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The Lift-Fan Powered-Lift Aircraft Concept: Lessons Learned

Wallace H. Deckert

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Prepared for
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Introduction

This is one of a series of papers presented at a Seminar held at NASA Ames Research Center, 1992.

The stated objective of this effort is to conduct a thorough review of, and document, the lessons learned from past research related to lift fans and lift-fan aircraft concepts. This includes conceptual design studies, wind tunnel tests, piloted simulations, flight tests of aircraft such as the XV-5B, and propulsion system component tests. The results will be made available to appropriate government personnel to help guide enabling technology validation programs.

A team of experts has documented lessons learned from past lift-fan aircraft research. These experts are NASA Ames retirees, and staff from NASA Ames and NASA LeRC. Each is the author or co-author of a technical paper in this series. The hope is that this effort will help foster the continued advancement of lift-fan aircraft technology, and in particular, "without reinventing the wheel".

The first lift-fan aircraft experimental research investigation in the nation featured a "lift fan" in a two-dimensional wing. Lacking a real lift fan, a propeller was used to simulate a lift fan. This research, conducted by Mr. David H. Hickey of NACA Ames, was initiated in 1956, thirty-six years ago. In 1957 Mr. Hickey published NACA RM A57F03, "Preliminary Investigation of the Characteristics of a Two-Dimensional Wing and Propeller With the Propeller Plane of Rotation in the Wing-Chord Plane". Since then, NACA and NASA researchers and contractors have authored hundreds of technical publications on the advancement of lift-fan aircraft technology. The summary report in this series contains a Master Bibliography of a selected set of these publications.

Most lift-fan aircraft research was conducted in the context of being applicable to subsonic aircraft. For supersonic lift-fan aircraft, takeoff, landing, conversion to and from powered-lift flight, and some mission legs are at subsonic speeds. This fact, and because some research was generic, makes some subsonic research applicable to supersonic aircraft. Some research was specific to supersonic aircraft.

Lift-fan aircraft research was applicable to all categories of powered-lift aircraft including those known by the acronyms STOL, VTOL, V/STOL, and STOVL. See Appendix I for definition of, and aircraft design implications for, the various powered-lift aircraft acronyms.

Mission Applications

Lift-fan aircraft are competitive throughout the powered-lift spectrum; STOL, VTOL, V/STOL, and STOVL. They are applicable to supersonic and subsonic aircraft, to civil and military aircraft, to fighters and transports, and to personal aircraft.

The applicability of lift-fan aircraft is partly because vertical flight often requires dynamic vertical flight as opposed to sustained steady-state hovering flight while in the vertical flight mode. Lift-fan aircraft are competitive for certain missions that do require sustained hovering flight as illustrated in two examples that follow.

One example is for the class of missions in which time is of the essence and radius of action is long, such as ocean-wide search and rescue. The helicopter, with its hovering capability, is not competitive for these missions that do require hovering flight because of limited range. Tilt rotor aircraft may have the range, but the higher speed lift-fan aircraft have the advantage when time is of the essence.

Another example is for the class of missions in which the sustained hovering requirement is for a short period of time, such as inflight vertical delivery of supplies for civil national disasters, and for replenishment and other military missions.

Though promising for certain missions that require sustained hovering flight, lift-fan aircraft are most promising for the civil and military missions that require dynamic vertical flight.

Aircraft design and operational considerations differ for sustained hovering flight and dynamic vertical flight. The considerations include fuel usage, reingestion, FOD, visibility, perceived noise, nonproductive time, ground-effect-induced performance changes and attitude upsets and instabilities, detectability, and requirements for preparation of the terminal site.

A lesson learned was that differences favor dynamic vertical flight.

For example, a ground-effect-induced upsetting moment during hovering flight may not be detectable during dynamic takeoff or landing. For lift-fan aircraft on missions requiring dynamic vertical flight, fuel usage during takeoff or landing and those problems associated with steady-state sustained hovering flight may not be issues.

Though lift-fan aircraft technology can be utilized to meet todays missions, it is better characterized as a technology for missions that yield new civil opportunities and new military strategies.

Civil opportunities include new or expanded services in such areas as:

1. Ocean resource operations, with "terminals" on oil rigs, ships, and mineral exploration platforms.

2. Direct city-center to city-center transportation.

3. Direct corporate office to factory service.

4. Transportation for underdeveloped countries.

5. Transportation for inaccessible communities.

6. Search and rescue.

7. Emergency medical services.

8. Disaster relief.

9. Private flying, including to/from terminal sites that are not airports.

Military strategies include new or expanded modes of operation in such areas as:

1. Enhanced operations from aircraft carriers.

2. Operations from "nonaviation" ships.

3. Operations from civil ships in time of need.

4. Solution for total runway denial.

5. Use of austere dispersed land-based sites.

6. Search and rescue.

7. In-flight vertical delivery.

8. Counter for terrorist activity

A view that is too limited is that lift-fan aircraft are promising for new civil opportunities and military strategies because of takeoff and landing capability such as STOVL or V/STOL.

A lesson learned was that lift-fan aircraft are promising for several reasons, namely as follows:

1. Short and/or vertical takeoff and landing.

2. Near-terminal departure and approach, and up-and-away flight performance and maneuverability. Enhancements are due to in-flight thrust vectoring, low-speed attitude control systems, and more.

3. Aircraft design tradeoffs. For example, lift-fan-in-fuselage installations compromise fuselage design to a degree. However, unlike for conventional aircraft, the lift fan assists takeoff and landing to the degree that the wing can be optimally designed for cruising flight.

4. Advantages from use of ground-based facilities. For example, lift-fan aircraft are compatible with ski-jumps. A STOVL aircraft "can not be thrown into the air before it is ready to fly" because minimum control airspeed, Vmc, is zero and thrust-to-weight ratio is not limiting. Civil lift-fan aircraft can utilize existing ground facilities in new ways, such as departing within the boundaries of the airport to eliminate noise annoyance in surrounding suburbs.

5. Total system considerations. This requires no explanation to DOD who are experts at total weapons system analysis. If the aircraft carrier does not have to be turned into the wind in order to launch some of its aircraft, DOD understands and accounts for that advantage. On the other hand, to the author's knowledge, there are no civil authorities responsible for total transportation systems. If a higher airline ticket price enables lower ground transportation costs, saves time, and lowers taxes, the airline operator is not impressed that his ticket prices are higher than competition. Despite this reality, there are significant total transportation system gains from use of civil lift-fan aircraft.

It is not unusual for military and civil potential customers to be as interested, even more interested, in all of the above attributes of lift-fan aircraft as they are in the one well-known attribute concerning short and/or vertical takeoff and landing. Elaboration is found in the various papers presented at the Seminar.

Lift-Fan Aircraft Design Studies

This section contains a description of and the lessons learned from lift-fan aircraft design studies. The studies are those about many powered-lift aircraft concepts of which the lift-fan aircraft concept was one, and those that were exclusively about lift-fan aircraft concepts.

The section is organized into eight subsections, with each subsection covering an aircraft design study or a related set of studies. The title for each of the subsections is the title used in the final report(s). Also see Appendix II which presents these design studies in a brief chronological format, and further correlates the presentation with the Bibliography.

The time period is 1956 to 1992. During the period 1956 to 1962, there were no NACA/NASA lift-fan aircraft design studies per se. Rather this period included exploratory lift-fan aircraft research, support for the Avrocar and XV-5A lift-fan aircraft, and NASA/General Electric studies of lift-fan propulsion. The section begins with the first NASA aircraft design study that included lift-fan aircraft, a study published in 1964.

Design and Operating Considerations of Commercial STOL Transports

This was a NASA in-house aircraft design study that supported FAA's program for a new short-haul aircraft for the local service airlines. Payload included 20 passengers and range was 690 sm that enabled four 100 sm stage lengths without refueling. Though emphasis was on propeller STOL aircraft, the study did include 1 lift-fan STOL. Also included were propeller VTOL and CTOLs and a turbofan CTOL for comparisons with the STOLs.

Using the original figures drawn 30 years ago, the final report argued: figure 1 -- that local service airlines approach at 90 kts, require airfields 3500 ft long, and thus can fly into 35% of existing fields, whereas the lift-fan STOL with a 60 kt approach could land in 95% of the existing fields; figure 2 -- that approach and takeoff patterns are much less for STOLs than CTOLs, and this has important implications in reducing traffic control problems, time lost in air maneuvering and more; and figure 3 -- that STOLs can land safely under IFR conditions of lower ceilings and less visibility which also improves schedule reliability. After 30 years neither the figures nor the text require change.

Some particulars about the lift-fan STOL were: fan-in-wing with 2 interconnected gas generators and 2 tip-turbine lift fans of 5.4 ft dia and 8200 lb thrust each; and an aircraft of 25800 lb DGW with a cruise airspeed of 390 kt and an approach airspeed of 60 kt into a 1500 ft field. See no figure for a drawing of this lift-fan aircraft, because no one ever drew it.

One study result was figure 4. It says the DOC of the jet having a 60 kt approach speed (i.e. the lift-fan STOL) is not much more than that of the jet CTOL, and further as stage length reaches 300 sm or more the lift-fan aircraft starts becoming competitive to propeller aircraft. The author can not resist adding to this paragraph that at the time we were concerned about fairness and objectivity so for the DOC computation we raised the price of gas to the high level of 12.5 cents/gallon.

One lesson learned from this first design effort was the knowledge that can be gained by including reference aircraft on each side of the powered-lift spectrum compared to the aircraft under study. For example, if design is about STOVL, then the scope should include designs to the same mission (as much as possible) of one reference V/STOL and one reference STOL.

Study on the Feasibility of V/STOL Concepts for Short Haul Transport Aircraft

These were the first NASA contractual studies that included design of lift-fan powered-lift aircraft. Prior to these NASA studies, U.S. Air Force contractual studies of large military transport designs had been completed. Known as the CX-6 studies, the Air Force studies included design of lift-fan VTOL transports, and these CX-6 designs were used as reference points for initiation of some of the NASA contractual designs.

The NASA studies, conducted during the mid 1960s, included NASA in-house activities and contracts to Boeing, Vought, and Lockheed. Prior to go-ahead, NASA spent months establishing the rules and creating a comprehensive document on design goals and criteria.

A lesson learned was the importance, for directing studies, for obtaining meaningful results, and for efficiency, of preparations prior to initiation of aircraft design studies.

Aircraft design goals included 500 statute mile range, cruise airspeed near miminum direct operating cost, 60 and 120 passengers, reserve fuel and revenue cargo, 1970 propulsion, aircraft low-speed control criteria for all engines and for critical engine inoperative, and control criteria that varied as a function of aircraft design gross weight. Studied were five VTOL concepts with trimmed thrust/weight ratios of 1.15 all engines and 1.05 critical engine inoperative, and four STOL concepts for commercial field lengths of 1000 and 2000 feet that corresponded to 55 and 85 knot approach airspeeds.

The VTOL concepts, illustrated in figure 5, were: rotor concepts -- one tilt rotor and one stowed rotor design; propeller concepts -- three design variations of the tilt wing; lift-fan concepts --three design variations; and lift jet concepts -- one design. Following are two examples of VTOL 60-passenger lift-fan aircraft designs

Figure 6 was the Boeing VTOL lift-fan aircraft design. VTOL DGW was 79,000 lb, or 85,500 lb if non-burning reaction control nozzles were used. Cruise speed was Mach 0.80. The propulsion system had 8 engines, 4 cruise and 4 to power the gas-driven lift fans. The 4 lift fans were cross ducted in the roll sense only. Lift fans were 6.45 ft dia, 1.3 PR, and partial admission scroll arc (163 deg) to facilitate installation. Low-speed controls had 4 reaction burn nozzles at aircraft extremities with nozzles also vectoring for yaw. Sixty percent of control was available without burn, so the argument was that the complicated (but also light weight) burning system would rarely be used.

Figure 7 was the Lockheed VTOL lift-fan aircraft design. VTOL DGW was 71,800 lb, and cruise Mach number was 0.80. Each wing tip pod had 3 gas generators, a variable stator gas-driven lift fan, and a cruise fan driven by a 4-stage turbine. The 3 gas generators discharged through isolation valves into a commom manifold to handle engine out. A concern at the time was whether engines could be manifolded in this manner. The cruise fan had vectoring Pegasus-type nozzles. The 1.3 PR lift fan had a diameter of 85 inches. Roll control was a spoilage system achieved by opposite fore and aft vectoring of the Pegasus nozzles and the lift fan exit louvers. Roll inertia was high, and roll control was less then desired. For pitch and yaw the design featured a turret type double spool valve on the fuselage aft extremity.

One design eliminated during this civil short-haul transport study was the pure fan-in-wing. For the fan-in-wing the same gas generators that drove remote lift fans during low-speed flight provided thrust for cruise. This fan-in-wing approach led to large diameter lift fans, compromised wing design, and a heavy aircraft. The fan-in-wing was eliminated in favor of the composite lift-fan aircraft with separate gas generators for cruise flight (with thrust deflectors for lift in low-speed flight).

A lesson learned was "a red flag of warning" that pure fan-in-wing designs may not be as competitive as other lift-fan aircraft configurations.

Figure 8 shows mission areas that were promising for the VTOL concepts in terms of stage length and payload. Lift-fan VTOL concepts were promising for 60 passengers at stage lengths of 500 sm or more. Lift-fan concepts become more promising as stage length increases. As figure 8 shows,lift-fan concepts also become more promising as payload is increased. The rate of increase in gross weight with payload is less for lift-fan VTOLs (and other jets). For intuitive confirmation of this trend, note the existence of 747s and comparatively small helicopters and propeller-driven aircraft. Figure 8 shows no competitive area for direct lift turbojet VTOLs for civil short-haul, primarily because of their high perceived noise levels.

One discriminator was gust sensitivity. Lift-fan and turbojet concepts had the least gust sensitivity due to high wing loading and low-aspect ratio swept wings.

Another discriminator was perceived noise. High-frequency noise attenuates with distance more than low-frequency noise, and lift-fan aircraft generate high-frequency noise. This led to the result that rotor VTOL aircraft were close to acceptable for city centers but unacceptably noisy unless many miles from residential areas. Lift-fan VTOL aircraft were unacceptable for city centers but acceptable when 2 miles from residential areas.

A lesson learned was caution before concluding lift-fan aircraft are noisier or quieter than other concepts.

Another lesson learned was that lift-fan aircraft have time on their side because of the impact of advancing technology.

In the 1960s, when pushing technology to 1980, improved propulsion and lighter materials had a more favorable impact on lift-fan aircraft than on lower disc loading types. If the 1960s studies were repeated in the 1990s, referring to figure 8, the 1990s results would show the white area favoring the low disc loading concepts to be smaller, and the black area favoring the lift-fan concepts to be larger. Most of the other relative results regarding the competing VTOLs would be about the same.

A lesson learned was the sensitivity of short-haul economics to nonproductive time. In particular, that an aircraft's deceleration capability during approach, of importance for many reasons, is also of importance to minimize nonproductive time.

Lift-fan aircraft can decelerate; for some concepts deceleration is a limitation. One VTOL lift-fan aircraft had a total deceleration, $\tan \gamma + \dot{u}$, of 0.58g. The value 0.58g was not used because the component of the deceleration along the flight path exceeded passenger acceptance. For non-passenger carrying civil aircraft and for military aircraft such a large deceleration is a major merit. A total deceleration of 0.30g was used for the lift-fan aircraft compared to 0.20g for the tilt wing, and to less for some STOL types. Such differences yielded less nonproductive time during landing approach for the lift-fan aircraft with favorable impact on direct operating cost, as well as the other advantages such as steeper glide slopes for terrain clearance and noise reduction.

The STOL concepts, illustrated in figure 9, were: propeller concepts --two variations of the deflected slipstream concept; lift-fan concepts -- two variations of the fan-in-wing concept plus one propulsive wing; and turbojet concepts -- one jet flap and one EBF (externally blown flap). As for VTOL, the STOL pure fan-in-wing was eliminated during the study.

Figures 10, 11, and 12 illustrate a 60-passenger STOL lift-fan aircraft of a different type, namely the Vought propulsive wing design. For the 1000 ft STOL, DGW was

67,500 lb and cruise Mach number was 0.90. Small-scale wind tunnel tests supported the contention that drag rise Mach number for the propulsive wing design was 0.90. As shown in figure 11, four gas generators drove 8 wing-mounted turbines which were shaft connected to 8 wing fans of 36.1 inch dia. Two additional gas generators drove two fuselage mounted turbines which were connected by long shafts to two fuselage nose fans. The fuselage nose fans operated in cruise as well as STOL. Each wing gas generator was interconnected to the corresponding gas generator on the opposite side by a gas duct. During slow speed flight, pitch control was augmented by differential thrust between nose and wing fans; and roll and yaw were by differential wing thrust vector and by differential wing thrust using gas power transfer.

The conclusion for STOL was for a commercial field length of 2000 feet, propeller, lift-fan, and turbojet concepts were competitive. For a field length of 1000 feet, the promising STOL concepts were the propeller, lift fan, and turbojet types in that order.

In the 1960s predictions for advancing technology were the same for STOL as for VTOL, namely that advancing technology favors turbomachinery STOLs. During the next thirty years came the YC-14, YC-15, QSRA, Russian and Japanese USBs, and the C-17. Today, propeller STOL short-haul transports can not challenge turbomachinery STOLs, such as QSRA USBs, even at the shorter field lengths within the STOL powered-lift category.

As of today, the STOL lift-fan short-haul transport aircraft has lost out to the STOL USB and EBF concepts. One point for consideration is as follows. There is no apparent straight-forward way to evolve STOL USB or EBF designs into VTOLs, V/STOLs, or STOVLs. STOL lift-fan aircraft, on the other hand, can be evolved into the other powered-lift aircraft categories that require vertical flight.

The lesson learned was that the lift-fan aircraft concept requires, periodically, review of the lift-fan "family-of-aircraft" approach. If a "second best" STOL concept uses some of the same propulsion components as its vertical flight counterpart, that STOL concept may not be second best for a total system.

Near-Term V/STOL Lift-Fan Research Transport

In the early 1970s NASA, McDonnell, Boeing, and Rockwell published design studies on the definition of candidate V/STOL lift-fan research transports. One of NASA's contributions was creation of design goals and criteria specifically for lift-fan research aircraft, which was different from that for design of operational aircraft. This led to a lesson learned, as presented below.

McDonnell proposed V/STOL lift fan plus lift/cruise fan Model 253, a modification of a DC-9, shown in figure 13. It was powered by six GE YJ97/LF460 engines interconnected in pairs. The gas generators in the wing tip pods were interconnected as were opposite forward and aft gas generators in the fuselage. This candidate research aircraft design featured an integrated propulsion/low-speed control system known as the Energy Transfer Control system which is presented in detail in a later section.

Boeing proposed V/STOL lift fan plus lift/cruise fan Model R984-33, a modified C-8 Buffalo, shown in figure 14. It was powered by four GE YJ97/LF460 lift fans. Two gas generators, located in the fuselage, powered the two remote tip-turbine lift fans in the wing pods; and two gas generators in the wing pods powered the two fans located in the rear of the wing pods.

Rockwell proposed modification of their OV-10 aircraft, using a lift fan wing pod on each semispan. This candidate V/STOL research aircraft is not illustrated.

One lesson learned from this lift-fan research aircraft design study concerned the NASA-developed research aircraft design goals and criteria. In the interest of minimizing absolute cost while maximizing research productivity per dollar, many of the design goals and criteria for research aircraft are, and should be, less demanding than those for design of their operational aircraft counterparts.

The lesson learned was to also give consideration to the opposite case. That is, to ask which of the design goals and criteria for powered-lift research aircraft should be tougher than for the operational aircraft.

Example possibilities out of many are (1) higher control power and/or control response for interpolation rather than extrapolation of research results, (2) though on a limited scale, certain critical provisions during design and fabrication so that the option exists for future modification of the research aircraft into a variable stability aircraft of this class, and (3) "excessive" lift fan thrust vectoring to enable definition of the amount for the operational aircraft.

Conceptual Design of a V/STOL Lift Fan Commercial Short Haul Transport

This study included NASA in-house activities; contracts to Boeing, McDonnell, Rockwell, and General Electric; and assistance from Hamilton Standard. It was conducted during the early 1970s.

Some of NASA's design goals and criteria were 100 passengers, 400 nm range for VTOL, 800 nm range for STOL with 1500 ft or less desired, cruise airspeed of 0.75 Mach no., critical gas generator out, and study of both philosophies safe-life and fail-safe fans but with emphasis on designing for a fan failure.

Studied were remote gas-driven, remote mechanically driven, and integral lift fans. Configurational variants were lift fan-in-wing pod, and hybrid lift fan-in-wing pod + lift fan-in-fuselage. All final configurations included lift/cruise fans on the aft fuselage. After the initial contracts and additional work, one final configuration had the lift/cruise fans in wing pods.

Figure 15 shows Boeing Model 984-134 100-passenger V/STOL integral fan transport design. DGW was VTO 110,200 lb, and 1000 ft STOL 119,100 lb. Cruise Mach number was 0.75.

The Boeing design had 8 integral fans, 12.7 bypass ratio, and 1.31 PR. The two integral lift/cruise fans on the aft fuselage were fixed in cruise position, with Pegasus nozzles for low-speed flight. Upon engine or fan failure, the opposite engine was shutoff for balance. Boeing advocated that civil transports must be designed to handle both engine and fan failure, a position well received by NASA.

In the Boeing design, figure 15, low-speed attitude control was provided by varying thrust magnitude and direction on all 8 integral engines. The integral fans were operated independently, and for control required both a rapid response system similar to spoilage systems used on remote fans, and an rpm change for the longer term effect.

From this Boeing design a lesson learned was not to make assumptions about operational characteristics of V/STOL lift-fan aircraft. For the civil transport in figure 15, with payloads less than 11,000 lb, VTOL yielded greater range than 1000 ft STOL. This occurred because VTOL and STOL civil fuel reserve requirements differ, favoring VTOL, because STOL DGW/VTOL DGW was only 1.08, and because of internal fuel capacity.

Figure 16 shows McDonnell Model VT102-6-6A 100-passenger V/STOL design. VTO DGW was 109,000 lb, 1000 ft STO DGW 121,300 lb, and cruise Mach number 0.75. Figure 17 shows the propulsion system layout and gas duct interconnect schematic. The design had six gas generators driving six fans of 1.25 PR and 87.9 inch dia. Thrust vectoring was by exit louvers of the four lift fans, and by the aft fuselage lift/cruise fans by extending and retracting the hood and also rotating the hood about the fixed lift/cruise fan's longitudinal axis. A paired interconnect system was used for gas generator out, and also for fan failure by distributing gas power to one operable fan and one emergency backup nozzle located adjacent to the failed fan. The low-speed pitch and roll control system was based on ETC.

From a contract extension, figures 18 and 19 illustrate McDonnell Model VT107-4-4I 100-passenger V/STOL transport design. This design had 4 engines, and was favored over the 6 engine design, partly because the 4-engine design had higher dispatch reliability. McDonnell contended that since all four engines operated for only 10 percent (or less) of mission time, and only two engines were operated for 90 percent of the time, the dispatch reliability of this V/STOL would be higher then that of a 4-engine CTOL.

For the 4-engine design (figure 18), VTO/STO DGW was 113,000/125,400 lb, and cruise Mach no. 0.75. The aircraft was designed for gas generator or fan out. The fans had 1.39 PR and a 97.9 inch dia. The normally "inactive" interconnect ducts were of 18.3 inch dia and during engine out the duct hot gas flow maximum Mach number was 0.4.

The 4-engine design used two positions of thrust vectoring during STO; best angle for ground roll acceleration (23 deg), and best angle for liftoff and climb to 35 ft (53 deg). (Even for powered-lift aircraft that can vector all thrust horizontally, maximum ground roll acceleration does not occur when the thrust is pointed straight down the runway, because small angles lighten gear loads and reduce horizontal thrust imperceptibly.) At the end of the STO mission the aircraft had the capability to land vertically.

The ETC system modulated thrust 28 percent for pitch and 25 percent for roll control. Fuselage fan exit louvers provided yaw, with the greatest deflection (21 deg) needed at minimum vertical landing weight. Typically V/STOL aircraft are more difficult to control at the lighter gross weights because of less fan thrust magnitude available.

Figure 20 shows Rockwell 100-passenger design called in their reports the Remote Fan/Turbojet V/STOL Transport. VTO DGW was 120,000 lb. STO DGW was 132,000 lb, but STO at that weight required a field length of a little more than 2000 ft. Cruise Mach number was 0.75.

The Rockwell design had 8 gas generators driving 8 fans, 6 lift fans and 2 lift/cruise fans with vectoring hoods. The propulsion system featured paired interconnected systems, thus there were 4 paired systems. A typical paired system is shown in figure 21. Figure 22 is a propulsion system schematic that shows overall layout and fan failure. Note that a fan failure led to shutdown of a second fan, and then the gas generator exhaust flow was directed to 2 emergency exit nozzles, one each located near the failed and shutdown fans. Cruise thrust was provided in part by an unusual feature. To augment cruise thrust from the 2 lift/cruise fans, 2 additional gas generators (labeled A and D in figure 22) were "converted" into cruise turbojets by directing their exhaust flow through convergent nozzles.

In the Rockwell design pitch and roll control were by ETC thrust modulation. Yaw was by differential fore and aft deflection of the thrust from all six wing pod lift fans.

Viewing the three contractual design studies collectively, the 100-passenger V/STOL designs with integral fans and those with remote fans were competitive.

One lesson learned from this lift-fan aircraft design activity was that for V/STOL aircraft (less so for STOL, VTOL, or STOVL aircraft) the design implications differ for military and civil applications.

For military aircraft, the STO gross weight is greater than the VTO gross weight with structural, gust sensitivity, and other design criteria typically based on the VTO gross weight. Thus, for STO missions the military V/STOL is an "overloaded" VTO aircraft.

For civil aircraft, overloading is not permitted. There are several design options available (see Appendix I for additional discussion). For these design studies the contractors selected the design option that follows.

The civil V/STOL aircraft performed a VTOL mission although the useful load for VTO was compromised by the STO-determined structural weight. For this civil design option, the STO gross weight can be "too much" as well as "too little". The STO/VTO gross weight ratio is the design issue for this class of civil V/STOL aircraft.

For example, McDonnell chose to increase VTO gross weight from 109,000 lb as required for the VTOL mission to a compromised VTO gross weight of 110,800 lb. Thus for the STO gross weight, structure was sufficient to maintain other values, such as high airspeeds for the STO mission legs. Other compromises such as placarding airspeeds when at the STO gross weight were not necessary.

Another lesson learned was that for lift-fan aircraft that can operate in more than one mode, in this case V/STOL that can operate VTOL or STOL, optimum in-flight requirements may differ between modes, and thus the aircraft must be designed to be non-optimum with respect to at least one of the modes. An example from these studies follows.

For this study, design ranges were 400 nm VTOL and 800 nm STOL. One tradeoff study result was that though a cruise Mach number of 0.75 was optimum for the VTOL mission, a Mach number of 0.80 was needed for the STOL mission. It was argued that, to generate sufficient production base, potential operators would have to be provided with 0.80 cruise Mach number for the STOL mission in order to compete with and be compatible with CTOLs. So a heavier and more costly aircraft resulted for the VTOL mode to accommodate the in-flight STOL requirement.

The lessons learned have programmatic implications. To illustrate, suppose it is proposed to develop a STOVL aircraft. The "best" STOVL will probably be non-optimum so that the total program can be optimum. The total program will consist of any number of elements selected from a laundry list such as follows.

* A STOVL aircraft operated only STOVL.

* A STOVL aircraft operated STOVL and STOL.

* In addition to a STOVL, a STOL variant that is a modest modification of the STOVL and operated only STOL.

* A STOL variant operated STOL and CTOL.

* A CTOL variant operated CTOL.

The STOVL designers will design the best slightly non-optimum STOVL if they understand what aircraft you are interested in and to what degree.

Conceptual Design Studies of a V/STOL Military-Civil Lift Fan Aircraft

In the early 1970s a McDonnell in-house activity yielded a 3-fan design known as the Model 260. Past NASA civil-oriented design activities and the McDonnell Model 260 design study provided the base for the first NASA-sponsored lift-fan aircraft contractual design study that included military applications.

In 1973 NASA awarded contracts to McDonnell, Rockwell, and GE for the conceptual design of a military lift-fan aircraft. Unlike post-1973 design efforts, this first effort did not give consideration to military multimissions, but rather focussed on the one mission, Vertical-On-Board (VOD) delivery. The VOD mission was for intrafleet and shore-to-ship logistics support.

