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PROPULSION SYSTEM FOR RESEARCH VTOL TRANSPORTS

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ABSTRACT

In anticipation of an eventual VTOL requirement for civil aviation, NASA has been conducting studies directed toward determining and developing the technology required for a commercial VTOL transport. In this paper, the commercial transport configurations are briefly reviewed; the propulsion system specifications and components developed by the engine study contractor are presented and described; and methods for using the lift-propulsion system for aircraft attitude control are discussed.

INTRODUCTION

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In anticipation of an eventual VTOL requirement for civil aviation, NASA has been conducting studies directed toward determining and developing the technology required for a commercial VTOL transport. Selected as a basis for these studies was a 100-passenger transport having the lift and cruise propulsion provided by fan-jet engines. Commercial transport configurations were proposed by three airframe contractors (refs. 1, 2, and 3). The propulsion systems required for these transports were identified in detail in references 4 and 5 and reviewed summarily in reference 6.

An important aspect of a VTOL technology program would be a research transport for proving out propulsion concepts, attitude control systems, and flight operational procedures. Research configurations would be existing aircraft modified for VTOL operation by the incorporation of the remote driven tip-turbine lift fan system described in reference 7.

The primary subject of this paper is the proposed propulsion system for a research VTOL transport. The remote driven lift-fan system is representative of a system which could be used on a commercial aircraft. In this paper, the commercial transport configurations proposed in the aircraft studies are briefly reviewed; the propulsion system specifications and components developed by the engine study contractor are presented and described; and methods for using the lift-propulsion system for aircraft attitude control are discussed.

AIRCRAFT CONFIGURATIONS

Aircraft configuration studies for a VTOL transport were made by The Boeing Company, North American Rockwell Corporation, and McDonnel Aircraft Company under NASA contract (refs. 1, 2, and 3). Configurations were evolved by each for a 1980-1985 time-period commercial transport.

Commercial Transports

The basic requirement for the commercial VTOL aircraft was that it be sized for 100 passengers with a 400 mile VTOL stage length or an 800 mile stage length when operated in the STOL mode and a Mach 0.75 cruise speed. Additional guidelines influencing the configuration and size were: a noise goal of 95 PNdB at 500 feet at lift-off power; engine or fan out capability; and gust sensitivity of 0.0295 g/fps.

Two types of engine systems were considered for the transport studies (fig. 1). These are an integral lift fan similar to the current turbofan engines but one-half the length, and a remotely driven tip-turbine lift fan similar to those used in the NASA XV5-B lightweight research aircraft. In the integral fan, special emphasis was placed in keeping the engine short. This resulted in a short compressor with the combustor folded back over the compressor making almost a square engine when viewed from the side. The tip-turbine fan is driven by the exhaust of a turbojet engine remotely located from the fan.

One of the primary Boeing transport concepts is shown in figure 2(a). This concept utilized 8 integral lift and lift-cruise engines mounted around the aircraft center-of-gravity. All the engines are identical except for differences in accessories and cowling which result from engine location and function. The forward two engines retract into the fuselage during cruise. Thrust vectoring is achieved by rotating the front and rear engines and by the use of louvers in the exhaust of the wing fans. The engine size is dominated by the thrust required to cruise and climb on two engines. This configuration had an estimated take-off gross weight of 116,700 pounds.

North American proposed a remotely driven lift fan configuration (fig. 2(b)) with a take-off gross weight of 120,000 pounds. Since the North American economic analysis showed very little difference in cost between the integral and remote lift systems, the remote fan selection was made on the projection that less technical risk would be involved in the aircraft and engine development. Six lift units are mounted in two wing pods with louvers used to obtain thrust vectoring. Two lift-cruise fans, which are the same size as the lift units, are mounted on the rear fuselage and use deflector hoods for the lift and transition mode. All fans are interconnected in pairs to compensate for engine out. In addition, emergency nozzles are provided on both wing pods and in the rear for use if a fan should fail.

