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STOVL AIRCRAFT PROPULSION INTEGRATION

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Abstract

This paper describes the Lockheed Aeronautical Systems Company's advanced STOVL aircraft design efforts from the perspective of propulsion system integration. The design approaches and performance characteristics of some of the aircraft concepts studied are briefly presented. The airframe/propulsion integration features of the split-flow-in-hover propulsion concept are then described in more detail. This is followed by a description of the propulsion integration features in general for STOVL designs. Specific inlet and nozzle performance data are presented which are applicable to a variety of STOVL concepts.

Introduction

The U.S. aircraft industry has long been interested in producing an operational supersonic short takeoff and vertical landing (STOVL) fighter aircraft. Many aircraft design concepts have been studied, but as yet no manufacturer has undertaken the development of a demonstrator program based upon any of the defined aero-propulsion design concepts. The primary reason has been a lack of funding, due in part to not having a well defined operational requirement from the military services. A secondary problem is that the technical community lacks agreement as to which of the propulsion system concepts is "best."

A successful supersonic STOVL aircraft will require a propulsion system design which has a high installed specific thrust. It must have a low frontal area for efficient supersonic level-flight operation. Also, it shall be easily controllable and have fully vectorable and environmentally benign nozzle exhaust in the transitional and landing modes. There is no propulsion system that can satisfy these requirements without imposing some compromise to the aircraft's weight, complexity, and supersonic cruise performance capability relative to a conventional takeoff and landing (CTOL) equivalent fighter. This is a natural consequence of integrating a lifting propulsion system into a supersonic aircraft design.

Fortunately, the technology advances being infused into modern aircraft and engine designs are contributing to a reduction in the magnitude of the STOVL penalty to a point where it is approaching an acceptable level. Therefore, a number of the proposed STOVL propulsion system concepts are becoming attractive.

In recognition of this, the Lockheed Aeronautical Systems Company and other major U.S. aircraft companies have been examining the engine manufacturers' proposed STOVL engine concepts to identify the most salable aircraft design. Under the recent US/UK Advanced STOVL (ASTOVL) program [1], four propulsion systems capable of providing vertical landing capability were examined: vectored thrust, remote augmented lift system (RALS), ejector augmentor, and hybrid fan vectored thrust (HFVT).

Figure 1 depicts the single-engine ASTOVL conceptual configurations developed for these propulsion systems by the U.S. aircraft industry. Lockheed participated in the ASTOVL studies [2] developing an aircraft design concept based upon the use of Rolls-Royce's HFVT engine system [3]. This engine concept incorporates a split-fan design. In a three-poster arrangement, when operating in the vertical mode, the front fan feeds two forward thrust posts very much like the AV-8 Harrier's Pegasus system. The rear post is provided by vectoring the engine's lift/cruise nozzle. An artist's concept of an HFVT STOVL aircraft design developed by Lockheed is shown in Figure 2. This particular design uses a rear ventral nozzle during hover instead of vectoring the engine's cruise nozzle.