The design mission was STOVL, to transport a VOD payload of 5000 lb a distance of 2000 nm at a cruise Mach number of at least 0.75. STO was engine-out, 400 ft, and 20 kts wind-over-deck (WOD). Though some VTOL capability was desired, VTOL was not specified but rather accepted as a design fallout.

The McDonnell Model VT 106-3-3D design, shown in figures 23 and 24, had 3 remote gas-driven lift fans of 1.40 design pressure ratio. Number of gas generators was 3 for "fail safe" and 2 for "safe life" design philosophies. Design gross weights for "fail safe" (engine-out) were 40,000 lb STOVL and 28,000 lb VTOL.

One lesson learned was the fundamental compatibility between military lift fans and civil lift fans, despite the fact that civil lift fans are compromised by noise level constraints. The study showed there was little difference in overall aircraft design and performance if using pure military lift fans or if using civil lift fans with those noise reduction features of the fan that were easy to remove stripped out. A military lift fan, with straight forward modifications, can be utilized by the civil community, or vice versa.

The Rockwell VOD design had 4 two-stage gas-driven fans of 1.5 pressure ratio and 4 engines as shown in figure 25. Design gross weights for engine-out were about 40,500 lb STOVL and 30,000 lb VTOL. Some design features were (1) single swivelling nozzle on each nacelle mounted lift/cruise fan as shown on figure 26, (2) use of two-stage fans, see figure 27 for a drawing of the two-stage fan and comparison to a single-stage fan, and (3) quad entry lift fan scrolls as shown on figure 28 including comparison to a dual entry scroll.

Two-stage fans become of interest for high speed subsonic STOVL aircraft when the cruise leg is long, in this case 2000 nm.

In the quad entry scroll the added entries supplied one-sixth of the flow each, thus allowing the two primary entries and associated scroll cross section diameters to be smaller. The added entries can be designed with various orientations with respect to the scroll to suit the needs for individual installation requirements, as illustrated by the alternate location in figure 28. Quad design reduced the overall planform dimensions of the fans from 4 to 7 inches. Dual and quad fan weights differed by 10 lb in favor of dual. The main advantage of the quad was beneficial effect on nacelle installation weight and drag.

Should a gas-driven lift fan mounted in the fuselage of a STOVL supersonic fighter, wherein fuselage fineness ratio is at a premium, have a quad entry scroll?

Design Definition Study of a Lift/Cruise Fan Technology V/STOL Aircraft, Part I, Navy Operational Aircraft

This was a national activity with NASA in-house effort; NASA/Navy contractual studies by Boeing/Allison/ Hamilton-Standard, McDonnell/GE, and Rockwell/GE; Navy contractual studies; and contractor in-house studies by nearly all U.S. aircraft airframe and engine companies. The first of many NASA CRs was published in 1975.

This was the first design in which the task was a lift/cruise fan V/STOL aircraft for Navy multimissions. Five STOVL missions were required, namely Anti-Submarine Warfare (ASW), Surface Attack (SA), Combat Search and Rescue (CSAR), Surveillance (SURV), and Vertical On-Board Delivery (VOD). Highest priority was the ASW mission, cruise out 150 nm, 4-hr loiter at 10,000 ft, and return.

Though STOVL was the primary mission, the aircraft had some V/STOL capability. STO was for 400 ft with 10 kts WOD. Critical engine out (but not fan out) was a requirement.

There were no design guidelines for civil missions. With minor modification the designs would yield civil aircraft to support off-shore oil rigs and other civil utility missions.

Design configurations included gas-driven and mechanically-driven fans, 2 and 3 engines, 2 lift/cruise fans, with and without a nose fan. A typical configuration had a STOVL DGW of about 38,000 lb and a cruise Mach number of 0.80.

The Boeing Model 1041-133 had mechanically driven and interconnected lift fans, 2 integral rotatable lift/cruise fans on the aft fuselage plus a fuselage nose lift fan. See figures 29 and 30. Design illustrations follow.

Figure 31 is a power train schematic. The clutch was used to isolate a failed engine or to permit loiter on one engine.

Figure 32is the lift/cruise fan engine pod. Note blow-in inlet doors for low-speed flight, Hamilton Standard 62 inch diameter variable pitch fan thats use included pitch and roll control, the fan variable exit area nozzle that reduced area to 70 % for cruise, the yaw control vanes, and the Allison T701 engine.

Figure 33 includes the structure and mechanisms used to pivot the two aft lift/cruise fan nacelles.

Figure 34 shows the drive shaft that connected the forward fuselage nose lift fan, through a clutch, to the main fan drive gear box.

The McDonnell gas-driven lift fan plus lift/cruise fan design is shown on figures 35 and 36. More information is not presented in this section because another McDonnell design that is fundamentally similar is discussed later.

The Rockwell gas-driven design without a nose fan and with puffer pipes for pitch control is shown on figure 37. Unlike Rockwell's design for the single mission VOD aircraft that used two-stage fans, for this multimission design Rockwell chose two 1.3 pressure ratio, single stage, 60 inch dia, lift/cruise fans. The design had 3 J97-GE-100 gas generators. Roll control was by ETC, yaw by differential operation of the nacelle single swivel nozzles, and pitch by puffer pipes powered by a third gas generator which also was available for auxiliary horizontal turbojet thrust.

One lesson learned is the flexibility available to the aircraft designer if lift fans are interconnected. The interconnect can be by gas-driven interconnect duct or by a mechanical shaft. Design flexibility is of more importance for multimissions than for single mission designs. With interconnect, straight-forward aircraft design variants are an option. For example, the same basic multimission design in this study had 2 or 3 gas generators as a function of the specific mission.

Another lesson learned concerned gyroscopic coupling. Consider the configuration that featured two aft fuselage mounted lift/cruise fans that were rotated for conversion (figure 30). Gyroscopic coupling in the vertical and low-speed flight modes occurred whenever the aircraft pitch or roll attitude was varied, or whenever the nacelle incidence was varied. When the entire aircraft pitched, all three fans contributed to gyroscopics. If only nacelle incidence was varied for conversion, then only the two aft lift/cruise fans contributed. The fans and engines were rotated in opposite directions to reduce total angular momentum.

For this study a guideline was that gyroscopic moment of less than 10 percent of the available control was considered acceptable. Example results were, despite use of opposite rotation, that nacelle incidence rate was limited to 22 deg/sec, and aircraft roll attitude rate was limited to 11 deg/sec. Not only must the designer minimize gyroscopics, the customer and the designer must have an understanding of what the gyroscopic design criteria are in the first place.

For a STOVL design with one 2-stage lift fan in the fuselage, should the 2 stages counter rotate?

Design Definition Study of a Lift/Cruise Fan Technology V/STOL Aircraft, Part II, Technology Aircraft

Paralleling the preceeding section on Navy multimission aircraft design were studies to define research aircraft, also known as technology aircraft, and also know as research and technology aircraft and therefore by the acronym RTA.

The NASA/Navy RTA studies included three approaches to design of the research aircraft, namely (1) new airframe -- full flight envelope, (2) modified existing aircraft -- full flight envelope, and (3) modified existing aircraft --flight envelope limited to low-speed capability.

Most effort was placed on modification of existing aircraft. All three airframe contractors selected modification of the Rockwell Sabreliner T-39 business jet. Two of the selected designs featured gas-driven fan systems, and one featured mechanically driven fans. All had three existing engines and two lift/cruise fans; and some had a fuselage nose lift fan. VTO design gross weights were in the 25,000 to 30,000 lb category.

An isometric of the McDonnell Model 260-RTA-1 is shown in figure 38, and some propulsion/control system details are in figure 39.

Over the years there have been many different lift fan scroll designs proposed. The scroll on the McDonnell RTA is shown in figure 40. It is known as the Scroll-in-Scroll concept. It consists of an outer scroll of 2/3 arc and an inner scroll of 1/3 arc. During normal operation both the ETC and 1/3 scroll valves are open, to provide 100% arc admission. For engine failure, the 1/3 scroll shutoff valve is closed and thus only a 2/3 arc is utilized. This Scroll-in-Scroll design was used on both the nose lift fan and on both aft lift/cruise fans. When initiating gas-driven lift fan design, review the types of scrolls already studied.

The McDonnell RTA low-speed control system used, as an integrated part of its ETC system, thrust spoilage systems on both the nose lift fan and the two aft lift/cruise fans as shown in figures 41 and 42. The name of these systems became Thrust Reduction Modulation and the acronym TRM.

A lesson learned concerned an attribute of a control system with TRM. Previously understood was that TRM quickened control response and prevented control coupling. This RTA design exercise included military considerations, which led to the following lesson learned.

The complementary functions of ETC and TRM provided an inherent safety feature by nature of the separate actuation of these devices at each fan. Loss of an ETC function did not interfere with TRM operation, and conversely loss of the TRM did not interfere with ETC operation. This feature thus provided survivability when multiple failures or battle damage were considered. When a total loss of a TRM or ETC function at a fan occurred, adequate aircraft control was maintained with some degradation in handling qualities.

A 3-view drawing of the Boeing Model 1041-135-2A RTA is shown in figure 43. Except for one difference as discussed below, this modified T-39 was very much like the Boeing Navy multimission aircraft presented in the preceeding section.

One major design difference, not shown in figure 43, was that a third engine was added, making it a mechanically driven 3-fan, 3-engine aircraft. To improve engine out thrust-to-weight margins for the T-39 RTA, a third Allison XT-701 engine was installed inside the fuselage aft of the center wing section. Modifications for the third engine included addition of a drop box (helical gear), drive shaft connecting the third engine to the drive system drop box, and fuselage inlet and exhaust ducting. Unlike the engines driving the lift/cruise fans, the third engine, being interbody mounted, was unsupercharged.

The final 3-fan, 3-engine gas-driven McDonnell T-39 RTA and the final 3-fan, 3-engine mechanical Boeing T-39 RTA were considered competitive.

Another T-39 RTA, designed by Rockwell, is shown in figures 44 and 45. It had the unusual feature of a third engine that was not normally used to drive either a lift fan or a lift/cruise fan. The third engine, during low-speed flight, powered the pitch axis puffer pipe system (see figure 45) and was on standby to power lift/cruise fans in the event of a lift/cruise fan engine failure.

In the interest of military and civil future aviation, the author was (and still is) disappointed that none of the RTA designs ever reached flight status.

Contractual Lift-fan Aircraft Design Studies During the Period 1978-1992.

There were no NASA contractual lift-fan aircraft design studies during this 15 year period. NASA continued to conduct basic and applied research on lift-fan aircraft technology. For completeness presented are two designs whose origins were due to contractor and Navy efforts, and for which NASA conducted research activities.

Figure 46 shows a large scale powered model of the Grumman V/STOL twin tilt nacelle design with mechanically interconnected integral lift fans (i.e. high-bypass turbofans). Figure 47 is a schematic of the propulsion system including the vanes for low-speed control.

Figure 48 shows the McDonnell V/STOL twin nacelle design with mechanically interconnected fixed turbofans. Thrust vectoring was by "vented D" nozzles. Figure 48 is a schematic of the propulsion/control system.

NASA research pertaining to these 2-engine V/STOL turbofan designs is highlighted in other papers of this series.

Design Integration

An important subject in lift-fan aircraft design is design integration. Which design has the best propulsion, low-speed controls, or structural weight fraction is less important than which design has systems and structure integrated to yield the best overall aircraft.

In addition to NASA contractual lift-fan aircraft design studies were many NASA contractual experimental investigations to validate aircraft designs. Three full-scale experimental investigations were selected for examples, namely (1) the behavior of gas generators when plumbed together by common manifold interconnect ducting, (2) the design, fabrication, and test of hot gas interconnect ducts, and (3) the integrated propulsion/low-speed control system known as Energy Transfer Control (ETC).

Manifolding of Gas Generators

Studies of lift-fan V/STOL transports and of research aircraft included designs with a pair or more of gas generators interconnected to drive a pair or more of remote fans. An example of a lift-fan V/STOL transport design that featured three interconnected pairs is shown in figure 13.

One research activity was a full-scale experimental investigation in which two GE YJ-97 gas generators were interconnected by a 50-foot gas-transfer duct with an ID of 14 inches, shown schematically in figure 50. YJ-97s were single-stream turbojet gas generators each with a rated thrust of 5200 lb. This contractual effort performed by McDonnell included a total of about 120 hours of gas generator operation.

The interconnect duct was designed for one-half of the rated exhaust gas flow from one gas generator. The duct gas flow Mach number was 0 with both gas generators operating and 0.4 Mach number with one gas generator failed.

The investigation demonstrated that the system was tolerant to differential gas generator speed conditions. Though normally operated at identical throttle settings, since differentials occur, tests were conducted to evaluate system stability during differential transient throttle operations. One gas generator was throttled to a lower speed. The low-speed gas generator recovered satisfactorily from all conditions, including from 80% speed with the other gas generator at rated speed, and from 65% speed with the other gas generator at 97% speed.

To investigate emergency operation (see figure 51), the simulated gas generator failure sequence was as follows. The throttle on one gas generator was abruptly chopped. Closure of the isolation valve was initiated, followed by initiating closure of one of the two lift-fan shut-off valves. The valve closure rates and the delay between throttle cutoff and initial valve movement were varied to determine system sensitivities.

Figure 52 is a time history of a throttle cutoff on gas generator no. 2. Gas generator no. 1 speed remained steady during and after cutoff of gas generator no. 2. Transition to the stabilized one gas generator failed state was completed in 6 seconds. The 2.5-second delay in initiating isolation valve closure did not result in reverse flow through the no. 2 gas generator.

Lessons learned were that the paired interconnected system was insensitive to transients, even to delays in recovering from gas generator failure. Transient time requirements for recovering from gas generator failure will depend on flight requirements. The time that transient lift loss can be tolerated in flight will dictate design and valve closure rates rather then concerns of gas generator or other propulsion component sensitivities.

Recommended for manifolding of gas generators is Bibliography number 11.

Interconnect Ducting

The experimental investigations of paired interconnected gas generators presented an opportunity for evaluations of full-scale interconnect duct segments. Flight-type metal and semi-flexible composite duct segments were designed, fabricated, and inserted in the boiler-plate interconnect duct. Figure 53 shows a conceptual drawing of the composite duct segment. Figure 54 is the duct wire wrapped screen liner. Figure 55 shows the final two components ready for assembly into the full-scale composite duct segment. The flight-type segments were subjected to control and engine-out cycles. An example engine-out condition was gas temperature 1460 degrees F, gas pressure 41 psia, flow Mach number 0.4, and time duration 4 minutes. Figure 56 shows an example time history during a simulated engine-out condition (the most severe case). Metal and composite duct segments were promising. The semi-flexible composite ducts offered advantages of weight, by weight per length of the duct and by the elimination of heavy duct connecting elements such as bellows.

For interconnect ducting see Bibliography number 12.

Energy Transfer Control

Discussed is an example of integrating the propulsion system with the aircraft low-speed control system to the degree that both systems lose their individual identities. The result is one system with a name such as integrated propulsion/aircraft low-speed attitude control system.

Lift-fan aircraft low-speed control systems have been designed with direct gas generator modulation, fan exit louver thrust spoilage, fan variable area scroll, variable inlet guide vanes, variable blade pitch, control vanes in the exhaust fan flow from lift/cruise fans, variable (fan exit) area control system known as VACS, gas generator exhaust modulation known as turbine energy modulation (TEM), and an exhaust modulation system chosen for this paper known as the Energy Transfer Control (ETC) system.

ETC was pioneered by McDonnell, and investigated by NASA in-house and sponsored activities. Figure 57 is a general arrangement of a paired ETC system. The basic attribute of ETC is that control moments are generated by capitalizing on short duration (fractions of a second up to a few seconds) transients of the propulsion system. This approach avoids penalties with installed gas generator power and the lift-fan steady-state thrust design point.

An experimental investigation was initiated using the pair of interconnected YJ-97 gas generators shown in figure 50. Figure 58 shows the full-scale, 14 inch dia ETC valves, and figure 59 shows the full-scale interconnect duct shutoff valve. Lacking full-scale tip-turbine lift-fan hardware, the lift-fans were simulated by using full-scale lift-fan designs. That is, the real gas generator exit nozzle gas energy data, steady-state and transient, were used to predict the behavior of the lift fans.

A result is illustrated in figure 60, with both gas generators operating near rated power and no. 1 ETC valves deflected 40 degrees. Shown are the gas-flow characteristics at the simulated entry to the lift-fan scrolls. The gas energy at the no. 1 exit nozzles remained nearly constant while the gas energy at the no. 2 exit nozzles increased by a factor of 1.64. The no. 1 exit nozzle gas energy remained constant because the increase in gas temperature and pressure upstream of the ETC valves offset the pressure drop across the deflected ETC valves. The no. 2 exit nozzle gas energy increased greatly because temperature, pressure, and gas flow all increased as in figure 60.

An example of ETC with lift-fan thrust calculated from measured gas energy data is shown in figure 61. Total fan thrust increased as the ETC valves were closed. System design included fan exit louver vanes. The louvers for a fan were activated only when the ETC valves for that same fan were activated. The louvers were used to spoil the thrust of the "constant" thrust fan. The purposes of the louvers were to spoil thrust to (1) generate large control moments, (2) decouple attitude control from height control, and (3) improve the aircraft first-order control moment time constants. Fan thrust modulation of 25% at takeoff power and 80% at landing power was achieved, and control moment time constants were 0.14 second at takeoff power and 0.25 second at landing power. These values met design goals.

The initial configuration for gas generator failure is shown in figure 62. Gas generator no. 2 has failed, and the isolation valve and ETC shutoff valves have been closed. Gas flow was distributed so both fans remained in operation, no asymmetric moments were generated to upset aircraft attitude, and transient fan thrust was provided by modulating one ETC valve at each fan location as required.

Figure 63 shows a transient thrust time history for a 30 degree step input of ETC valve no. 1 with no. 1 gas generator at 97.5% speed. Incremental thrust is presented for fan no. 1, for fan no. 2, for differential lift change (fan no. 2 -fan no. 1) as required for attitude control, and for total lift change (fan no. 2 + fan no. 1) to illustrate height control coupling with attitude when a gas generator has failed. For the emergency condition of a gas generator failure, these characteristics were satisfactory.

At the time ETC was investigated, it was in the context of being applicable to a short-haul transport aircraft. One of the configurational variants had six gas generators, six remote lift fans, and 21 valves. ETC became associated with lift-fan aircraft configurations that have many gas generators, many lift fans, and many valves. A lesson learned was that ETC is also applicable to lift-fan aircraft designs that have few gas generators, few lift fans, and few valves. Three examples follow.

Example no.1: Instead of one of three paired systems in a large transport, the ETC just described can be all of the system, applicable to a configuration with two gas generators, two lift fans, and seven valves (figure 57).

Example no. 2: Figure 60 is for all gas generators operating, and the gas generators interconnected and operating as a team. The experimental data base remains valid regardless of the number of gas generators assumed to be on line. The simplest case for all gas generators operating as a team is to have one, and since only one, no interconnect. Thus the data base is applicable to a configuration with one gas generator, two lift fans, and two valves. Two valves because gas generator isolation valves are not needed, nor an interconnect valve, and since the pair of ETC valves at each fan always operate in parallel, the number of ETC valves can be reduced to one per lift fan.

Example no. 3: For the civil transport, consideration was given to lift-fan failure. The design included an emergency exit nozzle located near each lift fan. Upon lift-fan failure, the propulsion/ETC system distributed flow to the emergency exit nozzle (more than one-half of the flow) and to the other on-line operating lift fan. This design approach worked well. This suggests an alternative design in which the exit nozzle is not an "emergency" nozzle. ETC can apply to a configuration having one gas generator, one lift fan, and one exit nozzle. Perhaps all three components are located on the aircraft's longitudinal axis, with the integrated system providing height and pitch and yaw control, with roll provided separately. This ETC design needs two valves, one upstream of the one lift-fan scroll and one upstream of the exit nozzle.

The point to the preceding examples of ETC systems with fewer components is not whether these examples have merit. The point is the potential wide applicability of integrated propulsion/ETC systems.

A further point is that the advantages of ETC improve as lift-fan pressure ratio increases. Past studies were based on fan pressure ratios from 1.25 to 1.40. As technology enables higher fan pressure ratio, or if the current lift-fan aircraft under study is conducive to use of higher lift-fan pressure ratio, ETC becomes increasingly attractive.

NASA Ames has an extensive ETC data base. The lesson learned is to ask whether ETC is applicable to the lift-fan aircraft configurations currently being addressed, and to stay knowledgeable with respect to the ETC data base.

For full-scale experimental investigations of ETC, see Bibliography number 11.

The Avrocar Flight Evaluations

On two occasions, in 1960 and 1961, the USA VZ-9AV Avrocar was evaluated in a series of flights by a two-man USAF team, the project pilot and the author.

The Avrocar was manufactured by Avro Aircraft, Limited, Malton, Ontario, Canada. Figure 64 is a photograph of the Avrocar in hovering flight. Figure 65 is an artistic schematic of the aircraft.

The circular planform Avrocar had a wing span (diameter) of 18 feet. The wing section was symmetrical about the vertical centerline, elliptical in profile, with a thickness/chord ratio of 20%. Gross weight was 5650 pounds.

The aircraft was powered by 3 Continental J69-T-9 gas generators rated sea level static thrust of 927 pounds each.

One lift fan was located in the center of the fuselage. The Orenda lift fan was a single stage axial flow fan. Fan inner and outer diameters were 20 and 60 inches. The 31 fan blades had a blade chord of 4.1 inches, a hub and tip thickness/chord ratio of 13% and 8%, and a tip Mach number of 0.78. Weight of the fan, with stator, shroud, and seal, was 338 pounds. The 124 turbine blades had a chord of 2 inches, and the turbine blade tip diameter was 65 inches.

Though production aircraft were envisioned of higher performance, the VZ-9AV research aircraft was originally proposed as capable of VTOL, and flight to 10,000 feet at an airspeed of 200 mph. Up-and-away flight was never achieved because of an unstable ground effect height, insufficient thrust-to-weight ratio, and inadequate low-speed control.

Of the many lessons learned from the Avrocar Flight Evaluations, ten are selected herein as follows.

1. The decision was made to fly first, and later to put the aircraft in NASA's full-scale 40 x 80 foot wind tunnel. That sequence of events was backwards.

2. The gas generator thrust, 3 x 927 = 2781 pounds, augmented by the lift fan, should have enabled VTO at 5650 pounds gross weight, but it didn't. Duct design was deficient; holes in the ducts for control cables were not sealed, duct contour was compromised, and "transition" doors in the ducts were not sealed. Lift-fan thrust augmentation was offset by duct losses. Duct design is as important as gas generator or lift-fan performance.

3. The low-speed aircraft attitude control system originally was a spoiler system that was later replaced with a focussing ring control system as seen in figures 66 and

67. The design approach to transition from the low-speed control system to the high-speed control system is illustrated in figure 68. (The transition was never attempted in flight.) The original spoiler control produced pitching and rolling moments by destroying lift on one side and not creating more lift on the opposite side. Thus attitude control and height control were severely coupled, and total lift loss during attitude control was very high. The decision, in 1959, to abandon the low-speed control system based on spoilage was a lesson learned. In design of lift-fan aircraft capable of vertical flight, effort should be directed at developing low-speed control systems that do not feature thrust spoilage. The second system installed on the Avrocar, the focussing ring system, featured little loss of thrust.

4. As shown in figure 69, the Avrocar exhibited two distinct types of air flow distribution in ground effect. Each type was stable, but transitioning between the two types was unstable. The Avrocar was unable to continue vertical takeoff through the unstable area, called the critical height, and the aircraft became a ground effects research vehicle. In figure 69, the flow changed from "curtain" flow to "tree-trunk" flow during a 6-inch vertical height change. At the unstable critical height, the Avrocar went into a severe oscillatory mode, that did not go divergent, that was named "hubcapping". When testing models or aircraft in ground effect, proceed in small height increments and/or use dynamic testing techniques. Despite the experience with the Avrocar and its unacceptable thrust-to-weight ratio, dynamic vertical flight operations may overcome apparent barriers such as a steady state hovering instability at a certain ground height.

5. The Avrocar was symmetrical, longitudinally and laterally. The lift fan was located in the center of the aircraft. Despite geometry, the Avrocar was not symmetrical. A rolling moment and side force of high magnitude resulted from intake flow entering the lift fan non-vertically. A STOVL design with the lift fan on the fuselage centerline is not symmetrical. In model testing, simulate the lift fan with another lift fan, and/or use the "real" lift fan at full scale. Simulating mass flow with an ejector or other device is, unfortunately, symmetrical.

6. In the Avrocar most of the mixed fan flow exited through an annular nozzle located about the outer edge of the circular planform. To help control ground effects, some of the air exited from an inner row, and some from an outer row, of bottom surface peripheral jets. In a STOVL lift fan design, particularly for a design wherein thrust-to-weight ratio is determined by in-flight requirements and not by VL, if necessary a ground-effects problem might be overcome by utilizing bottom surface auxiliary jet(s).

7. The Avrocar made one consider both sides of lift-fan gyroscopics. Adverse gyroscopics are well known; favorable gyroscopics less know. By using spherical bearings, the lift-fan hub was free to move by 1/4th of 1 degree. This small movement was amplified by mechanical linkage to provide input to the control system. The result was a low-speed automatic stability augmentation system that was inherent to the design and worked well. The lesson learned is to ask all questions, including whether gyroscopics should be harnessed in some manner to achieve a favorable result.

8. The Avrocar demonstrated that mixed fan and turbine -drive air is relatively cool. Hovering over dead grass did not start a fire and did not scorch the dead grass. During steady-state hover, environmental problems included recirculation, reingestion, reduced visibility, mud and other deposits degrading the wing airfoil contour, etc. These problems were eliminated by maintaining 10 knots forward speed. Operationally, VL may not mean vertical landing; VL may mean almost vertical landing.

9. The lift fan, fabricated in 1958, was one of the first lift fans installed in an aircraft that was intended for up-and-away flight. During hover and low-speed flight over several types of unprepared terrain, the lift fan was subjected to considerable FOD reingestion. Despite being a "pioneer" and despite rough environmental treatment, the lift fan performed well. This was the first lesson, to be followed by more lessons, that lift fans are tough and dependable.

10. The Avrocar cockpit got hot. On a cold day we shortened a flight because of cockpit heat. In a configuration with a gas-driven lift-fan in close proximity to the cockpit, give attention to insulating the cockpit. The noise level in the Avrocar cockpit was high. Far-field noise was low, near-field noise was high. The depth-of-installation of the lift fan was reasonable, (20% airfoil), but no attempt was made to reduce noise. Particularly for fan-in-fuselage or fan-in-wing pod designs with installation depth, spend effort and commit pounds to incorporate noise reduction.

Concluding Remarks

Much was and wasn't done.

Iteratively, technology was advanced, aircraft were designed, designs were validated with ground-based investigations, and technology was advanced.

And for 30 years no one built a lift-fan aircraft.

No lift-fan aircraft was built despite a history of XV-5A/B, excellence in R & T base, creditable advocacy on national need, and creation of interagency partnerships.

On one occasion NASA and Navy agreed on a lift-fan technology aircraft project, subject to approval by Office of President of the United States. The office agreed with justification advocacy, technical plan, management plan, and fiscal plan, with one exception. Though total funding was realistic, NASA and Navy were tasked to reallocate shares, with Navy's increased. Navy could not increase their funding share, nor, by direction, could NASA offer their original share. Result -- cancellation. Navy cancelled project funds were redirected to improve NASA Ames simulators which were deficient for vertical flight.

Priorities, in order, for future years are:

1. Build lift-fan research and technology aircraft. Projects exercise the too-inactive contractual design teams; augment related R & T base; include aircraft fabrication, ground-based qualifications, flight technology demonstration, and long-term flight research; and for mature technologies like the lift fan, are the mechanism needed for introduction of the technology to application.

2. Build full-scale flightworthy or flight-type lift fans and lift/cruise fans, and critical propulsion components. Arguably, the devastating technical deficiency in past proposed research aircraft projects was the non-existence of lift fans. Experience is needed to validate lift-fan weights, performance, cost, polar moment of inertia, acoustics, and more. And to sell aircraft projects. Any military or civil activity will benefit the other. For example, a 2-stage high pressure ratio fan-in-fuselage for a STOVL supersonic fighter will also enable a civil supersonic lift-fan business jet.

3. If numbers 1 and 2 above are, temporarily, not to be, then determine which national ground-based facility is deficient for advancing lift-fan aircraft technology, and fix it.

