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THE PILOT'S PERSPECTIVE

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INTRODUCTION

This paper is written from an engineering test pilot's point-of-view. Its purpose is to present lift-fan "lessons learned" from the perspective of first-hand experience accumulated during the period 1962 through 1988 while flight testing V/STOL experimental aircraft and evaluating piloted engineering simulations of promising V/STOL concepts.

Specifically, the scope of the discussions to follow is primarily based upon a critical review of the writer's personal accounts (and in particular, "lessons learned") of 30 hours of XV-5A/B and 2 hours of X-14A flight testing as well as a limited simulator evaluation of the Grumman Design 755 lift-fan aircraft.

Opinions of other test pilots who flew these aircraft and the simulator are also included and supplement that of the writer's. Furthermore, the lessons learned are presented from the perspective of the writer's flying experience background: 10,000 hours in 100 types of fixed- and rotary-wing aircraft including 330 hours in 5 experimental V/STOL research aircraft.

The paper is organized to present the reader with as clear as possible picture of "lift-fan lessons learned" from three distinct points-of-view in order to facilitate application of the lesson principles to future designs. Lessons learned are first discussed with respect to "case histories" of specific flight and simulator investigations. These lesson principles are then organized and restated with respect to four selected "design criteria" categories in Appendix I. Lastly, in Appendix II, lessons learned are discussed with respect to the design of a hypothetical supersonic STOVL fighter/attack aircraft.

"Lessons learned" presented in this paper were drawn from the following referenced flight and simulator investigations.

XV-5A flight test evaluations	(Ref. 1)
XV-5B flight test evaluations	(Ref. 2)
XV-5B terminal area approach flight tests	(Ref. 3)
X-14A roll control lift-fan flight tests	(Ref. 4)
Grumman Design 755 simulator evaluation	(Ref. 5)

"Lessons learned" are summarized in Appendix I where they are listed under one of the following design criteria headings.

Handling Qualities
Mission Suitability
Design Integration
Human Factors

Appendix III summarizes the author's V/STOL flight test experience.

XV-5A FLIGHT TESTS

The Ryan XV-5A which flew for the first time in July 1964, was a twin engine, mid-wing, research aircraft. Two J85-GE-5 turbojet engines were pneumatically connected to two 62.5-inch (X353-5B) wing lift-fans and one 36-inch (X376) pitch control lift-fan. (see figures 1 and 2) Moveable vanes ("exit louvers"), located in the exit plane of each wing fan, vector thrust from 7-deg. forward to 45-deg. aft of the vertical, and and could spoil as much as 25% of fan thrust by pinching action to provide lift control.

The pilot was provided with conventional helicopter controls. Pitch attitude was controlled by longitudinal stick which actuated pitch-fan thrust-reverser-doors. The collective stick provided height control during hover and slow flight by actuating the wing-fan exit louvers. Lateral stick provided roll control through differential actuation of the wing-fan exit louvers. Fan-mode (low) speed was controlled through a stick-mounted "beep" switch which changed the fan exit louver angle. Pedal movement provided yaw through differential actuation of fan exit louver angle.

RPM of the two J85 turbojet engines was independently controlled by the throttles which were locked together and mechanically connected to the twist grip of the collective lever. Wing fan rpm was neither governed (like the gas turbine-powered helicopter) nor independently controlled, but rather was determined by the combination of gas power input to the fan from the J85 engines and the loading due to fan flow which was sensitive to air flow conditions at the fan inlets. The pilot thus used J85 RPM as a direct reading reference for power settings.

Originally designed to validate the lift-fan aircraft concept, the 12,500 lb. (maximum gross weight) XV-5A was evaluated in late 1966 by 15 test pilots (the"XV-5A Fan Club") including the writer. Two aircraft were built but one was totally destroyed during an official flight demonstration in April 1965, and in October 1966 the second was extensively damaged during trials to evaluate the aircraft's potential as a strike escort/rescue aircraft for Viet Nam. This aircraft was subsequently rebuilt and modified as the XV-5B. Tragic lessons were learned as a result of these two fatal accidents.

Lessons learned from flight tests of the XV-5A include the following:

1. Ryan provided a fixed-base simulator for pilot familiarization prior to first flights in the aircraft. The simulator was found to be a great aid in assessing many of the handling qualities as well as a procedures trainer for first flight preparation.

2. Guest pilot evaluations consisted of 5 flights totaling 2 hours. During this time the entire flight envelope of the aircraft was investigated with relative ease and without any mishaps. The XV-5A evaluations demonstrated that the lift-fan concept was valid and that the operational procedures were relatively straight-forward and easy to adapt to in general.

3. The mixer box in the automatic interlocking system of the conversion controls contained some 70 electrical relays which had to be "confidence checked" by the pilot during pre-flight checks prior to every flight. This necessary procedure was too long and involved due to the complicated nature of the conversion system. It was recommended that the conversion system be redesigned to reduce complexity and improve reliability. (The XV-5B conversion system was modified to reduce the possibility of a "split" or uncontrolled conversion sequence.)

4. Handling qualities while hovering in ground effect (below 10 to 15 feet) were found to be unpleasant and noted to be more pronounced than that experienced with the X-14A jet-lift research aircraft.

5. The XV-5A did not have an integrated powered-lift flight control system. Height control was accomplished by modulation of wing- and pitch-fan "collective" lift which could be accomplished by controlling fan RPM with engine (gas producer) throttles or by varying fan exit louver opening with the collective-type lift-stick. The preferred method was to set the throttles at a near-maximum setting and use the lift-stick for height control. Hover height control with lift stick was found to be responsive and precise (PR=2) while using throttles to modulate fan rpm was unsatisfactory (PR=7) due to excessively high height control time constant.

6. Roll control in fan mode of flight was accomplished through differential modulation of wing-fan lift with the exit louvers which normally are also modulated for height control through the lift-stick. Control mixing was such that lateral control power (as well as directional control power) was reduced as lift-stick position was increased to open the fan exit louvers and increase lift-fan thrust. Without an integrated powered-lift flight control system, the pilot could set himself up in a potentially hazardous situation during a vertical take-off attempt. If engine power was not brought up to maximum, larger than normal lift-stick inputs would be required to climb up through ground effect disturbances at a time when lateral control power had been reduced.

7. Since directional control in fan mode of flight was controlled by differential wing-fan exit-louver vector angle, control mixing was such that directional control power was reduced (like the lateral control power case) as lift stick position was increased. Thus directional control had the potential of becoming weak as large lift-stick inputs were applied to lift-off through ground effect disturbances with lower than normal engine power settings.

8. The landing-gear geometry of the XV-5A was such that the pitch attitude of the aircraft had to be raised to a level attitude to prevent moving forward as fan thrust was increased to perform a vertical take-off. Without an integrated powered-lift control system, moderately high pilot workload was required to coordinate a smooth vertical take-off. Instead of simply raising the nose to the lift-off attitude while on the ground and then increasing vertical thrust to initiate lift-off, a rapid and simultaneous effort was required to release the brakes, increase lift-fan thrust, raise the nose to a level attitude and "pull" the aircraft into the air. Vertical landing touchdowns were similarly affected, requiring simultaneous wheel touchdown, brake application, lowering of the nose and rolling-off engine power to idle.

9. The 36-inch nose fan provided adequate pitch control in fan mode, but was responsible for a couple of adverse handling quality characteristics. The strong momentum drag of the pitch-fan caused the aircraft to exhibit negative weather-cock stability during sideward translations in hover, and negative directional stability during translational maneuvering in hover flight at about 30 knots. These divergent directional control characteristics were difficult to control due to the weak directional control power attained by differential wing-fan exit-louver vector angle. It was concluded that the placement of a pitch control lift-fan in the nose of the aircraft was far from optimal.

10. Conversion between jet and fan modes of flight was "the most exacting, interesting, and potentially hazardous operational aspect of the XV-5A." The conversion design and operational philosophy were felt to be completely unsatisfactory for every day, operational use. Conversion from jet-mode to fan-mode took about 3 seconds and from fan-mode to jet-mode about 1 second... ..a "bang-bang" or "go-no-go" operation. During conversions, two essential actions had to occur simultaneously for the aircraft to maintain longitudinal control: 1) diverter valve movement, which controlled the flow of J85 gases to either the tail pipes for jet-mode or to the fans for fan-mode and 2) stabilizer nose-up or nose-down trim which compensated for the powerful changes in pitching moment as the fans are powered up or down. If either of the actions occurred without the other ("split-mode"), the aircraft became uncontrollable in pitch. It was felt that a more gradual and completely reversible conversion system (such as found in the Harrier or Tilt Rotor aircraft) be incorporated in any follow-on lift-fan aircraft design. (A mechanical linkage between the stabilizer actuator and the diverter actuator controls was incorporated in the redesign of the XV-5B to preclude "split-mode" conversions.)

11. Conversions between jet and fan modes of flight had to be performed within a narrow airspeed corridor in order to maintain safe longitudinal control during the rapid "bang-bang" conversion sequence operation. This corridor which is illustrated in figure 3, was bounded by the overlap of maximum level-flight fan-mode airspeed (about 104 knots) and minimum jet-mode airspeed (about 89 knots). Ideally, jet to fan mode was performed at about 95 knots and fan to jet at about 88 knots. The requirements to perform conversions within this narrow operating envelope severely restricted the operational flexibility of the XV-5A and placed an unreasonable demand on the pilot's adherence to procedures. This method of conversion was not the way to go! (A "sequential conversion" scheme, was designed to expand the conversion corridor by converting one engine at a time. It was never employed on the XV-5A or B.)

12. Another scheme that was employed to expand the conversion corridor was the capability of shutting-down the pitch-fan prior to conversion-from fan to jet mode and thus increase the maximum (pitch-fan out) fan-mode airspeed. This modification, which reduced the pitch-fan ram drag, was incorporated during the latter stages of the XV-5A flight development program. (See Fig.3)

13. Two operational limitations were noted while performing roll-on or so called "STOL" landings (in fan-mode) during the XV-5A evaluation. The lift-stick was set at a prescribed setting while glide path and airspeed control were performed with engine throttles and longitudinal stick respectively. Speed control was difficult to maintain due to fan pitching moment variations that were induced as engine power was modulated to control glide path. Secondly, final approach and landing precision were markedly degraded due to the inadequate response of fan lift to engine throttle inputs. (Subsequently another "STOL" approach was performed with the XV-5B, but using lift-stick for glide path control. The approach and touchdown were precisely controlled this time, but hot gas reingestion just after touching down caused one engine compressor to violently stall.)