McDonnell's remote lift fan configuration is shown in figure 2(c). This aircraft, with a take-off gross weight of 109,000 pounds is powered by 6 remote fan-gas generator systems. Two of these are in the fuselage behind the cockpit, two are in wing tip pods, and two are mounted on the rear of the fuselage. The fans, all of which are the same size, are interconnected in pairs in case of engine out. The lift system configuration in the wing tip pod was made identical to the system in the forward fuselage. A rotating cascade system is used for thrust vectoring on the four lift fans. The cruise fans use deflector hoods for vertical and transition thrust.

Research Transport

If a commercial VTOL transport is ever to become a reality, a comprehensive base of aircraft design and performance knowledge must be available. There are several areas that require a large aircraft in order to obtain this data base. These include new techniques in airframe design; full scale lift fan development and flight test; and operation of a large vehicle with attention given to hover, transition, control response, terminal area operation, etc. A tool to obtain this data would be a research aircraft resembling in handling characteristics the proposed commercial transport. A research aircraft would be an existing aircraft modified for VTOL operation by the addition of lift fans. The General Electric YJ97/LF460 lift system (ref. 7), which is a 60 inch diameter fan with a tip turbine driven by the exhaust from a YJ97 turbojet, would be specified as the engine system for the research aircraft. This system would have a very close resemblance to an advanced remote system. The research vehicle would be designed so that flight envelopes and operating techniques could be explored which would be applicable to the commercial aircraft. The noise goal for a research aircraft is less than 100 PNdB at 500 feet sideline. This goal is a compromise between keeping the noise level low for demonstration purposes and maintaining the capability to explore a wide range of flight conditions.

RESEARCH TRANSPORT PROPULSION SYSTEM

When the transport study contracts were initiated, the LF460 remote tip-turbine fan (ref. 7) appeared to be the only one which could be available. Therefore, the LF460 was specified for use in the research transport configurations. In the following paragraphs, the lift fan requirements are presented, the fan and gas generator features are described, and energy-transfer methods for attitude control and engine failure are discussed.

Gas Generator

The YJ97 was specified as the gas generator since it had the desired exhaust conditions for the fan turbine and also was the only existing engine in the preferred size range. This engine was developed as an advanced military turbojet. Figure 3 is a photo of the YJ97. At the maximum speed of 13,900 rpm, the engine develops 5270 pounds of thrust on a sea level static standard day. At the maximum operating conditions, the YJ97 exhausts 70 pounds/sec of gas at 54.76 psia and 1375° F. Since the YJ97 is a constant speed machine, increased gas power may be obtained for short periods of time by back pressuring the turbine. When the burbine is back pressured, the turbine temperature is increased by the fuel control system to maintain speed. This is permissible for short times with turbine exit temperatures up to 1600° F.

Lift Fan

Several basic lift fan requirements were established before and during the fan design. (1) All fans were matched to use the full power from the YJ97 gas generator. (2) The individual fan noise level must be less than 92 PNdB at 500 feet at take-off power to meet the research aircraft noise goal of less than 100 PNdB for a six engine vehicle. (3) To permit the use of fan modulation for control, a response time of 0.2 second to reach 63 percent of a step input is necessary for effective aircraft control. (4) A design life of 1200 hours total time. (5) The fan should be able to operate satisfactorily in a 150 knot crossflow, which would arise during transition. (6) The scroll was designed in two 180° sections to facilitate the interconnection of fans which is necessary in case of gas generator failure. Two lift-fan designs are discussed herein. These are the LF460, which was used for the previously discussed aircraft studies, and a lower-noise derivative herein called the Quiet Lift Fan.

<u>LF460 Lift fan.</u> - The LF460 is a 60 inch diameter lift fan driven by a single stage impulse tip turbine (fig. 4). Some of the specifications for the LF460 are listed in table I. The design of the LF460 was nearly complete before noise became one of the major considerations in system design. Therefore, the LF460 has limited acoustical treatment in the rear duct with two short acoustical splitters and duct liners. An axial spacing of two chord lengths was used between the rotor and stators along with an 18 degree stator lean in the direction of rotation at the hub in order to reduce stage noise generation.