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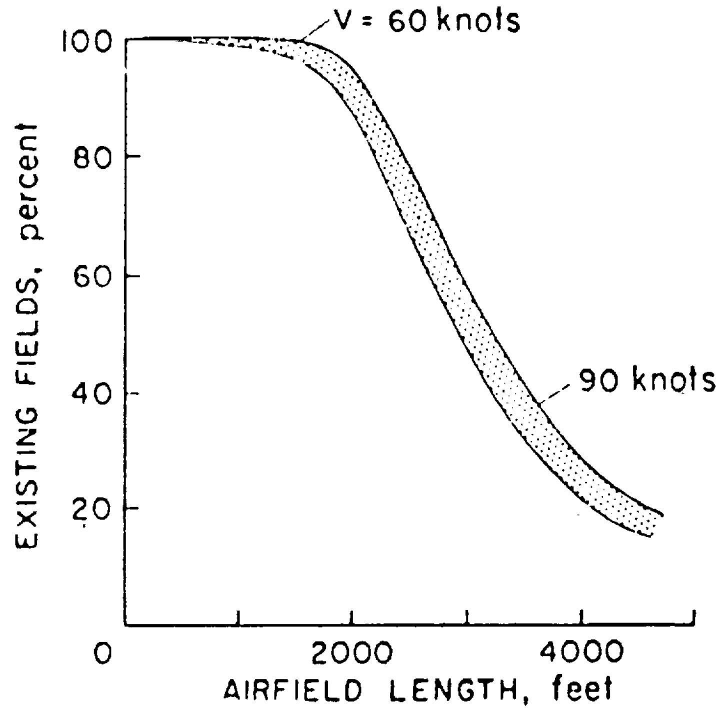


Figure 1. Percent of existing fields which can be used by aircraft with different approach speeds and field length requirements

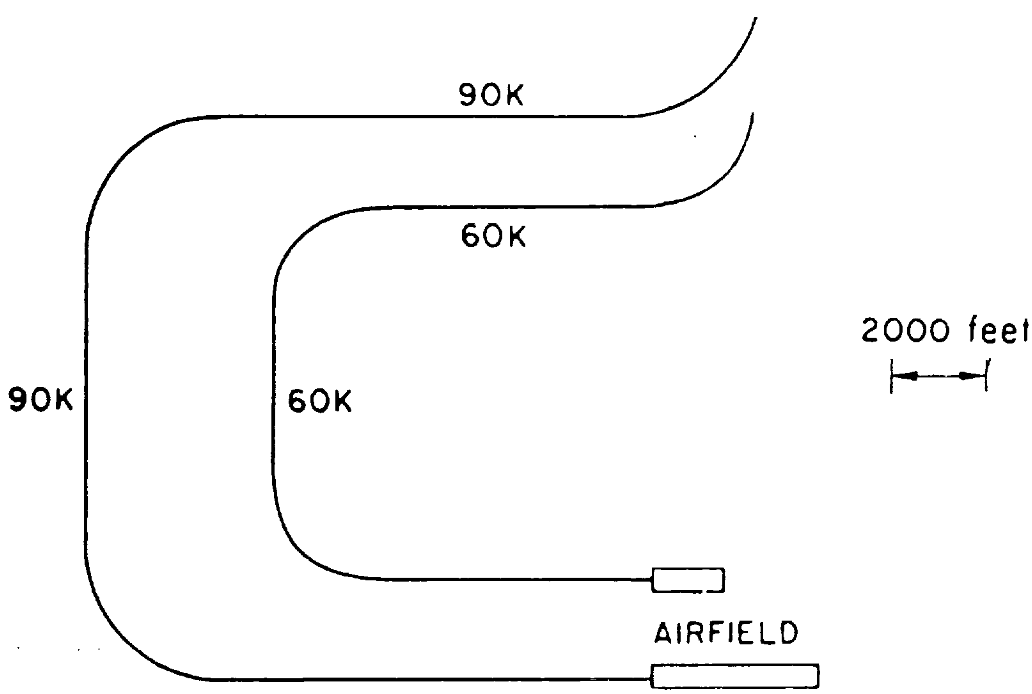


Figure 2. Effect of approach speed on pattern size

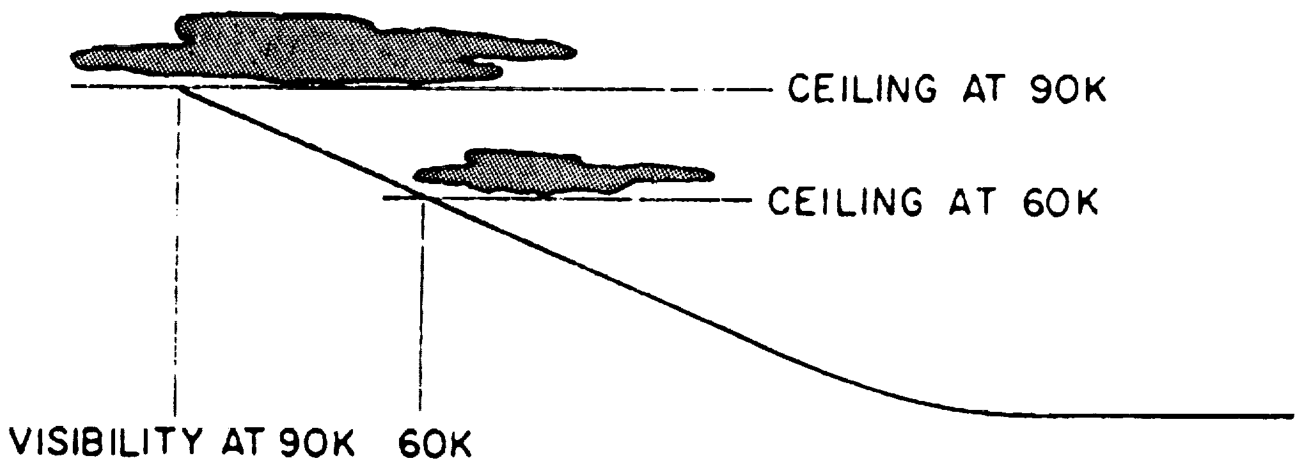


Figure 3. Benefits of reduced approach speed under IFR conditions

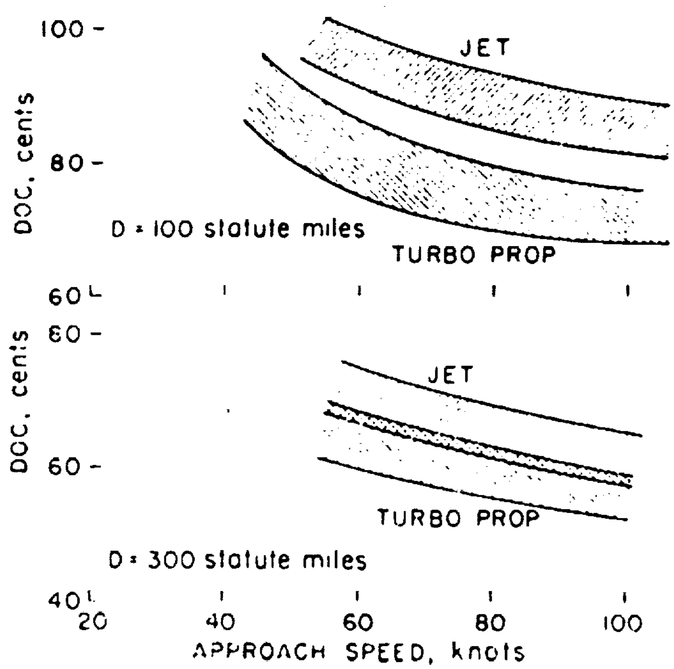


Figure 4. Direct operating cost for aircraft with different low-speed characteristics

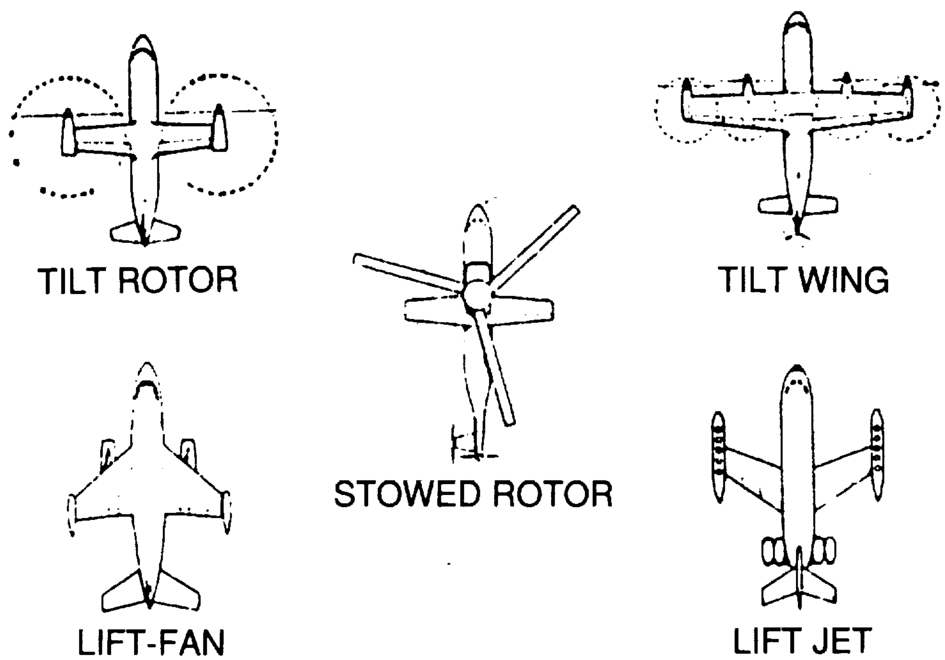


Figure 5. VTOL short-haul transport concepts studied

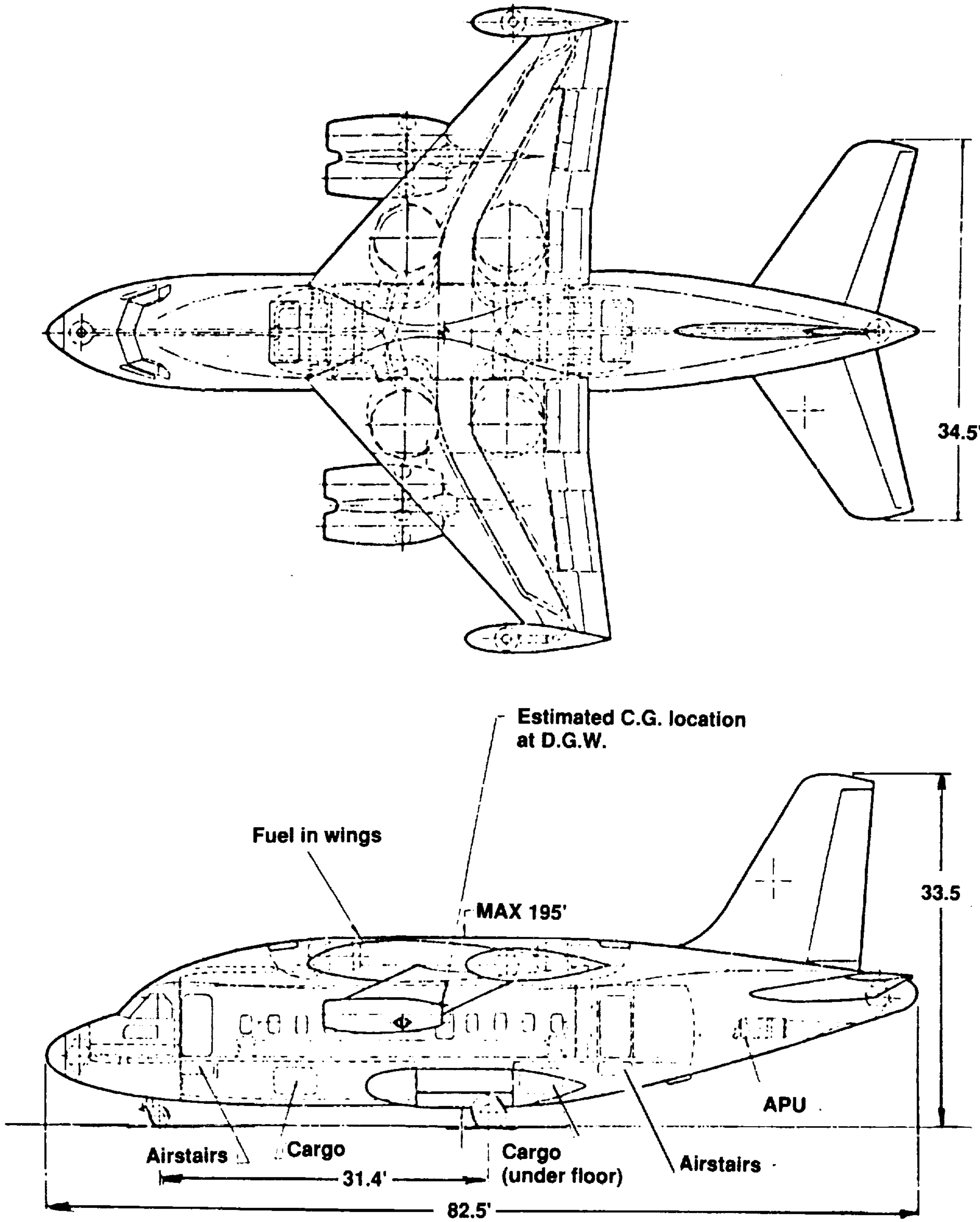


Figure 6. Boeing 60-passenger VTOL lift-fan aircraft design

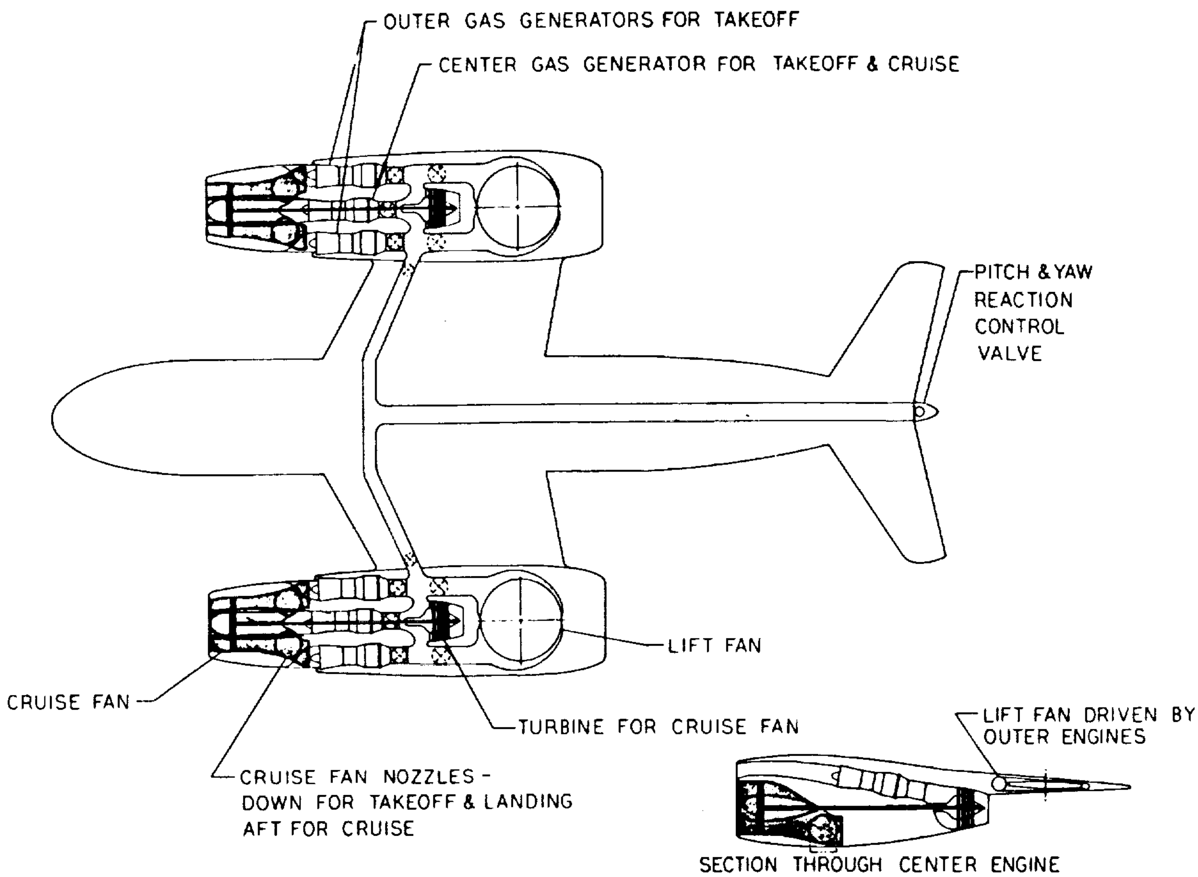


Figure 7. Lockheed 60-passenger VTOL lift-fan aircraft design

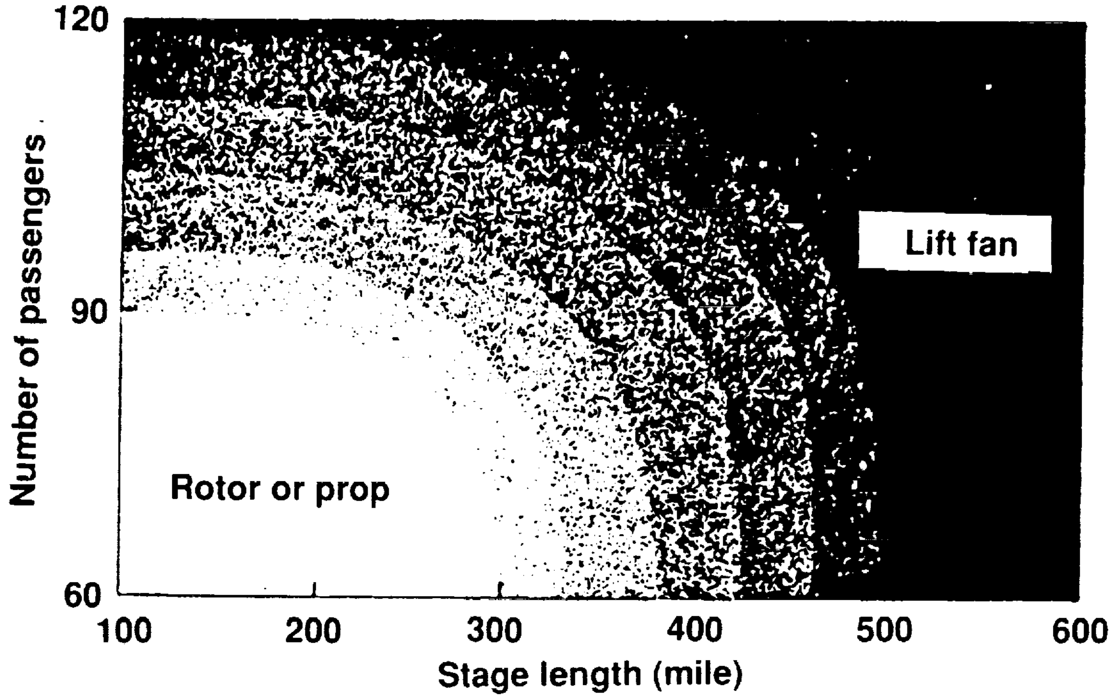


Figure 8. Summary of promising missions for VTOL designs in terms of stage length and payload

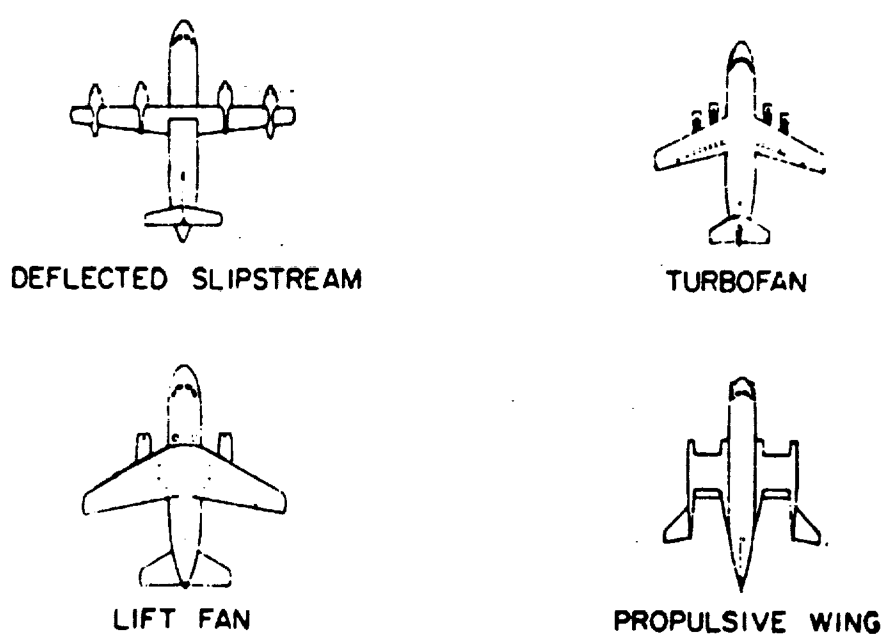


Figure 9. STOL short-haul transport concepts studied

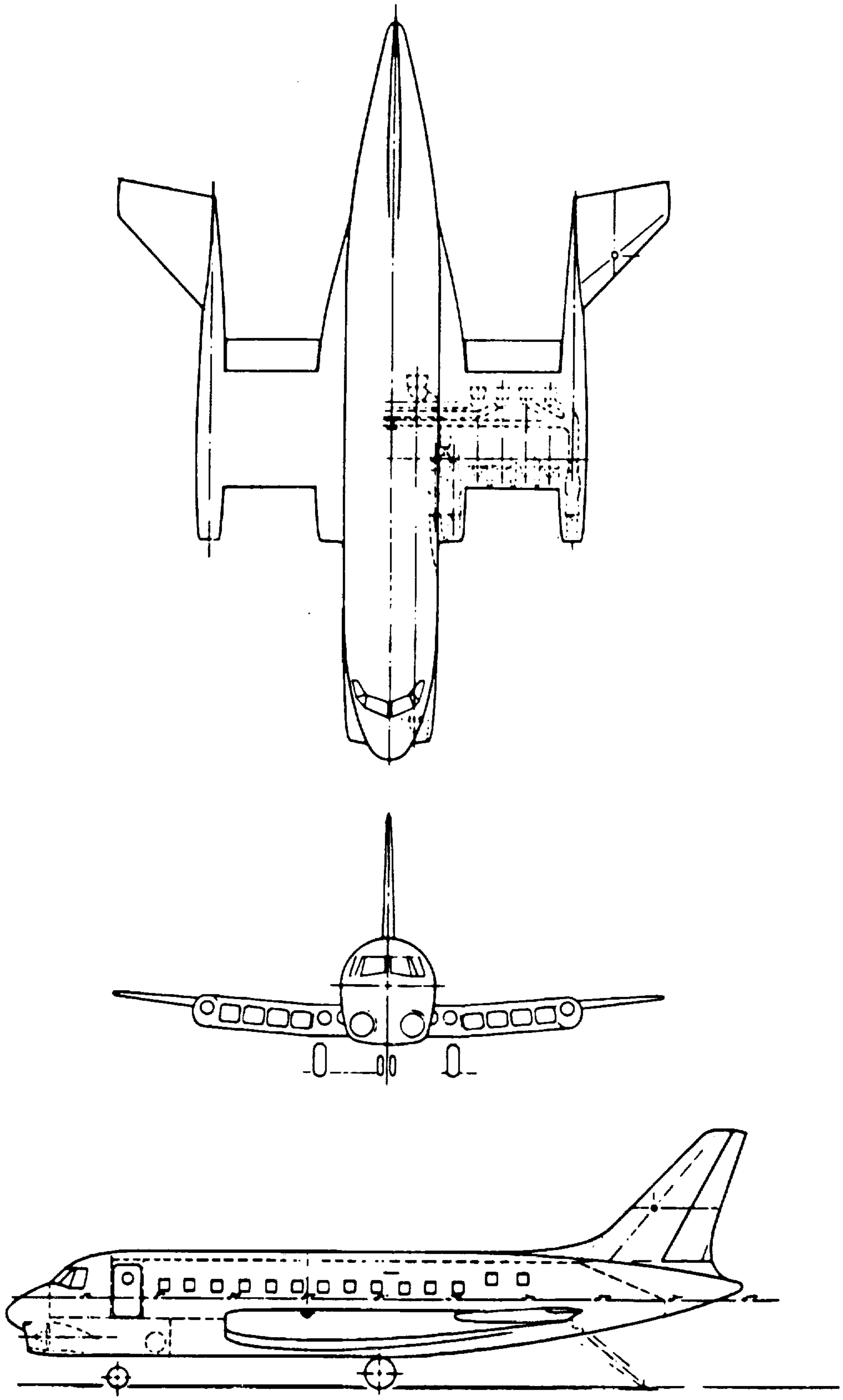


Figure 10. Vought 60-passenger STOL lift-fan propulsive wing aircraft design

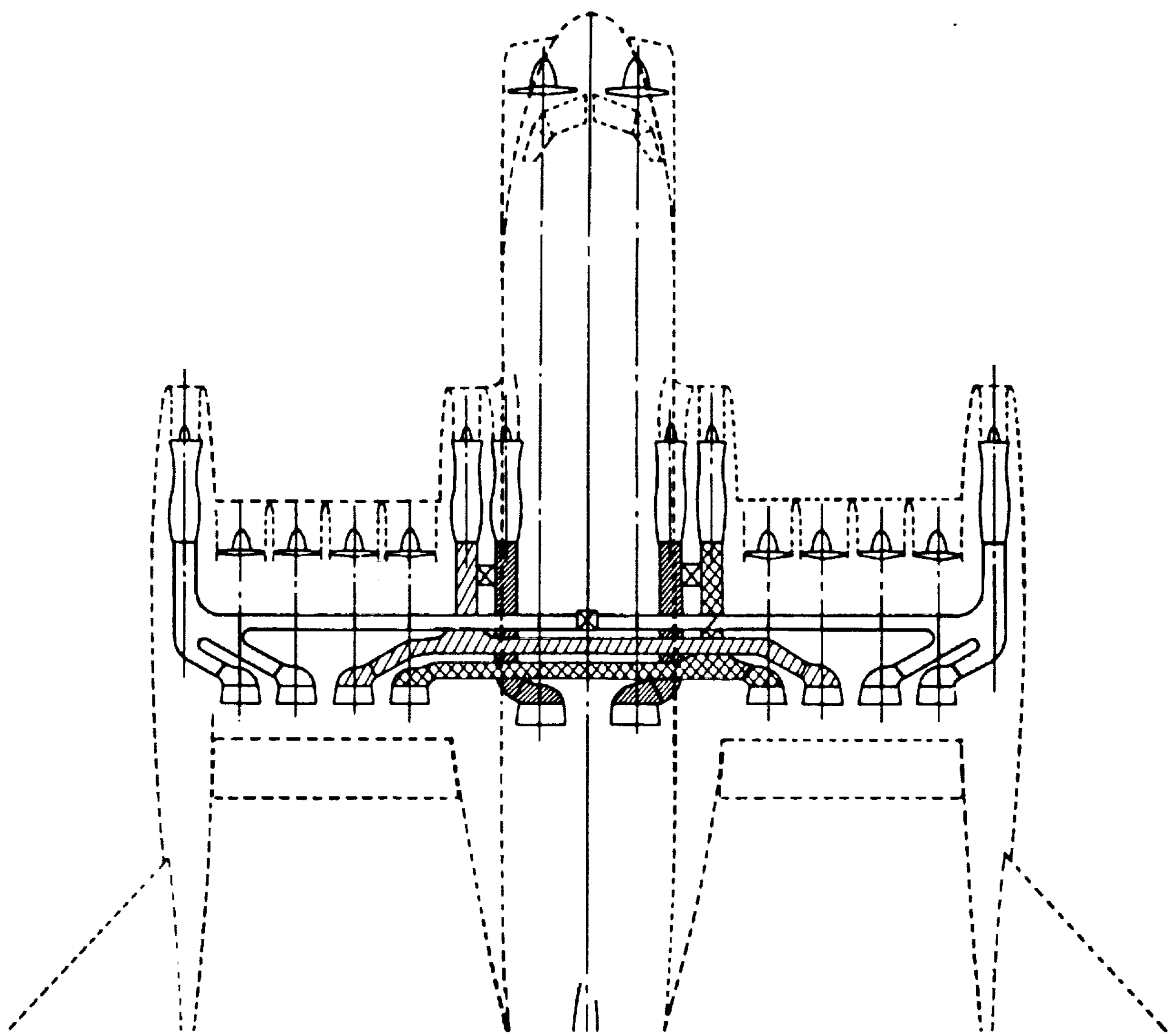


Figure 11. Vought propulsive wing propulsion system planform

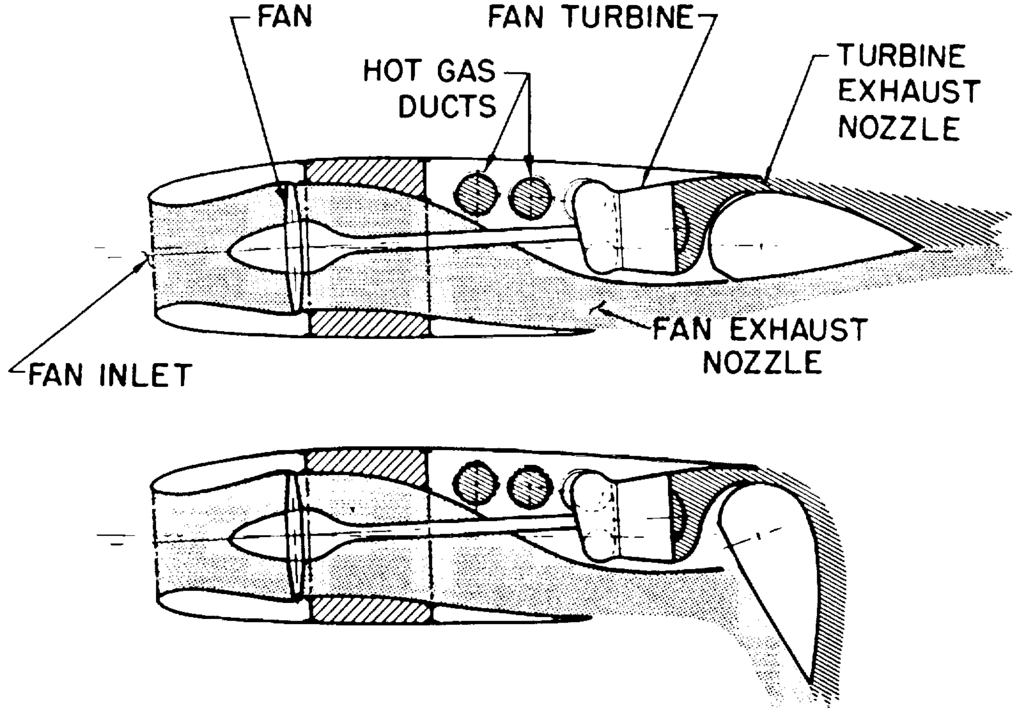


Figure 12. Vought propulsive wing cross section

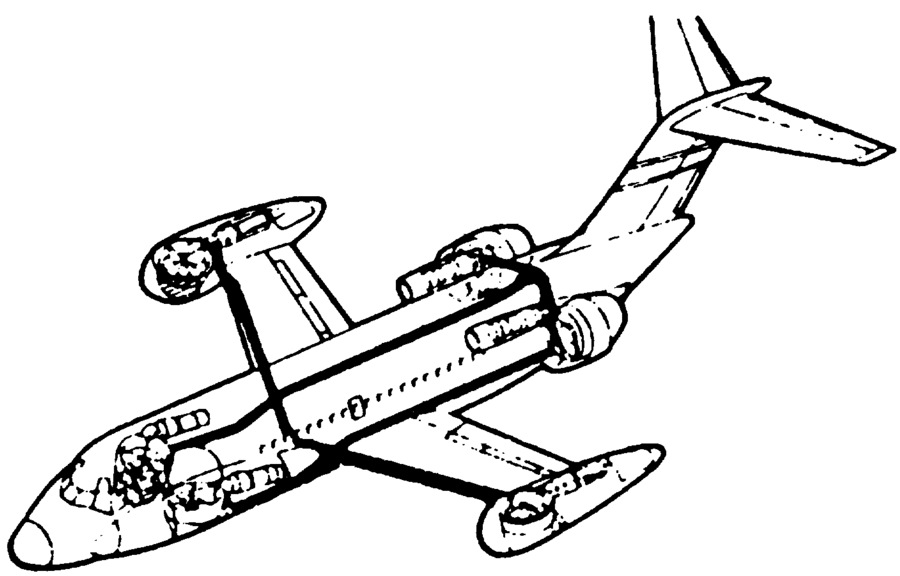


Figure 13. McDonnell modified DC-9/STOL lift fan plus lift/cruise fan research transport design

