 lb P&W TF30 cruise engine
- Hover control was achieved through control jets in nose, tail and wing tips
- Fastest V/STOL aircraft in the world, achieving Mach 2.04
- Large number of engines reduced significantly internal fuel capacity
- There was no room for any useful payload on this aircraft

**Flight Milestones**

- 12 February 1965 - First vertical flight
- March 1966 - First complete transition to horizontal flight
- 12 September 1966 - Achieves record speed of Mach 2.04
Combined Power Plant for Hover

- Used main propulsion system for both hover and cruise
- An additional propulsion system was used for additional hover thrust
Lift Plus Lift/Cruise

- One set of engines for lift only
- Additional set of engines for both lift and cruise
30. EWR VJ101C

- Produced by the German EWR (Messerschmitt, Heinkel, and Bölkow)
- Powered by six 2750 lb Rolls-Royce/MTU RB.145 turbojet engines
- Two engines mounted in tandem aft of cockpit
- Four engines in pairs in wingtip swiveling nacelles
- No reaction control system
- First supersonic V/STOL aircraft
- Suffered from high temperature and erosion issues
- Crashed due to significant power loss from hot-gas ingestion
- The follow-on, VJ101D, was very complex and cancelled

Flight Milestones

- 10 April 1963 - First vertical flight
- 31 August 1963 - First horizontal takeoff
- 20 September 1963 - First double transition
- July 1964 - Aircraft breaks the sound barrier in a shallow dive without afterburner
31. Dornier Do 31

- Used two 15,500 lb Bristol Pegasus 5-2 engines for cruise and hover with 30° forward and 80° back vectored thrust
- Used eight 4,400 lb Rolls-Royce RB.162-4D engines for hover with 15° forward and backward vectoring for take-off and landing
- Roll and yaw control was achieved with differential vectoring and thrust levels
- Pitch control was achieved with a puffer jet in the tail
- Engine pod high drag and weight reduced the useful payload and range

Flight Milestones

- 10 February 1967 - First conventional flight
- 22 November 1967 - First vertical flight
- 16 December 1967 - First transition from vertical
- 22 December 1967 - First transition to vertical
- April 1970 - Project was cancelled
32. Lockheed XV-4B Hummingbird II

- Was a modified Lockheed XV-4A Hummingbird
- Four 3,000 lb General Electric J85-GE-19 lift engines
- Two 3,000 lb GE J85-GE-19 for lift/cruise flight
- During hover, large diverter valves directed the cruise engine exhaust to a nozzle between the lift engines for additional vertical thrust
- In transition, one lift/cruise engine was diverted to forward flight
- Pitch and yaw jets at the nose and tail provided hover control
- The Hummingbird II had a fly-by-wire autostabilization system
- The aircraft never achieved hover

Flight Milestones
- 1964 - XV-4A cancelled and XV-4B program initiated
- 4 June 1968 - XV-4B is rolled out
- 14 March 1969 - Aircraft crashed during a conventional flight
33. VFW VAK 191B

- Two 6,000 lb Rolls-Royce/MTU RB.162-81 lift engines one mounted directly behind the cockpit and one aft of the wing
- One 16,163 lb Rolls-Royce RB.193-12 vectored thrust turbofan mounted between the lift engines
- The RB.193-12 was a smaller version of the Bristol Pegasus engine used with the Kestrel/Harrier
- The program was intended to develop a high-speed V/STOL strike aircraft
- Was cancelled due to a change in NATO strategy
- Small wing gave it very poor transition characteristics

Flight Milestones
- 10 September 1971 - First untethered hovering flight
- 26 October 1972 - First transition achieved
34. Yakovlev Yak-38 Forger

- Two in-line 6,722 lb Rybinsk RD-36-35FVR immediately behind cockpit
- One 13,444 lb Soyuz Tumanskiy/Khatchaturov R-27V-300 turbojet was mounted in the fuselage center exhausted through two vectoring hydraulically actuated nozzles
- One nozzle was situated on each side of the fuselage just aft of the wing trailing edge
- Primary roles were fleet defense, reconnaissance and anti-ship strike but never saw combat
- Deployed on the Kiev-class aircraft carrier
- A total of 231 aircraft were built

Flight Milestones
- Jan 1972 - First prototype flight
- July 1976 - First deployment of Yak-38 equipped Kiev
- 1988 - End of production line
- 1992-1993 - Forger is removed from front line service
35. Yakovlev Yak-141 Freestyle

- The supersonic Freestyle was optimized for air defense with a secondary attack capability
- A dozen FAI-recognized Class H.III records for V/STOL altitudes and time to altitude with loads were set by the Freestyle
- Maximum speed achieved was 1.7 Mach
- Maneuverability was claimed to be “almost as good as the MiG-29”
- Development was stopped due to shrinking Soviet military budget
- Yakovlev funded the development hoping to attract foreign investors but was unable to market the design

Flight Milestones
- 9 March 1987 - First conventional flight
- 29 December 1989 - First hover
- April 1991 - Yak-141 sets V/STOL records
- August 1991 - Government funding ended
- October 1991 - Second prototype crashed
Tip Jets