Structurally, the fan was supported by a deep major strut with a much smaller minor strut at right angles for stability. The scroll was split into two 180° segments, which are fed by separate ducts. This keeps the size of the ducts smaller and facilitates the use of duct valves for control. The large part of the scroll was divided into 3 bubbles and placed outside the turbine to maintain a minimum outer diameter. The scroll and other high temperature components are made from nickel alloys.

Turbine buckets of Udimet 700 are brazed directly to the Rene 95 fan blades instead of by mechanical attachment, so that weight and polar moment of inertia could be reduced.

Quiet lift fan (QLF). - The "Quiet Lift Fan" (QLF) is a derivative of the LF460 fan. Although the LF460 was specified for use in the research transport, calculations showed that it would be difficult to design the aircraft to meet the noise goals. Modifications were then made to the LF460 to lower the noise. Some of the design features for the QLF are listed in table II. The interplay between the required thrust, pressure ratio, acoustical treatment, noise, and losses resulted in the selection of a 64 inch diameter fan with a pressure ratio of 1.32, giving a design lift of 14,940 pounds on a sea level static standard day. The fan tip speed of 1125 ft/sec was selected after consideration of effects on blade loading, noise, and turbine performance. The tip speed then influenced selection of 88 fan blades since it is very desirable to keep the blade passing frequency above 5000 Hertz because of the Noy factor. The turbine design conditions were set by the gas available from one YJ97 plus an added 9 percent turbine flow which would be supplied from a second gas generator during maximum thrust modulation.

A cutaway view of the QLF is shown in figure 5. This fan uses a split single bubble scroll to supply the turbine. The scroll is positioned partially ahead of the turbine, thus resulting in a deeper bellmouth than for the LF460 fan. The deeper bellmouth is advantageous during crossflow and when the fan is mounted for cruise. A three-strut front frame supports the center housing with the struts leaned slightly to allow for differential thermal expansion. The strut loads are carried through the scroll to three aircraft mounting points located under the scroll.

The fan blades, because of their large aspect ratio, require two midspan dampers for stability. Three turbine buckets with their shrouds are brazed to the end of each fan blade. The use of brazing for attachment of the turbine buckets instead of bolts, as used on the XV5-B lift fan system, reduced the polar moment of inertia as well as the number of parts. The stator blades are leaned in the direction of rotation 18 degrees as measured at the hub as a noise reduction technique. This lean also allows for differential thermal expansion between the hub, stators, and casing. The acoustical treatment at the exit is in the form of four treated splitters with liners on both walls of the duct. The splitters and liners have perforations and chambers designed to reduce the noise caused by the dominant frequencies.

Most of the techniques used to reduce noise add weight to the fan while causing thrust loss. This penalty is illustrated for lift fans in figure 6. Heavy acoustical treatment such as is used in the QLF reduces the thrust to weight ratio by over 20 percent when compared to a bare fan.

The turbine exhaust passage has a diffusing section built into it to keep both the turbine static pressure and duct exit velocity low. The jet exit velocity for both the turbine and fan is below 700 ft/sec. The fan blades and all high-temperature parts are made from high temperature nickel alloys, while Ti6-4 or Al is used in the remainder of the fan depending on the strength requirements.

CONTROL SYSTEMS

A VTOL propulsion system must provide the necessary control forces in hover and low-speed flight as well as the basic lift. There are two basic control methods which may be employed. The simplest one is the fan thrust spoiling technique, which was employed earlier on the Ames Research Center's XV-5B VTOL research aircraft. Although simple, fan thrust spoiling requires larger installed power systems at an increase in gross weight. The other system is control by thrust modulation, where as one fan thrust increases, the interconnected fan has decreasing thrust. This can be done by transferring flow from one gas generator to the opposite fan through the interconnecting duct. The transferred flow can be either engine exhaust flow or compressor bleed flow. Both of these types of systems are discussed.