14. The "bang-bang" nature of the conversion procedure, as described in paragraph 11, was accompanied by an abrupt pitch attitude change of about 10 to 15 degrees and required coordinated control of power to hold level flight. It was the unanimous opinion of all pilots who performed this challenging maneuver that it was unsafe to do so during instrument flight conditions. (The "sequential conversion" scheme may have enabled pilots to perform IMC conversions on a routine basis.)

15. During the conversion process between jet-mode and fan-mode, J85 engine gas was diverted through a pair of butterfly-type diverter valves. The diverter valve gas seals tended to leak somewhat. This gas leakage caused the covered lift-fan cavities to heat up at times during prolonged periods of jet-mode flight. Fan cavity temperature indicators had to be monitored by the pilot to prevent overheat.

16. The gas ducts that powered the pitch fan were routed forward and under the cockpit floor. Conversion to fan-mode had the instant effect of turning on "the cockpit heater". Radiation of heat from these ducts into the non-air conditioned cockpit resulted in uncomfortably high cockpit temperatures, particularly during hover operations in desert climates.

17. One of the outstanding safety features of the gas-driven lift-fan concept is the robustness of the lift-fans themselves! The absence of drive shafts, shaft bearings, gear boxes and the attendant pressure lubrication systems resulted in relatively low maintenance headaches and high pilot confidence. The only indicators associated with the three lift-fans installed in the XV-5 were rpm and fan cavity temperature. The fans could take tremendous amounts of abuse including sand and pebble ingestion. The acid test occurred however when a rescue hoist weight was accidentally ingested resulting in a fatal accident which is described in paragraph #19.

18. Fatal Accident #1 - One of the two XV-5As being flown at Edwards AFB during an official flight demonstration on the morning of April 27, 1965, crashed onto the lakebed, killing Ryan's Chief Engineering Test Pilot, Lou Everett. (The writer witnessed this tragic accident.) The two aircraft were simultaneously demonstrating the high- and low-speed capabilities of the "Vertifan". During a high-speed pass, Everett's aircraft pushed over into a 30 degree dive and never recovered. The accident board concluded that the

uncontrolled dive was a result of an accidental actuation of the conversion switch that took place when the aircraft's speed was far in excess of the safe jet-mode to fan-mode conversion speed limit. The conversion switch (a simple 2-position toggle switch) was, at the time, (improperly) located on the collective for pilot "convenience." It was speculated that the pilot inadvertently hit the conversion switch during the high-speed pass which initiated the conversion sequence: 15-degrees of nose-down stabilizer movement accompanied by actuation of the diverter valves to the fan-mode. The resulting stabilizer pitching moment created an uncontrollable nose-down flight path. (Note: Mr. Everett initiated a low altitude (rocket) ejection, but tragically, the ejection seat was improperly rigged...another lesson learned!) As a result of this accident, the conversion switch was changed to a lift-lock toggle and relocated on the main instrument panel ahead of the collective lever control.

19. Fatal Accident #2 - The remaining XV-5A was rigged with a pilot-operated rescue hoist, located on the left side of the fuselage just ahead of the wing fan. An evaluation test pilot was fatally injured during the test program while performing a low-speed, steep-descent "pick-up" maneuver at Edwards AFB. The heavily-weighted rescue collar was ingested into the left wing fan as the pilot descended and simultaneously payed-out the collar. The damaged fan continued to rotate, but the resultant loss in fan lift caused the aircraft to roll-left and settle toward the ground. The pilot apparently leveled the wings, applied full power and up-collective to correct for the left wing-fan lift loss. The damaged left fan produced enough lift to hold the wings level and somewhat reduce the ensuing descent rate. The pilot elected to eject from the aircraft as it approached the ground in this wings-level attitude. As the pilot released the right-stick displacement and initiated the ejection, the aircraft rolled back to the left which caused the ejected seat trajectory to veer-off to a path parallel to the ground. The seat impacted the ground, and the pilot failed to survive the ejection. Post-accident analysis revealed that despite the ingestion of the rescue collar and its weight, the wing-fan continued to operate and produce enough lift force to hold a wings-level roll attitude and reduce descent rate to a value that may have allowed the pilot to survive the ensuing "emergency landing" had he stayed with the aircraft. This was a grim testimony as to the ruggedness of the lift-fan. The rescue hoist installation and post-accident damage to the aircraft are evident in the photograph of figure 4.

XV-5B FLIGHT TESTS

Although the pilot sustained fatal injuries in the above tragic accident, damage to the aircraft was moderate. During repair and rebuild into the XV-5B configuration, several modifications were incorporated as a result of lessons learned: 1) mechanical tie between the stabilizer and diverter valve actuators, 2) enlargement of main landing gear tread, 3) incorporation of an improved fuel supply and management system, and 4) an improved cockpit arrangement. The first flight of the XV-5B took place in July 1968, and the aircraft was turned over to NASA-Ames a month later. Flight tests which continued until January 1971, involved investigation of steep terminal area approaches and measurement of aircraft noise footprints. The XV-5B configuration can be seen in the hover photograph of figure 5 and the cutaway drawing of figure 6.

Lessons learned from flight tests of the XV-5B include the following:

1. The XV-5B exhibited a broad descent capability which was generally suited for steep terminal area approach profiles up to 20-degree flight path angles. Figure 7 illustrates the "deck-parallel" terminal area approach descent envelope of the XV-5B. Typical simulated instrument approaches were performed along a 10-degree flight path angle at 70 knots using a thrust vector angle of 20-degrees (point "B"). However, the major source of handling problems was found to be with the management of the powered-lift system in that the pilot was required to independently manage the engine power, collective lever inputs and pitch attitude to control flight path angle. An integrated power-management system that would simultaneously schedule engine power and fan-lift controls in response to a single powered-lift controller was recommended for improvement.

2. A 10-degree glide slope was used to evaluate the terminal area approach capabilities of the XV-5B. Two glide slope tracking procedures were evaluated to assess the powered-lift handling qualities of the lift-fan system. J85 power was set with the throttles while the glide slope was tracked with the collective lever. The other method used was to set the collective and track glide slope with the throttles. As to be expected, pilots preferred the collective for (direct lift control) glide slope tracking. When engine power was used, lags in both the J85 and the lift-fans caused the pilot to chase the glide slope with throttle movements.

3. Changing thrust vector angle was a very effective means of controlling velocity along the glide slope during decelerating terminal area approaches. However, changing thrust vector angle induced flight path disturbances during these decelerations, but the pilot was able to cope with them if vector changes were gradually "beeped" in 10-degree increments.

4. A 10-degree glide slope angle was selected for the terminal area instrument approach evaluations. Two approach procedures, shown in figure 8, were evaluated to document lift-fan performance characteristics: deck-level and deck-parallel (aircraft attitude). During the deck-level approach, the pitch attitude of the aircraft was held level and the lift-fans were essentially operated at an average angle-of-attack equal to the glide slope (or flight-path angle) of 10-degrees as illustrated in figure 9. In the deck-parallel method (Fig. 7), the longitudinal axis of the aircraft was pointed along the glide slope by holding angle-of-attack near zero, thus operating the lift-fans at an average angle-of-attack of zero. Although flying the approach with deck-level had the potential of reducing fuel consumption by supplementing fan lift with wing lift contribution, it was found that evaluation pilots preferred to fly the approach using the deck-parallel technique. Two adverse handling quality factors were encountered using the deck-level method: 1) Operating the fans at 10-degrees angle-of-attack reduced the fan stall maneuver margin boundary which in-turn limited the descent rate capability needed to correct for fly-down glide slope corrections. (Fan stall commenced at approximately 15 degrees.) 2) Maneuvering the aircraft along the glide slope at 10 degrees angle-of-attack was accompanied by random aerodynamic lift effects that hindered glide slope tracking performance which can be detected in the radar profile of figure 10. Presence of the fan stall boundary placed an operational restriction on using steeper than 10-degree glide slope angles while using the deck-level method.

X-14A FLIGHT TESTS

In 1969, the X-14A was temporarily fitted with tip-turbine-driven lift-fans to investigate the feasibility of their use for VTOL roll control. A number of lessons learned were generated as a result of this handling qualities flight test investigation. A general view of the modified X-14A is shown in figure 11.

The Bell X-14A VTOL Variable Stability and Control Research Aircraft was a vectored thrust airplane powered by a pair of General Electric J85 turbojet engines, similar to those installed in the XV-5. Attitude control during hover and low speed flight was normally accomplished through reaction control nozzles located in the tail for pitch and yaw and on each wing tip for roll control. Engine compressor bleed air provided the reaction control moments.

Two 12.8-inch diameter lift fans (Fig. 12), rated at 150 pounds of thrust at 12,000 RPM were added to each wing tip as shown in figure 13. Bleed air, normally supplied to the wing-tip reaction control nozzles, was used to drive the tip-turbine-driven fans. Fan thrust was controlled by varying the pressure ratio to the tip turbine and there-by controlling fan speed. Rolling moments were generated by accelerating the rpm of one fan and decelerating the other in such a way as to maintain a constant net lift. Control circuits were provided for both open- and closed- loop fan rpm operation.

Lessons learned from flight tests of the modified X-14A include the following:

1. The electronic and pneumatic fan control subsystems, as well as the fans themselves, were found to be simple to operate and reliable. A fan control panel provided selection of parameters such as zero rolling moment fan-trim speed, lateral control sensitivity, and open- or closed-loop operation.

2. For equal values of thrust, the fans required less than half the bleed air required by the reaction control nozzles. Hence, the total bleed air requirement was reduced by about 20 percent. This less stringent bleed air requirement meant that the jet engines could produce 4 percent more thrust, and the need to operate them above their temperature limit during vertical lift-off would be reduced with fan controls as compared to the reaction control nozzles.

3. During flight tests, the pilot rated the lift-fan roll control system as unacceptable (pilot rating of 6-1/2 to 7-1/2) even for emergency conditions because of his constant tendency to overcontrol roll attitude and thus induce oscillation during any maneuver. Control system lag was primarily responsible for the poor handling quality rating. Fan speed first-order time constants for open-loop and closed-loop operation were found to be 0.58 and 0.34 seconds respectively. Figure 14 shows the variation in open-loop fan rpm response as a function of fan speed, and figure 15 depicts a comparison of open- and closed-loop fan response to a step input. Figure 16, shows a time history of a step aileron input during hover, and it can be seen that fan speed never stabilized and thus the commanded fan thrust was never attained.

4. This test clearly demonstrated that the control system lag and the increases in the aircraft's moment of inertia caused by the placement of the control fans on the wing tips negated the desired increases in roll performance resulting from the fans having greater thrusts than the reaction control nozzles.

5. This test also demonstrated a principle that must be kept in mind when considering fans for controls. Even though the time response characteristics of a fan system are capable of improvement by such means as closing the loop with rpm feedback, full authority operation of the control eliminates the fan speed-up capabilities provided by the closed loop, and the fans revert to their open-loop time constants.