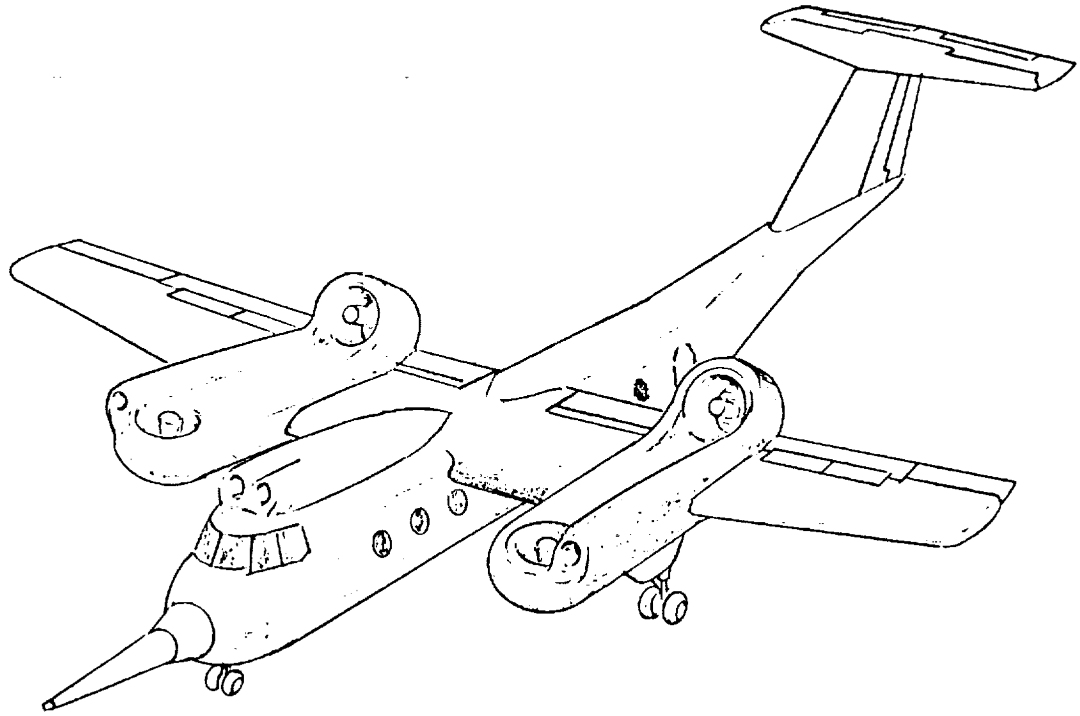


Figure 14. Boeing modified Buffalo V/STOL lift fan plus lift/cruise fan research transport design

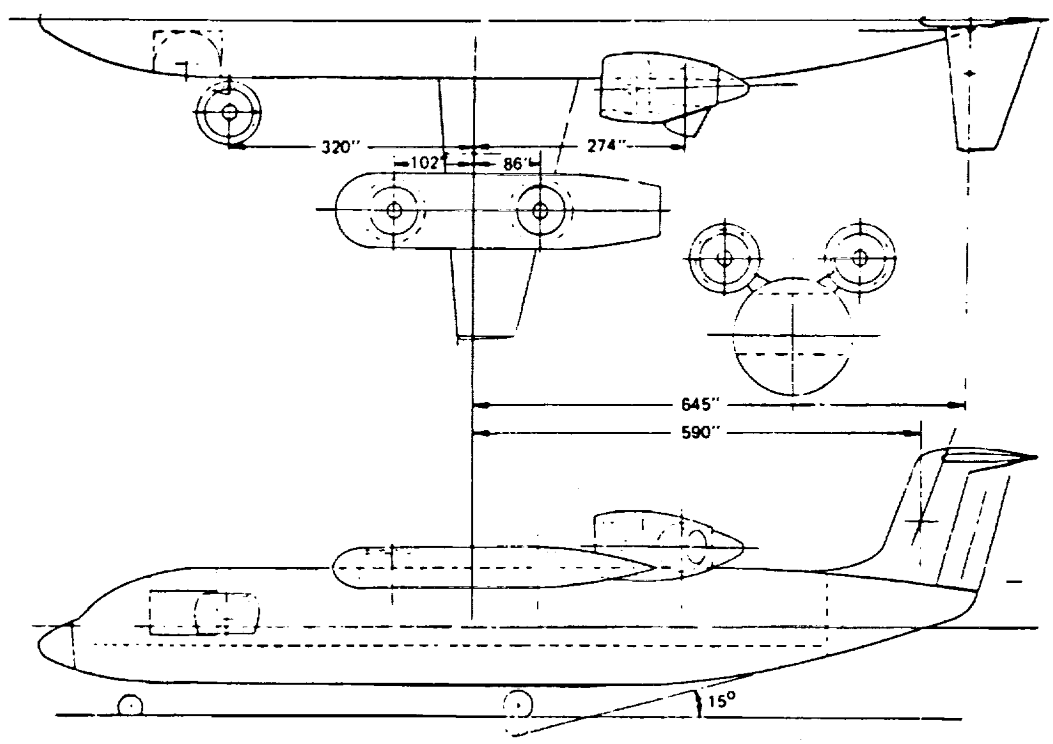


Figure 15. Boeing 100-passenger V/STOL integral lift-fan transport design

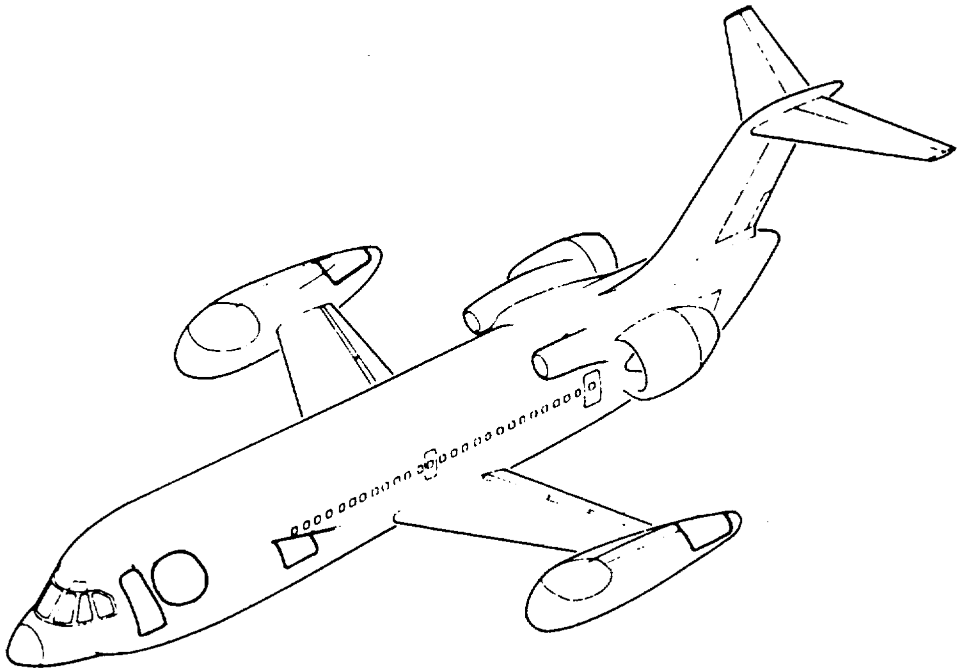


Figure 16. McDonnell 100-passenger V/STOL remote lift-fan transport design

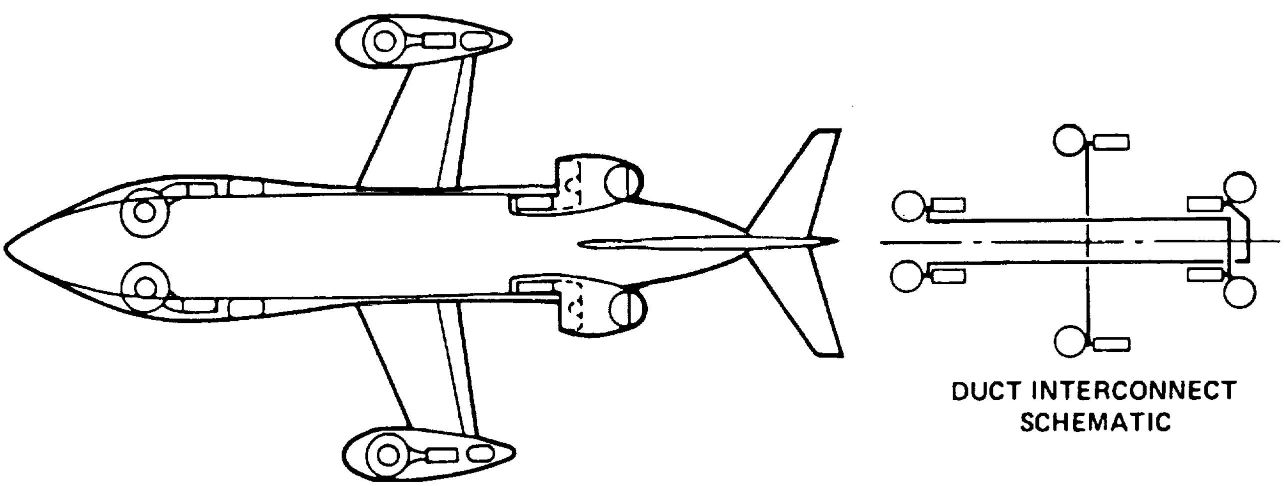


Figure 17. McDonnell propulsion schematic for design with six gas generators/six fans

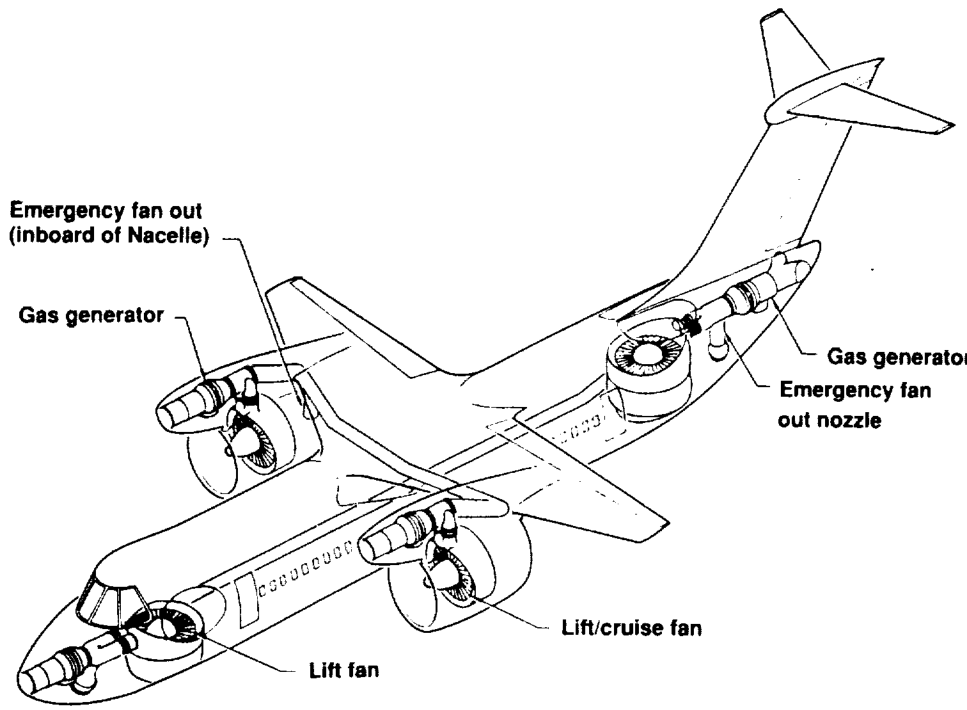


Figure 18. McDonnell 100-passenger V/STOL transport design (later version)

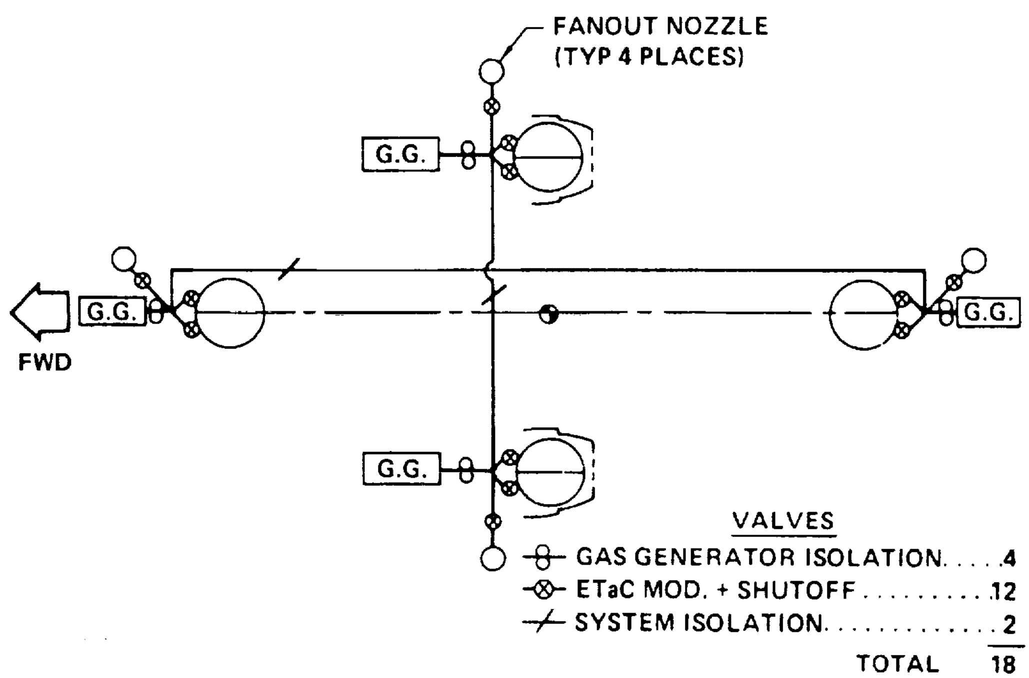


Figure 19. McDonnell propulsion schematic for design with four gas generators/four fans

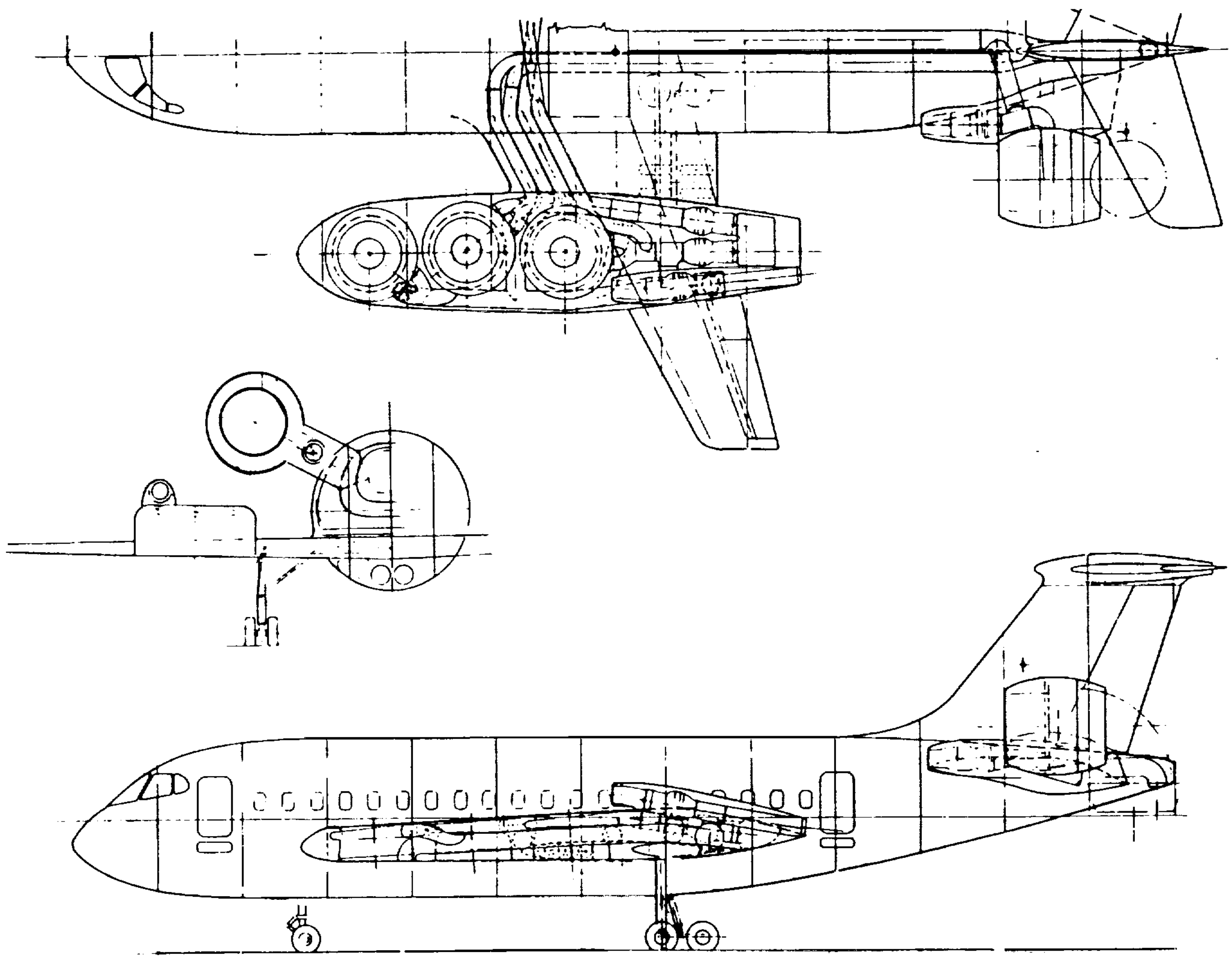


Figure 20. Rockwell 100-passenger V/STOL remote lift-fan transport design

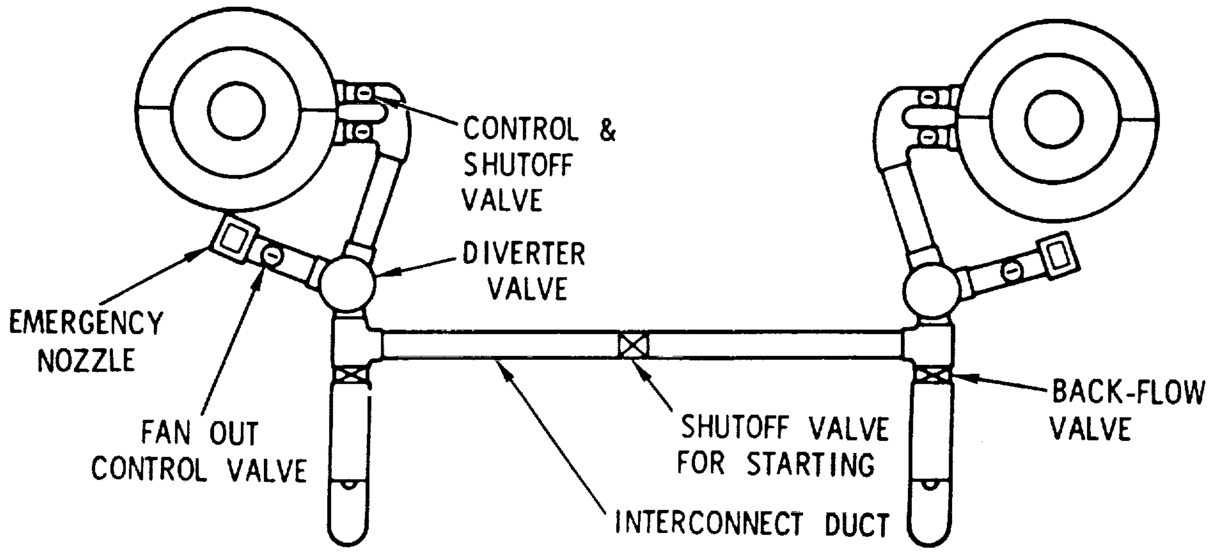
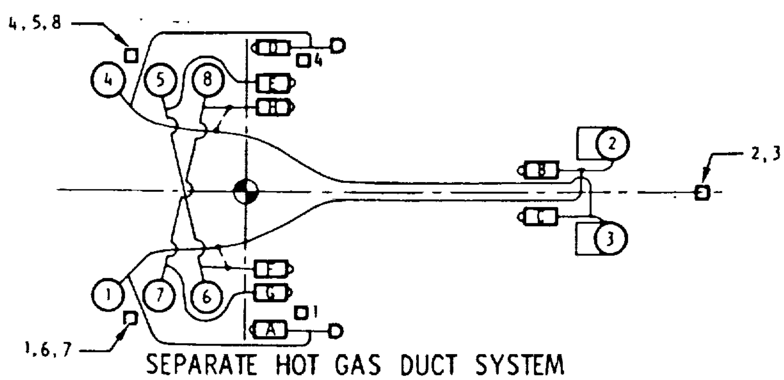


Figure 21. One of four paired gas interconnected systems in the Rockwell 100-passenger design



GAS GENERATOR FAILURE

GAS GEN FAILS	ACTION TAKEN	RESULT IS HALF THRUST FOR FANS
A OR B	F REPLACES A OR B	5 & 6
C OR D	H REPLACES C OR D	7 & 8
E OR F	NONE	5 & 6
G OR H	NONE	7 & 8

FAN FAILURE

FAN FAILS	SHUT DOWN FAN	DIVERT GAS FROM GAS GEN	TO EMERG NOZZLE
1 OR 2	2 OR 1	A & B	1 & 2
3 OR 4	4 OR 3	C & D	3 & 4
5 OR 6	6 OR 5	E & F	5 & 6
7 OR 8	8 OR 7	G & H	7 & 8