Engine Exhaust System

A control system developed by McDonnel Aircraft, utilizes a single interconnecting duct between pairs of gas generators and fans to provide attitude control and engine-out operation. This system, called "energy transfer and control" (ETC), is shown in figure 7. Valves are located at the entrance to the fan scrolls, as illustrated in figure 7, to enable transfer of the gas from both engines to either of the fans for thrust modulation. As an example, if differential thrust is needed with an increase for fan #2, ETC valve #1 would be partially closed. This increases the mass flow to fan #2, thus increasing its thrust. Since the engine rpm is fixed by setting the engine throttles, the back pressure on the turbine created by closing the ETC valve will cause an increase in turbine exit pressure and temperature, thereby increasing the power output of both engines. The net result is an increase in total lift with fan #1 remaining at nearly constant lift and fan #2 with increased lift because of the increased gas energy. To maintain the same total system lift and to increase the moment response rate, the lift from the #1 fan must be reduced by spoiling with louvers. At maximum control conditions, a transfer of 9 percent mass flow will increase the fan thrust approximately 22 to 23 percent.

Additional valves are required for startup and emergency operation (fan or engine out). The shutoff valve in the connecting duct is used only to facilitate engine start up. During operation, if an engine fails, the isolation valve is closed along with one ETC Scroll valve in each fan. This divides the flow from one engine between the two fans maintaining a balanced moment and providing approximately 60 percent of design thrust of each fan. In the event of fan failure, the ETC valves at the failed fan plus one scroll valve on the good fan would close and at the same time the fan emergency nozzle is activated. This sequence of valve operations delivers the flow from one and a half engines through the emergency nozzle. The net result is again a lift of around 60 percent of design thrust, the same as with an engine failure. The application of this concept will provide the required thrust for control plus sufficient thrust with either a fan or engine out while minimizing the installed thrust required. However, this approach requires a large number of valves, with both the valves and ducting operated at high temperatures.

This ETC system has been simulated by McDonnel Aircraft under contract to NASA Ames Research Center by using two YJ97 turbojets with choked nozzles used to simulate the fans (choked flow in tip-turbine). The engines were operated over a range of speeds and ETC valve settings.

Figure 8 shows the results when a typical set of test data are used to calculate the fan thrust change as the position of the ETC valves to one fan is varied. The data points shown are not measured fan thrust but calculated fan thrust at the valve setting based on data for engine exhaust conditions obtained from the experiment. For example, a 35-degree valve deflection upstream of fan #1 would produce an increase of approximately 3000 pounds in the thrust of fan #2 while the thrust of fan #1 would be reduced by approximately 200 pounds from its nominal valve of 12,500 pounds. This results in an increase in total lift, so that when the system is applied to an aircraft the thrust must be spoiled on the #1 fan.

Compressor Bleed System

One method of power transfer which has been investigated by computer simulation is a compressor bleed system (ref. 8). A schematic of the basic elements of this system for a two-fan configuration is shown in figure 9. When differential lift is required, air is bled from the compressor exit and ducted to the opposite fan turbine. The primary advantage of this system is the low temperature of the transfer flow. This air is below 1200° R, but at high pressure, about 200 psia, thereby requiring only small lightweight duct and valves made from titanium.

This system works in the following manner. If a thrust increase is required from fan F_1 (fig. 9), valve ports VF_1 and VE_2 are opened, permitting compressor flow from engine E_2 to flow to fan F_1. The thrust of fan F_1 increases because of the additional flow and also because of a temperature increase due to the increased back pressure on engine E_1. Fan F_2 loses thrust because of the reduced engine E_2 exhaust flow, but this is partly counteracted by an increase in engine E_2 exhaust temperature. As an example, to meet the roll requirements of a typical research aircraft would require approximately 9 percent compressor bleed.

A basic limitation of the compressor bleed system is in engine-out performance. In the six engine configuration, shown in figure 10, if either fan or engine failed both would be shut down, the emergency interconnect valve and the emergency nozzle valve on the failed side would open, energizing the emergency nozzle with bleed flow from the other five engines. This drives the temperature up in the remaining engines to their limit. The recovered thrust in this case is about 6 percent less than can be obtained by the ETC system. The major advantage of this system is the capability to use low temperature, small size ducting, and low temperature valves.

CONCLUDING REMARKS

This paper has reviewed the aircraft configurations which have been proposed for VTOL transports. There was no unanimous opinion among the designers on the best type of propulsion system, remote or integral, to be used on the commercial transports.