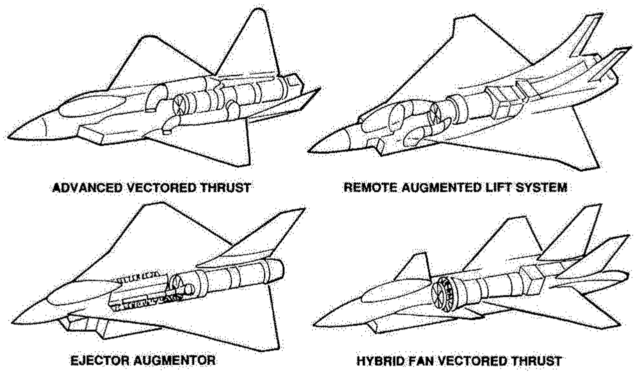

Figure 1. ASTOVL Configuration Concepts

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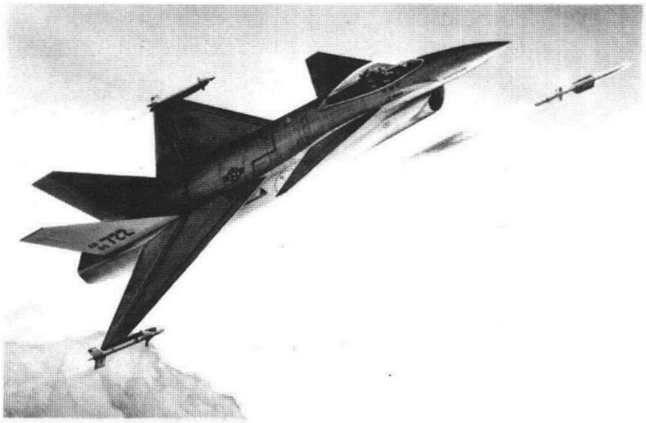

Figure 2. Artist's Concept of an HFVT STOVL Fighter

More recently Lockheed has directed it's in-house studies toward examining other STOVL propulsion concepts. These include the ejector augmentor, remote exhaust (REX), lift-plus-lift/cruise (LPLC), remote exhaust fan (REF), split-flow-in-hover (SFIH), and reverse-installation-vectored-engine-thrust (RIVET). The general arrangement of the LPLC aircraft is shown in Figure 3. It is the easiest concept to integrate into an aircraft design, since a lift engine system can be installed without having to alter or compromise the cruise engine system. The layout of a four-poster SFIH STOVL configuration concept is shown in Figure 4. The exhaust flow path of the SFIH engine is indicated in Figure 5 for both the forward-flight and powered-lift operating modes. In cruise it operates as a conventional low-bypass-ratio mixed flow turbofan. In the lifting mode, the engine's fan flow is ducted to the forward airframe-mounted vectoring nozzle system, while the core flow is exhausted through the rear engine-mounted nozzle system.