- A compound autogyro:
  - Transmits full power to the rotor for vertical flight
  - Transfers power to a horizontal propulsion device for forward flight and off-loads the rotor

- Wings provide lift in forward flight to allow the aircraft to fly faster than a conventional helicopter

- Tip Jet aircraft pump fuel and compressed air to small burner chambers at the rotor tips
  - This combustion generates thrust which turns rotor
36. McDonnell XV-1

- Powered by one 550 hp Continental R-975-19 nine cylinder radial piston engine
- Two air compressors powered by the engine drove the lift rotors
- 31 ft three-bladed rotors for vertical lift
- One 6 ft diameter two-bladed propeller for forward flight
- Yaw control was achieved through a small rotor at the end of each tail boom
- Exceeded contemporary rotorcraft speed records by attaining 200 mph
- Tip jet noise was very loud
- Tip jet flash at night made it an easier target

Flight Milestones
- 1954 - First tether test
- 11 February 1954 - First free flight
- 29 April 1954 - First transition to horizontal flight
- 10 October 1955 - 200 mph speed record is set
- 1957 - The program is cancelled
37. Fairey Rotodyne

- Powered by two 2,800 shp Napier Eland 3 turbine engines
- The 60 ft diameter four-bladed rotor was powered by tip jets in vertical flight and autorotated in cruise, providing half the lift
- Two four-bladed tractor propellers provided forward thrust
- Pitch and roll were controlled by cyclic rotor pitch
- Yaw was controlled by differential propeller pitch
- Aerodynamic surfaces augmented control in forward flight
- Tip jet noise was very unpleasant
- Aircraft cancelled when Westland took over Fairey

Flight Milestones
- 6 November 1957 - First vertical flight
- April 1958 - First transitions are begun
- October 1958 - Problem with jet relights at altitude is solved
- 1962 program fizzles out
Augmented Power Plant for Hover

- Uses power plant(s) to drive an auxiliary device
  - Ejector augmentors
  - Lift fans
  - Propeller
- These devices provide additional thrust for hover or cruise
- Wings provide lift in forward flight
Ejector

- Ejects high pressure engine efflux into a channel (augmentor) causing additional cooler ambient air to accelerate through channel and mix with engine exhaust

- At the augmentor exit the combined flow produces more thrust than input engine alone
38. Lockheed XV-4A Hummingbird

- Powered by two 3,300 lb P&W JT12 turbojet engines mounted on either side of the fuselage
- The thrust was diverted into augmentor ejectors for vertical flight, take-off and landing
- Engines fed interleaved ejectors in case of engine failure
- In transition one engine was diverted from ejectors to providing forward thrust until wing-born lift was sufficient
- Actual vertical thrust after installation losses was 7,500 lb for a 1.04 thrust to weight ratio

Flight Milestones
- 7 July 1962 - First conventional flight
- 30 November 1962 - First hover
- 24 May 1963 - First untethered hover
- 8 November 1963 - First transition completed
39. Rockwell XFV-12A

• Powered by one modified 30,000 lb (in afterburner) P&W F401 engine
• For vertical lift engine exhaust was diverted through ducts to ejector nozzles in the wings and canards
• Pitch and roll were controlled by differential variation of the four ejectors from fore to aft and left to right
• Yaw was controlled by differential ejector vectoring
• Expected max speed was over Mach 2
• Lab tests indicated augmentation of 55% was possible but only 12.5% (average) was demonstrated
• The program was discontinued due to cost overruns and waning Navy V/STOL interest

Flight Milestones
• 1974 - Engine rig testing begins
• July 1977 - Aircraft ground testing begins
• 1978 - Suspended tether trials performed
• 1981 - Program is cancelled
• July 1977 - Ground testing begins
Fan

- A horizontal oriented ducted propeller or fan is buried in aircraft wing or fuselage
- The propeller / fan is located close to the center of gravity (c.g.)
- Engine power can be redirected to propeller / fan to provide vertical thrust for hover
- The conventional wing provides thrust for horizontal flight

Augmented Power Plant for Hover
40. Vanguard Omniplane

- Powered by one 265 hp Lycoming O-540-A1A six cylinder piston engine (later a 860 hp Lycoming YT53-L-1)
- One 6 ft diameter three-bladed propeller was mounted in each wing for vertical flight
- One 5 ft diameter propeller in the tail provided forward thrust
- Covers above the rotors and louvers below sealed the wing for lift
- Pitch and yaw was controlled by elevator and rudder surfaces behind the rear propeller
- Roll was controlled in hover by differential blade pitch
- Aircraft damaged and program ended

**Flight Milestones**

- August 1959 - Ground testing of 2C
- 1962 - Omniplane is modified with larger engine and a third lift propeller in nose, redesigned 2D
- 1962 - Omniplane 2D completes hover tests
- 1962 - 2D version damaged and development discontinued
41. GE-Ryan XV-5A Vertifan