A detailed design of the LF460 lift fan, which was specified for use in the research aircraft studies, has been completed. This design contains technology that is well within the state of the art. The emphasis on reduced aircraft noise required some modifications to the LF460. Preliminary modifications in the design were completed which reduced noise but also reduced the thrust-to-weight ratio.

The results of the "Energy Transfer and Control" system tests show that this system can provide adequate attitude and engine-out control in the VTOL mode. By the use of fan emergency nozzles and interconnect ducting, the system can provide either fan or engine out operation at very little increase in the installed thrust that would be required for normal operation.

A research vehicle in the 50,000 pound gross-take-off-weight class powered by the YJ97/LF460 system can act as the integration medium for all the technology, such as airframes, propulsion, controls, navigation aids, flight techniques, etc., needed to develop a workable transport.

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8. Sellers, J. F. and Szuch, J. R.; "Control of Turbo-Fan Lift Engines for VTOL Aircraft," Paper April 1973, ASME Conference, Washington, D.C.

TABLE I. - LF460 LIFT FAN DESIGN PARAMETERS

Total pressure ratio, max. power	1.36
Total pressure ratio, take-off	1.29
Corrected air flow	617 lb/sec
Corrected tip speed	1125 ft/sec
Tip diameter	59.95 in.
Design thrust	15,057 lb
Number of fan blades	88
Number of fan stator vanes	56
Number of turbine blades	264
Turbine inlet pressure	54.74 psia
Turbine gas flow	76.22 lb/sec
Turbine inlet temperature	2060° R

TABLE II. - QUIET LIFT FAN DESIGN PARAMETERS (QLF)

Total pressure ratio, max. power	1.32
Total pressure ratio, take-off	1.25
Corrected air flow	711 lb/sec
Corrected tip speed	1125 ft/sec
Tip diameter	64 in.
Design thrust	14,940 lb
Number of fan blades	88
Number of fan stator vanes	56
Number of turbine blades	264
Turbine inlet pressure	54.74 psia
Turbine gas flow	76.22 lb/sec
Turbine inlet temperature	2060° R

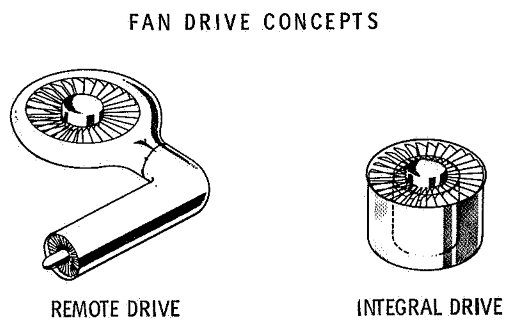
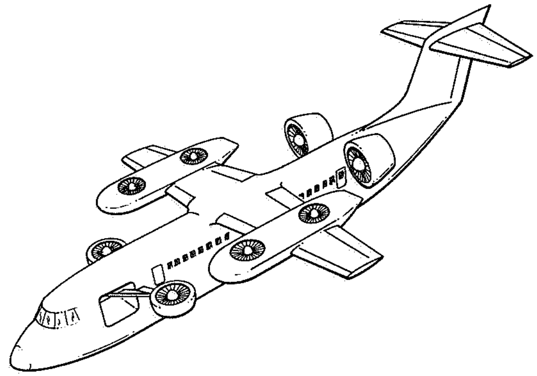
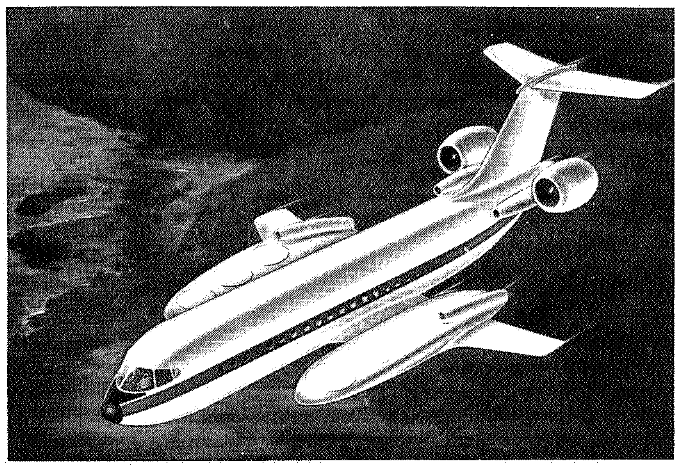