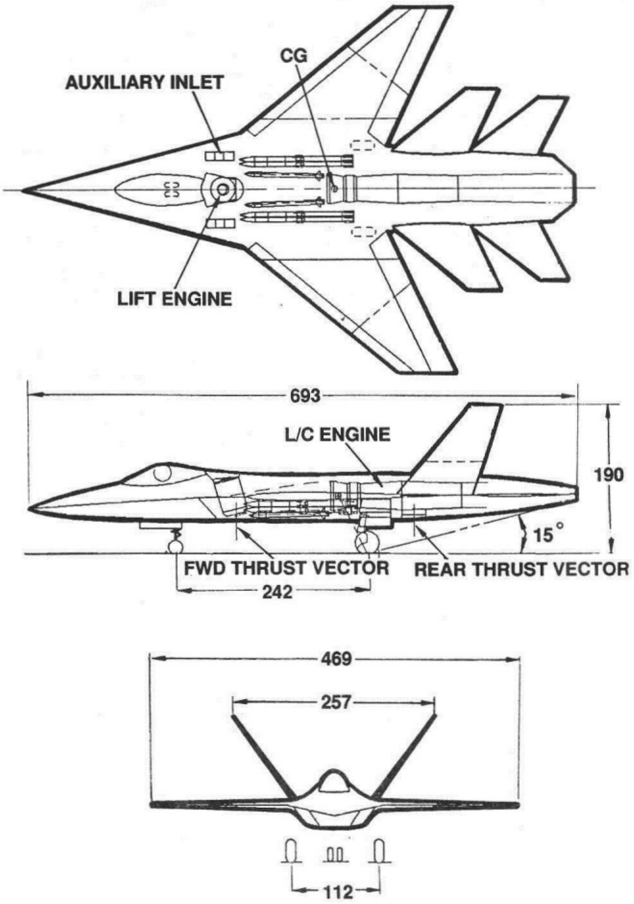

Figure 3. LPLC STOVL Conceptual Design

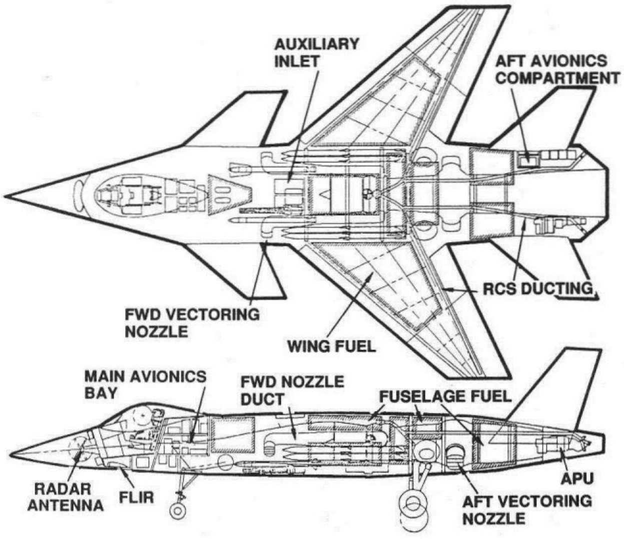

Figure 4. SFIH STOVL Inboard Profile

The STOVL aircraft concept which utilizes the Lockheed-patented RIVET design is shown in Figure 6. The primary advantage of reverse engine installation is that it locates the engine's exhaust nozzle system on the aircraft center of gravity. This allows the cruise nozzles to be swiveled for vertical-lift operation and to enhance air-to-air combat effectiveness. The 180°-turn inlet duct has been tested and was found to have acceptable performance. As no special engine exhaust ducting is required, more internal space in the aircraft is available for internal carriage of weapons.

The remainder of this paper presents an overview of selected results of these studies from a generic "propulsion system integration" perspective. The material presented is, therefore, applicable to more than one STOVL propulsion system concept.