(Note: The employment of light-weight, constant-speed fans with variable-pitch blades in present designs has significantly improved the thrust response characteristics that are needed for satisfactory control moment response.)

GRUMMAN DESIGN 755 FLIGHT SIMULATOR EVALUATION

The writer participated in a brief simulator evaluation of the proposed Grumman Design 755 at their Systems/Simulation Development Laboratory at Bethpage, L.I. on September 5, 1990. "Lessons learned" from this brief look at a state-of-the-art version of the basic XV-5 "Vertifan" fan-in-wing concept are presented.

Grumman's proposed Design 755 is an advanced fan-in-wing, multi-mission, single-placed aircraft. It is a true vertical takeoff and landing (VTOL) aircraft in that it is capable of VTOL operations at its design maximum gross weight. It is powered by a single turbofan engine and two General Electric LF2 wing-mounted, lift-fans similar to those that were installed in the XV-5. Mission requirements dictated the use of wing-mounted lift-fans, and Grumman chose to incorporate extrapolated XV-5 technology and X-29 fly-by-wire control system architecture in their design philosophy.

The flight control system of the 755 is somewhat similar to that of the XV-5 but with two very important exceptions that illustrate, in this case at least, the application of lessons learned from the XV-5. Design 755 incorporates an integrated powered-lift flight control system, and the pitch-fan was eliminated from the design.

In fan-mode flight, height and roll control are provided by collective and differential modulation of fan thrust through louver action as in the XV-5. Likewise, fan-mode velocity and directional control are effected by collective and differential modulation of fan thrust vector. Pitch attitude is controlled through fore- and aft-mounted engine bleed-air reaction-control nozzles.

A conventional throttle lever controls engine thrust and aircraft velocity during jet-powered flight. A flight-path control lever, mounted inboard and parallel to the throttle, is used to control flight-path vector while in fan-mode. A trigger switch, mounted on the throttle lever, is used to initiate conversions between jet and fan modes of flight.

Lessons learned from the Grumman Design 755 flight simulator evaluation are best presented by quoting directly from the evaluation report itself:

1. "As expected, execution of conversions was found to be the most critical handling quality issue. Converting any V/STOL aircraft close to the ground can be both challenging and outright hazardous. Unfortunately, the (fan-in-wing) lift-fan is one of the few V/STOL concepts that employs a "bang-bang" conversion where the powered-lift components are not continuously vectorable between hover and high-speed cruise such as with the tilt-rotor, tilt-wing and vectored-jet concepts. Furthermore, since the Grumman 755 is a single-piloted aircraft with high workload, multi-mission tasks, it is absolutely essential that the pilot be able to perform conversions between jet and fan modes of flight with Level I handling qualities.....however as in the XV-5 case, the conversion procedures were complicated and cumbersome."

2. "Conversion handling qualities were degraded because of cockpit layout and the requirement to switch back and forth between two power controllers (i.e. the engine throttle and the flight-path lever). ......I found myself grabbing the wrong lever at the wrong time, and it was difficult at times to apply precise lever movements to achieve desired results."

3. Just as in the XV-5 conversion process which was ..."the most exacting , interesting, and potentially hazardous operational aspect of the XV-5A", "the major handling quality problems (of the Grumman Model 755) were associated with the conversion. Conversion controls and procedures demanded high pilot workload and were too cumbersome for operational use".

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APPENDIX I

DESIGN CRITERIA SUMMARY

DESIGN CRITERIA	LESSONS LEARNED PARAGRAPH NUMBER
A. - Handling Qualities	
Unpleasant handling qualities were experienced in ground effect.	XV-5A #4
Collective was preferred over throttles for height control.	XV-5A #5
Vertical take-off attempts with low power and high collective resulted in reduced lateral and directional control power.	XV-5A #6 & 7
Vertical take-off and landing handling qualities were degraded due to landing gear geometry.	XV-5A #8
Pitch-fan inlet momentum drag was responsible for adverse directional stability during hover.	XV-5A #9
Conversion between jet and fan modes was the most exacting, interesting, and potentially hazardous flight operation.	XV-5A #10
Using throttle control for STOL landings was unsatisfactory due to adverse pitch and fan response.	XV-5A #13
The conversion was accompanied by an abrupt pitch attitude change requiring coordinated control of power to hold level flight.	XV-5A #14
Pilots preferred to use collective stick over engine throttles for glide slope tracking.	XV-5B #2
Large thrust vector changes induced flight path disturbances during decelerating terminal area approaches.	XV-5B #3
Pilots preferred to fly terminal instrument approaches using the "deck parallel" technique.	XV-5B #4
Flying the terminal area approach using the deck-level technique reduced fan stall margin and induced random aerodynamic disturbances.	XV-5B #4

Wing tip-mounted roll control fans were rated unacceptable due to poor fan rpm response characteristics.	X-14A	#3

Conversions between jet and fan modes was the most critical handling quality issue. Level I handling qualities should have been provided.	G755	#1
Conversion handling qualities were degraded due to cockpit layout and conversion procedures.	G755	#2

B. - Mission Suitability

Conversion system design and operational philosophy were unsatisfactory for every day use.	XV-5A	#10
The narrow operating envelope of the conversion system severely restricted operational flexibility of the XV-5.	XV-5A	#11
The conversion operating envelope was expanded by enabling independent shutdown of the pitch fan.	XV-5A	#12
Engine compressor stall was experienced just after touchdown from a fan-powered roll-on landing due to hot gas reingestion of the J85 engine. (XV-5B)	XV-5A	#13
The "bang-bang" nature of the conversion was considered to be unsafe for instrument flight operations.	XV-5A	#14
The robustness of the lift-fan was operationally proven, and resulted in low maintenance requirements and high pilot confidence.	XV-5A	#17 & 19

The XV-5B exhibited a steep descent capability of up to a 20-degree flight path angle.	XV-5B	#1
Both deck-level and deck-parallel approaches were demonstrated. Deck-parallel approach technique was preferred.	XV-5B	#4
Fan stall boundary limited glide-slope angle when using the deck-level approach technique.	XV-5B	#4

Conversion of the fan-in-wing is an abrupt process and not a continuously vectorable operation like that of other V/STOL aircraft concepts.	G755	#1

C. - Design Integration

Design of the XV-5 conversion system was too complex and unreliable which necessitated time consuming pilot preflight ground checks.	XV-5A	#3
The XV-5 did not have an integrated powered-lift flight control system which resulted in a significant increase in pilot workload.	XV-5A	#5,6,7
Lack of an integrated powered-lift control system complicated vertical take-off and landing procedures.	XV-5A	#8
Configuring a lift-fan aircraft with a nose-mounted pitch-fan can cause adverse handling qualities.	XV-5A	#9
The XV-5A conversion system was subject to a "split conversion" condition which eventually contributed to a fatal operational accident.	XV-5A	#10,18
Pitch-fan ram drag contributed to the XV-5's narrow conversion airspeed corridor. A pitch-fan cutout modification subsequently expanded the corridor.	XV-5A	#11,12
XV-5A diverter valves were subject to gas leaks which overheated the fan cavities in jet-mode at times.	XV-5A	#15
XV-5 pitch-fan gas ducts were routed under the cockpit, and overheated the cockpit at times while in fan-mode.	XV-5A	#16
Lift-fans are robust, reliable, simple and easy to maintain.	XV-5A	#17,19

An integrated powered-lift management system would have improved the descent capabilities of the XV-5B.	XV-5B	#1
Gas generator (engine) and fan RPM response characteristics degraded descent performance in the absence of an integrated powered-lift management system.	XV-5B	#2
The fan stall boundary significantly limited the descent capability of the XV-5.	XV-5B	#4

The roll-control fan system that was temporarily installed in the X-14A was reliable and simple to operate.	X-14A	#1
Roll control fans can reduce the engine bleed-air required for satisfactory hover roll control.	X-14A	#2
The X-14A roll control fans exhibited excessively high first-order rpm time constants.	X-14A	#3

The cockpit layout and controller characteristics degraded the G755 conversion handling qualities.	G755	#2

D. - Human Factors

A fixed-base simulator proved to be invaluable for pilot familiarization prior to first flights of the XV-5A.	XV-5A	#1
XV-5A evaluation flights demonstrated that pilots could adapt to the lift-fan concept with relative ease.	XV-5A	#2
The narrow conversion airspeed corridor placed unreasonable demand on the pilot's adherence to operational procedures.	XV-5A	#11
Radiation from the pitch-fan gas ducts overheated the cockpit of the XV-5 at times.	XV-5A	#16
It was speculated that an inadvertent actuation of the conversion switch, while the XV-5A was well out of the conversion airspeed corridor, was responsible for a fatal crash of the aircraft.	XV-5A	#18
Poor cockpit arrangement in the Grumman Model 755 contributed to degraded conversion handling qualities.	G755	#2

APPENDIX II

APPLICATION OF LESSONS LEARNED TO THE DESIGN OF A SUPERSONIC STOVL FIGHTER

INTRODUCTION

The discussion to follow is an attempt to apply the key issues of "lessons learned" to what might be applicable to the preliminary design of a hypothetical supersonic STOVL fighter/attack aircraft (SSF). Its objective is to incorporate pertinent sections of the "Design Criteria Summary" of Appendix I into a discussion of six important SSF preliminary design considerations from the viewpoint of the writer's lift-fan aircraft flight test experience. These key issues are discussed in the following order: (1) Merits of the Gas-Driven Lift-Fan, (2) Lift-Fan Limitations, (3) Fan-in-Wing Aircraft Handling Qualities, (4) Conversion System Design, (5) Terminal Area Approach Operations, and (6) Human Factors.

Some assumptions must be made with regard to mission requirements and general configuration of the proposed Supersonic STOLV Fighter prior to applying "lessons learned" to its preliminary design. For the purpose of the discussion to follow, the proposed SSF is assumed to include the following features:

- Single-engine, single-pilot fighter/attack aircraft.
- Enhanced operational flexibility, survivability and utility.
- Gas-driven Fan-in-wing propulsion system.
- Short Take-off and Vertical Landing capabilities for Navy missions.
- Provisions for "de-VTOLed" version for USAF missions.

MERITS OF THE GAS-DRIVEN LIFT-FAN

XV-5 flight test experience proved that gas-driven lift-fans are robust and easy to maintain and operate. Drive shafts, gear boxes and pressure lubrication systems, which are highly vulnerable to enemy fire, are not required with gas drive. Pilot monitoring of fan machinery health is thus reduced to a minimum which is highly desirable for a single-piloted aircraft such as the SSF. Lift-fans have proven to be highly resistant to ingestion of foreign objects which is a plus for remote site operations. In one instance an XV-5A wing-fan continued to produce substantial lift despite considerable damage inflicted by the ingestion of a rescue collar weight. All pilots who have flown the XV-5 felt confident in the integrity of the lift-fans, and it is felt that the combat effectiveness of the SSF would be enhanced by using gas-driven lift-fans. To achieve commonality, the lift-fan cavities could be used for additional fuel or weapons in the "de-VTOLed" version for the USAF.