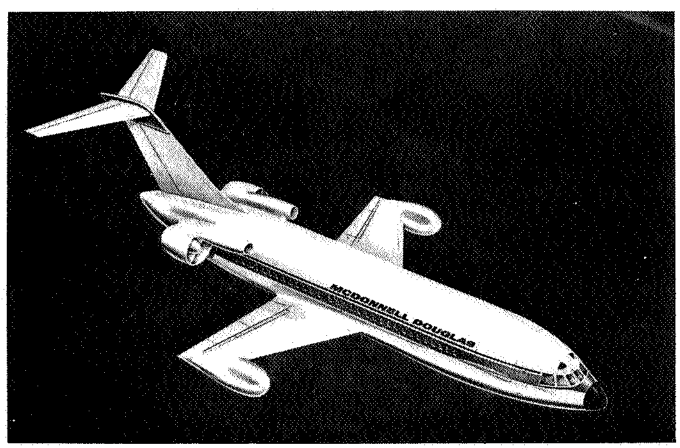
Figure 1. Lift system types.



(a) BOEING.



(b) NORTH AMERICAN ROCKWELL.



(c) MCDONNELL DOUGLAS.

Figure 2. VTOL commercial transport concepts.

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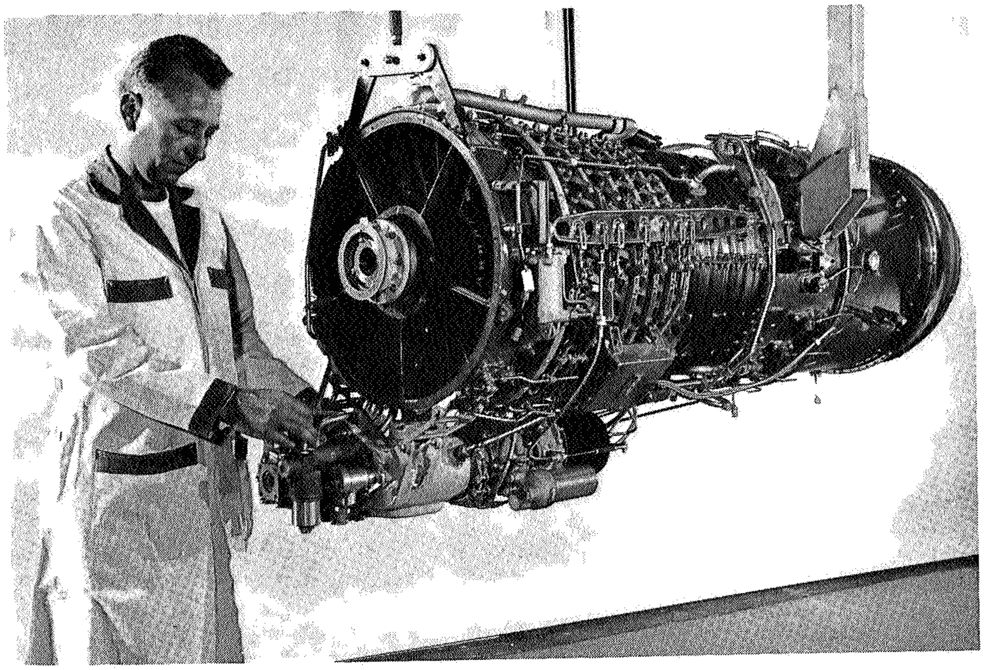

Figure 3. - YJ97 gas generator.