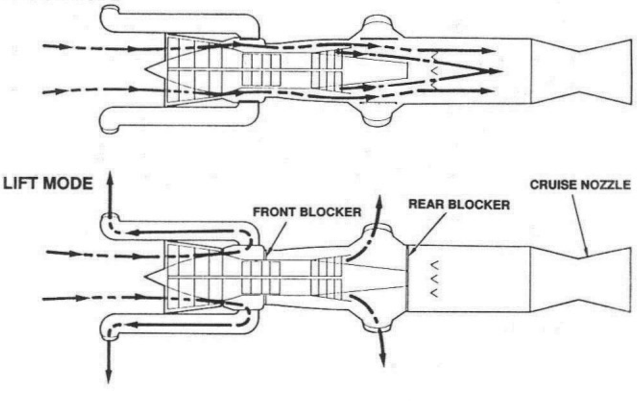

Figure 5. SFIH Engine Operating Modes

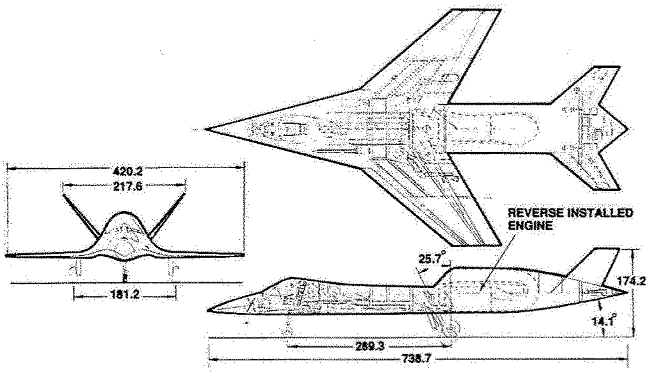

Figure 6. RIVET STOVL Conceptual Design

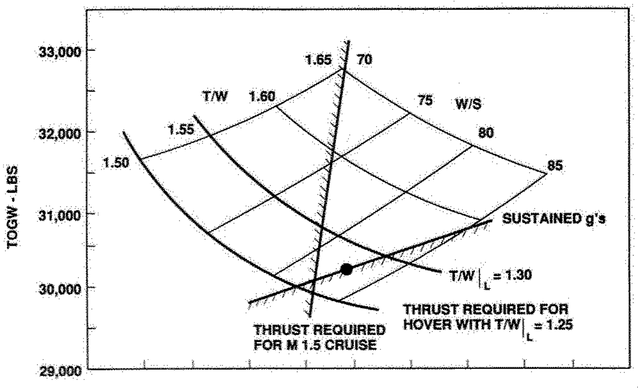

Figure 8. SFIH STOVL Sizing

General Considerations

The primary concern of the engineer developing the propulsion system integration is to avoid having to oversize the engine(s) for any one of the design mission operating conditions. The goal is to have the propulsion system's thrust availability matched as closely as possible to each of the aircraft's critical mission operational requirements. The critical operating conditions for the STOVL aircraft are short takeoff, transonic maneuver, dry-power supersonic cruise, and vertical landing. For Lockheed's studies, the mission used to design and size the STOVL aircraft concepts is presented in Figure 7. The requirements are: a mission radius of action of 300 n.m., supersonic cruise speed of Mach 1.5, and 4.5g maneuver at the combat condition.

The degree to which the match between cruise, maneuver, and vertical landing thrust can be achieved is illustrated in Figure 8 for the SFIH STOVL concept. This carpet plot shows how aircraft takeoff thrust-to-weight ratio (T/W) and wing loading (W/S) variations affect takeoff gross weight (TOGW). The constraints shown are: (1) cruise drag; (2) transonic sustained turn "g" requirement, and (3) hover lift thrust (with margin). Because of the close match between these constraints the aircraft's external configuration arrangement can be optimized for the cruise and maneuver conditions. This requires that the features needed to perform STOVL operations, e.g., vectoring nozzles, to be retracted within the aircraft's external skin in forward flight. They just cannot "hang out" as on the subsonic Harrier aircraft.

Figure 9 presents the normal area progression of Lockheed's SFIH STOVL concept, which is a measure of how well the external arrangement was optimized. The aircraft's cross-sectional area distribution, while not ideal, provides sufficient internal space for all of the STOVL-specific features, such as ducting, valves, and nozzles within an acceptable fineness ratio. To achieve a smooth external geometry, the use of some sophisticated propulsion system integration concepts is required.

During transition and hover, the cruise engine nozzle system must be capable of either fully vectoring to angles in excess of 90 degrees or being closed off. When it is closed off, the flow can be exhausted through either a ventral or Pegasus-type nozzle system. Whatever lift nozzle system is utilized, it must also be capable of being closed off and made flush with the aircraft's external surface during forward flight. The aircraft may also require a reaction control system (RCS) to enhance pitch, roll, and yaw control at low-speed conditions and during hover. It is an understatement that a supersonic-capable STOVL aircraft design presents some rather unusual propulsion-integration challenges.

The following sections are devoted to a discussion of the primary propulsion integration features which impact STOVL aircraft performance, namely inlet and nozzle design.