LIFT-FAN LIMITATIONS

It is recommended that a nose-mounted lift-fan NOT be incorporated into the design of the SSF for pitch attitude control. XV-5A flight tests demonstrated that although the pitch-fan proved to be effective for pitch attitude control, fan ram drag forces caused adverse handling qualities and reduced the conversion airspeed corridor. It is thus recommended that a reaction control system, similar to the one in the Grumman Design 755, be incorporated.

X-14A roll-control lift-fan tests revealed that control of rolling moment by varying fan rpm was unacceptable due to poor fan rpm response characteristics even when closed-loop control techniques were employed. Thus this method should not be considered for the SSF. However, lift-fan thrust spoiling proved to be successful in both the XV-5 and G755 designs and is recommended for the SSF.

Avoidance of the fan stall boundary placed significant operational limitations on the XV-5 and has the potential of doing the same with the SSF. Fan stall, like wing stall must be avoided and requires the observance of a safety margin during routine operations. Approach to the fan stall boundary proved to be a particular problem in the XV-5B while performing steep terminal area simulated instrument approaches. SSF preliminary designers must account for anticipated fan stall limitations and allow for adequate safety margins when determining SSF configuration and flight profile specifications.

FAN-IN-WING AIRCRAFT HANDLING QUALITIES

The XV-5 was a proof-of-concept lift-fan aircraft and thus employed a completely "manual" powered-lift flight control system. Having no integrated powered-lift system, the pilot was tasked with controlling aircraft flight-path through independent manipulation of stick, engine power, thrust vector angle and collective lift. This lack of an integrated powered-lift management system (and in particular, the conversion controls) was responsible for most of the adverse handling qualities of the aircraft. However, the Grumman 755 exhibited, with exception of the conversion, good handling qualities in general since it incorporated an advanced digital fly-by-wire control system which provided for integrated powered-lift management. It is presumed that the SSF will contain such a system to provide Level I handling qualities.

CONVERSION SYSTEM DESIGN

The manually operated conversion system was the most exacting, interesting and potentially hazardous flight operation associated with both the XV-5 and Grumman 755. This type of "bang-bang" conversion system MUST NOT be considered for the SSF. Ideally, the conversion should consist of a fully reversible and continuously controllable process. That is, the pilot should be able to control the rate of conversion and be able to reverse its direction at anytime during the conversion process. Good examples are the XV-15 Tilt Rotor, the X-22A and the AV-8 Harrier. Furthermore, the conversion of the SSF with an advanced digital flight control system should be fully decoupled such that the pilot would not have to compensate for lift, attitude or speed changes for example.

The conversion controller should be a single lever or beeper-switch that is safety-interlocked against inadvertent actuation. It is important that Level I conversion handling qualities be provided for single-pilot operation.

The conversion airspeed limit corridor must be wide enough to allow for operational flexibility and compensate for single-pilot operation where mission demands can compete for pilot attention.

A solution that was proposed to lessen the abrupt nature of the XV-5 ("bang-bang") conversion characteristics was to modify the system to incorporate a "sequential conversion" where gases from the two engines were diverted separately in sequence. This promising modification was never incorporated to evaluate its effects on pilot workload. However the basic principles of the sequential conversion may very well be applicable to the single-engine SSF. It is suggested that a "gradual conversion" could be accomplished by replacing the butterfly-type gas diverter valves with a new valve that allows for a continuous, constant engine-gas exit area, diversion of engine gases between the tail pipe and the fan inlet scrolls. For example, during a jet- to fan- mode conversion, as engine gas is diverted to the fans to increase their lift, tailpipe thrust is gradually decreased to decelerate the aircraft. The conversion process would be continuously controllable and fully reversible.

TERMINAL AREA APPROACH OPERATIONS

The XV-5B demonstrated that lift-fan aircraft are capable of performing steep simulated instrument approaches with up to 20-degree flight-path angles. Once more, lack of an integrated powered-lift flight control system was the primary cause of adverse handling qualities and operational limitations. The SSF's integrated powered-lift system should provide decoupled flight path control for glide slope tracking where a single controller, such as a throttle-type lever is used for direct flight-path modulation while airspeed and/or angle of attack are held constant. Simulator evaluations of such systems have indicated significant improvements in handling qualities and reductions in pilot workload..... a must in the single-piloted SSF.

Evaluations of the XV-5B's ability to perform simulated instrument landing approaches along a 10-degree glide slope revealed that pilots preferred to approach with a deck-parallel attitude (near-zero angle-of-attack) instead of using a deck-level attitude (near 10-degree angle-of-attack). Proximity to the 15-degree fan-stall boundary and random aerodynamic lift disturbances were cited as the causes. The 10-degree alpha approach may have resulted in reduced fuel consumption. SSF designers should encourage the development of lift-fans with increased angle-of-attack capability which would enhance IMC operational capability and improve safety.

All pilots that flew the XV-5 (the "XV-5 Fan Club") were of the unanimous opinion that the conversion handling qualities of the "Vertifan" were completely unsatisfactory for IMC operations. Trying to contend with the large power changes, attitude and altitude displacements, and abrupt airspeed changes while trying to fly instruments with the XV-5's "manual" control system was too much to handle. The enhanced operational flexibility requirement laid on the SSF requires that it have full IMC operational capability. Designers must provide Level I IMC handling qualities for efficient single-piloted flight.

HUMAN FACTORS

Human factors play a part in some of the key issues that have already been discussed above. Examples are: confidence in lift-fans, concern for approach to the fan-stall boundary, high pilot workload tasks, and conversion controller design.

The human factor issue that concerned the writer the most was that of the cockpit arrangement of the Grumman Model 755 flight simulator. An XV-5A and its pilot were probably lost because of the inadvertent actuation of an incorrectly specified and improperly positioned conversion switch. This tragic lesson must not be repeated, and careful human factor studies must be included in the design of modern lift-fan aircraft such as the Model 755 and the SSF. Human factor considerations should be incorporated early in the design and development of the SSF from the first simulation effort on through the introduction of the production aircraft.

It is therefore the writer's hope that SSF designers will remember the past as they design for the future and take heed of "Lessons learned".

APPENDIX III

FLIGHT TEST EXPERIENCE

Ronald M. Gerdes

Total Flight Time - 10,000 hrs.

Types of Aircraft - 100 fixed- and rotary-wing

V/STOL Flight Time - 330 hrs.

Types of Experimental V/STOL Aircraft - 5

XV-5A and B - 30 hrs.

X-14A and B - 81 hrs.

X-14A with Roll Control Fans - 2 hrs.

(YAV-8B, XV-15 & X-22A - 217 hrs.)

XV-5B Flight Test Experience (Ames Research Center)

Take-offs:

CTOL	59
VTOL	18

Conversions:

Jet- to Fan-Mode	52
Fan- to Jet-Mode	33

Terminal Area Approaches:

Pilot's Eye	18
Visual Approach Indicator	17
Instrument Landing System	32

Landings:

CTOL	40
STOL	1
VTOL	36

1. PITOT MAST
2. FIBERGLASS NOSE CONE
3. G. E: X376 PITCH FAN
4. NOSE FAN THRUST CONTROL DOOR
5. NOSE FAN INLET CLOSURE DOORS
6. WINDSHIELD
7. NOSE FAN SUPPLY DUCT
8. RUDDER PEDALS
9. INSTRUMENT PANEL
10. CONVENTIONAL CONTROL STICK
11. OBSERVER'S EJECTION SEAT
12. NOSE LANDING GEAR
13. THROTTLE QUADRANT
14. PIOLOT'S EJECTION SEAT
15. COLLECTIVE LIFT STICK
16. HYDRAULIC EQUIPMENT COMPARTMENT
17. SINGLE SPLIT ENGINE INLET DUCT
18. ELECTRICAL EQUIPTMENT COMPARTMENT
19. HYDRAULIC PUMP
20. FWD MAIN FUEL TANK
21. GENERATOR
22. RIGHT WING
23. G.E. J85-5 GAS GENERATOR
24. AILERON, R.H.
25. CROSS-OVER DUCT
26. WING FAN LOUVER ACTUATORS
27. DIVERTER VALVE
28. WING FAN INLET CLOSURE DOORS
29. G.E. X353- 5B LIFT FAN
30. ENGINE TAIL PIPE
31. TWO POSITION MAIN LANDING GEAR
32. LEFT WING
33. AILERON L.H.
34. WING FLAP, L.H.
35. THRUST SPOILER, L.H.
36. EXTERNAL LONGERON
37. VERTICAL FIN
38. FULL MOVEABLE HORIZONTAL STABILIZER
39. ANTI-SPIN AND DRAG COMPARTMENT
40. RUDDER
41. ELEVATORS

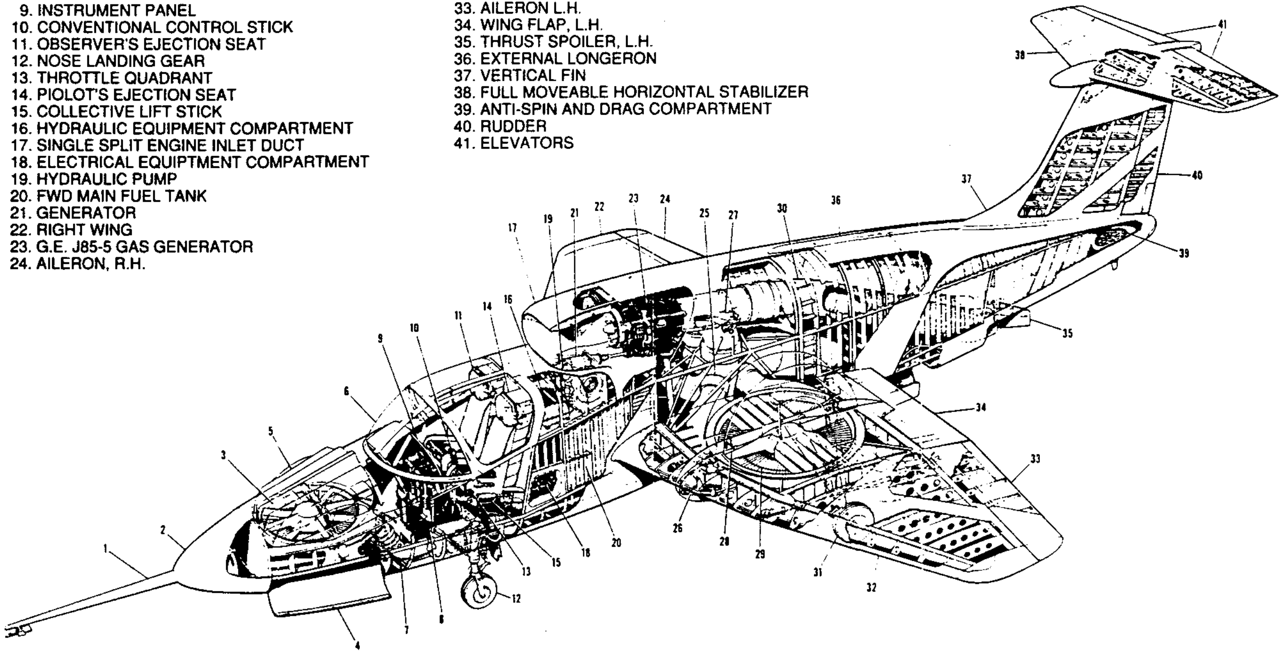

Figure 1. XV-5A aircraft cutaway drawing.