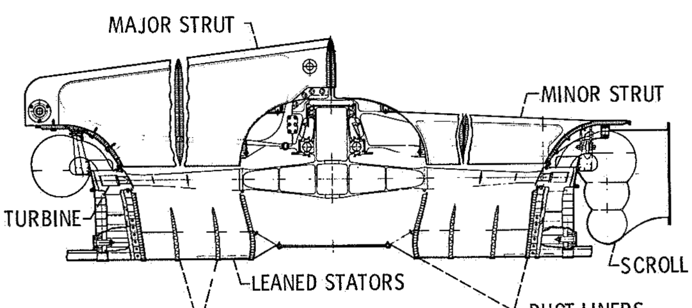

Figure 4. LF460 lift fan layout.

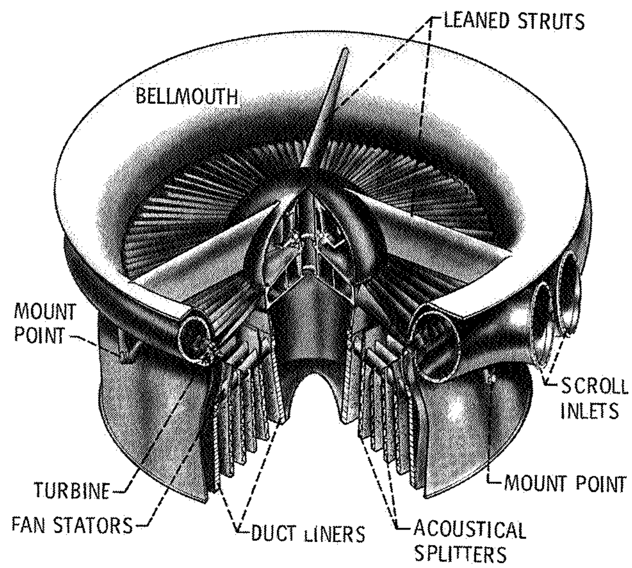

Figure 5. Quiet lift fan.

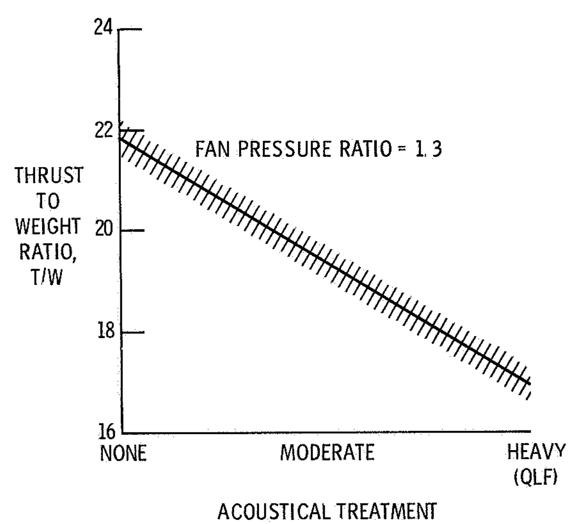

Figure 6. Effect of acoustical treatment on fan thrust-to-weight ratio.

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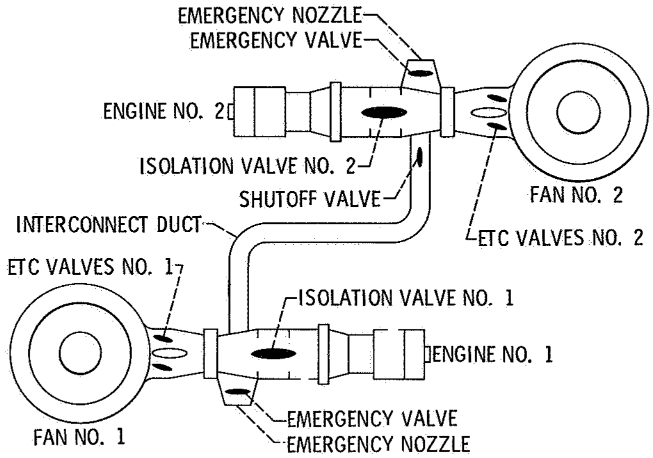

Figure 7 Schematic of an energy transfer and control system.