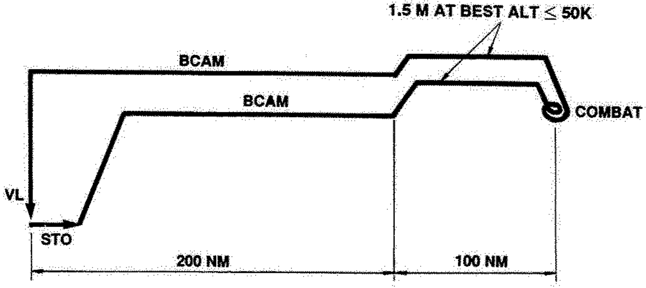

Figure 7. STOVL Design Mission

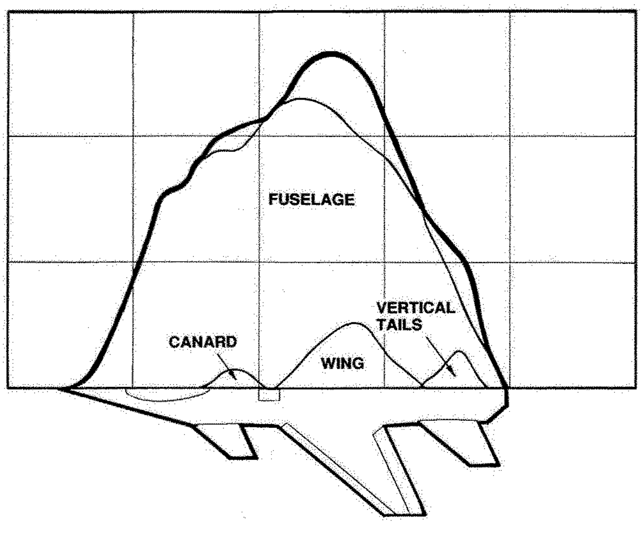

Figure 9. SFIH STOVL Area Progression

Inlet Design

The inlet system on a supersonic STOVL aircraft must provide as high an inlet total pressure recovery, and as low a level of flow distortion, as possible at the critical operating conditions. The designs examined by Lockheed utilize normal-shock, fixed-geometry inlet systems which have highly offset subsonic diffusers. Main and auxiliary inlets are located on the aircraft in favorable positions from a hot-gas-reingestion standpoint. On most of the configurations, the main inlets are located on the side of the fuselage and auxiliary inlets are located on top of the fuselage. Top-mounted inlets, such as the one shown in Figure 6, have obvious advantages from a reingestion standpoint, but do not generally integrate into the aircraft design very well.

The inlets of all supersonic aircraft are required to have sharp cowl lips to maximize cruise performance and minimize drag. Because such designs have poor low-speed performance, they require a large-size auxiliary inlet door system. Such systems have been designed into each STOVL concept. The inlet design features to be considered are shown in Figure 10. The auxiliary inlet door and cowl lip surfaces must be designed to minimize the losses through the system, and to avoid unfavorable distortions in total pressures.

Most of the aircraft designs feature an auxiliary inlet system which is sized to permit 40 to 100 percent of the required engine flow to enter at static conditions. The data presented in Figure 11, from [4] and [5], show the potential improvement in inlet pressure recovery, as a function of engine corrected fan speed at static conditions, through the use of auxiliary inlet systems. Improvements of over 10% are possible at high power settings. Similar improvements can also be achieved at Mach 0.20, as shown in Figure 12. Above Mach 0.20 there is a diminishing performance benefit, because of the reduction in inlet massflow ratio. Therefore, the auxiliary inlet is usually closed before Mach 0.30 is reached, particularly if some portion of the doors' variable geometry extends into the freestream flow.

Nozzle Design

The most important design consideration in a STOVL aircraft is the relative location of the lift nozzle system with respect to the aircraft's center of gravity and planform. Nozzle locations must be selected such that the engine/aircraft control system requirements are not excessive. The locations should minimize suck-down and provide favorable fountain effects during hover. Another nozzle design consideration is how to best vector the vertical lift nozzle system so that a smooth transition from horizontal to vertical flight is provided.