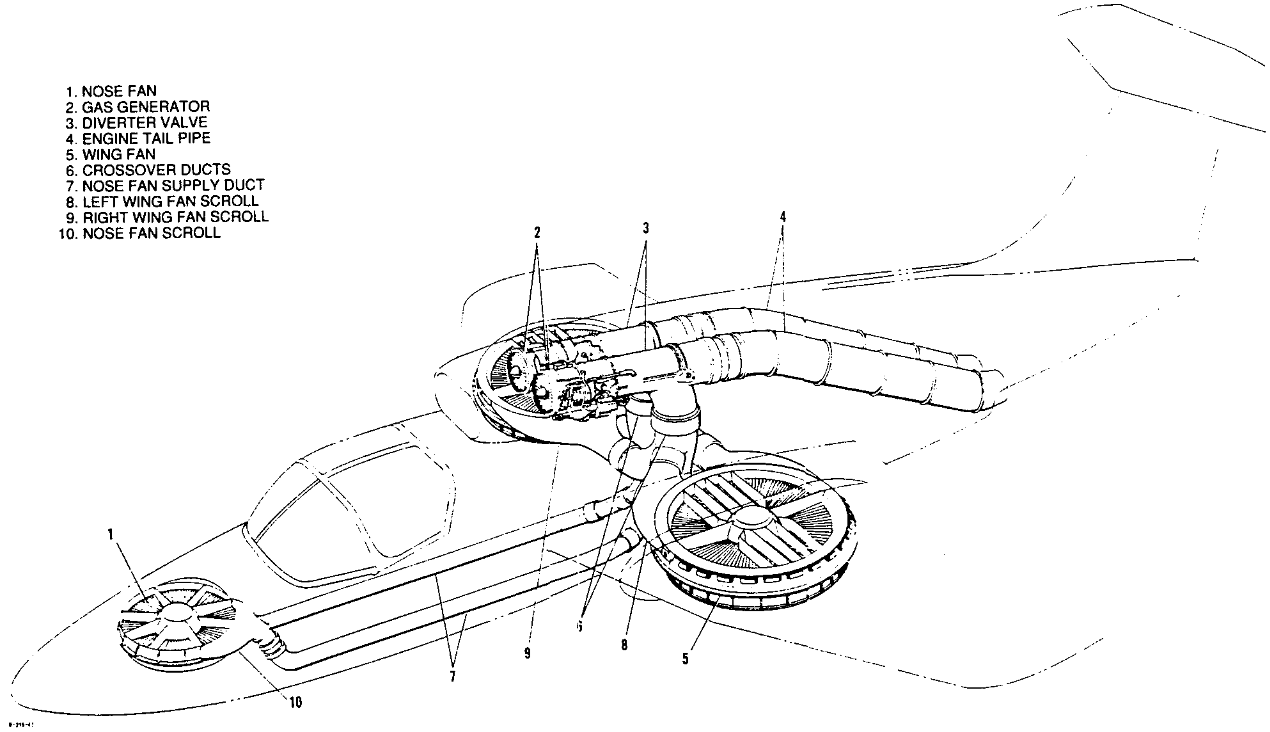

Figure 2. XV-5A propulsion system components.

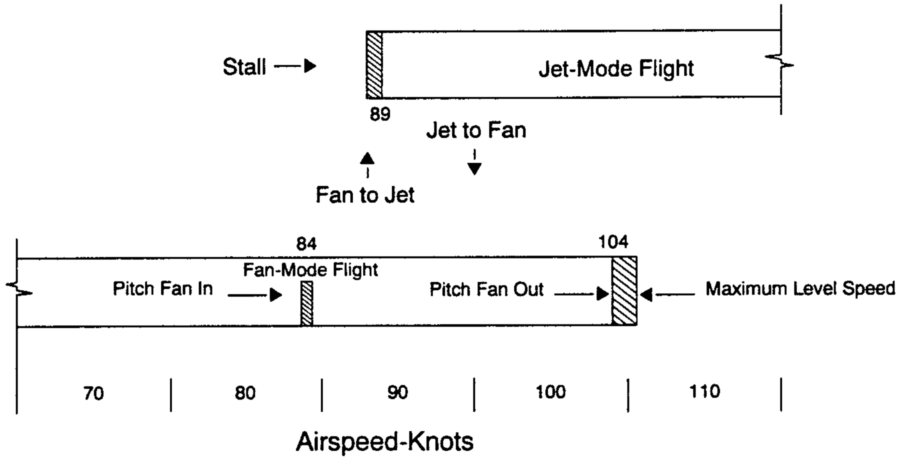

Figure 3. XV-5A safe conversion airspeed corridor.

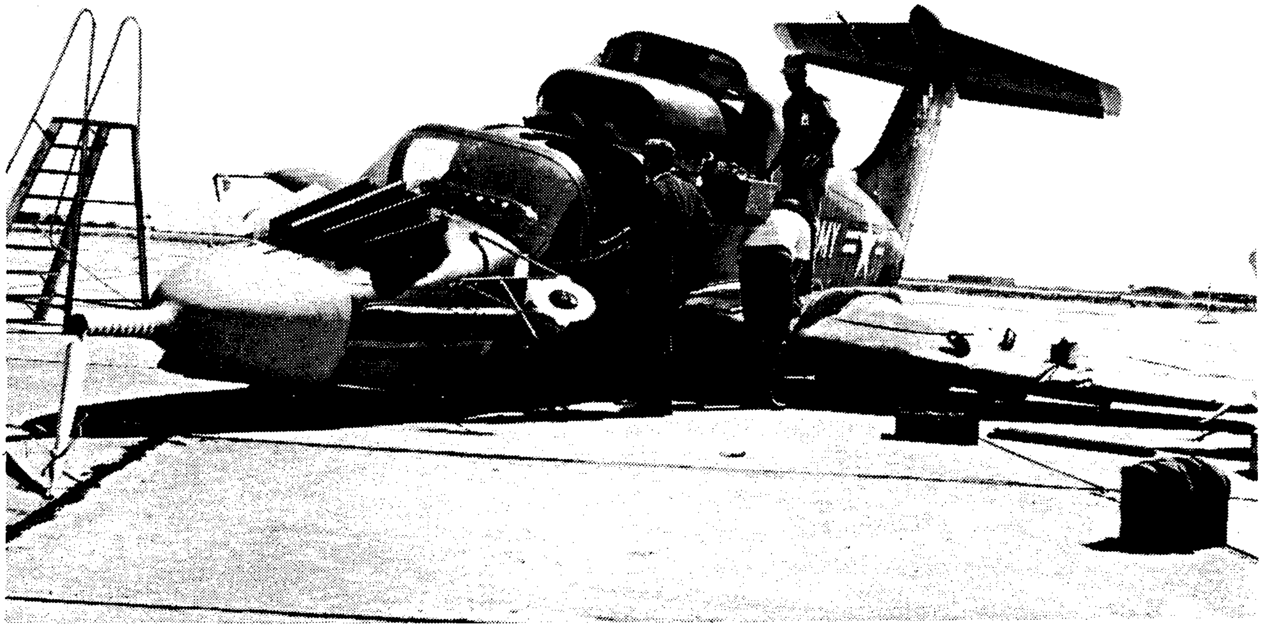

Figure 4. XV-5A after emergency landing at Edwards AFB on October 5, 1966.

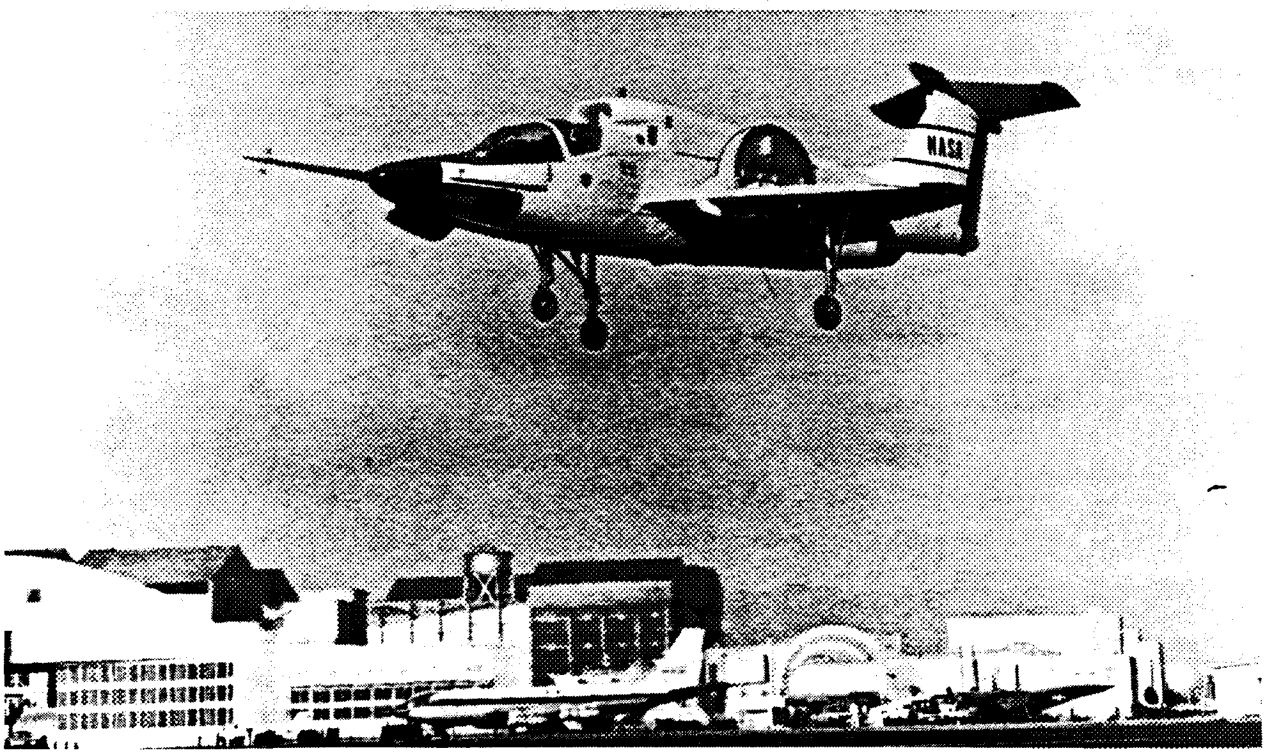

Figure 5. XV-5B airplane in hover flight.