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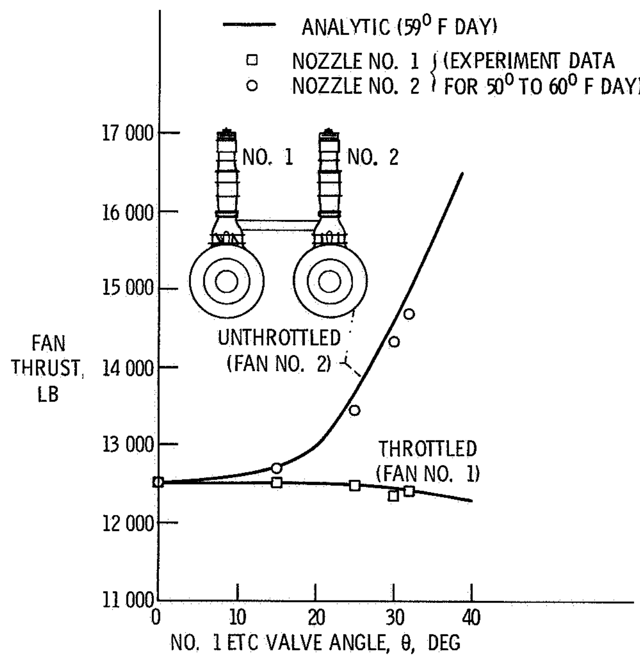

Figure 8. Typical date calculated from ETC test results with YJ97 engines at 101.5 percent engine speed.

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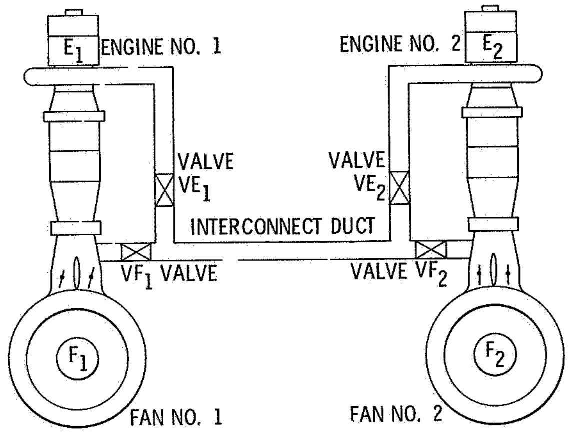

Figure 9. Schematic of a two engine compressor bleed transfer system.

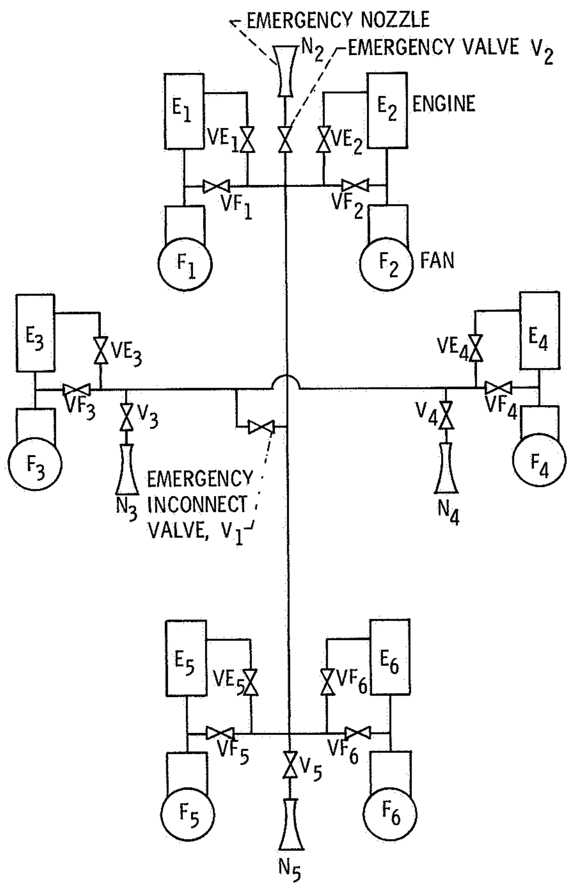

Figure 10. Schematic of a six engine compressor bleed system.

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