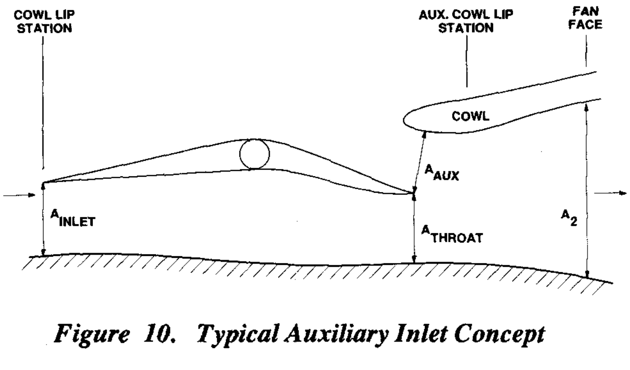

Figure 10. Typical Auxiliary Inlet Concept

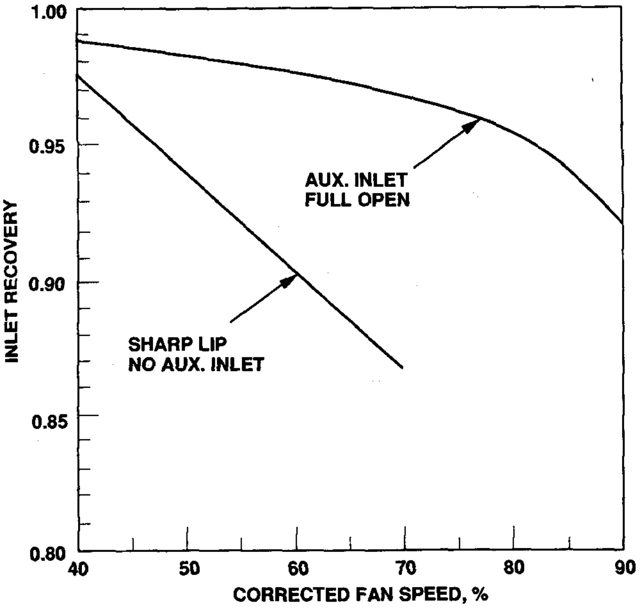

Figure 11. Inlet Total Pressure Recovery, $M_0 = 0$

Figure 13 illustrates the nozzle options considered by Lockheed for an LPLC propulsion system concept. For this concept, the favored approach combines the vectoring ability of the main cruise engine nozzle and a ventral nozzle, together with that of the lift engine nozzle. The cruise and lift engine nozzles are designed with 20-degrees of thrust vectoring, to limit their complexity and weight. The ventral nozzle incorporates turning vanes which allow it to operate to angles up to 70 degrees. A sketch of the ventral nozzle concept is shown in Figure 14. Thrust vectoring is accomplished by

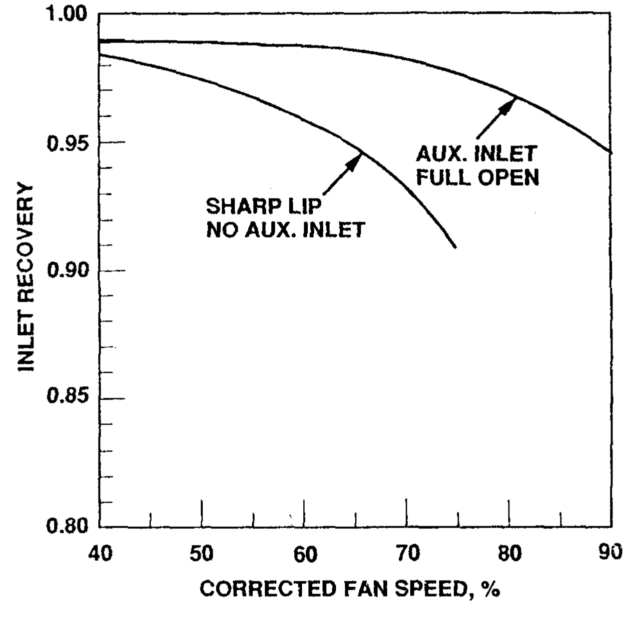

Figure 12. Inlet Total Pressure Recovery, $M_0 = 0.20$

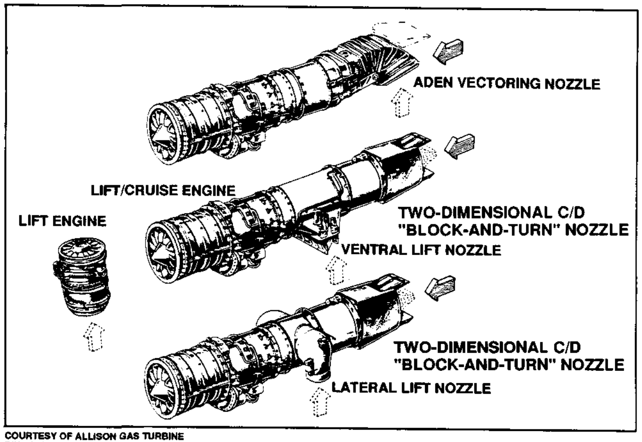

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Figure 13. LPLC STOVL Nozzle Options

moving the vanes. A sliding-door arrangement is provided to close off this system.