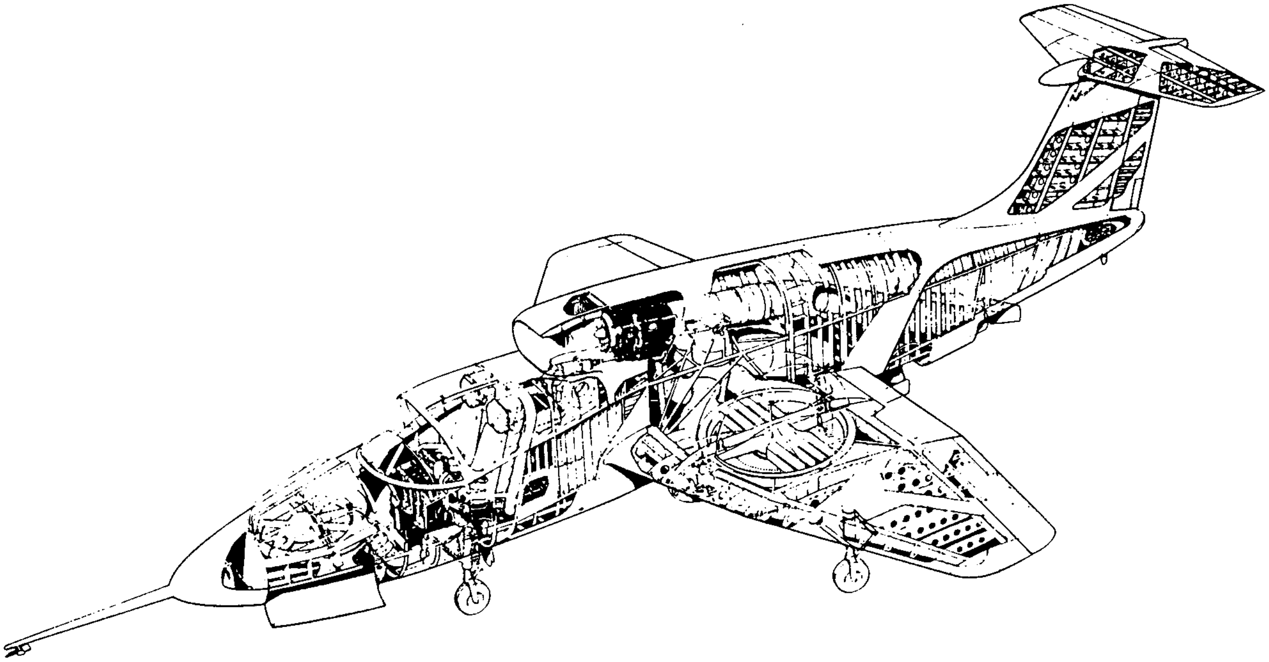

Figure 6. XV-5B cutaway drawing.

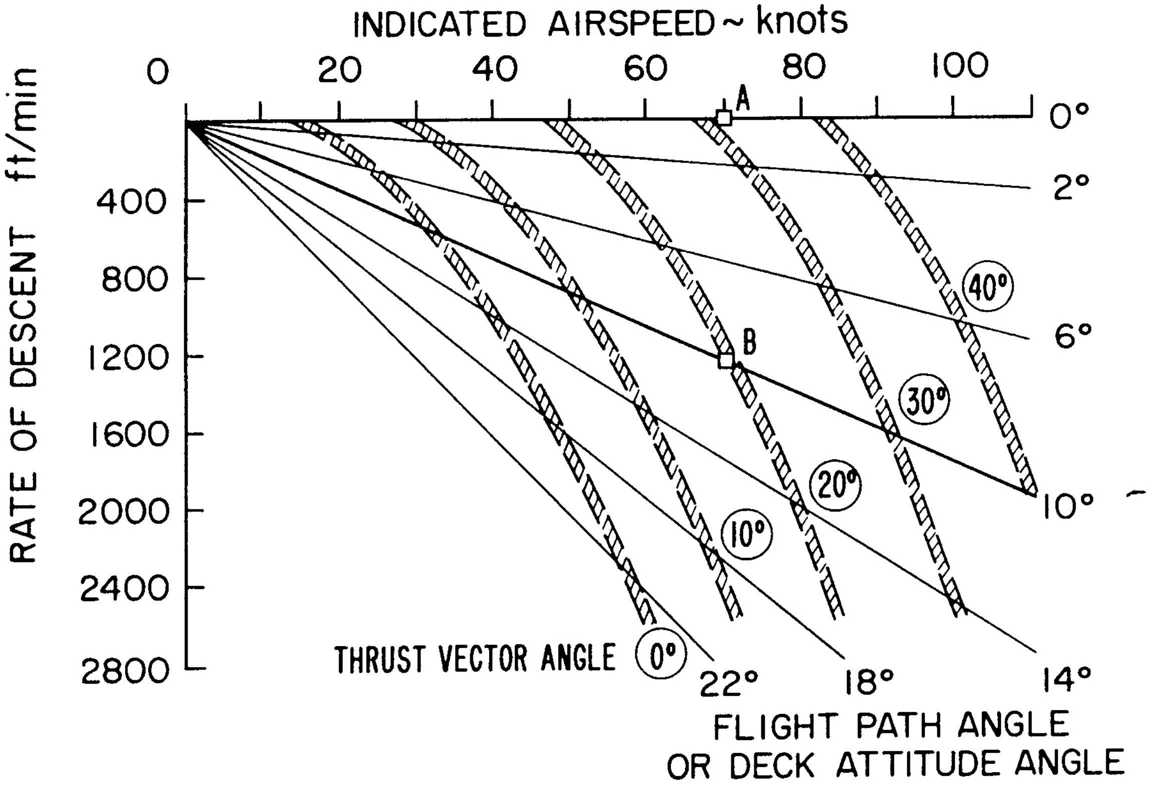

Figure 7. XV-5B deck-parallel terminal approach envelope.

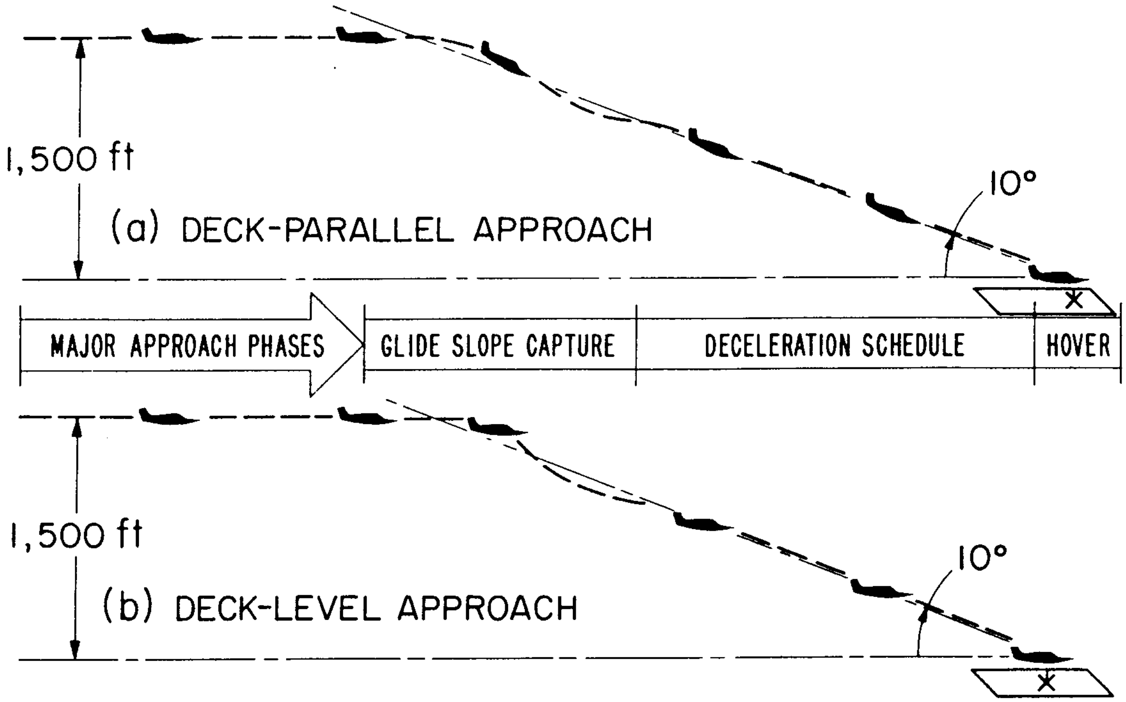

Figure 8. XV-5B terminal area procedures.