Figure 22. Propulsion system schematic for the Rockwell 100-passenger design

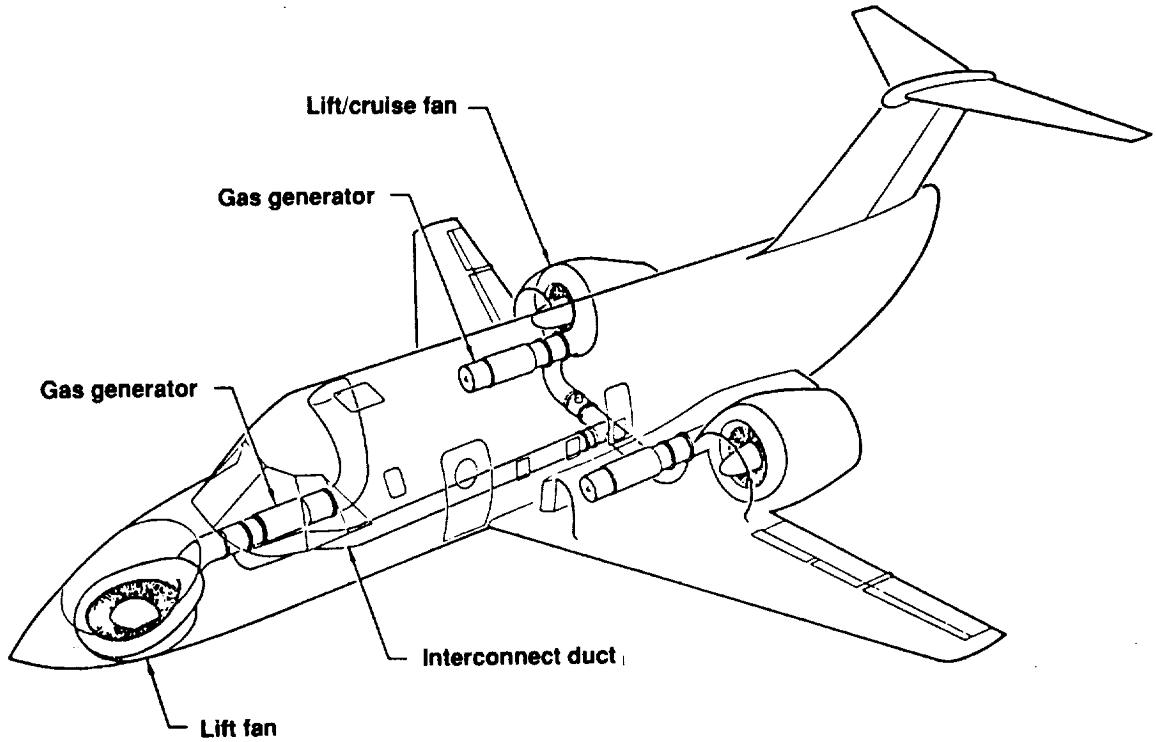


Figure 23. McDonnell STOVL design for Navy Vertical-Onboard-Delivery

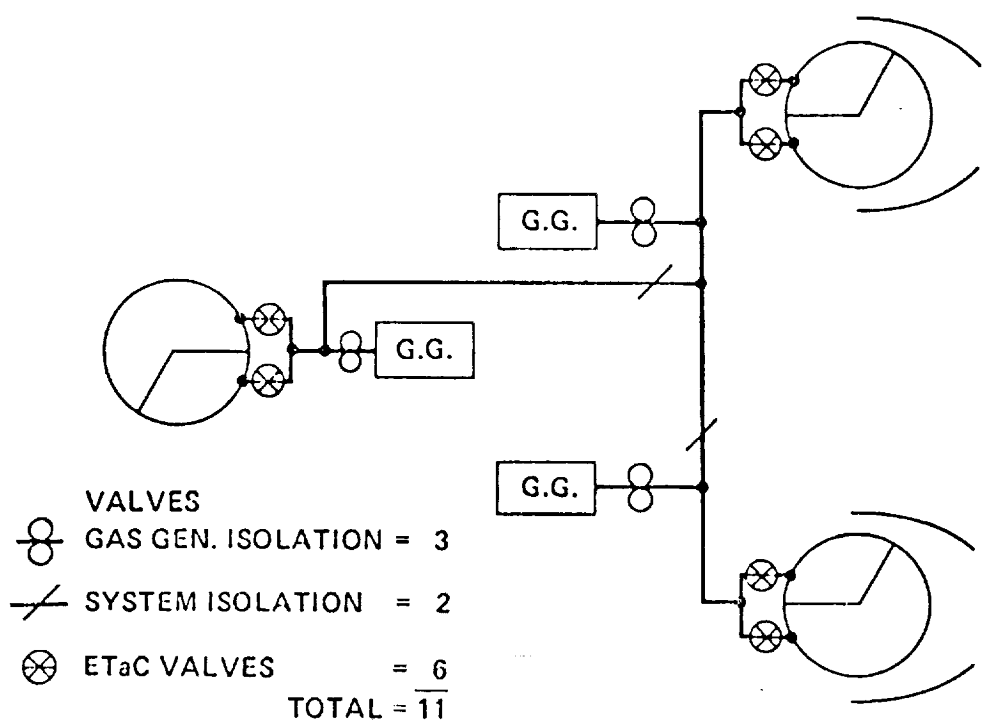


Figure 24. Propulsion schematic for McDonnell VOD design

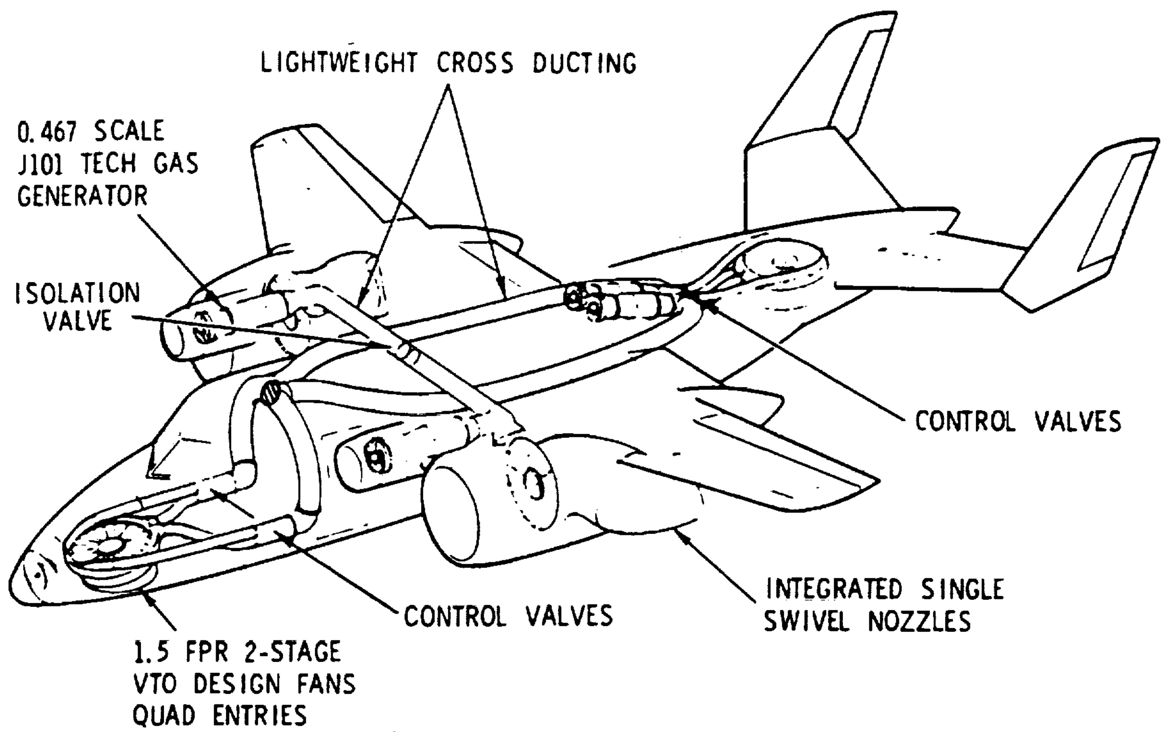


Figure 25. Rockwell STOVL design for Navy Vertical-Onboard-Delivery

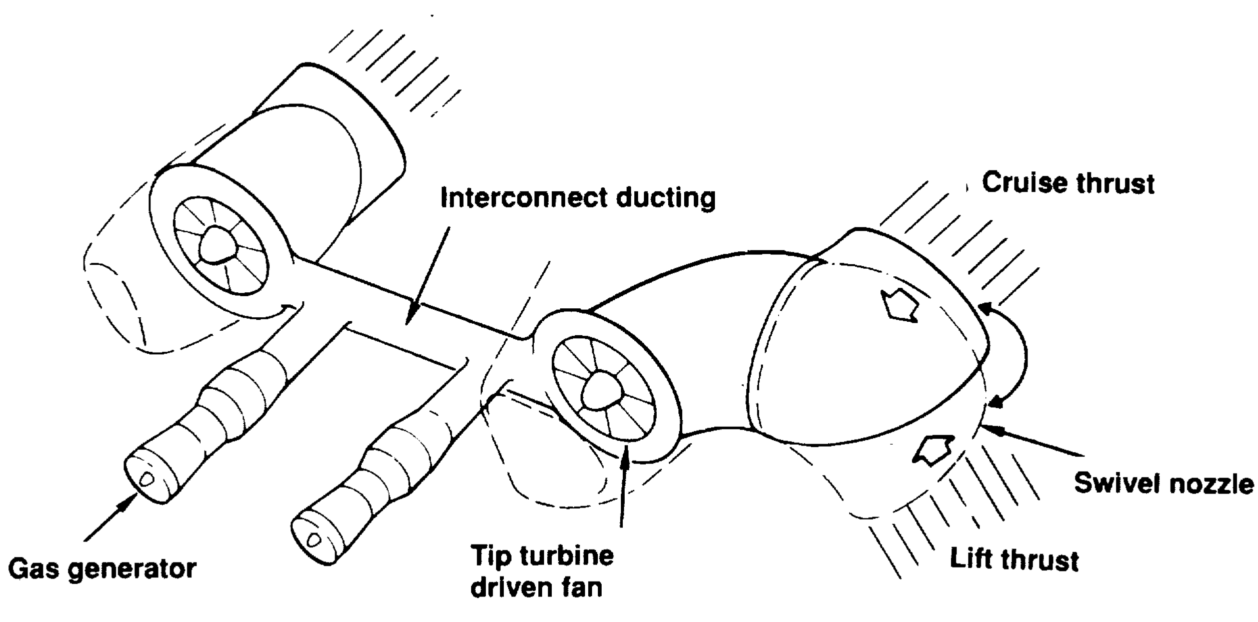


Figure 26. Single swivel nozzle on lift/cruise fan on Rockwell VOD design

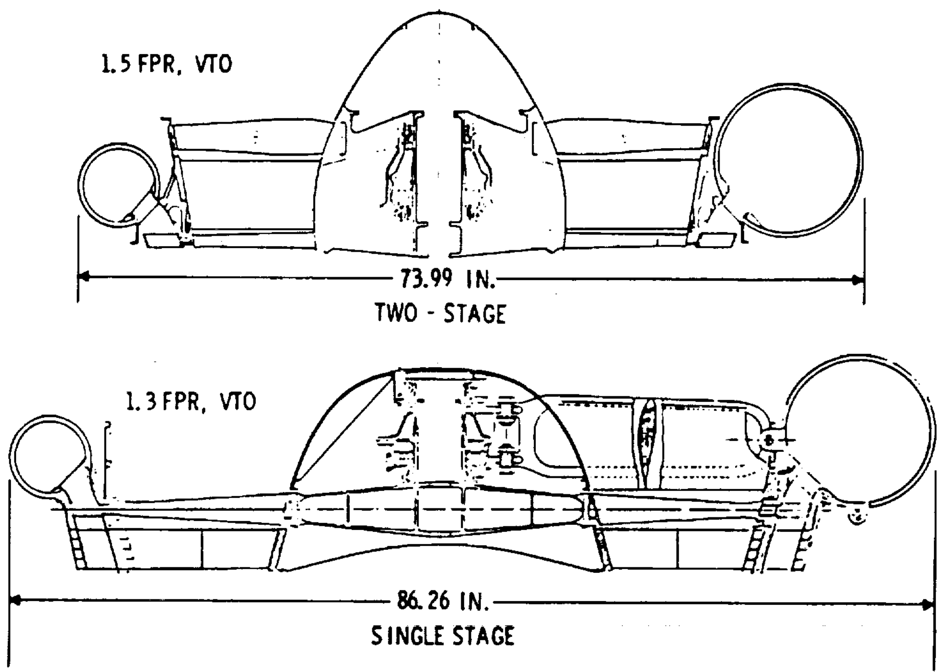


Figure 27. Two-stage fan on Rockwell VOD design, with comparison

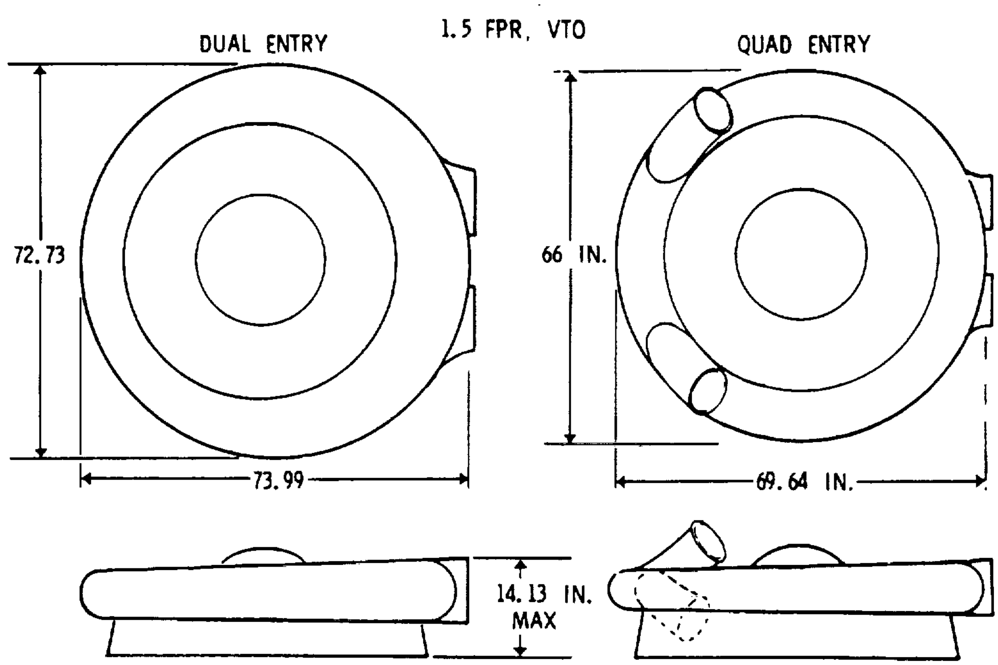


Figure 28. Quad entry scroll on Rockwell VOD design, with comparison

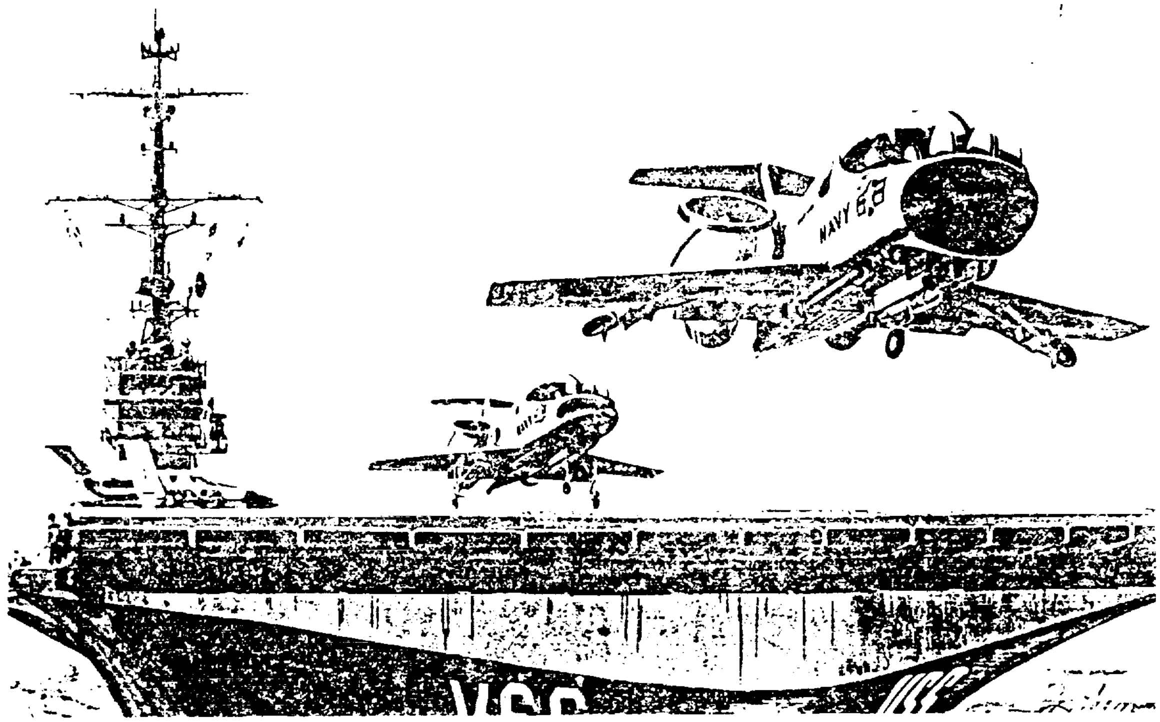


Figure 29. Boeing V/STOL design for Navy multimissions

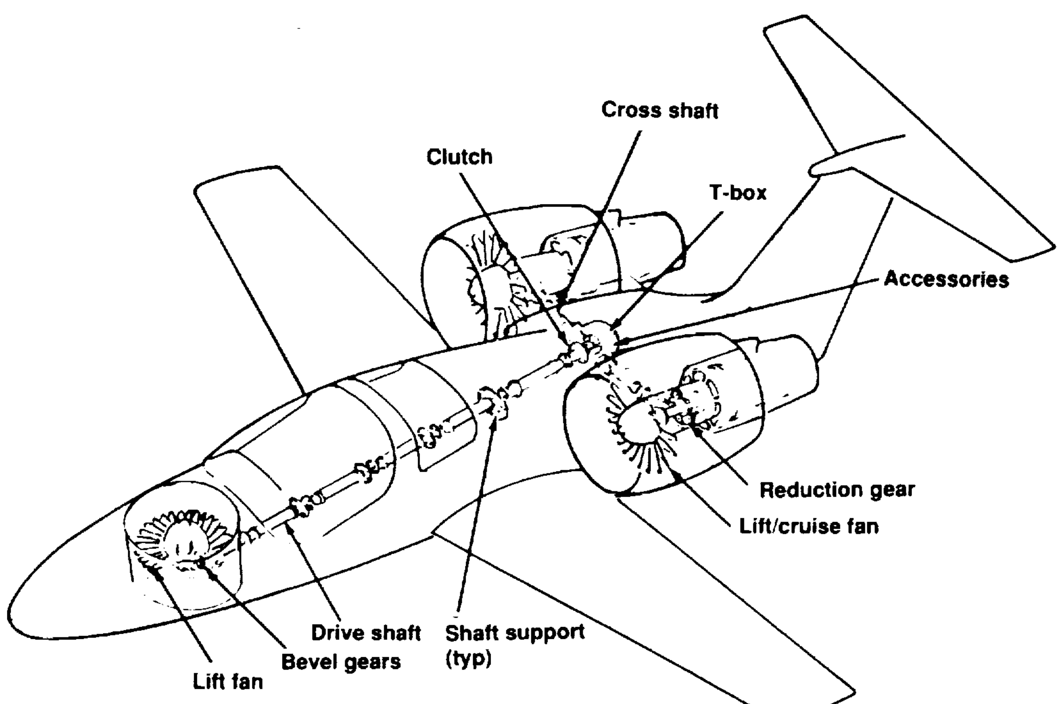


Figure 30. Isometric of Boeing Navy multimission design

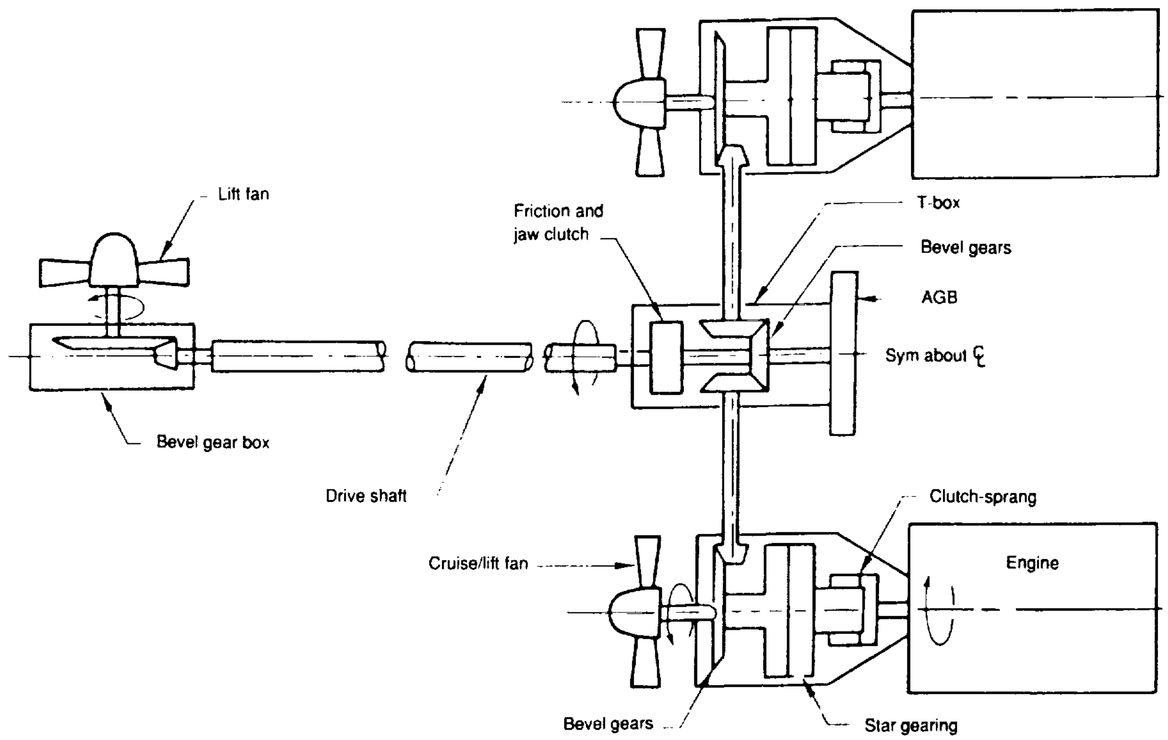


Figure 31. Power train schematic of Boeing Navy multimission design

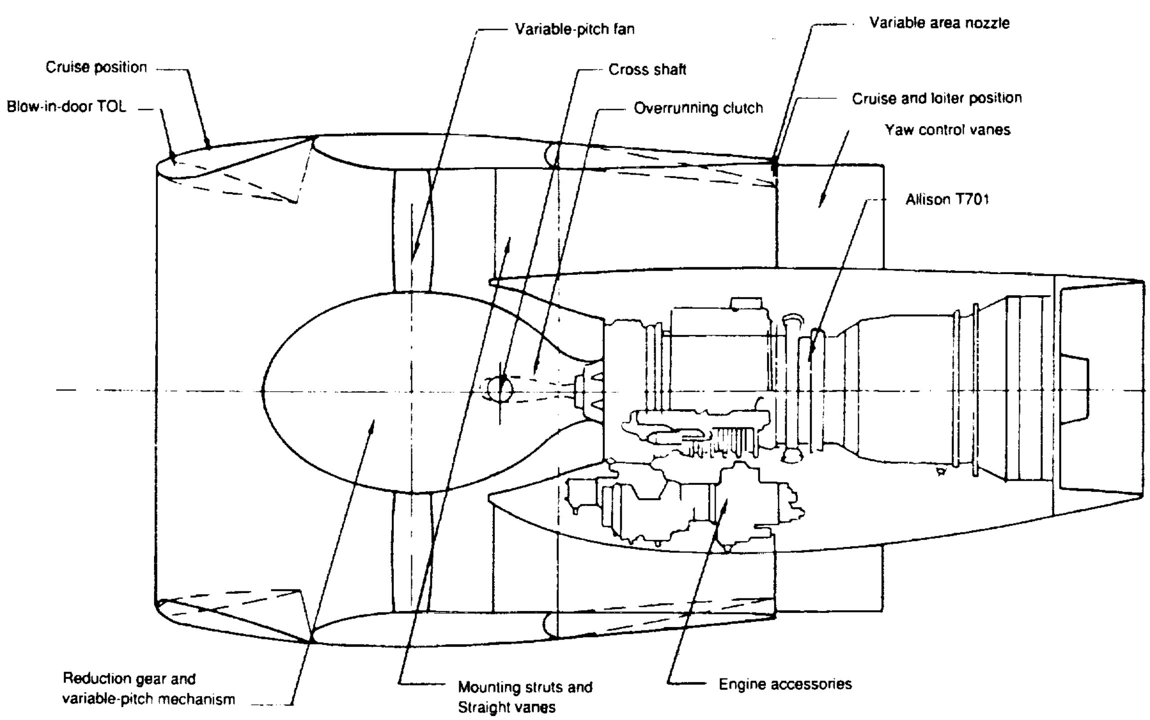


Figure 32. Integral lift/cruise fan pod on Boeing Navy multimission design

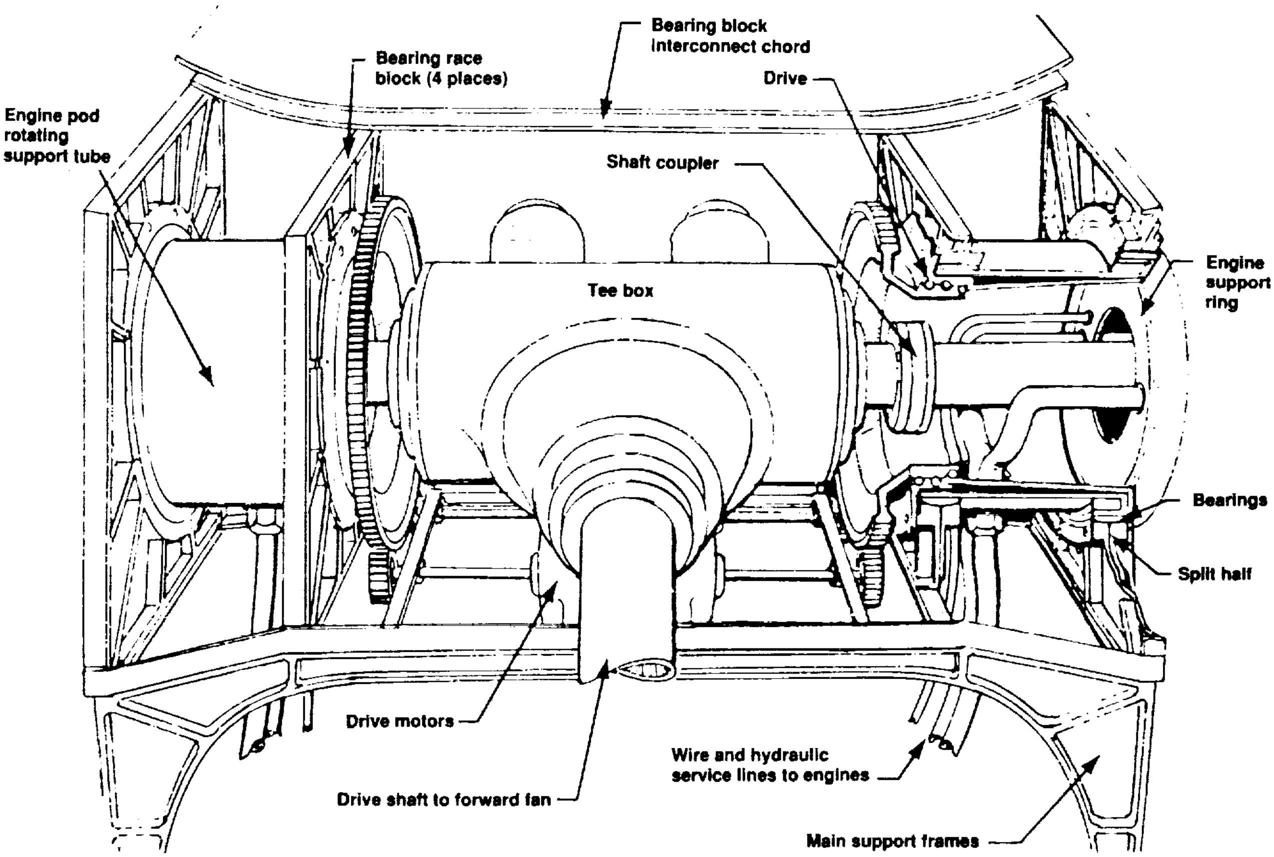


Figure 33. Pivot mechanism for lift/cruise fans on Boeing Navy multimission design