The advantage of using a ventral system is that it allows the designer the freedom to optimize the axial location of the engine and nozzle systems on the aircraft. On the particular LPLC STOVL aircraft studied (Figure 3), the use of the ventral nozzle allowed downsizing of the lift engine by 40 percent. It is because at the original lift engine location the lift/cruise engine had to be throttled back to provide balance in pitch. This is illustrated in Figure 15, which shows the amount of lift engine downsizing possible as a function of the forward-to-aft thrust ratio. In this case, the ventral nozzle was located just downstream of the engine turbine exit cone and upstream of the afterburner.

To achieve the maximum advantage of a ventral nozzle system, the nozzle must have a reasonably good thrust coefficient. For the concept presented, a nozzle thrust coefficient of .85 was used. Figure 16 shows that at this value the engine sizing criteria for vertical and forward flights are reasonably well matched. Figure 17 is a representative sample of test data which show that at the nozzle pressure ratios of interest a thrust coefficient of .85 is realistic.

Lockheed has recently completed a ventral nozzle test program with the General Electric Aircraft Engine Co. to validate some of the performance characteristics of the ventral nozzle system shown in Figure 14 during transition and hover.

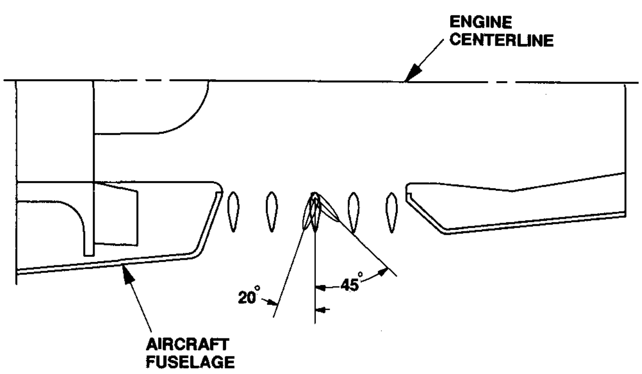

Figure 14. Ventral Nozzle Design Schematic

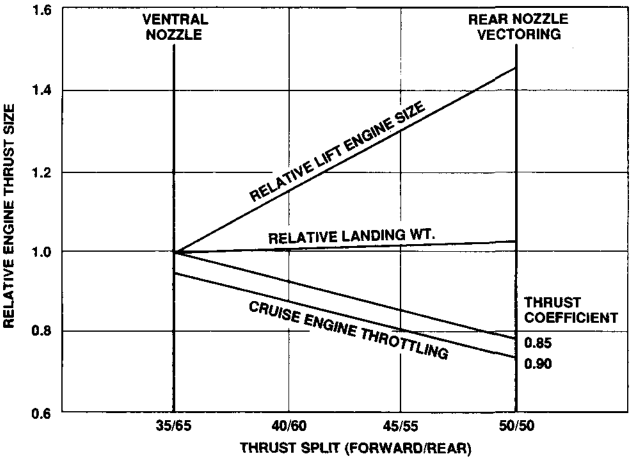

Figure 15. Effect of Thrust Split on LPLC Engine Size

Previous test results had shown that during transition a thrust drop-off occurs as the thrust vector moves between 20 and 40 degrees. This is illustrated in Figure 18, which shows axial and vertical gross thrust coefficients as a function of vector angle. While this thrust loss is only a momentary occurrence, it can significantly affect aircraft handling. Data from the test of a newer design are not yet available, but preliminary indications are that it has improved characteristics.