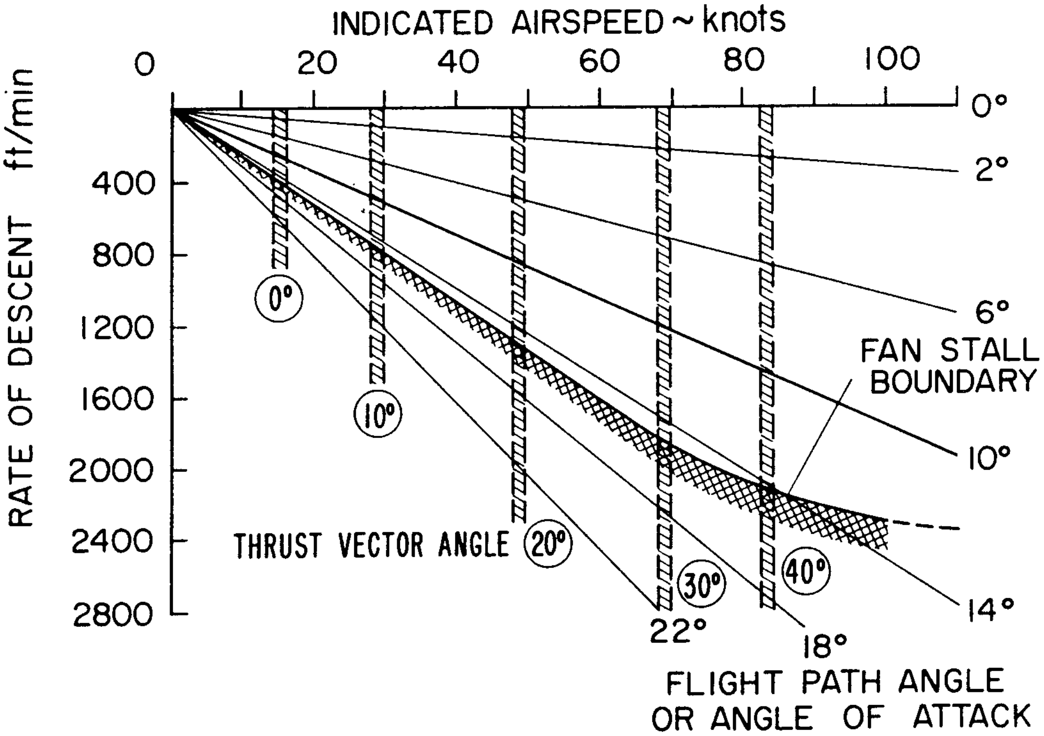

Figure 9. XV-5B deck-level approach envelope.

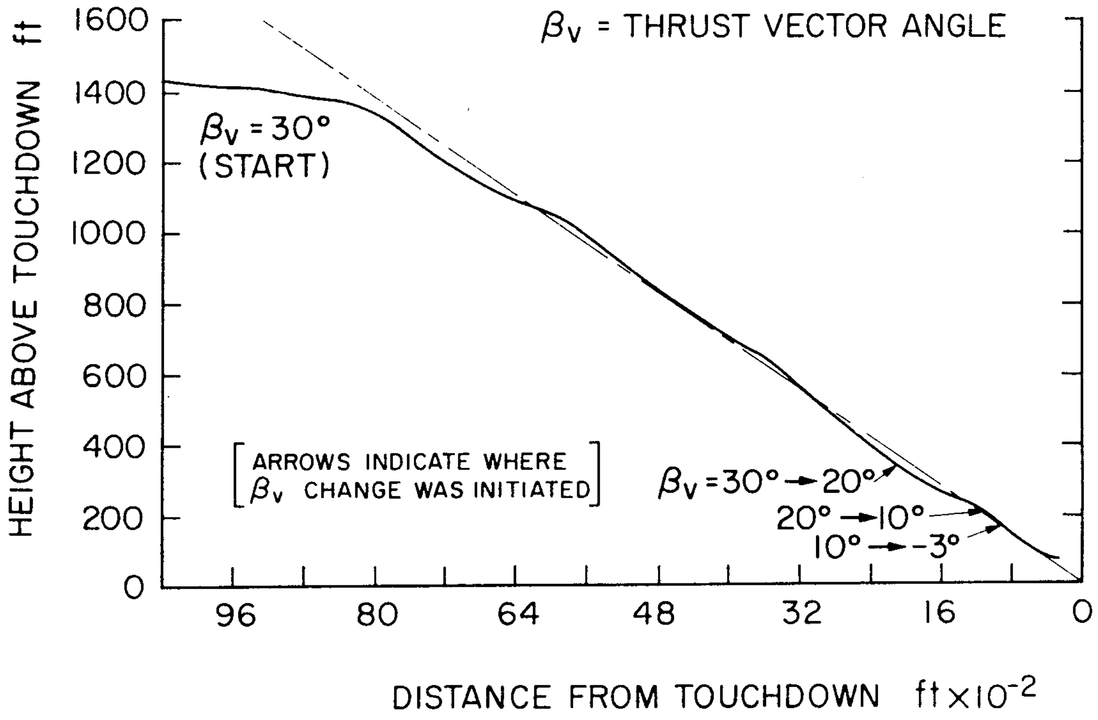

Figure 10. Radar profile of a XV-5B deck-level approach.

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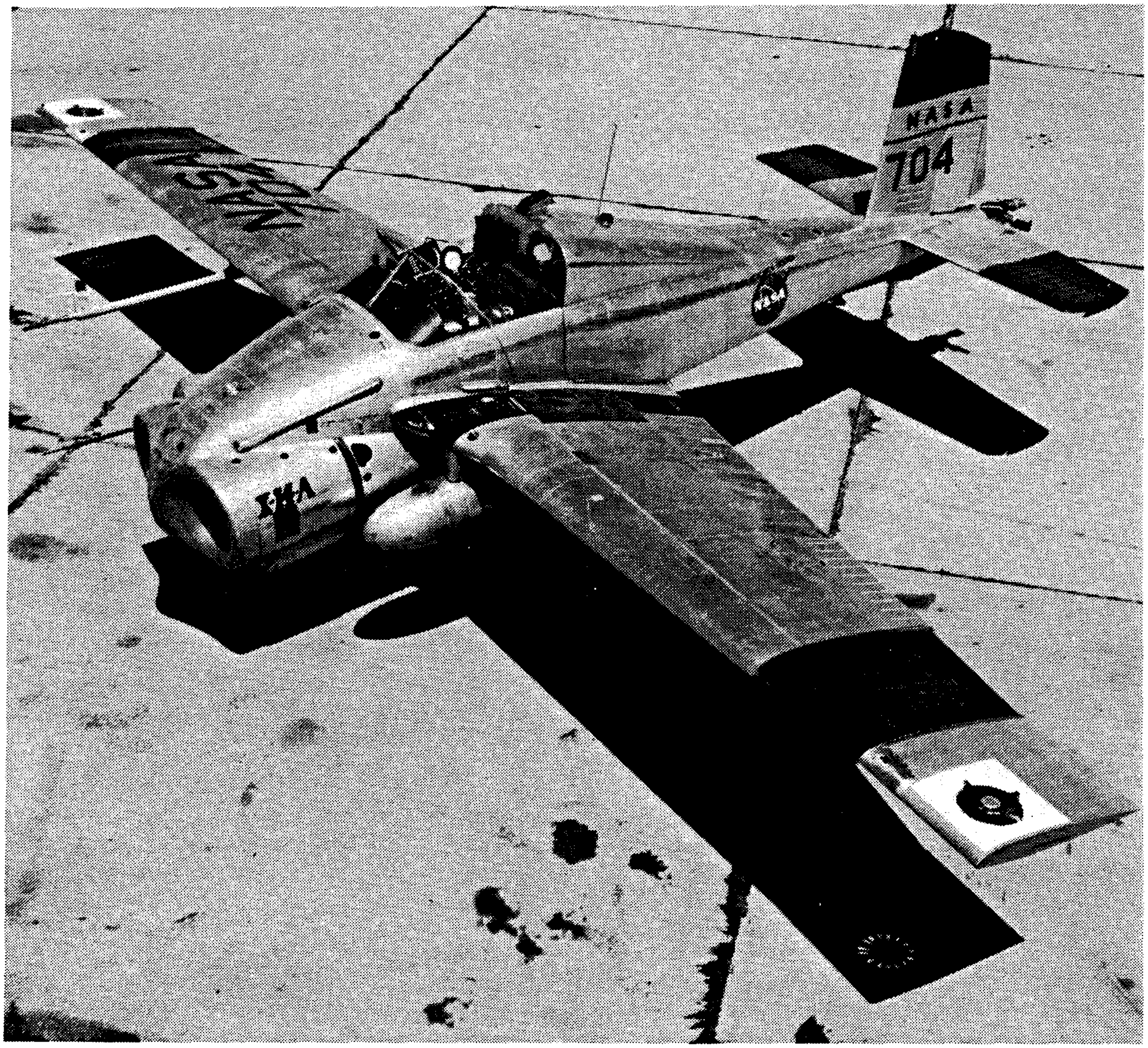
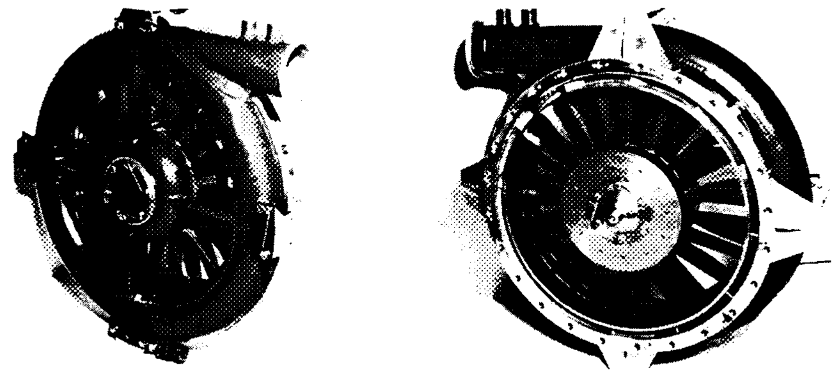


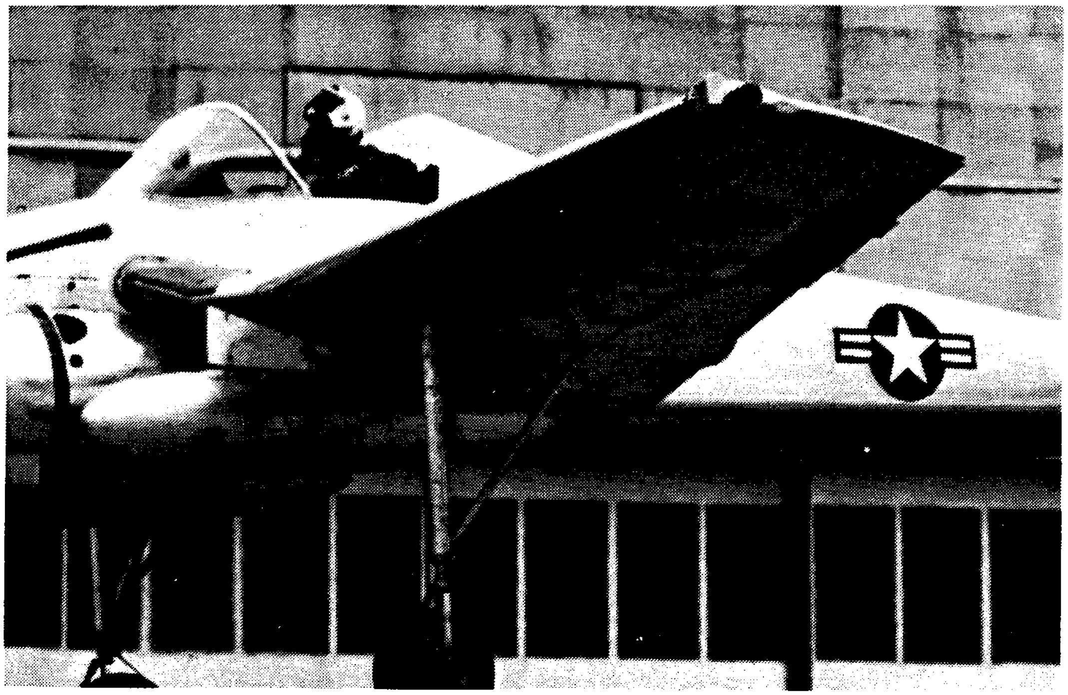
Figure 11. X14-A aircraft with tip-driven roll-control fans installed on wing tips.