- Powered by two 2,650 lb General Electric J85-GE-5 turbojets
- One 5 ft diameter fan in each wing for vertical lift
- Wing fans rotated in opposite direction and covered by doors
- Pitch control provided by one small fan in front of cockpit
- Roll control achieved by the wing fans
- Yaw control was provided by louvered vanes under the wing fans that could vector the thrust
- Had slow control response and a narrow transition corridor
- Lift system occupied a large volume and weight

**Flight Milestones**

- 25 May 1964 - First flight
- April 1965 - First prototype crashed
- June 1964 - First vertical flight
- November 1964 - First transition
- October 1966 - Second prototype crashed
42. Lockheed Martin X-35

- Joint Strike Fighter (JSF) Lockheed Martin concept demonstrator
- Powered by a derivative of the P&W F119 engine
- For vertical flight the P&W drives a shaft which turns an Allison lift fan ahead of the c.g.
- Rear lift force and yaw control is provided by a swiveling exhaust nozzle similar to the Yak-141
- Roll control is provided by two roll nozzles using ducted fan bypass air
- An 86% scale model powered by a P&W F100 was tested for nearly 200 hrs including in Ames wind tunnel

**Flight Milestones**
- 1993 - ASTOVL contract awarded
- 1995-1996 - Large scale model is tested
- 1996 - Selection as JSF demonstrator
- 2000 - Planned first flight of prototype
- 2001 - JSF source selection and possible development of operational version
Rotor

- Designed for missions where the aircraft needs to spend a large amount of time in hover
  - Rotor is the most efficient lifting device for these missions
- Very difficult for rotor to propel the aircraft forward and provide lift at high velocity
- To increase maximum velocity a variety of methods have been used to add propellers and wings to rotor aircraft forming compound helicopters
43. Kamov Ka-22 Vintokryl ‘Hoop’

- Powered by one 6,500 shp Soloviev D-25VK turboshift engine on each wingtip
- Each engine had one four-bladed rotor for vertical flight and one four-bladed propeller for cruise
- Could transport vehicles and other cargo, up to 36,400 lb or 80 seats
- Set a Class E.II speed record of 221.4 mph over a 15.25 km course
- Lifted record payload of 46,343 lb to a height of 6,562 ft
- Held several other payload to altitude records
- Abandoned after a crash

**Flight Milestones**

- 20 April 1960 - Flight testing starts
- 7 October 1961 - Sets Class E.II speed record
- 24 November 1961 - Sets payload record
- 1964 - Ka-22 abandoned
44. Piasecki 16H-1 Pathfinder

- Privately developed by Piasecki
- Powered by a 550 hp Pratt & Whitney PT6B-2 turboshaft engine
- One 41 ft fully articulated three-bladed rotor
- One 5.5 ft three-bladed ducted propeller in the tail for forward thrust
- Anti-torque control by four vertical vanes in duct
- Used its wings and pusher propeller to off-load the rotor and increase the max speed to 148 kts
- 16H9-1A Pathfinder II had a 1,250 shp T58 turboshaft engine
- 16H-1C engine upgraded to a 1,500 shp T58-GE-5
- Civil proposals were unsuccessful

Flight Milestones
- 21 February 1962 - First flight
- May 1964 - Piasecki contracted to test 16H-1A Pathfinder II
- 15 November 1966 - 16H-1A begins flight tests
- May 1966 - Research concluded after 40 flight hours
45. Lockheed AH-56 Cheyenne

- Powered by one 4,435 shp GE T64-GE-16 turboshaft engine
- Hover by one rigid 50 ft four-bladed rotor
- One 10 ft three-bladed pusher propeller
- One four-bladed anti-torque rotor
- Highly agile and capable aircraft
- Original production order for 375 AH-56s approved in 1968
- Ten aircraft built
- Maximum speed reached was 277 mph
- Project cancelled in 1972 due to defense budget cutbacks

Flight Milestones
- 21 September 1967 - First flight
- 12 March 1969 - Third prototype crashes killing the pilot
- 1968 - Production order approved
- 1972 - Project cancelled
Lessons Learned

• Lots of different concepts were tried -- some more seriously than others.
• Engine/mechanical system reliability is extremely important for powered lift concepts.
• Propulsion system sizing is very important: too small and the aircraft can't hover, too large and it may be too heavy and/or oversized for cruise.
• The propulsion system should not take up too much volume, or there is no room for fuel or payload.
• V/STOL development programs (like all programs) are often canceled for political reasons. They must also be fully funded and not tried on a shoestring budget.
• Pilot workload needs to be manageable, especially during vertical landing.
• The control system needs to be sufficient (speed and authority) for hover.
The Future of V/STOL

Joint Strike Fighter

Lockheed Martin X-35

Tilt Rotor

Bell Boeing V-22

Bell Agusta 609
On the Vertical Horizon

CarterCopter Powered Autogyro

Boeing Canard Rotor/Wing “Dragonfly”

Bell Quad Tiltrotor (QTR)

Duncan Tilt-propeller “Xantus”

Boeing Tilt-wing Advanced Theater Transport (ATT)