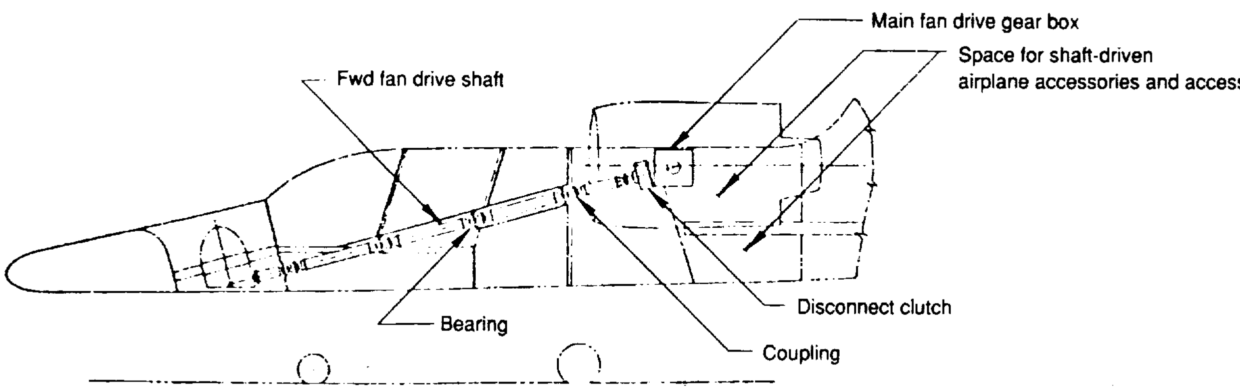


Figure 34. Nose lift-fan shaft drive system on Boeing Navy multimission design

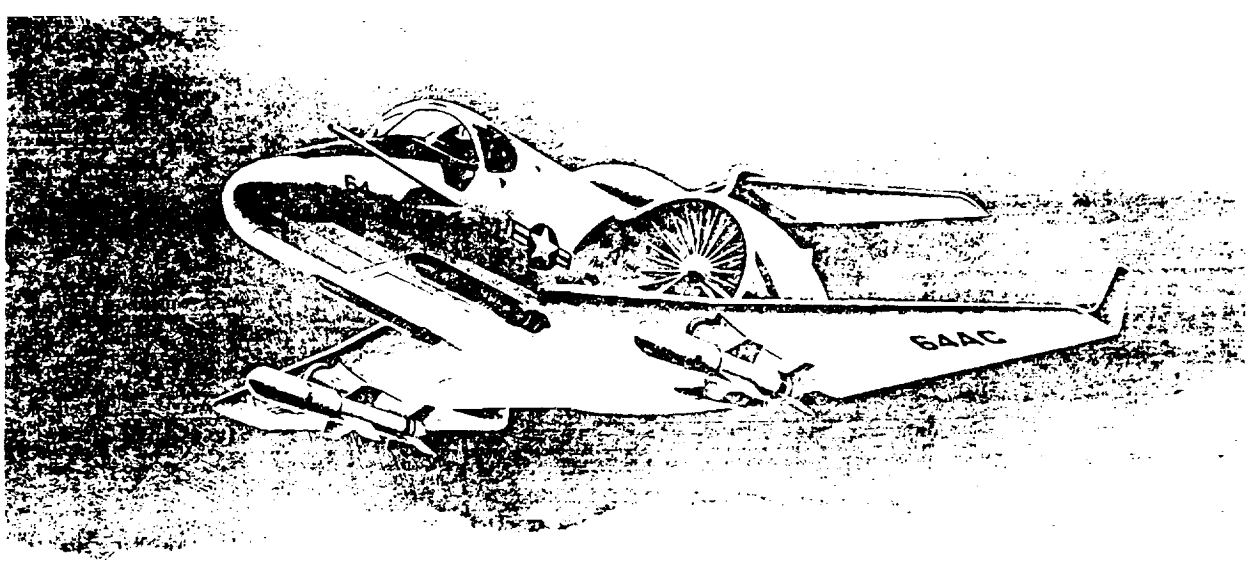


Figure 35. McDonnell V/STOL design for Navy multimissions

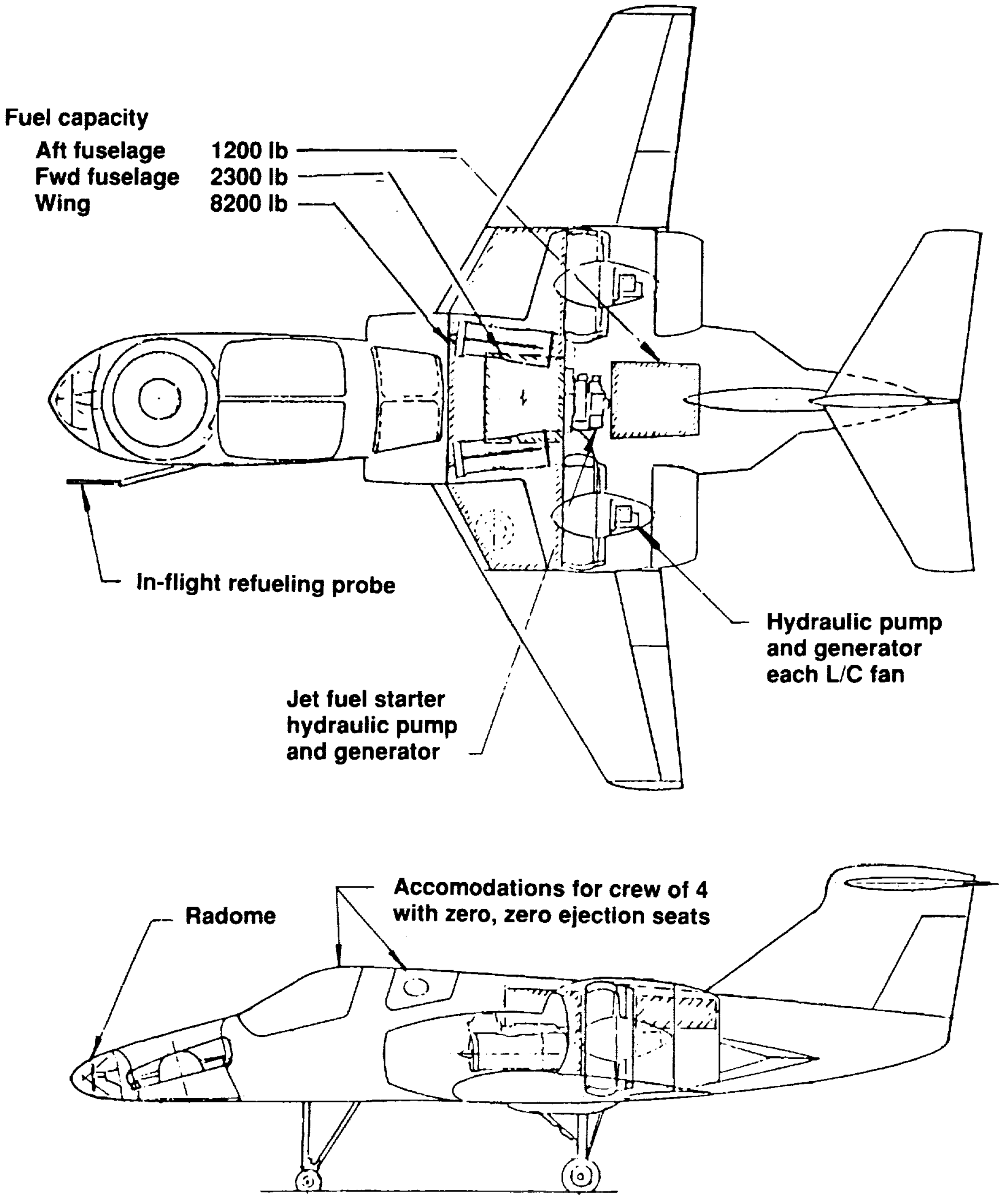


Figure 36. General arrangement for McDonnell Navy multimission design

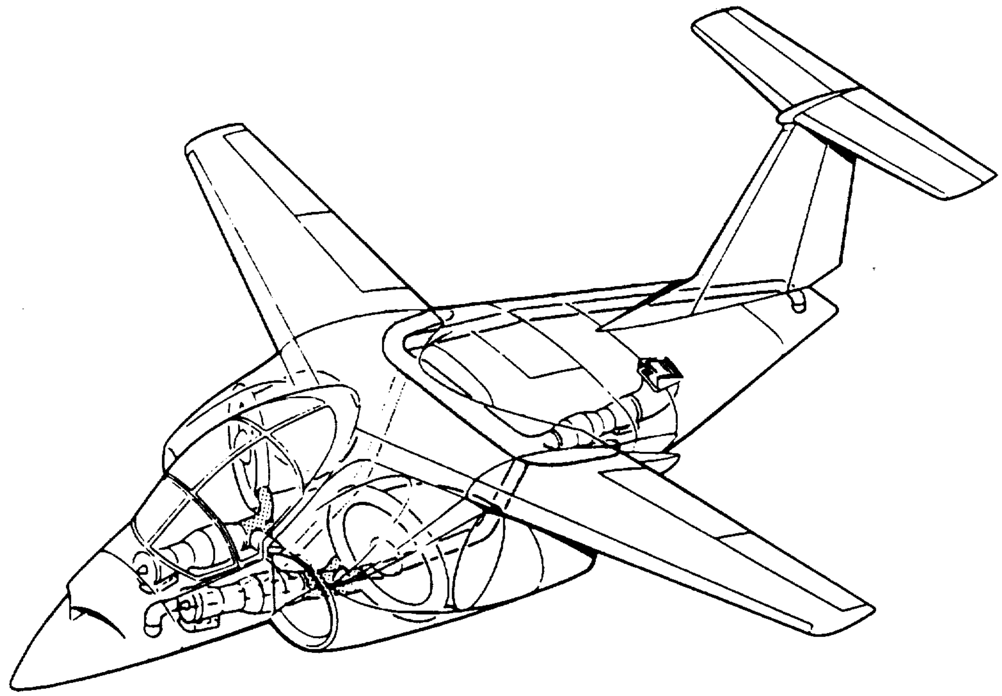


Figure 37. Rockwell V/STOL design for Navy multimissions

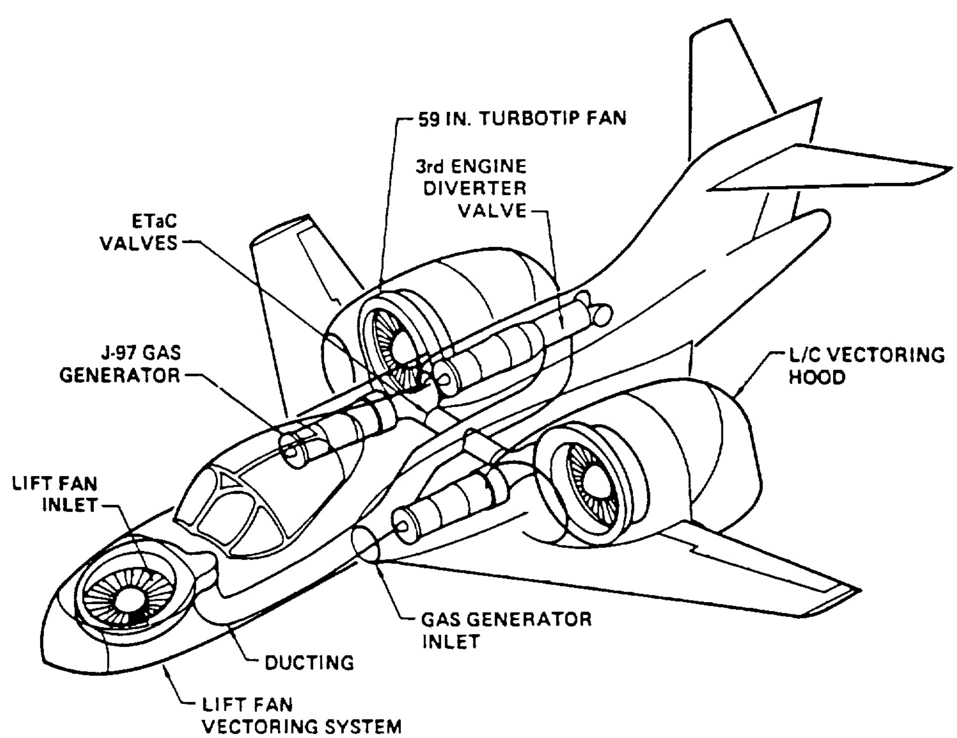


Figure 38. McDonnell modified T-39 RTA V/STOL aircraft design

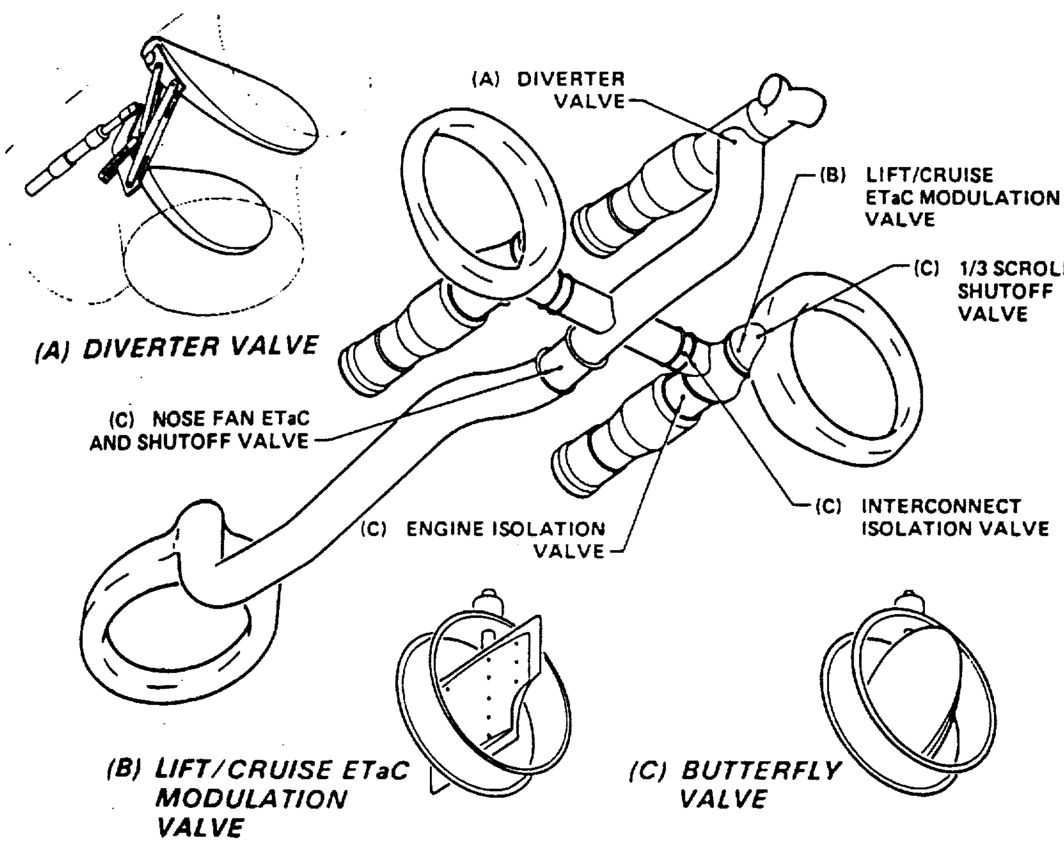


Figure 39. Propulsion/control and valving schematic for McDonnell T-39 RTA design

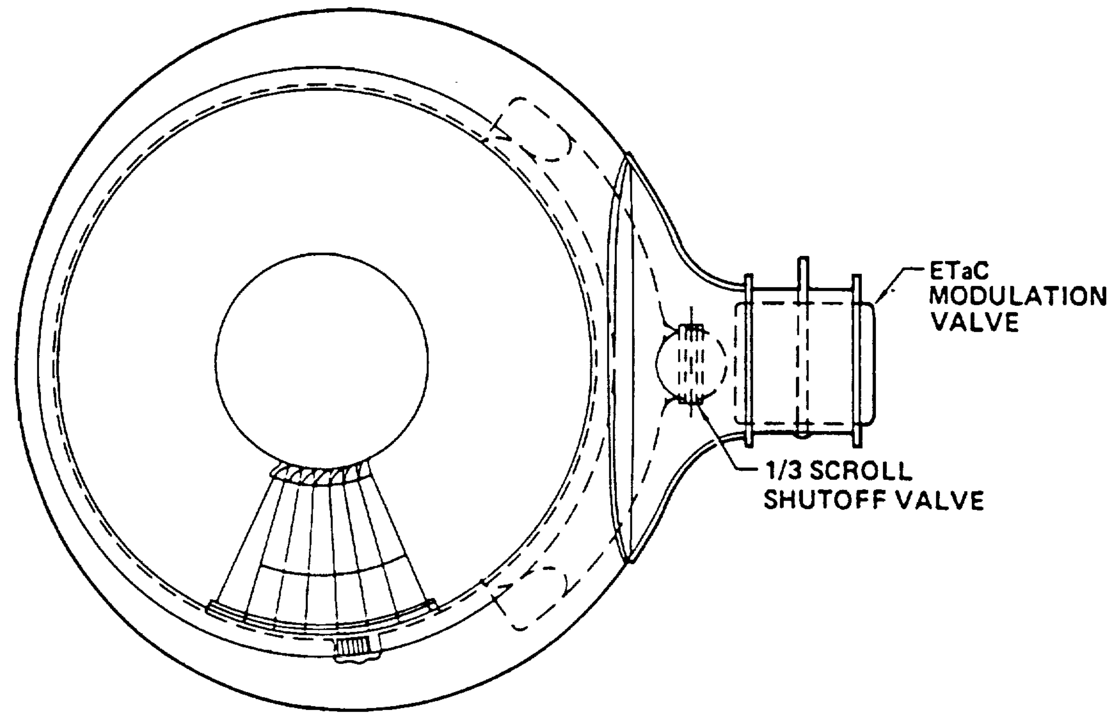


Figure 40. Scroll-In-Scroll on the McDonnell T-39 RTA design

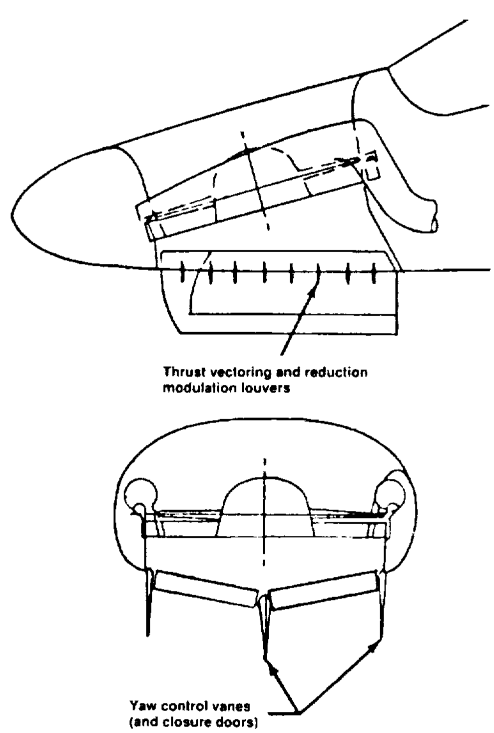


Figure 41. Thrust Reduction Modulation louvers and vanes in nose fan exit, McDonnell T-39 RTA design

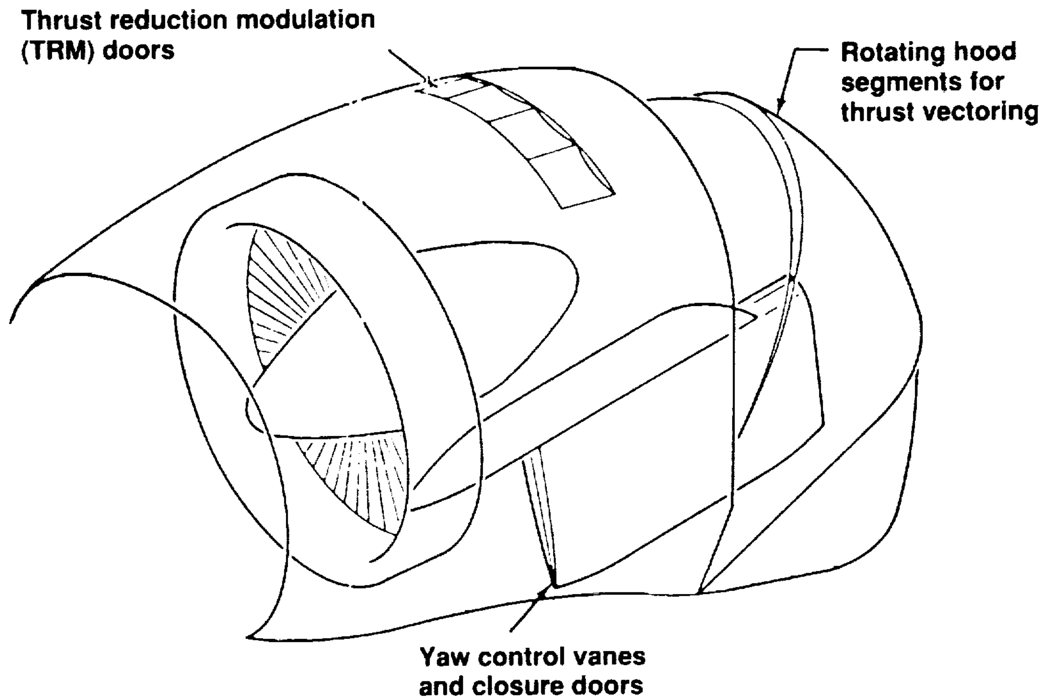


Figure 42. Thrust Reduction Modulation, hood, and vanes on lift/cruise fan, McDonnell T-39 RTA design