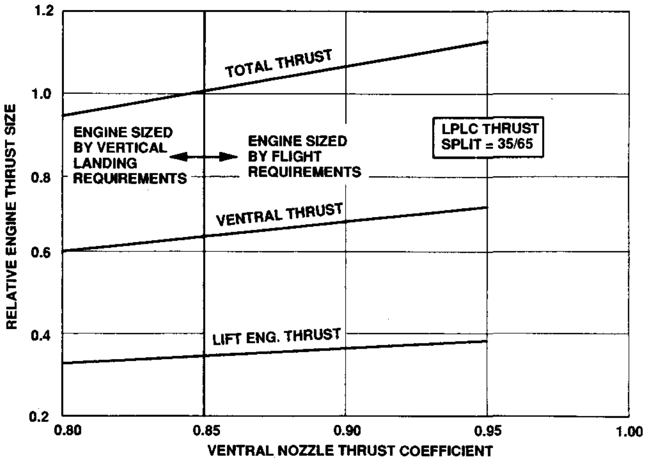

Figure 16. Ventral Performance Effect on Engine Thrust

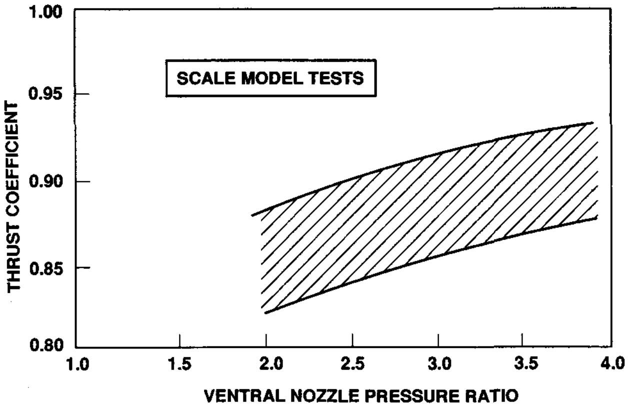

Figure 17. Ventral Nozzle Performance Range

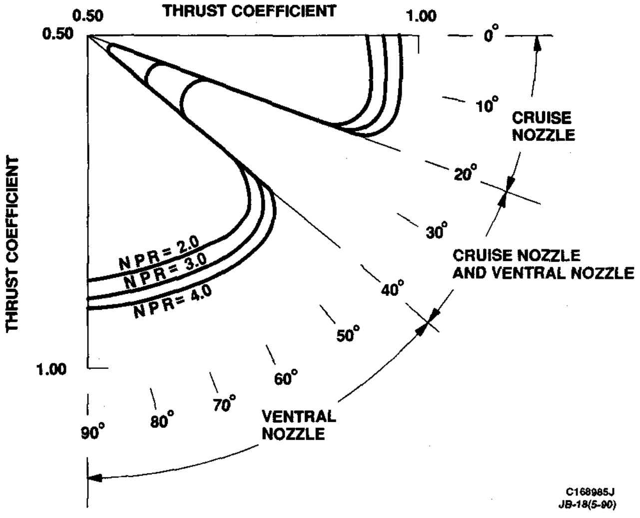

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Figure 18. Typical Nozzle Transition Performance

Concluding Remarks

A number of STOVL propulsion concepts have been examined. These concepts are capable of being integrated into an aircraft to satisfy a specific supersonic mission. Test data on scale-model components of STOVL key elements of the propulsion systems, i.e., inlet and nozzle, confirmed the validity of the performance assumptions made. The next logical step is to proceed with a large- scale demonstrator aircraft program to validate one of these concepts. At present, Lockheed is still evaluating the many concepts to determine which one is the most viable candidate for a demonstrator program. It is expected that a downselect will be made later this year for a competition next year with other airframe manufacturers to design and develop a STOVL flight demonstrator aircraft.

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