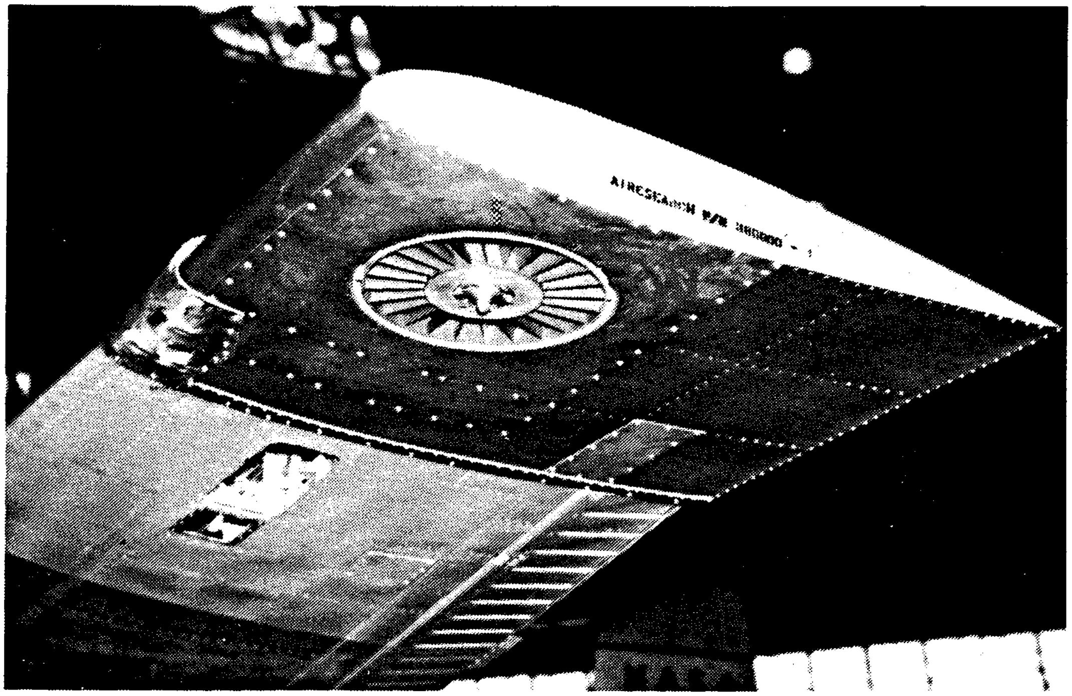
Inlet side.

Exhaust side.

Figure 12. Photograph of tip-driven control fan.



Original wing tip.



Modified wing tip.

Figure 13. Close-up view of original wing tip and wing tip with tip turbine-driven fan.

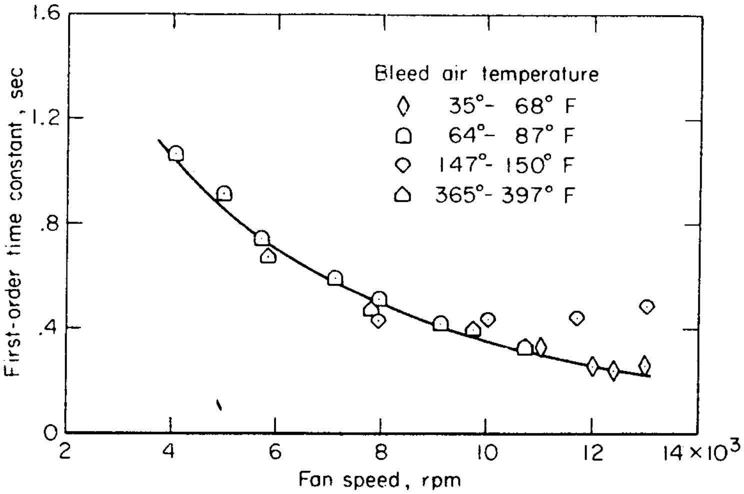


Figure 14. Open-loop fan response characteristics; test stand data.

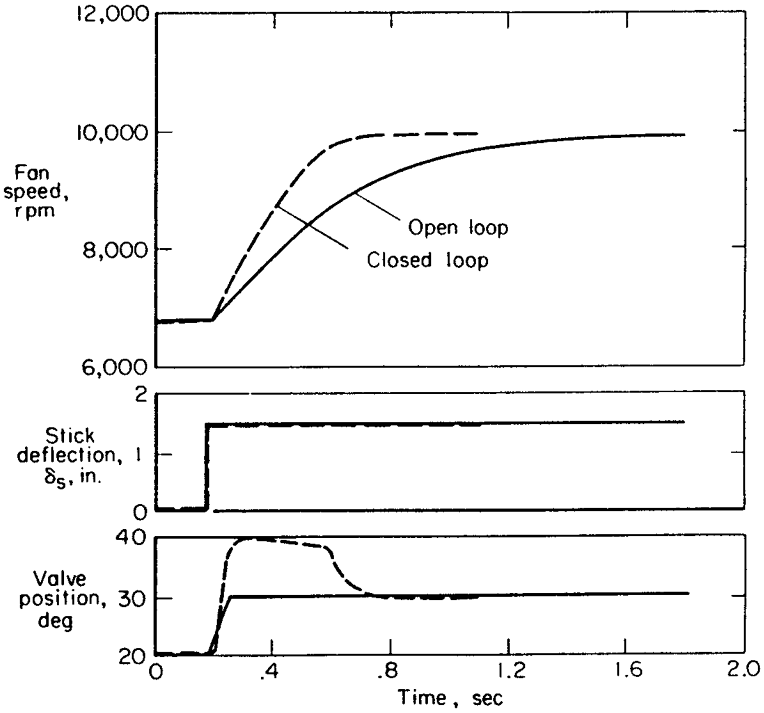


Figure 15. Comparison of fan response for open-and closed-loop controllers.

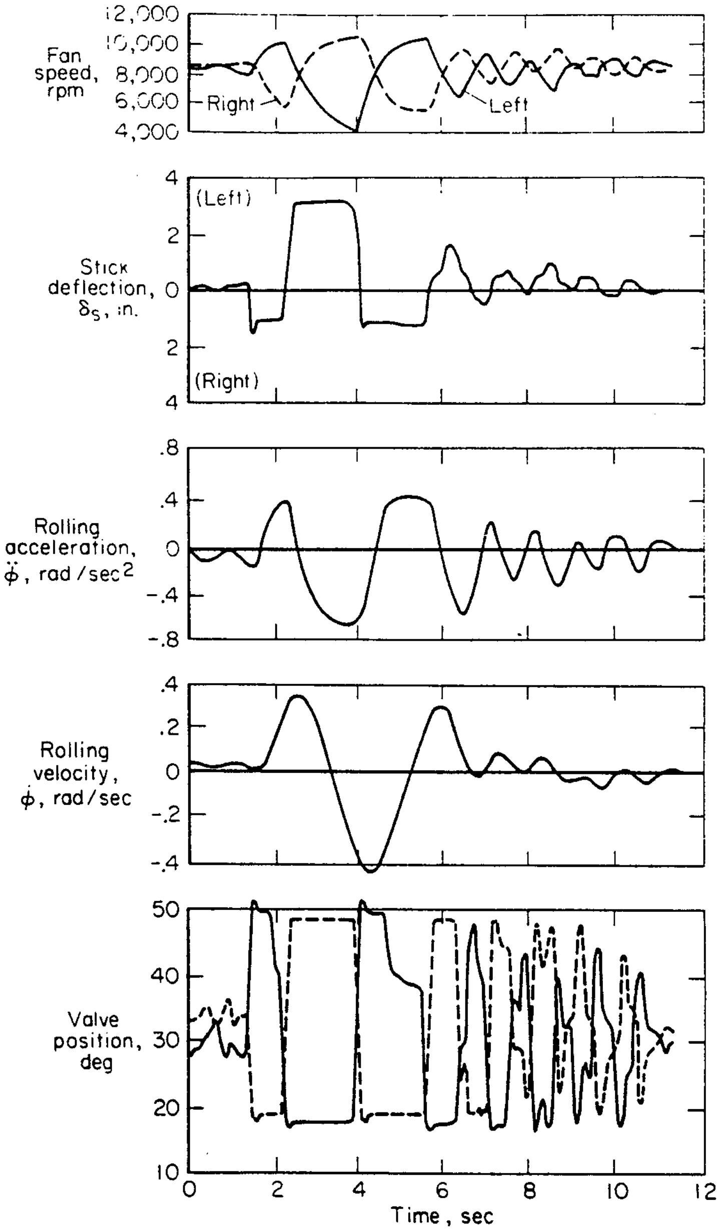


Figure 16. Time history of a step aileron input during hover.

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13. ABSTRACT ***(Maximum 200 words)***

This paper is written from an engineering test pilot's point of view. Its purpose is to present lift-fan "lessons learned" from the perspective of first-hand experience accumulated during the period 1962 through 1988 while flight testing vertical/short take-off and landing (V/STOL) experimental aircraft and evaluating piloted engineering simulations of promising V/STOL concepts.

Specifically, the scope of the discussions to follow is primarily based upon a critical review of the writer's personal accounts of 30 hours of XV-5A/B and 2 hours of X-14A flight testing as well as a limited simulator evaluation of the Grumman Design 755 lift-fan aircraft.

Opinions of other test pilots who flew these aircraft and the aircraft simulator are also included and supplement the writer's comments. Furthermore, the lessons learned are presented from the perspective of the writer's flying experience: 10,000 hours in 100 fixed- and rotary-wing aircraft including 330 hours in 5 experimental V/STOL research aircraft.

The paper is organized to present to the reader a clear picture of lift-fan lessons learned from three distinct points of view in order to facilitate application of the lesson principles to future designs. Lessons learned are first discussed with respect to case histories of specific flight and simulator investigations. These principles are then organized and restated with respect to four selected design criteria categories in Appendix I. Lastly, Appendix II is a discussion of the design of a hypothetical supersonic short take-off vertical landing (STOVL) fighter/attack aircraft.

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