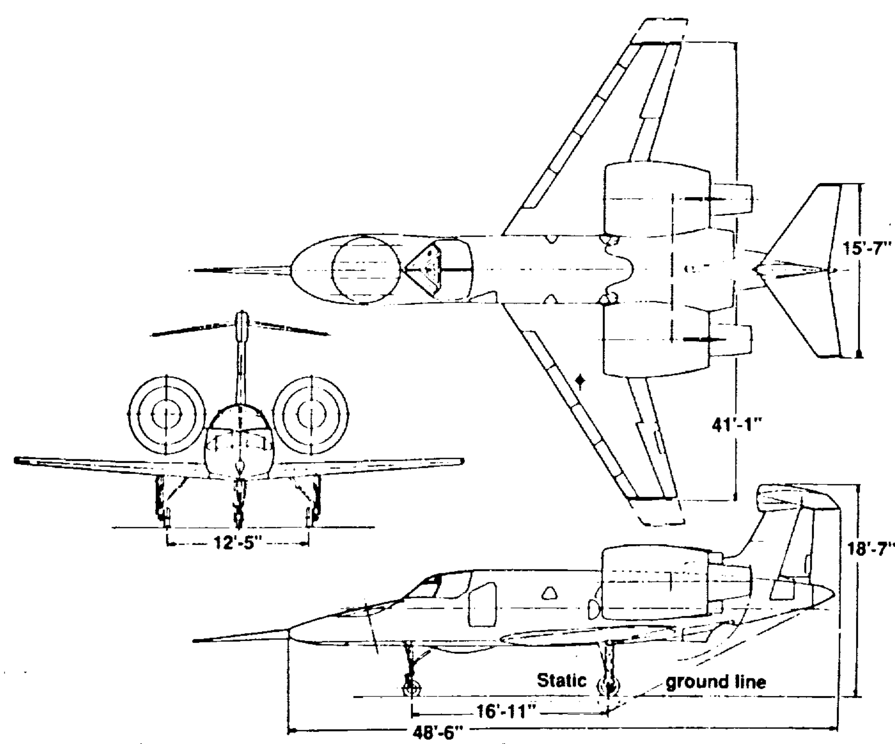


Figure 43. Boeing modified T-39 RTA V/STOL aircraft design

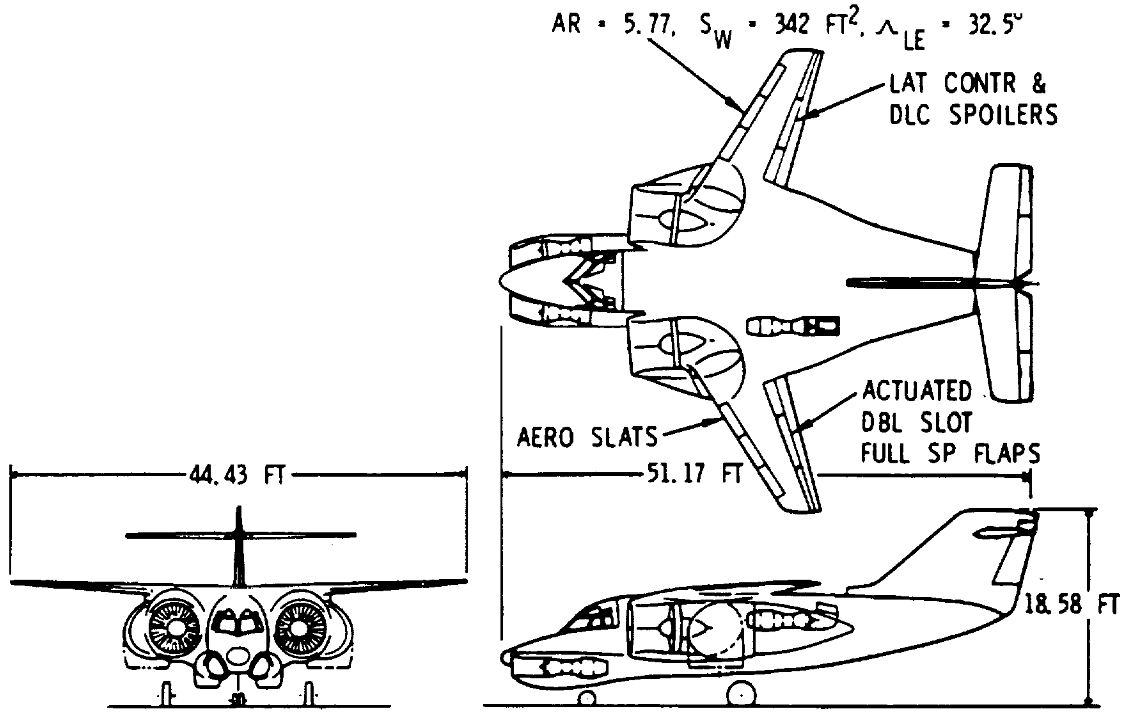


Figure 44. Rockwell modified T-39 RTA V/STOL aircraft design

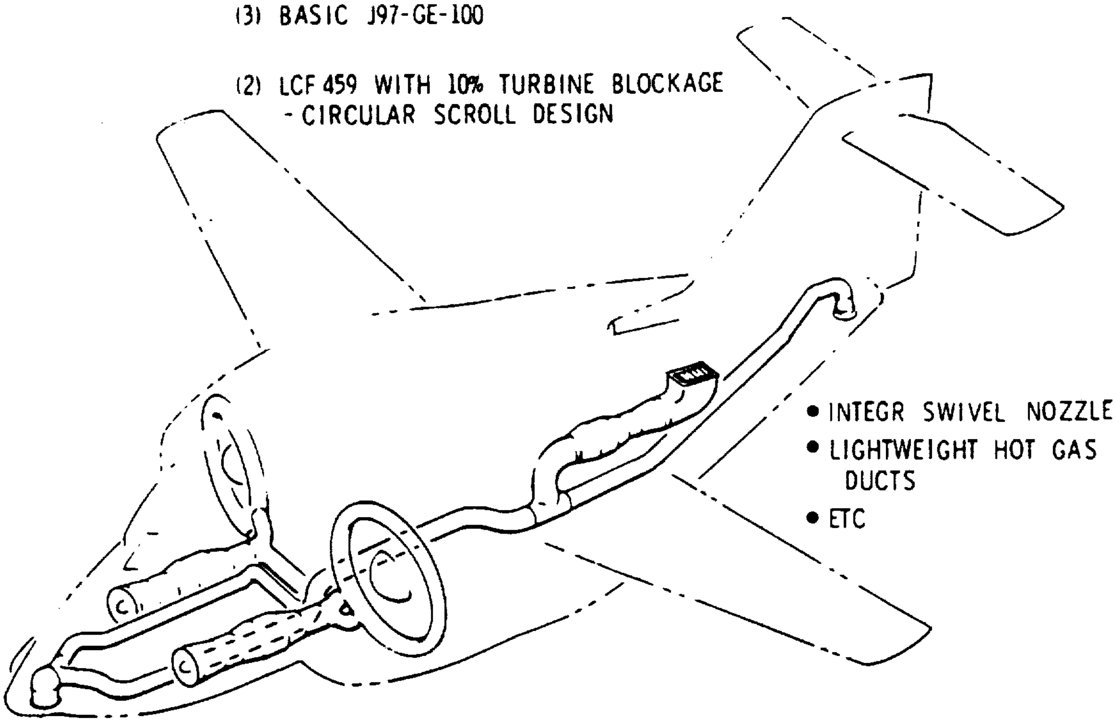


Figure 45. Propulsion system isometric, Rockwell T-39 RTA design

Figure 46. Large-scale model of Grumman V/STOL twin tilt nacelle design

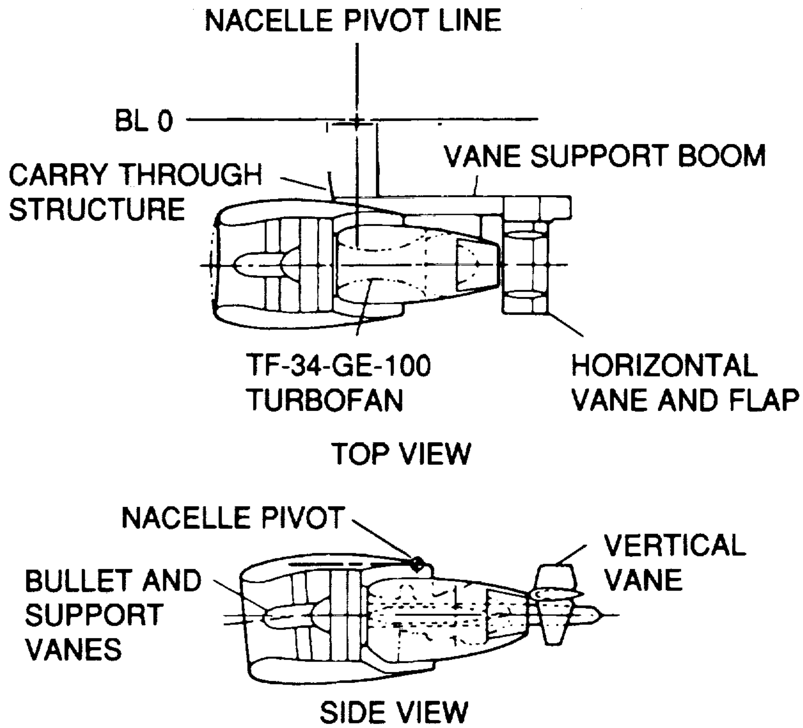


Figure 47. Propulsion schematic of Grumman twin tilt nacelle design

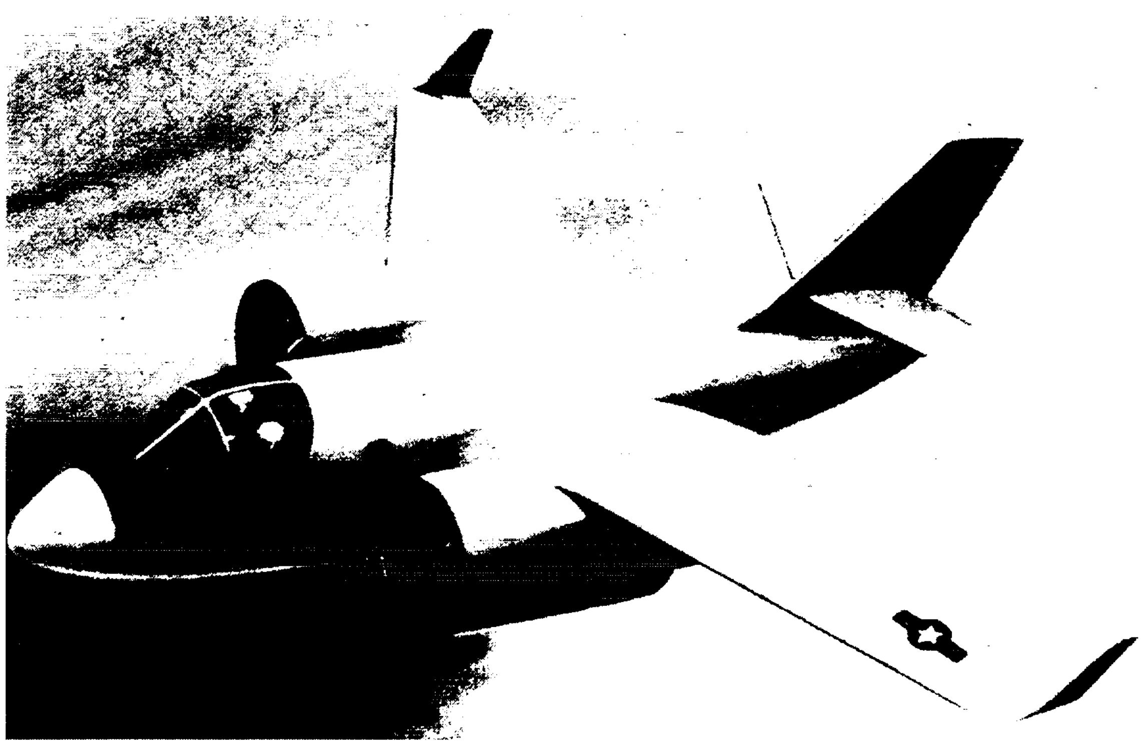


Figure 48. McDonnell V/STOL twin fixed nacelle design

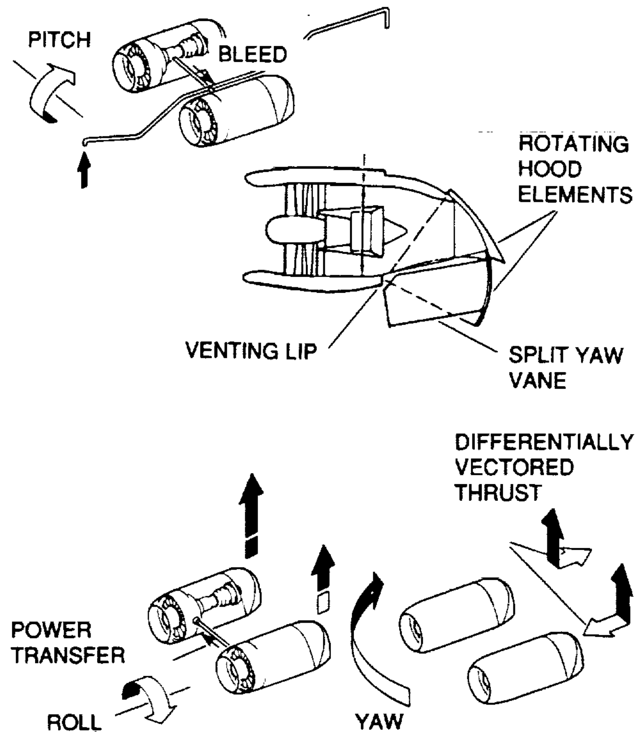


Figure 49. Propulsion/control schematic of
McDonnell twin nacelle design

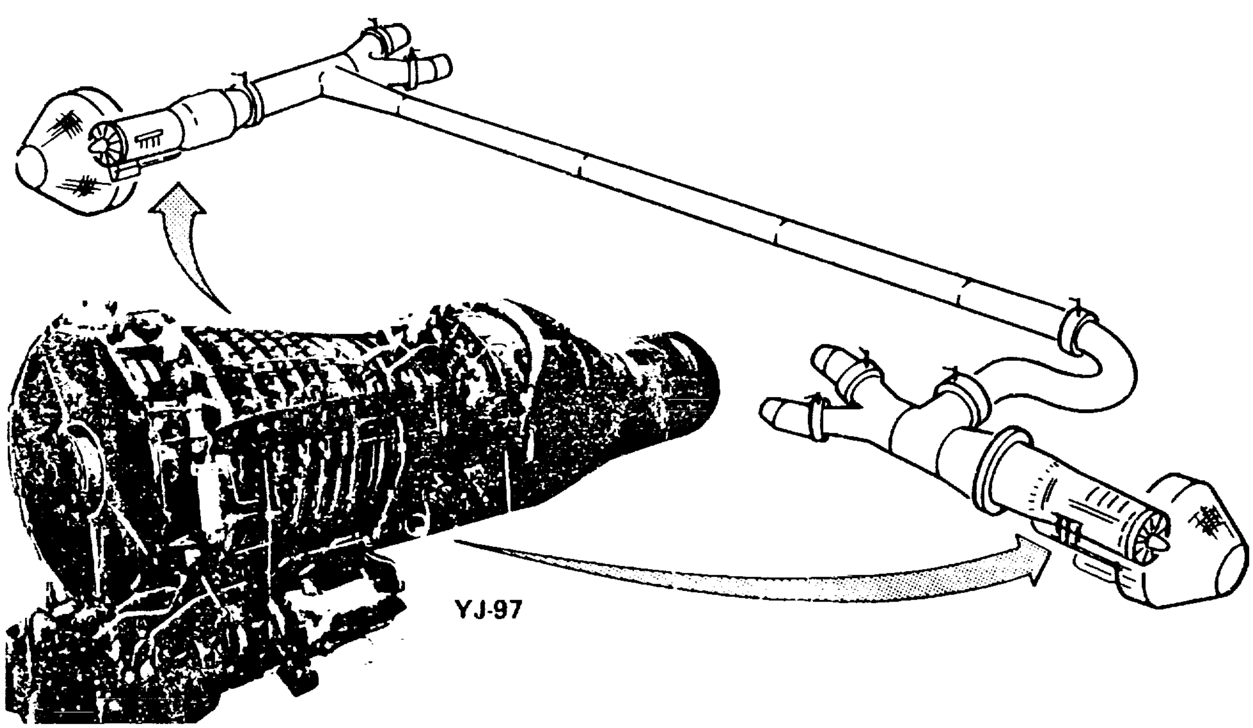


Figure 50. Full-scale investigation of characteristics of manifolded YJ-97 gas generators

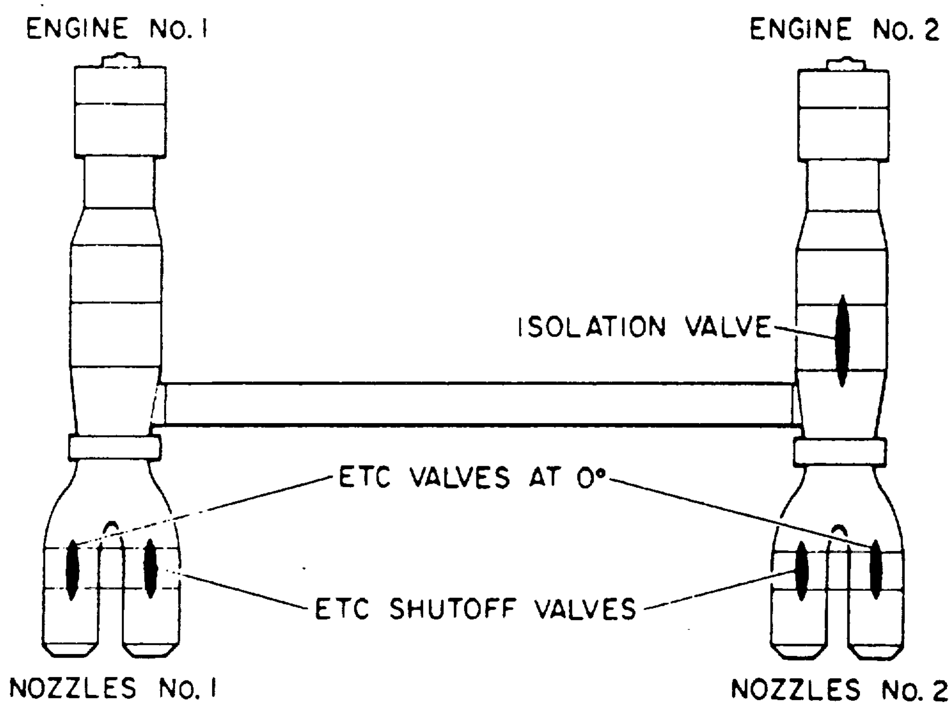


Figure 51. Initial configuration for investigating transient behavior during failure of no. 2 gas generator

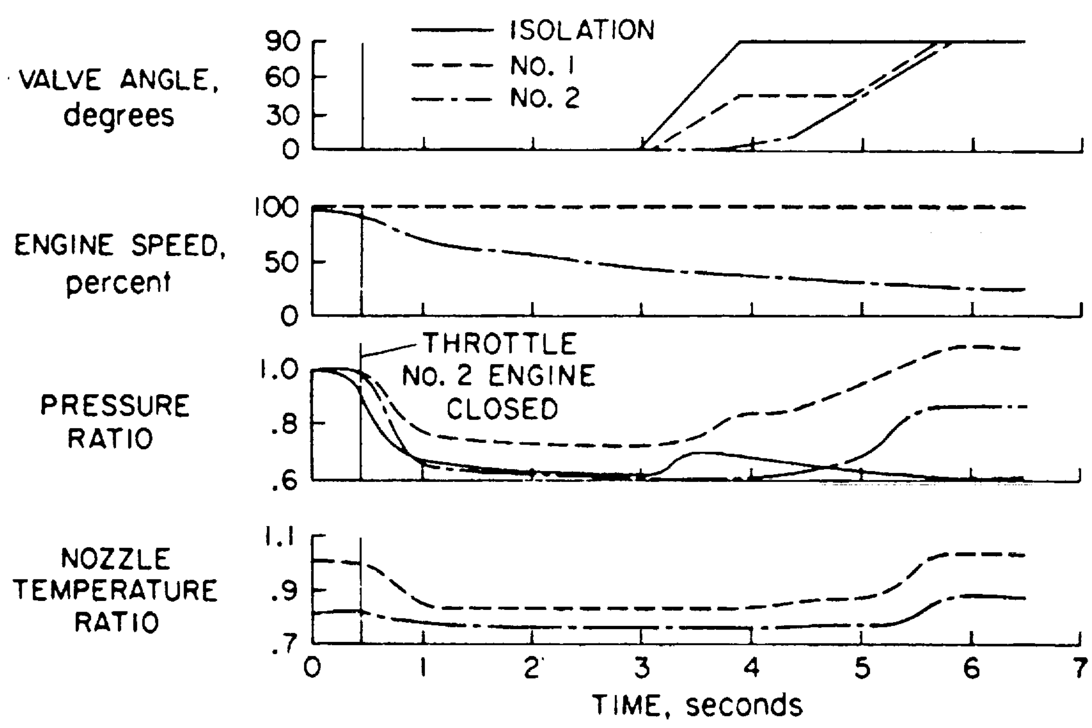


Figure 52. Time history of simulated failure of no. 2 gas generator

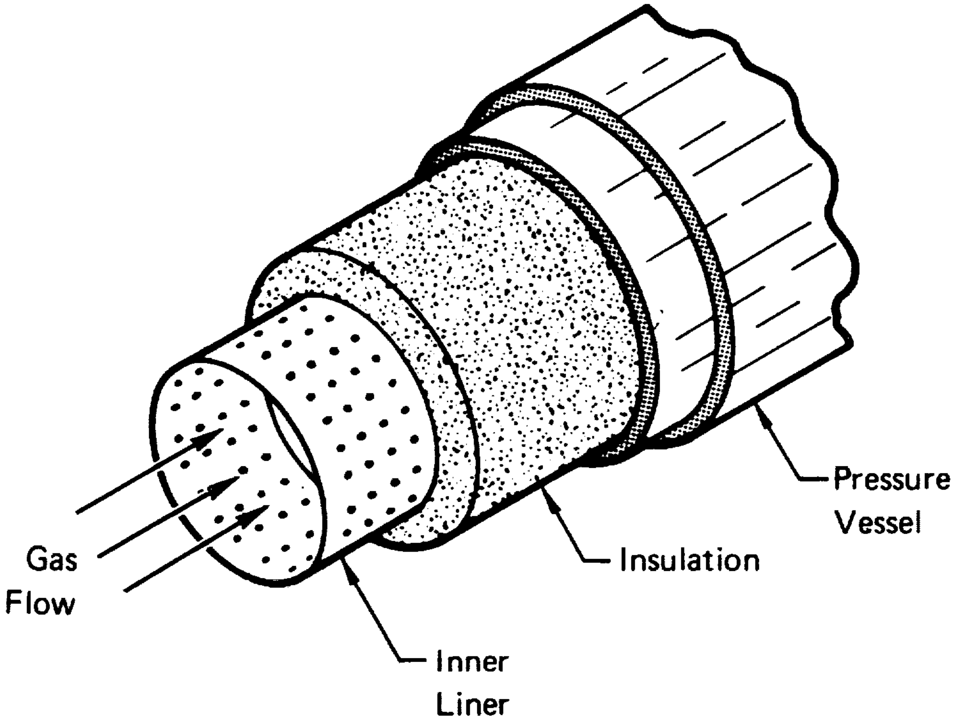


Figure 53. Composite duct concept

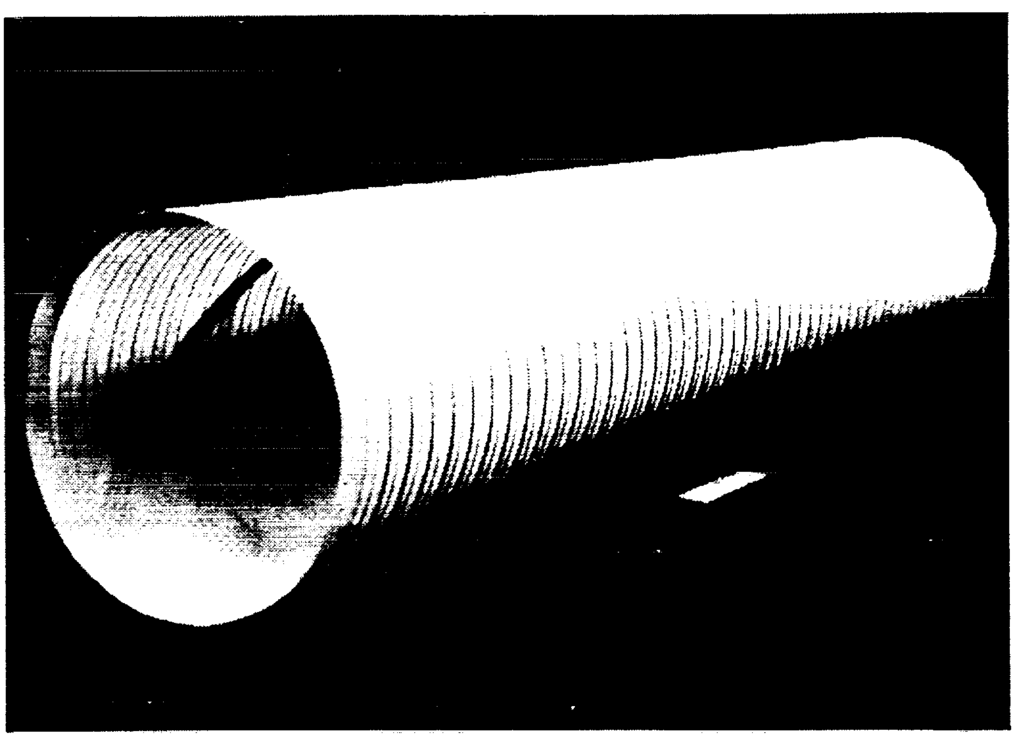


Figure 54. Full-scale duct wire wrapped screen liner

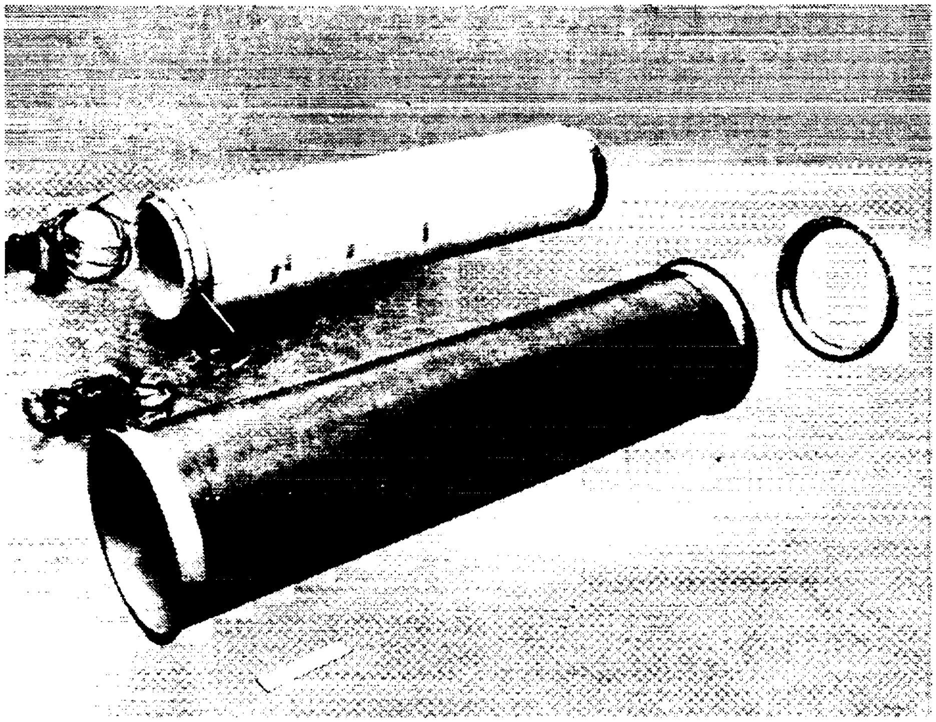


Figure 55. Final two components ready for assembly into the full-scale composite duct segment

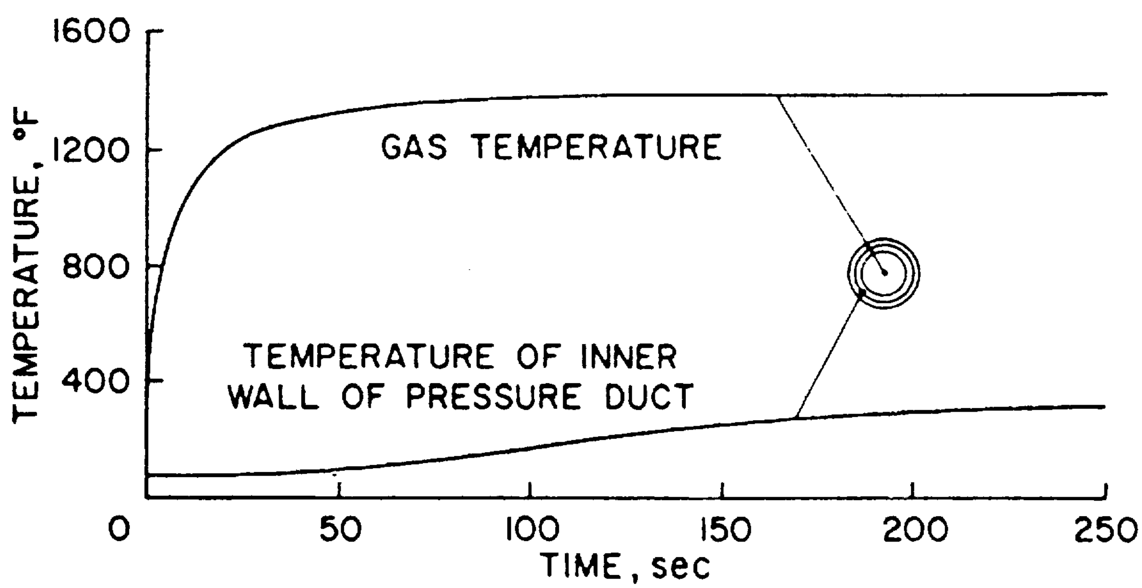


Figure 56. Experimental one engine-out temperature time history for the composite duct segment

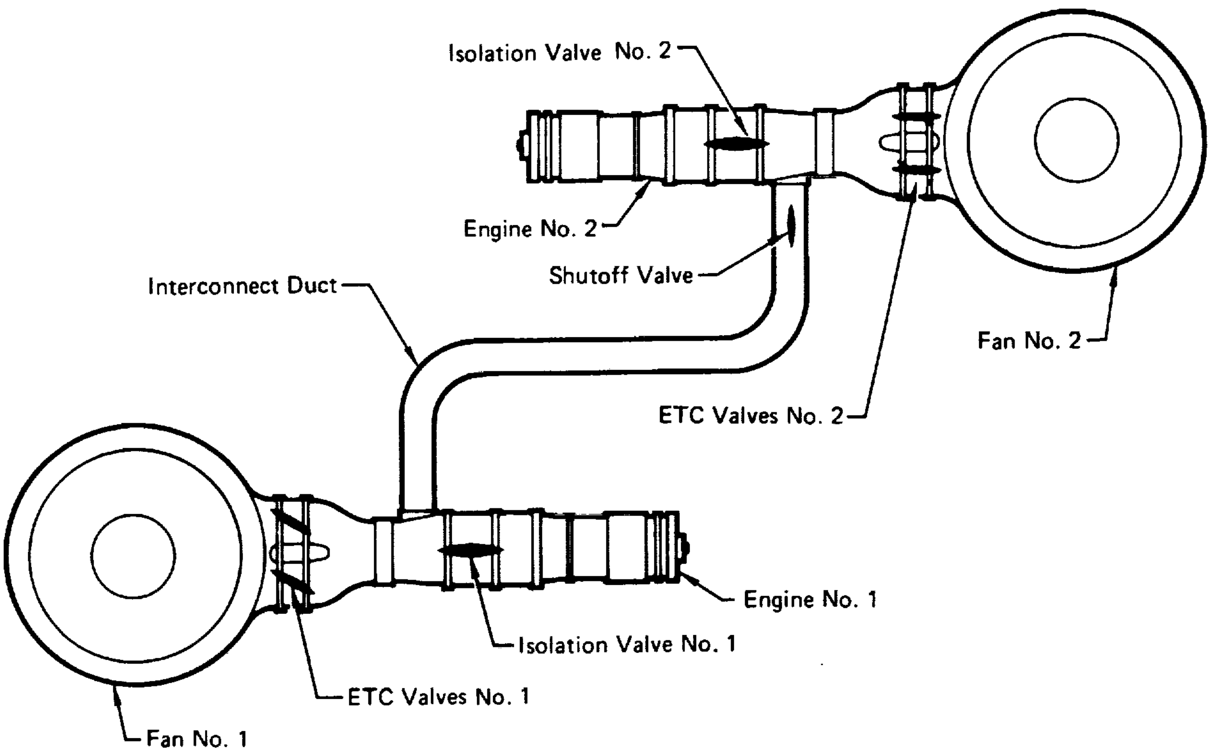


Figure 57. General arrangement of a paired Energy Transfer Control system

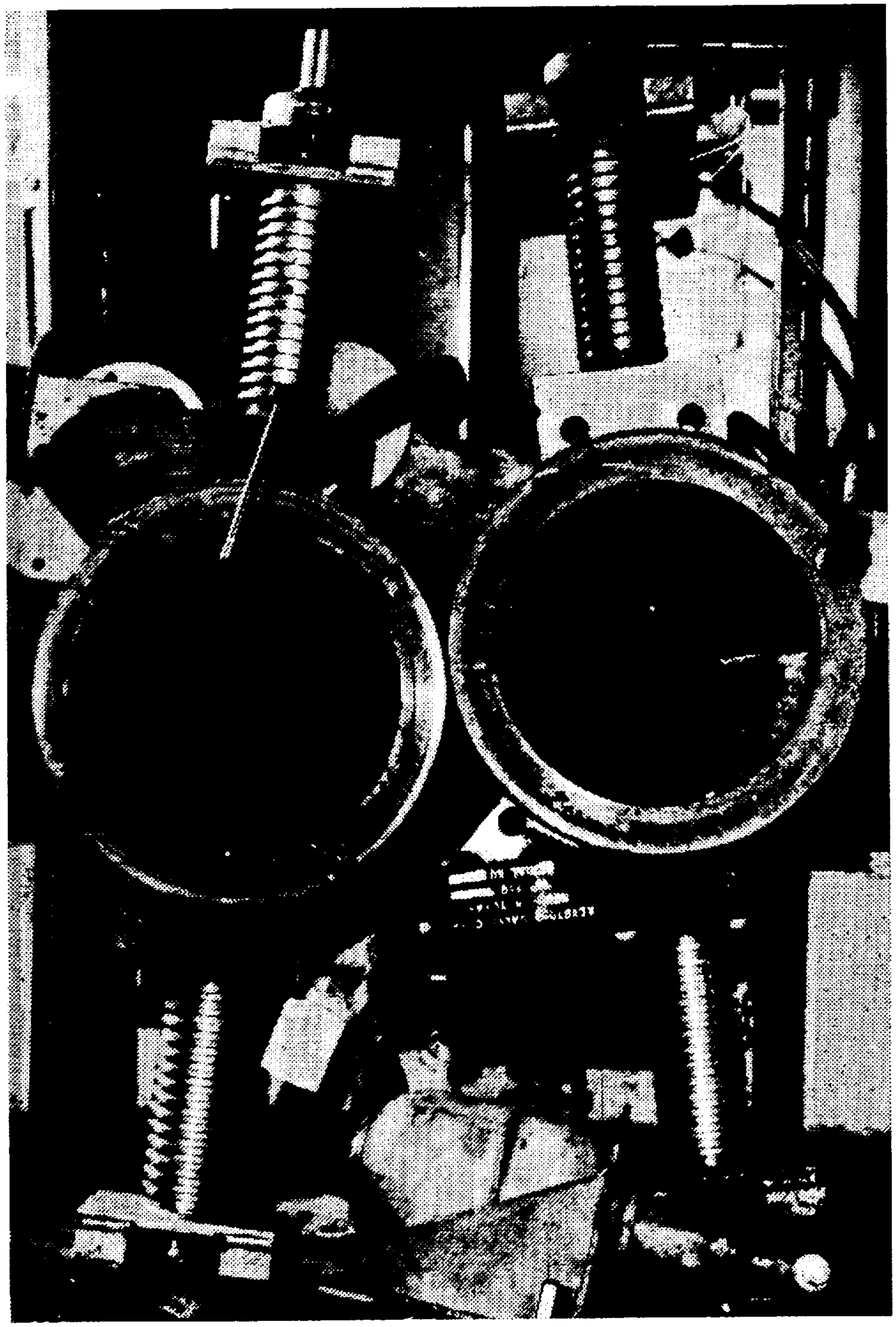


Figure 58. Full-scale ETC valves

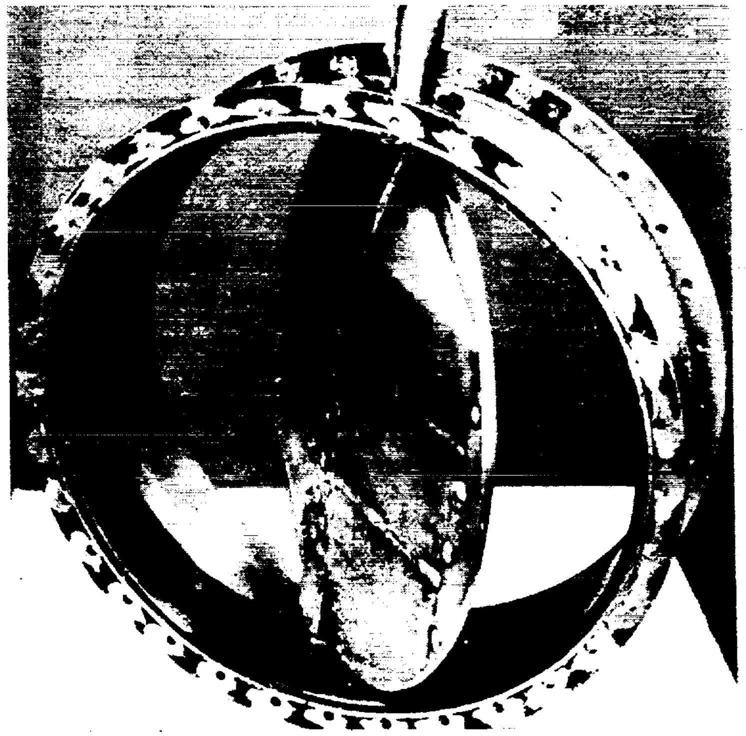


Figure 59. Full-scale interconnect duct shutoff valve

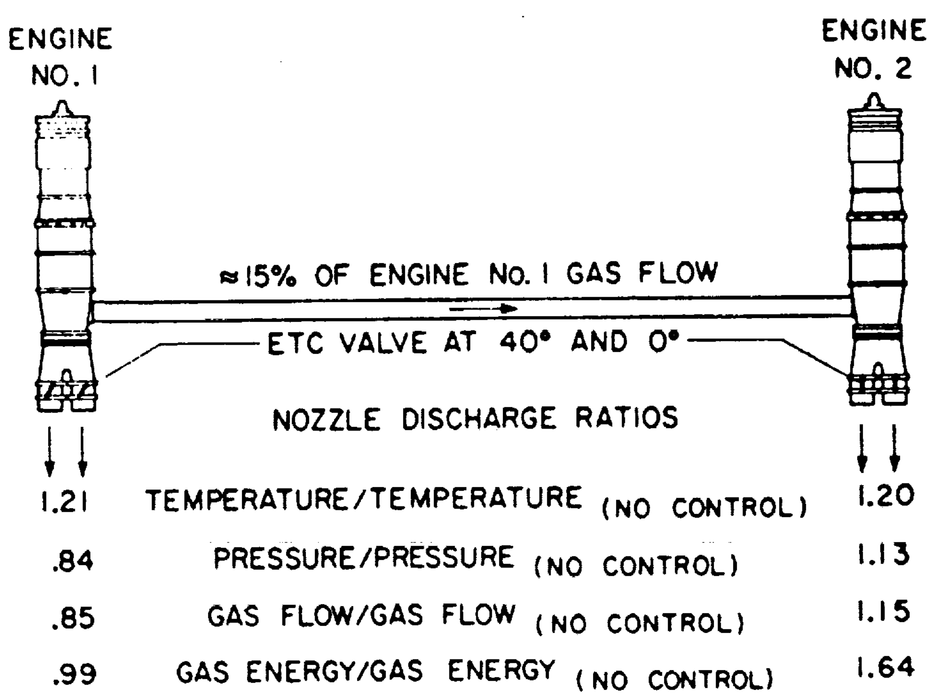


Figure 60. Steady-state gas conditions at lift-fan scroll entry with one pair of ETC valves deflected 40 deg and both YJ-97s operating at rated speed

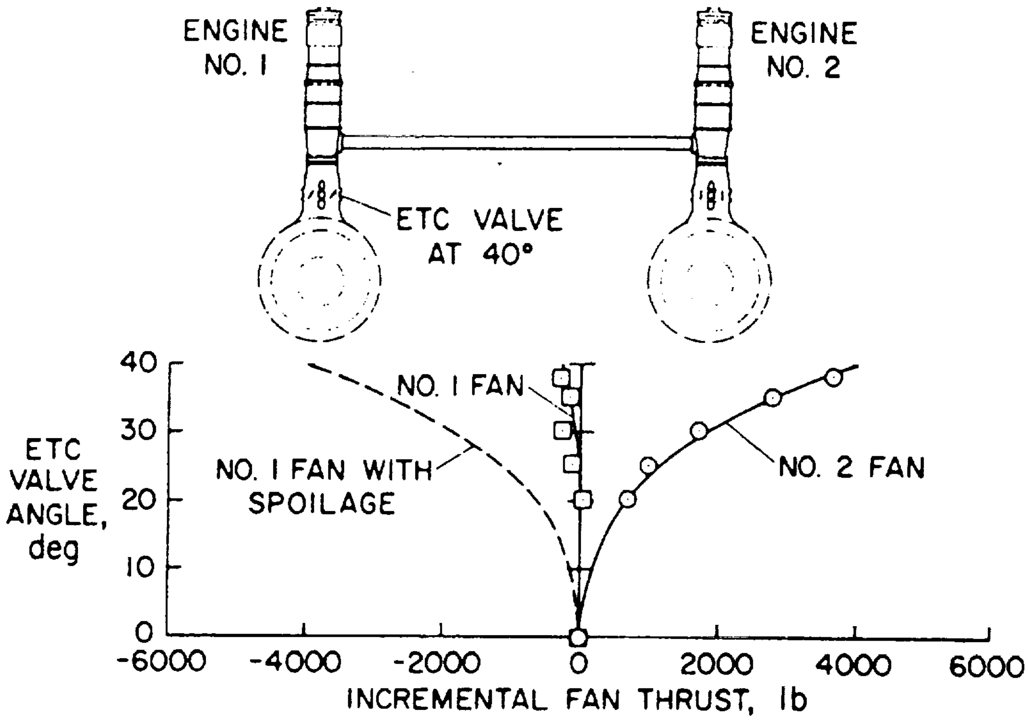


Figure 61. Calculated incremental lift-fan thrust based on measured gas energy for no. 1 ETC valves deflected from 0 to 40 deg

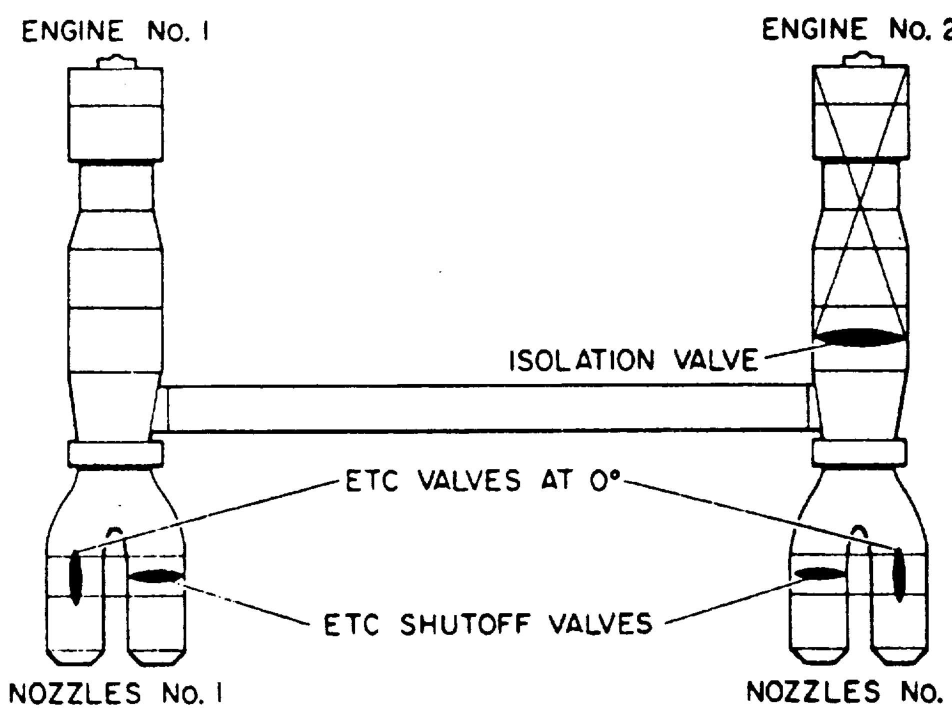


Figure 62. Initial configuration for investigating system behavior with no. 2 YJ-97 inoperative

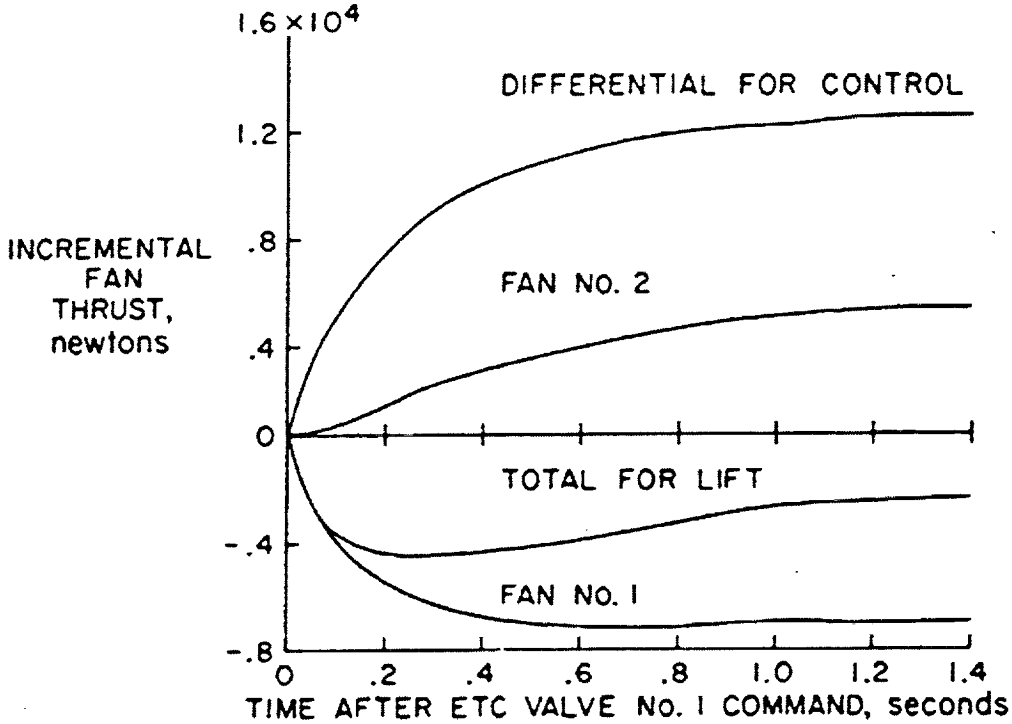


Figure 63. Time history of lift-fan incremental thrust after a 30 deg step input of ETC valves no. 1, with no. 1 YJ-97 at 97 percent speed and no. 2 YJ-97 inoperative

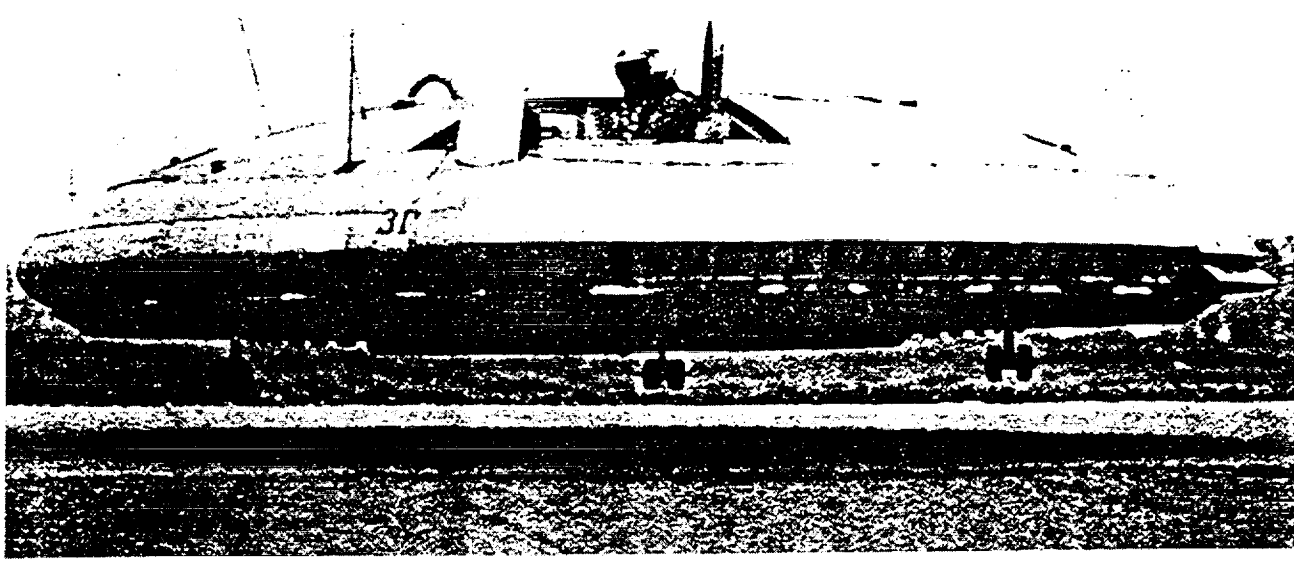


Figure 64. USA VZ-9AV/Avro Aircraft Limited Avrocar hovering 1 foot above concrete

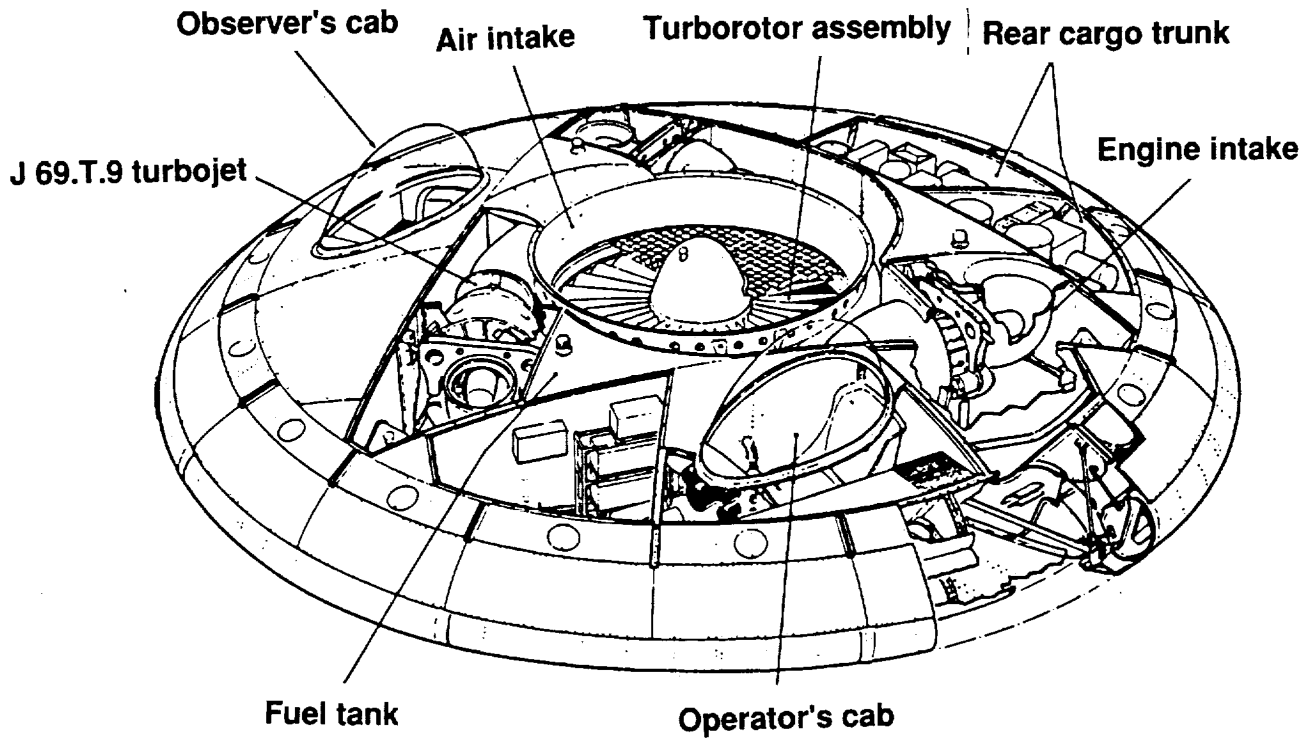


Figure 65. Artistic schematic of the Avrocar

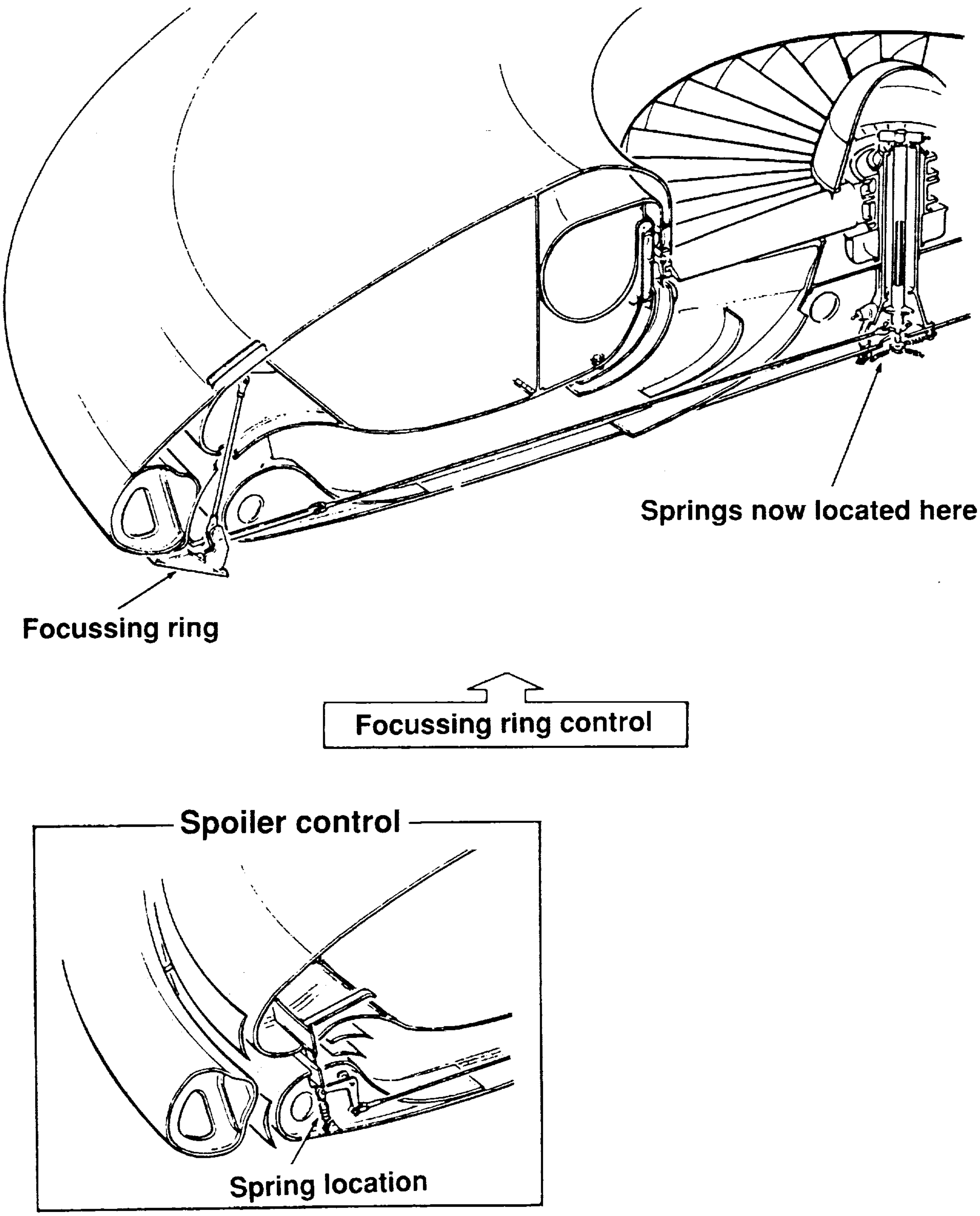


Figure 66. Avrocar original spoiler control system and final focusing ring control system

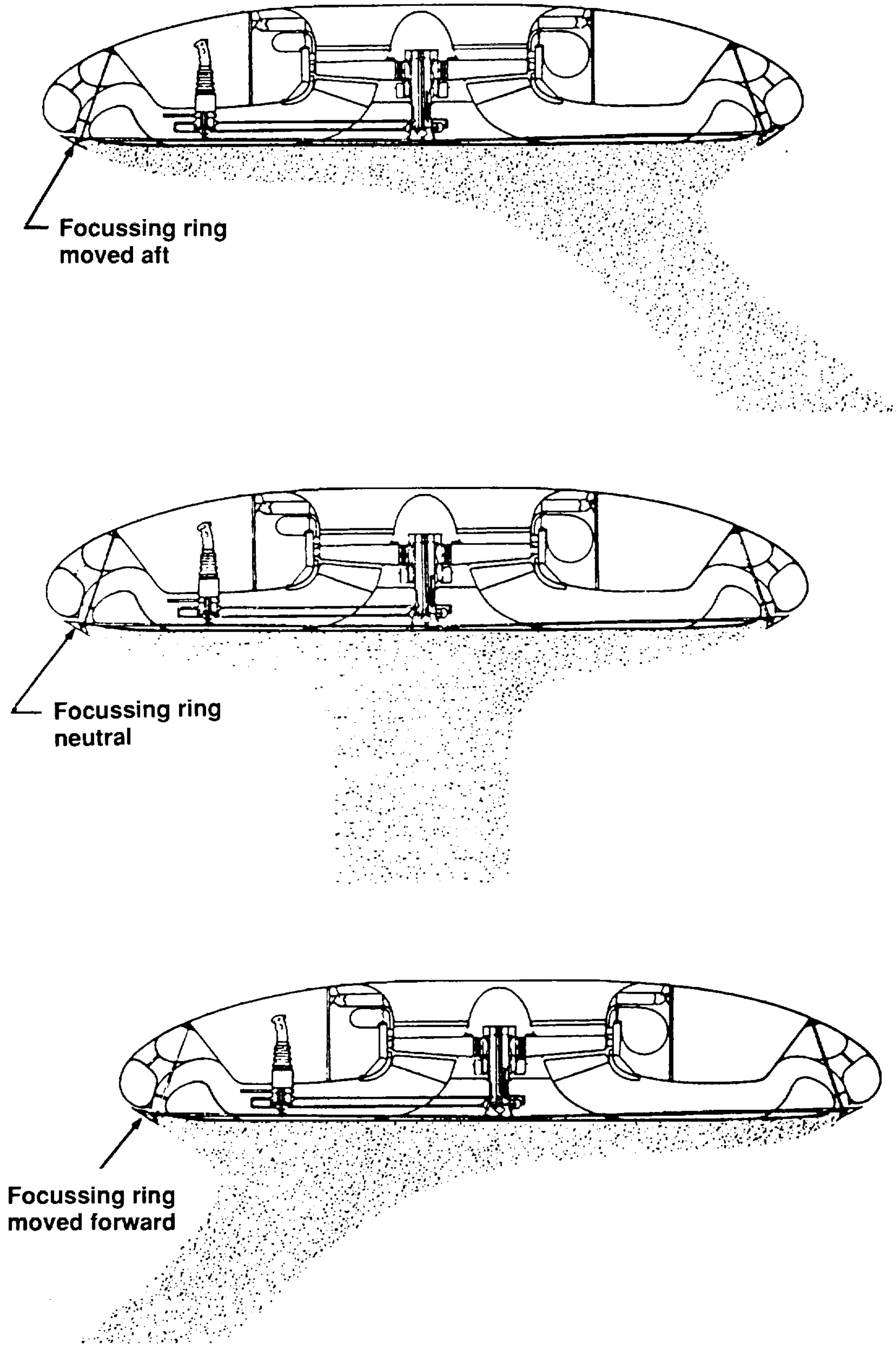


Figure 67. Effect of the focusing ring on the lift-fan annular nozzle jet exhaust

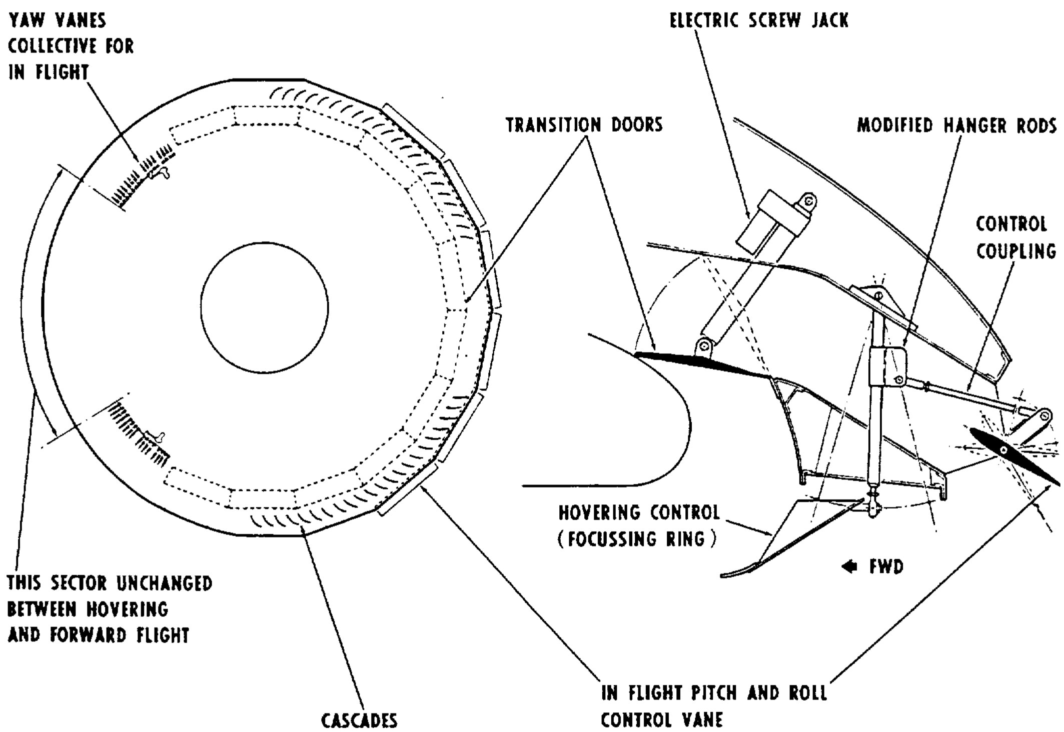


Figure 68. Illustration of design for transitioning from the low-speed to the high-speed control system

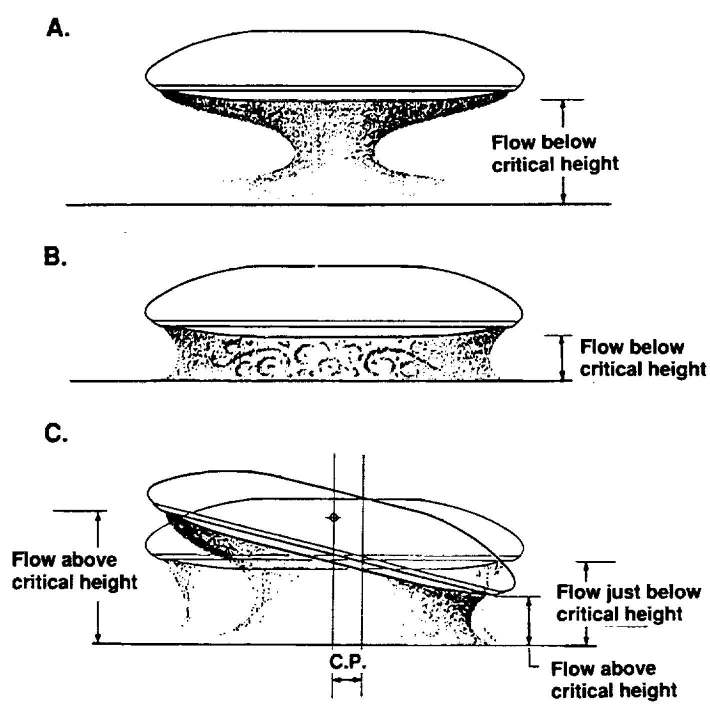


Figure 69. Illustration of cause of ground cushion instability at the critical hovering height

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This is one of a series of reports on the lessons learned from past research related to lift-fan aircraft concepts. An extensive review is presented of the many lift-fan aircraft design studies conducted by both government and industry over the past 45 years. This report addresses mission applications and design integration including discussions on manifolding hot gas generators, hot gas dusting, and energy transfer control. Past lift-fan evaluations of the Avrocar are discussed. Lessons learned from these past efforts are identified.

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